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An Analytical Evaluation of Unmanned Aircraft System Warning Signals as Processed by a Model of Color Deficiencies

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14. ABSTRACT
In order to assist in the determination of the need for U.S. Army color vision requirements for unmanned aircraft system (UAS) operators, representative cockpit display images from the Shadow and Gray Eagle Universal Mission Simulator (UMS) were collected and analyzed. The UMS monitors, graphics engines, display characteristics, and especially caution/warning imagery are identical to those used in Shadow and Gray Eagle tactical cockpits. Of particular interest were warning or cautionary signals consisting of text overlaid over colored backgrounds. Three background colors were used in order of priority: red for warning, bronze for caution, and blue for advisory. Color vision deficiency (CVD) matrix coefficients for protanomalous, deuteranomalous, and tritanomalous observers with CVD severity indices of 0 to 1.0 (normal to dichromat), were applied to the RGB values for each of the three alert background colors. Twenty-one swatches representing 21 severity scores were created for the three color deficiencies. Swatch RGB colors were converted to CIELAB color space in order to calculate distances between swatches which have previously been used to correlate with perceptual color confusion metrics. Using a CIELAB criterion separation distance of thirteen, only the red-yellow swatch distances for the more severe deuteranomalous observer fell below the criterion. Using a two times criterion distance, which may be better suited for establishing color vision requirements, resulted in some of the protanomalous separations falling below the raised criteria as

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Summary

The United States Army's minimum color vision requirement (Rabin Cone Contrast Test ≥ 55) for Unmanned Aircraft Systems (UAS) operators may conflict with the design of warning/cautionary signals utilized in UAS cockpits. Representative cockpit display imagery from the Shadow and Gray Eagle Universal Mission Simulator (UMS) were examined as a function of color vision deficiency (CVD), a matter of particular interest given the prevalence of CVD in the general population (about 8% of males, less than 1% of females). The UMS caution/warning imagery utilizes three colors to indicate different levels of alert priority: Red for warning, yellow-orange or bronze for caution, and blue for advisory. Using a model of CVD developed by Machado (2010) and perceptual confusion threshold criterion developed by Harding et al. (2018), the three warning signal colors were transformed to visualize the perceptual effects of increasing CVD severity and denote at which level of CVD severity lies the potential for color confusion between the warning signal colors.

Color vision deficiency can occur across multiple levels of severity. Roughly, 25% of color vision deficient individuals are dichromats, those individuals who only possess two functioning cones. The remainder are considered anomalous trichromats, a condition where all three cones are present, but one cone is significantly "weaker" than the others. Machado (2010) modeled the vision of anomalous trichromats and dichromats using a series of coefficients that can be applied to an image to simulate what it would look like to an individual with varying severities of CVD for each type of cone. In this model, a severity score of zero, as in zero deficiencies, represents the vision of a color vision normal observer. A severity score of one represents the vision of a dichromat. Each value between zero and one indicates a level of anomalous trichromacy of increasing severity. Applying Machado's coefficients to the warning/cautionary color signals used in the UMS imagery allowed for the examination of the colors across all levels of protanomalous (red cone deficient), deuteranomalous (green cone deficient), and tritanomalous (blue cone deficient) vision.

Using the author's subjective confusion contrast threshold criterion set to a CIELAB distance of 13 (Harding et al., 2018), the simulated perception of the UMS warning/cautionary color signals revealed that severe protanomalous (for two times criterion level: severity score ≥ 0.65) and deuteranomalous (severity score ≥ 0.70; for two times criterion level: severity score ≥ 0.40) observers will likely find difficulty in discriminating the red from the bronze signal colors. The other warning color combinations (red-blue, bronze-blue) posed no potential risk for confusion. To provide a comparison to a meaningful color vision standard, Machado's (2010) severity scores were related to the Rabin Cone Contrast Test (CCT), one of the standard color vision tests utilized by the United States Army. An introductory examination of the relationship is provided. Of note, the deuteranomalous severity score of 0.70 correlates to a CCT score of 60, which is only slightly higher than the required CCT score ≥ 55 (United States Army Aeromedical Activity, 2020). If the Army applies this same standard to UAS operators, then the results of our analysis suggests that some deuteranomalous UAS operators, who legitimately passed the Rabin CCT with a score of 55 or greater, may still have difficulty discriminating between warning and cautionary alerts.

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Introduction

In order to assist in the determination of the need for U.S. Army color vision requirements for unmanned aircraft system (UAS) operators, representative cockpit display images from the Shadow and Gray Eagle Universal Mission Simulator (UMS) were collected and analyzed. The UMS graphics and color images that are generated by the Multiple Unified Simulation Environment software is accredited by the U.S. Army Aviation Center of Excellence's Directorate of Simulation to be current with deployed tactical systems. Thus, the UMS monitors, graphics engines, display characteristics, and especially caution/warning imagery are identical to those used in Shadow and Gray Eagle tactical cockpits (Figure 1).

The warning or cautionary signals, which consists of white text overlaid over colored backgrounds, are of particular interest. The white text appears to provide sufficient contrast to be of no major concern. However, it is the background colors and their color separation that may be an important issue to evaluate. The operator station uses three background colors for alert messaging. In order of priority, they are red for warning, yellow-orange or bronze for caution, and blue for an advisory. This paper addresses the color discrimination of these three colors. The three colors are analyzed using perceptual color deficiency algorithms developed by Machado and colleagues (2010; 2009).

Figure 1. UMS laboratory at USAARL showing two person operator stations and mission control station in the foreground.

Modeling Color Vision Deficient Observers

In the general population, about 8% of males and less than 1% of females are color vision deficient (CVD). Of these, about 25% are dichromats and the remainder are anomalous trichromats characterized by different photopigments in cones that respond to medium and long wavelength light (i.e., red-green anomalous trichromats) or by a defective S-cone (i.e., blue-yellow anomalous trichromats) (Wright, 1952). Only about one in one-thousand CVD individuals have a defective or an absent S-cone. Recently Machado and associates (Gustavo M. Machado, 2010; Gustavo M. Machado et al., 2009) developed a color vision model based on photoreceptor spectral absorption and color opponent processing that occurs following receptor processing. The model appears to offer advantages for evaluating different severities of color vision deficiencies based on a scale of zero to one. Zero, as in zero deficiencies, is representative of normal color vision, whereas a score of one represents a dichromat. Scores between zero and one represent the severity of a diminished chromatic discrimination. For red-green color blindness, the model simply shifts the anomalous L- or M-cone photoreceptor absorption spectrum towards the normal M- or L-cone absorption spectrum. Each 10% reduction in the gap between the spectrums relates to a severity increase of 0.1. Therefore, a protanomalous score of 0.5 is representative of a shift of the L-cone photoreceptor absorption spectrum towards the M-cone spectrum to half of the normal separation. Machado et al. estimate the normal separation to be about 20 nm. Fortunately, the authors provide a simpler method for calculating and visualizing the perception of CVD colors. In an appendix to Machado's thesis (Gustavo M. Machado et al., 2009), matrix coefficients are provided for calculating CVD RGB values for the entire range of colorblind observers. The matrix coefficients are reproduced here and shown in the appendix.

Methods

Representative Unmanned Aircraft System Imagery

Representative imagery (Figure 2) from the UMS for both the Shadow and Gray Eagle were captured using a screen capture procedure. Captured images were saved in Portable Network Graphics (PNG) format. PNG is a bitmap image format that uses lossless data compression, that is, all pixels are retained intact and pixel RGB information is not altered.

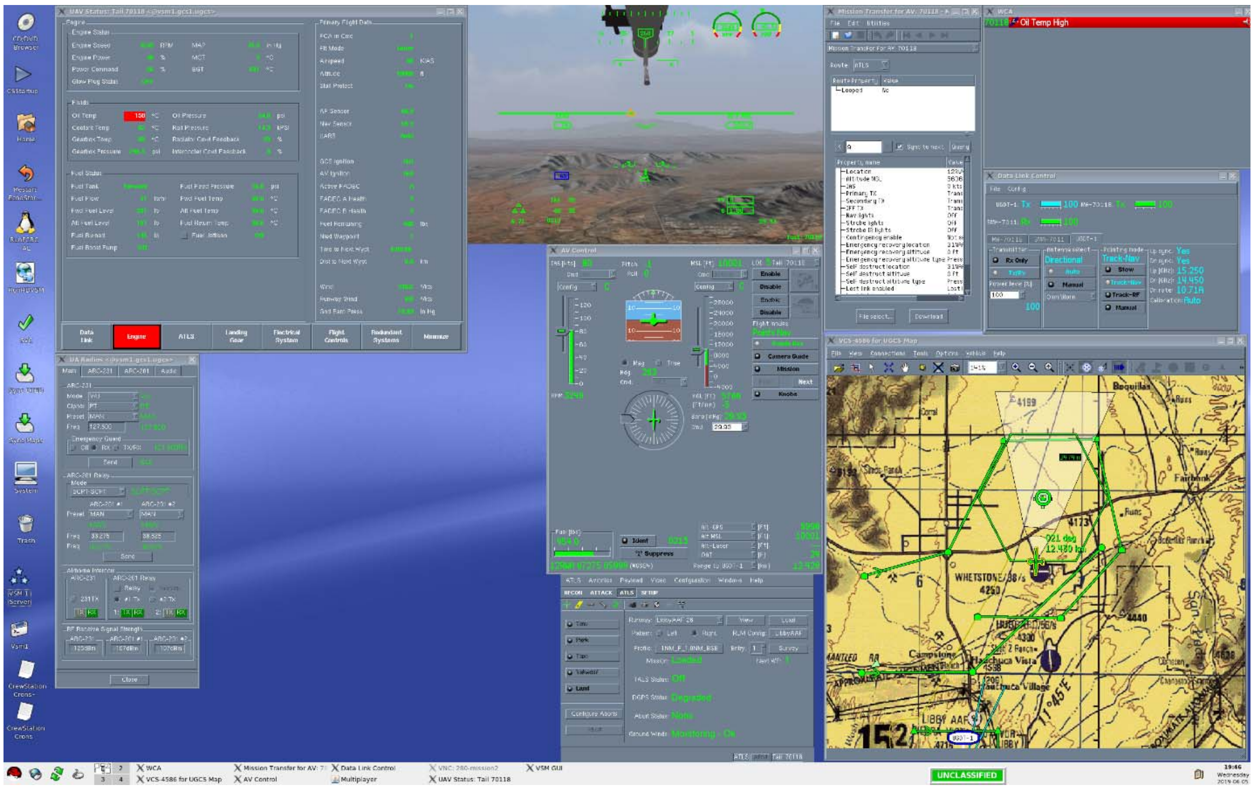

Figure 2. Gray Eagle captured image. Note Oil temperature caution (in red) in the upper right portion of the image.

Captured images were 2560 pixels wide by 1600 pixels high which equaled the screen resolution of the UMS operator displays. To reduce image processing time in MATLAB (Mathworks, Inc.), smaller images (segments of the captured images) were selected in Photoshop (Adobe, Inc.) and saved as separate images with no pixel compression or other alteration. For example, Figure 3 shows the alert window with multiple caution alerts appearing. The background colors (red, bronze, and blue) of each alert were analyzed and the RGB values are shown in Table 1. For each cautionary alert, the colored background varied slightly as can be seen in the range of RGB values depicted for each alert color. For calculations concerning color separation between cautionary alert background colors, RGB averages will be used. Figure 4 shows the three original background color compositions and an image constructed of the average RGB value within each background. Note that the perceived colors for each image appear quite similar and differences appear nearly imperceptible.

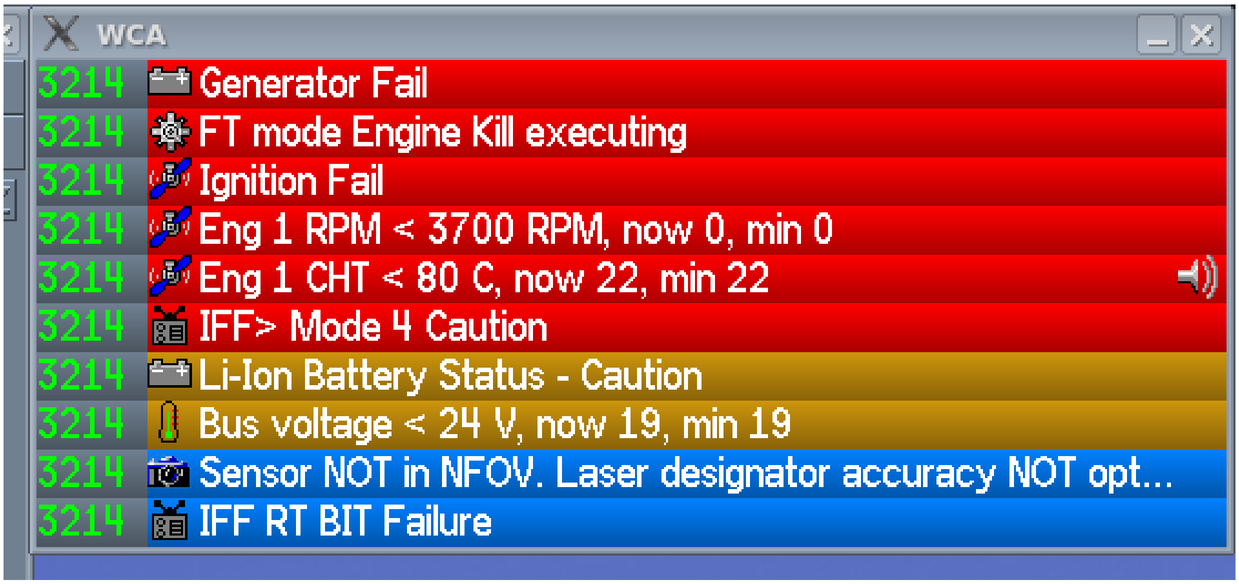

Figure 3. Shadow cautionary alert window. The same colors were used for cautionary alerts in both the Gray Eagle and the Shadow.

Table 1. RGB values for the cautionary alert background colors shown in Figure 3

RGB Values for UAS Cautionary Alert Background Colors			
RGB	**RED**	**Bronze**	**Blue**
Maximum R	253	203	0
Minimum R	172	139	0
Average R	213	171	0
Maximum G	0	148	127
Minimum G	0	100	86
Average G	0	124	107
Maximum B	0	12	253
Minimum B	0	8	172
Average B	0	10	213

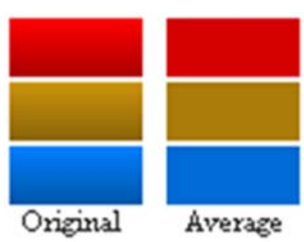

Figure 4. Original cautionary alert backgrounds and their average.

Given the average RGB values for each of the three colors, relative luminances can be calculated using a gamma of 2.4 and standard RGB (sRGB) luminance contributions of 21.26, 71.52, and 7.22% for red, green, and blue subpixels, respectively. As a percentage of maximum luminance (255, 255, 255), the bronze alert background was 20.8%, whereas the blue and red background colors were 13.6 and 13.8%, respectively. With an approximate 1.5 times range in background luminances, luminance is not likely to play an important role in background color discrimination. Photometric measurements of the UAS display confirmed the sRGB calculations (measured relative luminances were within ±5% of calculated luminances).

Results

Matrix coefficients for protanomalous, deuteranomalous, and tritanomalous observers with severity indices of 0.05 to 1.0, in 0.05 increments, were applied to the RGB values for each of the three cautionary alert background colors. The 0.05 step size increments were calculated by linear interpolation of the RGB coefficients shown in the Appendix. To calculate the CVD filtered colors, RGB values were converted to linear space (power transform) and the products of the RGB values and respective coefficients summed and then the inverse of the power transform applied using the following formulas:

$$R_{cvd} = 255 * [R_R * (R/255)^{2.4} + R_G *(G/255)^{2.4} + R_B * (B/255)^{2.4}]^{(1/2.4)}$$

$$G_{cvd} = 255 * [G_R * (R/255)^{2.4} + G_G *(G/255)^{2.4} + G_B * (B/255)^{2.4}]^{(1/2.4)}$$

$$B_{cvd} = 255 * [B_R * (R/255)^{2.4} + B_G *(G/255)^{2.4} + B_B * (B/255)^{2.4}]^{(1/2.4)}$$

Where R_R, R_G, R_B, G_R, G_G, G_B, B_R, B_G, and B_B are the coefficients as listed in the appendix for each CVD severity and R_{cvd}, G_{cvd}, and B_{cvd} are color vision deficient observer RGB values. The value of 2.4 in the above equations was equal to gamma for standard RGB or sRGB calculations. It should be noted that Machado did not specify a mathematical method used to process images with his model. To determine their methodology, we processed raw images from their published paper using different equations and compared them to their filtered images. The authors did not convert RGB values to linear values prior to multiplying by their coefficients; they simply multiplied them directly to the raw image RGB values (Gustavo M. Machado et al., 2009).

Figure 5 shows color swatches of the three cautionary alert background colors as seen by protanomalous, deuteranomalous, and tritanomalous observers covering the entire range of severity scores. Notice that the blue warning signal can be clearly discriminated by all observers, whereas the more severe protanomalous and especially the deuteranomalous observers will likely have a difficult time discriminating the bronze from the red signal.

To use a more quantifiable color discrimination metric, the tri-stimulus values of each of the RGB swatches, shown in Figure 5, were calculated and converted to CIELAB coordinates where color separation distances could be measured. In these conversions, D65 or 6500ºK was used as the standard illuminant.

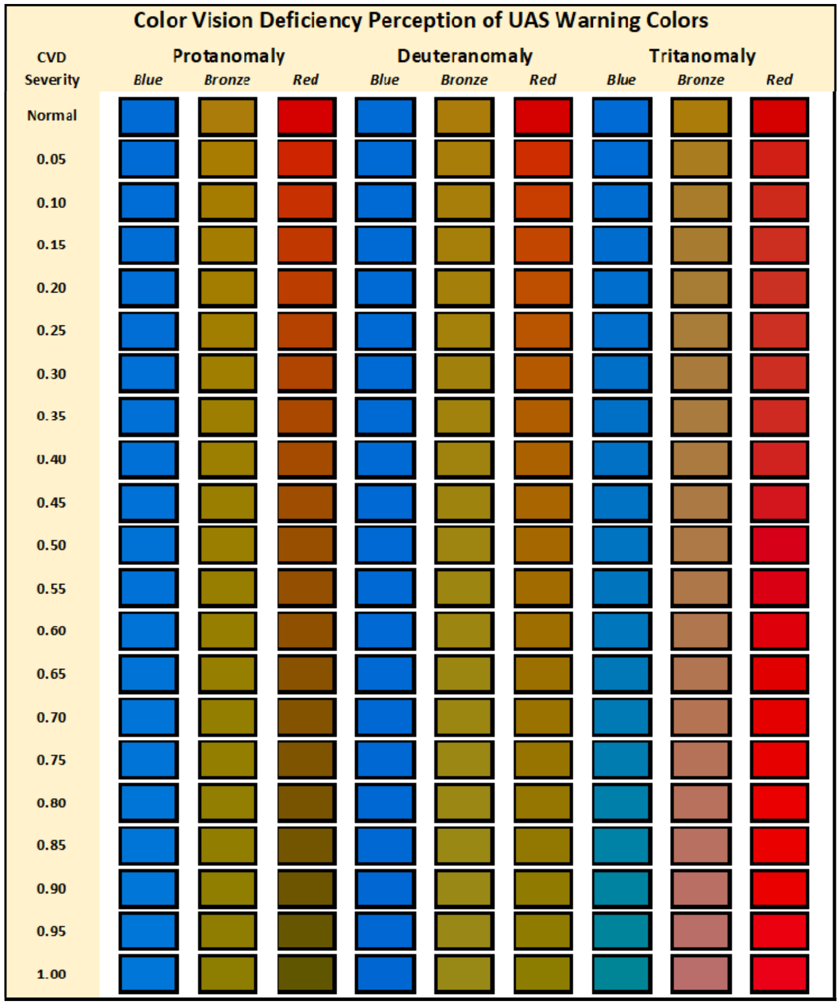

Figure 5. Simulated swatches of UAS warning colors as seen by protanomalous, deuteranomalous, and tritanomalous observers with increasing color vision deficiencies. The top row of swatches are the color vision normal warning colors and the bottom row represents the warning colors as seen by dichromats.

Harding, T., Hovis, J., Rash, C., and M. Smolek (2018) showed that a CIELAB distance criterion of 13 provided a good fit to the primary author's subjective confusion contrast threshold. The confusion contrast threshold was the color contrast level where one color could be easily mistaken for another. In other words, at this threshold level, the correct identification of a color was likely defined by chance performance. At the criterion distance of 13, only the red-bronze deuteranomaly comparisons at a CVD severity of 0.7 and above fell below the threshold distance. As a practical matter, a separation criterion greater than threshold may be needed when color discrimination accuracy is required. To help determine an adequate criterion, CIELAB distances are plotted for the three color pairings (i.e., blue-bronze, blue-red, and bronze-red) for protanomaly and deuteranomaly (Figure 6). The lowest separation distance for any of the tritanomaly color pairings was above 50 and is therefore not plotted. Only the bronze/red pairings for the red-green color deficiencies fell within the criterion ranges. For two times threshold criterion, the bronze/red protanomaly and deuteranomaly severity scores of 0.65 and 0.40, respectively, fell below the criterion.

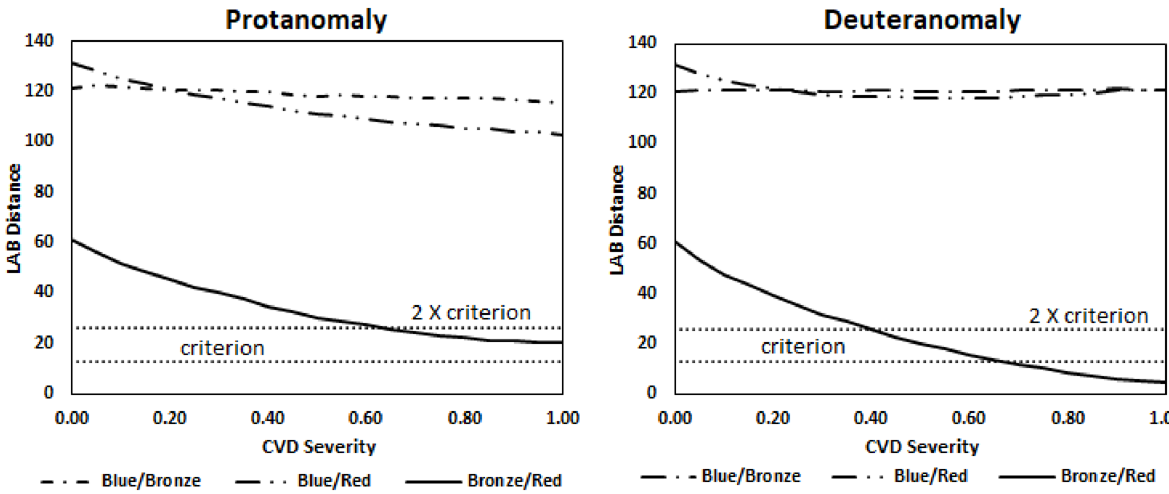

Figure 6. CIELAB distances between cautionary background colors for protanomaly and deuteranomaly as a function of CVD severity. One and 2 times the confusion contrast threshold criterion levels are also plotted.

To provide an example of the color confusion that could occur for deuteranomalous observers, the image in Figure 3 has been filtered with deuteranomaly severity scores of 0.7, 0.4, and 0.2, and the results shown in Figure 7. These severity scores are associated with one (Figure 7d), two (Figure 7c), and three (Figure 7b) times the threshold criterion. The white letter contrast against the background appears fairly unaffected and is easily read at all severity levels.

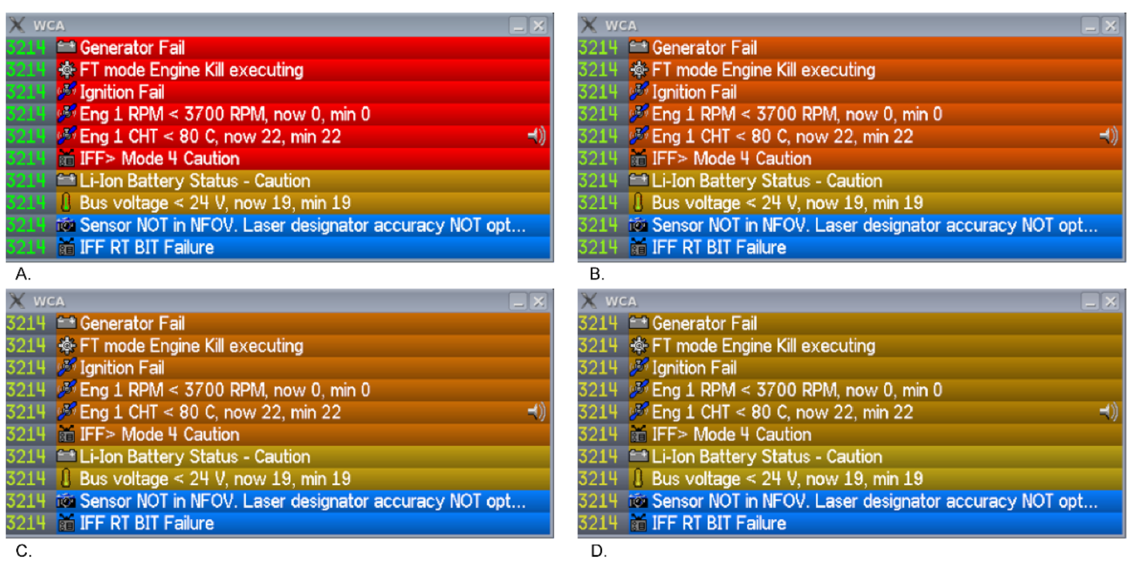

Figure 7. A–Normal color observer. B–Deuteranomalous observer with 0.2 severity. Color distance separation between red and bronze backgrounds is 38.99 (less than three times the criterion). C–Deuteranomalous observer with 0.4 severity. Color distance separation between red and bronze backgrounds is 25.83 (less than two times the criterion). D–Deuteranomalous observer with 0.7 severity. Color distance separation between red and bronze backgrounds is 11.50 (about one times the criterion).

In order to relate Machado's CVD severity scores to a meaningful color vision standard, we developed methods to relate severity scores to Rabin's Cone Contrast Test (CCT) scores (Rabin, Gooch, & Ivan, 2010). To do this, RGB values needed for single cone excitation charts of increasing contrast, like those produced by Rabin et al., (2010) were developed using a non-linear evolutionary solver. The solver identified the RGB population mean, for a given contrast, that would only stimulate the long, medium, or short wavelength cone populations. Charts were developed for both computer and visual assessment (Figures 8 and 9). With the particular background chosen for the two charts shown in Figures 8 and 9, the highest middle wavelength cone contrast that could be achieved was 22.5%, not 27.5% as shown on the charts. Machado's matrix coefficients for protanomalous, deuteranomalous, and tritanomalous observers were used to filter the computer chart and the cone contrasts were calculated for each of the patches. Chart cone contrasts were calculated and attenuation coefficients determined for the full range of CVD severities (from normal to dichromat) and these results were then related to Cone Contrast Test (CCT) scores using equations fit to the cone contrast data shown in Figure 10. Rabin et al., used identical contrasts for scoring sensitivity for the long and middle wavelength cones; therefore, only one curve is shown in Figure 10 for these cone contrasts. The long and medium cone contrasts have essentially the same slope as the short wavelength cones (based on least squares trend lines fit to Rabin's scoring metrics).

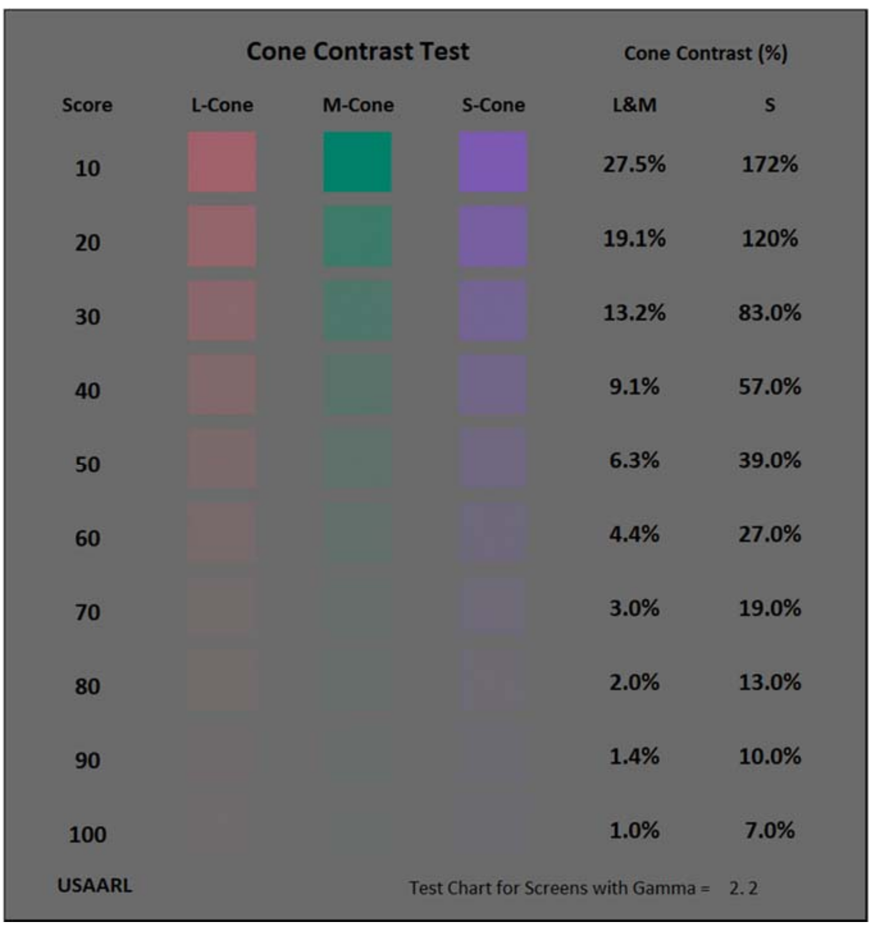

Figure 8. Cone contrast test chart developed for ease of computer assessment of colored patches.

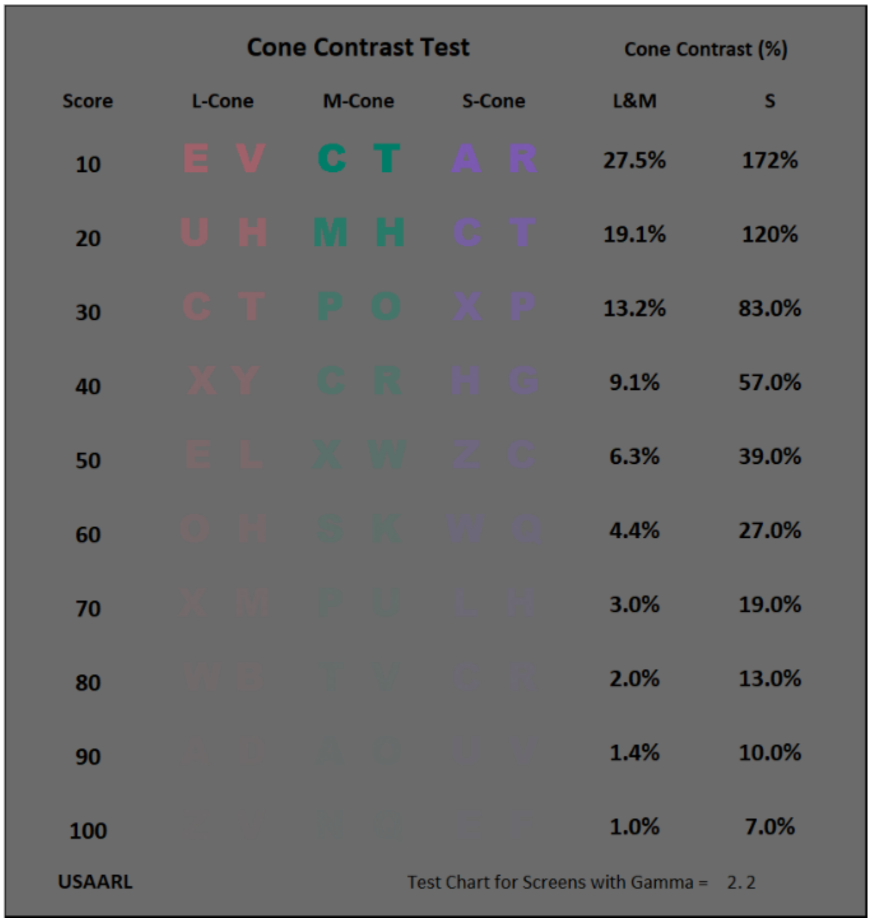

Figure 9. Cone contrast test chart with same cone contrasts as the chart shown in Figure 8.

Using the chart shown in Figure 8 and calculating the average cone contrast attenuation for each color column as a function of CVD severity provided an adequate solution for relating CCT scoring to Machado's CVD severity scores. Several other strategies for evaluating the filtering characteristics of Machado's RGB severity coefficients were analyzed and led to moderate differences in results and these analyses will be discussed in a later paper. Filtering the chart, shown in Figure 8, for each severity level produced cone contrast attenuations that varied across the 10 targets. For long and middle wavelength cone contrast measures, contrast attenuation variability was less for the high contrast targets in Figure 8 (≥ 6.3%). Variability was less for short wavelength cones, perhaps due to less attenuation overall.

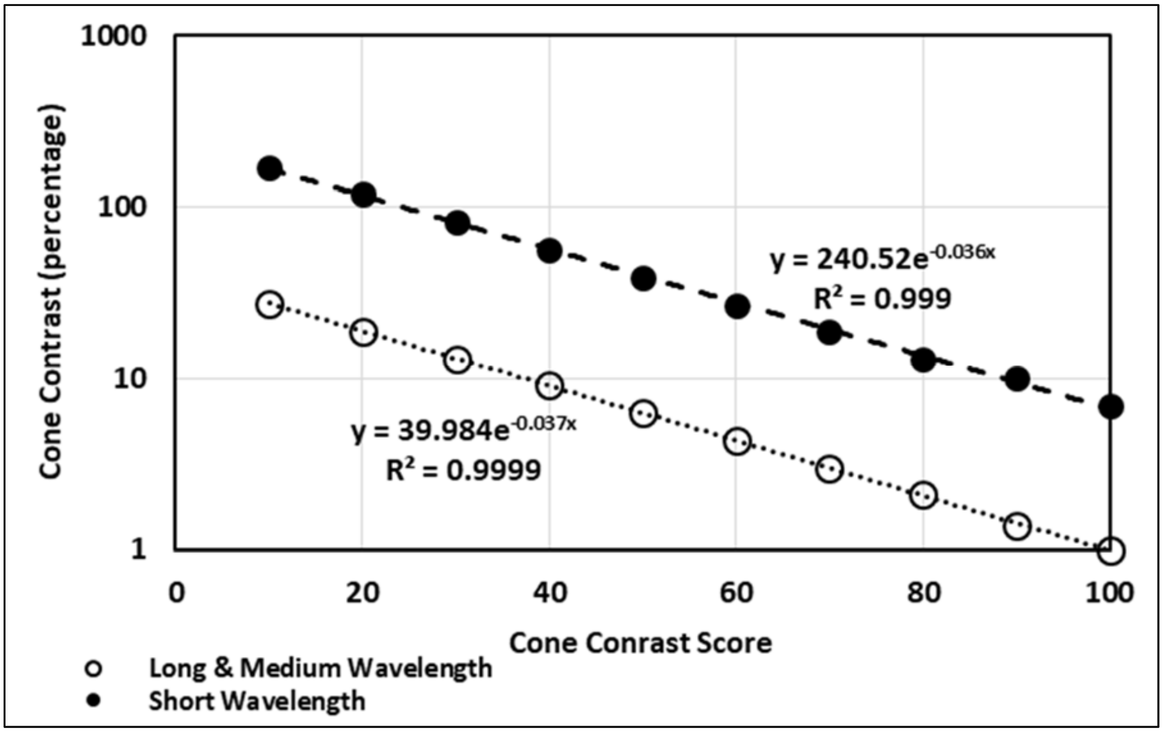

Figure 10. Cone contrasts as a function of CCT scores for short wavelength and long and middle wavelength cones.

The average CVD severity attenuations of contrast was used to plot the protanomalous data shown in Figure 11. A natural log transform was applied to the cone contrast values. Calculating the CCT scores at a natural log cone contrast value of zero (bold horizontal line in Figure 11), yields the protanomalous curve shown in Figure 12. Figure 12 also shows the relationship between Machado's CVD severity scores and the corresponding CCT scores. As might be expected, the protanomalous and deuteranomalous curves are fairly similar with the exception that the deuteranomalous data falls off more abruptly at higher severities.

Inspecting the red/bronze deuteranomaly curve shown in Figure 6, it intersects the single criterion curve at a Machado severity score of about 0.7. From Figure 12, a severity score of 0.7 is equivalent to a middle wavelength cone CCT score of 60.

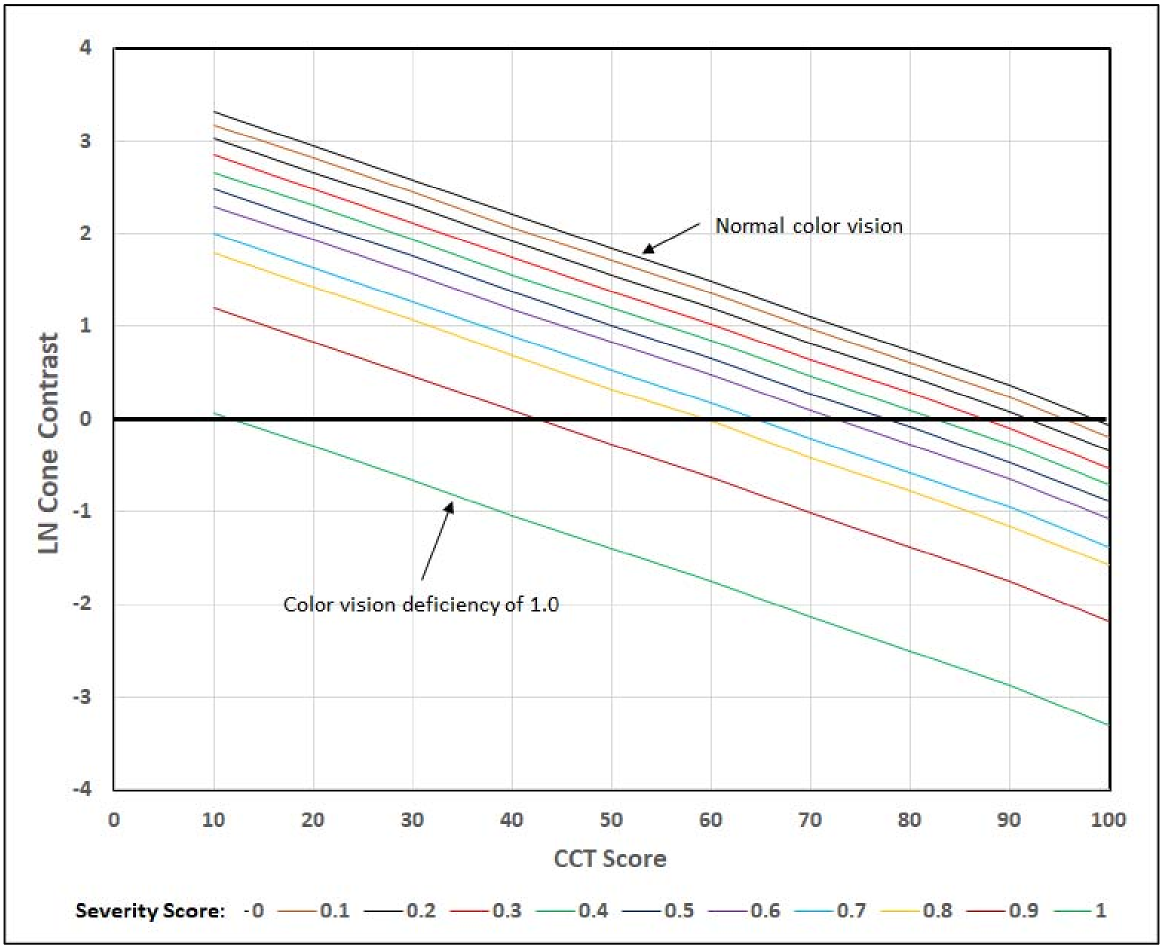

Figure 11. The exponential trend line fit to the long wavelength cone contrast data, shown in Figure 10, is replotted here and labelled normal color vision (top line). Also plotted is the same straight line for each for each 10 severity scores. The curves are simply shifted down based on the contrast attenuation caused by filtering the chart shown in Figure 8 with Machado coefficients for a protanomalous observer with a severity score of 0.1 to 1.0.

Discussion

UAS warning images were evaluated from a color vision deficient observer perspective using a model developed by Machado and associates (2010; 2009). Display warning signals, used by Shadow and Gray Eagle crews, were captured and filtered using RGB coefficients provided by Machado (2010) for different severity levels of color vision deficiencies (Figure 5). The bronze and red warning signals were the only combination that would likely lead to perceptual color confusion, at least for deuteranomalous observers, based on a CIELAB separation (distance) criteria developed by Harding et al. (2018).

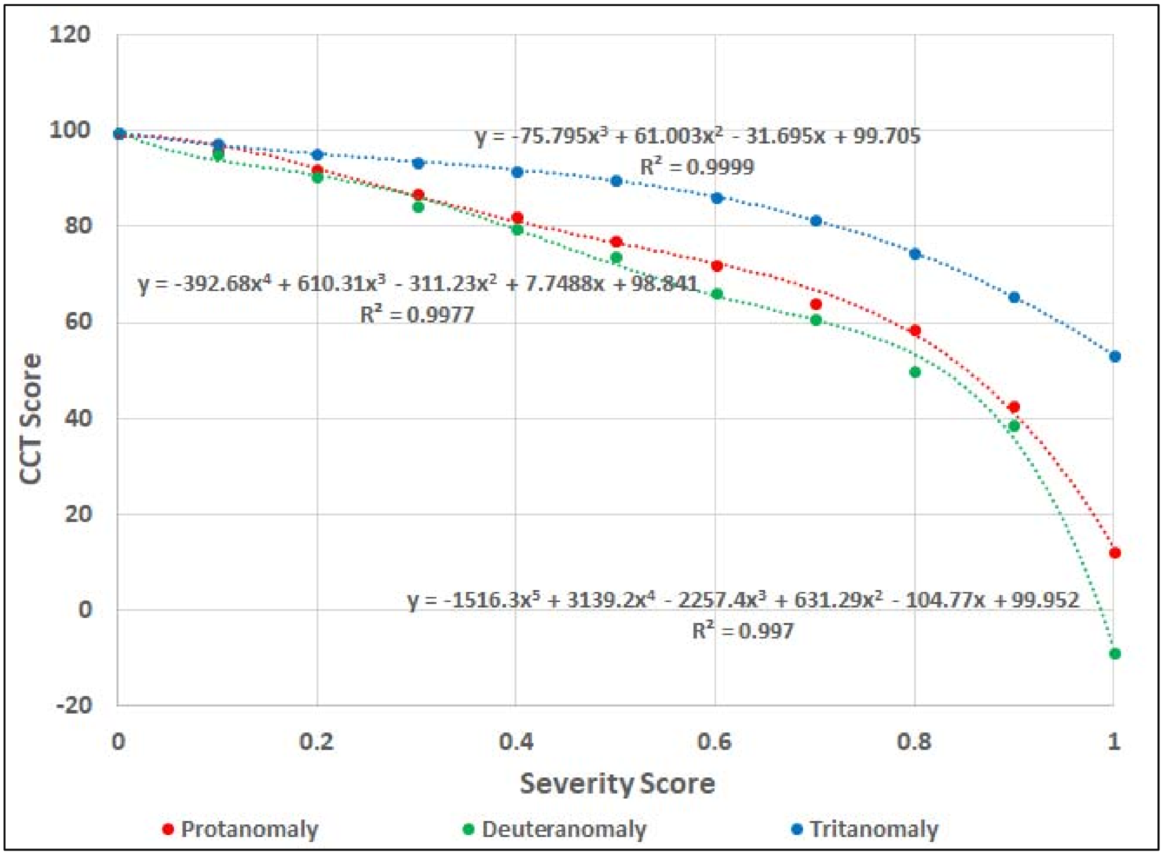

Figure 12. CCT scores as a function of Machado severity scores for protanomalous, deuteranomalous, and tritanomalous observers along with associated polynomial curve fits to the data.

Using data analysis techniques that correlated Machado's model of CVD deficits with Cone Contrast Test (CCT) scores, a CCT score was determined for deuteranomalous observers with a severity score of about 0.7. This severity correlated with a CCT score of about 60. The data were somewhat noisy, especially for the results of filtering the lower contrast targets shown in Figure 8 (< 6.3% for protanomalous and deuteranomalous observers). A score of 60 is slightly higher than the minimum score recommended for passage of the Army's color vision requirement. The most recent Army Policy Letter for Color Vision Deficits (United States Army Aeromedical Activity, 2020) lists a score of 55 or greater on the CCT as necessary for passing the color vision requirement for flying duties. If the Army applies this same standard to UAS operators, then the results of our analysis suggests that some deuteranomalous UAS operators, who legitimately passed the Rabin CCT with a score of 55 or greater, may still have difficulty discriminating between warning and cautionary alerts.

Conclusions

The application of color vision deficient simulation and assessment techniques in the operational environment shows promise for the diagnosis and remediation of potential problems that may occur for color vision deficient operators. This analysis was performed by applying CVD coefficients derived by Machado (2010) to digital imagery provided by a Shadow and Gray Eagle UMS. In the operational environment of the UAS operator, the case for either a redesign of the colors used in the warning imagery (specifically examining the red-bronze color combination) or an adjustment in the minimum passing color vision criterion may be warranted. This analysis showed that severe deuteranomalous (severity score ≥ 0.70) operators can pass the CCT with a score around 60 (minimum passing is 55), but those same individuals' ability to discriminate the red-bronze color combination may be suspect, given a color confusion threshold set to a CIELAB distance of 13. However, this assumes an operator can successfully discriminate between the warning (red) and cautionary (bronze) alert colors in a stressful situation during operation. It may be more practical to consider an operator's confusion threshold to be higher during these more demanding situations. Multiplying the color confusion threshold by two yields a larger population of both protanomalous (severity score ≥ 0.65) and deuteranomalous (severity score ≥ 0.40) observers who may struggle in the discrimination between warnings and cautionary alerts during extreme cases of UAS operation.

Extending Machado's (2010) model of CVD to the meaningful color standard of the Rabin CCT offers opportunities to remedy the problems highlighted here. Using an operator's known Rabin CCT score, an operator can be assigned a Machado severity score for their specific type of CVD. Using this severity score, a rotation of the color space used for a display an operator is logged into can be performed with the help of a custom shader program. This would yield an efficient method to both individualize the display for a specific operator as well as potentially increasing the range of acceptable CCT scores required for UAS flight operations. At this stage, however, the modeled relationship between Machado's (2010) CVD model and the Rabin CCT must be examined further due to excessive noise introduced by both models as they approached threshold.

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Appendix A: RGB Coefficients Developed for CVD Observers by Machado (2010)

Severity	Protanomaly			Deuteranomaly			Tritanomaly		
0.00	1.000	0.000	0.000	1.000	0.000	0.000	1.000	0.000	0.000
	0.000	1.000	0.000	0.000	1.000	0.000	0.000	1.000	0.000
	0.000	0.000	1.000	0.000	0.000	1.000	0.000	0.000	1.000
0.05	0.928	0.091	-0.019	0.933	0.089	-0.022	0.964	0.047	-0.010
	0.015	0.978	0.008	0.025	0.970	0.006	0.011	0.983	0.007
	-0.002	-0.001	1.002	-0.002	0.004	0.998	0.004	0.028	0.969
0.10	0.856	0.182	-0.038	0.866	0.178	-0.044	0.927	0.093	-0.019
	0.029	0.955	0.016	0.050	0.939	0.011	0.021	0.965	0.014
	-0.003	-0.002	1.004	-0.003	0.007	0.996	0.008	0.055	0.937
0.15	0.796	0.259	-0.054	0.814	0.249	-0.062	0.912	0.113	-0.024
	0.041	0.937	0.023	0.071	0.914	0.016	0.026	0.955	0.020
	-0.004	-0.003	1.007	-0.005	0.010	0.995	0.011	0.080	0.910
0.20	0.735	0.335	-0.070	0.761	0.319	-0.080	0.896	0.133	-0.029
	0.052	0.919	0.029	0.091	0.889	0.020	0.030	0.945	0.025
	-0.005	-0.004	1.009	-0.006	0.013	0.993	0.013	0.105	0.882
0.25	0.683	0.401	-0.083	0.718	0.377	-0.095	0.901	0.131	-0.032
	0.061	0.905	0.035	0.108	0.869	0.024	0.029	0.943	0.029
	-0.006	-0.006	1.012	-0.007	0.016	0.991	0.013	0.127	0.860
0.30	0.630	0.466	-0.096	0.675	0.434	-0.109	0.906	0.128	-0.034
	0.069	0.890	0.041	0.125	0.848	0.027	0.027	0.941	0.032
	-0.006	-0.008	1.014	-0.008	0.019	0.989	0.013	0.148	0.838
0.35	0.585	0.523	-0.107	0.641	0.482	-0.122	0.927	0.109	-0.036
	0.076	0.878	0.046	0.140	0.830	0.030	0.021	0.944	0.036
	-0.007	-0.010	1.017	-0.009	0.021	0.988	0.012	0.171	0.817
0.40	0.539	0.579	-0.118	0.606	0.529	-0.134	0.948	0.089	-0.038
	0.083	0.866	0.051	0.155	0.812	0.032	0.014	0.947	0.039
	-0.007	-0.012	1.019	-0.009	0.023	0.986	0.011	0.194	0.795
0.45	0.499	0.630	-0.128	0.577	0.569	-0.145	0.983	0.058	-0.041
	0.088	0.856	0.056	0.169	0.797	0.035	0.004	0.953	0.044
	-0.007	-0.015	1.022	-0.010	0.025	0.985	0.009	0.222	0.770
0.50	0.458	0.680	-0.138	0.547	0.608	-0.155	1.017	0.027	-0.044
	0.093	0.846	0.061	0.182	0.782	0.037	-0.006	0.958	0.048
	-0.007	-0.017	1.024	-0.010	0.027	0.983	0.006	0.249	0.745
0.55	0.422	0.725	-0.146	0.523	0.642	-0.165	1.061	-0.010	-0.051
	0.097	0.838	0.066	0.194	0.769	0.039	-0.019	0.965	0.055
	-0.007	-0.020	1.027	-0.011	0.029	0.982	0.004	0.284	0.713
0.60	0.385	0.769	-0.154	0.499	0.675	-0.174	1.105	-0.047	-0.058
	0.101	0.830	0.070	0.205	0.755	0.040	-0.032	0.972	0.061
	-0.007	-0.022	1.030	-0.011	0.031	0.980	0.001	0.318	0.681
0.65	0.353	0.810	-0.162	0.479	0.704	-0.182	1.149	-0.079	-0.071
	0.104	0.823	0.074	0.216	0.743	0.042	-0.045	0.976	0.070
	-0.007	-0.025	1.033	-0.012	0.033	0.979	-0.001	0.361	0.640

Severity	Protanomaly			Deuteranomaly			Tritanomaly		
0.70	0.320	0.850	-0.169	0.458	0.732	-0.190	1.193	-0.110	-0.083
	0.106	0.816	0.078	0.226	0.731	0.043	-0.058	0.979	0.079
	-0.007	-0.028	1.035	-0.012	0.034	0.977	-0.002	0.403	0.599
0.75	0.290	0.887	-0.176	0.441	0.757	-0.197	1.226	-0.125	-0.101
	0.108	0.810	0.082	0.236	0.721	0.044	-0.068	0.977	0.091
	-0.007	-0.031	1.038	-0.012	0.036	0.976	-0.003	0.452	0.551
0.80	0.259	0.923	-0.182	0.423	0.781	-0.204	1.258	-0.140	-0.118
	0.110	0.804	0.085	0.246	0.710	0.045	-0.078	0.975	0.103
	-0.006	-0.034	1.041	-0.012	0.037	0.974	-0.003	0.501	0.502
0.85	0.232	0.957	-0.188	0.408	0.803	-0.211	1.269	-0.133	-0.136
	0.112	0.800	0.089	0.255	0.700	0.046	-0.082	0.967	0.115
	-0.006	-0.038	1.044	-0.012	0.039	0.973	-0.002	0.551	0.451
0.90	0.204	0.990	-0.194	0.393	0.824	-0.217	1.279	-0.125	-0.154
	0.113	0.795	0.092	0.264	0.690	0.046	-0.085	0.958	0.127
	-0.005	-0.041	1.046	-0.012	0.040	0.972	-0.001	0.601	0.400
0.95	0.178	1.022	-0.200	0.380	0.843	-0.223	1.268	-0.101	-0.167
	0.114	0.791	0.096	0.272	0.682	0.047	-0.082	0.945	0.138
	-0.005	-0.045	1.049	-0.012	0.042	0.971	0.002	0.646	0.352
1.00	0.152	1.053	-0.205	0.367	0.861	-0.228	1.256	-0.077	-0.179
	0.115	0.786	0.099	0.280	0.673	0.047	-0.078	0.931	0.148
	-0.004	-0.048	1.052	-0.012	0.043	0.969	0.005	0.691	0.304

Appendix B: Acronyms and Abbreviations

CIELAB	International Commission on Illumination (CIE) L=Lightness; A=red to green coordinates; B=yellow to blue coordinates
CCT	Rabin's Cone Contrast Test
CVD	color vision deficient
PNG	Portable Network Graphic
RGB	red, green, blue
sRGB	standard red, green, blue
UAS	unmanned aircraft system
UMS	Universal Mission Simulator

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