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Binocular accommodative response with extended depth of focus under controlled convergences

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Vergence and accommodation can be mismatched under virtual reality viewing conditions, and this mismatch has been thought to be one of the main causes of visual discomfort. The goal of this study was to investigate how optical conditions of the eyes affect accommodative responses to different convergence. Specifically, we hypothesized that extending the depth of focus (DoF) could weaken the control of the screen on accommodation, so that accommodation could be induced by convergence. To test this hypothesis, we extended the DoF using Zernike spherical aberrations (fourth and sixth orders) induced by a binocular adaptive optics (AO) vision simulator. Nine normal subjects between the ages of 21 and 34 (26 ± 5) years were recruited. Three optical conditions were generated: AO condition (aberration-free), monovision condition, and extended depth of focus (EDoF) condition. Binocular accommodative responses, along with binocular visual acuity and stereoacuity, were measured under all three optical conditions with varied binocular vergence levels. At 3 diopters of binocular convergence, the EDoF condition was the most efficient in inducing excessive accommodative response compared with the monovision condition and the AO condition. Visual acuity was impaired with EDoF as compared with the other two conditions. The average stereoscopic thresholds (at 0 vergence) under the EDoF condition were degraded compared with the AO condition but were superior to those of the monovision condition. Therefore, despite some compromise to visual performance, extending the DoF could allow for a more natural vergence–accommodation relationship, providing the potential for alleviating the vergence–accommodation conflict and associated visual fatigue symptoms in virtual reality.

Introduction

Accommodation is the change in shape of the crystalline lens that helps us focus on objects at various distances to avoid blurry imagery. Vergence is the binocularly coordinated eye movement that brings objects at various depths into fusion at central vision (Goldstein, 2010) to avoid double imagery. Under natural viewing, vergence and accommodation stimulus demand change together in accordance with the object distance. Accommodation and vergence interact and couple to maintain clear and single vision at varied distances (Schor & Kotulak, 1986; Sweeney, Seidel, Day, & Gray, 2014). The interaction can be quantified by the accommodative convergence to accommodation (AC/A) and convergence accommodation to convergence (CA/C) ratios (Fincham & Walton, 1957). In comparison, artificially viewing stereoscopic displays can create different demands on the two systems. Although vergence changes in accordance with the disparity displayed on the screens, the eyes should maintain a fixed focus in order to perceive clear images of the screen, despite the fact that vergence can potentially induce accommodation change (Fincham & Walton, 1957). This uncoupling of the vergence and accommodation stimulus demand is described as the vergence–accommodation (VA) conflict (Emoto, Niida, & Okano, 2005; Hoffman, Girshick, Akeley, & Banks, 2008; Okada, Ukai, Wolffsohn, Gilmartin, Iijima, & Bando, 2006; Wann, Rushton, & Mon-Williams, 1995). We define the VA conflict as a conflict between accommodative and vergence demands determined

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solely by stimuli. Based on this definition, there is no conflict under natural viewing conditions even if a person with phoria or hyperopia could have different amplitudes of accommodative and vergence response.

Virtual reality (VR) systems, which use dichoptic viewing as vision stimuli, are widely used in entertainment, medical, and educational technologies. However, users tend to suffer from visual fatigue (Lambooij, IJsselsteijn, & Heynderickx, 2007) for many reasons, and the VA stimulus conflict is one of them. It is believed that the neural uncoupling resulting from the uncoupling of the vergence and accommodation stimulus (Cumming & Judge, 1986; Martens & Ogle, 1959) causes visual discomfort (Hoffman et al., 2008; Shibata, Kim, Hoffman, & Banks, 2011). The VA conflict can also influence binocular fusion speed, increase stereoacuity thresholds (Hoffman et al., 2008), and slow the vergence response dynamics (Vienne, Sorin, Blondé, Huynh-Thu, & Mamassian, 2014).

Many strategies have been proposed to minimize fatigue by overcoming the VA stimulus conflict. The multi-plane three-dimensional display prototype developed by Akeley, Watt, Girshick, and Banks (2004) could restore focus cues and reduce visual symptoms. Other techniques include using power changing lenses (Koulieris, Bui, Banks, & Drettakis, 2017), the retinal scanning display (Schowengerdt & Seibel, 2006), the Maxwellian view retina projector (Ando, Yamasaki, Okamoto, & Shimizu, 1998), holographic three-dimensional displays (Kim, Kim, Song, Lee, & Park, 2011; Maimone, Georgiou, & Kollin, 2017), and inducing chromatic aberration or image size change (Cholewiak, Love, & Banks, 2018; Fincham, 1951; Kruger & Pola, 1987). However, these systems either require bulky construction or are computationally intensive.

Fincham and Walton (1957) pioneered investigating the relationship between convergence and accommodation by independently controlling each factor. They created disparity to induce vergence change of the subject while maintaining the screen distance at 3 diopters (D). Accommodation stayed at 3 D even though convergence was higher than that. The screen distance stimulated blur-driven disaccommodation to compensate for the vergence-evoked accommodation (i.e., convergence accommodation). They also showed that using pinhole pupils caused accommodation to change with convergence. The pinhole eliminated the focus cues for accommodation so that the screen lost its control on accommodation. However, pinholes may not be practical, as the field of view is limited unless it can be placed on the pupil plane, and illumination is also decreased. Nevertheless, the pinhole technique demonstrated the possibility of weakening the focus cues as a solution for VA stimulus conflict. Koulieris et al. (2017) assigned different powers to each eye, creating a monovision condition, and examined the accommodative response to varying vergence in a stereoscope. Even though monovision weakened the binocular focus cues by creating two focal points, it failed to create a satisfactory accommodative response. In this study, we proposed to weaken the focus cues by extending the depth of focus (DoF) with spherical aberrations. The DoF is a dioptric range within which the retinal image quality is maintained above a certain level, as evaluated by an image quality metric (Rocha, Vabre, Chateau, & Krueger, 2009). Extended depth of focus (EDoF) has previously been used in presbyopia treatment (Breyer, Kaymak, Ax, Kretz, Auffarth, & Hagen, 2017; Wesley, 1962). As pointed out by Schor & Kotulak (1986), the VA interactions may be sensitive to velocity (the stimulus changing speed). We proposed to measure the sustained component of vergence accommodation after the stimulus was generated in a step fashion and was kept static (Schor, 1992; Schor & Kotulak, 1986). Adaptation to vergence could reduce the output of the vergence accommodation cross-link (Schor & Kotulak, 1986; Schor & Tsuetaki, 1987). Thus, we proposed to measure the accommodation immediately after stabilization of the VA interaction.

The first goal of this study was to examine the effect of EDoF on the VA relationship. Two other conditions (aberration-free and monovision) were also compared. The EDoF technique enlarged the DoF and weakened the control of the screen on accommodation (López-Gil & Fernández-Sánchez, 2010), such that accommodation could be more easily induced by convergence compared with the aberration-free condition. A similar effect was also achieved by an accommodation-invariant display (Konrad, Padmanaban, Molner, Cooper, & Wetzstein, 2017). With EDoF, we expected to observe an increase in the range of accommodative response resulting from convergence-induced accommodation to a fixed screen distance. To test this hypothesis, a binocular adaptive optics (AO) vision simulator with adjustable vergence was built. Spherical aberrations were induced using AO to extend the DoF. Convergence, which was measured in diopters (equal to meter angle) as the reciprocal of the distance in meters to the virtual target, was manipulated while screen distance remained fixed. Accommodation change was examined as the convergence varied. The second goal of this study was to evaluate the visual performance with EDoF in terms of binocular visual acuity and stereoacuity. EDoF created more similar image quality throughout the accommodation range between the two eyes; thus, it was expected to maintain the stereo performance compared with the monovision condition (Donzis, Rappazzo, Bürde, & Gordon, 1983; Westheimer & McKee, 1980). As a tradeoff, the usage of spherical aberrations could degrade the image quality of both eyes, resulting in poorer binocular visual acuity.

Methods

Participants

The University of Rochester Research Subjects Review Board approved this study, and all subjects viewed and signed the consent form before their participation. All procedures involving human subjects were in accordance with the tenets of the Declaration of Helsinki. Nine subjects between the ages of 21 and 34 (26 ± 5) years with healthy vision were recruited for the study. Eight of the nine subjects received phenylephrine hydrochloride ophthalmic solution (2.5%) ahead of the tests to dilate the pupils to at least 5 mm in diameter. One subject had naturally large pupil diameters and did not require dilation.

Materials

The experiment was conducted using a binocular AO vision simulator, which consisted of two identical monocular optical layouts. Each branch featured a wavefront sensor and a deformable mirror. The wavefront sensor measured the aberration of the central vision of an eye, and the deformable mirror compensated for the aberration by changing its shape accordingly. For separate purposes, aberration could also be induced by the deformable mirror, such that the subject could either perceive an aberration-free visual stimulus, or with altered aberration profiles. Details of the system were previously published (Sabesan, Zheleznyak, & Yoon, 2012). Apart from correcting and inducing aberrations, the system was also used to manipulate convergence. The defocus term was left uncorrected to measure changes in accommodative response.

Vergence stimuli were adjusted by rotation of two mirrors about vertical axes in front of the eyes while translating the head axially at the same time. As shown in Figure 1, the mirrors were rotated inward around two rotational centers to induce convergence as the head was translated closer to maintain the correct axial location of the pupil. Slight error was theoretically inevitable. For 3 D of induced convergence, small amount (under 1 mm) of error was observed in interpupillary distance, and that could be compensated for by adjusting the axial position of the mirrors. All tests were conducted at a luminance level of 50 cd/m^2, and the pupil diameter for both eyes was set to 4 mm by artificial pupils.

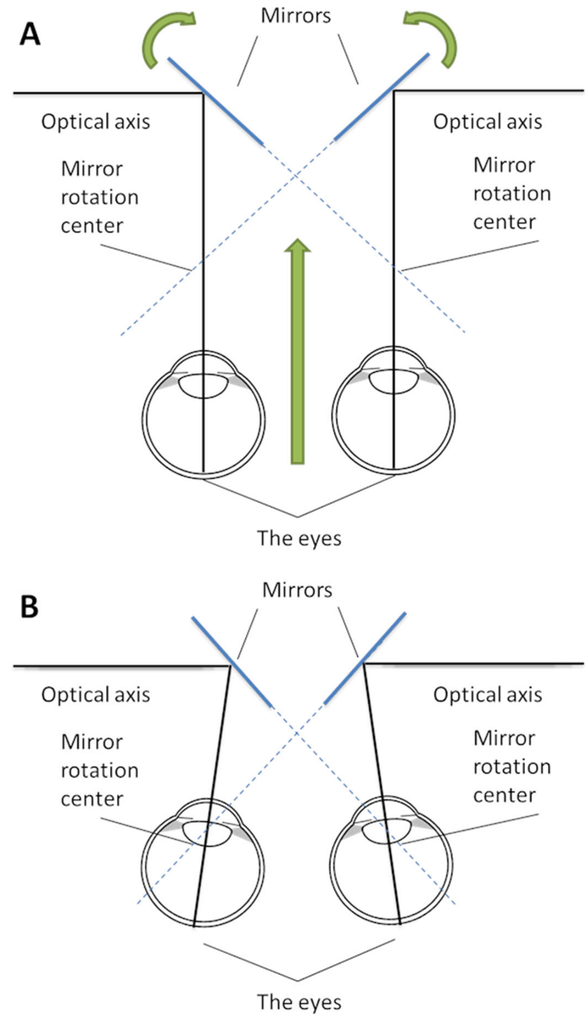

Figure 1. Mechanism for interpupillary distance fitting and convergence control in the binocular AO vision simulator. Convergence was manipulated by rotating the mirrors and translating the eyes inwards. Convergence is increased from (A) to (B).

The goal of the EDoF design was to enlarge the binocular DoF so that accommodative responses caused by vergence responses to the displayed disparity stimulus could be maximized. The resulting DoF allowed accommodation to follow the vergence response via cross-link interactions described as convergence accommodation (Fincham & Walton, 1957). The monocular DoF was extended by combining first- and second-order spherical aberrations (Z_4^0, Z_6^0), which are proven to effectively extend the DoF (Benard, Lopez-Gil, & Legras, 2010). The monocular image quality varied across a range of defocus, and a peak in the quality was observed at one polarity of the DoF. By creating opposite signs of spherical aberrations in the two eyes, two peaks of image quality were located at opposite polarities of the DoF. The superior

	Defocus, Z_2^0	Primary Spherical, Z_4^0	Secondary Spherical, Z_6^0
Left eye	−1.15 μm	−0.2 μm	0.05 μm
Right eye	−0.29 μm	0.2 μm	−0.05 μm

Table 1. EDoF profiles generated at the pupil planes in the left and right eyes. Primary and secondary spherical aberrations were used to produce large DoF. Pupil diameter = 4 mm.

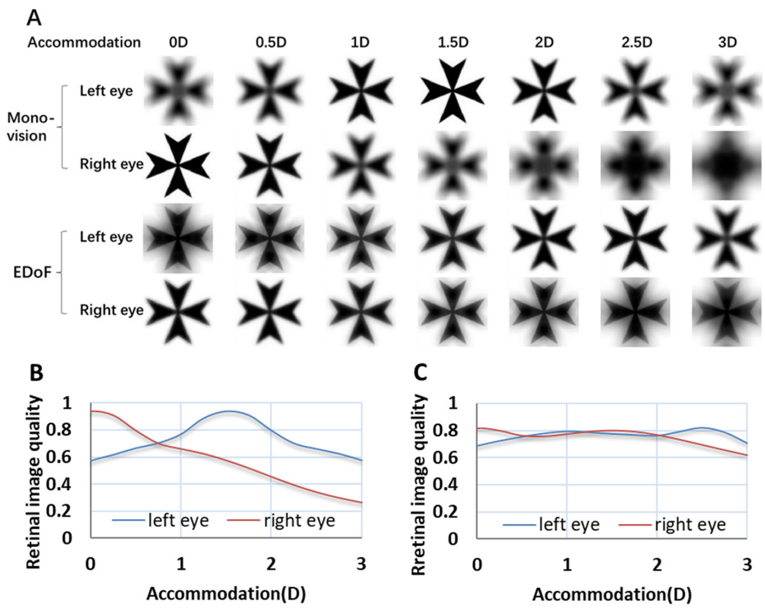

Figure 2. Image quality at various accommodation levels. (A) The simulated Maltese cross target perceived by the subject. (B, C) Retinal image quality, as given by the correlation coefficient between the aberrated image (convolved with the EDoF profile) and the reference image (perfect 20/40 Snellen letter "E"), under the monovision condition and the EDoF condition, respectively.

eye at either side improved the perceived binocular image. This method could optimize binocular image quality with the least sacrifice in stereoacuity. Spherical aberrations contain equivalent dioptric power (Salmon, West, Gasser, & Kenmore, 2003); thus, different defocus power was added to compensate for the offset caused by the different signs in spherical aberrations. Table 1 shows the coefficient magnitudes of the profiles for each eye. In all experiments, the subject's native aberrations (including the change in spherical aberrations with accommodation) were corrected before the EDoF profile was induced. Figure 2A shows the simulated images of a Maltese cross perceived by the subjects with respect to accommodation change. As shown in Figures 2B and 2C, image quality at various accommodation levels was examined by calculating the Pearson's correlation coefficient (Zheleznyak, Sabesan, Oh, MacRae, & Yoon, 2013) between a 20/40 size letter "E" convolved with the EDoF profile and the reference image (perfect 20/40 letter "E"), where 1 corresponded to a perfect image (Zheleznyak et al., 2013). Compared with the monovision profile with 1.5 D negative power added to the left eye (Figure 2B), for EDoF both eyes had balanced retinal image qualities through the accommodation range from 0 D to 3 D (Figure 2C). The peaks of image quality were observed at 0 D (right eye) and 2.5 D (left eye), as shown in Figure 2C.

Procedure

Far point detection

A Maltese cross that subtended 0.97° by 0.97° was chosen as the target for measuring accommodation because it possessed both high-contrast edges and a wide range of spatial frequencies (with high spatial frequency at the center) that could efficiently drive accommodation (Charman & Tucker, 1977). Except for defocus, all other optical aberrations were corrected simultaneously for both eyes. The participant was asked to locate the far point where accommodation was completely relaxed by moving the image produced by the Badal optometer and finding the most remote distance boundary between clarity and blur. This procedure was repeated three times, and the average of the three adjusted positions was taken to be the far point.

Binocular accommodative response

The subject's accommodation was measured after convergence was induced under three optical conditions: AO condition (aberration-free, all aberrations corrected by the AO system), monovision condition (1.5 D of hyperopic power was generated only in the left eye), and EDoF condition. All conditions were generated based on an infinitely far screen distance. Two identical Maltese crosses were presented separately to the two eyes. The subject was asked to fuse the static Maltese crosses and maintain the clearest vision possible. Four stationary convergence levels were induced: 0 D, 1 D, 2 D, and 3 D (3 D is equal to 3 meter angles, 9.3 prism diopters, or 5.3 degrees of eye rotation for 62 mm of interpupillary distance). After stabilization of the subject's accommodation and eye movements, wavefront measurements were taken at each vergence level and expressed in Zernike coefficients. The defocus term, Z_2^0, measured in micrometers, was converted into diopters to represent accommodative response. Three measurements were taken, and the average was calculated.

All measurements were taken in a static situation where both vergence and accommodation were stabilized, and the subject was given time to rest between different optical conditions or vergence levels.

Visual performance tests

Six of the nine subjects participated in the visual performance tests. The subject's binocular visual acuity was examined under AO, monovision, and EDoF conditions. A tumbling Snellen letter "E" was presented to both eyes at either 0 D or 3 D vergence levels. The letter size varied according to an adaptive staircase method using QUEST (Watson & Pelli, 1983). The data were fitted using a cumulative Weibull function, and the threshold at 62.5% determined the visual acuity. Visual acuity was measured independently three times as the $\log_{10}$ of the minimum angle of resolution (logMAR), and the average was calculated.

Stereoacuity was examined under all optical conditions. In any trial, the subject first fused a fixation dot and brought nonius lines into alignment to minimize fixation disparity. Then, a random dot stereogram that would be perceived as a sinusoidal corrugation in depth was presented for 0.5 second. Subjects judged the orientation of the corrugation with positive audio feedback. Five levels of peak-to-trough disparities were measured: 0 minute of arc (arcmin), 7.5 arcmin, 15 arcmin, 22.5 arcmin, and 30 arcmin, alongside three corrugation frequencies: 0.5 cycles/degree (c/deg), 1 c/deg, and 2 c/deg. Each combination of the five disparity levels and three spatial frequencies was randomly presented with five repeats. Stereoacuity was measured at two vergence levels, 0 D and 3 D. A Weibull distribution function was used to fit the data, and stereoacuity was determined at the 75th percentile. At each vergence level, stereoacuity was measured twice separately, and the average was taken.

Results

Binocular accommodative response

Under the AO condition, the average accommodative gain for 3 D of induced convergence was 17% ± 15%, as shown in Figure 3. With monovision, the average accommodation increase was 27% ± 16%. As shown in Figure 3, despite intersubject variability in accommodative response at 0 D vergence (Figure 4), EDoF induced the most significant accommodative response among all three conditions. The average accommodation gain was 37% ± 16% for 3 D of induced convergence. Moreover, the change in accommodation was gradual, as accommodation could rest at intermediate levels, rather than binary (Figure 4).

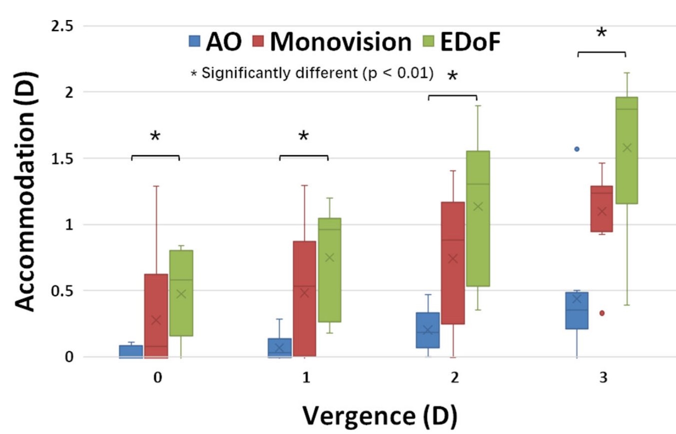

Figure 3. Box-and-whisker plot for accommodative response of the subjects ($N = 9$). Each box-and-whisker plot shows the statistical analysis of the accommodative response of all subjects under each optical condition and vergence level. Means are represented by crosses inside the boxes, and medians are represented by horizontal lines inside the boxes. *Significantly different ($P < 0.01$, Dunn's test).

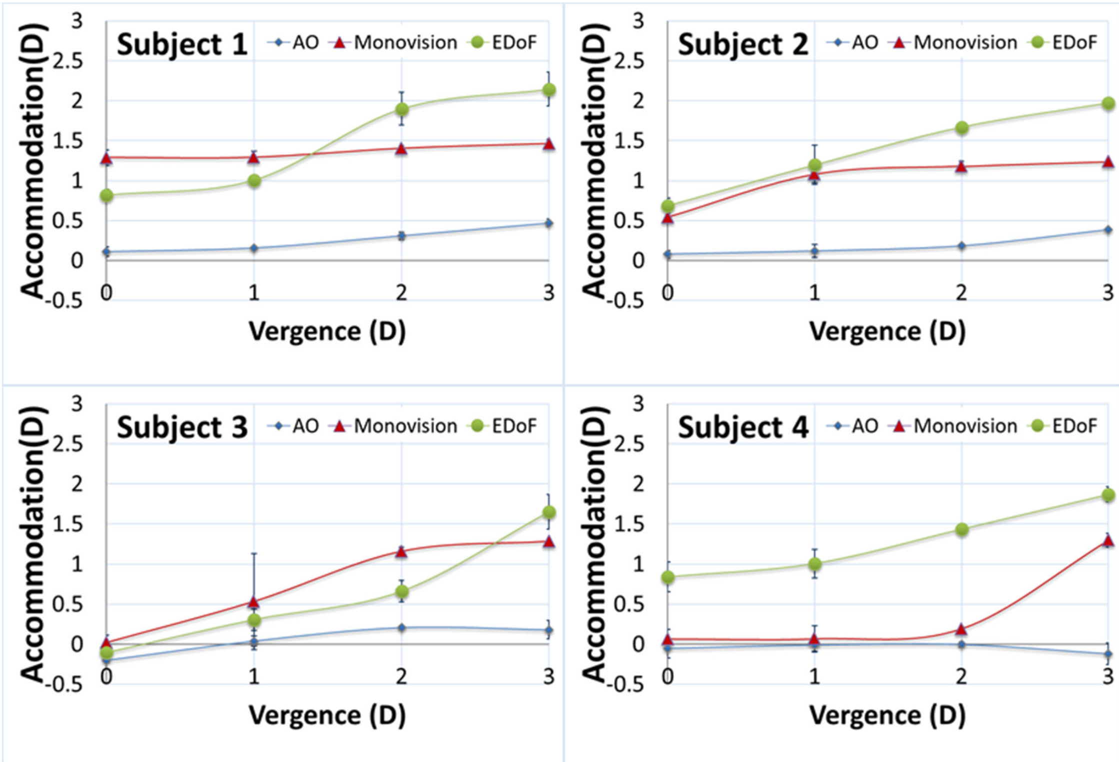

Figure 4. Accommodative responses of four out of nine subjects. Error bars indicate ±1 *SD*. For the complete data for all subjects, please see Appendix A, Figure A1.

Visual acuity

At 0 D vergence, the average binocular logMAR visual acuity was −0.18 ± 0.08 for the AO condition compared with −0.14 ± 0.07 for the monovision condition and −0.07 ± 0.05 for the EDoF condition. At the convergence of 3 D, it was degraded to −0.08 ± 0.12 for the AO condition. It remained approximately the same for the monovision condition (−0.17 ± 0.07) and for the EDoF condition (−0.06 ± 0.08) at 3 D of convergence, as shown in Figure 5.

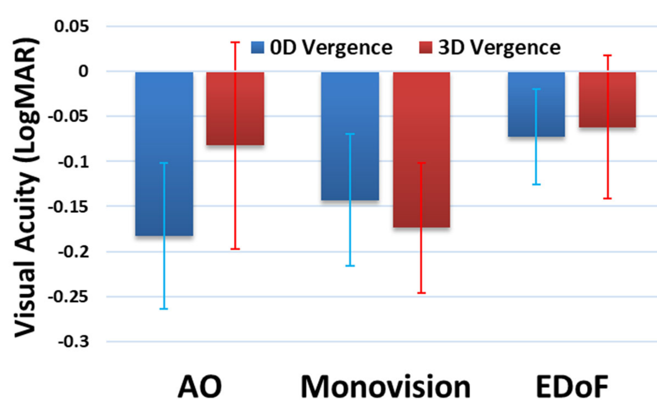

Figure 5. Averaged visual acuity of the subjects (*N* = 6) under the three optical conditions. Lower logMAR values correspond to better visual acuity. The blue bars represent 0 D vergence, and the red bars represent 3 D convergence. Error bars indicate ±1 *SD*.

Stereoacuity

As shown in Figure 6, under all optical conditions, stereo performance was the best with the corrugation frequency of 1 c/deg. More specifically, at 0 D vergence, stereoacuity was the best under the AO condition, with an average threshold of 0.46 ± 0.40 arcmin, and worst in the monovision condition, averaging 1.52 ± 0.44 arcmin. Two subjects did not even have measurable stereoacuity with the monovision condition. The stereo thresholds with EDoF (0.68 ± 0.13 arcmin) were worse than in the AO condition but were superior to the monovision condition. At 3 D of convergence, stereoacuity was degraded in the AO condition but improved with EDoF. Other corrugation frequencies (0.5 and 2 c/deg) had similar trends.

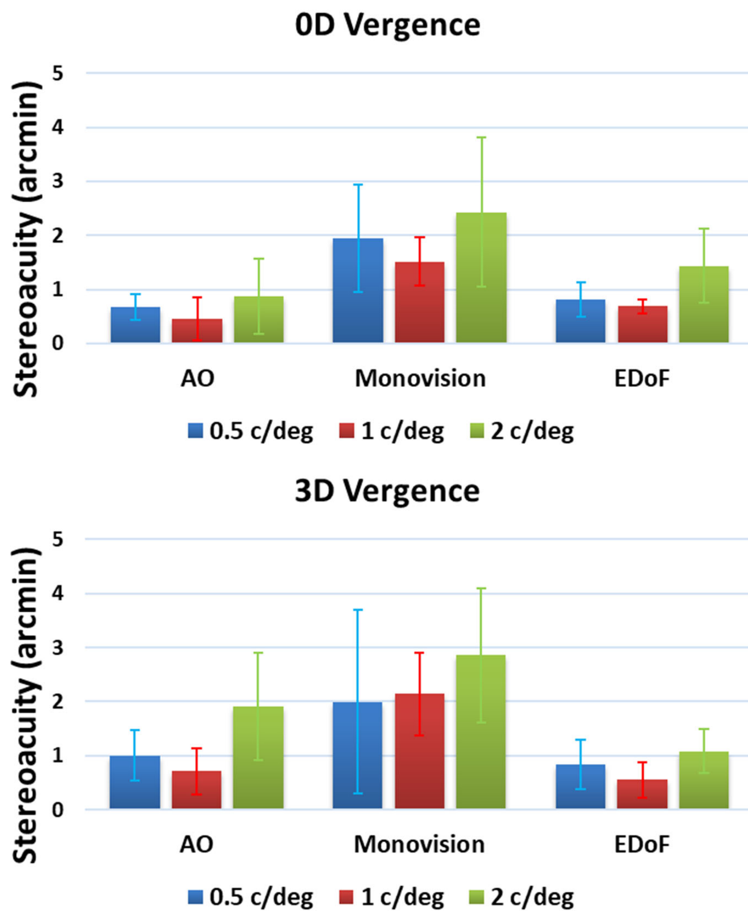

Figure 6. Stereoacuity at 0 D and 3 D vergence of the subjects ($N = 6$) under the three optical conditions. Lower stereoacuity indicates better performance. Blue bars indicate measurements at 0.5 c/deg corrugation frequency; red bars, at 1 c/deg; and green bars, at 2 c/deg. Error bars indicate ± 1 *SD*.

Discussion

In this work, we aimed to study the VA interaction under the EDoF optical condition that might serve as a possible solution to the VA stimulus conflict commonly occurring in VR. An adjustable disparity vergence control system was designed to be implemented in a binocular AO vision simulator. By combining spherical aberrations of different orders, an EDoF profile for binocular viewing was designed. We found that applying the profile to both eyes could induce greater amplitudes of accommodation as the eyes converged. Thus, the magnitudes of the accommodation and vergence responses became more alike, similar to the CA/C cross-link interactions observed in young adults (Fincham & Walton, 1957). However, as a tradeoff, visual acuity and stereoacuity were worsened.

The monovision condition assigned different powers (far and near) to each of the two eyes to extend the binocular DoF. The two eyes always had equal accommodative response, even if they received different accommodative demands (Flitcroft, Judge, & Morley, 1992). If the eyes were at the intermediate accommodation level (around 0.75 D), both eyes would perceive a blurry image. The accommodation of subject 2 stayed at 0.6 D during accommodation measurements with the Maltese cross but later shifted toward the best focus of either eye during the visual acuity tests. This implied that visual-dependent tasks might drive accommodation away from the intermediate accommodation level to avoid blur. Therefore, we expected that if the retinal image quality at the intermediate levels were improved then accommodation would follow convergence more easily. This could be achieved with the EDoF technique.

EDoF was efficient in dampening the defocus cue, originating from the screen distance, on accommodation. Spherical aberrations had been found to be an effective way to increase the DoF while compromising retinal image quality (Benard et al., 2010; Zheleznyak et al., 2013). Combining opposite signs of Z_4^0 and Z_6^0 had been shown to be more effective in extending DoF than with Z_4^0 alone, so we adopted this technique (Benard et al., 2010; Yi, Robert Iskander, & Collins, 2011). Within the DoF in our design, the retinal images had sharp edges but low contrast on one end of focal range and had blurred edges but high contrast on the other end (Figure 2a). We chose to induce reversed designs between two eyes to balance the binocular through-accommodation image quality. Compared with the monovision condition, EDoF offered improved image quality at the intermediate accommodation level (0.75 D). As a result, accommodation could transfer across or stay at intermediate levels, creating a more natural VA relationship. The EDoF profile can be applied to advanced contact lenses and easily worn by VR users (Sabesan, Jeong, Carvalho, Cox, Williams, & Yoon, 2007; Sabesan, Johns, Tomashevskaya, Jacobs, Rosenthal, & Yoon, 2013; Yoon, Jeong, Cox, & Williams, 2004). Future work is needed to test if EDoF can indeed reduce visual fatigue with a stereoscope, using contact lenses (in which case the spherical aberration caused by accommodation would be uncorrected).

Multiple additional factors could influence the final accommodation status. Subject 4 originally showed no accommodative response with EDoF; it was only after switching the EDoF profiles between two eyes that she started to have a significant accommodative response. As Flitcroft et al. (1992) pointed out, vergence and the need to accommodate in each eye both contribute to accommodation, and two eyes could contribute with different weighting. Similarly, we think that eye dominance can have an impact on the relative contribution to accommodative response. Also, intersubject variability in accommodation was observed. The accommodative response was little for subject 9 under all conditions. One of the conceivable explanations for the variability may be large variation in CA/C ratio between subjects. Convergence can be more or less efficient in inducing accommodation for a subject with a larger or smaller CA/C ratio. Fincham and Walton (1957) found that the accommodation induced by convergence also declined with age, and at the age of our subjects (26 ± 5), it was approximately 0.8 to 1 D per diopter of convergence, which was abundant for generating accommodation in our study. Older people may have a smaller CA/C ratio and hence may be less responsive to the EDoF method. What is more, phoria can influence the effort to change convergence; therefore, changing the input to the VA cross-link, despite the fact that no significant impact from phoria was found on visual comfort for three-dimensional stimuli (Wang, Wang, & Liu, 2015).

Apart from visual comfort, visual performance is also crucial to VR, so we examined the visual performance of all three conditions. The binocular visual acuity for the AO condition was comparable to the monocular visual acuity of either eye, but we noticed that the visual acuity at 3 D convergence was worse than that at 0 D vergence. This might be due to the slight increase in accommodative response at 3 D convergence, as the image was blurred by defocus. In monovision, however, the two vergence levels demonstrated the same visual acuity. Tracing the accommodation data during visual acuity measurement, we found that subjects tended to use either the near or the far eye to focus on the screen. The optically superior eye approximately determines the binocular visual acuity (Collins & Bruce, 1994; Collins, Goode, & Brown, 1993). The subject's binocular visual acuity matched the monocular visual acuity of the in-focus eye (Zheleznyak et al., 2013). With EDoF, the visual acuity of both eyes was impaired due to spherical aberrations (Seiler, Mrochen, & Kaemmerer, 2000). However, it was still better than 0 logMAR (typical visual acuity 20/20), which surpasses the VR device with the smallest angular resolution (equivalent to 0.4 logMAR) currently on the market (Underwriters Laboratory, 2020). Therefore, we assume that the visual acuity degradation is tolerable for contemporary VR uses.

The best stereoacuity was measured at 1 c/deg; however, in a previous study, the best stereoacuity occurred between 0.3 c/deg and 0.5 c/deg with horizontally oriented random dot stereograms (Bradshaw & Rogers, 1999). This difference could be explained by system limitations in the visual angle. The display size of our system did not allow sufficient wave cycles below 1 c/deg to be perceived accurately (Tyler, 1975).

Presumably, stereoacuity was the best under the AO condition because it optimized the image quality in both eyes. Increasing convergence to 3 D slightly induced accommodation in the AO condition and reduced image quality, resulting in stereoacuity degradation. The nonius lines provided feedback for precise vergence alignment, and vergence efforts to refine binocular alignment could have stimulated more convergence accommodation than measured without the nonius feedback. However, it is conceivable that the existence of the nonius lines might have relatively small impact for the following reasons: The main contribution of vergence demand came from the need to fuse dots in the random dot stimulus, and the nonius lines simply aided fusion. Even if there were not any nonius lines, numerous dot edges in the random dot stimulus would also serve as vergence alignment cues during relatively long presentation of stimuli. Also, if the binocular visual quality remains unchanged, interocular difference would also be detrimental to stereoacuity (Donzis et al., 1983; Westheimer & McKee, 1980). Unsurprisingly, monovision showed the worst stereo performance. Although EDoF degraded image quality, both eyes had similar image quality and hence largely superior stereoacuity that would be sufficient for identifying most of the disparities in natural scenes (Liu, Bovik, & Cormack, 2008) and VR.

Natural or created defocus blur can be utilized by the visual system in estimating the scale of the image (Held, Cooper, O'Brien, & Banks, 2010). The EDoF technique alters the DoF and the perceived blur in the image; hence, the perceived scale may be affected. It will be interesting to study the effect of EDoF on the perception of scale in the future.

Conclusions

Stimulus demand conflicts between vergence and accommodation caused disassociation between the two, as shown under AO condition. The monovision condition produced greater accommodation but lacked a gradual accommodation increase and impaired stereopsis. By using the EDoF technique, accommodative response could be increased following the CA/C cross-link interaction between vergence and accommodation. Visual acuity and stereoacuity were degraded, but they were preserved to some degree so that the three-dimensional images could still be appreciated. The accommodation response is influenced not only by vergence and screen distance but also by the aberration profiles in two eyes. Future study is needed to verify if the EDoF technique can effectively reduce the visual fatigue caused by using a VR stereoscope.

Keywords: vergence-accommodation conflict, extended depth of focus, adaptive optics, binocular vision

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Appendix A

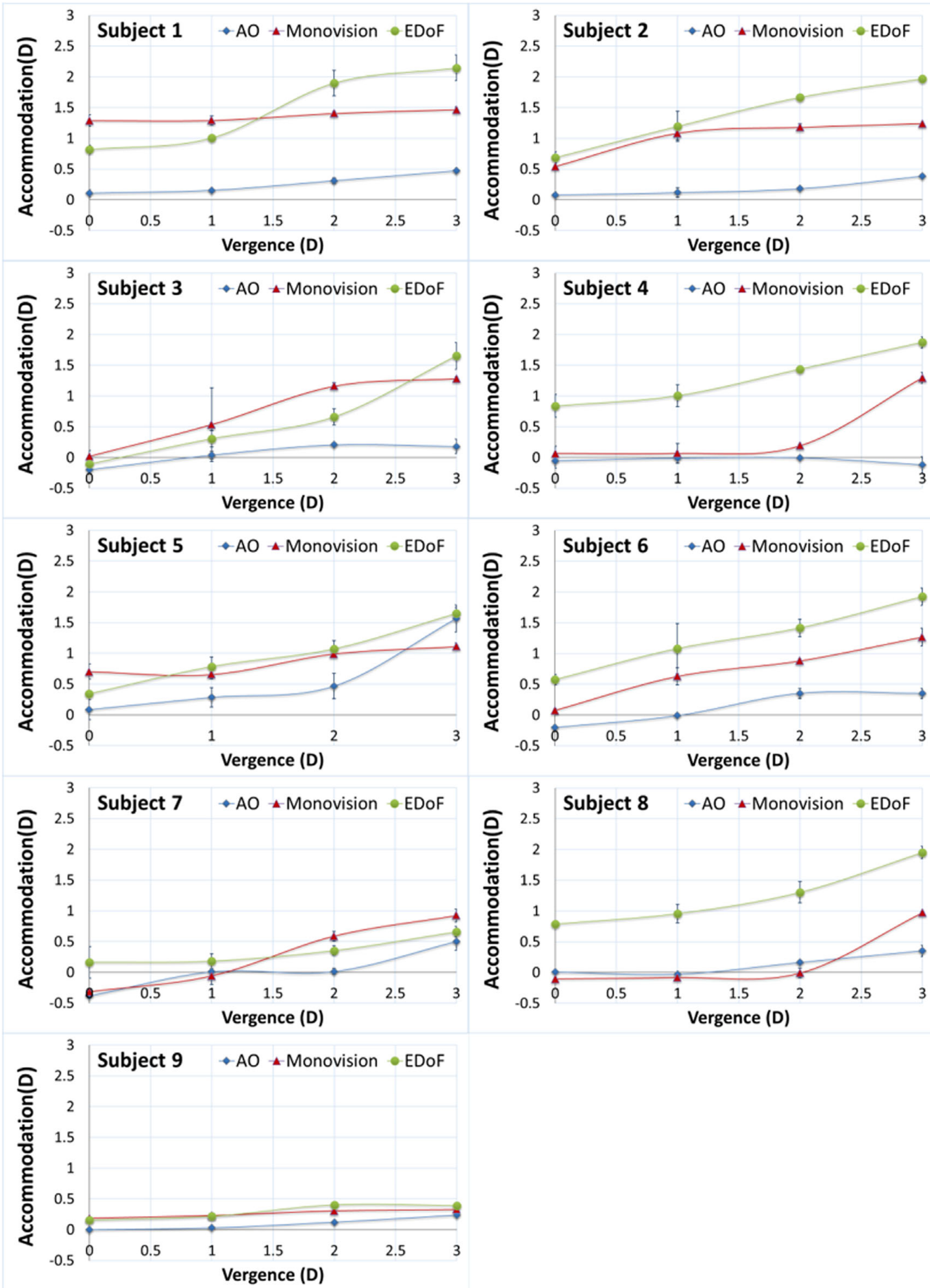

Figure A1. Accommodative responses of individual subjects. Error bars indicate ±1 *SD*.