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A New Perspective on Color Vision Deficiency Diagnosis: Individual Color Matching Functions and Illuminations to Improve Color Discrimination

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Abstract

In this study, a comprehensive test on 20 observers with color vision deficiencies was performed, including the standard Ishihara color vision test, the Farnsworth Panel D-15 test, and the anomaloscope test. In addition, a visual tricolorimeter to measure the individual color matching functions (ICMFs) of these observers was employed. The results showed that, except for the D-15 test, which exhibited some false negatives, the outcomes of the other three tests were completely consistent. This indicates the potential of ICMFs in diagnosing color vision deficiencies. Furthermore, the color discrimination abilities of these observers were tested under four specific light sources. The findings suggest that the vision for both Protan and Deutan observers can be significantly improved by one type of light source, especially for the Deutan observers.

Introduction

Human color vision relies on three types of cone cells—long- (L), middle- (M), and short-wavelength (S) cones—each with distinct spectral sensitivities. These cones convert the light spectrum into three separate cone signals [1]. Genetic factors can cause some individuals to lack one or more types of cone photoreceptors, or to have defective cones; such individuals are described as color vision deficient (CVD). Approximately 8 % of males and 0.4 % of females are affected by various forms of CVD [2]. When a person lacks one type of cone, they are considered dichromatic: protanopia (missing L cone), deuteranopia (missing M cone), or tritanopia (missing S cone). In cases where the cones are defective rather than absent, the conditions are known as protanomaly, deuteranomaly, or tritanomaly—depending on whether the L, M, or S cone is affected.

Currently, various methods have been developed to efficiently screen for CVD and assess its type and severity. Common approaches include the pseudoisochromatic plate (PIP) test, the hue arrangement test, and the color-matching test.

Among these, PIP tests—most notably the Ishihara test [3]—are widely used to detect the presence of CVD. The Ishihara test consists of plates featuring letters, numbers, or geometric shapes formed by colored dots of different sizes, set against a background of dots with the same lightness but different colors. Individuals with CVD have difficulty identifying these figures because the colors used for the figures and the background are selected to fall along confusion lines that are easily mixed by those with color vision deficiencies.

Hue arrangement tests are also commonly used to evaluate color vision deficiencies. The Farnsworth-Munsell 100-Hue (FM100-Hue) test [4] is the best-known and most widely used of these. It can provide quantitative scores that can be compared to statistical norms, making it well suited for both clinical and research purposes [5]. Another widely used test is the Farnsworth Dichotomous or D-15 panel [6], which distinguishes individuals with severe color vision loss from those with mild defects or normal vision. The D-15 test is faster than the FM100-Hue and can also determine the type of color vision deficiency present.

The anomaloscope test is a widely used method for detecting color vision deficiencies through color matching. To detect red-green color vision deficiencies, the Rayleigh match [7] is performed: one half of the viewing field displays a red-green mixture, the other half displays yellow light, and observers adjust the light intensities to achieve a match. The Rayleigh equation, along with its refinements, is considered the standard reference test for determining normal or abnormal red–green color vision and diagnosing the exact type of red-green color vision deficiency [8]. This method provides the highest accuracy among available techniques. For assessing tritan color vision deficiency, the Moreland match [9] is used, in which observers match cyan light with a mixture of blue and green lights.

Some image enhancement algorithms and special types of glasses have been developed to improve the color discrimination ability of color deficient observer (CDO). For example, EnChroma® [10] claims that their glasses can enhance color perception in people with color vision deficiencies. Several researchers have assessed the actual effectiveness of these glasses [11, 12]. The results of Venkata et al. [11] show a statistically significant improvement in scores on the Ishihara test and the D-15 test. Additionally, some researchers have designed specialized light sources to enhance color discrimination in people with CVD. Shigeki Nakauchi et al. [13] developed several light sources that alter the distribution of Farnsworth–Munsell hue test samples in color space. This approach led to some improvement in color discrimination for CDOs, but the enhancement was limited for protan-type deficiencies.

In this study, a color deficiency identification method based on color matching was utilised. This method enables measurement of the individual LMS curves of CDOs. Our approach utilizes a visual trichromator [14], combined with the Stockman and Rider extended CIEPO 06 model [15], to derive physiological visual parameters, including the long- and medium-wavelength cone spectral sensitivities shift. The type and severity of color vision anomaly are determined by analyzing this shift. Using this system, the color matching functions (CMFs) of one hundred Chinese observers were accumulated [16]. Both intra-observer and inter-observer variability analyses were conducted, and verified the stability and effectiveness of our method using an independent test set for cross-media reproduction [17]. Currently, this system is applied to analyze color vision deficiency observers and comparing the results with those obtained from conventional methods.

After classifying and testing color vision-deficient observers using various methods, our team designed four specialized illuminants and compared Ishihara test and D-15 test scores under different lighting conditions. These light sources also produced statistically significant improvements in color discrimination ability. Furthermore, these sources have few zero wavelengths and broad peaks, making it easy to convert them into glass transmission profiles with minimal energy loss.

Color deficiency evaluation

As noted above, several methods are available to evaluate color-deficient observers. In this study, each observer underwent a series of tests, including the Ishihara test, D15 test, and anomaloscope examination. Finally, their individual color matching functions were measured for comparison with the other test results. A total of 20 CDOs participated, all male school students with no prior background in color or vision science.

Apparatus and Environment

Observers viewed the Ishihara test plates under a D65 simulator (approximately 1000 lux), describing what they saw while the experimenter recorded their responses. This light box is also used to generate four special light sources designed to enhance the CDO's color discrimination capabilities. Subsequently, participants completed the D15 test, with all results documented. Rayleigh matching was performed using a NEITZ OT-II anomaloscope in a dark room.

Individual color matching functions

In this study, a multi-primary visual trichromator named LEDMax® was used to estimate each individual's LMS fundamental CMFs. The experiment setup is shown in Figure 1. This trichromator has been used and described in previous studies [14, 16]. Briefly, a matching half-field and a reference half-field were illuminated by separate LED cubes, each of which contained 18 LEDs with different peak wavelengths. The half-fields were abutting semi-circles making a circular stimulus with different field of view (FOV). A fixed triplet of lights produced the white reference field on the right side with luminance of 120 cd/m^2 and color temperature of 7500°K. We used 13 of the LEDs in various combinations to form 11 different triplets of lights in the matching half-field, listed in Table 1. The second triplets are also the triplets used in the reference field.

Although all participants were CVD, they found during training that using the CIELAB control method made it easier to achieve their desired colors compared to directly adjusting the intensities of the RGB LEDs. Therefore, they used the CIELAB control method to make 11 color matches at a 10-degree field of view. The spectral power distributions (SPDs) of all the matching half-field and the white reference standard of the LEDMax were measured using a JETI 1211 spectroradiometer imaged in the same position as observer's eye. These spectral data are then used to analyze and derive ICMFs.

Table 1. The 11 different triplets of lighs in the mixture half-field

Triplets	R (nm)	G (nm)	B (nm)
1	640	530	430
2	640	530	445
3	640	530	460
4	640	530	475
5	640	505	445
6	640	560	445
7	640	545	445
8	595	530	445
9	605	530	445
10	660	530	445
11	675	530	445

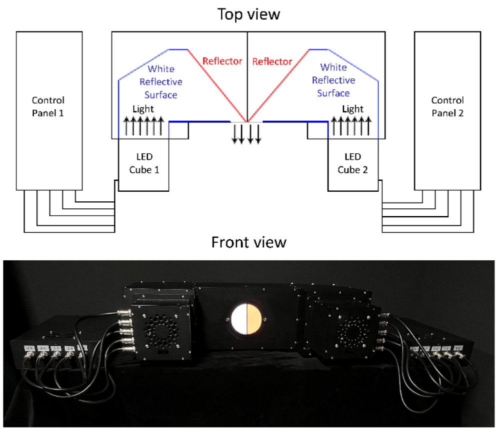

Figure 1. *The structure and appearance of the LEDMax*

Test results and comparison

In addition to identifying the type of color vision deficiency, the results of the above tests also quantified error scores. These error scores will be used in subsequent experiments to assess whether different light sources can improve the color discrimination ability of CDOs.

For the Ishihara test, the error score (eScore) was calculated by adding one point for each incorrect page; if two numbers were presented on a single page, 0.5 points were added for each incorrectly identified number. For the Farnsworth D15 test, color discrimination was quantified using the Confusion index (C-index), as described by Vingrys and King-Smith [18]. In the Rayleigh anomaloscope test, color matching performance was assessed by determining the range of red-green mixture ratios that the participant accepted as a match. Specifically, the matching interval was defined as the difference between the maximum and minimum Rayleigh mixture indices identified by the observer. Additionally, the table presents CVD type identification and LM cone photopigment shifts based on the ICMFs method. The specific derivation methods are described in subsequent section.Table 2 summarizes the type discrimination results and quantization scores of all the above methods.

To compare the results of different methods in determining

Table 2. Summary of all results for CVD tests. "P" represents Protan, "D" represents Deutan.

	Ishihara	D15	Anomaloscope	ICMFs
	Type / eScore	Type / C-index	Type / Range	Type / shifts
Obs 1	P / 20.0	N / 1.0	P / 65.0	P / L -19.50 nm
Obs 2	P / 18.5	N / 1.0	P / 35.5	P / L -12.50 nm
Obs 3	D / 17.5	D / 4.1	D / 73.0	D / M 10.50 nm
Obs 4	D / 18.5	N / 1.0	D / 10.0	D / M 16.50 nm
Obs 5	P / 17.0	P / 3.9	P / 73.0	P / L -15.50 nm
Obs 6	D / 20.5	N / 1.0	D / 5.0	D / L -19.51 nm
Obs 7	D / 19.5	D / 4.0	D / 40.0	D / M 15.57 nm
Obs 8	P / 22.0	P / 3.8	P / 73.0	P / L -19.50 nm
Obs 9	D / 19.5	D / 4.0	D / 64.5	D / M 18.50 nm
Obs 10	D / 18.5	D / 4.0	D / 73.0	D / M 19.50 nm
Obs 11	P / 19.0	P / 4.1	P / 73.0	P / L -17.50 nm
Obs 12	P / 21.5	P / 4.1	P / 73.0	P / L -19.51 nm
Obs 13	P / 21.5	P / 2.7	P / 70.0	P / L -19.50 nm
Obs 14	D / 20.5	D / 1.1	D / 2.5	D / M 14.68 nm
Obs 15	P / 20.5	P / 4.0	P / 7.5	P / L -19.50 nm
Obs 16	D / 16.0	N / 1.0	D / 8.5	D / M 19.50 nm
Obs 17	D / 17.5	D / 4.0	D / 73.0	D / M 19.50 nm
Obs 18	D / 17.0	D / 3.7	D / 40.0	D / M 19.51 nm
Obs 19	D / 20.0	D / 3.9	D / 73.0	D / M 19.50 nm
Obs 20	P / 19.5	P / 4.5	P / 63.5	P / L -19.50 nm

the type of CVD, the test types and calculated the Kendall correlation coefficient were reported. Specifically, for each detection method, a result indicating a Protan was coded as 1, a Deutan as -1, and no defect detected as 0. The Kendall correlation coefficient was then calculated based on these assignments. Table 3 presents the correlation coefficient matrix for the four methods. It can be noted that the ICMFs, Ishihara, and Anomaloscope methods show a correlation coefficient of 1 in determining CVD type, whereas the D15 test has a lower coefficient due to some CDOs passing the test undetected, resulting in missed detections.

Table 3.Kendall Correlation Coefficient Matrix for CVD Types by Different test Methods. Non-diagonal elements with a correlation coefficient of 1 are shown in bold.

	Ishihara	D15	Anomaloscope	ICMFs
Ishihara	1.00	0.82	**1.00**	**1.00**
D15	0.82	1.00	0.82	0.82
Anomaloscope	**1.00**	0.82	1.00	**1.00**
ICMFs	**1.00**	0.82	**1.00**	1.00

Color matching results

Figure 2 shows the matching results of color-deficient observers on the LMS chromaticity diagram. The color coordinates in the LMS chromaticity diagram are calculated using Equation 1, where $\bar{l}_{10}(\lambda)$, $\bar{m}_{10}(\lambda)$, $\bar{s}_{10}(\lambda)$, represents CIE2006 10 degree LMS color matching functions, $SPD(\lambda)$ represents the spectral power distribution of the color stimuli. L , M, S represents the color stimuli's cone excitation.

$$\begin{aligned} L &= \int_{390}^{780} SPD(\lambda)\bar{l}_{10}(\lambda)\,d\lambda \\ M &= \int_{390}^{780} SPD(\lambda)\bar{m}_{10}(\lambda)\,d\lambda \\ S &= \int_{390}^{780} SPD(\lambda)\bar{s}_{10}(\lambda)\,d\lambda \end{aligned} \quad (1)$$

The advantage of this chromaticity diagram is that it allows color deficient observer confusion lines to be plotted easily and in a way that is straightforward to understand. Specifically, the black triangle in the figure represents the color coordinates of the reference field. All points along the straight line connecting the L cone color coordinate and the reference point coordinate will be confused by Protan observers, as shown by the red dashed line in Figure 2. Similarly, all points along the straight line connecting the M cone color coordinate and the reference point coordinate will be confused by Deutan observers, as indicated by the green dashed line in Figure 2. The blue dots in the figure represent 11 matching color coordinates. It can be clearly observed that for all observers, their matching results are close to one of them, which clearly confirms that these people are indeed color-deficient observers and can be clearly classified.

The extended CIEPO06 model developed by Stockman & Rider was used to derive the individual color matching functions of these observers. By optimizing seven physiological parameters in the model to minimize the LMS error between the matched field and the reference field, the ICMFs can be derived. The specific methodology is detailed in our previous studies. Special attention is given during the optimization process to constrain the LM shift in order to prevent the L cone peak from occurring at a shorter wavelength than the M cone peak. The most critical LM shift for CDO is shown in Table 2.

Improving Color Discrimination for Color Deficient observers

Illuminants for color deficient observers

In this study, four illuminants were designed for CDOs. Since the distance between the LM cone peaks in CDO is narrower than those in normal observers, if it can be broadened or a second absorption peak outside the overlap region of the LM cones can be produced, it should be possible to improve the color discrimination ability of CDOs. A simple mathematical transformation in Equation 2 demonstrates that the LMS stimulus values produced by a standard illuminant passing through a filter are equivalent to the stimulus values generated by a standard illuminant and modified cone sensitivities. In the equation, $L(\lambda)$ represents the spectral power distribution of the light source, and $F(\lambda)$ denotes the spectral transmittance of a filter.

$$\begin{aligned} LMS &= \int_{390}^{780} \Big(L(\lambda)F(\lambda)\Big)\overline{lms}_{10}(\lambda)\,d\lambda \\ &= \int_{390}^{780} L(\lambda)\Big(F(\lambda)\overline{lms}_{10}(\lambda)\Big)\,d\lambda \end{aligned} \quad (2)$$

The ideal spectrum of each light source can be generated by multiplying the CIE Standard Illuminant D65 with Gaussian notch filters, each centered at 540 nm, 560 nm, 580 nm, or 600

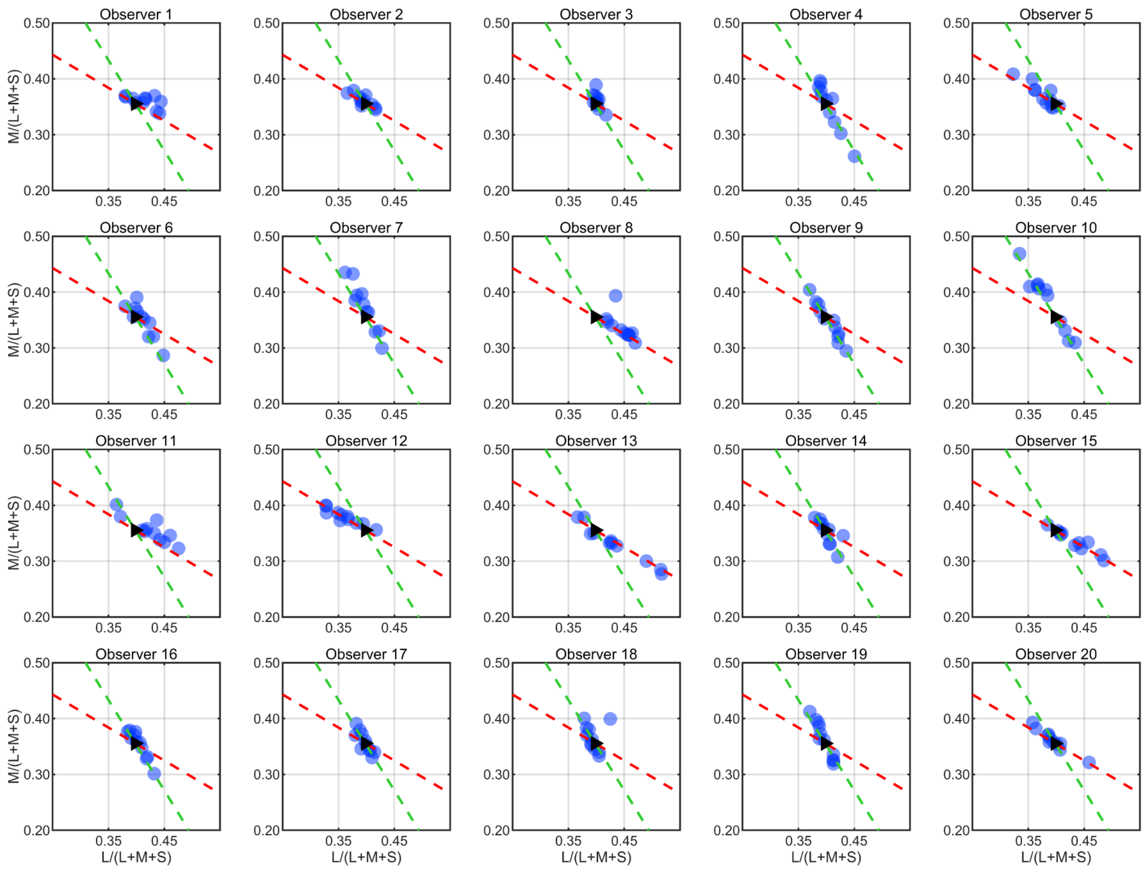

Figure 2. Matched results in LMS chromaticity diagram. Red dashed line represents Protan confusion line, green dashed line represents Deutan confusion line. Blue dots represent 11 matching triplets' color coordinates. Black triangle represents the color coordinate of the reference field.

nm, and by having a full width at half maximum (FWHM) of 40 nm. In the following sections, these are referred to as "Illuminant 540", "Illuminant 560", "Illuminant 580", and "Illuminant 600", respectively. This design allows the light sources to readily simulate the effect of corresponding spectral-transmittance glasses, making it easy to compare them with the effects of commonly used color filter glasses.

After completing the spectral design, a multi-channel light box equipped with 14 LEDs covering the visible wavelength range was used to reproduce these spectra. The target spectra were matched by adjusting the luminous intensity of each LED in the light box, with the resulting spectra shown in Figure 3. Due to the limited number of channels in the light box, there are some discrepancies between the final reproduced spectra and the originally designed spectra.

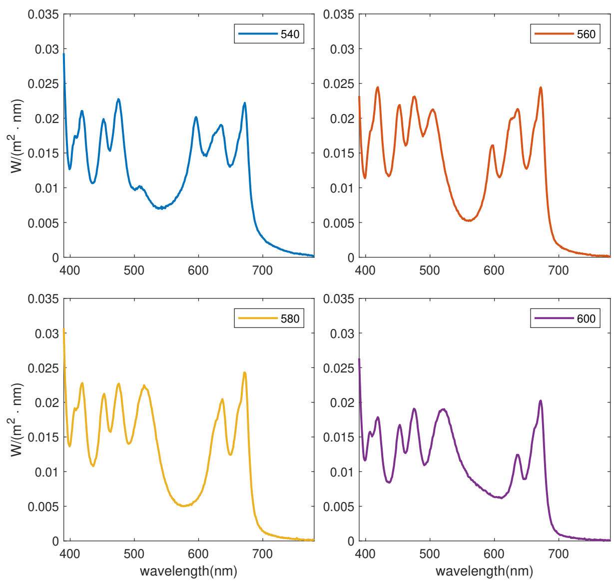

Figure 3. Illumination spectra of four light sources.

Improvement of illuminants

Under these four light sources, the same observers completed the Ishihara test and D-15 test following the same procedures as under the Illuminant D65. The final results were quantified into error scores and confusion indices using the same methods. During quantification, it was noted that the scores for observers with Protan and Deutan color vision deficiencies varied differently with changes in the light source. Therefore, these two conditions are discussed separately.

Table 4 and Table 5 summarized the Ishihara and D-15 test scores for the Protans and Deutans under four test illuminants and a reference D65 source. For Protan observers, the Illuminant 600 resulted in the most improvement on the Ishihara test, while the Illuminant 580 yielded the best results on the D-15 test; however, these improvements were modest. In contrast, Deutan observers showed greater improvements: the Illuminant 540 gave the lowest Ishihara error scores, and the Illuminant 560 led to the largest gains on the D-15 test. The bar chart in Figure 4 shows the mean scores and standard deviations of color defeficient observers under different lighting conditions.

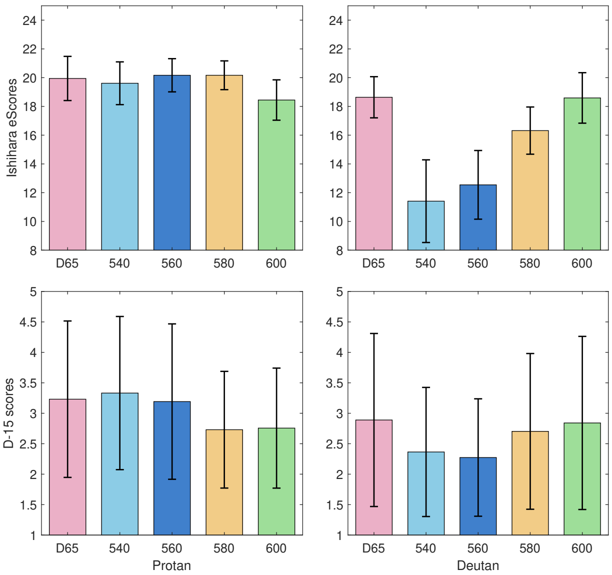

Figure 4. Mean scores of Ishihara and D-15 test for all subjects under different Illuminants. Error bars represent one standard deviation.

Table 4. Mean and standard deviation of Ishihara error scores and D-15 test scores for Protans under different Illuminants.

		D65	540	560	580	600
Ishihara	Mean	19.94	19.61	20.17	20.17	**18.44**
	SD	1.54	1.49	1.15	1.00	1.40
D-15	Mean	3.23	3.33	3.19	**2.73**	2.76
	SD	1.28	1.26	1.28	0.96	0.99

Table 5. Mean and standard deviation of Ishihara error scores and D-15 test scores for Deutans under different Illuminants.

		D65	540	560	580	600
Ishihara	Mean	18.64	**11.41**	12.55	16.32	18.59
	SD	1.43	2.87	2.39	1.64	1.76
D-15	Mean	2.89	2.36	**2.27**	2.70	2.84
	SD	1.42	1.06	0.96	1.28	1.42

One-tailed two-sample t-tests with a left tail were conducted based on the hypothesis that experimental illuminants would reduce error scores (i.e., improve color discrimination) compared to the D65 baseline, as summarized in Table 6.

For protan observers, a significant improvement on the Ishihara test was found only under Illuminant 600 (p = 0.0133), while the other illuminants showed no significant effect. In the D-15 test, Protan observers had significantly lower error scores with Illuminant 580 (p = 0.0139) and Illuminant 600 (p = 0.0259), but not with Illuminant 540 (p = 0.6794) or Illuminant 560 (p = 0.3111). For deutan observers, both the Ishihara and D-15 tests showed significant improvements under Illuminant 540 and Illuminant 560. Illuminant 580 significantly reduced Ishihara errors (p = 0.0035), while Illuminant 600 had no significant effect compared to D65.

Table 6. T-tests p values of Ishihara test and D-15 test between test Illuminant and D65, p less than 0.05 are shown in bold.

		540	560	580	600
Protan	Ishihara	0.3313	0.6252	0.6476	**0.0133**
	D-15	0.6794	0.3111	**0.0139**	**0.0259**
Deutan	Ishihara	**1.57E-05**	**1.18E-05**	**0.0035**	0.4741
	D-15	**0.0041**	**0.0024**	**0.0151**	0.2507

These findings show that certain experimental illuminants can improve color discrimination for CDOs, though the degree and significance of improvement depend on the type of color vision deficiency, the illuminant, and the test used. Deutan observers showed more consistent and significant improvements, especially under Illuminants 540 and 560. Protan observers benefited mainly from Illuminants 580 and 600 on the D-15 test, with only Illuminant 600 showing a significant effect on the Ishihara test. Overall, the color discrimination ability of observers with color vision deficiency can be improved by designing specialized light sources or filters. However, the enhancement for Protans are relatively limited compared to Deutans, which is consistent with previous research findings [13].

Conclusion

This study comprehensively investigated two primary aspects of color vision deficiency: the diagnostic utility of ICMFs and the potential of specifically modulated light sources to enhance color discrimination in CDOs. Our findings from testing 20 CDOs demonstrated remarkable concordance between ICMFs-derived diagnoses and those from established Ishihara and anomaloscope tests. All three methods consistently identified the type of CVD, whereas the Farnsworth D-15 test showed instances of false negatives, suggesting ICMFs offer superior consistency and reliability in CVD type identification. These results strongly support the utility of ICMFs not only for accurate diagnosis but also for quantifying the physiological basis of CVD, such as through LM cone photopigment shift analysis, offering a more nuanced understanding than traditional screening tests.

Furthermore, the investigation into color discrimination enhancement using four custom light sources (with spectral notches at 540 nm, 560 nm, 580 nm, and 600 nm) yielded promising results. Deutan observers experienced substantial and statistically significant improvements in both Ishihara and D-15 tests, particularly under illuminants with notches at 540 nm and 560 nm.

While improvements for protan observers were more modest, statistically significant gains were observed, notably with the 600 nm notch illuminant for the Ishihara test and the 580 nm and 600 nm notch illuminants for the D-15 test. These differential improvements underscore the necessity of tailoring interventions to specific CVD types. Importantly, the broader spectral distribution of our designed light sources, compared to some previously proposed narrow-band illuminants, suggests a more practical pathway for developing assistive technologies such as glasses, minimizing energy loss and potentially offering more naturalistic viewing experiences. In summary, this study makes two key contributions: it reinforces the value of ICMFs as a precise diagnostic tool, and it demonstrates a promising, tailored approach for improving color perception in people with CVD—especially Deutans.

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