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## Virtual Reality and Augmented Reality in Ophthalmology: A Contemporary Prospective

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### Abstract

**Purpose:** Most published systematic reviews have focused on the use of virtual reality (VR)/augmented reality (AR) technology in ophthalmology as it relates to surgical training. To date, this is the first review that investigates the current state of VR/AR technology applied more broadly to the entire field of ophthalmology.

**Methods:** PubMed, Embase, and CINAHL databases were searched systematically from January 2014 through December 1, 2020. Studies that discussed VR and/or AR as it relates to the field of ophthalmology and provided information on the technology used were considered. Abstracts, non-peer-reviewed literature, review articles, studies that reported only qualitative data, and studies without English translations were excluded.

**Results:** A total of 77 studies were included in this review. Of these, 28 evaluated the use of VR/AR in ophthalmic surgical training/assessment and guidance, 7 in clinical training, 23 in diagnosis/screening, and 19 in treatment/therapy. 15 studies used AR, 61 used VR, and 1 used both. Most studies focused on the validity and usability of novel technologies.

**Conclusions:** Ophthalmology is a field of medicine that is well suited for the use of VR/AR. However, further longitudinal studies examining the practical feasibility, efficacy, and safety of such novel technologies, the cost-effectiveness, and medical/legal considerations are still needed. We believe that time will indeed foster further technological advances and lead to widespread use of VR/AR in routine ophthalmic practice.

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## Keywords

augmented reality; ophthalmology; patient care; training; virtual reality

In 1962, Morton Heiling created what is considered to be the first true virtual reality (VR) system, the “sensorama”.<sup>1</sup> This 3D film allowed users to feel as if they were riding a motorcycle through Brooklyn by engaging 4 of the 5 senses.<sup>2</sup> Ivan Sutherland’s 1968 interactive head-mounted 3D display (HMD) took this one step further and created both an immersive and an interactive environment, what we define as a true modern-day VR experience.<sup>3</sup>

The goal of VR is to simulate a real environment using computer technology. Although there is no one unified definition of VR, three commonly agreed-upon components of all VR systems include immersion, sensory feedback, and interaction. Whereas VR has no real-life elements and is fully virtual, augmented reality (AR), on the other hand, supplements a pre-dominantly real environment with virtual elements. Meaning, AR can be defined as an interactive experience, overlaying virtual elements in the user’s perspective of the real world. One can better conceptualize their relationship using the reality-virtuality continuum coined by Milgram et al.<sup>4</sup> As illustrated in Figure 1, this continuum displays the relationship between a completely real environment on one end and a completely virtual one (VR) on the other. Mixed reality is the space in between the 2 extremes.

Keeping in mind these definitions, ophthalmology is a field of medicine that lends itself well to the implementation of VR/AR technology. Not only is there a heavy emphasis on multimodal diagnostic testing that can be made efficient and portable with VR technology, but also VR simulators such as the Eyesi (VRmagic, Mannheim, Germany) and MicroVisTouch (ImmersiveTouch, Chicago, Illinois) are already commonly used training tools for the fine microsurgical procedures involved in most ophthalmic education programs.

To date, there have only been systematic reviews that examine VR/AR simulation-based training and surgical assessment in ophthalmology.<sup>5-7</sup> In contrast, this is the first paper, to our knowledge, that provides a more comprehensive systematic review on the use of VR and AR in the broader field of ophthalmology. We will examine how VR/AR technology is used not only in ophthalmology for surgical training, assessment, and guidance, but also in the domains of clinical training, diagnosis, and treatment/therapy. We will conclude with a discussion on the limitations and the future trends of virtual environments associated with ophthalmology.

## METHODS

### Search Strategy

We performed a systematic review to identify the applications of VR and AR in ophthalmology according to the guidelines for reporting systematic reviews [Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)]. The protocol for our review was registered before the review started (PROSPERO: CRD42020216509). Literature searches were performed in the PubMed, Embase, and CINAHL databases from

January 2014 through December 1, 2020, using keywords and MeSH terms for virtual reality, augmented reality, and ophthalmology. Language and publication limits were not applied. Full search details can be seen in appendix 1, <http://links.lww.com/APJO/A97>. Two reviewers screened 1190 abstracts, with a third reviewer available to resolve conflicts, after which 285 were chosen for full-text review. References of studies selected for full-text review were reviewed for possible inclusion. A total of 77 articles were subsequently chosen for inclusion (Fig. 2).

### Eligibility Criteria

According to our eligibility criteria, we only included studies that had information available on the specific VR/AR technology used. The VR technology had to be immersive and interactive to be included. The technology was considered to be immersive if the device used a stereo/3D display, an HMD, or 2D screens in a manner that attempt to surround the participant. The technology was considered to be interactive if there was any potential for the participant to manipulate the virtual environment using a physical, device-based, or sensor-based interface. Letters to the editor and correspondences were excluded unless they reported on the applicability of VR/AR not found in other studies. Abstracts, non-peer-reviewed literature, review articles, qualitative studies, and studies with no English translation were excluded.

## RESULTS

A total of 77 studies were included in this review, as shown in Figure 2.

### Surgical Training/Assessment and Guidance

A total of 28 studies evaluated the use of VR and AR in surgical training/assessment and guidance as seen in Supplementary Digital Content, Table 1, <http://links.lww.com/APJO/A93>.

### Augmented Reality

Two studies utilized AR for surgical training.<sup>8,9</sup> Both demonstrated the feasibility of using their developed AR simulator with the HoloLens (Microsoft, US) to train vitreoretinal microsurgical skills.

### Virtual Reality

**Validation of Training Systems**—Three studies investigated the validity of the Eyesi surgical simulator as a training and assessment tool for vitreoretinal surgery.<sup>10–12</sup> Cissé et al<sup>10</sup> studied the construct validity (whether a test actually measures what it claims to measure) of vitreoretinal modules on the Eyesi surgical simulator and showed that experienced surgeons achieved significantly higher median scores than novices in 4 modules ( $P$  values ranged from 0.01 to 0.04). Vergmann et al<sup>11</sup> developed a vitreoretinal surgery training program on the Eyesi surgical simulator and found that in 4 (out of 6) vitreoretinal modules, the vitreoretinal surgeons had a better overall score than medical students ( $P < 0.01$ ). Finally, Jaud et al<sup>12</sup> designed a vitreoretinal surgery proficiency-based test on the Eyesi surgical simulator to establish a pass/fail score of 596.

In contrast, there were only 2 validation studies that applied VR to cataract surgery training. One study designed a proficiency-based cataract surgery curriculum for novices<sup>13</sup> and the other designed a test targeting experienced cataract surgeons.<sup>14</sup>

### Skill Transfer

Several studies looked at whether skills learned on the Eyesi were transferable amongst surgical specialties, between training modules and ultimately to the operating room (OR).<sup>15–22</sup> Thomsen et al<sup>15</sup> found improved OR performance after Eyesi training for novice cataract surgeons ( $P = 0.008$ ). Jacobsen et al<sup>16</sup> similarly found a significant correlation between the Eyesi score and surgical performance ( $P = 0.003$ ), and Ferris et al<sup>20</sup> showed that the unadjusted rates of posterior capsule rupture before versus after Eyesi simulator training was 3.5% versus 2.6%. Roohipoor et al<sup>17</sup> found a significant correlation between Eyesi scores of first-year ophthalmology residents and OR performance measured in the final year of residency (eg, forceps module  $P = 0.002$  and navigation training module  $P = 0.013$ ). At the very least, self-perceived difficulty scores on phacoemulsification procedures of residents without Eyesi training were significantly higher than reported difficulty scores of residents that did receive Eyesi training.<sup>18</sup>

Although simulator training can improve surgical performance, the converse has also been shown to be true. Sikder et al<sup>23</sup> found that more experience in the OR improved MicroVisTouch simulator performance. Oflaz et al<sup>24</sup> further showed a correlation between participants' surgical experience and their scores on the capsulorhexis module on the Eyesi simulator. In reality, any form of practice, be it surgical or simulated, likely improves overall surgical skills. Deuchler et al<sup>25</sup> even found that a warm-up session on the Eyesi simulator improved the average real surgery performance level of all surgeons, including surgeons with the most experience.

Subspecialty skill transfer is another topic of extensive study. Although some have found no difference in simulator performance between surgical subspecialists, McCannel et al<sup>26</sup> showed that residents that trained on the Capsulorhexis Intensive Training Curriculum had a higher portion of vitreous loss not associated with an errant capsulorhexis but not an overall lower rate of vitreous loss. These results imply that microsurgical training may be highly task-specific.

### Beyond Training

Ophthalmologists are taking advantage of the Eyesi as a surgical simulator in numerous other innovative manners—from testing out the efficacy of robot-assisted surgery<sup>27</sup> to understanding the impact that learning styles have on surgical performances.<sup>28</sup>

For example, several studies used simulators to study the impact of dexterity on surgical performance.<sup>29,30</sup> Vieira et al<sup>29</sup> found that 2 sequential training evaluations using the simulator showed improvement of microsurgery dexterity (increase in median score by 104 points;  $P < 0.001$ ). Gonzalez-Gonzalez et al<sup>30</sup> showed improved dexterity and overall score performance in both dominant ( $P < 0.05$ ) and non-dominant ( $P < 0.001$ ) hands after a structured Eyesi training. Additionally, Although the simulator training program led to significantly faster times in both dominant ( $P < 0.001$ ) and non-dominant ( $P < 0.02$ ) hands,

the learning curve was steeper in the non-dominant hand ( $P < 0.01$ ). This may be the first study to document this finding.

Two studies even used the simulators to assess the effect of distraction on surgical performance.<sup>31,32</sup> Mellum et al<sup>31</sup> found that lower simulated surgical performance was associated with auditory distraction ( $P = 0.0012$ ), fasting ( $P = 0.02$ ), sleep interruption ( $P = 0.02$ ), and sleep deprivation ( $P = 0.0006$ ). McGowan et al<sup>32</sup> gave surgeons a cognitive task to perform simultaneously while using a surgical simulator to mimic real-time OR distractions and found that this increased the time of surgery ( $P = 0.028$ ), while having no effect on the surgical task score.

### Surgical Guidance

Unlike in other surgical fields, relatively few studies utilized AR for surgical guidance.<sup>33,34</sup> DeLisi et al<sup>33</sup> found that surgeons who used their video augmentation system experienced faster endoscopic procedural times than surgeons who did not use AR ( $P = 0.020$ ). Pan et al<sup>34</sup> developed and implemented a deep learning framework to accurately detect corneal contours for accurate suturing in deep anterior lamellar keratoplasty procedures. Although the technology has not been implemented in most surgical suites quite yet, novel VR programs are even being developed to display 3D interactive optical coherence tomography images to guide in real-time surgical visualization and execution.<sup>35</sup>

### Clinical Training

Seven studies evaluated the use of VR and AR in clinical training as seen in Supplementary Digital Content, Table 2, <http://links.lww.com/APJO/A94>.<sup>32–38</sup>

### Slitlamp Examination

**Augmented Reality**—One study examined slitlamp education for optometry students using an AR slitlamp prototype.<sup>36</sup> The average success rate of the prototype based on user performance for a comprehensive simulation procedure was 83.8%, and the average user satisfaction score was 80.4%. The authors concluded that the AR slitlamp was a feasible method of education and that there was positive user feedback from the students.

### Direct Ophthalmoscopy

**Virtual Reality**—Although there were no studies that have implemented AR technology into direct ophthalmoscopy training or usage, 3 studies examined the application of VR for direct ophthalmoscopy examination.<sup>37–39</sup>

One study validated the use of the Eyesi Direct Ophthalmoscope,<sup>37</sup> and 2 studies described the usability of a prototype VR technology as a direct ophthalmoscope teaching tool.<sup>38,39</sup> Wilson et al<sup>38</sup> developed a 3D smartphone application combined with a VR headset to simulate direct ophthalmoscopy. Based on subjective user experience, the app was highly rated in questionnaires that assessed perceived usefulness and ease of use. Similarly, Nguyen et al<sup>39</sup> conducted a preliminary usability study of a VR direct ophthalmoscope using an HTC VIVE VR headset and controller. The System Usability Questionnaire (SUS) score for this tool was 75.6, where a score above 68 was considered above average. The authors

conclude that this is a cost-effective, immersive, and engaging educational tool for direct ophthalmoscopy.

### Indirect Ophthalmoscopy

**Augmented Reality**—Three studies looked at the application of AR as it relates to indirect ophthalmoscopy training.<sup>40–42</sup> Two of these studies demonstrated construct validity of the Eyesi Indirect Ophthalmoscope.<sup>40,41</sup> Chou et al<sup>40</sup> reported that medical students were outperformed by ophthalmology and optometry trainees on the simulator on all difficulty levels, and Rai et al<sup>41</sup> similarly reported that vitreoretinal fellows outperformed residents ( $P < 0.001$ ). Both these studies reported significantly faster mean examination times on the simulator by more advanced trainees.

Simulator training was also found to be a better method than conventional indirect ophthalmoscopy training. Rai et al<sup>41</sup> found that residents who had trained only on the simulator outperformed those who had completed only traditional teaching (13.95 vs 9.09,  $P = 0.006$ ), as measured by an evaluation module on the simulator. Leitritz et al<sup>42</sup> on the other hand measured performance using an ophthalmoscopy training score, which was calculated by evaluation of an optic disc drawing done by participants after their respective training. The median score of those trained with the simulator was significantly greater ( $P < 0.0033$ ) than the conventional method.

### Diagnosis/Screening

Twenty-three studies evaluated the use of VR and AR in diagnosis/screening as seen in Supplementary Digital Content, Table 3, <http://links.lww.com/APJO/A95>.<sup>44–66</sup>

### Visual Assessment

**Augmented Reality**—Two studies evaluated the use of AR to better determine visual function.<sup>43,44</sup>

Ong et al<sup>43</sup> developed an HMD visual acuity test using the Epson Moverio BT350 smart glasses. They found their prototype overestimated vision in patients with poorer visual acuities [VA worse than 0.30 logMAR (6/12)], in which sensitivity was 63.6% and specificity was 81.0%. The authors did note, however, that the portability and automated nature of the visual acuity test were advantages over the traditional methods. Another study used AR to gain insight into how ophthalmic diseases affect functional vision.<sup>44</sup> The authors used AR to simulate everyday difficulties caused by glaucoma, and found that participants with AR-simulated visual field loss had increased difficulties with visual mobility ( $P < 0.001$ ). Interestingly, participants made more head movements ( $P = 0.017$ ) and more eye movements when inferior visual field loss was simulated ( $P = 0.002$ ) versus superior visual field loss.

### Virtual Reality

Seven studies examined the use of VR to better understand how vision loss can affect function.<sup>44–50</sup>

Five of the seven used VR to evaluate the effect of glaucoma on several aspects of daily living.<sup>44–48</sup> For example, Goh et al<sup>45</sup> evaluated the efficacy of a smartphone-based VR device to assess activity limitation in glaucoma using 3 tests (stationary, moving ball, driving). They found that only the stationary test and moving ball test showed reasonable measurement. Lam et al<sup>46</sup> evaluated the application of VR to identify vision-related disability. They found that the overall VR disability score was associated with the National Eye Institute 25-item Visual Function Questionnaire Rasch score ( $R^2 = 0.207$ ,  $P < 0.001$ ), indicating that VR simulation is a useful method of evaluating vision-related disability. Finally, Jones et al<sup>44</sup> and Daga et al<sup>47</sup> found that participants with visual field loss had increased difficulties with visual search ( $P < 0.001$ ) and wayfinding ( $P = 0.001$ ) respectively.

Two other studies evaluated the effect of visual field loss on functional vision using VR.<sup>49,50</sup> Gopalakrishnan et al,<sup>49</sup> for example, found that normal vision subjects performed better than low vision subjects in everyday tasks in a VR environment. They demonstrated that VR performance scores in patients with peripheral field loss (56.65) and central field loss (63.25) were lower ( $P < 0.001$ ) than normal vision subjects (87). Qiu et al<sup>50</sup> validated VR as a method to evaluate peripheral field loss patients' ability to avoid collision with other pedestrians. They also tested whether high-power prisms improve pedestrian detection, and found that they improved detection rates and response times, and supported reasonable judgment among participants.

Three studies used VR for more specialized visual testing.<sup>51–53</sup> Pujol et al<sup>51</sup> studied a VR prototype as a method of testing spherical refraction, Versek et al<sup>52</sup> described a Neuro-Optical Diagnostic VR system (the NeuroDotVR), and Tatiyosyan et al<sup>53</sup> developed and validated an optokinetic nystagmus (OKN)-based VR device to test contrast sensitivity. Finally, 3 additional studies used VR environments to better understand the concepts of self-motion and oscillopsia.<sup>54–56</sup>

## Visual Field Testing

**Virtual Reality**—Four studies used VR technology to diagnose visual field deficits in glaucoma patients.<sup>57–60</sup> All 4 of these studies compared the VR to the Humphrey Visual Field Analyzer. Tsapakis et al<sup>57</sup> found that there was a high correlation coefficient ( $r = 0.808$ ,  $P < 0.0001$ ) between their VR visual field device and the Humphrey perimeter visual field. Alawa et al<sup>58</sup> similarly demonstrated that the VR visual field device had good agreement and high correlation coefficient ( $R^2 = 0.77$ ) with the Humphrey Zeiss FDT, and that there was no statistically significant difference between the 2 devices (Mann-Whitney test,  $P > 0.05$ ). Razeghinejad et al<sup>59</sup> found that the mean sensitivity of the VR device and the Humphrey Field Analyzer correlated significantly both in healthy participants ( $r = 0.5$ ,  $P = 0.001$ ) and in glaucoma patients ( $r = 0.8$ ,  $P < 0.001$ ). Mees et al,<sup>60</sup> on the other hand, reported that although their VR visual field device was highly sensitive and specific in identifying glaucoma subjects (AUROC = 0.77–0.86), the visual field deficits did not match that of the Humphrey Field Analyzer. Only 38% of patients with an 18 dB or worse deficit seen on the Humphrey field Analyzer were picked up by the VR device.

## Strabismus and Amblyopia

**Virtual Reality**—Three studies assessed the use of VR for determining ocular misalignment in strabismus patients.<sup>61–63</sup> The first study was a case series that tested the efficacy and feasibility of measuring ocular misalignment using an Oculus Rift VR headset.<sup>61</sup> They compared the performance of the VR-based technique to the traditional Lees screen test, and found good agreement between the pattern of ocular deviation obtained using the 2 methods. Another study utilized a FOVEVR headset to test for ocular deviation.<sup>62</sup> They compared the VR-based test results to the strabismologist's measurements of ocular deviation, and similarly found that the results were agreeable using the VR test (mean difference less than 0.7°). The third study testing children with intermittent exotropia on a VR-based block building task, found larger horizontal ( $P < 0.001$ ), vertical ( $P = 0.039$ ), and 3D distance disparities ( $P < 0.001$ ) compared to age-matched normal controls.<sup>63</sup>

Two studies examined the use of VR in the evaluation of amblyopia.<sup>64,65</sup> Panachakel et al<sup>64</sup> validated a new VR-based approach to quantify the severity of amblyopia by measuring suppression asymmetry during dichoptic image recognition tasks. Martin et al<sup>65</sup> implemented a VR-based test for binocular imbalance. They found that this test was correlated with interocular acuity difference ( $r = 0.575$ ,  $P < 0.0001$ ), stereoacuity ( $r = 0.675$ ,  $P < 0.0001$ ), and with the Worth 4-dots test ( $r = 0.538$ ,  $P < 0.0001$ ).

## Treatment/Therapy

Nineteen studies evaluated the use of VR and AR in treatment/therapy as seen in Supplementary Digital Content, Table 4, <http://links.lww.com/APJO/A96>.<sup>67–85</sup>

## Low Vision Services

**Augmented Reality**—Six studies evaluated the use of AR-based treatment of patients with low vision and/or loss of visual field.<sup>66–71</sup> All these studies examined ways in which AR can improve patients' functional vision.

Huang et al<sup>66</sup> utilized the Microsoft HoloLens to provide indoor wayfinding assistance for individuals with reduced vision, specifically through the AR device in identifying and enhancing signs and room numbers for the patients. They calculated a distance ratio for each participant and found that the mean distance ratio was significantly reduced for participants that used the AR device versus those that did not (0.36 vs 0.50,  $P < 0.001$ ), indicating that participants in the AR group took more direct routes than those not using the AR device. The AR group also reported the device helpful for wayfinding (96% of participants preferred the AR trial for ease, 83% for comfort, and 92% for confidence). Hwang et al<sup>67</sup> similarly used an AR device, the Google Glass, to enhance real-world information by overlaying edge information on the wearer's real-world view. The authors found that all the subjects had significantly improved contrast sensitivity, which could potentially help them navigate better real-world scenarios. The Google Glass was also found to significantly improve visual field in a case report performed by Trese et al.<sup>68</sup> Ho et al<sup>69</sup> evaluated the use of AR glasses to simulate reduced acuity, contrast, and visual field to investigate the utility of prosthetic central vision. They found that reading speed decreased with increasing pixel size and with a reduced field of view (78°–12°). In the face recognition task, participants identified faces



at over 75% of accuracy with 100 lm pixels and only 2 grayscale levels. In addition, both Sayed et al<sup>70</sup> and Kinatader et al<sup>71</sup> reported improved object recognition when participants used their respective AR device ( $P < 0.001$  for both).

**Virtual Reality**—Virtual reality has also been used to improve functional vision in people with reduced vision. Because VR does not incorporate the real environment, it cannot be used as a tool to improve functional vision in a real-world setting as with AR. Rather it can be used for functional vision training,<sup>72,73</sup> remapping,<sup>74–76</sup> and magnifying images.<sup>77</sup> Virtual reality has also been used to simulate treatments to low vision, specifically to elucidate the potential utility of retinal prosthesis.<sup>78–80</sup>

### Amblyopia/Strabismus

**Virtual Reality**—Three studies were found that examined VR-based treatment of amblyopia.<sup>81–83</sup> Herbison et al<sup>81</sup> specifically looked at a VR-based therapy called the Interactive Binocular Treatment (I-BiT) system, which is the first VR-based computer system that employs dynamic stimuli with preferential stimulation of an amblyopic eye. They noted an average VA improvement of 0.07 logMAR for all their participants 6 weeks after treatment ( $P < 0.001$ ). A VR-based amblyopia therapy has the advantage that it does not rely on visual occlusion, as is the current clinical standard in children.

Two studies looked at the use of the Oculus Rift headset to provide dichoptic visual training to anisometric amblyopic adults.<sup>82,83</sup> Both reported positive results, with visual acuity improving on average in the participants after the VR-based treatment. Ziak et al<sup>82</sup> found that mean best-corrected visual acuity (BCVA) in the amblyopic eye improved significantly from a logMAR value of  $0.58 \pm 0.35$  before VR training to  $0.43 \pm 0.38$  post-training ( $P < 0.01$ ). Halicka et al<sup>83</sup> also found an improvement in BCVA after VR training, with an observed improvement of 0.1 BCVA from 0.48 to 0.58 Sloan table ( $P < 0.05$ ).

A final study by Boon et al<sup>84</sup> looked at VR as a treatment of convergence insufficiency. A VR intervention showed significant improvement in near point of convergence ( $F_{1,16} = 38.32$ ,  $P < 0.0001$ ), near positive fusional reserve break, and recovery ( $F_{1,16} = 21.94$ ,  $P < 0.0001$ ). Importantly, they found that not only did VR therapy improve convergence insufficiency, but it improved participants' compliance to treatment (82% compliance to the VR game, 51% compliance to conventional treatment).

### Limitations and Safety VR/AR

There are several limitations to the use of VR/AR. The weight and comfort of the VR/AR systems are one concern for its universal adoption. This is especially important when thinking of adopting HMD devices into the OR, or as a treatment/diagnostic method for patients. The Microsoft Hololens 2 AR headset weighs 1.248 pounds, and the Oculus Rift S VR headset weighs 1.1 pounds. Use for prolonged periods of time may put a strain on the neck and back. These devices may not be feasible for use by surgeons or patients who are injury-prone or for particularly long surgeries. Additional battery packs will also add bulk to the apparatus. Luckily, technological advancement almost always results in the reduction

of the weight and size of hardware over time, and so one can predict that cumbersome and heavy VR/AR devices are likely not a long-term concern.

In addition, cybersickness (CS), which is a constellation of motion sickness–like symptoms,<sup>85</sup> has been well documented as it relates to the virtual environment. A review done by Weech et al<sup>86</sup> discussed multiple factors that are thought to contribute to CS including visual-vestibular mismatch and display characteristics such as low frame rate and higher field-of-view. Although the majority of the time CS symptoms stop upon termination of the exposure, there are reported long-lasting effects in some individuals.<sup>87</sup> However, it should be noted that studies that applied VR/AR technologies addressed both the risk of motion sickness and the subsequent risk of falls and did not report any adverse outcomes.<sup>88</sup> Further research is needed to elucidate the real risk of CS and sources of these motion sickness–like symptoms so that VR/AR developers can find ways to mitigate this.

Furthermore, long-term safety concerns need to be addressed particularly in children, as the product safety warnings on VR headsets ban their use with children under the age of 13. As young children are in a “critical period in visual development,” there is fear that these devices may affect future visual function. However, the evidence behind these claims is mixed. Tychsen et al<sup>89</sup> studied the effects of 3D immersive HMD on the visuomotor function of 50 children after their exposure to two 30-minute VR gaming sessions and found no deleterious effects. Other studies reported transient refractive error, but no long-term effects on the vision of children or adolescents.<sup>90</sup> Critics have also worried about the effects that prolonged screen time may have on the ocular surface or on myopia progression. In reality, a few studies have actually found increased lipid layer thickness, tear film stability, and increased choroidal thickening with VR headset wear in the general population, arguing against these concerns.<sup>91,92</sup> Despite these findings, there is a need for more long-term standardized studies to be done before anything can be concluded on the ocular effects of VR/AR technology.

### **Future Scope of VR/AR in Ophthalmology**

Adopting VR/AR into clinical practice and training poses unique challenges that must be addressed. Ultimately, lower costs, improved hardware, and validated studies are needed for this technology to be adopted and utilized more widely in ophthalmology programs. The fidelity and accuracy of the VR/AR technology is fundamental due to the high stakes and high precision nature of ophthalmology. Similarly, cost-effectiveness must be examined before implementing new technology in medicine. More research is needed in validity and analyzing cost-effectiveness to effectively incorporate reality technology into the field. Although several VR/AR projects remain at a preliminary stage of research in ophthalmology, rapid technological advancements in hardware and the integration of VR into the computer gaming industry, have generated a new impulse in reality technology research and published studies over recent years.<sup>93</sup> Finally, to be accepted as more than a niche gimmick or a current transient fad, well-designed studies need to be highlighted at educational conferences and meetings. There needs to be more widespread dissemination of study results leading to greater awareness and better education across ophthalmology programs as to the use of VR/AR technologies.

## VR/AR and COVID-19

During COVID-19, the impetus to adopt VR and AR into ophthalmology is now stronger than ever.<sup>94</sup> The COVID-19 pandemic has momentarily changed the landscape in which we practice medicine. As we adapt to what is the new “norm” surrounding social distancing and interpersonal contact, innovative ways to practice medicine are in high demand. As such, telemedicine and virtual visits have rightly spiked since the beginning of the pandemic. Kaur et al<sup>95</sup> discuss the importance of the use of 3D heads-up displays in ophthalmic surgery in the COVID-19 era. The study points to the fact that this technology allows the adequate interpersonal distance between the surgeon and the patient. They additionally address the concern of aerosol production during phacoemulsification, and the potential hampered vision of the surgeon using face shields or goggles as a protective measure. The 3D heads-up displays may not require the use of these additional goggles or shields as the adequate distance is maintained from the surgical field. Likewise, the smaller and more compact of VR headsets makes them portable, transferable, and more hygienic. This applies to VR visual field devices as well. Finally, VR/AR devices are currently being studied for the feasibility of use by patients at home and during virtual visits.<sup>96</sup> If future research validates their use in such a manner, they could be invaluable for the duration of the pandemic and in the future.

## Limitations

Although we adhered closely to the PRISMA guidelines for systematic reviews, some limitations may affect the validity of our findings. Our review is susceptible to publication bias as grey literature was not included in this review. There could be VR/AR devices used in ophthalmology that did not publish results and therefore were excluded from our review (such as Eyesi Slit Lamp studies). Although comprehensive search terms were applied, reports using different terminology could have been missed. Similarly, studies published in technology journals would have been missed as we focused on health care databases for this review. Because of the heterogeneity in the methodologies and outcomes of the studies, quantitative analysis was not feasible for this review. Finally, as our review was limited to studies evaluating immersive and interactive VR/AR technology, articles regarding the cost-effectiveness, and legal/ethical and regulatory considerations of such novel techniques, were not in the scope of this article.

## CONCLUSIONS

This systematic review is the first to comprehensively report on the application of VR and AR in the field of ophthalmology. With its dependence on imaging, highly precise microsurgical procedures, and tradition of being on the cutting edge of new technology, ophthalmology has seen the widespread introduction of VR and AR. As reality technologies improve in hardware and software, and approach their ultimate goal of making the user truly believe that the virtual is real, we are optimistic that ophthalmology will greatly benefit from the widespread adoption of this technology in practice.

## Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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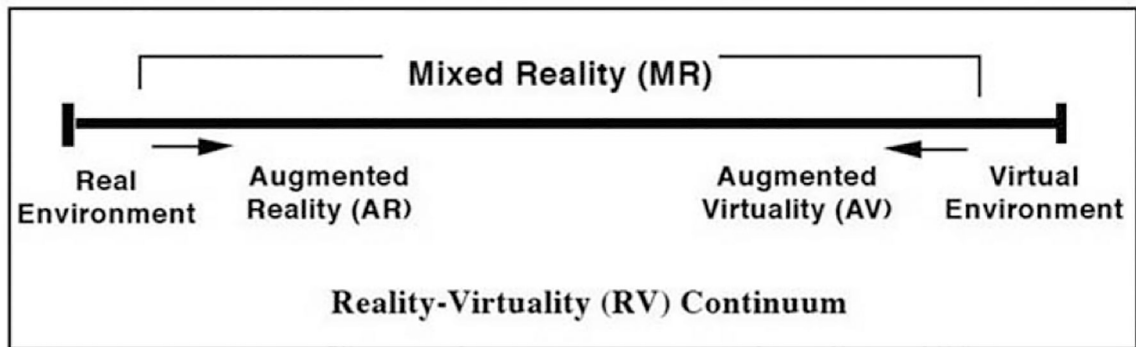
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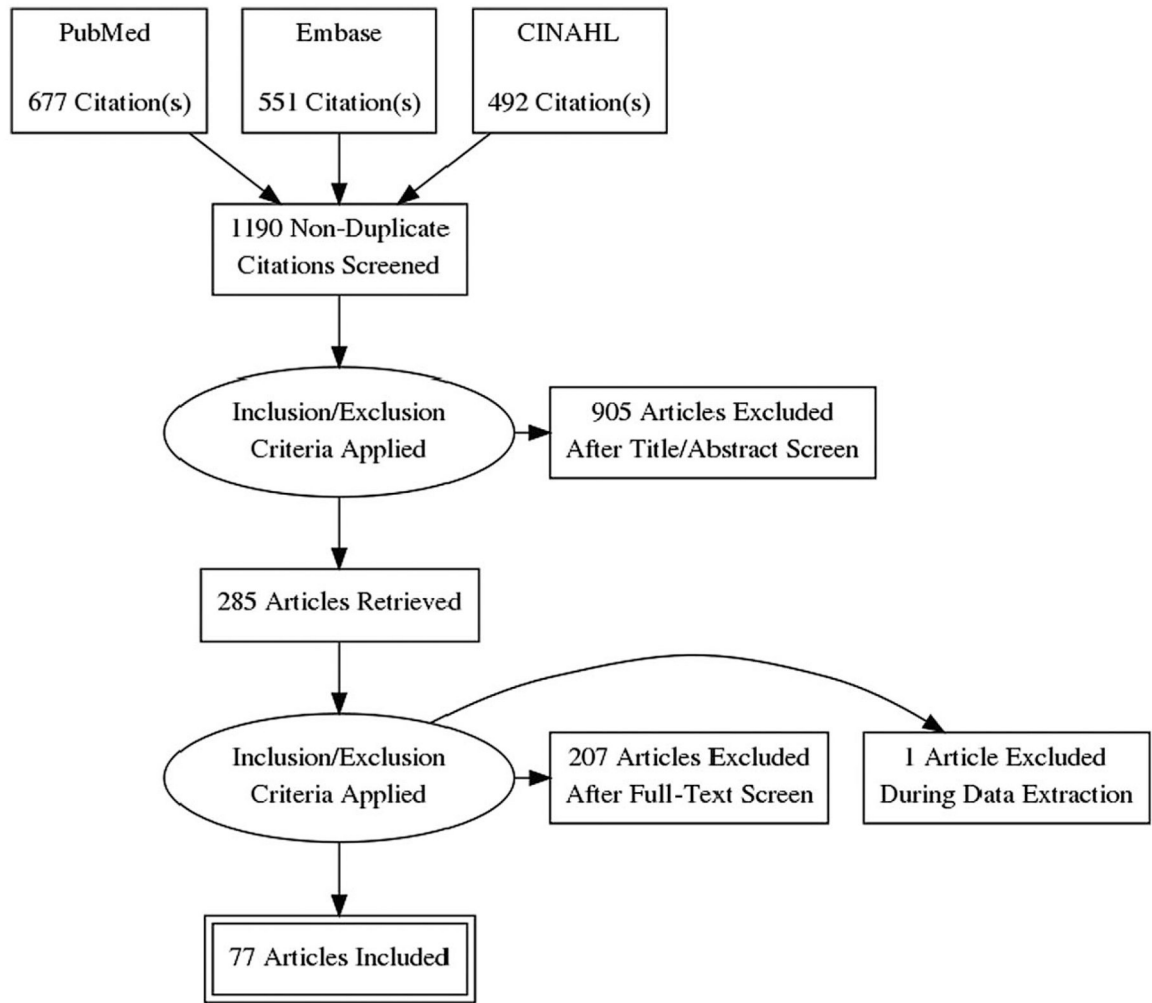
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**FIGURE 1.**

This continuum displays the relationship between a completely real environment on one end, and a completely virtual one (VR) on the other. Mixed reality is the space in between the 2 extremes.



**FIGURE 2.**  
Search Strategy.