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A systematic review of myopia compensation techniques in HMDs

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ABSTRACT: Myopia remains a major barrier to immersive VR use, causing blur and discomfort. This review compares software, hardware, and hybrid compensation approaches. Software methods offer flexible, low-cost enhancement but limited optical correction. Hardware solutions provide accurate adjustment at ergonomic cost. Hybrid systems combine adaptive optics and real-time rendering, showing promise for personalized correction. Key trade-offs and future design directions are outlined.

KEYWORDS: myopia compensation, virtual reality (VR), ergonomics, user experience, inclusive design

1. Introduction

Myopia is a widespread visual condition affecting more than two billion people worldwide. It occurs when the eye's optical system focuses incoming light in front of the retina, causing distant objects to appear blurry (Chakraborty et al., 2020). The prevalence of myopia has been rising globally, particularly among children and young adults, making it a major public health concern (Holden et al., 2016).

In parallel, Virtual Reality (VR) has experienced rapid growth and is now widely used in gaming, education, medical training, and industrial design. Virtual Reality (VR) can be implemented using various display configurations, including head-mounted displays (HMDs), projection-based systems, and screen-based environments. However, HMD-based VR currently represents the dominant paradigm and is therefore the primary focus of this review. However, users with myopia often experience blurred visuals and visual discomfort when using HMDs. This reduces immersion and may discourage frequent or long-term use (G.-A. Koulieris et al., 2017). Such problems compromise the advantages of VR and hinder user engagement.

Most consumer HMDs employ fixed-focus optics, which can limit visual clarity and comfort for users with refractive errors such as myopia. As the focal distance presented by the headset is typically fixed, myopic users may experience blur and discomfort without appropriate correction (Hua, 2017). The underlying optical mechanisms and related constraints (e.g., fixed focal distance and vergence–accommodation conflict) are summarized in the Technical Background section.

To address this challenge, various compensation strategies have been explored in both research and commercial development. These approaches generally operate at the software level, the hardware level, or through a combination of both. While differing in mechanism and implementation complexity, they share the common goal of improving clarity, comfort, and visual accessibility for myopic users in VR (Zhang, 2024). However, their effectiveness and practicality vary considerably, highlighting the need for a structured review to compare their strengths, limitations, and development potential.

This paper provides a systematic review of current myopia compensation techniques in VR. It compares software, hardware, and hybrid methods in terms of visual performance, user comfort, implementation cost, and technical feasibility. Finally, it identifies key challenges and research opportunities, with the broader goal of supporting more inclusive VR systems that offer comfortable and clear visual experiences for myopic users. The methodology of the systematic review, including the search strategy and study selection process, is presented in the following section.

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2. Methodology

This study applies a systematic review methodology to identify and categorize existing technical approaches that support myopic users in virtual reality environments. The focus lies in evaluating how these approaches improve visual clarity, comfort, and usability through software-based, hardware-based, and hybrid techniques. This review focuses solely on technical strategies for myopia compensation in immersive VR environments. Other aspects of visual health or unrelated conditions, such as hyperopia and astigmatism, were excluded. The goal is to evaluate and categorize methods that support myopic users in VR by improving clarity, comfort, and visual usability. The outcomes of this review provide structured insights into current trends, limitations, and future development opportunities for inclusive VR technology.

The review was conducted using four academic databases: IEEE Xplore, ACM Digital Library, ScienceDirect, and Web of Science. The review considered publications between 2015 and 2025, covering the period in which consumer-level VR headsets became widely available.

A systematic keyword strategy using Boolean operators was applied to refine the database search. The search strategy was structured around key concept groups, and the corresponding Boolean keyword combinations are summarized in Figure 1. The final search queries combined these concept groups using Boolean AND operators and were adapted to the syntax of each database. For example, a representative Boolean search string was:

("myopia" OR "near-sightedness" OR "refractive error") AND ("virtual reality" OR VR OR HMD OR "head-mounted display") AND (compensation OR correction OR diopter OR "prescription-aware" OR varifocal OR autofocal) AND ("dynamic focal rendering" OR "tunable lens" OR "adaptive optics").

Concept	Search terms
Refractive condition	myopia OR nearsightedness OR refractive error
Virtual reality	"virtual reality" OR VR OR HMD OR "head-mounted display"
Compensation technique	compensation OR correction OR diopter OR "prescription-aware" OR varifocal OR autofocal
Rendering / optics	"dynamic focal rendering" OR "tunable lens" OR "adaptive optics"

Figure 1. Overview of database search strategy and Boolean keyword combinations

Inclusion criteria were defined as follows:

(1) peer-reviewed publications written in English and published between 2015 and 2025;
(2) studies focusing on immersive VR systems with near-eye displays;
(3) studies explicitly addressing myopia or refractive-error-related visual clarity or comfort;
(4) studies proposing a concrete technical approach for myopia compensation, including software-based methods, hardware-based optical designs, or hybrid systems;
(5) studies providing at least one form of technical evaluation, such as a prototype demonstration, algorithmic or optical simulation, system performance analysis, or user study.

Exclusion criteria included:

(1) studies focusing exclusively on augmented reality or non-immersive displays;
(2) studies addressing general VR comfort or usability without a direct link to refractive error or myopia;
(3) purely conceptual or opinion-based papers without a defined technical mechanism or evaluation; and
(4) non-English publications.

The initial screening of titles, abstracts, and full-text articles was conducted by the first author following the predefined eligibility criteria. To reduce potential selection bias, a second researcher independently reviewed the final inclusion decisions. Any discrepancies were discussed and resolved by consensus.

The procedure is summarized in the PRISMA diagram (Figure 2), following the PRISMA 2020 guidelines (Page et al., 2021). A total of 432 records were initially identified. After removing duplicates, 375 records remained. Title screening excluded 263 unrelated records, and abstract screening further reduced the selection to 112 papers. Following full-text review, 32 studies met the inclusion criteria and were included in the final analysis.

The selected studies were categorized into three thematic clusters: software-based techniques ($n = 16$), hardware-based techniques ($n = 4$), and hybrid or integrated systems ($n = 12$). This structured process ensured coverage of both the technical diversity and the practical application scope of current VR myopia compensation research.

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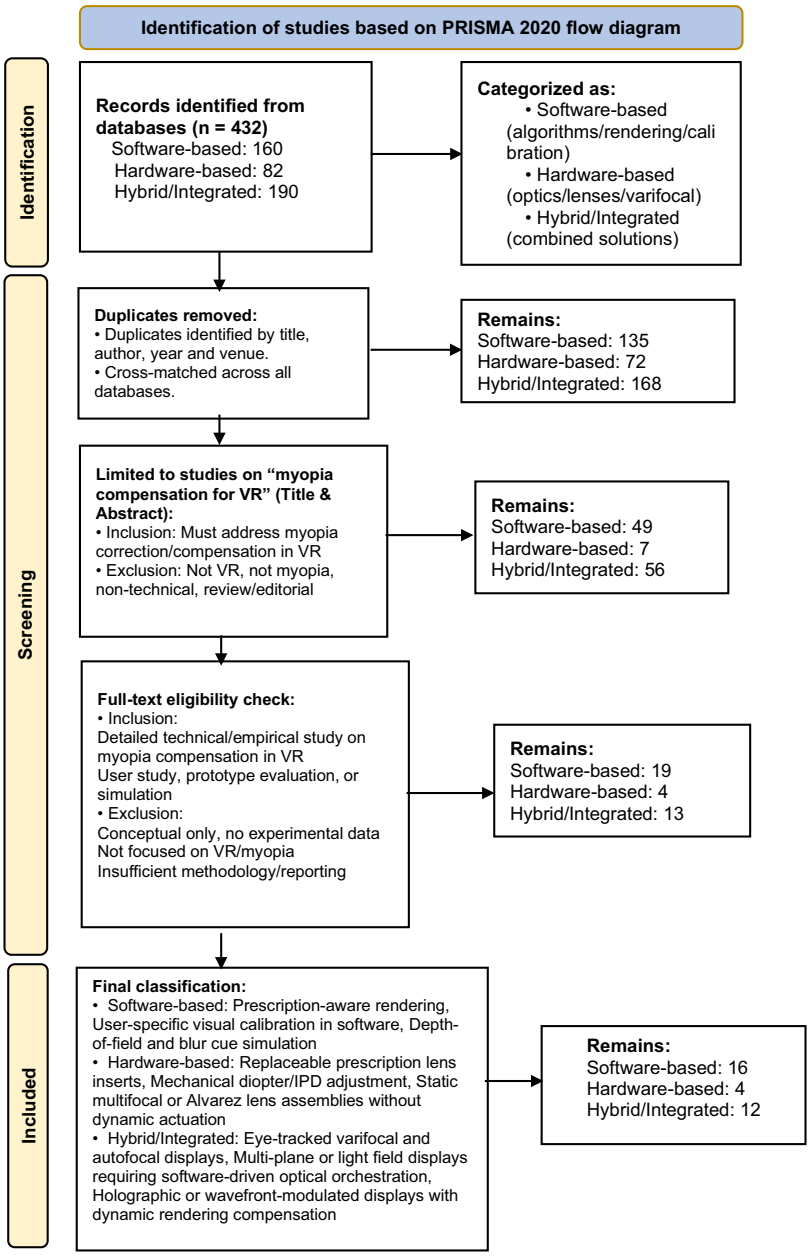


Figure 2. Process of sorting the literature review

3. Technical background

3.1. Imaging principles of VR headsets

Modern VR head-mounted displays (HMDs) typically consist of a close-range display and a fixed-focus optical lens system. Although the display is positioned only a few centimeters from the eyes, the lenses project the image to a virtual distance of approximately 1.5 to 2 meters (Cheng et al., 2024). This configuration reduces the need for accommodation and enhances spatial depth perception. Figure 3 illustrates the basic imaging principle of VR headsets (Dörner et al., 2019).

For users with normal vision, this optical arrangement provides a clear and immersive experience. In contrast, myopic users, due to the elongated axial length of the eye, experience image blur as light focuses in front of the retina. The virtual image, despite being optically relocated, remains out of focus without external correction such as eyeglasses or lens inserts (Lugtenberg et al., 2025; Padmanaban, Konrad, Stramer, et al., 2017).

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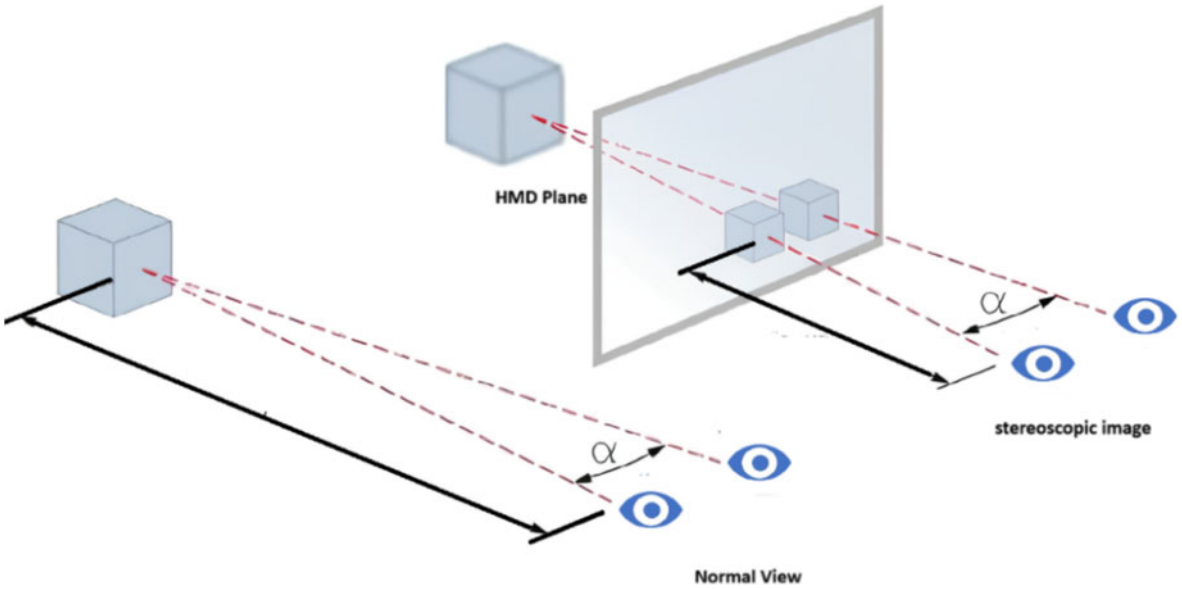


Figure 3. Stereoscopic image is rendered by the VR system on the HMD display (García et al., 2019)

In addition, VR scenes often involve frequent depth changes, requiring the eyes to adjust vergence and accommodation. However, fixed-focus HMDs maintain a constant focal distance. This discrepancy, known as the vergence-accommodation conflict (VAC), is recognized as a major cause of visual fatigue and discomfort during extended use (Lugtenberg et al., 2025).

3.2. Challenges faced by myopic users in VR

For myopic users, reduced image clarity in HMDs can impair interaction accuracy and diminish immersion, particularly in tasks requiring fine detail or precise depth judgments (Konrad et al., 2020). Long exposure to blurry images can strain the eyes because they must keep adjusting focus. This strain is stronger in scenes with changing depth or lots of visual detail. It may lead to symptoms like dry eyes, discomfort, or dizziness (Kourtesis et al., 2019).

Wearing conventional eyeglasses within VR headsets introduces further limitations. Limited space inside the device may cause discomfort, restrict the field of view, and introduce optical distortions. Glasses may also shift during use, leading to reduced image stability and degraded visual quality (Padmanaban, Konrad, Stramer, et al., 2017).

3.3. Technical challenges of myopia compensation

Several technical challenges arise when developing effective myopia compensation mechanisms for VR systems:

- Personalized Adjustment: Users exhibit varying degrees of refractive error. Compensation systems must provide individualized correction to support a wide range of visual conditions (H. Huang et al., 2016).
- Real-Time Responsiveness: Frequent gaze shifts and rapidly changing scenes require fast adaptation of optical or software adjustments to preserve image clarity (Chang et al., 2020).
- Design and Cost Constraints: Implementing adaptive optics, eye-tracking modules, or custom rendering techniques increases system complexity and cost. Practical solutions must balance performance, scalability, and manufacturability (Padmanaban, Konrad, Cooper, & Wetzstein, 2017).

Current HMD designs do not fully meet the needs of myopic users. The following sections review and analyze existing approaches to address these limitations.

4. Results

The reviewed studies are presented below according to the technical characteristics of the proposed myopia compensation approaches.

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4.1. Software-based techniques

Software-based approaches aim to improve perceived visual clarity and usability without modifying the physical optical pathway of the headset. These methods operate entirely within the rendering pipeline, adjusting image generation and display parameters to better match individual visual conditions (Chang et al., 2020). They are generally cost-effective and highly adaptable, but their corrective capacity remains fundamentally constrained by the fixed optical system of the device (Adhanom et al., 2023).

One representative direction is software-based dynamic focal rendering, in which focal cues are simulated rather than physically produced. These systems estimate depth from gaze direction and adjust the rendered blur profile or depth-of-field effect accordingly. Eye tracking is frequently used to infer focus-relevant visual attention. When implemented effectively, this reduces subjective vergence–accommodation mismatch during near-field manipulation (Sauer et al., 2022; Wernikowski et al., 2024). Examples include gaze-contingent detail allocation and foveated rendering pipelines (Adhanom et al., 2023; Konrad et al., 2020; Konrad et al., 2017; Krajancich et al., 2020; Padmanaban et al., 2018).

Another direction is prescription-aware rendering, which digitally pre-compensates visual content based on the user's refractive error (Reddy et al., 2024; Shindou et al., 2024). Rendering engines incorporate individualized dioptre or wavefront parameters so that the projected retinal image approximates corrected vision (Güzel et al., 2023; F.-C. Huang et al., 2014; H. Huang et al., 2016).

Finally, user calibration interfaces enable individuals to tune clarity-related parameters such as contrast, sharpness, or image scaling. Some approaches integrate quick in-headset visual tests or automated recommendations based on machine learning models (Zaman et al., 2023). Related developments include rapid visual acuity testing and the deployment of universal display profiles (Cheng et al., 2024; G. A. Koulieris et al., 2019; Piszczek et al., 2022).

Despite these advantages, software-based methods do not alter the physical light path. As a result, their effectiveness declines with increased levels of myopia or decreased calibration accuracy. Prior literature on the vergence–accommodation conflict and VR eye tracking emphasizes the importance of accurate sensing and rendering timing (Kramida, 2016; Patney et al., 2016; Xiong et al., 2021).

4.2. Hardware-based techniques

Hardware-based techniques directly modify the optical characteristics of the headset. These solutions adjust the physical light path to achieve optical correction and produce clearer retinal images.

A basic category involves manual dioptre adjustment. Some headsets incorporate mechanical controls that change lens-to-eye distance, allowing users to partially compensate for refractive error through physical adjustment (Robert Stevens et al., 2017).

Prescription lens inserts constitute another hardware-oriented approach. These lenses are placed between the eye and the headset optics and are matched to the user's clinical prescription, including corrections for astigmatism or higher-order aberrations. While generally effective, they require individual configuration and may introduce constraints related to available space inside the headset (Zhan et al., 2020).

Electronically tunable lenses, such as liquid-crystal or Alvarez-based designs, enable controlled modification of optical power (Luo et al., 2024; Wilson & Hua, 2019). When used in a standalone manner with preset or manual adjustments, these lenses operate as hardware solutions that replace the need for fixed prescription inserts.

Hardware-based methods typically provide more consistent optical correction than software-based approaches, particularly for moderate to high myopia. However, they often increase device size, require additional manufacturing resources, and may affect ergonomic comfort.

4.3. Hybrid and integrated systems

Hybrid systems integrate rendering algorithms with adaptive optical components to align perceived depth and optical focus in real-time (Padmanaban et al., 2019). These systems coordinate adjustments in both the virtual image and the physical light path, enabling more continuous and personalized visual correction.

A major research trend involves electronically tunable varifocal and autofocal lens architectures. When paired with eye tracking, these systems modulate optical power based on where the user is looking, approximating natural accommodation and improving depth continuity and visual comfort (Choi et al., 2024). Autofocal prototypes extend this principle by maintaining continuous real-time linkage between

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gaze estimation and focal plane adjustment (Gururaj et al., 2022; Hamasaki & Itoh, 2019; Piszczek et al., 2022). Empirical evaluations report reductions in visual fatigue and improved task performance during interactive viewing (Padmanaban et al., 2018, 2019).
Optical design choices influence performance and ergonomics: Fresnel configurations reduce mass but may introduce halo artifacts, aspheric lenses improve clarity at the cost of added weight, and liquid-crystal optics offer dynamic adaptability while requiring precise calibration and stable power supply (Chakravarthula et al., 2018; Chen et al., 2022; Choi et al., 2024; G. A. Koulieris et al., 2019; Rob Stevens & Ganeswaran, 2024; Vijayalakshmi et al., 2023).
Hybrid systems therefore offer the potential for continuous and visually coherent correction across varying viewing distances (Lee & Hua, 2025). However, challenges remain regarding synchronization latency, calibration reliability, power management, and integration into compact consumer-grade devices (Bosch et al., 2021; Zeng & Zhao, 2023).

5. Discussion

This section synthesizes the findings regarding software-based, hardware-based, and hybrid myopia compensation techniques in virtual reality. The analysis focuses on the relationship between optical correction effectiveness, system complexity, and practical feasibility in user-centered deployment contexts.

5.1. Comparative strengths of existing approaches

Software-based techniques provide flexible and cost-efficient compensation without modifying headset optics. Methods such as dynamic focal rendering and prescription-aware rendering improve perceived clarity and visual comfort for low to moderate refractive error, particularly in short to medium duration sessions. These techniques are also advantageous due to their ability to be deployed through software updates and platform-level rendering pipelines.
Hardware-based solutions address refractive error directly by modifying the physical light path. Prescription lens inserts and manual diopter adjustment offer stable optical correction when alignment tolerances match individual needs. Electronically tunable optics extend this capability by allowing adjustable focal power. These approaches are generally associated with more stable optical correction than software-based methods, although this comes at the cost of increased mass, cost, and ergonomic constraints.
Hybrid systems integrate adaptive optics with depth-aware rendering to maintain consistency between focal power and intended viewing depth. Reported outcomes indicate improved clarity continuity and reduced vergence–accommodation conflict during depth transitions. These results suggest that hybrid systems combine the adaptability of software approaches with the optical precision of hardware solutions.

5.2. Limitations and system constraints

Software-based methods remain limited by the unaltered optical path. Their performance depends on accurate gaze tracking, stable calibration, and low rendering latency, and they are insufficient for high myopia or complex refractive conditions. Hardware-based solutions increase system mass, manufacturing demands, and power consumption, which in turn influence wearability and sustained comfort. Hybrid systems, while promising, require reliable synchronization between eye-tracking signals, adaptive lenses, and rendering pipelines. Their commercial readiness is currently constrained by sensing accuracy, controller stability, and energy management requirements.
User variability also remains a determining factor. Comfort responses differ across session duration, content characteristics, and individual sensitivity to motion. Existing studies predominantly evaluate short-term usage, leaving long-term adaptation effects insufficiently documented. Standardized measurement protocols will be necessary to support broader generalization.

5.3. SWOT and derived TOWS analysis of hybrid systems

The SWOT factors were derived directly from the findings of the reviewed literature. Reported advantages of hybrid systems, including coordinated optical and rendering-based correction, improved focal adaptability, and reduced vergence–accommodation conflict, were consistently observed in studies

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on varifocal and autofocal display architectures (e.g., Padmanaban et al., 2018; Choi et al., 2024) and therefore informed the identified strengths.
Conversely, limitations reported across experimental and prototype-based studies, such as increased system complexity, sensitivity to eye-tracking accuracy, synchronization latency, and elevated power consumption, were reflected in the identified weaknesses.
External opportunities were derived from trends discussed in the literature, including advances in compact tunable optics, improvements in low-power sensing technologies, and the growing demand for inclusive and personalized VR systems. Potential threats were identified based on reported challenges related to manufacturability, cost constraints, calibration stability, and user comfort degradation when system alignment deteriorates.
Hybrid systems exhibit the following profile:
Strengths: Coordinated rendering and optical adjustment, potential for continuous clarity across depths, reduced vergence–accommodation conflict, improved perceptual stability.
Weaknesses: Dependence on eye-tracking precision, synchronization latency sensitivity, elevated power consumption, increased system complexity.
Opportunities: Advancements in compact tunable optics, improved low-power sensor architectures, increasing demand for inclusive VR accessibility, integration with personalized visual profiles.
Threats: Manufacturing cost constraints, user discomfort if calibration degrades, variability in device form factors, challenges in scaling to mass-market hardware.
Based on the SWOT results, a TOWS matrix was constructed (Figure 4) to identify strategic directions for future system development.

TWOS-Matrix	**Opportunities:** Advances in tunable optics, low-power sensor design, personalized visual profiling, growing demand for inclusive VR systems	**Threats:** High manufacturing cost, calibration variability, ergonomic constraints, limited scalability
Strengths: Coordinated optical and rendering control, reduced vergence-accommodation conflict, improved perceptual stability and clarity continuity	**S–O Strategies:** Leverage strong optical–Rendering integration to accelerate adoption of tunable lens technologies and personalized user profiles. Develop demonstrator prototypes emphasizing inclusivity, visual comfort, and adaptive clarity for diverse users.	**S–T Strategies:** Exploit system coordination and perceptual stability to mitigate risks from calibration drift and production variability. Apply modular and self-calibrating architectures to maintain visual quality and reliability across devices.
Weaknesses: High power consumption, synchronization latency, dependency on eye-tracking precision, increased system complexity	**W–O Strategies:** Address energy and latency constraints through low-power sensor architectures and predictive synchronization algorithms. Transform current weaknesses into innovation potential by integrating energy-efficient control systems.	**W–T Strategies:** Reduce system complexity and calibration dependency to minimize ergonomic issues and ensure scalability to mass-market headsets. Simplify hardware–software interfaces to prevent comfort degradation during long-term use.

Figure 4. TOWS matrix for hybrid myopia compensation systems

6. Conclusion and future work

This work reviewed visual compensation strategies for myopic users in virtual reality. Three technical approaches present distinct trade-offs. Software-based methods are flexible and easy to deploy, hardware-based methods offer higher optical accuracy, and hybrid systems provide improved visual comfort and focal adaptability but require tighter synchronization and more complex control.
According to the TOWS analysis, the most urgent priorities are to enhance energy efficiency and synchronization performance, develop modular self-calibrating architectures, and integrate personalized visual profiles for inclusive hybrid systems. Future research should focus on three directions.
First, hybrid systems need improved temporal coordination between gaze tracking, rendering, and optical adjustment. Advances in tunable optics and predictive control will be central to achieving stable

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performance. Second, compensation should become personalized. Models that adapt to individual refractive profiles and visual behavior, supported by learning-based user profiling, may enable long-term adaptive support. Third, future systems should accommodate more complex refractive conditions, including astigmatism and higher-order aberrations. Modular optical designs and computational imaging approaches offer promising paths.

As myopia prevalence continues to increase worldwide, developing VR systems that balance performance, comfort, and affordability is essential for broader adoption in education, training, communication, and immersive content creation.

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