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EFFECT OF COLOR FILTER LENSES ON COLOR VISION SCREENING TESTS

KBR LABORATORIES, INC.

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PREFACE

The views presented herein are those of the authors and do not reflect views of the United States Air Force, the Department of War (DoW), or any other government agency. All studies described within this report were accomplished in accordance with Air Force Research Laboratory Institutional Review Board-approved research protocols. Appearance of, or reference to, any commercial products or services does not constitute DoW endorsement of those products or services.

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1.0 SUMMARY

There is significant variation in human color vision phenotypes. In the extreme, this variation can lead to color perception deficits, known as color vision deficiency (CVD). CVD can impact the safety of operations in a number of transportation-related industries, prompting the implementation of color vision-related occupation safety screening standards. In the aviation community, both civilian and military authorities require adequate color vision metrics (though specific tests used vary). In response, a number of commercially available products have been designed to help individuals with CVD pass color vision screening tests, with mixed results. This investigation addresses one such device, the Colormax ColorCorrection System (Colormax, Baltimore, MD), a form of color-filtering eyewear. To test the efficacy of this device, we obtained Colormax lenses custom fit for 6 individuals with CVD and measured their color vision status on a number of different screening tests. For 2 deuteranomalous individuals, the Colormax system led to improvement on the screening tests. For 4 protanomalous individuals, the system improved the scores on the R-Cone (red) subtest but led to failure on the G-Cone (green) subtest. Further, we tested these individuals on a simulated aviation task involving color discrimination and found little or inconsistent improvement with the addition of the lenses. These results suggest that this particular color-correcting lens system leads to inconsistent improvement in color vision screening tests with results that do not broadly translate into the simulated cockpit.

2.0 BACKGROUND

Human color vision is mediated by cone photoreceptors with different, overlapping spectral sensitivities. In typical trichromatic vision, signals from short- (blue), medium- (green), and long- (red) wavelength sensitive cones, commonly referred to as S-, M-, and L-cones (or B-, G-, and R-cones), are compared through post-receptoral opponent mechanisms that support discrimination along red-green, blue-yellow, and luminance axes. This trichromatic encoding allows observers with normal color vision to distinguish many stimuli that differ in spectral composition, including color differences in natural scenes, displays, signs, and signal lights.

CVD is an umbrella term encompassing a spectrum of inherited and acquired impairments in color discrimination. In the present report, CVD refers primarily to congenital red-green CVD, which is the most common form and is usually associated with X-linked variation in the genes encoding the L- and M-cone photopigments. Congenital CVD includes anomalous trichromacy, in which three cone classes are present but one photopigment has abnormal spectral sensitivity, and dichromacy, in which one cone class is functionally absent. Protanomalous defects affect the L-cone pathway and may reduce sensitivity to long-wavelength light, causing reds to appear darker. Deuteranomalous defects affect the M-cone pathway and impair red-green discrimination without the same characteristic darkening of reds but darkening of green stimuli instead. Tritan defects, involving the S-cone pathway, and monochromatic forms of color vision loss are comparatively rare.

Recent large-scale epidemiological evidence estimates the global prevalence of congenital CVD among children and adolescents at approximately 2.6 percent (%), with substantially higher prevalence in males than females due to the X-linked inheritance pattern of most red-green deficiencies (Jeong et al., 2025). Population-specific estimates are often higher, with frequently cited values approaching 8% of males in some Northern European ancestry groups (Almustanyir, 2025). These higher values should be interpreted as population-specific estimates rather than global averages.

CVD is operationally important because many transportation, military, medical, and aviation systems use color as a primary or partially redundant information channel. In some cases, two stimuli that are readily distinguishable to observers with normal color vision may be difficult or impossible for observers with CVD to distinguish, particularly when the stimuli differ primarily along the affected chromatic axis. These stimuli may be described as confusable colors, and in carefully specified cases may be metameric for a color-deficient observer. Such confusions are especially relevant when color is used to indicate state, warning level, direction, or required action.

Historically, transportation industries were among the earliest domains to develop occupational color vision standards because rail, maritime, road, and aviation operations rely on colored signal lights. Railway operations require accurate interpretation of red, yellow, green, and white signals, and prior work has supported the continued use of color vision standards in safety-critical transport occupations (Cole & Vingrys, 1982; Hovis & Oliphant, 2000; Vingrys & Cole, 1988). Road traffic signals are also affected by CVD; color-deficient observers can show slower response times and increased errors when identifying simulated traffic lights, with performance varying by CVD type and severity (Atchison et al., 2003).

Aviation presents several analogous color-critical tasks. Exterior aircraft position lights use aviation red, aviation green, and aviation white to communicate aircraft orientation, and these colors are specified by regulatory chromaticity limits. Approach path guidance systems also use color-coded information. For example, interpretation of Precision Approach Path Indicator (PAPI) lights can be degraded in pilots with deficient color vision, and the FedEx Flight 1478 investigation raised concerns that passing legacy lantern tests may not ensure reliable interpretation of PAPI signal colors (Cole & Maddocks, 2008; National Transportation Safety Board, 2004). Within the cockpit, color-coded symbology can also be problematic: observers with CVD have shown reduced speed and accuracy when using red-green color-coded symbols representative of modern aircraft displays, particularly when the task depends on chromatic rather than luminance contrast (Gaska et al., 2016). Thus, a number of industries require color vision testing and maintenance of minimal color vision standards.

The growing use of augmented reality (AR) and other optical see-through (OST) display systems introduces additional challenges for color-coded information. In OST displays, virtual imagery is additively combined with light from the physical environment. As a result, the perceived luminance, chromaticity, and contrast of displayed symbology can vary with the background scene. Prior work has shown that AR interface colors can become washed out as background luminance increases and can shift depending on the color of the real-world background against which they are viewed (Gabbard et al., 2013). More recent work in an aviation-relevant OST helmet-mounted display (HMD) flight simulation environment further demonstrated that color-coded symbology can affect response time, accuracy, and eye behavior, and that increasing the number of displayed colors may reduce performance for both color-normal and color-deficient observers (Erickson et al., 2026). These findings suggest that a symbol color that is discriminable on one background may become difficult to detect or identify on another, especially when the relevant contrast falls along an impaired chromatic axis.

For these reasons, many safety-critical industries require color vision screening and maintain minimum color vision standards. These standards are intended not simply to diagnose CVD, but to determine whether an individual has sufficient color discrimination for the visual tasks required in a given operational environment. In the aviation community, both civilian and military agencies have adopted aeromedical screening standards related to cone specific contrast thresholds (Rabin et al., 2011) and other types of higher order color processing, like pseudoisochromatic plates (PIP)

(Federal Aviation Administration, 2025; *USAF Medical Standards Directory*, 2021), that have been deemed critical for safe aviation operations.

Concurrently, a number of commercially available color-filtering spectacles and contact lenses have become available with claims to help pass occupational color vision screening tests. Many of these devices operate along a similar filtering mechanism, known as a “notch filter”, which selectively transmits specific wavelengths to reduce metameric stimuli for CVD. For example, the Colormax system guarantees improvement on color vision tests (*Colormax - Color Vision Correction*, 2026). However, notch filtering methods have had mixed results on color vision screening tests (e.g., Almustanyir et al., 2026; Almutairi et al., 2017; Somers et al., 2024; Varikuti et al., 2020). Furthermore, the use of color correcting lenses designed to pass CVD screening tests may not translate to operational safety in aviation related tasks. Because the USAF and most other military and commercial aviation organizations allow some level of color deficiency for pilots, methods of potentially improving color discrimination performance, such as color filters or customized color displays, are of significant interest.

The purpose of this investigation is to evaluate a specific form of color correcting eyewear, Colormax lenses, on individuals with red-green CVD in a clinical setting and in a simulated operational setting. Our main research questions are as follows:

- What is the underlying mechanism of the color filter of the Colormax lenses?
- Do Colormax lenses affect user performance in clinical color vision tests?
- Do Colormax lenses affect user performance in flight simulation?

The remainder of this paper describes our methods for addressing the above research questions, including obtaining six pairs of individually fit Colormax glasses, evaluating the spectral transmittance of each pair of lenses, evaluating their effects on clinical color vision testing, and finally exploring their effects on user performance in a flight simulation.

3.0 METHODS

3.1 Participants

Six male adults (ages 23-46 years old, mean 36, standard deviation 10) were recruited to be fit with individualized color correcting eyewear through the Colormax system. All participants were previously confirmed to be protanomalous or deuteranomalous based on the Konan Medical ColorDx CCTHD Cone Contrast Test (CCT) scores. Participants scoring less than 75 on either the red or green (L-cone or M-cone) subtests on the Konan were considered eligible for the study. The sample presented in this work included two deuteranomalous and four protanomalous participants. Participants were not professional pilots. Participants signed informed consent documentation approved by the Air Force Research Laboratory Institutional Review Board (Protocol numbers FWR20170095H and FWR20190044H) and were compensated for their time and travel. The study adhered to the Tenets of the Declaration of Helsinki.

3.2 Lens fitting and samples

Participants traveled to Baltimore, Maryland for on-site consultation and evaluation by Colormax personnel, who conducted initial color vision testing and fit each participant with individualized Colormax lenses through proprietary methodologies. Plano lens spectacle frames were purchased with the Colormax filters for each individual and shipped to the Operational Based Vision Assessment (OBVA) laboratory for testing.

One additional protanomalous observer was recruited to complete the color vision testing battery using the Colormax lenses from the participant whose baseline color vision test results most closely matched their own CVD profile. This participant was included to provide an additional preliminary estimate of whether Colormax-associated changes in test performance generalized beyond the individual for whom the lenses were originally prescribed. Additional commercially available color-filtering lenses were acquired for similar evaluation including all five models available from Pilestone (Pilestone, Inc., Philadelphia, PA) and one model from EnChroma (EnChroma Inc., Berkeley CA). Brands, lens names, intended user populations, and lens types are summarized in Table 1.

Table 1. Commercially available color filtering lenses

Device	Vendor	Commercial Availability	Lens Types
ColorCorrection System	Colormax (Baltimore, MD)	Requires consult including a full eye exam and battery of color tests.	Lenses are individually fit for customized glasses or contact lenses.
Pilestone	Pilestone Inc. (Philadelphia, PA)	Available online	Five types of glasses lenses are available: Model A for mild–intense red-green deficiency in bright indoor/outdoor light; B for intense red-green deficiency in bright indoor/outdoor light; C for mild–intense red-green deficiency for use indoors; D for protan use indoors; E for tritan use in bright indoor/outdoor lighting.
EnChroma	EnChroma Inc. (Berkeley, CA)	Available online	Indoor universal red-green.

3.3 Spectral Transmittance Measurements

The spectral transmittance of each lens was measured using a SpectroCal MK2 (Cambridge Research Systems, Rochester, UK) spectroradiometer, calibrated by the manufacturer and positioned 50 centimeters (cm) from a broadband halogen light source (XG-1025 Performax Halogen Work Light, 250 Watt (W), 60 Hertz (Hz)). Lenses were positioned normal or approximately normal to the aperture of the spectrometer and light source, with the spectrometer positioned at the optical center of the lens. Because the lenses themselves were plano, any non-extreme deviation in the angle of incidence was not expected to have a large effect on the spectral

transmittance. All measurements were taken through the left lens of the Colormax glasses. For each measurement, the spectral power distribution at each integer wavelength between 380 nanometer (nm) and 780 nm of the light source was first measured directly. The measurement was then repeated from the same position with the color-filtering lens placed between the light source and the spectrometer. Lens transmittance was calculated as a percentage of light transmitted by the filtering lens relative to the light source.

Spectral measurements were repeated 20 times for each lens and averaged prior to calculating spectral transmittance. The resulting transmittance functions were used to compare the spectral filtering characteristics of the commercial lenses and to identify broad regions of wavelength attenuation relevant to color vision testing and simulator performance.

3.4 Color Vision Tests

Each participant completed a battery of color vision tests with and without the Colormax lenses; Pilestone and Enchroma lenses were not included in this assessment. The color vision tests are listed in Table 2. The test battery included the Konan ColorDx CCT HD, Innova Rabin CCT, Waggoner Federal Aviation Administration (FAA) Color Vision Test Battery, NCI OcuTest, and Colour Assessment and Diagnosis (CAD) test. Of these tests, only the Innova Rabin, the CAD, and the Waggoner are currently approved for use in FAA color vision screening. For these tests, participant pass/fail criteria were set to the FAA's standards (FAA September 9, 2025). The Konan and NCI color tests were included for research comparison but are not currently acceptable tests for FAA color vision screening. For the Konan, pass/fail criteria were set using Konan Medicals guidelines for use with the Konan CCT, and for the NCI OcuTest, the pass/fail criteria for the United States Air Force were used. Table 2 depicts the pass/fail criteria for each test.

The Innova Rabin CCT and NCI OcuTest were performed in their default monocular testing modes, with one eye covered at a time (right-eye only or *oculus dexter* (OD) or left-eye only or *oculus sinister* (OS)). To simplify the results and analysis, and since most observers are right eye dominant (Bosten et al, 2015), only OD results were used for this analysis. Further, there was only one discrepancy in test outcome between the eyes for one tested participant (participant 1 in the NCI OcuTest data). The raw color vision test results for each participant (and each eye where applicable) are included in the appendix. The Konan ColorDx CCT HD, Waggoner FAA Color Vision Test Battery, and CAD were performed binocularly with both eyes open (*oculus uterque*, OU). For each participant, testing was completed once without the Colormax lenses and once while wearing the Colormax lenses.

One limitation of this approach is that it does not account for normal test-retest variability in repeated color vision measurements. Consequently, the observed effect of the Colormax lenses is confounded with normal measurement variability, and changes in test scores or pass/fail outcomes should be considered preliminary. Test-retest reliability has previously been characterized for the Innova, NCI, and Konan tests (Winterbottom et al., 2019); however, these reliability estimates describe the expected variability of repeated measurements and cannot determine whether a change observed for an individual participant in this study resulted from the lenses or from normal test-retest variation. Repeated measurements within each lens condition would be required to better separate these effects. Furthermore, test-retest variability is also a constraint in fielded color testing devices that is not easily controlled and thus provides a layer of ecological validity in this experiment; for the lenses to improve screening performance they must overcome both CVD and testing limitations.

Participants were randomly assigned to one of two test-order groups: participants in Group 1 completed testing without the Colormax lenses first, whereas participants in Group 2 completed testing with the Colormax lenses first. Masking of participants and test administrators was not feasible because the Colormax lenses produced an obvious change in the appearance of the visual scene. Potential expectation and observer effects were therefore mitigated through standardized test administration and scoring procedures.

Table 2. Color vision tests used to assess CVD

Abbreviation	Test	Manufacturer	Tested Eye	Pass/Fail Criteria
Konan	ColorDx CCT HD	Konan Medical (Irvine, CA)	OU	≥ 75 (red, green, and blue)
Innova	Rabin CCT	Innova Systems (Burr Ridge, IL)	OD/OS	≥ 55 (red, green, and blue)
Waggoner	Waggoner FAA Battery	Waggoner Diagnostics (Bentonville, AR)	OU	General (≥ 21 of 25) Tritan (≥ 10 of 12) OR Protan (≥ 20 of 32) Deutan (≥ 20 of 32) Tritan (≥ 10 of 12)
NCI	NCI OcuTest	NCI Vision Systems (Burr Ridge, IL)	OD/OS	≥ 55 (red, green, and blue)
CAD	Colour Assessment & Diagnosis	COL-AEGLIA Institute for Occupational Vision (Lelystad, Netherlands)	OU	RG – (≤ 1.7 if normal, < 6 if Deutan, < 12 if protan) BY – (< 2.4)

3.5 Operational Task

In addition to standardized color vision testing, participants completed an operational flight simulation designed to evaluate whether any changes in color vision screening performance translated to task performance in an aviation-relevant display environment. The simulation was conducted using the Operational Based Vision Assessment Laboratory's EXtended Reality Experimental Simulator (XRES), a flight simulator research platform that synchronizes imagery across an OST head-mounted display, a head-down display (HDD), and out-the-window (OTW) scene displays (Erickson et al., 2026; Seemiller et al., 2022).

Participants wore an SA-62/S OST AR HMD (Vision Products, Los Gatos, CA) while seated at the simulator controls. The simulator also included a HDD, and five large OTW displays that depicted the virtual environment outside the participant's aircraft (Figure 1). The display models, resolutions, field of view, and viewing/focal distances are shown in Table 3. Additionally, display metrology data including luminance, chromaticity, and gamma are included in the appendix. Participants controlled the simulated aircraft and completed task responses using a Logitech X56 hands-on-throttle-and-stick (HOTAS) control interface. The HMD's binocular vergence distance was calibrated to 2.5 meters (m) to match the OTW displays. The manufacturer specifies a nominal optical focal distance of 4 m. Exploratory post-study measurements yielded focus demands of approximately -0.25 to -0.50 diopter (D), consistent with a beyond-infinity focus setting under the measurement calibration. Sine-grating and full-field broadband analyses suggested interocular best-focus differences of approximately 0.25 – 0.38 D. These estimates remain preliminary.

Table 3. Simulation display specifications

Display	Manufacturer, Model & Size	Resolution	Field of View	Viewing/Focal Distance (m)
OTW	LG OLED83G4WUA 83"	3840x2160	120x41 (combined)	2.5
HDD	Acer Nitro XV2 27"	2560x1440	44x25	0.75
HMD	Vision Products SA62/S	1920x1200	55x33	4



Figure 1: Over-the-shoulder view of the XRES simulation

3.5.1. Experimental Design

The simulator experiment included two independent variables: Colormax lens condition and symbology color set. The Colormax lens condition consisted of two levels: lens absent and lens present. The symbology color set also consisted of two levels: monochrome green and primary red-green-blue (RGB). These variables were evaluated in a 2×2 full-factorial design, resulting in four total simulator conditions, as shown in Table 3.

The monochrome green color set served as a control condition. In this condition, all task-relevant symbology presented on the HMD and HDD was rendered in green, requiring participants to rely on redundant non-color encodings, notably symbol shape, to complete each trial. The primary RGB color set consisted of red, green, and blue symbology and was included to evaluate performance when task-relevant information could be conveyed by chromatic differences (Figure 2).

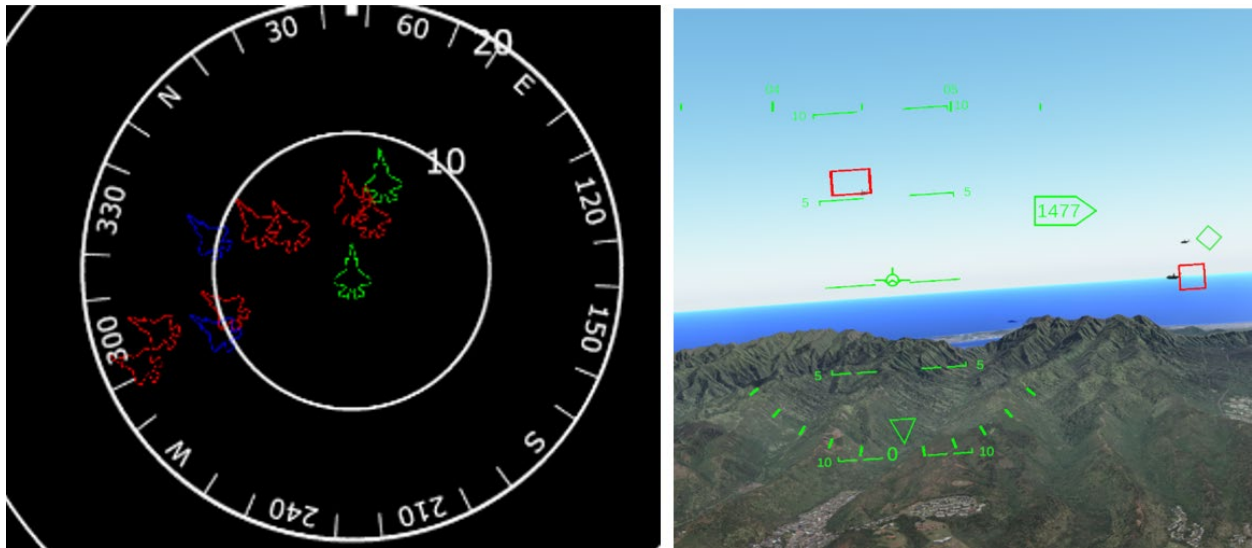


Figure 2: XRES HDD symbology (left) and the corresponding HMD symbology (right) in the RGB test condition. The target aircraft for this trial is green

In the Colormax lens conditions, participants wore the Colormax spectacles underneath the optical elements of the HMD. This configuration allowed the lenses to filter imagery from the HMD, HDD, and OTW displays, thereby capturing any potential task-performance benefits associated with altered color discrimination across the full simulator environment. However, because the Colormax lenses attenuate broad regions of the visible spectrum, this configuration also reduced the retinal illuminance of viewed stimuli and may have altered the effective luminance and chromatic contrast of displayed symbology. This issue is particularly relevant for OST HMD imagery, where virtual symbology is additively combined with the background scene and may already have limited luminance contrast.

Table 4. List of conditions tested in the simulation on the XRES platform

Condition	Colormax	Color Set
1	Lens Absent	Monochrome Green
2	Lens Absent	Primary RGB
3	Lens Present	Monochrome Green
4	Lens Present	Primary RGB

3.5.2. Operational Task Procedure

During each simulator condition, participants completed a sequence of repeated trials for 30 minutes. Conditions were presented in a randomly chosen order across two visits to the laboratory, including both the Colormax conditions evaluated in this study and additional display-color conditions included as part of the broader experimental protocol. Randomization was intended to reduce systematic effects of fatigue, learning, and adaptation to the Colormax lenses. However, with only six participants completing the simulator portion of the study, these effects may not have

been evenly distributed across conditions thus remain a potential confound and the simulator findings should be interpreted as preliminary.

Each trial consisted of several subtasks involving the HDD, HMD, and OTW scene. Figure 3 depicts a flowchart of the subtasks involved with each trial in the simulation, along with screenshots of the stimuli used for each subtask. Subtask timing and participant accuracy in each subtask was recorded for analysis.

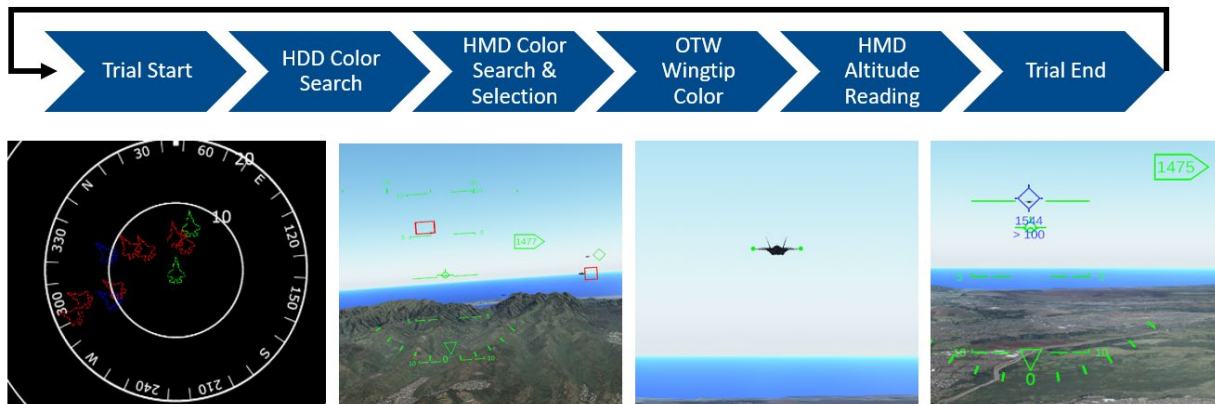


Figure 3: Operational task procedure

At the start of each trial, participants completed a visual search task on the head-down cockpit display (Figure 4). The target aircraft color was indicated in the center of the display, and participants were required to locate an aircraft of the same color among 10 distractor aircraft pseudo-randomly positioned around their own aircraft. In the primary RGB color-set conditions, the target color was randomly selected and was unique among the distractors. Once the target aircraft was located, participants banked left or right to acquire the target.

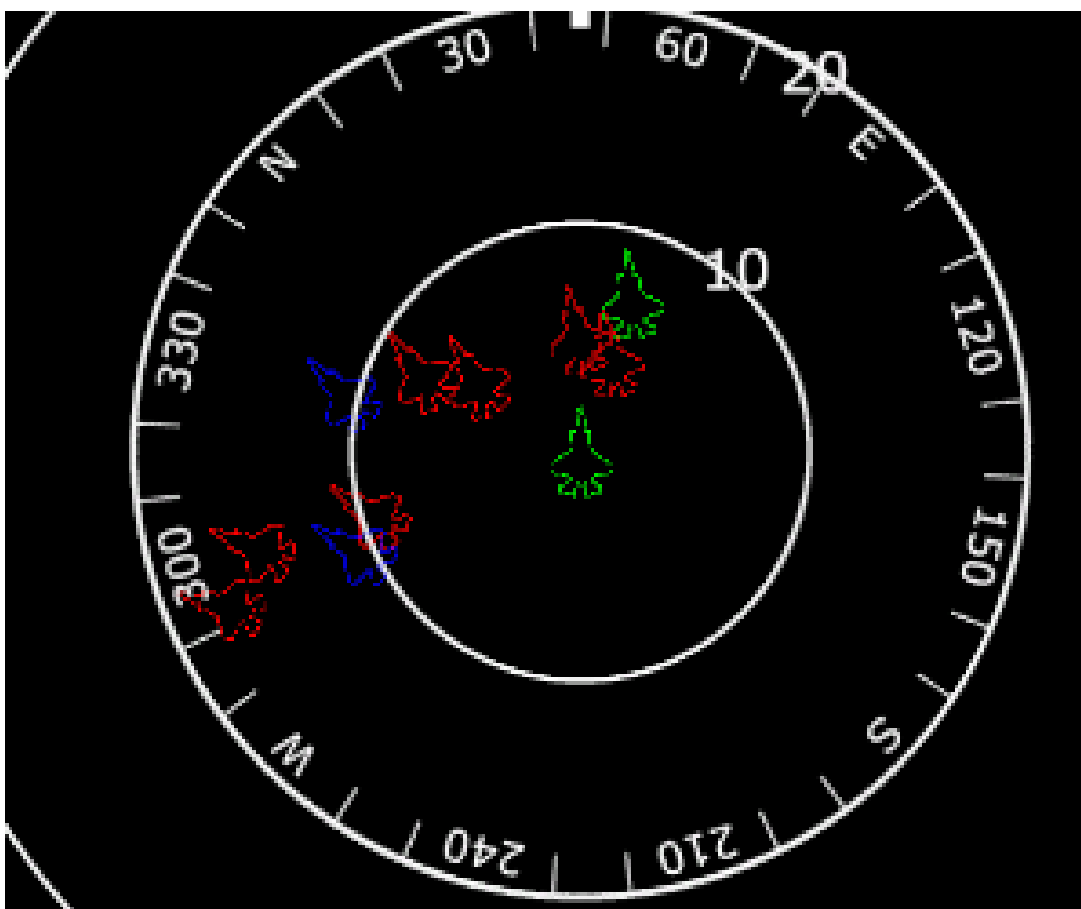


Figure 4: Screenshot of the HDD during the initial search task

Participants then searched for the target aircraft using the HMD imagery (Figure 5). The target aircraft was identified by a unique diamond symbol rendered in the target color. Distractor aircraft were marked with HMD symbology rendered as either squares or rectangles. Once the target was located, participants used the hat switch on the HOTAS joystick to position a cursor over the target aircraft and selected it using a trigger press.

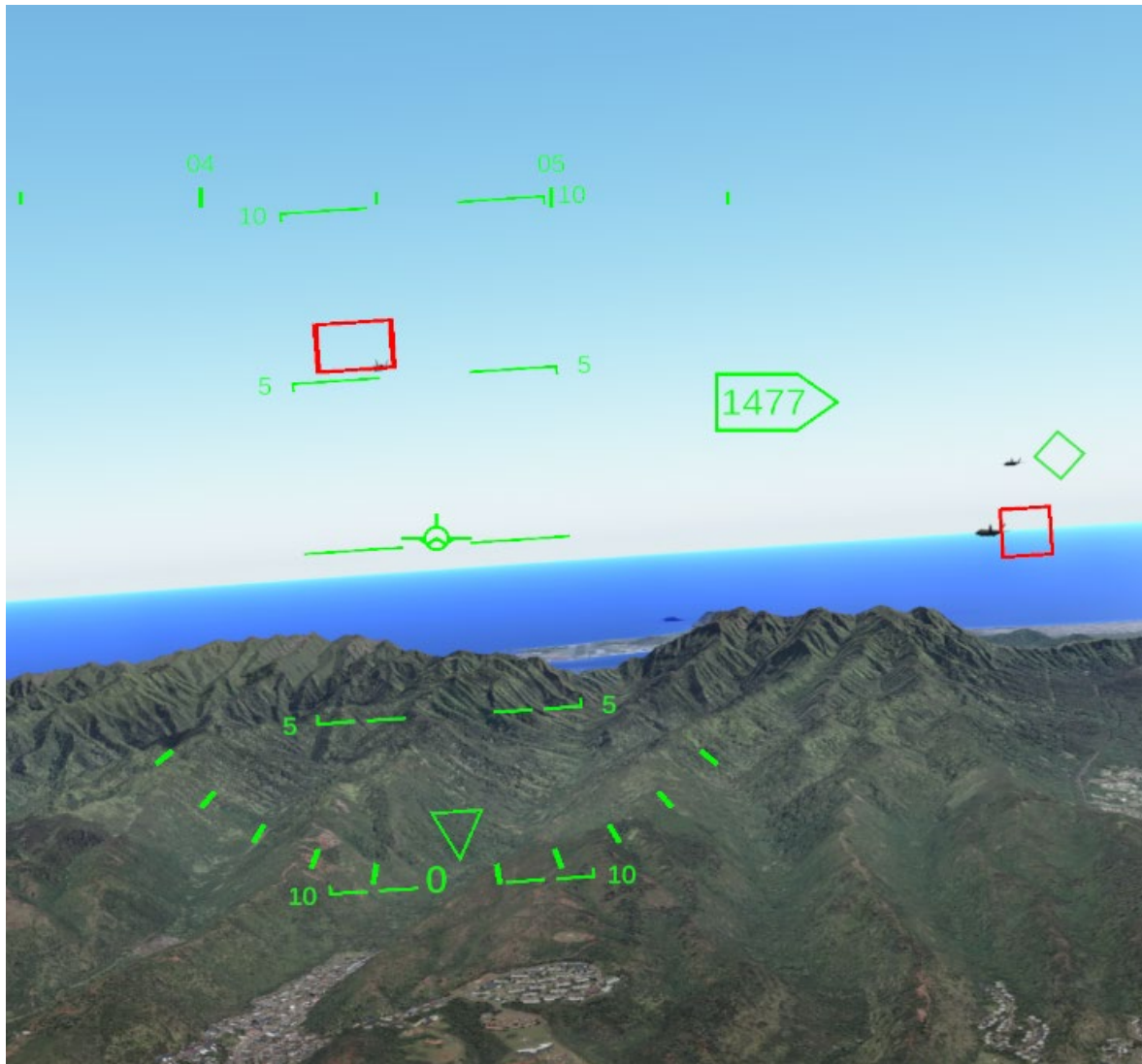


Figure 5: Illustration of the HMD symbology superimposed over the OTW scene

The target aircraft is designated by a diamond symbol in green for this trial. Note that there are no alignment issues between symbology and OTW targets when viewed in the simulator.

After target selection, wingtip lights appeared on the target aircraft (Figure 6). The wingtip lights were either both red or both green. Participants indicated the perceived color of the wingtip lights using the hat switch and confirmed their response with a trigger press. Following the wingtip-light decision, the altitude of the target aircraft was displayed below the aircraft on the HMD (Figure 7 and Figure 8). Participants indicated whether the target aircraft was within 100 altitude units of their own aircraft using the hat switch and confirmed their response with a trigger press. Participants then pressed a separate button to begin the next trial.

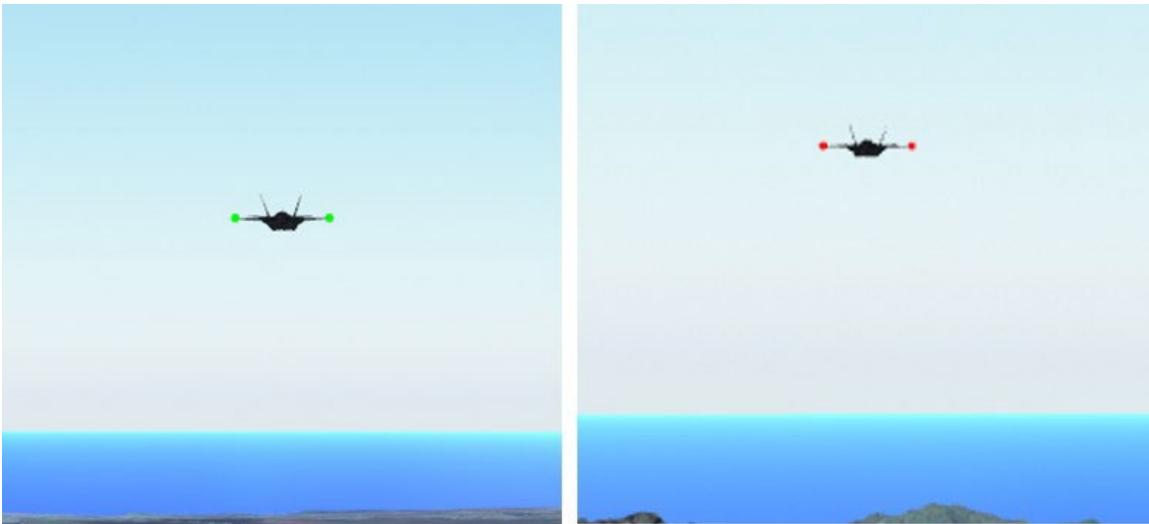


Figure 6. Screenshots of the OTW wingtip light discrimination task

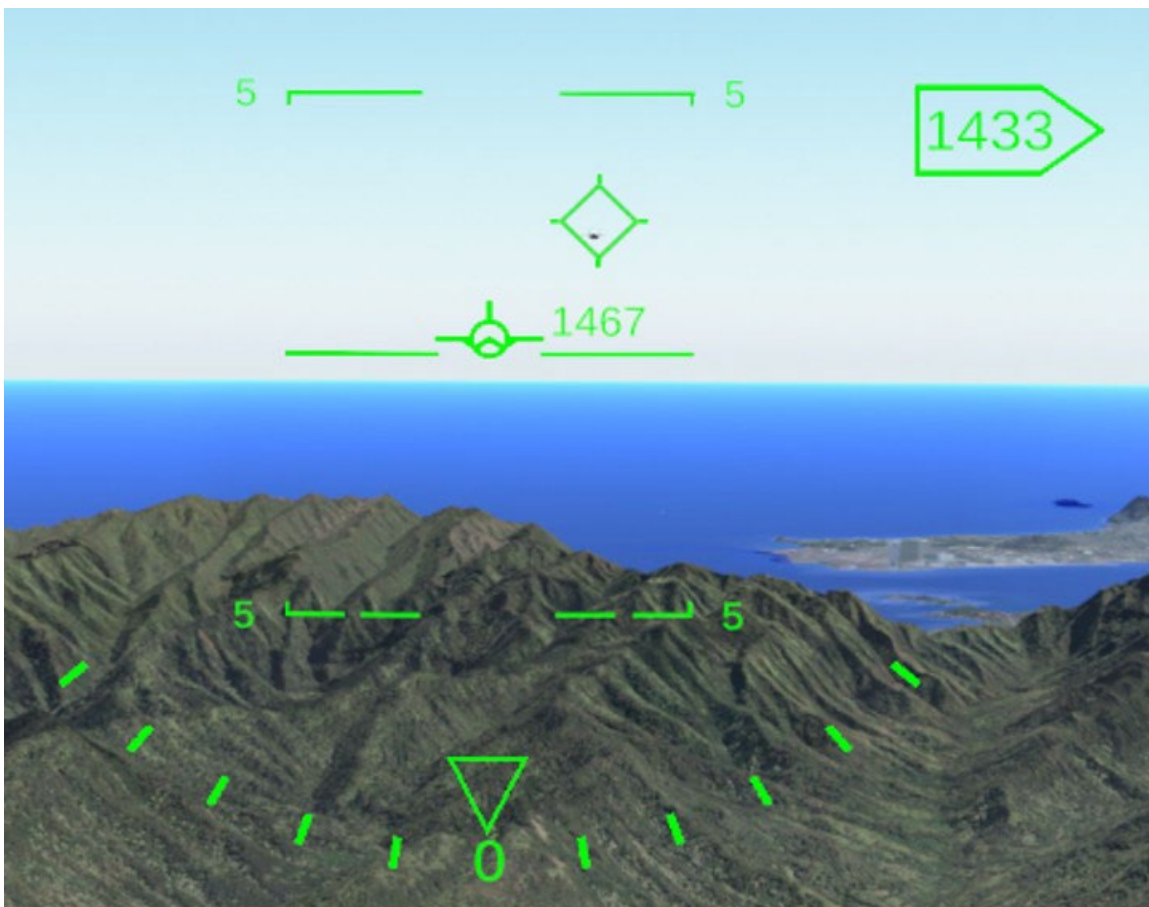


Figure 7. Illustration of the HMD symbology superimposed over the OTW scene during the altitude subtask in the monochrome green condition

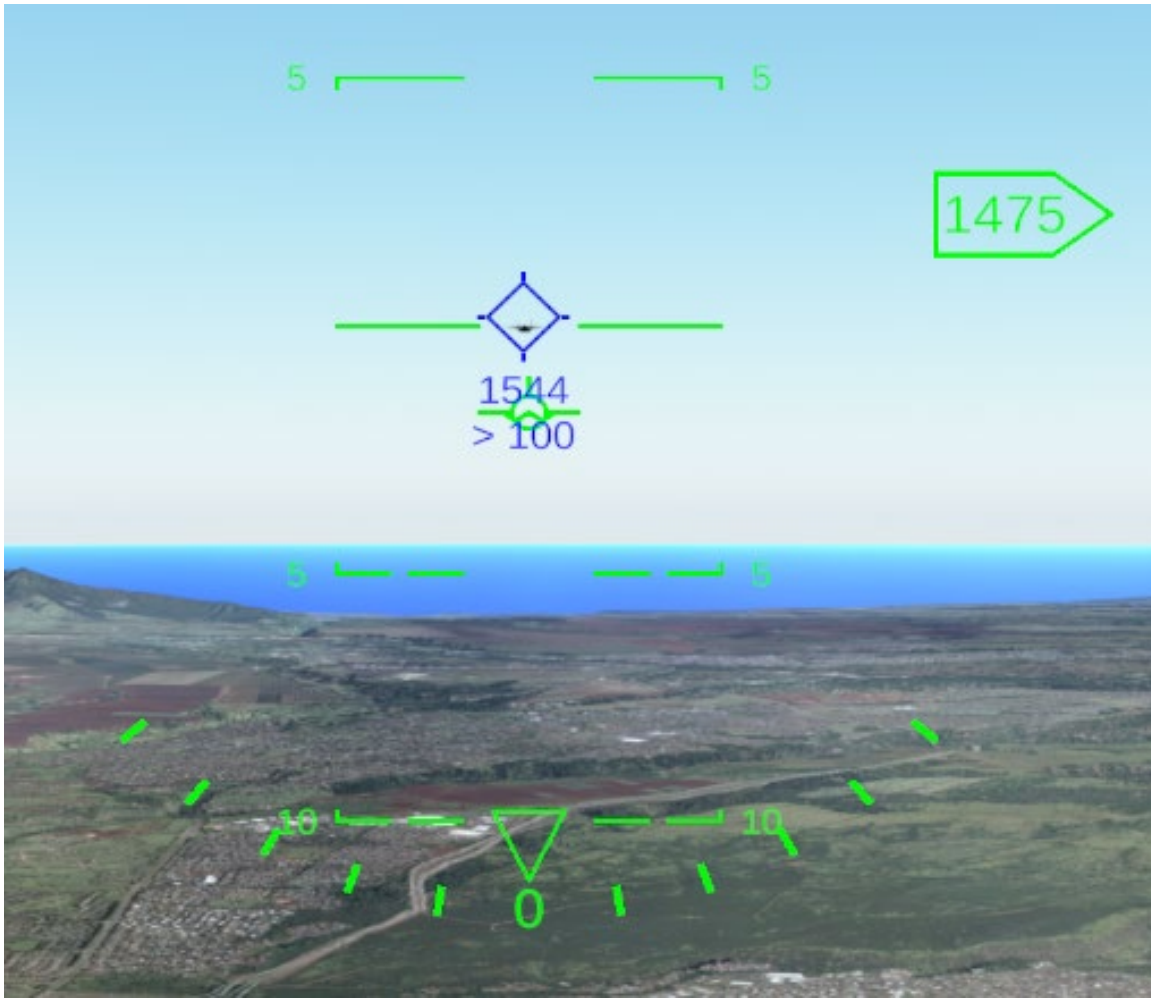


Figure 8: Illustration of the HMD symbology superimposed over the OTW scene during the altitude subtask in the RGB condition

Participant accuracy and response time were recorded for each subtask and used as dependent measures of simulator task performance.

4.0 RESULTS

4.1 Spectral Transmittance of Commercial Color-Filtering Lenses

The spectral transmittance of the tested lenses is shown in Figures 9, 10, and 11. The spectral transmittance curves for the six Colormax lens pairs were highly similar, despite being supplied as individually fitted lenses. Each pair exhibited the same general spectral profile, characterized by a notch filter centered at approximately 520 nm. At the notch, the lenses transmitted only approximately 10–40% of incident light, corresponding to roughly 60–90% attenuation in this region of the visible spectrum. The lenses also attenuated shorter-wavelength light, with blue-region transmittance reduced by approximately 20–60%, and longer-wavelength red-region transmittance reduced by approximately 10–20%. Although the six lens pairs differed somewhat in overall transmittance, the shape and spectral location of the attenuation profile were largely

consistent across lenses. These differences in overall transmittance may reflect a combination of manufacturing variation, lens-positioning differences during measurement, and measurement noise.

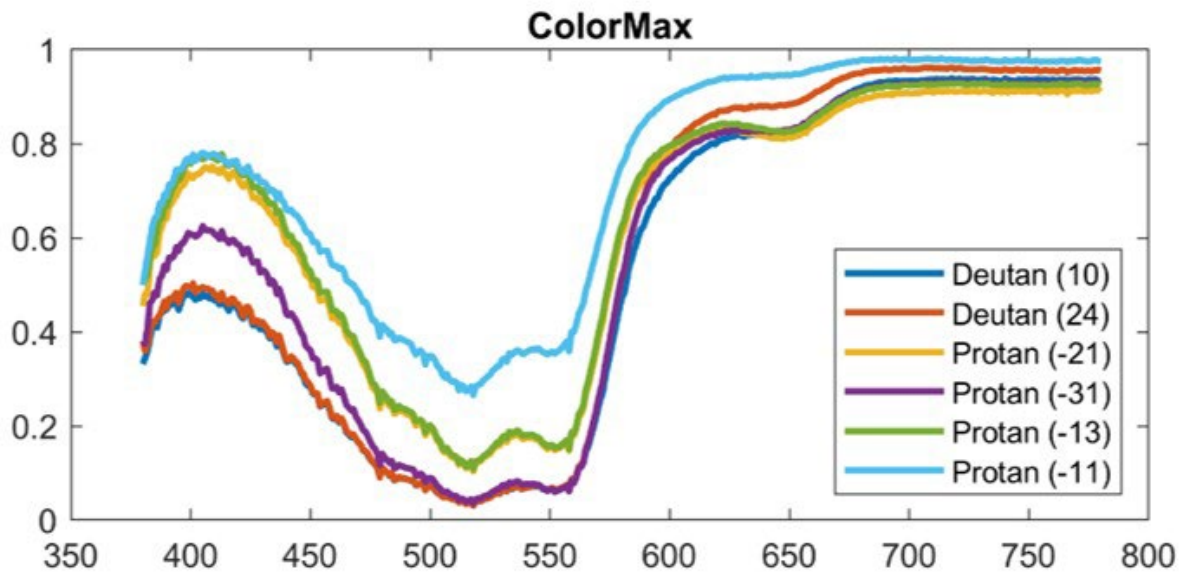


Figure 9. Spectral transmittance of the six Colormax lenses

Y-axis depicts the observed transmittance, and x-axis depicts the wavelength at which that transmittance was observed (in nanometers). Each individual's specific CVD and severity on the Konan CCT are listed in the legend.

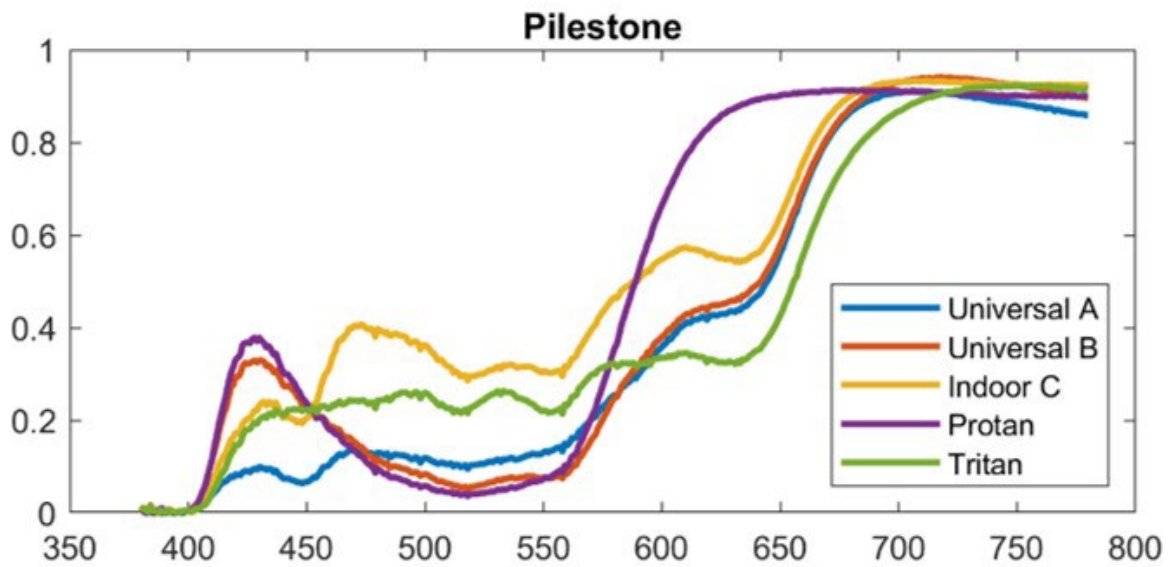


Figure 10. Spectral transmittance of the Pilestone lenses

Y-axis depicts the observed transmittance, and x-axis depicts the wavelength at which that transmittance was observed (in nanometers).

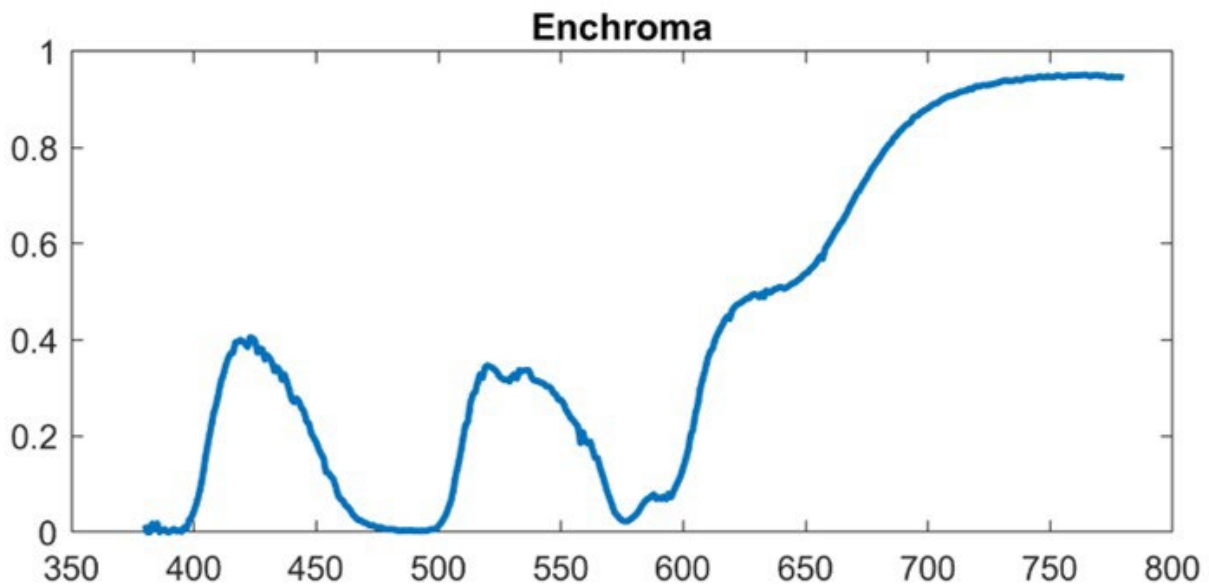


Figure 11. Spectral transmittance of the EnChroma lenses

Y-axis depicts the observed transmittance, and x-axis depicts the wavelength at which that transmittance was observed (in nanometers).

Based on the measured Colormax transmittance profiles shown in Figure 9, we hypothesize that the lenses are likely to improve some color vision test outcomes by altering the relative luminance

of test stimuli, rather than by restoring normal red-green color perception. The lenses do not correct the observer's underlying L/M cone deficit or replace normal cone spectral sensitivity. Instead, they selectively attenuate green-region light relative to longer-wavelength light. As a result, red/green stimuli that are designed to rely primarily on chromatic discrimination, particularly stimuli that are approximately isoluminant for the intended observer class, may become discriminable through lens-induced luminance differences. This mechanism could explain why the transmittance curves were highly similar across lenses fitted for protanomalous and deuteranomalous participants: a green-region notch filter can disrupt the intended stimulus structure of many red-green screening tests regardless of the observer's specific red-green deficiency classification.

The spectral transmittance curves for the five Pilestone lens variants are shown in Figure 10. The Universal C and protan-specific lenses exhibited transmittance profiles that were similar to those observed for the Colormax lenses, although with greater attenuation at shorter wavelengths. Based on these similarities, we hypothesize that these Pilestone lenses could also potentially disrupt the intended isoluminance of the test stimuli in red/green color vision testing. In contrast, the Universal A, Universal B, and Tritan lenses, which are advertised for outdoor use, exhibited broader spectral attenuation profiles, with substantial attenuation of short- and middle-wavelength light while preserving relatively greater long-wavelength transmittance. These characteristics may reduce retinal illuminance and alter the luminance contrast or color appearance of test and display stimuli, particularly under low-luminance conditions. However, behavioral testing with participants wearing these lenses would be required to evaluate their effects.

Finally, the spectral transmittance of the EnChroma lenses shown in Figure 11. The profile for these lenses was defined by two notch filters, with attenuation bands near approximately 475 nm and 575 nm. This filtering strategy differs from the Colormax and Colormax-like Pilestone filters. Rather than primarily attenuating the green region around 520 nm, the EnChroma lenses attenuate multiple spectral regions where adjacent cone responses may overlap. In theory, this could alter the separation of some color signals by changing the relative cone-excitation patterns produced by incoming light. However, this filtering strategy also does not restore normal cone spectral sensitivity or replace absent or altered photopigment mechanisms. Any benefit would therefore be expected to depend on the specific observer, stimulus spectra, and task demands. For display-based or operational tasks, any potential chromatic benefit must also be weighed against the reduction in overall light transmission caused by the notch filters.

4.2 Color Vision Test Outcomes

The results of pass/fail classifications on each screening test for 2 deuteranomalous subjects are listed in Table 4 and shown in Figure 12. Pass/fail classifications were based on FAA screening standards for the Innova Rabin CCT, Waggoner FAA Color Vision Test Battery, and CAD (see Table 2) (Federal Aviation Administration, 2025). Because equivalent FAA standards were not available for the NCI OcuTest and Konan ColorDx CCT HD, pass/fail thresholds were set using comparable score-based criteria. For the NCI OcuTest, participants were classified as failing if any cone-specific subtest score was less than 55, a standard in use by the United States Air Force for color vision screening. For the Konan ColorDx CCT HD, participants were classified as failing if any cone-specific subtest score was less than 75, as recommended by Konan Medical's guidelines for use of the Konan CCT HD. Raw test scores and subtest-level outcomes are provided in the appendix.

These deuteranomalous individuals showed the clearest improvement with Colormax lenses. Without the lenses, all deuteranomalous participants failed the color vision screenings while passing with the lenses. This pattern suggests that the Colormax lenses can substantially alter the effective stimulus information available to deuteranomalous observers during digital color vision testing. Specifically, the lenses may introduce or exaggerate luminance differences among stimuli that are intended to isolate chromatic discrimination, allowing some observers to use luminance-based cues rather than the intended color-vision mechanism.

Table 5. Deuteranomalous color vision screening results

Participant	Test	Subtype	No Colormax	With Colormax	Change
032	Innova	R	Pass	Pass	
		G	Fail	Pass	Improvement
		B	Pass	Pass	
	Waggoner	General	Fail	Fail	
		Protan	Fail	Pass	Improvement
		Deutan	Fail	Pass	Improvement
	NCI	R	Pass	Pass	
		G	Fail	Pass	Improvement
		B	Pass	Pass	
	CAD	BY	Pass	Pass	
		RG	Fail	Pass	Improvement
	Konan	R	Pass	Pass	
		G	Fail	Pass	Improvement
		B	Pass	Pass	
571	Innova	R	Pass	Pass	
		G	Fail	Pass	Improvement
		B	Pass	Pass	
	Waggoner	General	Fail	Pass	Improvement
		Protan	Fail	N/A	
		Deutan	Fail	N/A	
	NCI	R	Pass	Pass	
		G	Fail	Pass	Improvement
		B	Pass	Pass	
	CAD	BY	Pass	Pass	
		RG	Fail	Pass	Improvement
	Konan	R	Pass	Pass	
		G	Fail	Pass	Improvement
		B	Pass	Pass	

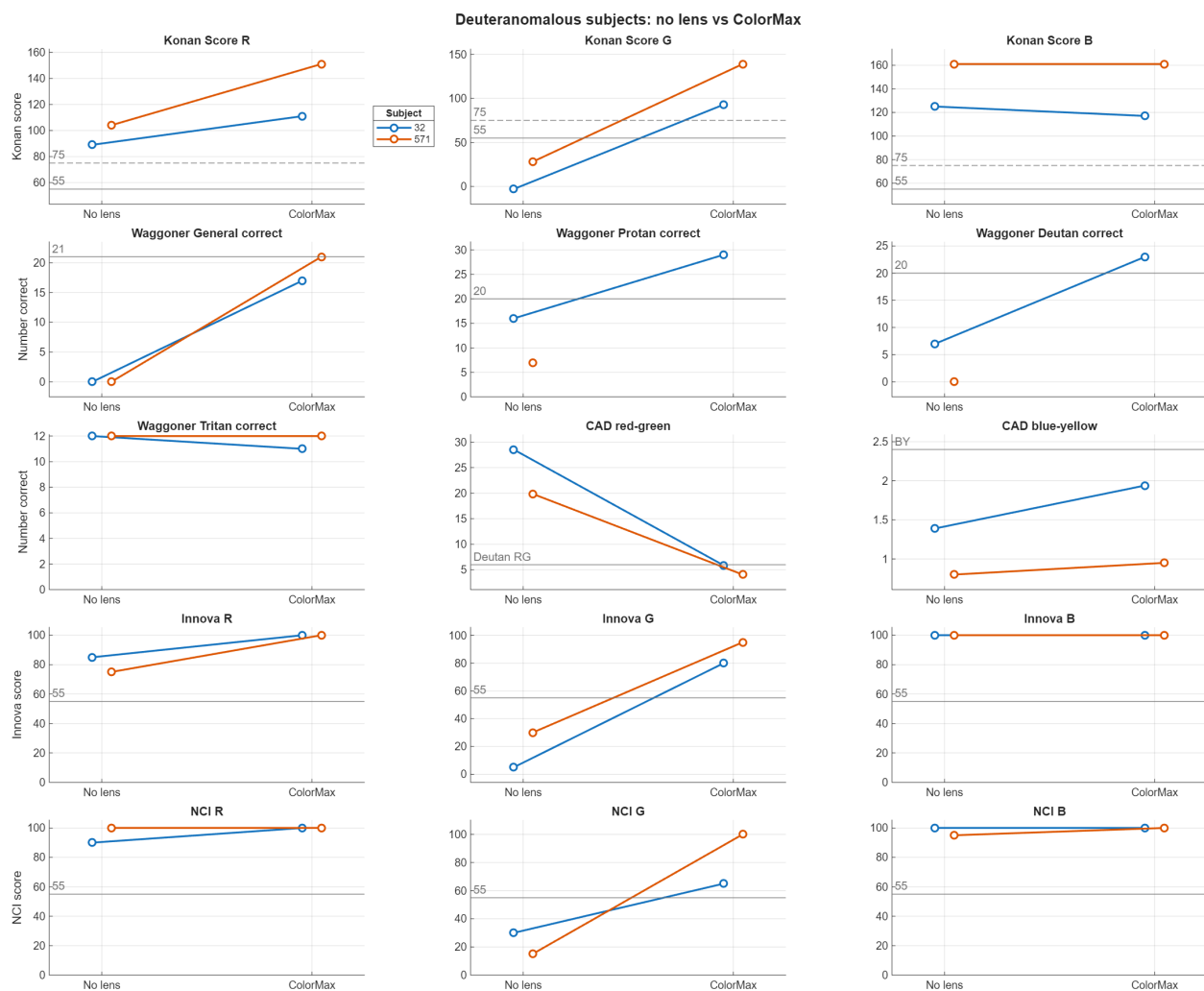


Figure 12: Deuteranomalous vision testing results

Conversely, there was inconsistent improvement and even impairment among protanomalous subjects (Table 5, Figure 13). Among these participants, three out of four saw improvement from failing to passing scores on the Innova test and all four showed improvement from failing to passing on the NCI R-cone tests. Two out of four saw improvement from failing to passing on the Konan R-cone test. Only one participant saw improvement on the Waggoner Protan sub-test, while one saw improvement in the CAD tests. Curiously, all participants exhibited impairments on the Innova G-cone test, going from passing scores to failing scores with the Colormax lens. Three participants showed this impairment on the Konan G-cone and three showed it on the NCI G-cone test. This suggests that the lenses did not produce a uniform improvement in color vision screening performance for protanomalous observers and may shift the relative difficulty of different subtests rather than improving performance across the full screening battery.

One additional protanomalous participant (Participant ID 001) was recruited who was not fit with an individualized Colormax lens but used the lens of a similarly sighted participant. Their color vision testing results are shown in Figure 15. This participant performed similarly to the other protanomalous participants passing the R-cone subtests of the Konan, Innova, and NCI, while conversely failing the corresponding G-cone subtests on the Konan and Innova. While these results

are exploratory, they provide initial support for the hypothesis that the Colormax lenses are not truly individualized.

Table 6. Protanomalous color screening results

Participant	Test	Subtype	No Colormax	With Colormax	Change
1	Innova	R	Fail	Pass	Improvement
		G	Pass	Fail	Impairment
		B	Pass	Pass	
	Waggoner	General	Fail	Fail	No Improvement
		Protan	Fail	Pass	Improvement
		Deutan	Fail	Fail	No Improvement
	NCI	R	Fail	Pass	Improvement
		G	Pass	Pass	
		B	Pass	Pass	
	CAD	BY	Pass	Pass	
		RG	Pass	Pass	
	Konan	R	Fail	Pass	Improvement
		G	Pass	Fail	Impairment
		B	Pass	Pass	
616	Innova	R	Fail	Pass	Improvement
		G	Pass	Fail	Impairment
		B	Pass	Pass	
	Waggoner	General	Fail	Fail	No Improvement
		Protan	Fail	Fail	No Improvement
		Deutan	Fail	Fail	No Improvement
	NCI	R	Fail	Pass	Improvement
		G	Pass	Fail	Impairment
		B	Pass	Pass	
	CAD	BY	Pass	Pass	
		RG	Fail	Fail	No Improvement
	Konan	R	Fail	Pass	Improvement
		G	Pass	Fail	Impairment
		B	Pass	Pass	
864	Innova	R	Fail	Pass	Improvement
		G	Pass	Fail	Impairment
		B	Pass	Pass	
	Waggoner	General	Fail	Fail	No Improvement
		Protan	Fail	Pass	Improvement
		Deutan	Fail	Fail	No Improvement
	NCI	R	Fail	Pass	Improvement
		G	Pass	Pass	

		B	Pass	Pass	
	CAD	BY	Pass	Pass	
		RG	Fail	Fail	No Improvement
	Konan	R	Fail	Pass	Improvement
		G	Pass	Pass	
		B	Pass	Pass	
886	Innova	R	Fail	Pass	Improvement
		G	Pass	Fail	Impairment
		B	Pass	Pass	
	Waggoner	General	Fail	Fail	No Improvement
		Protan	Fail	Fail	No Improvement
		Deutan	Fail	Fail	No Improvement
	NCI	R	Fail	Pass	Improvement
		G	Pass	Fail	Impairment
		B	Pass	Pass	
	CAD	BY	Pass	Pass	
		RG	Fail	Fail	No Improvement
	Konan	R	Fail	Fail	No Improvement
		G	Pass	Fail	Impairment
		B	Pass	Pass	
887	Innova	R	Fail	Pass	Improvement
		G	Pass	Fail	Impairment
		B	Pass	Pass	
	Waggoner	General	Fail	Fail	No Improvement
		Protan	Fail	Fail	No Improvement
		Deutan	Fail	Fail	No Improvement
	NCI	R	Fail	Pass	Improvement
		G	Pass	Pass	
		B	Pass	Pass	
	CAD	BY	Pass	Pass	
		RG	Fail	Fail	No Improvement
	Konan	R	Fail	Fail	No Improvement
		G	Pass	Fail	Impairment
		B	Pass	Pass	

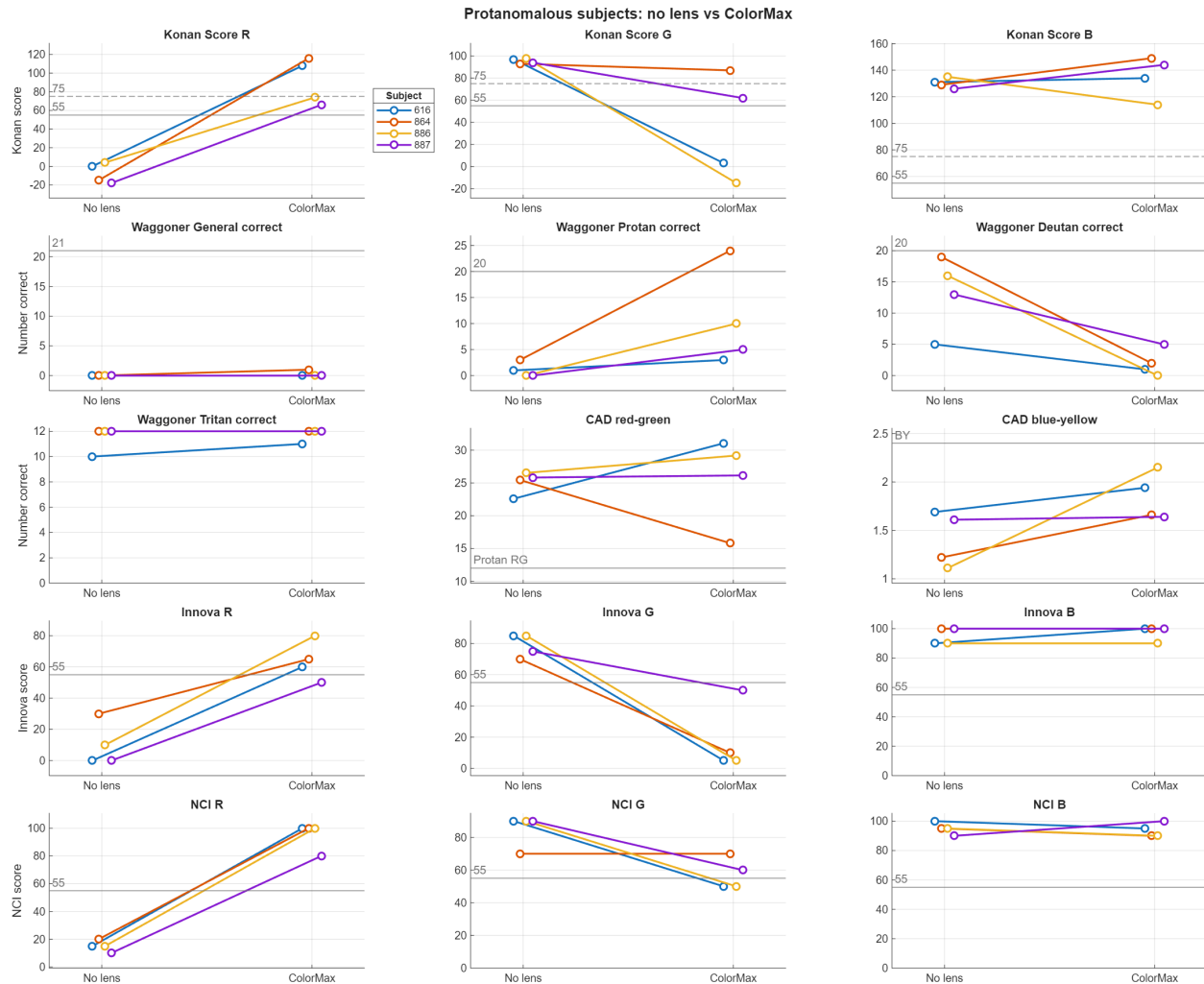


Figure 13: Protanomalous vision testing results

As an additional exploratory comparison, a convenience sample of five color-normal internal laboratory volunteers, including one author, completed the Konan CCT with and without the Colormax lenses (Figure 14). All five participants used the same pair of Colormax lenses originally fitted for participant 616, and the order of the with- and without-lens conditions was randomized. This convenience sample was not recruited or designed as a formal control group, and participants completed only the Konan CCT. All five participants remained within the passing range with and without the Colormax lenses. Red- and green-cone subtest scores showed small apparent increases for most participants, whereas blue-cone scores showed no consistent pattern. These descriptive results provide additional context for interpreting the findings in participants with color vision deficiencies but should not be considered controlled evidence of the effects of Colormax lenses in individuals with normal color vision. Further testing using a prospectively recruited control sample and the complete color vision test battery would be required to characterize these effects.

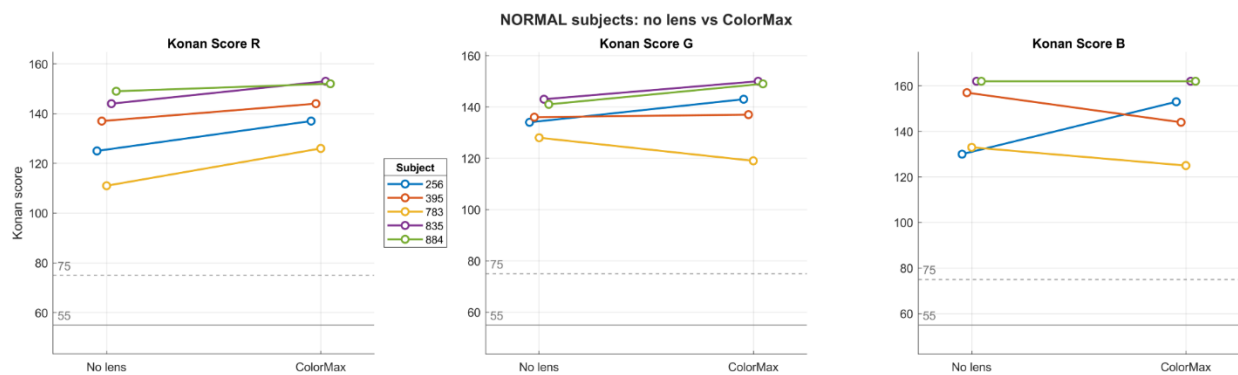


Figure 14: Color normal participant Konan performance with and without Colormax lenses

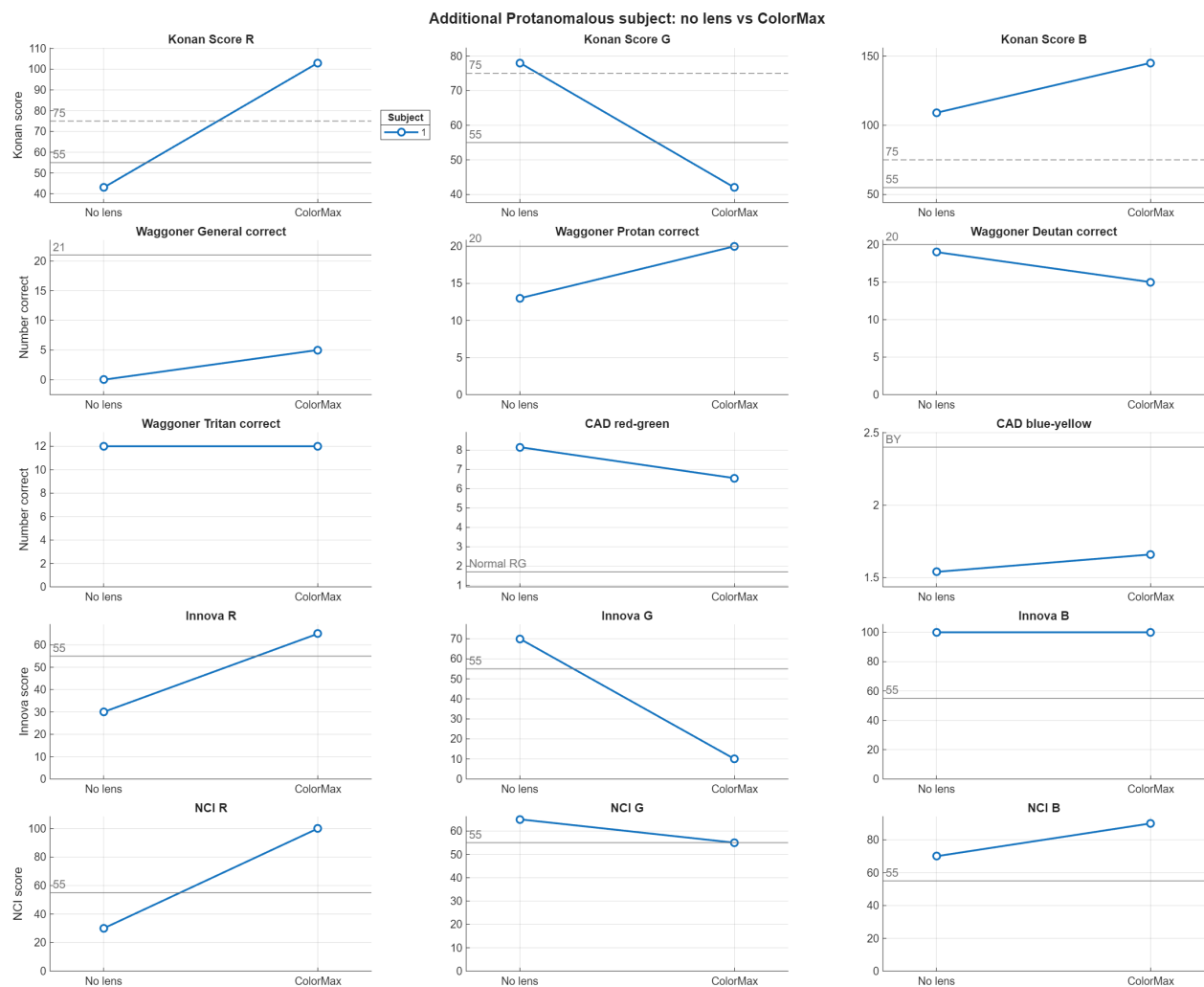


Figure 15: Additional protanomalous participant performance with and without Colormax lenses

4.3 Operational Task Performance

Five of the six subjects recruited for the Colormax lens fitting also performed the operational task simulation. Participant 887 withdrew from the simulation portion of the study due to limited availability, and was subsequently replaced with participant 846, another protanomalous observer. Participant 846's color vision testing data is included in the appendix.

Participant accuracy and response time was recorded for each trial, for each of the four subtasks. The corresponding variables for these measures are shown in Table 4. For each trial in the simulation, participant accuracy was aggregated using the following formula:

Equation 1: Aggregated trial accuracy

$$A_t = \frac{A_{hdd} + A_{hmd} + A_{otw} + A_{alt}}{4}$$

From here, trial level throughput was calculated as trial accuracy divided by the total length of the trial in seconds:

Equation 2: Trial level throughput

$$Q_t = \frac{A_t}{R_t}$$

Finally, condition level throughput was calculated as the average throughput across all completed trials (N) in the 30-minute block:

Equation 3: Condition level throughput

$$\bar{Q} = \frac{1}{N} \sum_{t=1}^N Q_t$$

Participant level data is included in the appendix in terms of response times, accuracy, and throughput. Figure 16 depicts overall simulator performance, as measured by mean throughput aggregated across all subtasks, for the six participants across the four simulation conditions. Higher throughput values indicate more efficient performance, reflecting both greater accuracy and faster responding. Three of the six participants showed reduced overall throughput while wearing the Colormax lenses, including both deuteranomalous and one protanomalous. Three protanomalous individuals saw slight improvements in throughput with the Colormax lenses across both color set conditions.

Table 7. Variables used in analysis of user performance in the flight simulation

Variable	Description
A_{hdd}	Accuracy in the HDD visual search task measured via the participant's initial bank direction. 1, if they banked in the correct direction toward the target, otherwise 0.
A_{hmd}	Accuracy in the HMD visual search and selection task. 1, if the participant selected the correct target, otherwise 0.
A_{otw}	Accuracy in the OTW red/green wingtip light discrimination task. 1, if the participant indicated the correct color of the lights, otherwise 0.
A_{alt}	Accuracy in the HMD altitude arithmetic task. 1, if the participant correctly indicated if the magnitude of the difference was greater than 100 units, otherwise 0.
A_t	Overall trial level accuracy. This combines accuracy metrics across all subtasks.
R_{hdd}	Response time for the HDD visual search task, measured as the duration from the start of the trial to the time of initial bank maneuver.
R_{hmd}	Response time for the HMD visual search task, measured as the duration from the initial bank maneuver to the time of target selection.
R_{otw}	Response time for the OTW red/green wingtip discrimination task, measured as the duration from the time of target selection to the time when red/green input was received.
R_{alt}	Response time for the HMD altitude arithmetic task, measured as the duration from the time of input received for the OTW task to the time input was received for the altitude task.
R_t	Trial length, measured from the start of the trial to the time the altitude task input was received.
Q_t	Trial level throughput, measured as the number of subtasks performed correctly divided by the number of subtasks and again divided by the trial length (see Equation 1 and Equation 2).
$\bar{Q}$	Condition level throughput, calculated as the average of the trial level throughputs for a given condition in the simulation.

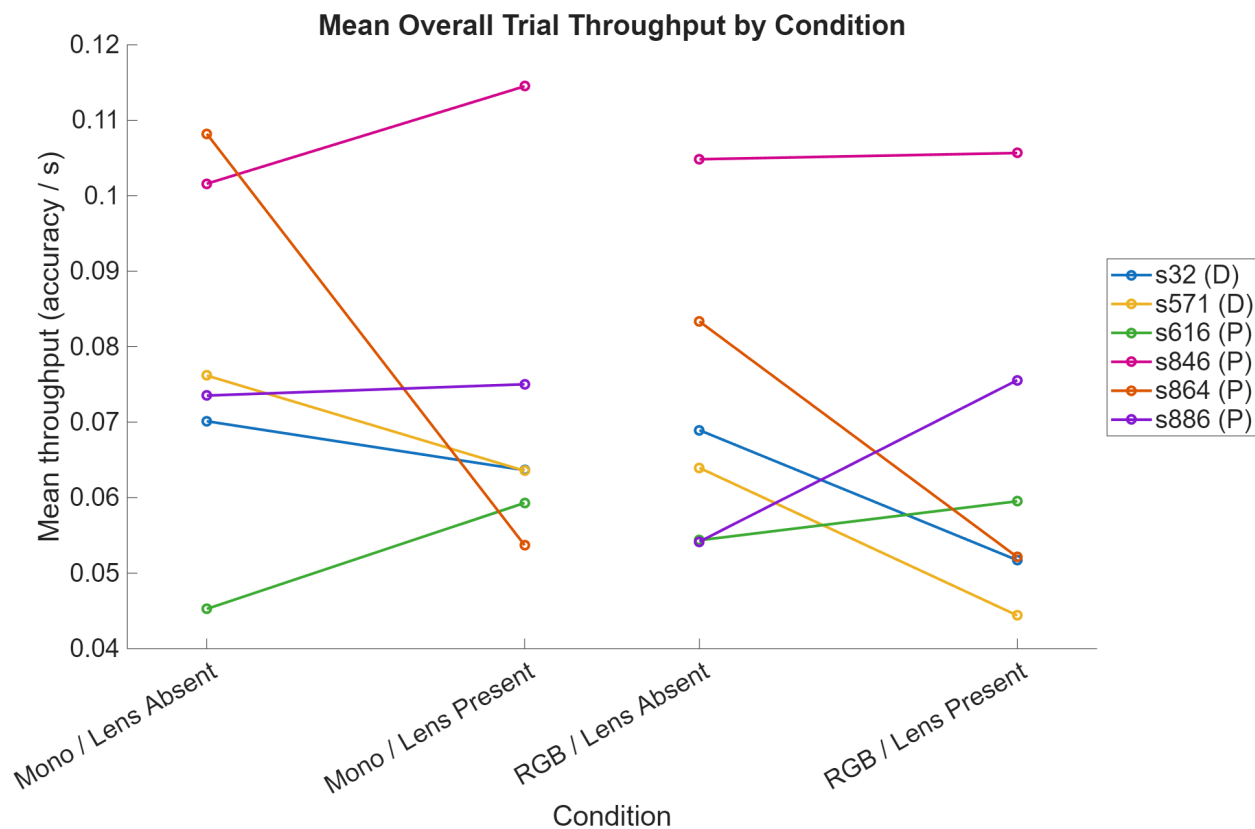


Figure 16: Mean throughput by condition for the simulated flight task

Figures 17 and 18 depict participant-level throughput in the HDD color search subtask and the HMD color search and selection subtask, respectively. In the monochrome condition, five of the six participants showed slightly increased throughput in the HDD task while wearing the Colormax lenses. We hypothesize that this occurs due to the attenuation of the lenses reducing the luminance of the green distractor aircraft shown on the HDD, whereas the red target aircraft was unaffected. This effect theoretically increases the salience of the red target symbol by reducing the salience of the distractors. In the RGB condition, participants showed relatively stable performance in the HDD task. For the HMD search and selection subtask, no obvious effect was observed in the data. These results suggest that any lens-related benefit in the search tasks was limited and task-dependent, rather than producing a consistent improvement across simulator display conditions.

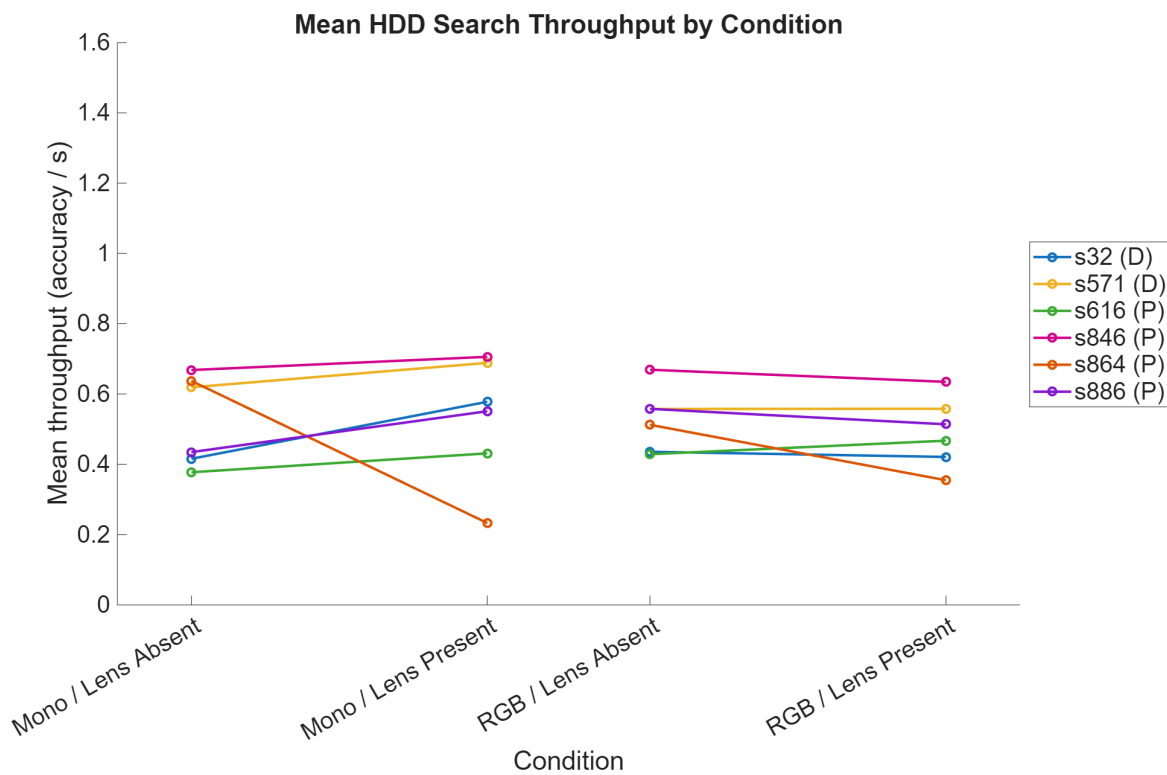


Figure 17. HDD search throughput by condition

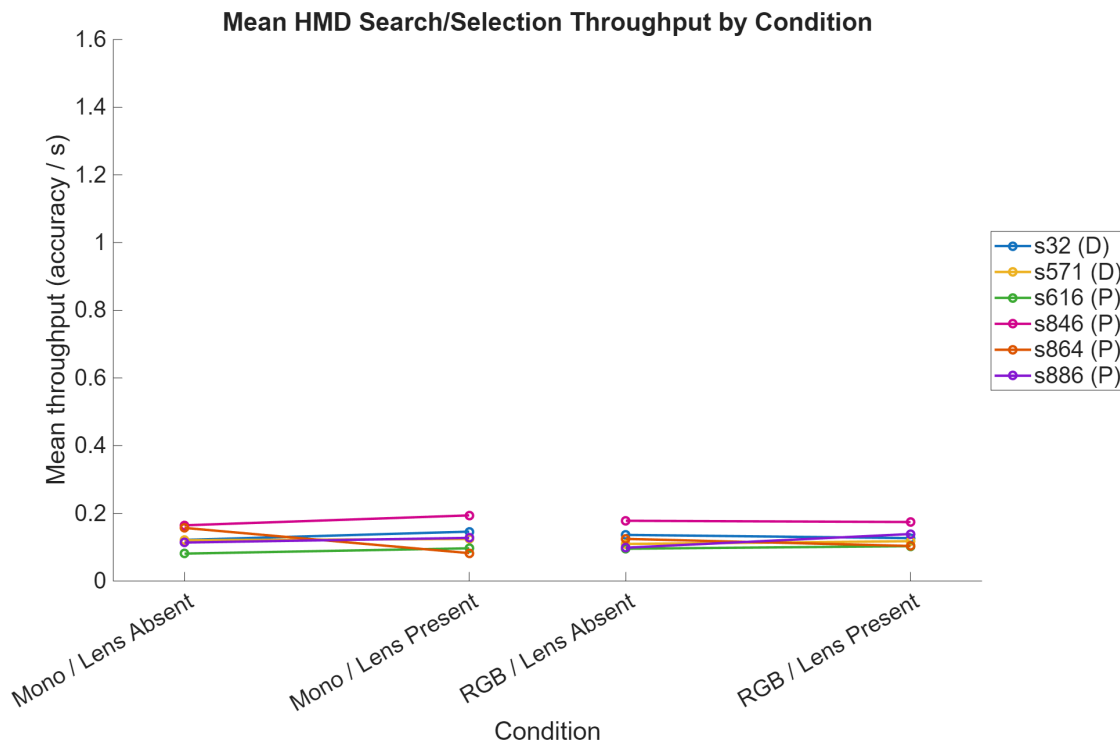


Figure 18: HMD search and selection throughput by condition

Figure 19 depicts throughput performance in the red/green wingtip light discrimination task performed on the OTW displays. Throughput was lower with the Colormax lenses for most participant-condition comparisons, indicating an apparent reduction in performance under lens use. The exceptions were participants 616 and 846 in the monochrome condition, and 886 in the RGB color set condition, for whom throughput increased while wearing the Colormax lenses. Because the OTW wingtip light task itself did not vary as a function of the color set condition, substantial differences in performance across color set conditions were not expected. Accordingly, this isolated increase may reflect order-related effects, normal trial-to-trial variability, or other sources of measurement variability rather than a systematic effect of the lenses. Given the small sample size, these results should be interpreted descriptively.

Figure 20 depicts throughput performance in the altitude subtask performed on the HMD. In contrast to the pattern observed for the wingtip light discrimination task, no consistent directional effect of Colormax lens use was apparent for the altitude task. Three participants experienced increased throughput when wearing the lenses across color sets, while 2 experienced decrease performance and one remained relatively stable. These mixed individual responses provide no clear evidence of either improved or reduced altitude-task performance under lens use in this sample.

Post hoc optical characterization of the HMD identified an interocular difference in optical power and orientation-dependent focus consistent with astigmatism. Because this optical discrepancy was present across all simulator conditions, it does not provide a systematic explanation for differences between the Colormax lens conditions; however, it may have affected absolute performance or reduced sensitivity to lens-related effects on the HMD-mediated subtasks. Accordingly, these results should be interpreted with this optical limitation in mind.

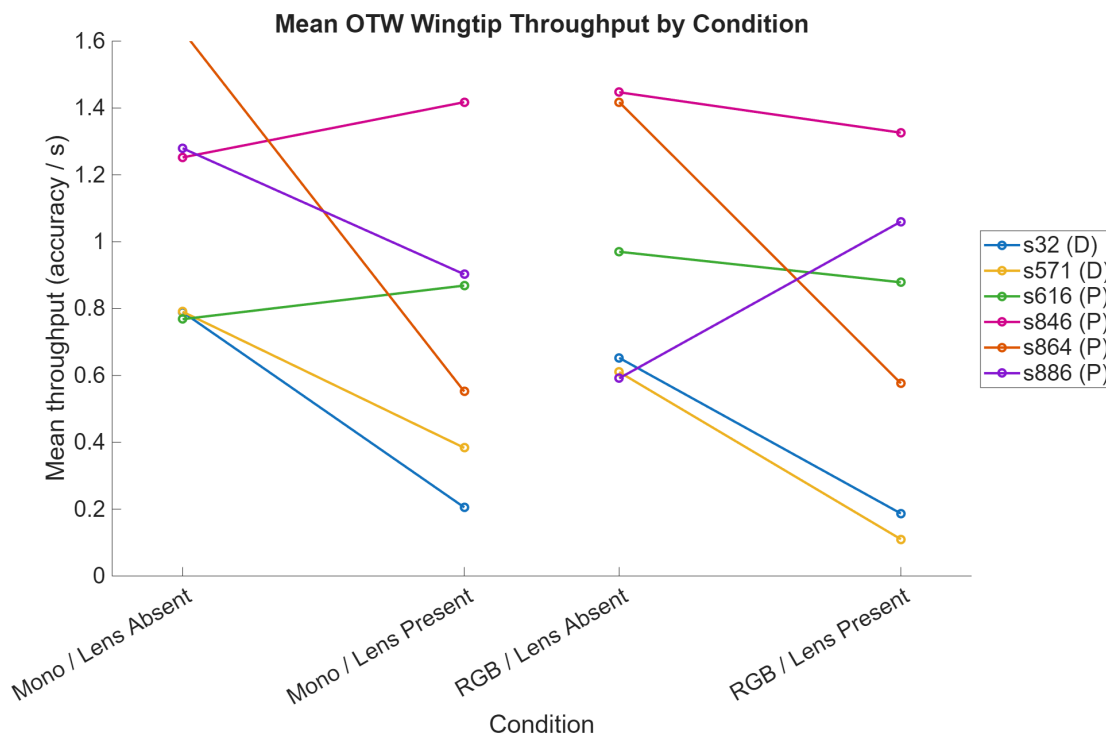


Figure 19: Wingtip light task throughput by condition

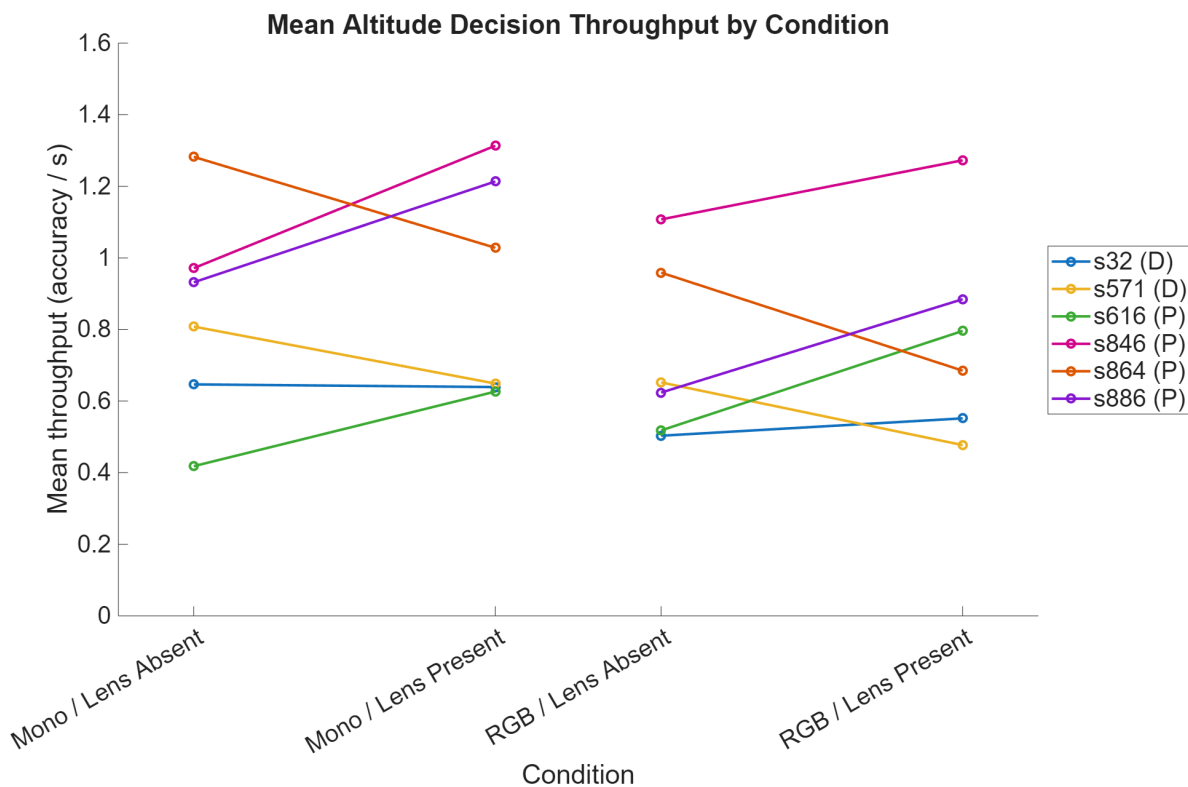


Figure 20: Altitude task throughput by condition

5.0 CONCLUSION

This investigation suggests that Colormax CVD-correcting lenses can substantially alter performance on digital color vision screening tests in some individuals, but these effects were not consistent across observer groups or tests, nor did they result in any consistent improvement on a simulated color-based aviation task. The clearest screening-test benefits were observed for the two deuteranomalous participants, who failed the color vision screenings without the lenses but passed while wearing the lenses. In contrast, protanomalous participants showed mixed outcomes, with participants continuing to fail one or more screenings. Though the lenses helped them pass the R-cone subtests, they subsequently were more likely to fail the G-cone subtest. These findings suggest that the lenses may not reliably improve color vision screening outcomes across all individuals and improvement in one test may come at the expense of impairment in another test.

Additionally, results on the operational task results did not provide evidence that the Colormax lenses lead to improved task performance. Overall task throughput (accuracy divided by response time) was reduced for three of the six participants when Colormax lenses were worn, with the largest performance decrement appearing in the OTW red/green wingtip discrimination task. Five of six participants experienced task-specific benefits with the Colormax lenses for the HDD search task under the monochrome condition, but these benefits were not consistently observed across RGB task conditions and did not offset the reduction observed in the OTW task. These results suggest that pass/fail improvements on color vision screening tests should not be assumed to indicate improved performance on aviation-relevant display tasks.

The present findings also highlight the importance of the display system used to administer digital color vision tests. For software-based tests, the nominal RGB values specified by the test do not uniquely determine the visual stimulus presented to the observer. The emitted luminance, chromaticity, and spectral power distribution depend on the display technology, calibration state, operating-system settings, brightness level, and viewing environment. These factors may be especially important when color-filtering lenses are used, because the functional effect of the lens depends on the interaction between the lens transmittance profile and the spectral emissions of the display primaries. As a result, lens-related changes in screening performance may vary across display architectures and field-testing environments, even when the same software test is used. An erroneously calibrated display used for testing may have detrimental interactions with color-filtering lenses and may prohibit the broader utility in these use-cases.

These findings have practical implications for aviation medical screening. Medical flight examiners should be aware that color-filtering technologies, including spectacle lenses and contact lens variants, can alter color vision screening outcomes and not always in obvious or useful ways. Contact lens implementations may be especially difficult to detect during routine screening and could allow some color-deficient applicants, particularly deuteranomalous individuals, to pass selected screening tests despite not demonstrating normal unaided color discrimination, which may not translate appropriately to the cockpit. Because the present results suggest that screening improvements may arise from altered stimulus cues rather than restored color vision, the use of color-filtering lenses during color vision screening should not be treated as evidence of normal operational color vision without additional validation.

Overall, the present results do not support the use of Colormax lenses as a validated exception to aeromedical color vision standards at this time. The lenses changed screening outcomes for some participants, but the effects were observer- and test-dependent, and operational task performance did not show a consistent corresponding benefit. Future work should evaluate the variability of digital color vision testing across fielded examiner environments, including display calibration, spectral output, ambient lighting, and software settings, and should further examine whether screening outcomes obtained with color-filtering lenses predict performance on aviation-relevant color discrimination tasks. Future research should also examine whether digitally customized color display palettes could potentially improve in-cockpit color discrimination performance for color deficient pilots.

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APPENDIX – COLOR VISION TESTING AND SIMULATION DATA

Tables A1 through A5 show raw data collected from each color vision tests used in this assessment.

Table A1: Innova Rabin color vision testing results

Innova Rabin								
PID	ColorMax	CVD Type	LeftRScore	LeftGScore	LeftBScore	RightRScore	RightGScore	RightBScore
886	no	Protan	5	85	85	10	85	90
886	yes	Protan	70	0	95	80	5	90
864	no	Protan	35	85	100	30	70	100
864	yes	Protan	65	30	100	65	10	100
887	no	Protan	0	85	95	0	75	100
887	yes	Protan	60	50	95	50	50	100
616	no	Protan	0	75	65	0	85	90
616	yes	Protan	65	5	80	60	5	100
571	no	Deutan	80	20	100	75	30	100
571	yes	Deutan	100	90	100	100	95	100
32	no	Deutan	50	5	100	85	5	100
32	yes	Deutan	85	80	100	100	80	100
846	no	Protan	15	100	100	50	90	100
846	yes	Protan	90	55	100	85	55	100
1	no	Protan	35	85	100	30	70	100
1	yes	Protan	65	30	100	65	10	100

Table A2: NCI OcuTest color vision testing results

NCI								
PID	ColorMax	CVD Type	LeftScoreR	LeftScoreG	LeftScoreB	RightScoreR	RightScoreG	RightScoreB
886	no	Protan	10	75	95	15	90	95
886	yes	Protan	90	40	100	100	50	90
864	no	Protan	25	80	95	20	70	95
864	yes	Protan	95	70	100	100	70	90
887	no	Protan	10	90	90	10	90	90
887	yes	Protan	90	65	100	80	60	100
616	no	Protan	20	90	95	15	90	100
616	yes	Protan	90	50	90	100	50	95
571	no	Deutan	90	15	100	100	15	95
571	yes	Deutan	100	100	100	100	100	100
32	no	Deutan	80	15	95	90	30	100
32	yes	Deutan	100	100	100	100	65	100
846	no	Protan	50	100	100	55	95	100
846	yes	Protan	100	60	100	100	55	100
1	no	Protan	15	65	90	30	65	70
1	yes	Protan	90	50	90	100	55	90

Table A3: Waggoner FAA Battery color vision testing results

Waggoner										
PID	ColorMax	CVD Type	GeneralCorrect	GeneralTotal	ProtanCorrect	ProtanTotal	DeutanCorrect	DeutanTotal	TritanCorrect	TritanTotal
886	no	Protan	0	5	0	32	16	32	12	12
886	yes	Protan	0	5	10	32	0	32	12	12
864	no	Protan	0	5	3	32	19	32	12	12
864	yes	Protan	1	6	24	32	2	32	12	12
887	no	Protan	0	5	0	5	13	28	12	12
887	yes	Protan	0	5	5	15	5	15	12	12
616	no	Protan	0	5	1	9	5	13	10	12
616	yes	Protan	0	5	3	10	1	6	11	12
571	no	Deutan	0	5	7	32	0	32	12	12
571	yes	Deutan	21	25	-	-	-	-	12	12
32	no	Deutan	0	5	16	32	7	32	12	12
32	yes	Deutan	17	22	29	32	23	32	11	12
846	no	Protan	1	6	16	32	24	32	12	12
846	yes	Protan	5	10	29	32	24	32	12	12
1	no	Protan	0	5	13	32	19	32	12	12
1	yes	Protan	5	10	20	32	15	32	12	12

Table A4: CAD color vision testing results

CAD				
PID	ColorMax	CVD Type	rg	by
886	no	Protan	26.54	1.11
886	yes	Protan	29.19	2.15
864	no	Protan	25.45	1.22
864	yes	Protan	15.81	1.66
887	no	Protan	25.83	1.61
887	yes	Protan	26.15	1.64
616	no	Protan	22.59	1.69
616	yes	Protan	31.07	1.94
571	no	Deutan	19.87	0.8
571	yes	Deutan	4.06	0.95
32	no	Deutan	28.54	1.39
32	yes	Deutan	5.85	1.94
846	no	Protan	5.45	1.16
846	yes	Protan	4.34	1.39
1	no	Protan	8.15	1.54
1	yes	Protan	6.55	1.66

Table A5: Konan CCT HD color vision testing results

PID	ColorMax	CVD Type	Konan		
			ScoreR	ScoreG	ScoreB
886	no	Protan	4	98	135
886	yes	Protan	74	-15	114
864	no	Protan	-15	93	129
864	yes	Protan	116	87	149
887	no	Protan	-18	94	126
887	yes	Protan	66	62	144
616	no	Protan	0	97	131
616	yes	Protan	108	3	134
571	no	Deutan	104	28	161
571	yes	Deutan	151	139	161
32	no	Deutan	89	-3	125
32	yes	Deutan	111	93	117
846	no	Protan	56	98	162
846	yes	Protan	108	76	159
1	no	Protan	43	78	109
1	yes	Protan	103	42	145
783	no	Normal	111	128	133
783	yes	Normal	126	119	125
256	no	Normal	125	134	130
256	yes	Normal	137	143	153
884	no	Normal	149	141	162
884	yes	Normal	152	149	162
395	no	Normal	137	136	157
395	yes	Normal	144	137	144
835	no	Normal	144	143	162
835	yes	Normal	153	150	162

Table A6: Simulation response times

PID	Condition Number	ColorMax	Color Set	Total Trials	Overall Trial Time (s)	HDD Search Time (s)	HMD Search/Selection Time (s)	OTW Wingtip Time (s)	Altitude Decision Time (s)
s32	1	No	Monochrome	118	14.792	2.984	9.291	1.646	2.139
s32	2	No	RGB	117	14.696	2.444	8.544	1.816	2.256
s32	3	Yes	Monochrome	120	14.454	2.023	8.277	2.278	2.115
s32	4	Yes	RGB	89	19.849	2.728	11.636	2.692	2.648
s571	1	No	Monochrome	126	13.739	1.808	9.253	1.474	1.520
s571	2	No	RGB	106	16.199	1.889	10.069	1.900	1.946
s571	3	Yes	Monochrome	107	16.196	1.516	9.073	3.622	1.928
s571	4	Yes	RGB	84	20.739	1.935	9.716	5.203	3.205
s616	1	No	Monochrome	76	23.106	1.894	16.001	1.784	2.430
s616	2	No	RGB	93	18.894	1.995	12.191	1.234	2.088
s616	3	Yes	Monochrome	103	16.943	2.136	11.627	1.241	1.782
s616	4	Yes	RGB	102	17.167	2.041	11.192	1.271	1.531
s846	1	No	Monochrome	162	10.626	1.564	7.063	0.923	1.203
s846	2	No	RGB	163	10.353	1.570	6.634	0.772	1.073
s846	3	Yes	Monochrome	179	9.571	1.479	6.184	0.817	0.982
s846	4	Yes	RGB	166	10.304	1.626	6.791	0.862	0.910
s864	1	No	Monochrome	173	10.214	1.683	7.619	0.656	0.844
s864	2	No	RGB	134	13.152	2.207	9.628	0.778	1.152
s864	3	Yes	Monochrome	92	19.645	4.377	16.472	0.949	1.128
s864	4	Yes	RGB	92	19.393	2.356	14.480	1.097	1.903
s886	1	No	Monochrome	118	14.902	2.638	10.468	1.030	1.366
s886	2	No	RGB	90	19.130	1.929	11.772	1.938	2.005
s886	3	Yes	Monochrome	127	13.842	1.993	9.748	1.270	1.049
s886	4	Yes	RGB	129	13.520	2.342	8.698	0.879	1.413

Table A7: Simulation subtask accuracy

PID	Condition Number	ColorMax	Color Set	Total Trials	Overall Trial Accuracy (%)	HDD Search Accuracy (%)	HMD Search/Selection Accuracy (%)	OTW Wingtip Accuracy (%)	Altitude Decision Accuracy (%)
s32	1	No	Monochrome	118	92.37	97.46	100.00	77.97	94.07
s32	2	No	RGB	117	92.95	96.58	100.00	78.63	96.58
s32	3	Yes	Monochrome	120	81.04	99.17	99.17	28.33	97.50
s32	4	Yes	RGB	89	83.71	98.88	100.00	38.20	97.75
s571	1	No	Monochrome	126	98.21	99.21	100.00	97.62	96.03
s571	2	No	RGB	106	96.93	100.00	100.00	88.68	99.06
s571	3	Yes	Monochrome	107	93.93	100.00	100.00	80.37	95.33
s571	4	Yes	RGB	84	82.44	100.00	100.00	35.71	94.05
s616	1	No	Monochrome	76	88.49	69.74	100.00	96.05	88.16
s616	2	No	RGB	93	94.09	81.72	100.00	97.85	96.77
s616	3	Yes	Monochrome	103	92.48	86.41	100.00	86.41	97.09
s616	4	Yes	RGB	102	94.36	91.18	100.00	87.25	99.02
s846	1	No	Monochrome	162	98.61	99.38	100.00	100.00	95.06
s846	2	No	RGB	163	99.85	100.00	100.00	100.00	99.39
s846	3	Yes	Monochrome	179	99.58	100.00	100.00	100.00	98.32
s846	4	Yes	RGB	166	98.95	98.80	100.00	99.40	97.59
s864	1	No	Monochrome	173	99.28	98.27	100.00	98.84	100.00
s864	2	No	RGB	134	97.95	95.52	100.00	97.01	99.25
s864	3	Yes	Monochrome	92	81.25	77.17	100.00	47.83	100.00
s864	4	Yes	RGB	92	78.26	70.85	100.00	48.91	93.48
s886	1	No	Monochrome	118	98.09	96.61	99.15	98.31	98.31
s886	2	No	RGB	90	91.94	100.00	100.00	70.00	97.78
s886	3	Yes	Monochrome	127	89.76	90.55	100.00	75.59	92.91
s886	4	Yes	RGB	129	90.50	97.67	100.00	70.54	93.80

Table A8: Simulation subtask throughput

PID	Condition Number	ColorMax	Color Set	Overall Trial Throughput (accuracy/s)	HDD Search Throughput (accuracy/s)	HMD Search/Selection Throughput (accuracy/s)	OTW Wingtip Throughput (accuracy/s)	Altitude Decision Throughput (accuracy/s)
s32	1	No	Monochrome	0.070	0.416	0.122	0.790	0.647
s32	2	No	RGB	0.069	0.436	0.136	0.653	0.503
s32	3	Yes	Monochrome	0.064	0.578	0.146	0.205	0.639
s32	4	Yes	RGB	0.052	0.421	0.127	0.187	0.552
s571	1	No	Monochrome	0.076	0.619	0.121	0.791	0.808
s571	2	No	RGB	0.064	0.558	0.110	0.610	0.652
s571	3	Yes	Monochrome	0.064	0.689	0.124	0.383	0.649
s571	4	Yes	RGB	0.044	0.558	0.118	0.110	0.477
s616	1	No	Monochrome	0.045	0.377	0.081	0.768	0.418
s616	2	No	RGB	0.054	0.429	0.095	0.970	0.518
s616	3	Yes	Monochrome	0.059	0.431	0.097	0.869	0.626
s616	4	Yes	RGB	0.060	0.467	0.103	0.879	0.796
s846	1	No	Monochrome	0.102	0.668	0.165	1.252	0.971
s846	2	No	RGB	0.105	0.669	0.178	1.447	1.108
s846	3	Yes	Monochrome	0.115	0.706	0.194	1.417	1.313
s846	4	Yes	RGB	0.106	0.635	0.174	1.326	1.273
s864	1	No	Monochrome	0.108	0.637	0.157	1.630	1.282
s864	2	No	RGB	0.083	0.512	0.125	1.418	0.959
s864	3	Yes	Monochrome	0.054	0.233	0.082	0.552	1.028
s864	4	Yes	RGB	0.052	0.355	0.104	0.576	0.685
s886	1	No	Monochrome	0.074	0.435	0.114	1.280	0.932
s886	2	No	RGB	0.054	0.558	0.098	0.592	0.624
s886	3	Yes	Monochrome	0.075	0.551	0.128	0.903	1.214
s886	4	Yes	RGB	0.076	0.514	0.139	1.060	0.885

Table A9: Simulator Display Luminance and Gamma

Luminance measurements at indicated color intensity (cd/m^2)							
Display	Color	0	64	128	192	256	gamma
HDD	white	0.28	6.6	29.6	73.4	144	2.31
HDD	red	0.28	1.79	6.83	16.7	33.2	2.32
HDD	green	0.28	4.79	21.2	52.8	103	2.3
HDD	green	0.28	0.56	1.83	4.16	7.87	2.13
OTW	white	0.16	9.74	46.5	105	187	2.02
OTW	red	0.16	2.15	10	24.6	44.9	2.14
OTW	green	0.16	6.55	30.6	70.6	127	2.06
OTW	blue	0.16	1.14	4.03	8.78	17.8	2.27
HMD	white	0.003	3.35	26.04	74.1	122.73	2.04
HMD	red	0.003	0.65	8	17.74	26.79	1.72
HMD	green	0.003	1.94	27.18	62.16	95.4	1.78
HMD	blue	0.003	0.126	2.16	5.1	7.96	1.83

Table A10: Simulator Display Chromaticity

Display	Color	CIE x	CIE y	Luminance (cd/m ²)
HDD	white	0.307	0.43	144
HDD	red	0.619	0.379	33.2
HDD	green	0.242	0.713	103
HDD	green	0.138	0.075	7.87
OTW	black	0.284	0.382	187
OTW	red	0.604	0.382	44.9
OTW	green	0.258	0.663	127
OTW	blue	0.141	0.08	17.8
HMD	black	0.3509	0.4138	122.73
HMD	red	0.64	0.3449	26.79
HMD	green	0.2945	0.5354	95.4
HMD	blue	0.1236	0.1357	7.96

LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

%	percent
AR	Augmented Reality
CAD	Colour Assessment and Diagnosis
CCT	Cone Contrast Test
cm	Centimeters
CVD	Color Vision Deficiency
CVN	Color Vision Normal
D	Diopter
FAA	Federal Aviation Administration
G-Cone	Green cone
HDD	Head-Down Display
HMD	Helmet-Mounted Display
HOTAS	Hands-on-Throttle-and-Stick
M	Meter
nm	Nanometer
OBVA	Operational Based Vision Assessment
OD	<i>Oculus dexter</i> (right eye)
OS	<i>Oculus sinister</i> (left eye)
OST	Optical See-through
OTW	Out-the-window
OU	<i>Oculus uterque</i> (both eyes)
PAPI	Precision Approach Path Indicator
PIP	Pseudoisochromatic plate
RGB	Red-green-blue
R-Cone	Red cone
W	Watt
XRES	EXtended Reality Experimental Simulator