

# Oculomotor behavior in response to vergence-accommodation conflict

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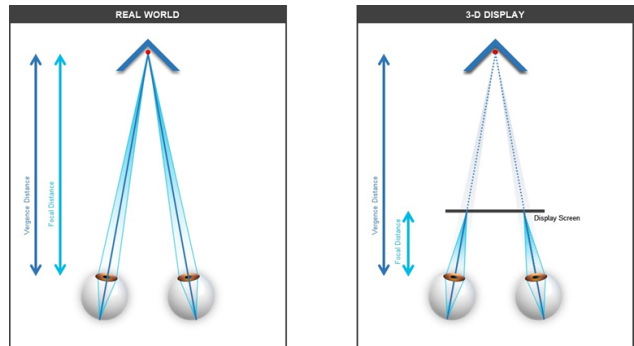
## Abstract

When viewing a stereoscopic 3D (S3D) display, the stimuli for binocular vergence (binocular disparity) and accommodation (defocus) are often in disagreement, leading to vergence-accommodation conflict (VAC). This is likely a significant source of discomfort and greatly affects the usability of such displays. One possible oculomotor strategy to mitigate the strain from VAC is to constrict the pupil, which serves to increase the depth of focus and reduce accommodative demand. The goal of this investigation was to analyze the relationship between by accommodation, vergence and pupil response while performing a precision depth task using an S3D display with varying degrees of VAC. Over the course of one-hour epochs, refractive error, vergence posture and pupil size were recorded at 50 Hz using an eccentric photorefractor. We found multiple strategies for mitigating VAC, including the dampening of the accommodative response and the recruitment of pupil miosis. Though this likely served to relax VAC, not all participants employed this oculomotor strategy, suggesting individual differences that may relate to general discomfort and usability.

## Introduction

During typical natural viewing of the three-dimensional world, the two eyes will make a disconjugate eye movement called vergence, in which the two lines of sight intersect on a target in depth, creating a single image. In order to focus the image, the intraocular lenses will make an eye movement called accommodation, in which they change shape to alter the optical power of the eye. These two eye movements are tightly linked in the brain [1], such that stimulus for vergence (binocular disparity) can drive an accommodation response and the stimulus for accommodation (defocus) can drive a vergence response. Because the stimulus demands for vergence and accommodation are usually in agreement, this relationship is generally synergistic (Figure 1; left). However, when using a stereoscopic 3D (S3D) display, the binocular disparity cue is often driven by scene content, while the accommodative demand rests at the plane of the display (Figure 1; right), placing the two cues in conflict. This situation is called vergence-accommodation conflict (VAC) or VA mismatch and is believed to severely limit the usability of S3D displays [2, 3].

Though it is a widely accepted as principal human factors concern in S3D applications, few studies have actually measured the V and the A in the VAC. Seemiller et al. [4] found a tight relationship between vergence and the pupil miosis during VAC, which they hypothesized serves to reduce accommodative demand (though they did not directly measure the accommodative response). Yang and Sheedy [5] found an increase in accommodative



**Figure 1.** Vergence and accommodation demands in agreement (left) such as during natural viewing and in conflict (right) such as in an S3D display

instability while watching a 3D movie relative to 2D viewing and Koulieris et al. [6] suggested instability and inaccuracy may be direct sources of discomfort. Furthermore, Spiegel and Erkelens [7] showed reduced accommodative dynamics and temporal lag in the presence of VAC. Yego et al. [8] also found a lingering influence on accommodative behavior after exposure to VAC (but did not measure accommodation during those periods).

One reason for the lack of oculomotor data in VAC is the difficulty in objectively measuring accommodation. Experimenters often rely on self reports of defocus and blur, slow and specialized clinical methods, or bulky, expensive laboratory grade equipment. However, the technology used to measure accommodation in humans has improved. For example, the PowerRef3 (PlusOptix GmbH, Nuremberg, Germany) uses eccentric photorefraction to measure relative changes in optical power of the eye as a proxy for the accommodative response. It reports eye position, optical power and pupil size at 50 Hz. Though designed as a clinical tool for high fidelity screening of developmental refractive problems, it has been adapted to study dynamic oculomotor responses in a number of scientifically interesting settings [9, 10, 11].

In this experiment, we used the PowerRef3 eccentric photorefractor to measure oculomotor behavior in the presence of high degrees of VAC. Participants performed a simulated aerial refueling task at 3 different viewing distances on an S3D display for one-hour epochs along with a control condition performed on a 2D display. We found behavioral changes in the accommodative response both during and after each session relative to the control condition. We also found several individualized strategies, including pupil constriction, which may be indicative of a strategy to alleviate the discomfort due to VAC.

## Methods

### Participants

Six pre-presbyopic individuals participated in this study, including three authors (ESS, EO, LK). Participants provided informed consent through documents approved by the Air Force Research Laboratory Institutional Review Board, protocol numbers FWR20170095H and FWR20130074H. The study adhered to the tenets of the Declaration of Helsinki.

### Display

Stereoscopic imagery was presented using a Sony VPL-GTZ280 4k laser projector, with a resolution of 4096 x 2160 pixels. Dichoptic imagery was presented using temporal interlacing, such that left eye and right eye imagery were presented on alternating frames at 60 Hz. Corresponding shutter glasses worn by the participants were synchronized with the interleaved frames of the projector. The 3D environment was rendered using a multi-channel FlightSafety Vital 1150 image generator system. These two channels were fed into a video combiner box and OBS Studio was used to format the video into a single stereo image and projected onto the screen.

Participants were seated in a chair and positioned so that they could comfortably rest on a chin rest. The aerial refueling task performed is described in detail elsewhere [12]. They were instructed to perform the task as quickly and accurately as possible and given ample practice time prior to the beginning of the experimental session. They controlled the simulated refueling boom using two flight control sticks. One controlled the azimuth and elevation of the boom, while the other controlled the extension. Because it was not part of the scope of this project, refueling performance data is not presented here.

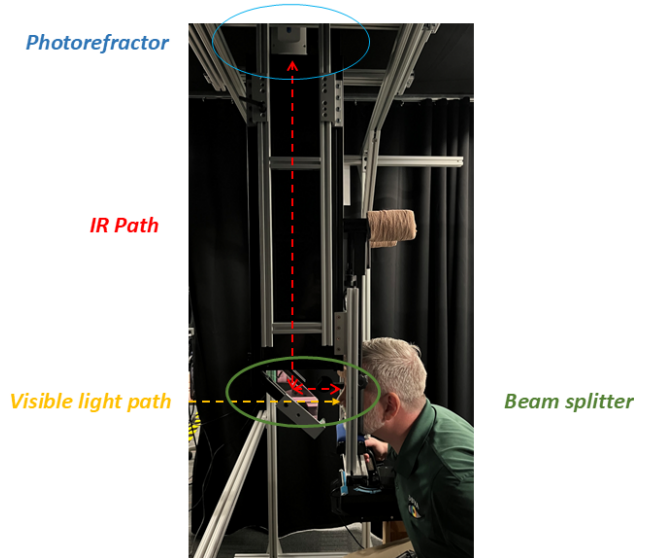
In order to manipulate the level of VAC while minimizing confounding changes in the scene content, we changed the viewing distance; this served to change the focal demand of the screen. Three viewing distances were chosen: 0.5 m, 2.0 m, and 4.0 m. A fourth control condition was run at 2.0 m, but with 2D imagery, in which both eyes received the same imagery without horizontal disparity. VAC is the difference of demand between accommodation and vergence in diopters (D). Computed from the center of the refueling window in the scene, these conditions yielded VACs of 1.91 D, 0.48 D, and 0.24 D, plus 0 D for the control condition. Parameters for each condition are listed in Table 1.

**Table 1 - Viewing Conditions**

Viewing Distance (m)	VA Mismatch (diopters)	Display FOV (°)	Luminance (cd/m <sup>2</sup> )
0.5	1.91	82.70	1.78
2.0	0.48	24.81	20
4.0	0.25	12.55	78
2.0*	0	24.81	20

\* 2D condition

No attempt was made to eliminate changes in other depth cues. The display width was constant so the angular display field-of-view (FOV) necessarily changed in each viewing condition. Because of this, we changed the brightness level in each condition to minimize the pupillary light reflex. We computed the luminance required for each FOV that best maintained 4.4 mm pupil for a 35-year old viewer [13]. Luminance was adjusted using neu-



**Figure 2.** Side view of the measurement apparatus. Visible light from the display is transmitted through a beamsplitter, while infrared light from the photorefractor reflects to the observer's eyes.

tral density filters. Participants refueled for one-hour epochs for each condition, with only one session per day.

### Measurement Apparatus

To measure vergence, accommodation and pupil size we used a PowerRef3 eccentric photorefractor (PlusOptix, Nuremberg, Germany). This commercially available device records eye position and relative optical power at 50 Hz. We suspended it above the participant with an optical path of approximately 1 m to the front surface of the eyes (Figure 2). The device emits near infrared (IR) light that reflects off the participant's retina. We added a hot mirror beam splitter on the optical path that would reflect IR light to and from the photorefractor, while allowing the user to see visible light transmitted from the display through the beam splitter. The beam splitter was situated approximately 5 cm from the chin rest. The entire apparatus was constructed using 80/20 aluminum framing and was on wheels to allow for quick movement between viewing distances relative to the screen. It was also height adjustable relative to the screen, so the user could set it at a comfortable height prior to the start of the trial, while the optical path between the photorefractor and the eyes remained fixed.

The PowerRef3 does not have a native calibration procedure and thus a manual calibration is necessary for estimates of absolute gaze position and refractive power [14]. To do this, a near infrared filter was placed in front of the right eye to occlude visible light, while still allowing the photorefractor to record data. Then hand held lenses of known power (-2.0 D, -1.0 D, +1.0 D, +2.0 D, +3.0 D and +4.0 D) were placed in front of the occluded eye for approximately 5 second periods each and flagged in the data file. The visual stimulus was fixed at 2 m. Because the visual input did not change, one could assume the change in refractive power recorded was due exclusively to the added lens. Thus, a calibration offset could be estimated by computing the linear relationship between the added lens power and measured power of the occluded eye. A similar procedure was done for gaze position with four base-out prisms (4 prism diopters (pd), 8 pd, 12 pd and

16 pd) and measuring the gaze deflection caused by the prism. After calculating these two calibration factors, accommodation and vergence data were then adjusted by simply multiplying raw data by the calibration factor. The calibration procedure was done once per individual and analysis was completed offline.

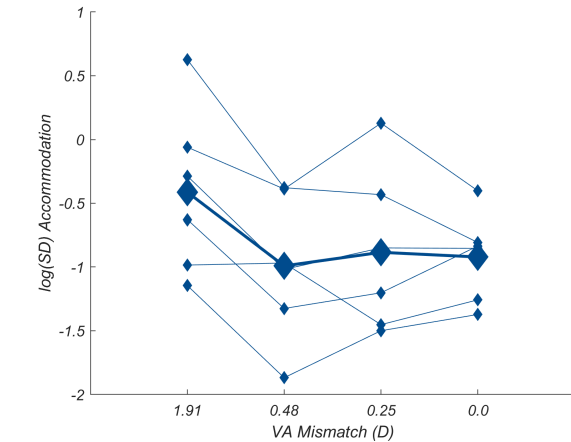
## Results

All six participants provided usable data in all conditions and provided usable calibration protocols. Examples of two one-hour sessions (1.91 D and 0.48 D) from one individual are shown in Figure 3.

One major human factors concern with VAC is the rapid fluctuation of accommodative state [15, 5]. Though vergence is driven by disparity in the scene, the accommodative demand should be static, and any fluctuation (such as fluctuation driven by the disparity in the scene) may be deleterious in both a motor and sensory sense. To address this we computed the standard deviation of the accommodation response in all conditions. The log standard deviation for each participant and the global mean of those standard deviations is shown in Figure 4. There was a statistically significant effect of VAC magnitude (repeated measures ANOVA:  $F = 5.49, p = 0.01$ ). Correspondingly, we analyzed the fluctuation of the vergence response (5 and found a similarly high standard deviation at the highest VAC magnitude (repeated measures ANOVA:  $F = 79.86, p < 0.001$ ).

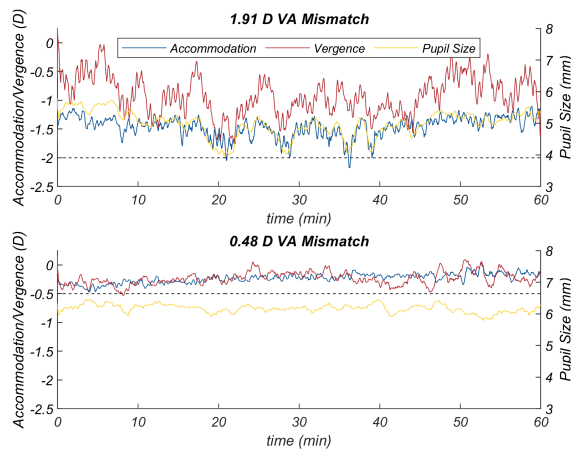
We also explored other oculomotor behaviors that may mitigate the impact of VAC. For example, pupil miosis may increase the depth of focus and reduce accommodative demand. We computed the mean pupil size across conditions (Figure 6). We found a statistically significant effect of VAC magnitude (repeated measures ANOVA:  $F = 8.04, p = 0.002$ ). Pupil size was smallest at the highest level of VA mismatch. Interestingly, the size of the pupils was also slightly reduced on average during the 2D control condition.

We additionally tested for lingering effects or adaptations in the normal accommodative response. To assess these, we implemented a separate test of accommodative amplitude both before

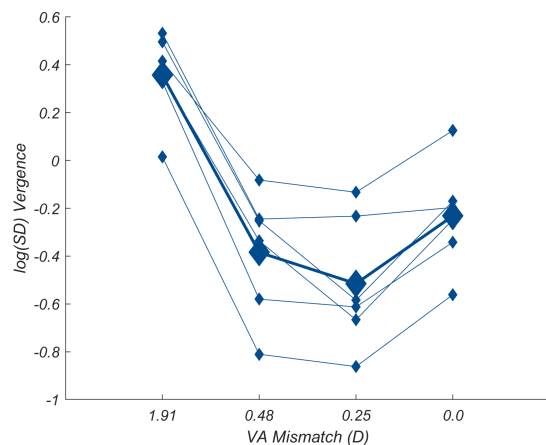


**Figure 4.**  $\log(\text{Standard Deviation})$  of accommodation for each subject across conditions (small diamonds) and the global mean of standard deviations across subjects (large diamonds).

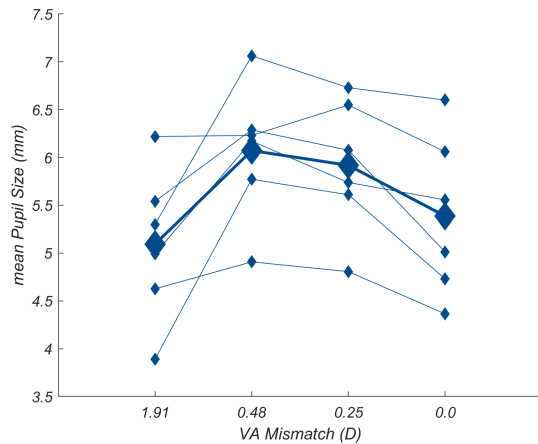
and after each session. In this test, participants viewed a target presented on an LED screen mounted on a motorized track. The target was a high-contrast 2 cycle per degree square wave grating, drawn using MATLAB and PsychToolbox [16, 17]. The physical distance of the screen cycled between 1.9 m and 0.33 m (0.53 D and 3.03 D). It stayed at these distances for 10 seconds before cycling to the next distance. The cycle repeated 4 times. The physical size of the stimulus updated on each frame according to the position of the motor so that it always subtended 2 degrees. Accommodative amplitude was measured as the gain of the accommodative response between the near and far viewing distances. We computed the percentage change in the accommodative gain before and after each one-hour session (Figure 7). There was a statistically significant effect on the change in accommodative amplitude as a function of VAC (repeated measures ANOVA:  $F = 6.79, p = 0.004$ ).



**Figure 3.** Example raw data recorded from one individual in two VAC conditions: 1.91 D VA mismatch (top) and 0.48 D VA mismatch (bottom). Accommodation, vergence (left y-axis) and pupil size (right y-axis) are shown over the entire one hour session. The focal demand of the screen is represented by the hashed line.



**Figure 5.**  $\log(\text{Standard Deviation})$  of vergence for each subject across conditions (small diamonds) and the global mean of standard deviations across subjects (large diamonds).

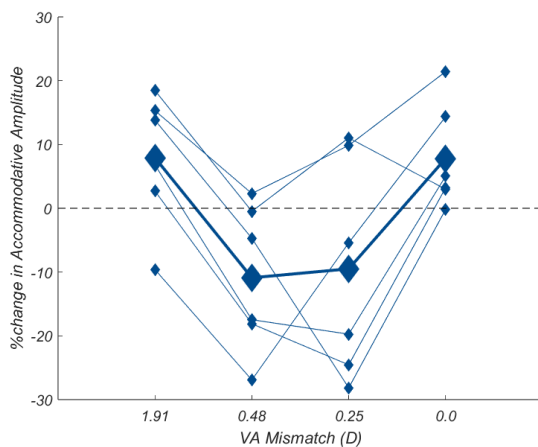


**Figure 6.** Mean pupil size (mm) for each subject across conditions (small diamonds) and the global mean across subjects (large diamonds)

## Discussion

Though VAC is a well-known problem limiting the usability of S3D displays, few studies have actually measured the oculomotor elements leading to the conflict (e.g., [4, 5, 6, 7, 8]). This is likely because of the difficulty of measuring accommodation in more applied settings. Here we describe an apparatus that uses a commercially-available eccentric photorefractor that records accommodation, vergence and pupil size of viewers interacting with a remote S3D display. We manipulated the degree of VAC by changing the viewing distance, which led to changes in oculomotor behavior that may be influencing the discomfort related to VAC.

Our main finding was an increase in accommodative instability at the highest level of VAC. Because the focal demand of the display is fixed, there should be little fluctuation in accommodation. In fact, humans are known to lag slightly behind their true accommodative demand [18], which can be seen in Figure 3.



**Figure 7.** Percentage change in accommodative gain before and after the session. A larger value means an increase in accommodative gain after the session. Small diamonds are individual subjects and larger diamonds are the group mean. The hashed line represents no change in accommodative gain.

Any deviation from the focal demand will either be perceived as blur or must be overcome through a motor correction (or both), which may contribute to discomfort [5]. Additionally, the pattern of instability shown here is consistent with Shibata et al., [3] who predict VAC greater than 0.5 D may lead to discomfort. VAC less than 0.5 D tested in this experiment did not show elevated instability relative to the 2D control condition.

We also identified pupil miosis as potentially an important adaptation to VAC. We controlled the lighting of the S3D to minimize the effect of the pupillary light reflex [13], in order to isolate the pupil's relationship to the near triad. Pupil miosis is also neurally linked to accommodation and vergence [19]. It can serve to increase the depth of focus of the eye and reduce accommodative demand by either reducing the perceived blur in the user or reducing the motor demand of the accommodative system [20, 21]. Thus, in extreme levels of VAC, the pupil on average may be constricting to alleviate some of the conflict. An alternative interpretation however is that it may be a stress response related to the discomfort itself [22], and further investigation is required to delineate these possibilities.

Yego et al. [8] discovered a small reduction in the accommodative response after performing a manual virtual precision depth task in an AR environment with VAC. We replicated those results here, showing a significant reduction in accommodative gain following one-hour of exposure to low levels of VAC (0.48 and 0.25 D). Interestingly, we found the opposite effect at high levels of VAC (1.91 D); most users actually increased their accommodative gain. One possible explanation for this is that the accommodative system may simply be in a primed state, with phasic neurons already active in order to overcome the vergence influence from the VAC [23]. Conversely, the small magnitudes of VAC may be lulling the accommodative response into a sluggish state and a reliance on tonic neurons, reducing accommodative gain. However, this fails to account for a slight increase in accommodative gain in the 2D control condition, and further investigation is required to consider whether a single model can explain both of these results.

## Conclusion

To fully understand the limiting properties of VAC, one must understand the component oculomotor behaviors by measuring vergence, accommodation and pupil size. Here we described an apparatus for measuring all three during active viewing of a remote S3D display and presented multiple oculomotor responses to varying degrees of VAC, including accommodative fluctuation, pupil miosis and changes in accommodative gain. Future research should continue to investigate how these factors interact with the actual self-reported discomfort and usability concerns related to VAC to link these oculomotor behaviors as either a cause of discomfort or a response to discomfort. Significant technological advances will also be necessary to employ this data collection strategy in wearable S3D displays.

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ficial views of the United States Air Force, nor the Department of Defense. Mention of trade names, commercial products, or organizations do not imply endorsement by the U.S. Government. This work is cleared for public release: AFRL-2026-1277.

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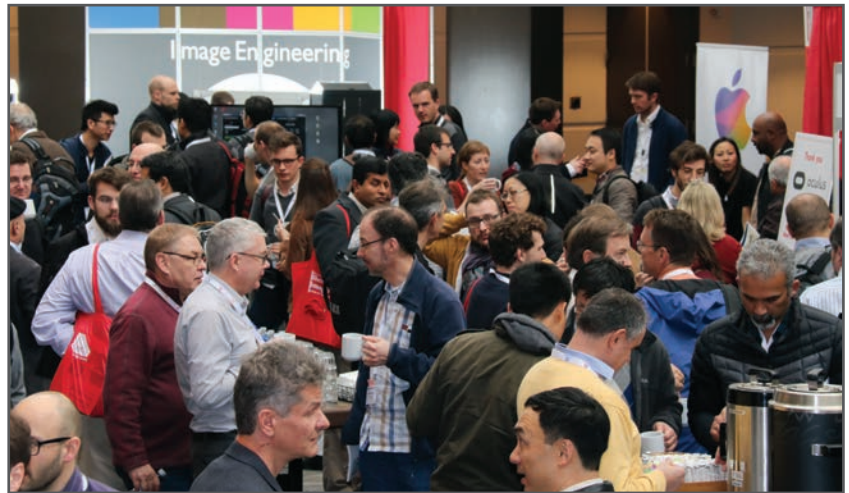
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