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Designing Virtual Reality Headsets to Prevent Myopia

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Claremont McKenna College

Designing Virtual Reality Headsets to Prevent Myopia

A Thesis Presented

by

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To the Keck Science Department

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Abstract

Virtual reality (VR) headsets are currently being designed and developed for consumer use. Simultaneously, the rate of myopic development is increasing around the world. Little is known about the connection between the proximity viewing in VR headsets and myopic development. The past three decades of research have indicated a probable relationship between near-work activities and the development of myopia. Based on the current research, VR headsets do not appear to induce a strong myopiagenic stimulus on axial elongation. This paper offers a potential explanation and proposes a set of design recommendations for designing future VR headsets that prevent myopia.

Introduction

Virtual reality has become a trending technology in recent years. In 2021, Meta, formerly known as Facebook, invested 10 billion dollars into developing its VR technology.[1] Statista estimates the market size for VR to more than double between 2021 and 2024 from 5 to 12 billion dollars.[2] Classified as a near work activity, VR is experienced through head mounted displays showing images through lenses at close proximity to the eyes.[3] The close viewing distances required for VR is an area of concern that needs greater attention as VR headsets developed.

Research from the past three decades has indicated a significant relationship between near work activities and the development of myopia.[4, 5, 6, 7, 8] The term ‘near work’ describes any activity performed at a close viewing distance. Reading, writing, computers, phones and microscopy are examples of near work activities.[9] As the amount of near work has increased [10, 11], the development of myopia has risen in tandem. Myopia is a type of refractive error that results in distant objects appearing blurry.[12] The World Health Organization estimates that over half of the world's population will have myopia by 2050.[13] In the United States, the prevalence has increased from 25% to over 40% of the population between 1970 and the early 2000's.[14] Left untreated, myopia can result in several complications including cataracts, glaucoma, and macular degeneration.[15]

Based on previous research comparing near work activities with the development of myopia, it is reasonable to hypothesize that the near viewing distances required for VR immersion could increase the development of short-sightedness. The current research however does not indicate that VR use is strongly associated with myopic development. This thesis will evaluate the current association between VR headsets and myopic development to determine how VR devices should be designed to prevent myopic development.

Background: Myopia and its possible causes

The development of myopia is a result of both genetic and environmental influences. Children with two myopic parents had a greater chance of developing the condition than children with only one myopic parent.[16] Near work activities have been indicated as another source of myopic development.[17] Amongst different near work activities, reading has been shown to have a strong association with myopic development.[6,8]

Myopic eyes have several physiological differences compared to emmetropic (non-myopic) eyes. It is believed that myopic refraction, where light is focused before the retina, is caused by the abnormal axial elongation of the eye. Emmetropic eyes have an average length of

23.0 mm, while myopic eyes have an average length range of 22.1 mm to 27.3 mm.[18] Figure 1 shows the axial length and refraction differences between emmetropic and myopic eyes. Differences in choroidal thickness have also been identified. The choroid is a vascular tissue located between the retina and sclera. Choroidal thinning is associated with myopic development.[3,19]

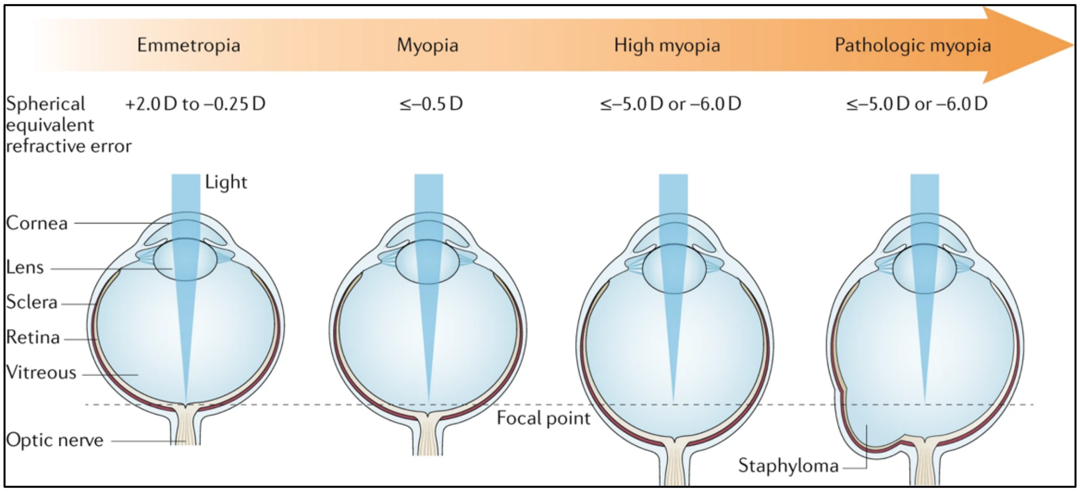


Figure 1: Ocular differences between emmetropic eyes and varying degrees of myopic eyes[20]

There are several near work variables which mediate myopic progression. Various studies have suggested that near work proximity, duration, image sharpness, contrast, and sunlight exposure can modify the degree of myopic development. Dopamine signaling and peripheral defocus within the eye have received strong support as mechanisms by which near work variables can regulate myopic eye growth.

Near work proximity and duration

Increased viewing proximity during near work has been correlated with an increase in myopic development. Near viewing distances of closer than 30 cm have been associated with higher odds of myopic progression.[21, 6, 22] Uninterrupted durations of more than 30 minutes have also been found to increase myopic development.[23, 6, 24] Specifically long durations of reading have been shown to be significantly associated with myopic development. One possible explanation is that people do not accommodate enough when they read, creating a lag of accommodation.[25] Near work duration has also been associated with myopic development. A meta-analysis of near work myopia articles from 1989 to 2014, concluded that every additional hour of near work increased the odds of myopia by 2%.[9] The myopic progression associated with close viewing proximity, uninterrupted durations, and total near work hours, suggests that reducing total near work hours especially with reading and taking more frequent breaks could remedy the development of myopia. Multiple studies report that taking breaks after continuous reading were significantly protective against myopic development.[26] One limitation in these assessments is that proximity and duration of viewing was largely self-reported, and thus may not be fully accurate.

Image sharpness

Deprivation of sharp imagery has been shown to increase eye growth. Image sharpness is a measure of how clearly a visual stimulus can be interpreted. In 1993, Weiss et al. were the first to find that chicks deprived of sharp imagery through occluders experienced greater nighttime axial elongation within days. It was found that retinal dopamine levels decreased by 30%.[27] Feldkaemper et al. found that eye growth in chicks doubled from 100 μm/day to 200 μm/day after chicks were deprived of sharp imagery through either diffusers or negative lenses.[28] While eye growth during the day remained constant, the increased nighttime growth resulting in the difference. The peripheral defocus state imposed by diffuser wear may modulate the be one way that diffuser suggests that defocus in the periphery offers a potential explanation for how sharp image deprivation during diffuser wear may regulate the release of dopamine by amacrine cells found in the retina.[28]

Sunlight exposure

Outdoor sunlight exposure has been shown to have a protective effect against Myopia.[29] [30] [31] [32] A positive association between outdoor exposure and myopic reduction is well documented in the literature.[33, 34, 35, 36] Monkeys and chicks exposed to outdoor sunlight saw a reduction in axial elongation.[30, 32] The study on chicks indicated that the effects of sunlight can be replicated with high luminescence laboratory lights.[32] School children who spent 11 hours a week outside saw a reduction in rapid myopia development by 54%.[29] In a study tracking first graders it appeared that daily sunlight exposure of 40 minutes for a school year was enough to reduce the rate of myopia for the next three years.[37] It was found that indoor sports activities had no effect on myopic reduction, while outdoor physical activity did.[34] The absence of sunlight during indoor physical activity would explain why indoor sports do not reduce axial elongation. The corrective effects of sunlight exposure are believed to be mediated through the release of dopamine.[38] The protective effects of sunlight on eye growth suggests that daily sunlight exposure could be an intervention strategy to prevent the development of myopia in early age, and during periods of heavy near work. The pairing of near work breaks with sunlight exposure could implicate an efficient way to protect against shortsightedness. Findings suggesting the benefits of high indoor luminescence and the benefit of ultraviolet light could offer a potential option for myopia protection indoors.

Chromatic alterations

Different wavelengths of light have been shown to alter refractive states in the eye. Short wavelength violet light and long wavelength red light have been independently reported to reduce myopic progression. Violet light has been shown to suppress myopic development in chicks, mice, and humans.[39] Short wavelength violet light appears to induce a hyperopic response by affecting the cones in eyes.[40] Interestingly, low-intensity red light therapy was an effective strategy for reducing axial elongation in children in East Asia.[41] Red light therapy was performed for 9 months, twice daily for 3 minutes. Labhishetti et al. note that the different wavelengths of light induce varying refractive states at different distances. Longer wavelengths of light are sharply focused when the stimulus is far while short wavelengths of light are in focused more sharply when the stimulus is near.[42] The chromatic contrast of visual environments may also have an influence on myopic development. Aleman et al. found that reading black text on a white background resulted in significantly thinner choroids while reading white text on a dark background resulted in significantly thicker choroids after an hour.[25] The changes in choroid thickness are believed to be modulated by ON/OFF pathways in the eye. Figure 2 shows the change in choroid thickness between the two different contrast profiles.

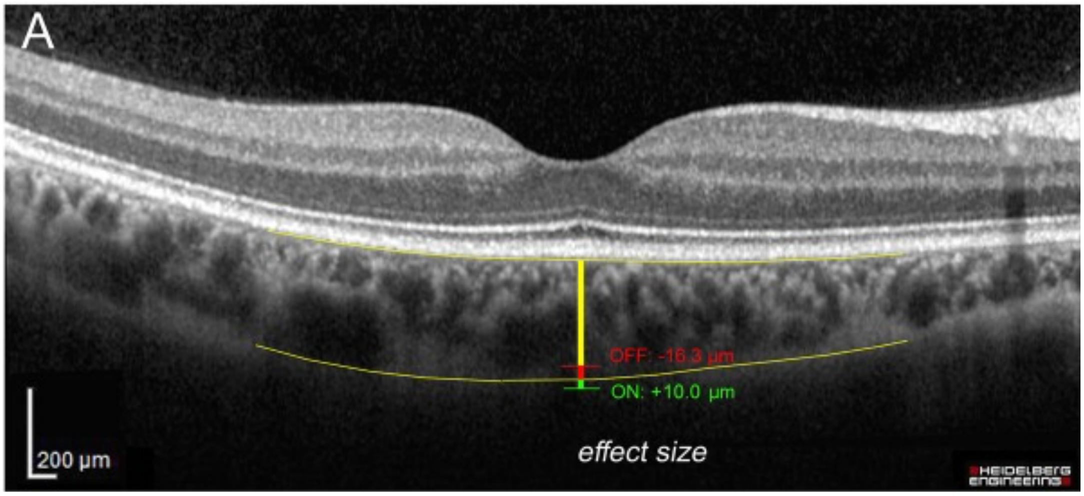


Figure 2: The average difference in choroid thickness in the foveal region after one hour. Stimulation of the OFF pathway resulted in average choroidal thinning of 16.3 μm. Stimulation of the ON pathway resulted in choroid thickening of 10.0 μm. [25]

Peripheral defocus

Peripheral defocus is a potential explanation for why near work activities increase the axial length of the eye.[3] Peripheral defocus refers to unfocused light rays that hit the retina on either side of the fovea.[43] Hyperopic peripheral defocus, the condition where light is focused beyond the peripheral retina, has been indicated as a mechanism by which eye elongation occurs.[44] Figure 3 illustrates how hyperopic peripheral rays enter the eye. In marmosets, chickens, and tree shrews hyperopic peripheral blur induced by negative lenses resulted in the elongation of the eye.[45, 46, 47] It is believed that peripheral hyperopic defocus is induced by the lag of accommodation that is created during near work activities.[44] Lags in accommodation occur when light from near objects is focused beyond the retina.[42, 25] In near work activities such as reading, lags in accommodation may result from reduction in accommodation while the eye shifts focus quickly to read text.[25] There is still no clear consensus if lags in accommodation explain why hyperopic peripheral defocus increases the odds of myopia in humans. Chen et al. were unable to find a significant relationship between accommodative lag and myopic development. The researchers speculated in accordance with other studies that accommodative lag may be a result of myopic progression rather than a cause.[48, 49, 25]

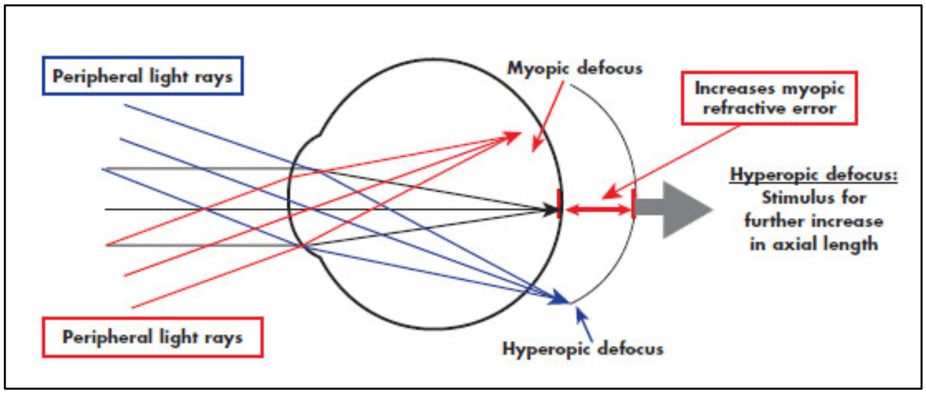


Figure 3: Myopic and hyperopic peripheral defocus on the retina[50]

Dopamine signaling

Retinal dopamine release is one supported mechanism of eye growth. Within the eye, the increase of dopamine has been shown to reduce the rate of axial eye elongation in humans.[28, 38, 51] Dopamine has been suggested to modulate the signaling between the retina and sclera.[28] High luminescence and image sharpness are two variables involved myopic prevention that have been associated with increasing retinal dopamine levels.[28] Dopamine influences eye growth in a multistep process. First light enters the eye through the lens, which refracts light onto the retina. In the retina, the light signal is received by amacrine cells, where dopamine is both synthesized and released.[38] The release of dopamine may limit the growth of the sclera through the upregulation of the ZENK/erg-1 transcription factor.[28] The sclera is the connective tissue making up the outer surface of the eye.[52] Backhouse et al. note that changes in eye length are facilitated by changes in the surface area of the sclera.[52] Additionally, the choroid contains a high concentration of dopamine receptors and may modulate the movement of dopamine from amacrine cells in the retina to the sclera.[28] Dopamine has been shown to increase the thickness of the choroid, a biomarker of axial length maintainence.[38]

The relationship between VR and myopia

The relationship between virtual reality headsets and the development of myopia is not well understood. Given the recency of VR technology, most of the studies investigating myopic development in VR have been published very recently. Based on background in the previous section, it would appear the near viewing distance, indoor use, and blurry image quality would implicate VR headsets as a myogenetic stimulus. VR headset safety documentation does not recommend headset use for young individuals. Oculus Quest 2 documentation states VR headsets may have adverse health effects during a, “critical period of visual development” and prolonged use should be avoided.[53] With evidence pointing to the protective aspects of VR on myopia as well, this section will aggregate the existing research to access the effects of VR on myopic development.

Virtual reality headsets create immersive experiences by placing a screen at near proximity to the eyes and creating binocular disparity by displaying an image in two different positions in front of each eye.[54] Current VR headsets have two convex fresnel lenses that bring the screen images into a closer field of view.[55] Each lens is designed to be adjusted to center on each user’s eye to provide a detailed view. A design of a near eyed light field VR headset is displayed in figure 4.

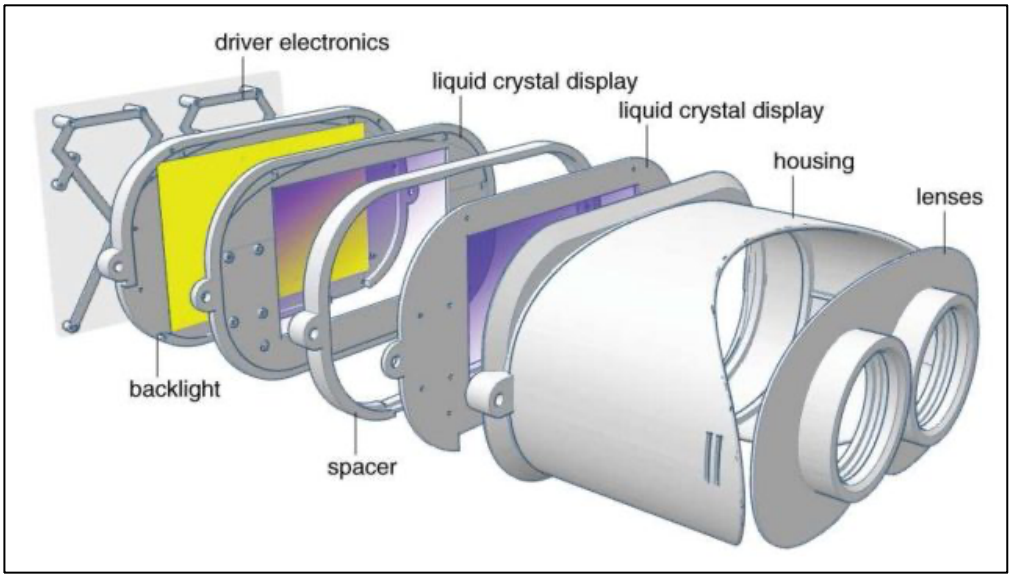


Figure 4: Near eye light field display schematic. [54]

Choroidal thickening in VR use

The use of VR headsets was found to induce choroidal thickening, indicating a protective effect against myopia.[3, 56] Turnbull et al. found that after 40 minutes of VR use the choroid became thicker compared to real world outdoor and indoor exposure, figure 5 shows the results of the experiment.[3] A study conducted by Harb et al. in 2019 found similar results. In two 40 minute trials, PC gaming resulted in choroidal thinning while similar gaming on a VR headset resulted in choroidal thickening.[56] One potential explanation for the increase in choroid thickness is the lead of accommodation imposed by VR headset viewing.[3, 57] A lead in accommodation is where the eye is focused closer than the stimulus.[42] Since VR lenses are set for distanced viewing in the vista space, 2-3 meters in front of the user, the eye is accommodated to distance.[58, 59] When objects are magnified and brought into the personal space, the eyes need to converge in front of the screen to bring object into focus. The magnified convergence needed for near viewing in VR creates a lead of accommodation which results in myopic defocus.[3] Being that choroidal thickening is associated with myopic defocus and reduced myopic progression, the greatest changes in choroidal thickness in the indoor virtual reality scene can be explained.[60] Since objects in the indoor scene are experienced more closely, greater convergence is needed, resulting in a greater lead of accommodation. In conjunction with the myopic protection of leads in accommodation, lags in accommodation show the opposite effect. Studies have found that accommodative lag induces hyperopic defocus, a stimulus for axial elongation.[61]

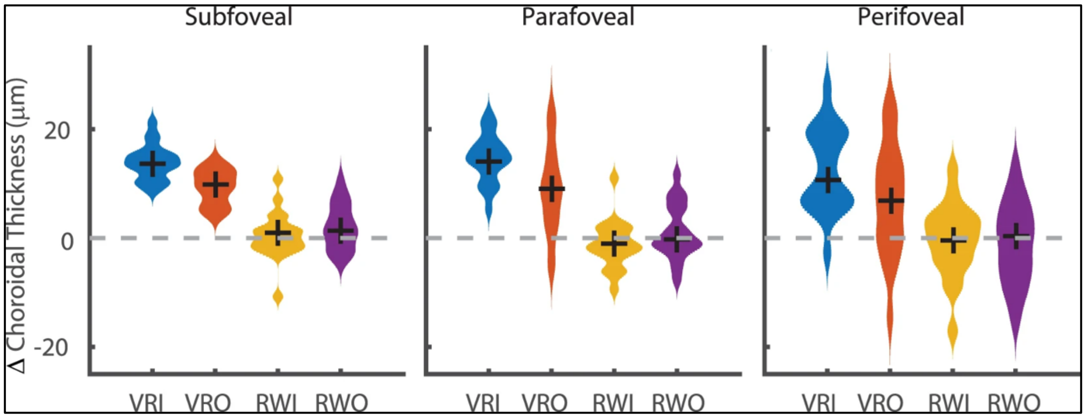


Figure 5: Subfoveal, parafoveal and perifoveal changes in choroid thickness between virtual reality indoor and outdoor environments and real world indoor and outdoor environments.[3]

Improved visual acuity for myopic eyes

Panfili et al. found that visual acuity in VR did not decrease in myopes as it did for corrected eyes when compared against a 2D acuity test.[62] In the study 15 participants, 10 with emmetropic or corrected vision were recruited to do an visual acuity test in both VR and 2D screen environments. It was found that when myopic participants did not use corrective instruments, they performed marginally better in the VR acuity test than the 2D screen acuity test. Figure 6 indicates the visual acuity differences found in the experiment. The moderate improvement in visual acuity for myopic participants may be a product of modified amplitudes of accommodation in myopia. The amplitude of accommodation is a measure of the furthest point of focus to the closest point of focus.[63] In myopic individuals the furthest point of focus is closer and thus clear far viewing distances would benefit the visual acuity of myopic individuals.

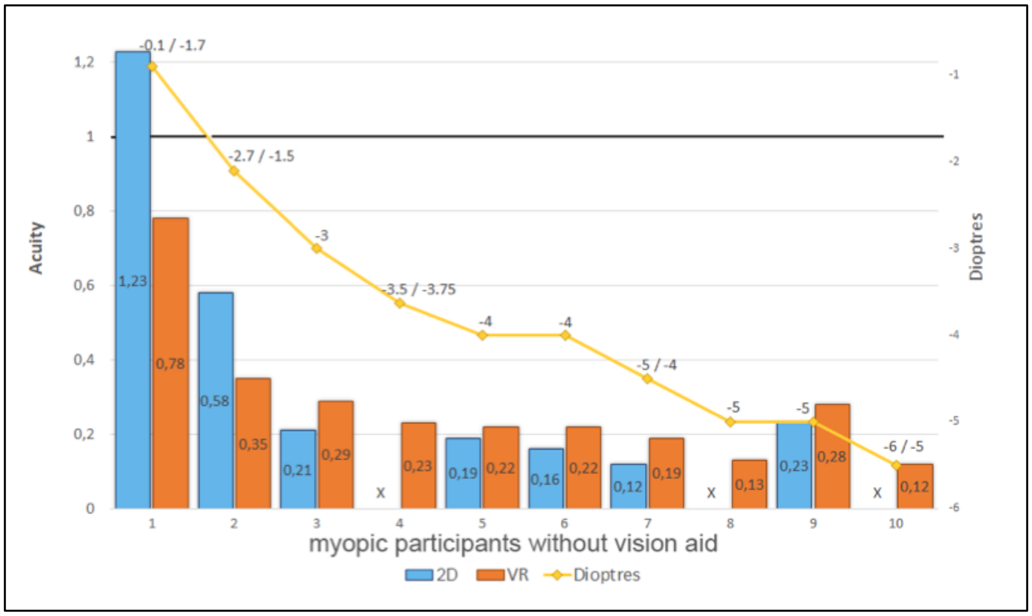


Figure 6: Visual acuity differences between 2D and VR environments at different diopters of distance in myopic participants without visual aid.[62]

Vergence accommodation conflict

The lead of accommodation and the heightened visual acuity of distant objects in VR headsets can be explained by the vergence accommodation conflict (VAC). Vergence and accommodation are two depth cues that allow the eye to establish a sense of depth.[64] In VR headsets there is a mismatch between vergence and accommodation. Figure 7 illustrates the disparity implicated in the VAC. Current VR sets establish vergence depth by displaying shifted images between the right and left eye.[65] However, VR headsets are unable to accurately portray depth from accommodation. Since objects in VR are at a fixed depth of the screen distance from the eyes, objects cannot be viewed clearly at a close depth, figure 8 illustrates effect.[66] is not yet clear how the VAC affects myopic development in VR headsets. Turnbull et al. mention that VAC is responsible for creating the lead in accommodation which resulted in choroidal thickening. However the retinal blur created at close VR viewing distances may increase myopic development by depriving users of sharp imagery.[67, 28]

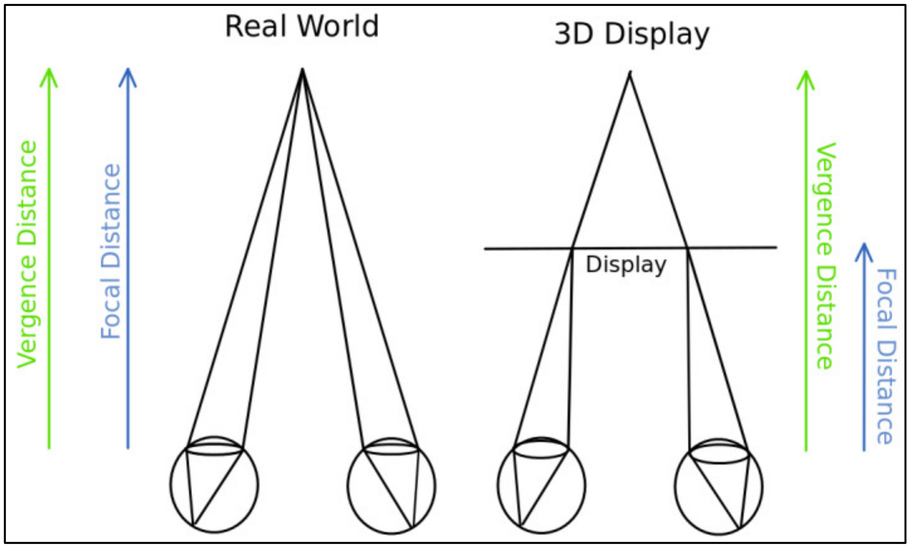


Figure 7: Vergence and focal distances between read world and Virtual reality headset viewing.[68]

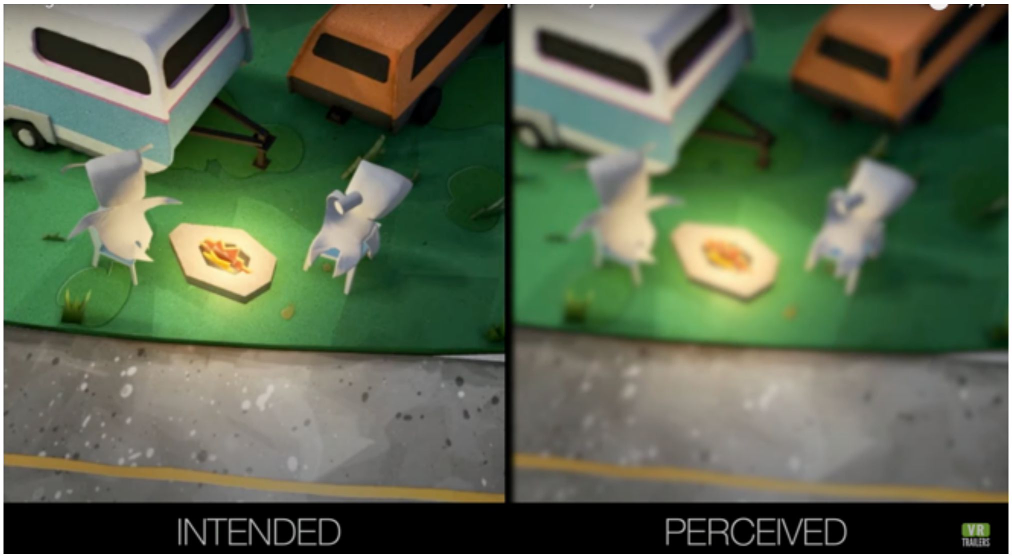


Figure 8: Difference between intended clarity and perceived clarity in a virtual reality headset. Perceived clarity at near viewing appears blurry due to the vergence accommodation conflict.[58]

Blind spot stimulation

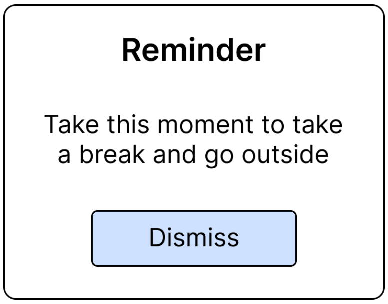
Stimulation of the ocular blind spot with short-wavelength blue light was found to be associated with reduced axial elongation in a phone mounted VR headset.[69] The study focused short-wavelength light onto the blind spot for 10 seconds, 1 minute, and 10 minute intervals. It was found that there was an increase in b-waves, and electrical signal produced by photoreceptors.[70] The increase in b-waves was positively associated with axial elongation. The paper noted that an increase of b-waves could indicate an increase of dopamine induced ON pathway stimulation. This stimulation has been associated with myopic reduction by increasing choroidal thickness.[25, 71] The reported effect of exposing the blind spot to short wavelengths of light suggests that VR headsets can influence specific regions of the eye to induce dopamine mediated axial maintenance.

VR design recommendations

VR headsets are currently being designed and development for consumer use. Popular VR headsets feature immersive experiences with consideration for designing using depth, field of view, and interactions. However there has been limited focus onto how to design for myopia prevention. The following guidelines build off the research done on myopia interaction in near work and virtual reality use.

Break reminders

Software break reminders should be integrated into the VR interface to reduce the myogenetic stimulus of uninterrupted viewing. Reminders every 20-30 minutes for 10 minutes have been demonstrated to help reduce myopic progression.[72] In 2019 the average time of a VR session was 20 minutes.[73] This suggests that typical VR activities have a duration of around 20 minutes. Breaks in activities can thus be a good time to alert the user to remove the headset in an unaversive manner. Break reminders should be optional as to not create an annoyance for a user. Figure 9 illustrates possible design of a break reminder.



Reminder

Take this moment to take a break and go outside

Figure 9: A virtual reality pop out to remind users to take intermittent breaks between VR sessions.

Contrast

Developing the correct contrast settings in virtual reality can help reduce axial elongation. During reading presenting white text on a black background has been indicated to reduce the axial elongation greater than reading black text of black backgrounds.[25] Figure 10 shows the shift in contrast. While not all interface components are suitable for black backgrounds, options to toggle between white and black backgrounds should be available. Further it has been indicated that deprivation of image sharpness may be a myogenetic stimulus. As greater contrast can make images appear sharper, higher contrast ratios between colors should be used for items in focus.

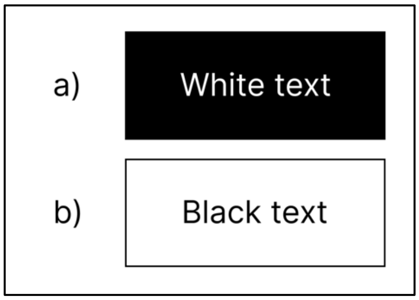


Figure 10: White text on a black background and black text on a white background option for toggling between contrast profiles.

Depth-color adjustment

Different wavelengths of color can be used to bring objects into better focus at different depths. If a stimulus is located at a distance from the viewer, longer wavelengths such as red light will be focused better onto the retina. If the stimulus is located near the viewer, shorter wavelengths such as blue and violet light will be in better focus.[42] This insight can be implemented by highlighting focused near objects with shorter color wavelengths to increase the level of object acuity.

Indoor scenes

Indoor virtual environments should be used opposed to outdoor environments in virtual reality to increase the degree of convergence in the presence of fixed accommodation displays.[3] This effect would increase the lead of accommodation, a protective factor against myopia. Indoor environments can serve as lobbies and backdrops for different VR activities. Figure 11 displays a possible indoor scene that can be used in VR software development.

Figure 11: Indoor virtual reality scene set inside a forest cabin in Oculus Quest 2.

Resolving the vergence accommodation conflict

One of the primary issues with accommodation in current virtual reality headsets is close are shown out of focus. While this effect may create a lead of accommodation, a potentially protective affect against myopia, it does impose the issue that near work in VR cannot be performed. Further the VAC has been cited to cause fatigue, blurry vision, a discomfort during long viewing sessions.[59] Below are a solutions that will hopefully mitigate the VAC without imposing a myogenetic stimulus on the eyes.

Varifocal displays

Varifocal lenses offer a solution to the VAC by using eye tracking to adjust the focus of the lens to different depths. Two different methods have been indicated in the varifocal approach. The first way is to mechanically change the distance of the screen from the eyes the second is to adjust the focus of the lens itself. Based on the need for mechanical movement and the sound and power resources needed, changing the focus of the lens may be a better more efficient approach. In both instances eye tracking is used to determine what object the user’s eyes are verging on. Figure 12 shows the effect of varifocal lenses. A recent varifocal module designed by the Facebook reality labs team, created a lens system made of 6 polarized dependent lenses placed together with switchable half wave plates in between.[58] Using voltage each of the plates can be selectively turned on and off to adjust to the correct depth.

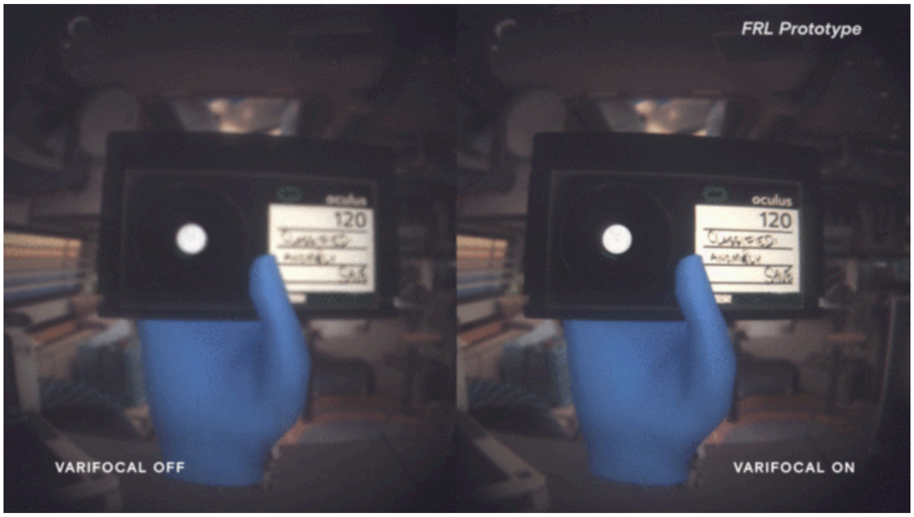


Figure 12: Near viewing in VR with Varifocal turned off and on.[74]

Depth blur

To accompany precise depth focus, defocus blur is a necessary stimulus to facilitate eye accommodation in VR headsets[75] [76] [77] As current VR systems have a single display, depth blur must be graphically rendered in real time. Cholewiak et al. report that rendered defocus blur might drive accommodation more effectively than optical methods.[78] A team at Facebook Reality Labs has developed a methodology called Deep work which utilizes a neural network image processing system to drive retinal defocus in real time. Once eye tracking is implemented into VR headsets the incorporation of retinal blur will help drive the accommodative response to correctly perceive the scale of depth of a stimulus.[79]

Discussion

The design proposals in this paper combine the aggregated findings of how near work and VR headsets independently affect myopia progression. It was hypothesized that current VR headsets would create an increased myopic stimulus that is suggested in near work. However, based on the evaluated research, VR headsets may be helpful for myopia prevention. A possible explanation is proposed by Turnbull et al. stating that VR headsets may be helpful for myopia prevention by creating a lead of accommodation caused by excessive convergence. VR use resulted in the thickening of the choroid and improved visual acuity for myopes at far distances. At closer distances however, stimuli in VR appear blurry due to the vergence accommodation conflict. While no studies have been done on the effects of this blur on myopia, Feldkaemper et al. have shown that deprivation of sharp imagery is a stimulus for axial elongation, a biomarker of myopic progression. The current inability to focus on virtually close objects means that it is currently difficult to perform near work in VR. Much of the current development in virtual reality headsets is focused on addressing the inability to focus on virtually near objects by developing varifocal lenses, eye tracking, and peripheral blur. While this innovation will allow for alterations in accommodation to make near focused images clear, it is unclear if this development will remove the protective effects credited to the lead in accommodation seen in current VR headsets.

In addition to the hardware changes suggested, multiple software design recommendations were proposed. The incorporation of break reminders can act to reduce the total uninterrupted time spent in VR and serve as a cue for the user to obtain sun exposure. Reducing both VR duration and increase the amount of sunlight will help reduce myopic progression in addition to alleviating eye strain. Displaying white text on a black background is another visual alteration that has been implicated as a method by which to reduce axial elongation. While not all content may be suitable for this inverted color arrangement, the option to turn on this dark mode should be available in reading situations. The use of indoor environments in current VR may further offer protection against myopia by making the user converge to a greater degree than in virtual outdoor environments. Turnbull et al. found that virtual indoor environments imposed the greatest change in choroid thickness when compared to virtual outdoor environments. There is no certainty that the design recommendations above will help prevent myopic development in VR headsets. None of the design recommendations presented have been isolated and tested for their effect on myopia in VR headsets. More research needs to be conducted on the effects of VR headsets on myopic progression. With greater research in this area, product developers will have greater insight into how to design VR headsets as they gain popularity in the coming years.

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