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Investigating the Use of Spectacle Lenses to Alleviate Vergence-Accommodation Mismatch in a Stereoscopic Remote Vision System

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Abstract

Vergence-accommodation (VA) mismatch is a component of stereoscopic 3D remote vision system (RVS) design linked to depth misperception and visual discomfort. VA mismatch is caused by an unnatural conflict between the focal distance of the image (and thus accommodative demand) and the binocular vergence demand. A possible solution to mitigate VA mismatch is to change the accommodative demand with an optical correction, reducing the mismatch with the vergence demand. This experiment investigated the effect of low-add spectacle lenses (eyewear) on RVS performance and visual comfort. While previous research showed a positive effect of decreasing VA mismatch with the use of switchable lenses to adjust focal distance, the optical changes in this investigation were insufficient to make a difference. We conclude that the use of eyewear with a small dioptric add is not an effective solution to improve stereoscopic RVS performance or viewing comfort.

Disclosures

The views expressed are those of the authors and do not necessarily reflect the official policy or position of the Air Force, the Department of Defense, or the U.S. Government. This research was supported by USAF contract FA8650-18-C-6932 to KBR. This research was accomplished in accordance with approved Air Force Research Laboratory Institutional Review Board human subjects research protocol number FWR-2013-0074. Appearance of, or reference to, any commercial products or services does not constitute DoD endorsement of those products or services.

Background

Previous generations of boom operators in the United States Air Force (USAF) have utilized an out-the-window view at a workstation located at the rear of the tanker aircraft (e.g., KC-10, KC-135) during air-to-air refueling. The next generation KC-46 tanker, however, is equipped with a remote vision system (RVS) Air Refueling Operator Station (AROS). Two cameras mounted on the underside of the aircraft generate real-time video displayed as stereoscopic 3D imagery at the AROS. Initial system tests of the KC-46 RVS revealed operational issues including an increased number of contacts-outside-the-receptacle (COTRs) and operator discomfort (i.e., eyestrain and headache). A potential cause of these issues common in stereo displays is vergence-accommodation (VA) mismatch. In the natural world, when individuals direct their gaze to an object, they converge their eyes to maintain single vision and accommodate their intraocular lens to reduce defocus. These two actions are neurally linked and help preserve a single and clear view of objects of interest [1]. In artificial stereo scenes, the eyes converge to the virtual object distance while they accommodate to the screen distance (see Figure 1). This mismatch has been shown to cause discomfort and lead to decreased performance [2-3]. Current research recommends VA mismatch not exceed approximately ± 0.5 D (cf. 0.25 D blur perception threshold) to minimize discomfort [2].

VA mismatch is affected not only by stereoscopic display design, but also by the optical characteristics of the individual using the display. For example, both average pupil size and the range of accommodation decrease with age [4]. Older observers (40-60 years) have an average pupil size approximately 0.5 mm smaller than younger observers (under 30 years), leading to a potential increase in depth of focus [5-6]. This increase in depth of focus, and the decreased coupling between vergence and accommodation in older observers (presbyopia), could mean that older users are less likely to experience discomfort when viewing stereoscopic displays. Individual differences in binocular function and the zone of clear single binocular vision may predict variations in visual discomfort because of their relation to vergence and accommodation [2, 7].

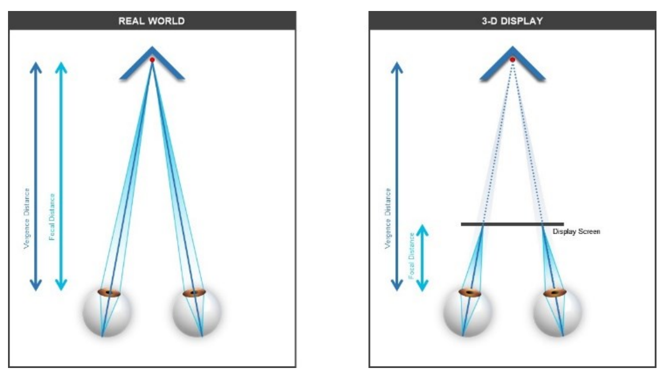

Figure 1. *Left: Real world viewing conditions, where focus and fixation distances are in agreement. Right: Stereoscopic display conditions, where the focal distance is at the distance of the screen and the fixation distance varies with the virtual depth of the image. Illustration provided by the 711 HPW media department.*

One possibility to reduce VA mismatch in an RVS is to employ spectacles with a small amount of optical add (such as reading glasses) [3]. This would reduce the accommodative demand of the stereo imagery, moving it closer to the convergence distance, decreasing the total mismatch. However, there are several reasons eyewear may not help alleviate the negative effects of VA mismatch. The binocular disparity of the 3D object is the stimulus for ocular vergence, and consequently, VA mismatch will vary based on both the object of fixation and any movement of that object within the 3D scene. The additional eyewear could also have a differential impact on individual users based on their refractive status. For example, hyperopes are used to over-accommodating and any prescription may not completely correct the refractive error.

The purpose of this study was to examine the impact of using eyewear with small dioptric adds (i.e., reading glasses) to reduce VA mismatch, as measured by differences in simulated RVS refueling performance and reported visual discomfort. Previous research used a switchable lens volumetric display to adjust focal distance and found a significant effect on reported vision symptoms while performing a 3D stereo task for cues consistent vs. cues inconsistent viewing conditions [2]. Thus, we anticipated that even with individual differences in age and refractive status, changing the accommodative demand optically would have similar effects.

Methods

Participants

The study was carried out at McConnell Air Force Base (AFB) near Wichita, KS. This allowed us to obtain a relatively large sample of trained boom operators with a representative range of age, interpupillary distance, and overall ocular health. All operators had passed the Flying Class III vision standards, which include at least 20/20 visual acuity, at least 120 arcseconds stereoacuity (40 arcseconds passing score, waiverable to 120 arcseconds), less than 10 prism diopters (PD) esophoria, less than 6 PD exophoria, and less than 1.5 PD hyperphoria. Experience in aerial refueling included both RVS and non-RVS refueling operations. Participants provided informed consent under protocol numbers FWR20170095H and FWR20130074H, as approved by the Air Force Research Laboratory Institutional Review Board.

Apparatus

Stereoscopic imagery was presented on an RVS display on loan from Boeing and Collins Aerospace, shown in Figure 2. During testing, participants viewed the display through passive circularly polarized 3D glasses provided with the display. The 3D environment was rendered using a multi-channel FlightSafety Vital 1100 image generation (IG) system (FlightSafety International Visual Systems, Hazelwood, MO). Stereoscopic images were generated with two separate IG channels, each using an Nvidia Quadro P6000 video card (Nvidia, Santa Clara, CA) and frame buffers were synchronized using NVidia Quadro Sync II cards. To interlace the video into a single stereo image, the IG transmitted video signals for each eye into a Westar EZwindow Video Combiner box (Westar Display Technologies, Saint Charles, MO). Video output from the EZwindow box was then transmitted into a hardened-DVI (HDVI) converter to reformat the video signal into a HDVI signal, to be interpreted by the aircraft display. The active area of this 24-inch display was 52 x 32 cm with a resolution of 1920 x 1200 pixels. The display was spatially interlaced with micro polarizers reducing the resolution to 1920 x 600 pixels per eye. For all conditions, the viewing distance to the 3D RVS display was 0.89 meters.

The flight control apparatus included a flight control stick and telescope control stick, (Saitek X56 flight controllers; Logitech, Lausanne, Switzerland). This design was similar to those used in a previous Boeing human factors study [8].

The eyewear used in the study was fabricated by the USAF School of Aerospace Medicine's Aerospace Ophthalmology Branch (USAFSAM/FECO, Wright-Patterson AFB, OH). Eighteen spectacles were made in total: two pairs for each combination of optical power (+0, +0.25, and +0.50 D) and size (small (52 mm), medium (55mm), and large (58mm)). The different eyewear conditions were expected to expose participants to different degrees of VA mismatch (reported as percent change in VA mismatch; Table 1). Details of the KC-46 RVS design are proprietary, thus the specific VA mismatch cannot be described here.

Interpupillary distance (IPD) of each pair of glasses was confirmed using a NIDEK lensometer (NIDEK, Plain City, OH) after the completion of the study. The IPD for the medium sized +0.25 D glasses was larger than expected, and the IPD for the large glasses was smaller than expected (see Table 2). The lens power was verified to meet the ANSI Z80.1 standard (± 0.13 D) using a NIDEK lensometer.

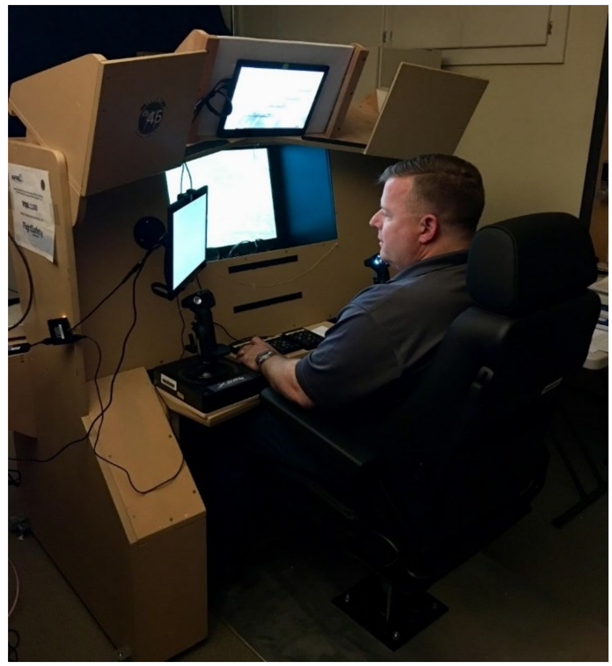

__Figure 2.__ Simulated KC-46 Aerial Refueling Operator Remote Vision System console used in this study.

Table 1. VA mismatch for the three RVS conditions

Eyewear (D)	VA Mismatch (%)	VA Mismatch (D)
+0	100%	>0.5 D
+0.25	28% less	>0.5 D
+0.50	56% less	<0.5 D

Table 2. Eyewear sizes and measured IPDs

Eyewear Size	Optical Power (D)	Eye size (mm)	IPD (mm)
Small	+0.00	52	--
Small	+0.25	52	62
Small	+0.50	52	64
Medium	+0.00	55	--
Medium	+0.25	55	74
Medium	+0.50	55	62
Large	+0.00	58	--
Large	+0.25	58	60
Large	+0.50	58	60

The lenses were mounted in an authorized ArtCraft DR frame (ArtCraft Optical, Rochester, NY) and shown in Figure 3. This frame was specifically chosen as it has a bayonet temple, making it easier to wear over existing prescription glasses.

Figure 3. *Small dioptric add eyewear fabricated by USAFSAM/FECO for this study.*

Based on an evaluation carried out by USAFSAM/FECO, it was not possible to integrate the polarizing filter required for viewing the 3D display with the dioptric add due to the curvature of the standard lens blanks (see Figure 4). Therefore, all participants wore two pairs of eyewear: the dioptric add eyewear and the polarized 3D glasses. For eyeglass-wearing participants, three pairs of eyewear were required: the participant's prescription eyewear, dioptric add, and 3D glasses, as shown in Figure 5.

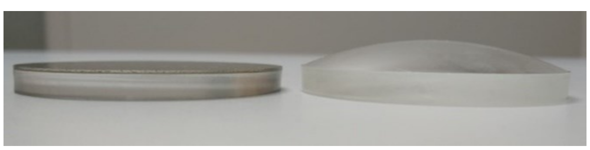

Figure 4. *Commercially available circular polarized filter stock, left, standard ophthalmic lens blank, right.*

Figure 5. *Stacked eyewear used in eyewear study: 1) Circular polarizing 3D glasses; 2) + 0.5 D optical add in aircrew-approved frames; 3) operator's prescription eyewear.*

All participants had their refractive error measured using a NIDEK autorefractor (NIDEK Auto Ref/Kerato/Tonometer model TONOREF II). Participants were categorized as emmetrope (between - 0.5 and +0.5 D), myope (< -0.5 D), or hyperope (> 0.5 D).

Tasks

Research participants were asked to complete a depth tracking task in the RVS simulation. Participants tracked the receptacle of a receiver aircraft with the simulated boom while the receiver flew counterclockwise around the boundaries of an average contact envelope. Their goal was to track the receptacle as closely as possible without hitting the aircraft with the boom. Each trial was initiated once the participant moved the boom within seven feet of the receiver aircraft. The distance of the receptacle was randomized each trial from three possible distances (8, 14, and 19 ft), which emulated short, mid, and long boom extensions. Figure 6 shows the receiver aircraft at select positions around the path and at each boom extension distance. Relative turbulence was added in all three directions as the aircraft moved around the track. The aircraft flew away and the trial ended if the participant either struck the receiver aircraft (indicated by a red 'X' on screen), or the participant successfully tracked the receptacle through a complete cycle. There was a total of eight different receiver aircraft models (F-16, A-10, KC-10, F-15, C-17, AC-130, B-1B, and EC-130) that appeared in random order. The distance from boom tip to receiver receptacle was recorded at 10 Hz and root mean square (RMS) error was computed over one complete tracking cycle. Trials where the participant hit the aircraft were not included in this measure. During practice, participants were instructed to purposefully just barely touch the receiver near the receptacle at least twice. This permitted participants to adjust to any changes between sessions.

Figure 6. *Receiver aircraft at selected positions around the path and at each boom extension distance.*

Participants also completed a visual comfort questionnaire. This six-item questionnaire addressed issues associated with the use of stereoscopic displays such as comfort, eyestrain, and headache (Table 3). The items were based on the visual symptom questionnaire [2] and the Simulator Sickness Questionnaire [9]. Participants input their responses on a Lenovo ThinkPad x1 tablet (Lenovo, Beijing, China) using a five-point Likert scale.

Table 3. Visual Comfort Questionnaire.

Question	Answer Choices
Do your eyes?	Feel good, no eye strain
	Feel OK, minimal eye strain
	Have mild pain or discomfort due to eye strain
	Have moderate pain or discomfort due to eye strain
	Hurt with severe pain due to eye strain
Are your eyes?	Not tired – wide awake
	Not tired – OK
	Mildly tired
	Moderately tired
	Very tired
How is your vision?	Clear, scene and objects are very clear and sharp
	Clear, everything looks OK
	Things do not look sharp
	Things look a little blurry
	Things are very blurry
Does your head feel?	Relaxed
	OK
	Mild ache
	Moderate ache
	Severe ache
In general, do you feel	Alert and rested
	OK
	Mild fatigue
	Moderate fatigue
	Severe fatigue
Are you experiencing?	No nausea – feel great
	No nausea – feel OK
	Mild nausea – starting to feel sick
	Moderate nausea – feel sick
	Severe nausea – feel very sick

Procedures

The three eyewear configurations were completed once per participant in separate sessions, in random order. A minimum 3-hour break between sessions was enforced, though most participants completed each session on separate days. During each session, participants completed the tracking task, beginning with eight minutes of practice. Participants completed the visual comfort questionnaire before and after each session. Responses to the questionnaire at the beginning of the session were examined at the end of the study to check if high responses (large amounts of discomfort) resulted in poor tracking task performance, while responses at the end of the session were used for hypothesis testing. Total data collection time was 1.5 hours per participant per session.

Results

Participants consisted of 24 boom operators, nine of whom had KC-46 refueling experience (in air or flight simulator training), ranging from 2 to 500 hours with a mean of 85 hours (SD = 158). Of the 21 who had KC-135 experience, flight hours ranged from 31.6 to 3100 hours with a mean of 669 hours (SD = 834). Participant ages ranged from 20 to 48 years, with a median of 29 years. All participants were male. Seven participants wore glasses and two wore contact lenses. Seven participants were myopic with a max of -3.75 D (spherical equivalent), five participants were hyperopic with a max of 1.88 D, eleven participants were emmetropes, and no participants were anisometropes. The one participant over 45 was likely presbyopic. One participant was unable to come in for refractive measurement and was excluded from analyses. Another participant was excluded as his tracking distances were more than twice the average of all other participants and he had the highest variability across trials.

Tracking distance was calculated using RMS error, controlling for receiver aircraft. Mean tracking performance across the +0 D, +0.25 D, and +0.50 D conditions was analyzed by refractive category in a 3 x 3 mixed measures ANOVA. Average tracking distance for each diopter level and refractive category is shown in Figure 7. There was no significant effect of eyewear condition ($F(2,38) = 0.18$, $p = 0.83$) or refractive category ($F(2,19) = 0.15$, $p = 0.86$), nor was there an interaction between eyewear condition and refractive category ($F(4,38) = 0.79$, $p = 0.54$). The number of COTRs was also the same across eyewear condition ($F(2,38) = 1.84$, $p = 0.17$) and refractive category ($F(2,19) = 2.85$, $p = 0.08$), with no interaction ($F(4,38) = 1.00$, $p = 0.42$).

Responses for the six visual comfort questionnaire survey questions items were analyzed separately across the dioptric conditions. Using the Friedman Test F statistic, no significant differences in responses were found across +0 D, +0.25 D, and +0.50 D (Table 4). Similarly, a qualitative assessment showed no strong trends linking ratings to refractive status. The most common survey responses were “1” and “2” to all questions, indicating little perceived fatigue/discomfort. Extreme responses of “4” or “5” are not attributable to any vision category. Only one participant responded with “5s” and was considered an outlier.

In addition to the structured questionnaire responses, unsolicited comments made by participants during experimental sessions were recorded. Overall, 22 comments were made by 12 participants. Sixteen comments regarded discomfort, and of these, seven comments directly contradicted participant responses on corresponding items on the visual comfort questionnaire (eye strain, headache, eye tiredness and vision blur).

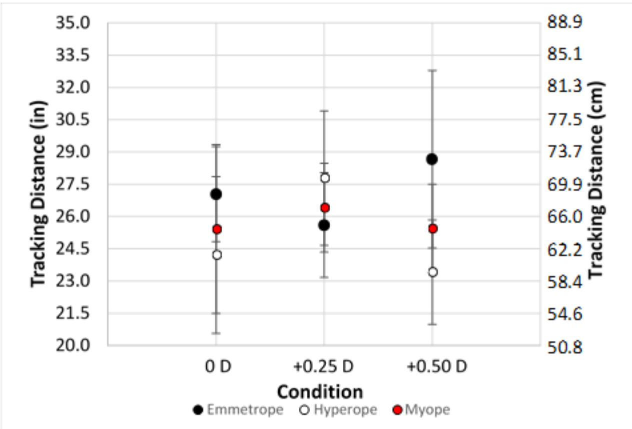

Figure 7. *Mean tracking distance for each vision category and each eyewear condition. Error bars represent standard error.*

Table 4. Comparing +0 D, +0.25 D, +0.5 D visual comfort questionnaire results.

Survey Question	*F* approximation	*p*-value
Eyestrain	0.04	0.96
Eye tiredness	0.10	0.90
Vision blur	0.10	0.90
Headache	0.42	0.66
Fatigue	0.07	0.93
Nausea	0.24	0.79

Discussion

A simulated aerial refueling task on a stereoscopic RVS display with VA mismatch was used to evaluate the use of small powered dioptric add lenses (i.e., reading glasses), as an approach to reduce VA mismatch and improve usability. The impacts of these changes were assessed using a receiver aircraft tracking task and self-reported visual comfort ratings. There were no statistically evident trends regardless of experimental condition, suggesting that this approach did not improve usability (though it may still have reduced VA mismatch). An earlier study suggested that reported discomfort decreased with decreased VA mismatch [10]. In that study, VA mismatch was decreased by increasing viewing distance (while increasing screen size to keep FOV constant) instead of increasing focal distance. Here, neither the addition of +0.25 D nor +0.5 D lenses to decrease VA mismatch improved tracking performance or had any effect on reported visual comfort.

The lack of significant performance and subjective visual comfort differences resulting from the eyewear may indicate that other factors negated the intended effect of the eyewear. For example, it is possible that visual accommodation "lags" very close imagery (i.e., focuses farther than the object) and "leads" more distant imagery (i.e., focuses closer than the object) [11], though this effect may be related to measurement problems [12].

Plus add lenses of 0.25 and 0.50 D are considered marginal by optometrists. In a survey of Israeli optometrists, the smallest prescription for hyperopia considered was a refractive error of +0.50 D [13]. The responses indicated that even this level of refractive error would be considered for correction by half the respondents only if an adult (age 20-40) patient reported symptoms (e.g., likely eyestrain, but left undefined). Other studies cited by [14] indicate that the average threshold for prescription was +0.75 D - and again only with reported symptoms.

It's possible that much of the defocus change created by the lenses in this study was within the participant's depth of field. The depth of field is the range over which an object appears "in focus" with good image quality [15]. The 100 cd/m^2 monitor luminance through the glasses and polarizing filter produces a pupil size of about 3 mm, which gives a depth-of-field of approximately 0.7 D, which is the above range of adds tested here [16- 17]. Thus, the RVS +0.5 D optical correction is likely not perceptually different from the RVS +0 D condition in terms of either image quality or blur detection, though it may still be a non-negligible input in the VA control systems [18 - 19].

The relatively large accommodative range and flexibility for young observers may be an additional contributing factor to the apparent lack of effectiveness of the eyewear. The participants in this study had a median age of 29. Accommodative power ranges from approximately 11 D for the youngest participants in this study to approximately 4 to 5 D for even the oldest participants in this study [20]. It is possible that the younger participants in this study simply adapted to the small dioptric add – essentially nulling-out the eyewear dioptric power within the depth of focus. The small dioptric add may have little effect on the vergence-accommodation coupling. In addition, if any of the older participants were presbyopic, the vergence and accommodation link would already be weak.

There were no differences in task performance or subjective visual comfort based on refractive category. As participants were not recruited based on their categories, each group had a varied number of participants, and the number of hyperopes was especially small. Additionally, the participants only represented a small range of refractive error. Individual differences in tonic accommodation or depth of field may have obscured any trends.

Recommendations for Future Work

It is possible that the large IPD (74 mm) for the +0.25 D medium-sized eyewear could have induced base-out prism. Similarly, the small IPD for the large sized eyewear could have induced base-in prism. However, the amount of prism expected based on participant IPD vs. eyewear IPD and the power of the lenses is still small (based on Prentice's rule, [15]), and within a standard tolerance of 0.67 D (horizontal, ANSI Z80.1-2015 tolerance standard). Thus, it is not likely that the eyewear IPD affected the results of this study. Nonetheless, eyewear IPD should be more carefully controlled and possibly even customized for each participant in any future work. Polarized lenses should be added to dioptric adds when possible so that there is no need for two pairs of eyewear (to be worn over any pre-existing eyewear).

The dioptric values of +0.25 D and +0.50 D chosen for this investigation were based on physical optics and did not anticipate variations in operator visual accommodation. Larger dioptric values that would increase the focal distance of the monitor imagery may be worth testing. Measuring participant accommodation values during testing would give true VA mismatch instead of estimated values based on RVS specs.

In the current study, even though leadership assured the boom operators that their results/answers would have no bearing on their career, the booms may have still felt pressure to give low visual fatigue ratings. As noted in the results, there were a large number of inconsistencies between responses on the visual comfort questionnaire and the unsolicited open-ended comments. Future studies should consider nonmilitary participants as well as including objective measures of visual strain.

Conclusion

No definitive evidence was found that supports the proposed use of small dioptric adds to decrease RVS VA mismatch as measured by performance in a simulated KC-46 boom operator task or by self-reported visual comfort. This is in contrast to the results of a previous study [10], which indicated that reducing VA mismatch by increasing viewing distance resulted in decreased reported discomfort. The lack of significant differences may indicate that other factors negated the intended effect of the eyewear. For example, the relatively large accommodative range and flexibility for young observers may be a contributing factor to the apparent lack of effectiveness of the eyewear.

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