A Scoping Review of Assistance and Therapy with Head-Mounted Displays for People Who Are Visually Impaired

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Given the inherent visual affordances of Head-Mounted Displays (HMDs) used for Virtual and Augmented Reality (VR/AR), they have been actively used over many years as assistive and therapeutic devices for the people who are visually impaired. In this paper, we report on a scoping review of literature describing the use of HMDs in these areas. Our high-level objectives included detailed reviews and quantitative analyses of the literature, and the development of insights related to emerging trends and future research directions.

Our review began with a pool of 1251 papers collected through a variety of mechanisms. Through a structured screening process, we identified 61 English research papers employing HMDs to enhance the visual sense of people with visual impairments for more detailed analyses. Our analyses reveal that there is an increasing amount of HMD-based research on visual assistance and therapy, and there are trends in the approaches associated with the research objectives. For example, AR is most often used for visual assistive purposes, whereas VR is used for therapeutic purposes. We report on eight existing survey papers, and present detailed analyses of the 61 research papers, looking at the mitigation objectives of the researchers (assistive versus therapeutic), the approaches used, the types of HMDs, the targeted visual conditions, and the inclusion of user studies. In addition to our detailed reviews and analyses of the various characteristics, we present observations related to apparent emerging trends and future research directions.

CCS Concepts: • **General and reference → Surveys and overviews**; • **Human-centered computing → Mixed / augmented reality**; **Virtual reality**; • **Social and professional topics → Assistive technologies**.

Additional Key Words and Phrases: head-mounted display; HMD; visual impairment; assistance; therapy; virtual reality; augmented reality

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1 INTRODUCTION

A great number of studies have been conducted in the broad field of ophthalmology, and tremendous resources have been invested in the prevention and treatment of a variety of visual conditions. As our global population grows, and human lifespans increase, the need for mechanisms for visual assistance and therapy continues to grow. As reported by the World Health Organization (WHO) in 2019, a growing range of effective strategies are available to address the needs associated with eye conditions and vision impairments, including treatment ("curing as well as addressing symptoms and progression") and rehabilitation ("maximizing the use of residual vision and providing practical adaptations to address the social, psychological, emotional, and economic consequences of vision impairment") strategies [72].

While there is evidence that the pervasiveness of personal electronics has increased the prevalence of ocular symptoms [38], it also seems that the increasing availability and prevalence of HMDs is increasing the opportunities for related treatment and rehabilitation. In 1999, Harper et al. discussed the "emerging" head-mounted Low Vision Aid (LVA) devices based on video technology, characterizing them as having a promising future, and articulating fundamental advantages including hands-free operation and ready adaptation to a wide range of tasks, and disadvantages (at that time) including bulky size, high cost, and complexity of use [32]. The Low Vision Enhancement System (LVES) by Visionics Corporation was one of the leading players in the head-mounted LVA market in the 1990s. However, at that time HMDs did not seem to be practical for the general public. In 2003, Peterson et al. conducted a study with 70 visually-impaired subjects, comparing three types of electronic vision enhancement systems with a conventional optical magnifier. At the time, the HMD-based systems performed the worst [57]. In 2004, Culham et al. compared the clinical performance of four head-mounted LVAs with the performance of conventional optical LVAs, and suggested that practitioners should only consider head-mounted LVAs in certain circumstances [19]. Not surprisingly, it seems that the early head-mounted LVAs ended up quietly disappearing.

A seminal use of HMDs for vision therapy was for Unilateral Spatial Neglect (USN), which is a neurological condition characterized by a failure to explore and allocate attention in a particular region [65]. In 2009, Tsirlin et al. reviewed the use of Virtual Reality (VR) in assessing, treating, and studying USN, admitting that there were little data documenting the effectiveness of VR-related treatments [68]. They articulated advantages and disadvantages of HMDs similar to those by Harper et al. (*id.*), concluding that the technology was attractive, but that several characteristics of current VR technologies—including ergonomics, complexity, and cost, can pose a challenge to the development of new applications for USN.

In the 2010s, HMDs have significantly improved in several respects, including cost and availability. As such, there has been a resurgence in the market related to the use of HMDs in visual assistance and therapy. For example, founded in 2006 in Canada, eSight released its first generation product, eSight 1, in the same year, while the second generation came to the market in 2015 [2]. Founded in 2014 in the US, Iris Vision employs phone-based VR devices to help certain visually impaired individuals see better [4]. Founded in 2014 in the UK, Give Vision's first generation product SightPlus is another example of a phone-based VR aid. They carried out a clinical trial in 2019 on 60 low-vision participants testing their visual acuity, contrast sensitivity and reading performance with and without SightPlus [18]. Nearly half of the participants indicated willingness to use this product. Their second generation product is based on a pair of Optical See-Through (OST) glasses for AR [3].

Also founded in 2014, the US company Vivid Vision has offered products for the treatment of eye conditions including amblyopia ("lazy eye"), strabismus ("crossed eyes"), and convergence insufficiency [5]. Their system, which was already in use by clinicians in 2018, provides the HMD version of dichoptic training [9]. They conducted a study on 17 adults with amblyopia, a vision disorder regarded as incurable after the age of eight, and received positive preliminary results [83].

Here we provide a scoping review of the progress researchers have made using HMDs for visual assistance and therapy to date. While we identified eight review papers during our screening, they turned out to be focused on very specific vision conditions, or were not conducted for scoping purpose. Three of the identified survey papers focused purely on the VR-based assessment and treatment of USN, all of which emphasized the importance of comparing the performances of VR methods with the conventional methods, the needs to customize the ergonomics of VR devices and user study settings for people with USN as they are likely to have other medical issues such as mobility difficulties, and the necessity of lowering the cost to make the apparatus practical for clinical uses [54, 56, 68]. Tsirlin et al. described different implementations of the conventional and VR methods, while no systematic literature search was conducted [68]. Pedroli et al. and Ogourtsova et al. looked systematically into 13 and 22 studies, respectively, with detailed information of participants [54, 56]. Two out of the eight survey papers looked into the use of VR as a vision therapy to stereo vision dysfunctions. Fortenbacher et al. went through the history and development of this research direction, and envisioned a bright future with improved HMDs and software designs [26]. They highlighted that the long-term professionally instructed therapy was more effective than therapies with other settings. Coco-Martin et al. reviewed clinical studies associated with the use of VR for the treatment of a specific visual condition, amblyopia, and suggested that repetitive training, multisensory simulation, user engagement, and customizable designs are key for studies in neurorehabilitation [16]. The remaining three survey papers are all about HMDs for low vision rehabilitation. Besides the aforementioned envisioning of Harper et al. in 1999 [32], Ehrlich et al. investigated different types of HMD technologies that could be useful for vision enhancement and rehabilitation, and various optical and human factors considerations for each display type [24]; Deemer et al. focused on the software side of AR approaches to vision enhancement with HMDs, including contrast enhancement, image remapping, and motion compensation [20]. Though no systematic literature searches were conducted, the two papers provided useful insights into what the display technology and software design for low vision rehabilitation have evolved into, and further asserted the promising future envisioned two decades ago.

Rather than focus on treatment or rehabilitation of specific vision conditions, we provide here an up-to-date scoping review of previous work using HMDs to assist or treat people who are visually impaired. We focus on the following research questions:

- **RQ1**: How have HMDs been used to improve vision care and human vision?
- **RQ2**: What are the research gaps and opportunities in the visual assistive or therapeutic technology with HMDs?
- **RQ3**: What influences can technological advances bring to the adoption of HMD-based visual assistive or therapeutic applications?

2 METHODOLOGY

Following the scoping study framework [8] [51], we describe how the literature pieces were searched and screened in this section (see Figure 1 for overall screening process).

From an initial set of 24 related papers, we extracted the frequently-seen AR/VR/HMD-related and vision-related keywords as shown in Table 1. We conducted the literature search using those keywords on September 22, 2020, in six digital libraries, namely, Institute of Electrical and Electronics

Table 1. Search Terms Used in This Literature Review

Search Criteria	Search Terms
AR/VR/HMD-related	“virtual reality" OR “augmented reality" OR “mixed reality" OR “virtual environment" OR “virtual environments" OR “head-mounted display" OR “head-mounted displays" OR HMD OR HMDs
Vision-related	“visual impairment" OR “visual impairments" OR “vision impairment" OR “vision impairments" OR “impaired vision" OR “low vision" OR amblyo* OR macular OR cataract* OR “vision loss" OR “visual loss" OR “vision losses" OR “visual losses" OR “unilateral spatial neglect"

Engineers (IEEE), Association for Computing Machinery (ACM), Springer Science+Business Media (Springer), ScienceDirect (SD), Web of Science (WoS) and PubMed. We intended to search in the fields of abstract and author keywords to not go down into every detail but also not miss important information; however, due to different restrictions of the search engines, only IEEE, ACM and WoS were able to meet this expectation. In the case of Springer, we applied full body in search range and refined the topic to computer science; in SD, we searched title, abstract and author keywords; and in PubMed, we searched title and abstract. No time constraints were set during the search. The search result (1,248 papers) is composed of 104 papers from IEEE, 61 papers from ACM, 613 papers from Springer, 37 papers from SD, 264 papers from WoS and 169 papers from PubMed. We also included three additional papers that did not appear in the search result but were previously read by the first author considering their relevance [9, 18, 32]. In total, 1251 papers were forwarded to the screening stage.

To filter out papers that are not qualified or relevant to the topic of this literature review, the following exclusion criteria were applied during the screening stage: no HMDs were employed; not written in English; focused only on hardware design; early stage poster/demo presentation, e.g., the length was less than four-/eight-page in double/single-column; focused mostly on non-visual affordances, e.g., audio or haptic feedback; HMDs were not used for visual assistance or therapy purpose, e.g., HMD as visual condition simulator.

Given the above criteria, our team, including experts in VR/AR, vision science, and scoping and systematic literature reviews, conducted four rounds of screening: the first author merged duplicates and checked the title and abstract of the papers for relevance in the first and second round of screening; the first six authors conducted the third round of relevance checking on full texts, and the forth round of explicit tagging. The full text of a paper was checked by at least one author. Ambiguous papers were discussed in group meetings or assigned to multiple authors. The tagging categories were agreed by all seven authors and are introduced in the following section. After screening, 917 papers were excluded. The remaining 69 papers (Table 2) were used for our detailed full-text analysis, and eight review papers were excluded from the high-level meta-analyses. To balance the volume of papers and our workforce, we did not conduct a reference harvesting.

3 CLASSIFICATION CATEGORIES

For the high-level analysis of the 61 papers, we collected potential terms for classification with respect to the aspects of research and technologies for visual impairments during the review, and determined the following categories after iterative refinements. Note that papers can potentially be tagged with multiple categories since a single paper can generally cover multiple aspects.

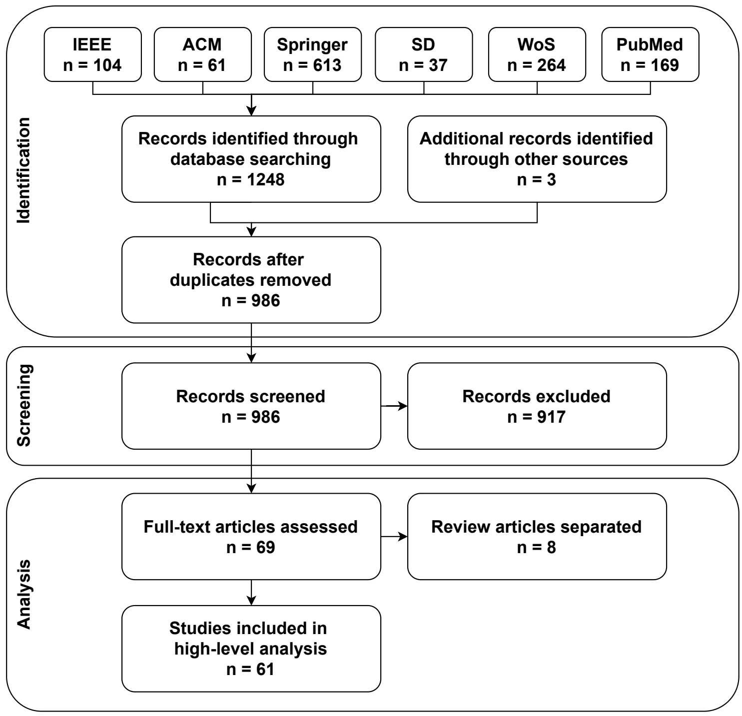


Fig. 1. Review Process

Objectives. While reviewing the collected papers, we pinpointed the papers using HMD technology for visual assistance and therapy, and classified them into two categories:

- **Assistive Technology**: work that aims at helping users cope with the limitations due to visual conditions, e.g., low vision aid;
- **Therapeutic Technology**: work that aims at improving or preventing further loss to the user's natural visual capability, e.g., amblyopia therapy.

Approaches. Based on how the HMDs were used for visual assistance or therapy regarding the visualization approaches, the papers were classified into the following three categories:

- **Virtual**: work that creates a completely synthetic environment for the user, e.g., VR-based visual therapy;
- **Augmented**: work that adds computer-generated virtual content to the real world, e.g., virtual arrows to guide the user;
- **Modified**: work that presents visually enhanced/modified imagery based on the real scene using computer vision or image processing techniques, e.g., edge enhancement.

HMD Types. The types of the HMDs used in the papers were collected and classified into the following three categories:

- **Immersive Virtual Reality (IVR)**: work whose display completely blocks the user from the real world, e.g., Oculus Rift;
- **Optical See-Through (OST)**: work whose display combines virtual imagery with a view of the real world, usually by looking through a semi-transparent mirror, e.g., HoloLens;

- **Video See-Through (VST)**: work whose display physically blocks the user's view but combines virtual contents along with the real scene captured by a camera, e.g., Oculus Rift with external cameras or smartphone-based VR headsets.

Visual Conditions. Various visual conditions were addressed in the papers. To identify technological trends in the use of HMDs for visual assistance and therapy associated with the visual conditions, we determined four categories to classify the papers as shown below. Note that one condition may lead to multiple limitations and thus fall into multiple categories.

- **Central Vision**: visual conditions that affect the central area of vision, e.g. Age-Related Macular Degeneration (ARMD) and retinopathy;
- **Visual Field**: visual conditions that affect the size of the visual field, e.g., USN and retinitis pigmentosa;
- **Stereopsis**: visual conditions that affect depth and stereo perception, e.g., amblyopia and strabismus;
- **Color Vision**: visual conditions that affect the ability to perceive or distinguish colors, e.g., color vision deficiency.

User Study. To evaluate the effectiveness of HMD-based visual assistive and therapeutic technology, user studies that investigate visual performance and human factors are critical and essential—especially involving qualitative research of the people who are visually impaired. We classified the papers into two categories according to the inclusion of a user study in the paper: yes and no. The number of participants was also recorded. In the case of multiple studies in one paper, the sum was taken.

4 HIGH-LEVEL ANALYSIS

This section presents the results of our high-level quantitative analysis, which provides insights into our first research question about the use of HMDs for vision care and human vision (**RQ1** in Section 1). During the analysis, we first evaluated the chronological changes in the volume of the papers that we collected through the literature search using keywords related to AR/VR/HMD and visual impairments, and then classified all the 61 screened papers for more detailed analyses based on the categories defined in Section 3.

The chronological distribution of the screened papers with and without user studies is presented in Figure 2. While this increasing trend generally aligns with the recent increase in the volume of literature in the VR/AR research community [22, 39] and the popularity of powerful, yet affordable low-cost HMD devices [1], it also indicates the growing use of VR/AR HMDs for visual impairments.

We analyzed the chronological trends under the categories of *objectives*, *approaches* and *HMD types* over the years, presenting the results in Figure 3. Regarding the *objectives* categories (shown in Figure 3a), two thirds (41) of the 61 papers were classified as *assistive* technology while the remaining (20) were classified as *therapeutic* technology. This phenomenon could be explained by the fact that a sizeable portion of the targeted visual illnesses are not treatable to date through external equipment. This is also supported by the proportions among the *objectives* and *visual conditions* categories shown in Figure 4a (63 data points are presented due to multi-tagging [44, 52]). All the works focusing on the impaired *central vision* and *color vision*, which are mostly caused by incurable or hard-to-cure illnesses, are not *therapeutic*. The same applies to the papers falling under the *visual field* category except one specific type of illness—hemineglect, which is known to be treatable. In contrast, all the papers working on deficiencies in *stereopsis* aimed to treat their targeted user group, which can be explained by the fact that the ability of HMDs to display two

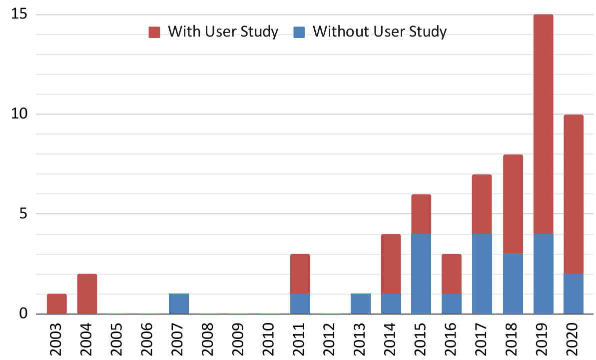
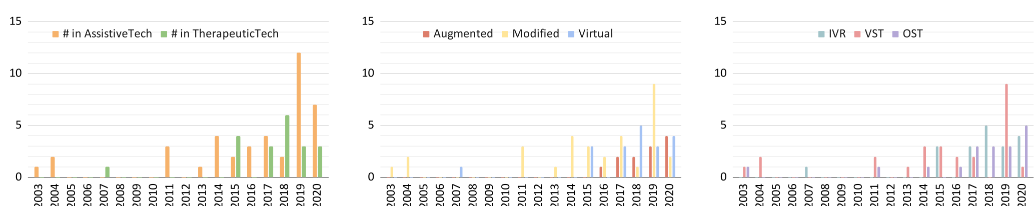


Fig. 2. Overview of the number of publications with and without user studies over the years.

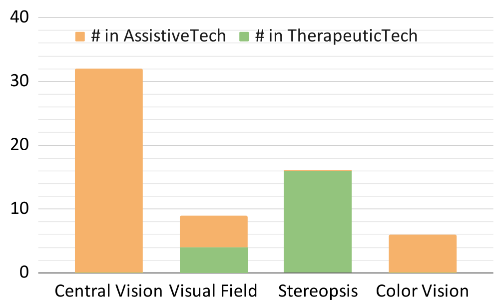


(a) *Objectives* (b) *Approaches* (c) *HMD Types*

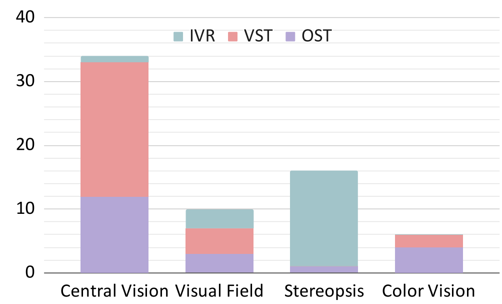
Fig. 3. Number of papers published per year grouped by classification categories.

different images to the left and right eyes of the wearer is naturally compatible with dichoptic training, a promising novel therapy for stereoblindness.

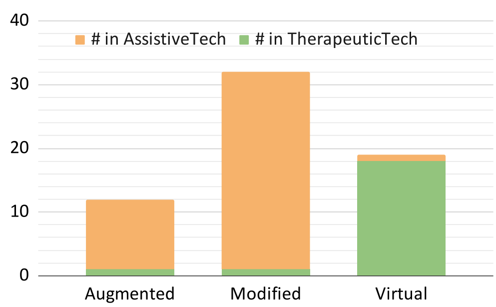
Two papers were tagged with multiple *approaches* [60, 75], resulting in 63 data points in Figure 3b which shows the annual distribution of the papers classified in the *augmented*, *modified* and *virtual* approaches. The *modified* approach is the most frequently implemented method (32 papers), followed by *virtual* approach (19) and *augmented* approach (12). We also present the proportions among the categories of *objectives* and *approaches* in Figure 4c to see if there are any correlations between them. We found the majority of the papers using *modified* approach was for *assistive* technology—31 out of the 32 papers (see Figure 4c). The single paper falling under *therapeutic* technology is about therapy for hemineglect, the treatable type, in which the idea of real-time stimuli overlaying the real world is proposed but not implemented [12]. In contrast to the *modified* approach, the *virtual* approach is most often used for *therapeutic* technology. As shown in Figure 4c, only one out the 19 papers is categorised as *assistive* technology. And even in this paper, the *virtual* approach was not designed to be used in the ultimate assistive tool, but used by the researchers to simulate scotomas in VR before experimenting on visual assistance with the proposed strategy [77]. Many papers using VR as illness simulators or virtual testers were excluded based on our exclusion criteria (see Section 2), while this paper was kept for the reason that it described a means to assist the people who are visually impaired. This paper also contributed to the only data point in Figure 4b using *IVR* for *central vision*. Compared with *modified* and *virtual*, the *augmented* approach is a



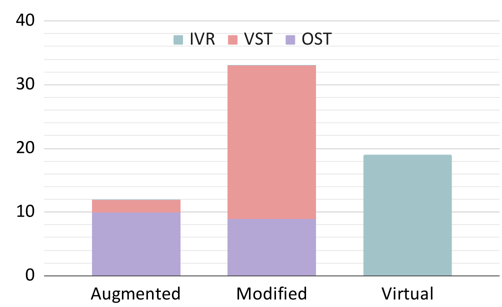
(a) *Visual Conditions* and *Objectives*



(b) *Visual Conditions* and *HMD Types*



(c) *Approaches* and *Objectives*



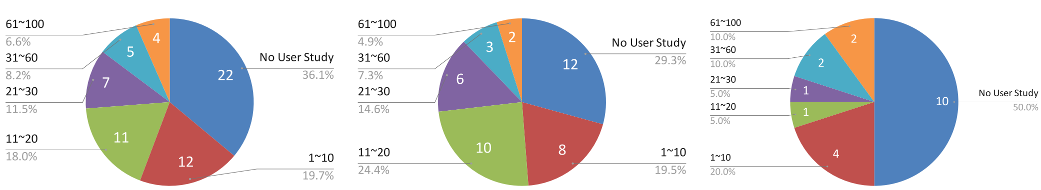
(d) *Approaches* and *HMD Types*

Fig. 4. Correlation between classification categories.

relatively new and less developed method but its appearance has been continuously increased since 2016 (Figure 3b). The *augmented* approach is mostly applied to assist the people who are visually impaired—11 out of 12 papers were classified as *assistive* technology as shown in Figure 4c. The one exception implemented dichoptic training using the *augmented* approach, instead of the common *virtual* approach in an attempt to leverage some advantages of AR, such as less cybersickness; however, their research was not comprehensively examined by a formal user study [53]. This data point is also reflected in Figure 4b as the only paper used *OST* devices for *Stereopsis*.

Regarding the categories of *HMD types*: *IVR*, *OST* and *VST*, many on-brand devices were used in the papers, such as, Oculus Rift (8 appearances), Microsoft HoloLens (7), HTC Vive (5), Google Cardboard (6), Google Glass (3) and Gear VR (2). DIYs are frequently used as well, especially before the year of 2015—note that the consumer versions of Oculus Rift and HTC Vive appeared, and HoloLens Development Edition was shipped in 2016. Figure 3c shows the number of papers employing different HMD types throughout the years with 63 data points as there are papers including multiple HMDs. In total, there are 18 papers under the category of *OST*, 26 under *VST* and 19 under *IVR*. By observing the proportions between the categories of *approaches* and *HMD types* in Figure 4d, we can clearly see most papers with the *augmented* approach used *OST* HMDs, while the *modified* approach used both *OST* and *VST* HMDs. For the *modified* approach that requires any vision enhancement techniques, VST HMDs would be convenient and tractable to modify the captured imagery from the mounted cameras and merge with the real world scene.

As user evaluation is a key factor in accessibility research and clinical trials play an important role in medical-related research, we recorded the existence of user studies in an attempt to gain some insights in this aspect. Figure 2 shows the number of papers with and without a user study among the screened 61 independent research papers along the years, and we noticed a general trend of increasing involvement of user studies in the recent decade. An overview of all 61 papers based on the number of participants in the user studies is shown in Figure 5a. Though over half of the papers have no user study or a user study with less than ten participants, we observed that the proportions varied between papers focusing on different *objectives—assistive* and *therapeutic*, in Figure 5b and 5c. There are 50% of *therapeutic* papers that did not conduct a user study, whereas the statistics of *assistive* papers is less than 30%. This could be due to stricter user study rules for medical-related research. For example, research for assistive uses can be more likely to get approved or get approved quicker by human research ethics committees or review boards than research for therapeutic uses as clinical user studies are subjected to stricter inspections. Nevertheless, as far as time is concerned, all identified papers with more than 30 participants were published in the recent three years, and the two papers with the highest number of user study participants (100) among the analyzed papers were both published in 2020 with one for *assistive* and one for *therapeutic* uses [29, 47]. As rigorous evaluations are increasingly demanded by the research community, we expect that the trend towards more user studies will continue and accelerate in the future.



(a) All identified papers (b) *AssistiveTech* (c) *TherapeuticTech*

Fig. 5. Overview of the number of user study participants.

5 DETAILED REVIEWS

In this section, we present in-depth qualitative reviews of the collected papers based on the four visual conditions categorized in Section 3: *central vision*, *visual field*, *stereopsis*, and *color vision*. We cover most of the papers that we identified but focus more on seminal highly-cited papers and research presenting novel approaches, considering the impact of the work. These reviews are intended to provide an understanding of the current state of HMD-based visual assistance and therapy and to provide insights that may support the identification of research gaps and potential future research directions, which are discussed in Section 6.

5.1 Central Vision

Our analysis shows that 32 of the 61 papers in the survey investigated HMDs for *central vision* conditions, including blurry foveal vision and complete central vision loss caused by eye disorders, such as Age-Related Macular Degeneration (AMD) and Retinitis Pigmentosa. Though all of the papers are classified as *assistive* technology (see Figure 4a), they introduce various *approaches* to enhance the visual quality of the targets in the real world. There are 22 papers that adopted the *modified* approach, eight adopted *augmented*, one adopted *virtual* and one adopted both *modified* and *augmented*. *OST* and *VST* HMDs are both popularly used, with one *IVR* device used for the paper that adopted the *virtual* approach.

As a noticeable and highly influential research effort related to the *central vision* conditions, Zhao et al. have published a series of papers for the past few years [78–82]. They presented VST head-mounted vision enhancement systems, named “ForeSee” [80] and “CueSee” [81]. The former, “ForeSee”, manipulates the real world view captured from the camera attached on the user’s HMD to enhance the visibility of the target of interest [80]. In the system, different computer vision or image processing techniques were employed for the vision enhanced imagery, such as magnification and contrast/edge enhancement. They conducted a user study that examined the low vision participants’ preference and their user experience with the system while performing different viewing tasks, and found that the participant’s preference for the vision enhancement methods varied depending on the tasks they perform. For example, while the magnification is a generally preferred feature, the participants addressed that combining different vision enhancement techniques would improve the user experience significantly and help users the most. They further extended the paper to a journal article while including more data and discussion regarding a user-centered design process for the low vision population [82]. For the latter, “CueSee”, Zhao et al. particularly focused on enhancing visual search performance for low vision people by employing different visual highlight approaches on VST HMDs, such as guideline, spotlight, and flash to emphasize the target object in the real world [81]. They found the visual highlight approaches outperformed the conventional methods in assistive tools, e.g., magnification.

More recently, Zhao et al. developed assistive applications for indoor navigation using *augmented* approaches on OST HMDs, and compared the effects of different visual cues on navigation performance and usability while combining with other aural cues [78, 79]. In a stair walking-down task, one of the challenging and dangerous activities for people with low vision, they found that participants most preferred the visual glow effect with beeping sound, which displayed colorful highlights at the edge of the stairs, to guide them for safe stair navigation compared to other methods such as path visualization [78]. In the recent study, in which they compared the effects of visual cues with aural cues for navigation, the results showed the visual feedback was more effective for the task performance, e.g., fewer mistakes with lower cognitive load; however, it turned out that the participants preferred the audio feedback mainly due to its convenience and short learning curve [79]. Hence, the inclusion of audio cues should be carefully considered when designing similar visual assistive technology.

There are also many other researchers who focused on the *central vision* conditions, and the majority of them used *modified* approaches to enhance the visual quality or highlight particular regions of interest in the real world. For example, Hwang and Peli developed a contrast enhancement system that uses the Google Glass and edge detection to provide better contrast for users with AMD [36]. The results of their study showed that users’ contrast sensitivity scores increased while using the system; however, they noted that due to the limitations of the device’s camera, their system would only help improve contrast sensitivity when users have log contrast sensitivity scores of 1.5 or less. Coco-Martin et al. also developed a visual assistive VST HMD system that used image processing algorithms to detect edges in the scene and visualize depth information on the display for the people who are visually impaired [17]. While the research aimed to investigate fast and accurate edge detection methods, the conducted preliminary study with people who have low vision confirmed the usefulness of the system that improved the walking performance (walking speed) with less anxiety.

Deemer et al. evaluated two magnification approaches—virtual bioptic telescope and virtual projection screen magnification strategies, implemented in a smartphone-based VST HMD as an assistive system in terms of its validity and effectiveness [21]. The virtual bioptic telescope strategy enabled the users to adjust the scale of the target area in the view using a "magnification bubble", and the virtual projection screen strategy used an extended panoramic screen to magnify a certain portion of it for the users. Participants in the formal study experienced the technology for seven to ten days in their ordinary lives at home after being trained. The results revealed that the technology helped the participants perform daily tasks, such as reading and visual information processing, but did not show benefits in terms of mobility and visual motor function. It was also noted that participants reported discomfort related to simulator sickness during the HMD experience. Lussier-Dalpé et al. researched the effects of a visual assistive HMD technology particularly for a focus group of pianists with low vision, who experienced difficulty in reading musical notation [45]. In an exploratory study, they identified issues and benefits of an HMD-based visual assistive technology using a commercial eSight Eyewear system based on a qualitative analysis with a phenomenological approach. The eSight Eyewear allowed the pianists with low vision to read and interpret musical notation by providing an adjustable magnification feature while freeing up their hands; however, the study also revealed that some level of training was needed in order to use the technology competently. Gopalakrishnan et al. also examined acuity enhancements for low vision participants using the Samsung Gear VR and the Relumino application [29]. The experimenters utilized the variable magnification feature of the Relumino app in a user study in which they compared the participants' visual acuity with and without the AR device. The results of their study indicated that participants with a wide variety of different visual impairments experienced significant improvements in their visual acuity when using the Gear VR compared to a typical low vision aid. Their average acuity scores significantly improved from 0.9 to 0.2 logMAR (logarithm of the minimum angle of resolution) distance acuity and from 0.4 to 0.1 logMAR near acuity when using the device.

Moshtael et al. investigated several different presentation methods for text on low-vision reading aids [50]. In particular, they investigated a text presentation strategy called biomimetic scrolling, in which the user maintains a fixed eye gaze position and the text steps across their gaze point mimicking saccades inherent to natural eye gaze behavior. This method was compared against other more traditional display methods including smooth continuous scrolling, presentation of one word at a time at the eye gaze position, and presentation of a static paragraph of text. The results showed that users greatly preferred using smart glasses compared to text magnifiers, and read at the fastest speeds with the biomimetic scrolling method. Angelopoulos et al. developed a visual assistive system in which objects in the user's proximity were highlighted in different colors based on their distance from the user [7]. They performed a user study that showed that participants with Retinitis Pigmentosa had fewer collisions with physical objects when their proposed system was used. The participants also made significantly fewer errors in mobility and grasping tasks when using the system. Culham et al. conducted a human-subject study that compared four commercial electronic HMDs with conventional optical low-vision aids which were normally prescribed for clinical purposes [19]. The study with 20 participants, who had either Early Onset Macular Disease (EOMD) or AMD, showed that there were some significant benefits of HMDs depending on the task and user's profile, such as better distance acuity for younger participants.

Additionally, a few papers focused on the *augmented* approach, for instance, Stearns et al. developed a couple of AR magnification prototypes integrating image enhancement techniques with an OST HMD to modify the visualization of text and improve its readability for low vision users [63]. The first prototype consisted of a HoloLens and a finger-mounted camera capturing images of text from a book, and the second used a smartphone as a camera and an input device instead. These systems not only adjusted the captured text image for visibility, but also attached it on a virtual layer, which the users could move around at their convenience. Proof-of-concept studies with seven visually impaired participants showed that there were advantages of the HMD-based magnification systems in terms of their portability and readability, but also highlighted the slow learning curve with this technology. Lang et al. prototyped an AR symbolic and alphanumeric representation system, which could recognize emotional expressions of conversational partners and the time on the user's wristwatch and visualize the information on an HMD for low vision users [40]. For example, the system used abstract icons and emojis to represent the emotion of the partner, and adjusted the size or color of numerical representations for the time.

Hommaru and Tanaka noted that low vision people experienced difficulty walking with conventional support tools, such as a combination of a braille block and a white cane [33]. They explored the benefits of an HMD-based assistive technology that augmented virtual content to visualize a color-coded walkable area. They designed a prototype system using a HoloLens that could present 3D virtual braille blocks in different colors with audio feedback, and a smartphone that provided additional warning signals using the blinking screen and vibration when there would be collisions expected. The system could also identify obstacles on the way using Microsoft Azure Custom Vision Service to guide the users. A preliminary study involving eight normal vision participants with simulated visual impairments evaluated the system's usability and usefulness, revealing that the system had the potential for practical use cases given the complexity of installation of braille blocks in public places and the potential social problems in the use of conventional visual aids such as white canes. Sandnes and Eika studied the potential of inexpensive smartphone-based *OST* HMDs, e.g., Google Cardboard, as *assistive* technology for people with low vision [60]. They evaluated the effectiveness of such HMDs for the purposes of navigation aids and face recognition, while exploring different filters and post-processing sketches to visualize directional information with primitive 2D/3D contents.

As mentioned in Section 4, there is one paper that used an *IVR* HMD [77]. They developed a visual aide system for users diagnosed with scotomas, which allowed users to define a scotoma kernel by comparing amsler grids between their affected and unaffected eyes. In this manner, the user could build up a simulated scotoma, which can later be applied as a shader to the imagery seen on a VR HMD. The authors investigated suppressing the virtual scotoma by blocking the central portion of it with a variable sized opaque circle, and their results showed that mid level sizes of scotoma suppression resulted in the best visual performance from the user, while small sizes had little effect on visual performance and large sizes resulted in reduced visual function.

5.2 Visual Field

A subset of nine papers returned in the survey consisted of research in which HMDs were used to provide therapeutic treatment for visual field loss (four papers), or were used to assist users diagnosed with visual field loss (five papers).

Interestingly, there were several papers in this section using HMDs as treatments for people with visual field issues that could be caused by brain damage, such as Hemispatial Neglect and Homonymous Hemianopsia. Birnbaum et al. proposed a hypothesis in 2015 that AR may be suitable for treating Homonymous Hemianopsia [12]. They proposed that therapies could be designed in a way that incoming imagery was presented solely to the affected part of the user's visual field in high contrast and low temporal frequency. In this manner, they believed that users could improve their ability to detect and recognize objects in the affected part of their vision, although testing of their hypothesis was left to future work. Teruel et al. implemented a VR therapy approach for people with Hemispatial Neglect in 2015 [67]. Their system allowed for a customizable therapy session and contained two VR games that used visual, aural, and haptic signals to stimulate the users as they navigated to avoid obstacles in a virtual environment. Their work, however, did not present an evaluation or user study. In 2017, Yasuda et al. also investigated VR-based therapies for spatial neglect, however they focused on near and far spatial neglect in addition to peripheral neglect [74].

They developed a system consisting of a distance-based task where users were required to verbally identify a flashing object located 15 meters away, and a near-based task where users needed to reach forward to touch a sequence of three objects on the desk in front of them from right to left. As the user progressed, the Field of View (FoV) was restricted and slowly shifted from the user's unaffected side to their affected side. The authors tested their system in a user study of ten participants, where they found no improvement between a pre and post behavioral inattention test for the near task, but found a significant improvement for the far task. Yasuda et al. continued their work in 2018 by performing a longitudinal study with the same VR therapy device [73]. One participant went through both the near and far VR therapy once a day, five days a week for six weeks. Results showed that the participant improved on a line cancellation test and a line bisection test but did not improve on the Catherine Bergego Scale, which assesses the user's functions in daily tasks, such as getting dressed.

The other five papers presented assistive systems for users with reduced FoVs. In 2011, Luo and Peli developed several visual aid systems for people with tunnel vision, a condition in which significant peripheral vision loss is experienced with otherwise unaffected central vision [44]. They provided assistance through transforming and shrinking a camera view of the user's environment into their usable FoV. Initial testing showed that the gaze behaviors of the user became more efficient, which led to better performance in search tasks. Ostrander and Morelli investigated increasing the user's FoV in a similar manner in 2016, although their work targets users with reduced visual fields due to little or no vision in one eye [55]. They evaluated several methods of combining wide FoV camera feeds and presenting it to the user's good eye, suggesting that split-screen approaches, in which multiple camera streams were shown side by side, performed better than approaches which provided alternating views of the two cameras. In the system proposed by Murai et al. in 2016, a different way to guide user gaze was attempted—users with reduced visual fields were assisted in locating objects of interest by following virtual rings that were presented at the object's center [52]. However, no user study was conducted to evaluate their prototype. Younis et al. developed two prototype systems in 2017, one providing visual notifications of objects that were near the user but might lay outside of their FoV, and one compressing visual information from the user's periphery into their usable FoV [75]. In 2019, they extended the notification system to utilize deep learning to visually identify objects in the user's proximity via an on-board camera, and then used results of the user's visual field tests to determine which objects fall outside [76]. Their work also indicated that users with peripheral vision loss tended to prefer notifications about moving objects over stationary objects.

5.3 Stereopsis

We identified 16 out of the 61 papers focusing on stereo vision conditions, all of which worked for the therapeutic purpose. Most of these papers utilized *IVR* setups and *virtual* approaches (15 papers), while one used an *OST* HMD for AR implementation of dichoptic training (previously discussed in Section 4).

The majority of the contributions (11 papers) solely studied the effectiveness of using AR/VR technology for developing dichoptic training modules for people with amblyopia. To overcome some of the limitations of traditional treatments (e.g., occlusion therapy [15]), increasing user compliance and engagement was considered as one of their primary motivations; therefore, the dichoptic training modules were presented to users in the form of interactive games. Different approaches were used to implement the dichoptic aspect of the games. In the system developed by Qiu et al., the images delivered to the amblyopic eye included more dynamic features [58]. Gargantini et al. and Bonfanti and Gargantini developed mobile game applications where the differences in the two images presented were synced with the game's difficulty level, and the target content visible to the non-amblyopic eye became more transparent or degraded as the game level increased [13, 28]. In the VR game developed by Vichitvejpaisal and Chotined, the visibility of the images seen by the non-amblyopic eye was reduced through post processing filters, such as blurring [70]. In the only AR example by Nowak et al., the primary game elements were rendered for the amplyopic eye and the supplementary elements (e.g., the background) were rendered for the non-amblyopic eye [53]. In the VR system developed by Greuter et al., users were allowed to tweak certain features for each eye, such as central and peripheral brightness, contrast and blurriness, and could show and hide specific objects, forcing cooperation between the two eyes and improving binocular fusion [30]. In the VR game developed by Scrocca et al., some game targets were rendered for one eye and tasks were designed to involve hand gestures with the intent to improve users' eye-hand coordination on top of enhancing their binocular collaboration [62].

A few of the papers targeting amblyopia treatment conducted multi-session studies and in some cases compared and/or combined their solution with other practiced treatments [31, 35, 42, 83]. For instance, Ziak et al. and Halička et al. conducted user studies on adult subjects playing dichoptic training VR games for eight sessions over a four-week time span [31, 83]. Stating that treatment of amblyopia in adults is known to be difficult, they found improvements in best-corrected visual acuity in both studies and stereoacuity in the first study supporting the potential of VR dichoptic training for adults.

Besides amblyopia, a few of the contributions developed multi-purpose prototypes aimed at providing therapy for several stereopsis related conditions [9, 25, 61]. Backus et al. [9] developed several VR games in their Vivid Vision System with different depth-perception-related visual conditions in mind, for instance, separating the presentation of dependent game elements where the dominant eye sees one while the non-dominant eye sees the other, forcing image fusion on the user's side, the prism offset solution to account for binocular misalignment, and adjustment of luminance and contrast to enhance interocular balance. The only major problem of this study is the lack of a user study to evaluate the performance of the system. Martin et al. [47] developed a binocular imbalance test in VR to gauge visual acuity, stereoacuity and interocular imbalance for clinical monitoring purposes. A user study of 100 participants using the Worth's Four Dot test as the ground truth, found the results to be highly accurate and repeatable. Its performance can also potentially benefit from the development of HMD technology such as the increase of resolution and the adaptation of wider interpupillary distances. Cepeda-Zapata et al. focused on addressing different needs of strabismus treatment and developed three VR exercises for this purpose [14]. Positive results were observed through a user study for aspects such as pragmatism and attractiveness which could influence user adoption and engagement. Though the little entertainment value of the exercises could be a notable problem for long-term user compliance.

5.4 Color Vision

Six out of the 61 papers focused on developing prototypes and/or algorithms for improving color distinguishing abilities of individuals with Color Vision Deficiency (CVD). As no cure for CVD has been presented to date, all the six contributions focused on augmenting the vision of CVD individuals rather than treating the condition and thus all six are under the *assistive technology* category. They also adopted similar strategies—the *modified* approach, but four papers used *OST* HMDs and two used *VST*.

In this category, Google Glass has been commonly used [27, 41, 66]. In one of the most influential contributions here, Tanuwidjaja et al. developed an AR system using Google Glass called Chroma to provide real-time assistance with color detection in daily life activities [66]. The system design was informed by the identified needs of a color-blind population captured through semi-structured interviews. The Chroma system was designed to adapt to each individual's color deficiency needs and consisted of four modes: highlighting, contrast, daltonization, and outlining. Evaluations of the Chroma system compared to a no-assistance condition showed that participants were more successful at color identification in a number of tests, e.g., Ishihara test. On top of the Chroma system, Langlotz et al. and Sutton et al. presented the idea of computational glasses for mitigating the effects of visual impairments [41, 64]. They developed five algorithms that aimed at shifting the undistinguished colors in a scene to those that can be perceived by a person with CVD using their ChromaGlass prototype. For instance, for someone with Protanopia the shift would be towards the color blue. Their findings showed that participants' ability in passing the color blindness test and feeling of confidence significantly improved. Interestingly, they found lower levels of mental workload with their system than the previous Chroma system, which could be an effect of the content matching step. However, this is more difficult for smaller details and content presentation in the periphery of a Google Glass.

Melillo et al. and Besic et al. developed VST HMD prototypes and algorithms to remap the colors in the scene to the color spectrum perceivable by individuals with CVD to improve their color vision, with findings supporting improvements in the Ishihara test [10, 49]. Beyond helping those with CVD, another valuable contribution of such applications is the opportunity for individuals with normal color vision to experience and gain a better perspective on the quality of daily life activities of those with CVD [10].

6 EMERGING TRENDS AND FUTURE DIRECTIONS

In this section we present research gaps and opportunities to promote visual impairment assistance and therapy technology to a larger population (**RQ2**) and discuss how technological advances can influence the adoption of HMD-based applications (**RQ3**).

HMD Technology Trends. The resurgence of the use of HMDs in visual impairment assistance and therapy is partially a result of recent developments and ease of access to low-cost consumer grade commercial off-the-shelf HMDs. We believe this stimulus-response relationship will keep growing in the near future, as more specialized versions of HMDs emerge. For instance, child-friendly HMDs with adjustable interpupillary distances (IPDs) and suitable sizes and weights can help solve the device limitations for children mentioned by Martin et al. [47].

Advances in display technologies should also bring progress into this research field. For instance, higher resolutions will improve the user experience of all systems we discussed above, larger FoVs can further help people with visual field loss, and robustness in harsh lighting conditions can expand the user scenarios to places like in outdoor environments. Virtual Retinal Displays, which project a raster image directly onto the retina of the eye, have been around for a while and keep promising some unique advantages, such as the potential to shrink the size of HMDs and be more eye-friendly [43]. However, no recent work using this type of display has been found, indicating an opportunity for further exploration. Similarly, Light Field Displays have shown tremendous potential to correct optical aberrations in the human eye, such as near-sightedness or far-sightedness, which may at some point in the future provide a versatile solution to many vision problems, once the hardware challenges and computational complexity are overcome [34]. We noticed a trend that more and more researchers have been using on-brand HMDs since year 2016 as mentioned in Section 4. These HMDs have greatly lowered the threshold to conduct research in this area. However, we would also like to point out that customized HMDs have shown their own irreplaceable advantages—flexibility and innovation.

Looking at the stereopsis category where the majority of the therapeutic solutions were presented to users in VR, we identified very few examples where simulator sickness or its associated symptoms, such as fatigue, dizziness, and nausea, were discussed either as a factor influencing the system design or as a measure [35, 47, 61]. As simulator sickness is an ongoing issue experienced by many users of VR applications and can be dependent on a wide range of variables [23], methods should be included for measuring simulator sickness. Collecting such data may shed light on the effectiveness of the suggested VR solutions, the potential interference of simulator sickness symptoms on users' performance, and provide guidance for future design and development. Another possible strategy to lower the likelihood of sickness is to adopt OST HMDs [71], which have recently received more attention, for instance, the OST AR version of dichoptic training by Nowak et al. [53].

More Clinical Evaluations. User study is a key feature of research related to clinical use. It could not only help evaluate the usability of the proposed methods, but also help researchers identify specific needs of the users. One of the major problems that the aforementioned off-the-shelf products face is the high rate of device abandonment due to mismatches of the device to the end user. Customized service could be useful, but sufficient user studies in early stages could help solve the issue earlier and with a lower cost. Birckhead et al. proposed a three-phase framework of VR clinical trials that in the first stage, participants are involved in designing through the format of interviews; in the second stage, participants focus on evaluating whether the method is feasible, suitable and accountable; in the third stage, Randomized Controlled Trials are conducted to compare the outcomes of the VR methods and conventional methods [11].

As discussed in Sections 3 and 4, we are seeing an increasing percentage of work conducting user studies and the scale has been getting larger, but still, only nine papers among the screened 61 conducted studies contained user studies with more than 30 subjects; hereby, we would like to emphasize that larger sample sizes are important to assess the efficacy of the proposed methods, as noted by Lee and Kim in their work on residual amblyopia treatment [42]. Though we speculate that the growing HMD market could help increase sample sizes both with at-home participants and facilitation of parallel recruitment of patients [1], the situation can be unpredictable for the next few years considering the ongoing COVID-19 pandemic. In 2021, Radiah et al. summarized a framework for conducting remote VR studies from an online survey with 227 valid submissions and two case studies [59]. This framework could be a good reference but might not be enough for studies involving participants with visual impairments. Whether participants have the capability to complete the studies remotely need to be considered, for example, people with USN are likely to have mobility issues and thus might require special study settings [54, 56, 68]. Also, the study effectiveness could be lowered as Fortenbacher et al. stated in their survey paper of using VR as a therapy for stereo vision dysfunctions that therapy sessions conducted in an office environment with professional supervisions were significantly more effective than sessions conducted in other settings [26].

Besides the scale, we would also like to stress the importance of user study duration. Overall, we observed a few instances where multi-session or long-term study designs were considered under both *therapeutic* and *assistive* technology categories [31, 42, 73, 83]. In one of the large multi-session studies conducted by Haličcka et al. for amblyopia treatment, they noted that some participants might require longer sessions compared to the eight one-hour sessions utilized in their work and longer treatment duration could better indicate the effectiveness of their findings in terms of stability [31]. In the work of Deemer et al., participants used HMDs at home to understand and experience the visual assistive technology for about a week, which helped to collect more ecologically valid results [21].

More Field Studies and Use Cases. The majority of the user studies that were included in our analysis take place in laboratory settings as opposed to in the field, which may be explained by the need to provide the same experience for all participants consistently [41]. While this provides a good starting point for understanding how HMDs can be used as assistive or therapeutic technology, it does not provide us with the whole picture capturing a variety of vision-support use cases. As we move forward in this domain, more work needs to take place that involves field studies focusing on active daily life tasks in the environments that users would be typically using the devices, rather than passive observation and identification tasks. For instance, it has been emphasized that CVD introduces many obstacles to the daily life of individuals with this condition; however, we observed only one example that utilized tasks that reflect to some degree daily life activities [66]. Although standard measurements (e.g., Ishihara test [37] for color deficiencies) are highly valuable and informative, adoption of field studies can shed more light on the needs of different populations with vision impairment and the efficacy of the presented prototypes.

Even beyond the visually impaired population, developing new use cases for vision-support HMDs may present the potential for non-disabled users to extend their vision capability through these assistive HMD technologies—especially considering environments or contexts where some of these users may experience visual challenges, for example, first-responders scenarios [6].

Novel Sensing and Processing Techniques. Our detailed review in Section 5 revealed that the *modified* approach was most often used for visual assistance, enhancing the user's view through different visual enhancement methods. While the research community and industry in computer vision and machine learning are experiencing unprecedented technological achievements based on the enormous multimedia data and advanced deep learning techniques, the HMD-based *assistive* technology can adopt such advanced technologies to provide more context-relevant semantic information to the people who are visually impaired. Most recent papers in our review captured such a trend; for example, vision-based obstacle detection and identification using Azure Service [33] and facial expression recognition for better social interactions [40].

The visual assistance context involves not only the surrounding environment, but also the users, such as understanding of their behavior and intent. Overall, we observed a few examples where eye tracking data was collected to better understand participants' behaviors [25, 44]. For instance, Luo et al. tracked users' gaze path to measure their performance with and without an assistive system in a search task [44]. In several examples, researchers discussed the future use cases of eye trackers as a means to provide objective measurements, such as measuring deviation angles [47], eye movement velocity [9, 35], and accuracy [9]. Others discussed the future use of eye trackers in the context of adaptive systems [80–82], user interaction, and automatic calibration mechanisms [41, 53]. In recent years eye trackers are becoming more robust and more commonly available in many commercial HMDs, e.g., FOVE, VIVE Pro Eye, HoloLens 2. This trend increases opportunities for realizing many of the aforementioned use cases in the context of visual impairment assistance and therapy and adopting some of the already established trends in the realm of eye-based interactions [46].

However, novel or more complex sensing and processing approaches also tend to increase the demands on the underlying computing capabilities of the mobile setups, which can slow visual assistive technologies down and make them unusable from a practical point of view. HMD-based visual assistance systems need to provide very-low-latency and highly accurate feedback to users or they could impair their users' safety. To achieve such real-time operation in this field, researchers have started employing advanced Graphics Processing Unit (GPU) and Field-Programmable Gate Array techniques [48, 69]. We see more demand in the future for such specialized high-performance processing solutions.

7 CONCLUSION

In this paper, we presented a scoping review of previous work using HMDs as visual assistive or therapeutic tools. We provided a high-level analysis and detailed reviews of 61 related papers selected from a pool of 1251 papers. The analysis revealed the increasing use of HMDs for visual impairments, while indicating the prevalent visualization approaches (*augmented, modified, virtual*) with respect to the technology objectives and the users' vision conditions. Our review captured the current state of assistive and therapeutic technologies with different types of HMDs associated with different visual conditions. We shared our insights on the research gaps, emerging trends and future directions for the research and development of visual assistive and therapeutic technology with HMDs.

We would also like to acknowledge the limitations of this work: Our utilized search terms included commonly-seen vision conditions but could not explicitly cover all conditions that could potentially benefit from HMD assistance or therapy. We also did not include papers focusing on non-visual assistance and therapy solutions, such as audio or haptic VR/AR head-mounted devices, which led to a gap on covering blind users who could not benefit from the enhancement of the visual sense. Future work may continue this literature research by expanding the database of related papers to all uses of HMDs for the people who are visually impaired.

Table 2. The identified 69 papers with corresponding tags defined in Section 3 ordered by the publication year. Note that the eight survey papers were not tagged. About User Study, "Y" implies the inclusion of a user study and the number followed refers to the number of participants; "N" implies no user study. The ★ symbol implies the three papers that were not from the search result but previously collected by the first author.

Title	Year	Objectives	Approaches	HMD Types	Visual Conditions	User Study
★ Head mounted video magnification devices for low vision rehabilitation: A comparison with existing technology	1999			Survey Paper		
Testing visual search performance using retinal light scanning as a future wearable low vision	2003	Assistive	Modified	Range from VST to OST	Central Vision	Y - 5
Development of a head mounted visual enhancement device for people with low vision	2004	Assistive	Modified	VST	Central Vision	Y - 21
Clinical performance of electronic, head-mounted, low-vision devices	2004	Assistive	Modified	VST	Central Vision	Y - 20
Interactive binocular amblyopia treatment system with full-field vision based on Virtual Realty	2007	Therapeutic	Virtual	IVR	Stereopsis	N
Uses of virtual reality for diagnosis, rehabilitation and study of unilateral spatial neglect: review and analysis	2009			Survey Paper		
Development and evaluation of vision rehabilitation devices	2011	Assistive	Modified	OST	Central Vision, Visual Field	Y - 19
A portable low vision aid based on GPU	2011	Assistive	Modified	VST	Central Vision	N
Substituting depth for intensity and real-time phosphene rendering: visual navigation under low vision conditions	2011	Assistive	Modified	VST	Central Vision	Y - 4
Embedded system for contrast enhancement in low-vision	2013	Assistive	Modified	VST	Central Vision	N

Table 2 continued from previous page

Title	Year	Objectives	Approaches	HMD Types	Visual Conditions	User Study
High dynamic range imaging system for the visually impaired	2014	Assistive	Modified	VST	Central Vision	N
Evaluating the image quality of closed circuit television magnification systems versus a head-mounted display for people with low vision	2014	Assistive	Modified	VST	Central Vision	Y - 21
An augmented-reality edge enhancement application for Google glass	2014	Assistive	Modified	VST	Central Vision	Y - 3
Chroma: a wearable augmented-reality solution for color blindness	2014	Assistive	Modified	OST	Color Vision	Y - 23
Assessment and rehabilitation of neglect using virtual reality: a systematic review	2015	Survey Paper				
Virtual reality treatment and assessments for post-stroke unilateral spatial neglect: A systematic literature review	2015	Survey Paper				
Troyoculus: an augmented reality system to improve reading capabilities of night-blind people	2015	Assistive	Modified	VST	Central Vision	Y - 2
ForeSee: a customizable head-mounted vision enhancement system for people with low vision	2015	Assistive	Modified	VST	Central Vision	Y - 19
Multisensory treatment of the hemispatial neglect by means of virtual reality and haptic techniques	2015	Therapeutic	Virtual	IVR	Visual Field	N
Enhancing visual performance in individuals with cortical visual impairment (homonymous hemianopsia): Tapping into blindsight	2015	Therapeutic	Modified	VST	Visual Field	N
A low-cost virtual reality game for amblyopia rehabilitation	2015	Therapeutic	Virtual	IVR	Stereopsis	N

Table 2 continued from previous page

Title	Year	Objectives	Approaches	HMD Types	Visual Conditions	User Study
Amblyopia rehabilitation by games for low-cost virtual reality visors	2015	Therapeutic	Virtual	IVR	Stereopsis	N
CueSee: Exploring visual cues for people with low vision to facilitate a visual search task	2016	Assistive	Augmented	VST	Central Vision	Y - 12
Low vision aid through laser retina imaging - toward building eyesight-aid	2016	Assistive	Modified	OST	Central Vision, Visual Field	N
Using virtual reality to enhance vision for people who Are blind in one eye	2016	Assistive	Modified	VST	Visual Field	Y - 11
Head-mounted display technology for low-vision rehabilitation and vision enhancement	2017			Survey Paper		
Head-mounted augmented reality displays on the cheap: a DIY approach to sketching and prototyping low-vision assistive technologies	2017	Assistive	Augmented, Modified	VST, OST	Central Vision	N
Augmented and virtual teality approaches to help with peripheral vision loss	2017	Assistive	Augmented, Modified	OST, VST	Visual Field	N
Validation of an immersive virtual reality system for training near and far space neglect in individuals with stroke: a pilot study	2017	Therapeutic	Virtual	IVR	Visual Field	Y - 10
Amblyopia treatment of adults with dichoptic training using the virtual reality oculus rift head mounted display: preliminary results	2017	Therapeutic	Virtual	IVR	Stereopsis	Y - 17
Virtual reality photo hunt game application for amblyopia patient	2017	Therapeutic	Virtual	IVR	Stereopsis	N
Image level color classification for colorblind assistance	2017	Assistive	Modified	OST	Color Vision	N

Table 2 continued from previous page

Title	Year	Objectives	Approaches	HMD Types	Visual Conditions	User Study
Wearable improved vision system for color vision deficiency correction	2017	Assistive	Modified	VST	Color Vision	Y - 24
Vision therapy and virtual reality applications	2018			Survey Paper		
Low vision enhancement with head-mounted video display systems: are we there yet?	2018			Survey Paper		
Design of an augmented reality magnification aid for low vision users	2018	Assistive	Augmented	OST	Central Vision	Y - 3
Differing effects of an immersive virtual reality programme on unilateral spatial neglect on activities of daily living	2018	Therapeutic	Virtual	IVR	Visual Field	Y - 1
Effectiveness of binocularity-stimulating treatment in children with residual amblyopia following occlusion	2018	Therapeutic	Virtual	IVR	Stereopsis	Y - 22
Jazzy: Leveraging virtual reality layers for hand-eye coordination in users with amblyopia	2018	Therapeutic	Virtual	IVR	Stereopsis	N
Towards amblyopia therapy using mixed reality technology	2018	Therapeutic	Augmented	OST	Stereopsis	N
Virtual interactive environment for low-cost treatment of mechanical strabismus and amblyopia	2018	Therapeutic	Virtual	IVR	Stereopsis	Y - 41
★ Use of virtual reality to assess and treat weakness in human stereoscopic vision	2018	Therapeutic	Virtual	IVR	Stereopsis	N
ChromaGlasses: Computational glasses for compensating colour blindness	2018	Assistive	Modified	OST	Color Vision	Y - 38
Designing AR visualizations to facilitate stair navigation for people with low vision	2019	Assistive	Augmented	OST	Central Vision	Y - 12

Table 2 continued from previous page

Title	Year	Objectives	Approaches	HMD Types	Visual Conditions	User Study
Enhanced depth navigation through augmented reality depth mapping in patients with low vision	2019	Assistive	Augmented	OST	Central Vision	Y - 18
★ Benefit of an electronic head-mounted low vision aid	2019	Assistive	Modified	VST	Central Vision	Y - 60
Measuring changes in device use of a head-mounted low vision aid after personalised telerehabilitation: Protocol for a feasibility study	2019	Assistive	Modified	VST	Central Vision	Y - 60
The challenge of reading music notation for pianists with low vision: An exploratory qualitative study using a head-mounted display	2019	Assistive	Modified	VST	Central Vision	Y - 5
Development and evaluation of a head-mounted display system based on stereoscopic images and depth algorithms for patients with visual impairment	2019	Assistive	Modified	VST	Central Vision	Y - 11
Designing and evaluating a customizable head-mounted vision enhancement system for people with low vision	2019	Assistive	Modified	VST	Central Vision	Y - 20
Preliminary evaluation of two digital image processing strategies for head-mounted magnification for low vision patients	2019	Assistive	Modified	VST	Central Vision	Y - 30
A parametric perceptual deficit modeling and diagnostics framework for retina damage using mixed reality	2019	Assistive	Modified	VST	Central Vision	N
A smart context-aware hazard attention system to help people with peripheral vision loss	2019	Assistive	Augmented	VST	Visual Field	N
Implementation of a virtual reality rendered in portable devices for strabismus treatment based on conventional visual therapy	2019	Therapeutic	Virtual	IVR	Stereopsis	Y - 45

Table 2 continued from previous page

Title	Year	Objectives	Approaches	HMD Types	Visual Conditions	User Study
Video game and fuzzy logic to improve amblyopia and convergence insufficiency	2019	Therapeutic	Virtual	IVR	Stereopsis	Y - 3
Virtual reality video game paired with physical monocular blurring as accessible therapy for amblyopia	2019	Therapeutic	Virtual	IVR	Stereopsis	Y - 9
Computational Glasses: Vision augmentations using computational near-eye optics and displays	2019	Assistive	Modified	OST	Color Vision	N
Time-domain color mapping for color vision deficiency assistive technology	2019	Assistive	Modified	VST	Color Vision	N
The potential of virtual reality for inducing neuroplasticity in children with amblyopia	2020	Survey Paper				
Augmented reality for people with low vision: Symbolic and alphanumeric representation of information	2020	Assistive	Augmented	OST	Central Vision	Y - 3
Engineering details of a smartglasses application for users with visual impairments	2020	Assistive	Augmented	OST	Central Vision	N
Walking support for visually impaired using AR/MR and virtual braille block	2020	Assistive	Augmented	OST	Central Vision	Y - 8
The effectiveness of visual and audio wayfinding guidance on smartglasses for people with low vision	2020	Assistive	Augmented	OST	Central Vision	Y - 16
Use of augmented reality technology for improving visual acuity of individuals with low vision	2020	Assistive	Modified	VST	Central Vision	Y - 100
Dynamic text presentation on smart glasses: A pilot evaluation in age-related macular degeneration	2020	Assistive	Modified	OST	Central Vision	Y - 23

Table 2 continued from previous page

Title	Year	Objectives	Approaches	HMD Types	Visual Conditions	User Study
A mixed reality system for modeling perceptual deficit to correct neural errors and recover functional vision	2020	Assistive	Virtual	IVR	Central Vision	Y - 80
AmblyopiaVR: immersive game-based virtual reality system for the treatment of amblyopia	2020	Therapeutic	Virtual	IVR	Stereopsis	N
Evaluation of a virtual reality implementation of a binocular imbalance test	2020	Therapeutic	Virtual	IVR	Stereopsis	Y - 100
Visual training in virtual reality in adult patients with anisometric amblyopia	2020	Therapeutic	Virtual	IVR	Stereopsis	Y - 84

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