https://doi.org/10.2352/EI.2026.38.2.SDA-335

The effects of vertical misalignment in a stereoscopic display during long-haul aerial refueling simulation

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Abstract

With increased use of stereoscopic devices, it is important to emulate real-world practices and study physiological and perceptual effects over long viewing periods. Stereoscopic channels may not always be perfectly aligned, and alignment may shift with use. In this experiment, we investigated the impact of vertical misalignment between left and right-eye imagery during stereoscopic remote vision system (sRVS) use. For three-hour periods, participants performed a simulated aerial refueling task. Their goal was to fly the boom into a receiver aircraft receptacle as quickly as possible without scratching the aircraft. After each successful connection, the participant monitored several systems, which required changes to version and vergence position. Binocular eye position was recorded throughout the task. While performance increased over time, the survey results showed that participants were experiencing strain over time and with increased misalignment. However, only one oculomotor change – horizontal vergence – was observed over time. Time series analysis revealed a more complex relationship between pupil size and time within each block. To further investigate the relationship between eye movement behavior and vertical misalignment, a principal component analysis was performed. These results identified eye movement behaviors that are sensitive to changes in stereoscopic misalignment and have the potential to be used to indicate oncoming fatigue. This experiment highlights the importance of considering the visual system as a whole when assessing stress and not simply relying on performance metrics.

Background

The effect of stereoscopic display misalignment over long duration task performance is not well understood and is pertinent to the operational community. In particular, there is interest in predicting fatigue and visual stress using objective physiological data, such as eye movements. There is also concern that image misalignment and other distortions in stereoscopic systems may be tolerable over short periods of time but will have negative effects with longer term use.

In the natural environment, in the response to horizontal disparity, the visual system will make a horizontal vergence movement is necessary to bring the object into alignment. However, there is no such analogous natural vertical disparity, aside from the role it plays in the ocular tilt reaction [1]. In fact, cortical vertical-disparity-detectors may not exist [2]. It stands to reason then that our eyes have little tolerance for vertical disparity as compared to horizontal disparity [3]. In spite of this, humans can still combine motor and sensory fusion to accommodate small amounts of vertical disparity [4]. However, just because fusion is possible does not mean it is not a strain on the visual system, especially over significant time periods.

A number of studies have aimed to provide guidelines for maximum vertical misalignment in general stereoscopic image presentation (i.e. not specific to headwear). Recommendations vary: 12 arcminutes or less [5], 15 arcmin [6], 15 to 20 arcmin [7], and 34 arcmin or less [8]. Other studies provide summaries of limits for optical devices specifically, including augmented and virtual reality [9-11]. These recommendations also show large differences (e.g., 3.4 to 34.5 arcmin), which are likely due to study methodologies, device tolerance limits, and the phenotype of usability (i.e. diplopia versus visual discomfort [11]). The majority of these studies base their recommendations on visual discomfort and fatigue ratings without measuring any effect on task performance or oculomotor behaviors.

The purpose of this investigation was to systematically investigate a range of vertical misalignments in a stereoscopic remote vision system (sRVS) and assess the impact on task performance, oculomotor behavior and self-reported discomfort. The vertical misalignments tested were chosen to both span the values in the literature and represent field-measured HMD misalignments. The experimental task was an aerial refueling task performed at a simulated boom operator station representative of the current version on the US Air Force KC-46 refueling tanker. Two means of eyestrain/visual fatigue measurement were used. One was a visual comfort questionnaire, based on those developed by Shibata et al. [12] and Kennedy et al. [13]. The second included objective measures related to the user's oculomotor behavior, measured online while the participant was completing the task. For example, an increase in the frequency of saccades may be an indicator of fatigue/visual stress [14-16], as well as variations in pupil behavior, such as changes in the velocity of constriction or dilation [17-21]. The study design allowed us to easily differentiate between changes due to misalignment and those due to the long task duration.

Methods

Participants

This study was carried out at Wright Patterson Air Force Base (WPAFB), Dayton, OH. A total of 17 participants were recruited through the OBVA participant database and word of mouth. Participants provided informed consent through protocol numbers FWR20170095H and FWR20130074H as approved by the Air Force Research Laboratory Institutional Review Board. The study adhered to the tenets of the Declaration of Helsinki.

Design and Procedures

The study compared three different misalignment conditions between the left and right scene cameras in an sRVS aerial refueling simulation: no misalignment, 0.21° vertical, and 0.42° vertical (0, 12.6, and 25.2 arcmin). Participants first visited the lab for one-hour of aerial refueling practice (no misalignment). The three experimental sessions were taken over three separate days, one misalignment condition per day, randomized per participant. All sessions proceeded as follows: the participant was seated at the simulated boom operator station and underwent the eye tracking calibration and validation procedure. While the eye tracker was recording, they refueled for three 55-minute blocks, each followed by a five-minute break during which they completed a visual comfort survey.

Stereoscopic RVS Simulation

The aerial refueling station monitor was a 24-inch spatially interlaced linear polarized stereoscopic display. The 3D environment was rendered using a multi-channel FSI Vital 1100 image generator (IG) system (FlightSafety International, Columbus, OH). Stereoscopic images were generated by means of two separate channels each with an Nvidia Quadro RTX 5000 video card. Frame buffers were synchronized using NVidia Quadro Sync II cards (Nvidia, Santa Clara, CA). These two channels were fed into a Westar EZwindow video combiner box in order to interlace the video into a single stereo image (Westar Display Technologies, Saint Charles, MO). Video output from the EZwindow box was then fed into a hardened-DVI converter so it could be interpreted by the aircraft display. Images were generated in greyscale. Participants viewed the imagery through passive polarization glasses supplied with the monitor. The scene camera specifications (e.g. distance between right and left cameras, focal length) were matched to those used on the USAF KC-46 refueling tanker sRVS, known as the enhanced RVS (eRVS). Vertical camera pitch misalignments were based on preliminary misalignment data from a separate pilot study. The three different conditions were 0° (no misalignment), 0.21°, and 0.42° of vertical pitch difference split equally between the left and right cameras.

Participants used two flight control sticks (Saitek X56 flight controllers; Logitech, Lausanne, Switzerland) to perform the task, while seated in a Ricaro chair (Ricaro, Stuttgart, Germany). Figure 1 shows the RVS station, eye tracker, and joysticks. A Lenovo ThinkPad x1 Tablet (Lenovo, Beijing, China), was used for the vision comfort survey.

***Figure 1.** sRVS set-up with aircraft monitor, EyeLink eye tracker and Saitek flight control. Photo by OBVA Lab personnel.*

Performance Task

The performance task was an aerial refueling task designed with input from experienced boom operators. At the start of each trial a receiver aircraft flew into pre-contact position. When the participant was ready, they pulled the trigger on the right joystick and the receiver aircraft moved to contact position. Here, the participant was able to control the on-screen boom and manipulate it into the receiver aircraft receptacle. The right joystick controlled the azimuth and elevation of the boom, and the left joystick controlled the extension and retraction of the boom nozzle.

Participants were instructed to attempt to maneuver the boom into the receiver receptacle as accurately and as quickly as possible while avoiding hitting the receiver aircraft outside the receptacle. If the boom nozzle did hit outside the receptacle (referred to as a contact outside the receptacle, or COTR), scratches appeared on the receiver aircraft to alert the participant. Once successfully connected, the participant had to monitor for the occurrence of any of three events: 1) once the “actual fuel” indicator reached the “planned fuel” amount, 2) if fuel spray occurred behind the receiver receptacle (20% probability); 3) if the receiver drifted outside the contact envelope limits (25% probability). At the first of these events to occur, the participant disconnected from the receiver by pressing the trigger on the right joystick. Monitoring these different systems required vergence and version movements between aligned and misaligned imagery. Once the participant disconnected, the receiver aircraft flew away, and the trial was complete.

The aerial refueling performance task yielded the following measures: (1) connect time, or the time to a successful connection between the boom nozzle and the receiver aircraft and (2) COTRs/Trial, or the number of contacts outside the receptacle (COTR) made on the receiver per aircraft per trial. For both metrics, a smaller value indicates better performance.

Questionnaire

The visual comfort questionnaire was modified from the visual symptom questionnaire [12] and the Simulator Sickness Questionnaire [13]. Participants took the questionnaire electronically after every refueling block (three times per session), responding to each question using a slider with a symptom description at each end. The slider scale was evenly divided into steps of 0-100, with no markings on the line. This eleven-item questionnaire yielded the following measures: Eyestrain, Eye Tiredness, Vision Blur, Headache, Focus, Eye Dryness, General Fatigue, Nausea, Hard Work, Discouragement, and Neck/Back Tiredness.

Eye tracking

Binocular eye position and pupil size were recorded using an EyeLink 1000 Plus (SR Research Ltd., Ottawa, Canada). This eye-tracker has a binocular sampling rate of 1000Hz and a reported spatial accuracy of 0.5 degrees. A thirteen-point calibration and validation procedure was used. Blinks were removed using custom blink detection software with 0.5 second epochs before and after the blink removed to preserve data quality. Saccades were identified automatically using a strategy that looks for contiguous periods of high velocity in horizontal and vertical eye position [22]. The eye tracking data yielded the measures described in Table 1.

Table 1. Eye Tracking outcome metrics

Measure	Units	Description
Pupil Size	mm	Median pupil size over the length of a refueling trial
Pupil Size Variance	mm^2	Variance in pupil size over the length of a refueling trial. Generally increased variance indicates increased visual stress [17-21].
Saccade Frequency	Hz	Median number of saccades per second over the length of a refueling trial. Increased saccade frequency can indicate visual stress [14-16]. Any recorded frequency over 10Hz was removed.
Horizontal Vergence	degrees	Median amount of convergence/divergence over the length of a refueling trial. Negative values convey convergence.
Vertical Vergence	degrees	Median of absolute values of vertical vergence over the length of a refueling trial.

Results

Performance Task

3x3 within-subject ANOVAs were used to compare the three different misalignment conditions and three refueling blocks as well as check for any interactions. For the outcome variable connect time, there was a significant effect of block (F(2,30) = 11.06, $p < .001$), but not a significant effect of misalignment (F(2,30) = 0.54, p = 0.59) nor a significant interaction (F(4,60) = 1.49, p = 0.22) (Figure 2). Across all misalignment levels, participants were faster to make a successful connection from the first to the second block (p = 0.005), and the first to the third block (p = 0.01), but not the second to the third block (p = 0.10).

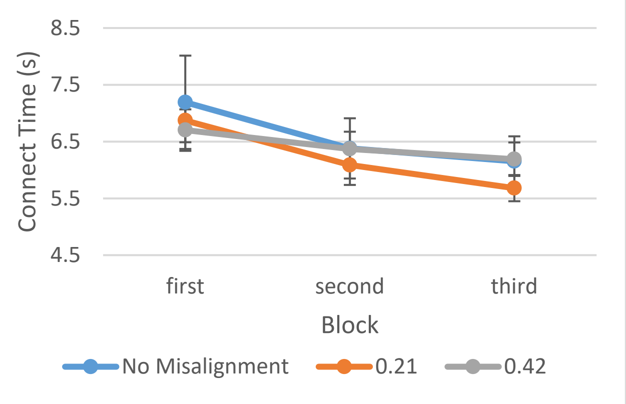

Figure 2. *The average length of time to make a successful connection for all three misalignment conditions and all three 55-minute blocks/session.*

For the outcome variable COTRs/trial, there were no significant effects of block (F(2,30) = 2.12, p = 0.13) or misalignment (F(2,30) = 0.34, p = 0.71), nor was there an interaction (F(4,60) = 0.82, p = 0.52) (Figure 3). Considering these results only, misalignment made no difference in performance, and the long session time actually aided in performance.

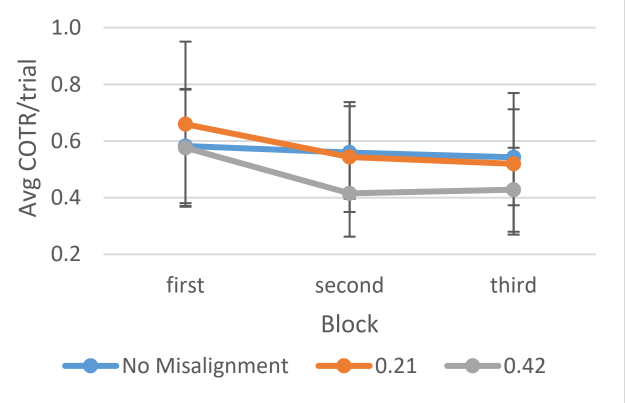

Figure 3. *The average number of COTRs per trial for all three misalignment conditions and all three 55-minute blocks/session.*

Questionnaire Analysis

The results of each question in the visual comfort questionnaire were graphed and then analyzed across time (collapsed across misalignment condition) or misalignment (collapsed across block). Tables 4 and 5 present the chi-squared and p values for the Friedman tests that were found to be significant. Compared to the performance results, the questionnaire results told a different story, one that mirrors the aforementioned literature. Eyestrain, vision blur, and nausea were rated significantly higher across misalignment, while headache, general fatigue, and neck/back tiredness were rated significantly higher across time.

Table 4. Visual comfort questionnaire results for those items compared across misalignment conditions.

Survey Question	Statistic	Misalignment Comparison
Eyestrain	^{2}	10.34
	p	0.006
Vision Blur	^{2}	7.90
	p	0.02
Nausea	^{2}	6.53
	p	0.04

Table 5. Visual comfort questionnaire results for those items compared across blocks.

Survey Question	Statistic	Block Comparison
Headache	^{2}	12.49
	p	0.002
General Fatigue	^{2}	7.48
	p	0.02
Neck/back Tiredness	^{2}	11.47
	p	0.003

Eye Tracking

3x3 within-subject ANOVAs were used to compare the three different misalignment conditions and refueling blocks for all of the eye tracking outcome metrics. For pupil size, there were no significant effects of block (F(2,30) = 1.26, p = 0.22) or misalignment (F(2,30) = 1.78, p = 0.19), nor a significant interaction (F(4,60) = 0.99, p = 0.42). However, pupil size data over each trial appeared to decrease across each block regardless of misalignment (see Figure 4). Autoregressive integrated moving average (ARIMA) time series modeling was used to evaluate the decrease for each block at each misalignment level. Autocorrelation and partial autocorrelation requirements were met for both blocks one and two at all misalignment levels. Therefore, six autoregressive terms could be predicted (2 blocks x 3 misalignments), and similar values for these terms were found. However, the third block under all misalignment conditions did not meet the autocorrelation requirements; meaning that pupil size averaged across each trial did not correlate with the trial before. This was not due to an increase in pupil size variance (Figure 5), as the ANOVA run on pupil size variance did not show any significant differences across block (F(2,30) = 2.60, p = 0.09), misalignment (F(2,30) = 1.31, p = 0.29), or a significant interaction between the two (F(4,60) = 0.62, p = 0.65). This finding suggests that as the length of time using the sRVS increased, pupil size may became more stochastic and generally more independent of a homeostatic state.

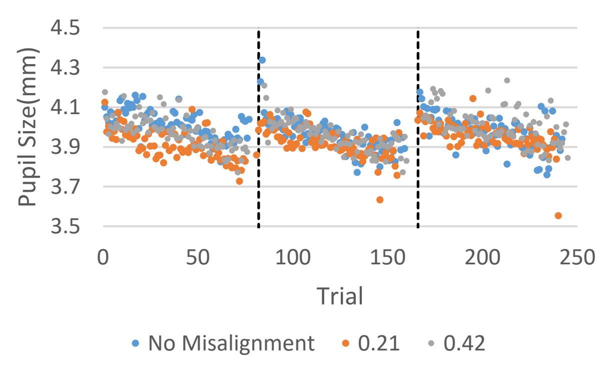

__Figure 4.__ Pupil size averaged across participants for each refueling trial where at least over half of the participants completed the trail. Dashed lines indicate the cutoff between blocks.

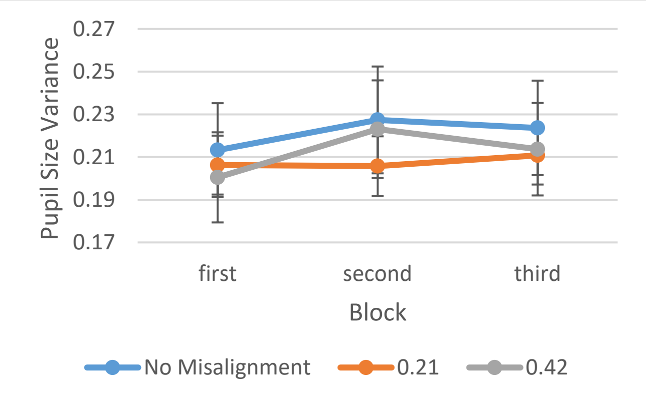

__Figure 5.__ The average pupil size variance for all three misalignment conditions and all three 55-minute blocks/session.

Out of the remaining three eye tracking outcome metrics, only one showed any significant changes. Horizontal vergence significantly decreased across block (F(2,30) = 3.59, p = 0.04), meaning. participants became less converged across the three-hour refueling sessions (see Figure 6). Though there was no effect of misalignment (F(2,30) = 0.19, p = 0.83), nor was there significant interaction (F(4,60) = 0.30, p = 0.88). In the event that absolute eye position was not reliable due to eye tracker calibration imprecision with the small vergence values, each value within one trial was normalized to the median value of that trial. These new values were then averaged across trials and participants for each condition (block and misalignment). The ANOVA showed no significant effect of block (F(2,30) = 2.07, p = 0.14), no effect of misalignment (F(2,30) = 2.61, p = 0.09), and no significant interaction (F(4,60) = 0.66, p = 0.62) (Figure 7).

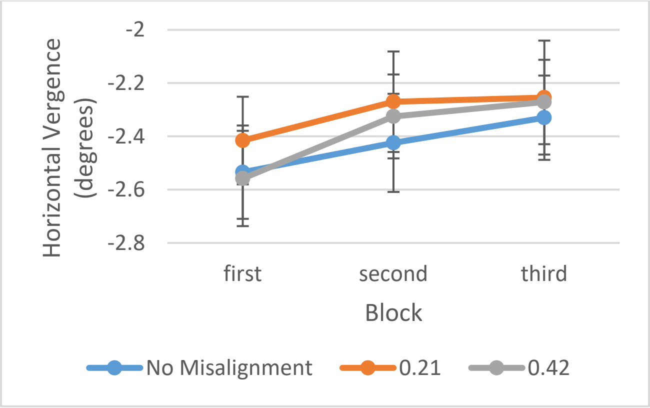

***Figure 6.** The average horizontal vergence for all three misalignment conditions and all three 55-minute blocks/session.*

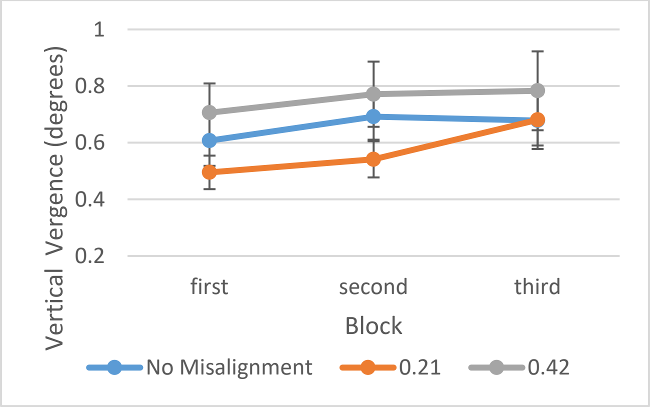

***Figure 7.** The average normalized vertical vergence for all three misalignment conditions and all three 55-minute blocks/session.*

There was no significant effect of block on saccade frequency ($F(2,28) = 1.62$, $p = 0.22$), misalignment ($F(2,28) = 1.31$, $p = 0.29$), nor was there a significant interaction ($F(4,56) = 0.65$, $p = 0.63$) (Figure 8). The saccade frequency analysis excluded two participants due to poor data quality.

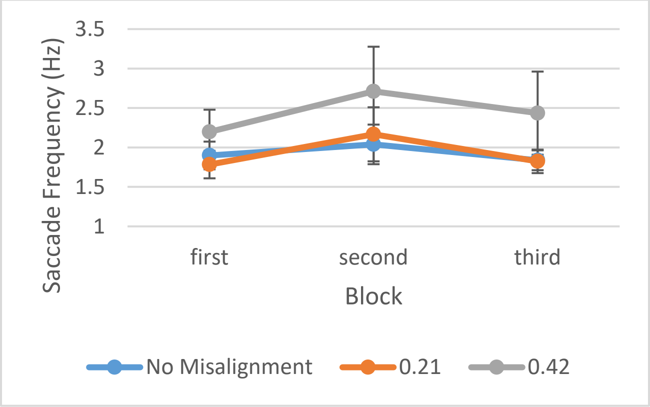

***Figure 8.** The average saccade frequency for all three misalignment conditions and all three 55-minute blocks/session*

Principal Component Analysis

The survey results were still only partially explained. The analyses of variance only showed some changes in oculomotor behavior over time, but the participants also reported eye strain with increased misalignment. We postulated that perhaps discomfort from misalignment was related to changes between these oculomotor behaviors. To capture the underlying factors of physiological performance a principal component analysis (PCA) was run on the eye tracking outcome metrics, comparing the no misalignment condition to the largest (0.42°) misalignment condition. Four principal components accounted for 79.8% of the variance. The loadings are shown in Table 3. We describe them as: saccade behavior, position stability, pupil behavior, and re-alert behavior. Their descriptions, loadings, and the eye tracking metrics that significantly contributed to each factor (asterisked) are listed in Table 3. PC 4, or re-alert behavior, likely represents an event where the participant realizes they are no longer concentrating and re-directs their focus back to the task.

Both saccade behavior and re-alert behavior decreased with vertical misalignment. This means that saccades were smaller and likely in a more condensed area with high vertical misalignment, while participants were slower to re-attend to the task at hand. Pupil behavior increased with vertical misalignment, indicating the pupil is larger and its size varies to a greater degree. Position stability showed no change with great individual variability (see Figure 9).

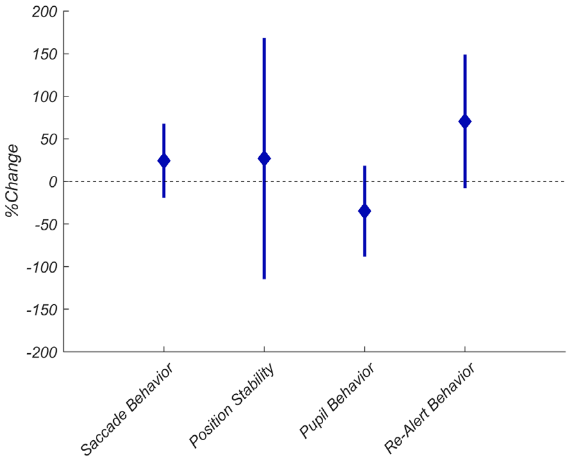

***Figure 9.** Four principal components resulting from PCA analysis and percent change with misalignment. Positive changes indicate the PCA value decreased with increased misalignment, and negative changes indicate the PCA value increased with increased misalignment.*

Table 3. The four principal components.

	PC 1	PC 2	PC 3	PC 4
Name	Saccade Behavior	Position Stability	Pupil Behavior	Re-alert Behavior
Insight	Large value means larger saccades	Larger value means more sporadic vergence stability	Larger value means larger, more sporadic pupil	Larger value indicates presence of “alerting” event
Variance Explained	28.9	25.1	14.3	11.5
Pupil Size	0.036	0.145	0.798*	-0.212
Pupil Size Variance	0.123	0.314	0.386*	0.726*
Saccade Frequency	-0.123	0.431*	0.128	-0.626*
Saccade Amplitude	0.446*	-0.203	-0.169	-0.062
Saccade Velocity	0.629*	0.057	0.019	-0.106
Saccade Velocity Peak	0.610*	0.048	0.034	-0.111
Vertical Vergence Stability	0.016	0.569*	-0.284	0.086
Horizontal Vergence Stability	0.044	0.570*	-0.295	0.038

Discussion

This experiment explored the effect of vertical misalignment of stereoscopic imagery on simulated aerial refueling task performance and online eye tracking metrics over three 3-hour periods. The task was performed at a simulated KC-46 boom operator station. Vertical camera misalignment values were chosen based on experimental field data and current guideline recommendations for tolerable vertical misalignment. Participants completed a subjective visual comfort survey three times per session, after each 55-minute refueling block.

The questionnaire results showed that participants were struggling with both the length of the sessions and with the increase in vertical misalignment. This was not reflected in the aerial refueling task performance. Even though participants were highly practiced, the time to make a successful connection with the receiver aircraft decreased across the three hours of refueling for all misalignment conditions.

Analysis of the individual online eye tracking outcome metrics showed some changes with time. Horizontal convergence decreased across the three hours of refueling, likely due to oculomotor fatigue of converging to the stimuli over such a long epoch. Interestingly, while there were no changes from one refueling block to another, pupil size significantly decreased across each block returning to its original size during the 5-minute break. This finding, and the magnitude of the size decrease were similar to those found in previous research [18]. Surprisingly, there were no changes in vertical vergence, even though the vertical misalignment of the imagery increased. This may indicate that participants were relying on sensory instead of motor fusion to combine the stereoscopic imagery, more likely with the small vertical misalignments used here. ARIMA analysis of pupil size across block showed an autocorrelation between trials during blocks one and two only. There was no correlation in the third block for any of the misalignment conditions, meaning that the pupil became stochastic in the third hour of refueling.

To continue the search for possible explanations of the visual fatigue with increased misalignment, we looked into changes in the relationships among oculomotor behaviors. A principal component analysis between the no misalignment and 0.42° misalignment conditions revealed four principal components: saccade behavior, position stability, pupil behavior, and re-alert behavior. Saccade and re-alert behavior decreased with increasing misalignment, suggesting participants made shorter saccades and that they were slower to re-attend to the task if any drift in attention or concentration occurred. Pupil behavior increased, signifying a larger, more sporadic pupil in the 0.42° misalignment condition. None of these components showed a change over time, confirming that these metrics are indicative of changes due to vertical misalignment and not the length of the task.

Conclusion

This work investigated the effects of operationally relevant vertical misalignment in a simulated stereoscopic remote vision system over a longer time period than usually studied. Aerial refueling task performance, eye tracking metrics indicative of visual stress, and visual comfort survey results were all evaluated as outcome metrics. Results showed users had visual strain and tiredness with both increased time and misalignment. This was not explained by performance; in fact, participants got better at the task. Both horizontal vergence and pupil size autocorrelation changed over time, likely indicative of fatigue. Considering relationships among oculometric behaviors revealed changes in combinations of eye tracking metrics caused by vertical misalignment. Surprisingly, changes in vertical vergence were not detected, suggesting sensory fusion of the misaligned stereoscopic imagery.

Acknowledgements

The views expressed are those of the authors and do not reflect the official views of the United States Air Force, nor the Department of War. Mention of trade names, commercial products, or organizations do not imply endorsement by the U.S. Government. This research was supported by USAF contract FA8650-21-C-6277 to KBR. Cleared for public release (AFRL-2026-0523).

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Author Biography

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