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Functional Outcomes with ChromaGen Filters in Red–Green Color Vision Deficiency: D-15 Arrangement Accuracy and Contrast Sensitivity

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Abstract

Colored filters alter the spectral composition of incident light reaching the retina and may influence performance on clinical color vision tests. This study evaluated the effects of three ChromaGen filters (magenta, pink, and violet) on Farnsworth D-15 arrangement performance and contrast sensitivity in individuals with congenital red–green color vision deficiency. Seventy-nine male participants with protan and deutan defects, classified using anomaloscopy, completed D-15 testing with Color Difference Vector analysis and contrast sensitivity assessment with Pelli–Robson chart under four conditions: no filter, magenta lens, pink lens, and violet lens. All three ChromaGen lenses were associated with significant reductions in confusion index (Cohen's $d_z = 0.57$–0.76) and total error score (Cohen's $d_z = 0.58$–0.81) compared with the no-filter condition, indicating improved performance on the D-15 arrangement task, with lens-specific effects. All lenses significantly reduced crossing errors (Wilcoxon r = 0.51–0.65), while transposition rates remained unchanged ($\chi^2(3) = 3.11, p = 0.37$). Pelli–Robson contrast sensitivity did not differ significantly between the no-filter and filter conditions (mean 1.92 logCS in all conditions). However, baseline scores were close to the test ceiling, and testing was limited to a single photopic luminance level and a single letter-chart format; therefore, this finding does not establish equivalence and should not be generalized to other luminance levels or spatial frequencies. Because the filters differed in luminous transmittance and no neutral-density control was included, a contribution of luminance-mediated cues to the D-15 improvements cannot be excluded. ChromaGen filters were associated with improved D-15 arrangement performance under the study conditions; the underlying chromatic and luminance mechanisms remain to be established.

Keywords: ChromaGen filter; contrast sensitivity; color vision deficiency; Farnsworth D-15; Color Difference Vector

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Academic Editor: Jeong-Min Hwang

Received: 25 September 2026
Revised: 6 November 2026
Accepted: 13 November 2026
Published: 18 November 2026

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1. Introduction

Color vision plays a critical role in many aspects of daily life, including education, occupational performance, and safety. Color vision deficiency (CVD) may be congenital, arising from inherited alterations of the cone photopigments, or acquired, resulting from disease or damage affecting the retina, optic nerve, or visual pathways [1]. Congenital red–green CVD, the focus of the present study, is X-linked and affects approximately 8% of men

and 0.4–0.5% of women of European ancestry, with lower rates in other populations [2,3], whereas the prevalence of acquired CVD varies with the underlying condition and with age [1]. In clinical practice, individuals with red–green CVD often report challenges not only in color discrimination but also in broader visual tasks involving low-contrast environments.

Color vision testing is essential for identifying the presence, type, and severity of CVD. In professions that require accurate color discrimination, such as graphic design, photographic processing, and pathology, hue discrimination tests are particularly useful for evaluating chromatic perception [4–6]. These assessments enable clinicians to diagnose CVD efficiently and recommend appropriate management or support strategies. Current color vision tests are generally designed either to detect CVD or to assess hue discrimination ability. Pseudoisochromatic plate tests are widely used for detecting CVD, whereas the Farnsworth 100-Hue and Farnsworth D-15 tests evaluate hue discrimination performance. The Farnsworth–Munsell D-15 (D-15) test is a standardized color discrimination tool used to assess the type and severity of CVD [7–21]. It was developed to distinguish normal or mildly deficient color vision from moderate to severe impairment and to classify defects as protan, deutan, or tritan. The test is widely used in clinical and occupational screening, particularly in professions where accurate color discrimination is critical, such as aviation, rail transport, and electronics.

While the primary deficit lies in chromatic processing, secondary issues such as contrast sensitivity (CS) impairment, especially under specific lighting conditions, can influence daily activities like reading colored maps, interpreting color-coded data, and identifying traffic signals [1–3]. CS refers to the visual system's ability to distinguish subtle differences in brightness between adjacent areas of an image. The concept of CS relates not to overall visual quality but to the ability to perceive boundaries and details within an image, particularly when adjacent areas have minimal differences in brightness [12].

Although red–green CVD is fundamentally a disorder of chromatic discrimination resulting from altered cone photoreceptor responses [1–3], spectral filters used in clinical practice inevitably modify both the spectral composition and overall intensity of light reaching the retina [13–21]. Because luminance-dependent mechanisms contribute to contrast detection and spatial boundary perception [12,22–25], any intervention that alters retinal illuminance has the potential to influence CS independently of its chromatic effects. Consequently, evaluating CS alongside D-15 arrangement performance is methodologically important in the evaluation of spectral filters. Such dual assessment allows differentiation between performance changes arising from altered task-specific stimulus cues or luminance-related effects within color space [26–28] and unintended luminance-based trade-offs introduced by spectral filtering. These considerations have motivated interest in spectral filters as supportive interventions that may improve performance in selected visual tasks.

One such approach is the use of ChromaGen filters, which are colored spectacle or contact lenses designed to selectively alter wavelength transmission to the retina. Spectral filters, including multi-notch filters, selectively attenuate specific wavelength bands, thereby altering the spectral composition of light reaching the retina [17,18]. Unlike gene- or pigment-based interventions, these filters do not modify cone photoreceptor sensitivities. Instead, they alter the spectral composition of incident light, thereby modifying the relative excitation of long- and medium-wavelength cones. This spectral modification is hypothesized to influence the separability of stimuli on clinical color vision tests and reduce ordering errors on tasks such as the Farnsworth D-15, though the relative contributions of chromatic and luminance-mediated cues to any observed improvement remain to be quantified. Chromatic effects refer to changes in color perception arising from alterations in relative cone excitation and chromatic signal processing, whereas luminance-mediated effects refer to changes in perceived brightness or contrast between stimuli that may provide

non-chromatic cues for task performance. Because spectral filters simultaneously alter both chromatic relationships and overall luminance contrast between stimuli, the relative contributions of chromatic versus luminance-mediated effects cannot be determined from behavioral data alone. Such changes do not restore absent cone mechanisms and should not be interpreted as recovery of intrinsic chromatic discrimination or normalization of cone-opponent pathways. Several studies have investigated the impact of ChromaGen filters on both objective and subjective measures of color vision. Early clinical evaluations reported improvements in performance on pseudoisochromatic plate tests, such as the Ishihara test, and arrangement tests, including the Farnsworth D-15, particularly among individuals with congenital red–green CVD [18,29–31]. These findings suggest that ChromaGen filters may facilitate color differentiation under certain testing conditions.

However, the effectiveness of ChromaGen filters remains a subject of debate within the literature. While some studies demonstrate measurable improvements on specific color vision tests, others report limited or inconsistent benefits, particularly in tasks requiring real-world signal discrimination or occupational standards compliance, such as signal light recognition [32–34]. Variability in outcomes has been attributed to differences in CVD type and severity, testing methodology, lighting conditions, and the subjective nature of color perception. Consequently, questions remain regarding the clinical relevance and practical applicability of ChromaGen filters as an assistive intervention for CVD [21,22,35].

Recent work has emphasized that evaluation of CVD aids should move beyond simplistic interpretation of clinical plate and panel tests and instead quantify whether an aid increases task-relevant information while distinguishing chromatic effects from luminance-mediated cues [36–39]. This contemporary framework, articulated in the Optics Express Virtual Feature Issue on Aids for Color Vision Deficiency [24], highlights the importance of assessing information gain from spectral filters particularly in anomalous trichromacy while clarifying the inherent limitations of "color enhancement" approaches. Quantitative modeling studies further demonstrate that optical filters can alter chromaticity distributions and modify performance metrics on standard color vision tasks, often with trade-offs across chromatic axes and reductions in luminous transmittance, rather than restoring normal chromatic processing [25]. Importantly, these analyses reiterate that spectral filters cannot restore absent cone mechanisms and that apparent improvements on clinical tests may reflect altered chromatic or luminance cues rather than enhanced underlying neural color discrimination [23–25]. Computational modeling studies of multi-notch spectral filters have further shown that predicted improvements in color signal separability are limited and vary across observer types, supporting the view that such filters may modify stimulus representations in a task-dependent manner [26]. Accordingly, improvements observed on clinical color vision tests should be interpreted as arising from changes in spectral input and relative cone excitation, rather than restoration of normal cone-opponent processing or underling photoreceptor function.

Contrast sensitivity reflects the ability to detect luminance differences and is essential for tasks such as night driving, reading, and object recognition under low-contrast settings. Reduces CS can impair visual performance even when visual acuity is normal, particularly under suboptimal lighting [16,40–44]. Colored filters have been proposed to influence CS by selectively modifying wavelength transmission, potentially improving visual comfort and performance in specific conditions [13–15]. However, because spectral filters also reduce retinal illuminance, their effects on CS are often luminance-mediated rather than indicative of enhanced visual processing.

Standard photopic CS measurements may not fully capture performance changes associated with light scatter or glare, which are known to reduce both visual acuity and CS. Short wavelengths scatter more strongly and contribute to glare, and filters targeting

these wavelengths have been suggested to improve visual performance under such conditions [14,15]. Among available clinical tests, the Pelli–Robson chart is widely used due its high repeatability and reliable assessment of contrast sensitivity [32,45].

ChromaGen, a popular approach in CVD management, utilizes colored filters to alter the spectral composition of light entering the eyes. However, the primary focus was not on enhancing color vision. Altering the spectral composition of light through these filters can influence color perception to an extent. Several studies have addressed the effects of colored filters on enhancing visual performance in individuals with glare problems [4,15,19,46]. The present study aimed to evaluate the effects of three ChromaGen filters on D-15 arrangement performance and luminance-based contrast sensitivity in individuals with congenital red–green CVD. By examining both D-15 ordering metrics and contrast sensitivity under identical testing conditions, the study aimed to determine whether filter-related performance changes are confined to task-specific color arrangement performance or are accompanied by measurable alterations in luminance-dependent visual function [12,42–45]. A clearer understanding of these mechanisms may help define the clinical role of spectral filters and guide appropriate patient counseling regarding their potential benefits and limitations. Magenta, pink, and violet ChromaGen lenses were examined because they are among the tints commonly prescribed for red–green CVD in clinical practice and have distinct spectral absorbance profiles (Figure 1), allowing filter-specific effects to be compared. Improved D-15 performance should not be assumed to translate to real-world color judgments or to fulfilment of occupational color vision requirements.

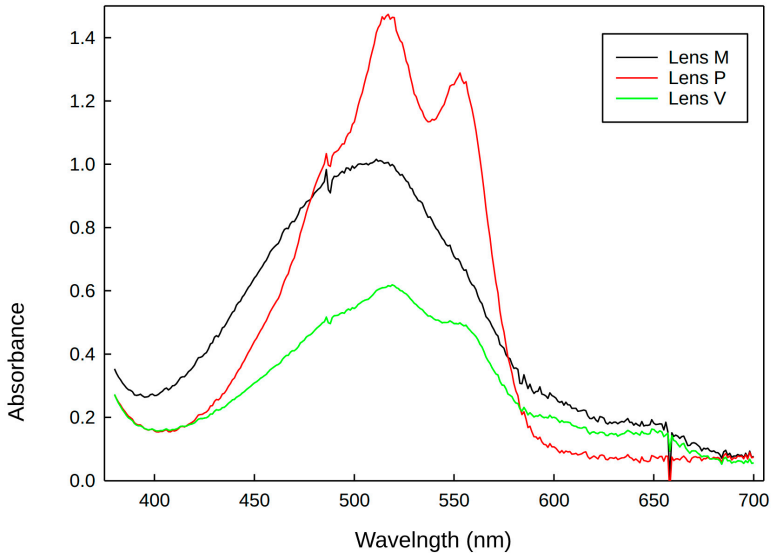


Figure 1. Light absorbance of ChromaGen Lenses M, P, and V. The ChromaGen Lenses M, P, and V were assessed using an Agilent Cary 8453 UV-Visible Spectrometer (Agilent, Santa Clara, CA, USA) at the geometric center. Higher absorbance indicates lower transmittance ($A = -\log_{10} T$). M, magenta; P, pink; V, violet.

It was hypothesized that if ChromaGen filters primarily influence task performance through stimulus-dependent effects, improvements would be observed in D-15 arrangement performance without measurable change in luminance-based contrast sensitivity under standardized photopic conditions. While previous studies have examined the effects of spectral filters on color vision test performance, relatively few have simultaneously evaluated whether such performance changes are accompanied by alterations in luminance-based visual function. The present study addresses this gap by combining quantitative D-15 analysis with contrast sensitivity measurements under identical testing conditions.

This approach allows differentiation between task-specific improvements in color arrangement performance and potential changes in broader visual processing. Both anomalous trichromats and dichromats were included, as spectral filters may influence task performance through cue-dependent mechanisms even in the absence of physiologically available chromatic signals.

2. Materials and Methods

A total of 79 male individuals with congenital red–green color vision deficiency participated in this study, with a mean (±standard deviation [SD]) age of 24.6 (±8.5) years (range: 13–52 years). Although contrast sensitivity may decline with advanced age, the sample was predominantly composed of young adults and all participants demonstrated normal baseline contrast sensitivity under standardized photopic conditions. Age was therefore not included as a covariate in the primary analysis. Additionally, participants were classified based on the Oculus Heidelberg Multi-Color anomaloscope (Oculus Optikgeräte GmbH, Wetzlar, Germany) and were recruited from hospitals, schools, universities, and public places. All participants had a best-corrected VA of 0.10 logMAR or better in each eye and a refractive error within ±4.00 D spherical equivalent. Participants with known acquired CVDs were excluded using a screening questionnaire. None of the participants reported ocular or systemic diseases. In addition, participants with ocular conditions that could affect color perception or contrast sensitivity (e.g., media opacities such as cataract or other anterior segment abnormalities) were excluded based on slit-lamp examination and participants' ocular history. During the tests, the participants were allowed to wear their current distance or near corrections; however, tinted spectacles or contact lenses were not permitted. The D-15 test was illuminated by a light-emitting diode lamp (model G45-14 E27; NEW POWER, Ningbo City, China) with a correlated color temperature of 6500 K and a color rendering index > 90, which served as the standardized illuminant for color vision testing and provided an illuminance of approximately 500 lux at the test surface. The ChromaGen lenses available at the clinic were magenta, pink, and violet (Lenses M, P, and V, respectively). These filters were selected because they represent commonly prescribed ChromaGen lens types in clinical practice and exhibit distinct spectral transmission profiles, allowing evaluation of differential effects on color vision task performance. A pair of lenses of each type was attached to a spectacle frame to facilitate the task. Luminance was not matched across lens conditions, because the study aimed to evaluate the filters under conditions representative of clinical use (see Section 4.3). The order of the no-filter and lens conditions was randomized using a block design. Masking of participants to lens type was not feasible because the filters were visibly different in tint. The sample size was determined by feasibility and the availability of individuals with an anomaloscope-confirmed diagnosis; no a priori power calculation was performed (see Section 4.3).

The distance VA was measured monocularly under standard testing conditions using an Early Treatment Diabetic Retinopathy Study chart (ETDRS) (Good-Lite Company, Elgin, IL, USA), which was transilluminated to a luminance of 130 cd/m^2. Log contrast sensitivity (CS) was assessed using the Pelli–Robson (PR) chart (Precision Vision, Woodstock, IL, USA). (mean luminance: 112 cd/m^2) at a viewing distance of 3 m [47]. The PR chart consists of Sloan letters arranged in triplets, with contrast decreasing in 0.15 log unit steps for each successive triplet. Testing was performed binocularly under standardized photopic illumination conditions while participants wore their habitual distance refractive correction. Participants were instructed to read the letters from highest to lowest contrast, and the log CS score was determined using the standard criterion of correctly identifying at least two of three letters within a triplet. For the color test, the Farnsworth D-15 test (Good-Lite Co., Elgin, IL, USA) was performed binocularly under the LED illuminant described above, at

a viewing distance of approximately 50 cm. The caps were randomly mixed before each administration. Participants were instructed to begin with the cap closest in color to the fixed reference cap and then to place, one at a time, the cap that looked most similar to the last cap placed, until all caps were arranged in the box; they were allowed to adjust the arrangement before indicating that they had finished. There was no time constraint on completing the test.

Procedure: All measurements were completed in a single session lasting approximately 40 min. After anomaloscope classification and VA measurement, participants adapted to the room illumination for approximately 3 min. CS and the D-15 test were then performed under each of the four viewing conditions (no filter, Lens M, Lens P, and Lens V) in randomized order; within each condition, CS was measured first, followed by the D-15 test. No additional adaptation period was provided between viewing conditions.

Errors observed in the D-15 color arrangement tests range from minor transpositions to major crossings. In transpositions, a cap is placed one or two positions away from its correct location, whereas major crossings occur when caps situated on opposite sides of the hue circle are placed adjacent to each other. These major errors are identified as major crossings. Typically, the presence of two or more crossings in either version of the D-15 test is classified as a failure, indicating moderate to severe CVD [5,9,10,48,49].

In this study, the test results were analyzed using the Color Difference Vector (CDV) method [39–41]. Key parameters included the confusion index (C-index) and the confusion angle. The C-index represents the degree of deviation from ideal cap arrangement, with higher values indicating greater error severity. The confusion angle characterizes the orientation of errors in color space and is used to classify the type of color vision defect (e.g., protan or deutan axis). Total Error Score (TES) is a single numerical value that reflects the overall magnitude of ordering errors, with lower value indicating fewer and smaller errors on the D-15 task. Crossing errors refer to instances where the cap sequence crosses established confusion axes, indicating major classification errors, while transposition errors represent local misplacements between adjacent caps.

All CDV parameters were computed for each arrangement using a custom GNU Octave program (Version 4.0.0, 2015). Vingrys and King-Smith [39] noted that CDV indices depend on the choice of U′ and V′ coordinates; hence, variations in these coordinates across light sources may lead to slight differences in CDV values even when the cap order remains the same. Consequently, CDV parameters should be rescaled for each light source to enable direct comparisons. The CIELUV color space was chosen primarily for convenience in quantifying D-15 arrangement patterns. However, any approximately uniform color space would be suitable for the Vingrys–King-Smith analysis, as the calculations depend on relative color differences between adjacent caps in the subject's arrangement.

Statistical analyses were performed using SPSS (version 31; IBM Corp., Armonk, NY, USA). Normality of continuous variables was assessed using the Kolmogorov–Smirnov test. Repeated-measures analysis of variance (ANOVA) was applied to compare C-index and total error score (TES) across lens conditions; these are continuous composite indices derived from the CDV analysis and were therefore analyzed parametrically, with Mauchly's test used to assess sphericity and the Greenhouse–Geisser correction applied where required. Although deviation from normality was detected for some variables, repeated-measures ANOVA was retained due to its robustness to moderate violations of normality in balanced within-subject designs with moderate sample size. Visual inspection of residuals did not indicate severe departures from normality. Non-parametric Friedman tests were used for count-based variables (crossings and transpositions), as these data were not normally distributed and, being discrete counts with many tied and zero values, were not suitable for parametric analysis; pairwise follow-up comparisons for these variables used Wilcoxon

signed-rank tests. CS was likewise analyzed with the Friedman test, because Pelli–Robson scores are discrete (0.15 log unit steps) and were clustered near the upper limit of the chart. Presentation order was not included as a factor in the primary analysis (see Section 4.3). When significant main effects were observed, post hoc pairwise comparisons with Bonferroni correction were performed. A significance level of $p < 0.05$ was adopted for all analyses. To supplement inferential statistics, standardized effect sizes were calculated for all primary comparisons. Cohen's d_z was computed for parametric comparisons (C-index and TES) using the formula $d_z = MD/(SE \times \sqrt{n})$ [50]; r was computed as $Z/\sqrt{N}$ for Wilcoxon comparisons [47]; and Kendall's W was computed as an overall effect size for the Friedman test. Effect sizes were interpreted using conventional benchmarks: $d_z \geq 0.2$ small, ≥0.5 medium, ≥0.8 large; $r \geq 0.1$ small, ≥0.3 medium, ≥0.5 large; and Kendall's $W \geq 0.1$ small, ≥0.3 moderate, ≥0.5 large [51].

3. Results

The absorbance spectra of ChromaGen Lenses M, P, and V were measured using an Agilent Cary 8453 UV-Visible Spectrometer (Agilent, Santa Clara, CA, USA) at the geometric center (Figure 1). Because absorbance (A) and transmittance (T) are related by $A = -\log_{10}(T)$, higher absorbance indicates lower transmittance (e.g., A = 1.0 corresponds to 10% transmittance). All three lenses transmitted relatively well at short (approximately 400–430 nm) and long (>590 nm) wavelengths and attenuated the middle of the visible spectrum, with maximum absorbance at approximately 510–520 nm. Lens P showed the strongest attenuation (peak absorbance ≈ 1.46 at ≈515 nm, with a second peak at ≈553 nm; absorbance > 0.5 between approximately 460 and 570 nm) and a steep transition to high transmittance between approximately 570 and 590 nm. Lens M showed a broader but shallower absorbance band (peak ≈ 1.0 at ≈510 nm; absorbance > 0.5 between approximately 440 and 565 nm), whereas Lens V showed the weakest attenuation (peak ≈ 0.6 at ≈520 nm). The photopic luminous transmittance (CIE 1924 V(λ)-weighted, CIE D65 illuminant) was estimated as approximately 30% for Lenses M and P and 43% for Lens V.

Based on the anomaloscope, deuteranomaly was the most prevalent diagnosis, accounting for 51.9% of cases ($n = 41$), followed by protanomaly (26.6%; $n = 21$). Dichromatic defects were less common, with deuteranopia and protanopia representing 16.5% ($n = 13$) and 7.6% ($n = 6$) of the sample, respectively.

3.1. D-15 Test

Figure 2 shows the mean and 1 SD of each CDV parameter with no filter used relative to the three ChromaGen lenses. The results illustrate a clear trend showing a reduction in the mean values obtained during testing with ChromaGen lenses. Notably, the lowest mean C-index, TES, and number of crossings were all obtained with Lens P.

3.2. C-Index

To facilitate interpretation beyond *p*-values alone, 95% confidence intervals for pairwise comparisons are reported in Appendices A and B, and 95% confidence intervals are displayed for contrast sensitivity in Figure 3. Repeated measure analysis of variance revealed significant differences in C-Index between most lens conditions (Appendix A). Compared to the no-filter condition, C-Index values were significantly reduced with Lenses M ($p < 0.001$, $d_z = 0.57$), P ($p < 0.001$, $d_z = 0.76$), and V ($p < 0.001$, $d_z = 0.58$), indicating medium to medium-large effect sizes for all filters. Further comparisons showed that Lens P produced a significantly lower C-Index than Lenses M ($p = 0.01$, $d_z = 0.37$) and V ($p < 0.001$, $d_z = 0.55$). No statistically significant difference was observed between Lenses M and V ($p = 0.995$,

$d_z = 0.16$). Therefore, Lens P demonstrated the greatest reduction in C-Index, followed by Lenses M and V.

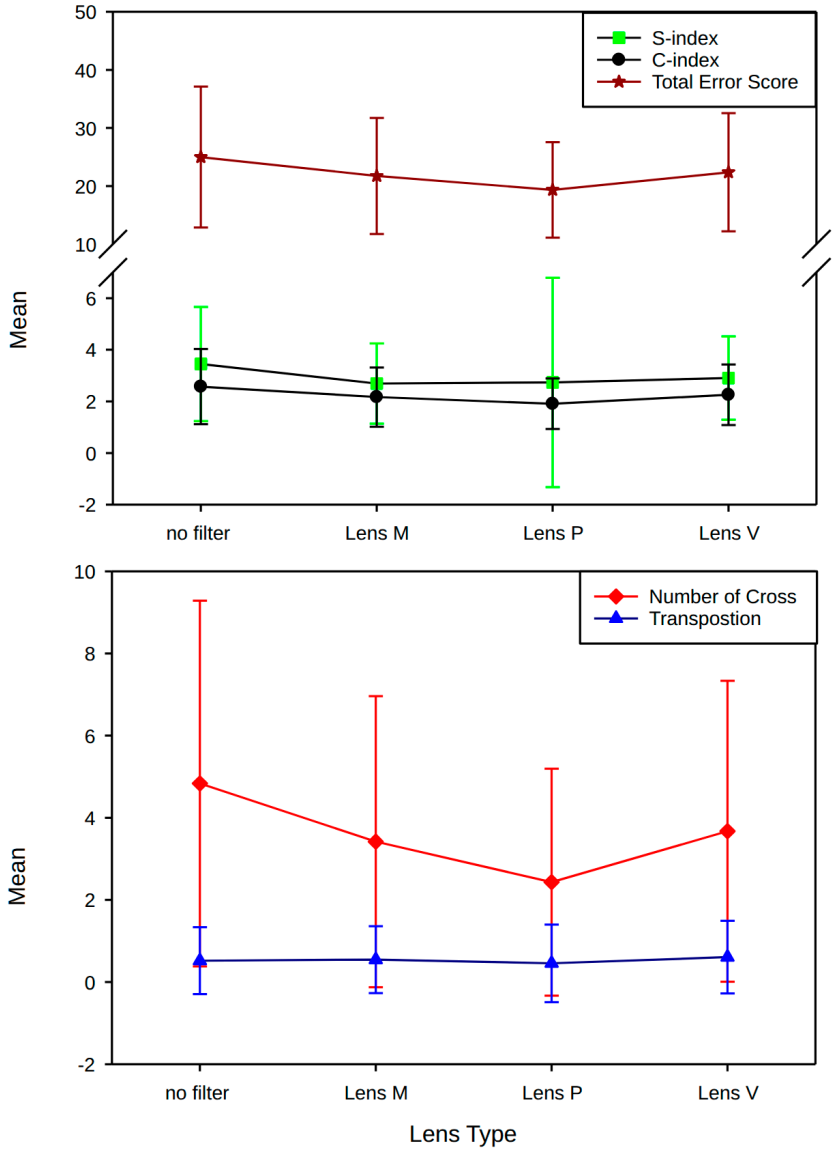


Figure 2. The mean values and 1 SD obtained by the participants with color vision deficiency for each of the D-15 color vision tests using each type of ChromaGen lens. The error bars represent one standard deviation from the mean, SD, standard deviation; S-index, selectivity index; C-index, confusion index.

3.2.1. TES

Bonferroni-adjusted pairwise comparisons based on estimated marginal means demonstrated statistically significant differences in TES among most lens conditions (Appendix B).

Compared with the no-filter condition, TES was significantly reduced when participants were tested with Lenses M ($p < 0.001$, $d_z = 0.58$), P ($p < 0.001$, $d_z = 0.81$), and V ($p < 0.001$, $d_z = 0.60$), representing medium to large effect sizes. These findings indicate a consistent reduction in ordering errors on the D-15 task with all ChromaGen lenses relative to the no-filter condition.

Further pairwise comparisons revealed that Lens P produced significantly lower TES than both Lenses M ($p = 0.003$, $d_z = 0.41$) and V ($p < 0.001$, $d_z = 0.59$). No statistically

significant difference in TES was observed between Lenses M and V ($p = 1.00$, $d_z = 0.13$), indicating comparable performance between these two filters.

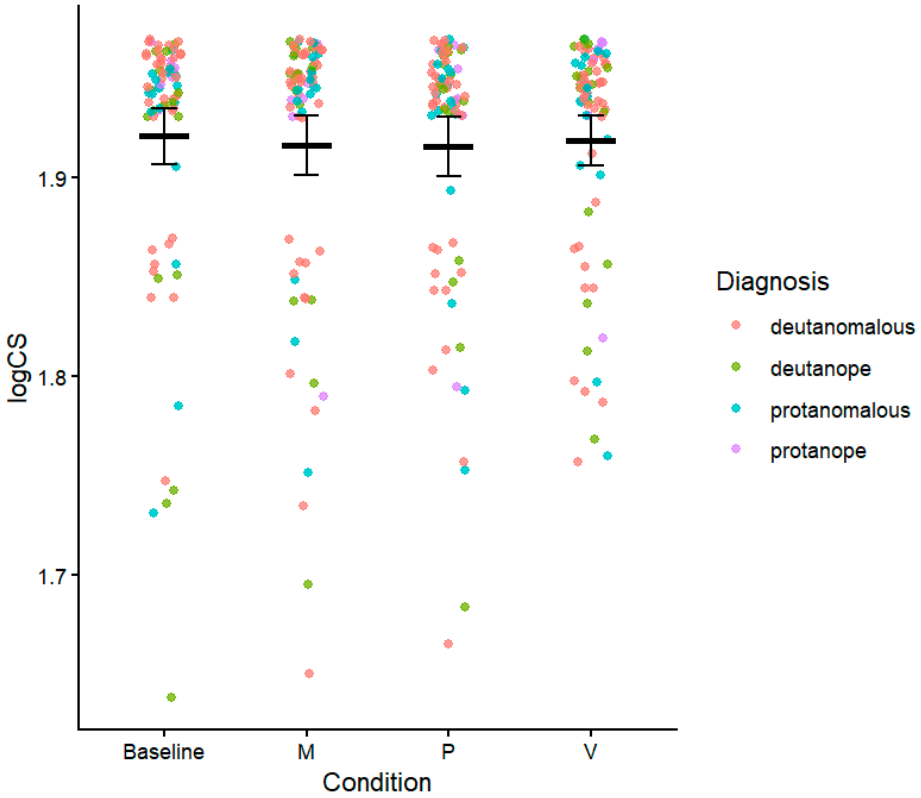


Figure 3. Individual contrast sensitivity (logCS) values under baseline (no filter) and three ChromaGen lens conditions: magenta (M), pink (P), and violet (V). Colored points represent individual participants grouped by CVD (deutanomalous, deutanope, protanomalous, protanope). Horizontal black bars indicate mean values, and error bars represent 95% confidence intervals. No statistically significant differences were observed between conditions (Friedman test, $p > 0.05$).

3.2.2. Number of Crossing

A nonparametric Friedman test was conducted to evaluate whether there were statistically significant differences in the number of Crossings (crossings: major ordering errors across confusion axes) across the four viewing conditions: No filter, ChromaGen Lens M, ChromaGen Lens P, and ChromaGen Lens V. This test was selected because the Cross score is a count variable and its distribution was non-normal.

The Friedman test indicated a significant overall effect of condition on Cross scores, $\chi^2(3) = 64.374$, $p < 0.001$, Kendall's W = 0.21 (small-to-moderate effect), based on $N = 79$ participants. This result demonstrated a significant effect of viewing condition on Cross scores, indicating that the presence of ChromaGen lenses significantly altered participants' color ordering performance.

Subsequent Wilcoxon signed-rank comparisons revealed that all three lenses significantly reduced crossing errors relative to the no-filter condition Lens M ($Z = -4.519$, $p < 0.001$, r = 0.51), Lens P ($Z = -5.789$, $p < 0.001$, r = 0.65), and Lens V ($Z = -4.658$, $p < 0.001$, r = 0.52), all representing large effect size. Lens P also produced significantly fewer crossings than Lens M ($Z = -3.691$, $p < 0.001$, r = 0.42) and Lens V ($Z = -4.489$, $p < 0.001$, r = 0.51), whereas Lenses M and V did not differ significantly ($Z = -1.008$, $p = 0.31$, r = 0.11) (Appendix C). These results support an effect of ChromaGen lenses in reducing crossing errors on the D-15 task, with Lens P showing the largest reduction.

3.2.3. Transposition

A nonparametric Friedman test was conducted to examine differences in transposition (Trans) errors (transpositions: local misplacements between adjacent caps) on the Farnsworth D-15 test across the four conditions (no filter, Lens M, Lens P, and Lens V) in a sample of 79 participants. The analysis revealed no statistically significant difference in transposition scores among the lens conditions, $\chi^2(3, N = 79) = 3.113$, $p = 0.37$, Kendall's W = 0.01, indicating negligible effect size. These findings indicate that transposition errors remained statistically comparable across all lens conditions, suggesting that the use of ChromaGen lenses (M, P, or V) did not significantly alter the occurrence of transposition responses relative to the no-filter condition.

3.3. Angle

Figure 4 presents scatter plots of the CDV confusion angle across different lens conditions and highlights substantial inter-individual variability in response to the filters. There is minor overlap between the results, but most of the distributions were separated using the Vingrys and King-Smith's criterion, where an angle close to 0 adequately classifies the color vision defect into protans and deutans [39]. The results showed that ChromaGen lenses produced only modest changes in average D-15 confusion angles for anomalous trichromats, with the mean confusion angles for protanomaly and deuteranomaly across Lenses M, P, and V remaining broadly similar to those under the no-filter condition. In contrast, protanopes and deuteranopes demonstrated marked shifts in their confusion angles with lens wear, moving from small positive or mildly negative values without a filter to larger negative angles, particularly with Lens P, indicating stronger rotation of the confusion axis in dichromats. Importantly, ChromaGen filters did not normalize confusion angles to values typical of normal color vision in any subtype, consistent with the interpretation that these filters modify stimulus cue availability rather than restore underlying cone-opponent processing.

3.4. Contrast Sensitivity

The Friedman test was subsequently performed to investigate the potential differences in CS across four conditions: baseline and the three distinct lens types. No significant differences in CS between the baseline condition and each of the three lenses were revealed (Table 1). The *p*-values for comparisons between the baseline and each lens were as follows: Lens M vs. baseline, $p > 0.1$; Lens P vs. baseline, $p > 0.1$; and Lens V vs. baseline, $p > 0.1$. Figure 3 presents scatter plots of CS across different lens conditions in individuals with various types of red–green CVDs. Across all groups, baseline measurements showed consistently high CS. Some variability was observed with the use of different lenses, with sensitivity slightly reduced for certain lenses. However, the general trend suggests that while lens type may have modest effects on CS, the overall performance remains relatively stable across conditions.

Table 1. Contrast sensitivity (logCS) at baseline and with the three ChromaGen lenses, presented as mean ± SD; median.

Contrast Sensitivity (CS)	Baseline	Lens M	Lens P	Lens V
logCS, mean ± SD; median	1.92 ± 0.06; 1.95	1.92 ± 0.07; 1.95	1.92 ± 0.07; 1.95	1.92 ± 0.06; 1.95

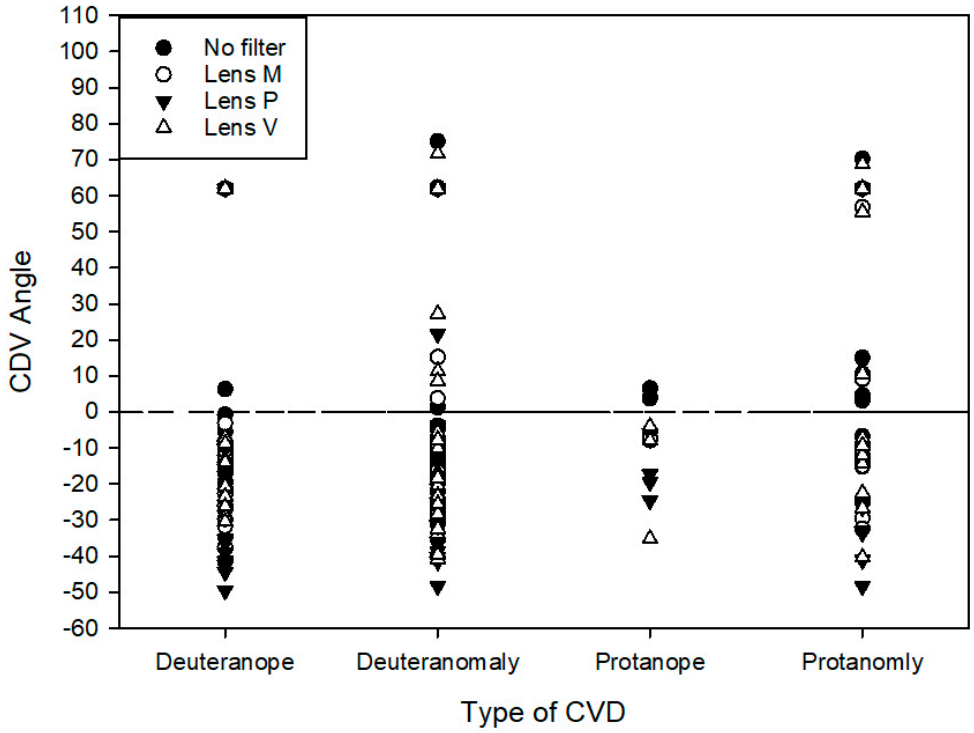


Figure 4. The association between the type of color vision deficiency (CVD) and angular size for the D-15 for all participants using the ChromaGen lenses. The dashed line represents the cut-off point separating deutans from protans based on the Vingrys and King-Smith criterion (0°). CDV, Color Differences Vector.

4. Discussion

The effects of ChromaGen filters on D-15 and CS in individuals with congenital red–green CVD were investigated. This condition often makes daily visual tasks challenging. Findings from this study indicate that ChromaGen filters can significantly modify performance on the D-15 arrangement task in individuals with congenital red–green CVD, while exerting little to no measurable effect on CS under standard testing conditions. Effect sizes for primary comparisons (no filter vs. each lens) ranged from medium to large across all metrics (d_z = 0.57–0.81 for C -index and TES; r = 0.51–0.65 for crossing errors), indicating moderate-to-large effects on D-15 performance, although their practical significance for real-world color tasks was not assessed. This pattern suggests that spectral filtering primarily modifies stimulus cue availability within the D-15 arrangement paradigm, an effect consistent with altered spectral composition and potentially altered relative cone excitation, rather than reflecting recovery of underlying chromatic processing mechanisms. These effects are therefore better interpreted as change in stimulus-driven performance rather than enhancement of intrinsic color discrimination. This interpretation is consistent with contemporary frameworks demonstrating that improvements on clinical color vision tests are more parsimoniously attributed to altered stimulus cue availability, whether chromatic, luminance-mediated, or both, rather than restoration of normal cone-opponent processing or photoreceptor function [25,52].

The dual assessment of chromatic discrimination (D-15) and luminance-based contrast sensitivity provided a broad characterization of filter effects on visual performance. However, it should be noted that the Pelli–Robson contrast sensitivity test measures broadband achromatic contrast at suprathreshold levels and is not designed to distinguish chromatic from luminance-mediated contributions to D-15 arrangement performance; that distinction would require luminance-matched conditions, neutral density controls, or threshold

chromatic sensitivity measures. Evaluating both outcomes within the same participants under identical photopic conditions allowed us to examine whether observed improvements were confined to D-15 task performance or accompanied by broader changes in luminance processing. Significant reductions in C-index, TES, and major crossings were observed, whereas no statistically significant change in contrast sensitivity was detected. This finding is compatible with a spectrally mediated effect on chromatic cue availability, though it does not exclude a contribution from subtle luminance differences between individual D-15 caps that the Pelli–Robson chart is not designed to detect. This interpretation is consistent with quantitative modeling studies showing that optical filters can modify chromaticity distributions and task performance metrics, often with trade-offs across chromatic axes and reductions in luminous transmittance, without restoring normal color vision mechanisms [25]. This interpretation is further supported by computational modeling studies of multi-notch filters, which demonstrate that predicted gains in color signal separability are limited and observer-dependent, and do not correspond to restoration of normal chromatic processing [26].

4.1. D-15 Color Vision Test

The D-15 results from this study demonstrate that ChromaGen filters significantly altered D-15 ordering performance in individuals with congenital red–green CVD, as reflected by consistent reductions in the C-index and TES across all three lens types relative to the no-filter condition. Since both indices are established quantitative descriptors of error magnitude and defect severity on panel tests, these changes indicate a reduction in ordering errors on the Farnsworth D-15 without altering the fundamental classification of the deficiency. The consistent direction and magnitude of reduction across lens conditions suggest systematic task-related effects rather than random measurement variability.

Importantly, these changes should not be interpreted as restoration of neural color discrimination. Spectral filters do not modify photopigment sensitivities or reconstruct absent opponent channels; rather, they reshape the spectral composition of incident light, altering relative cone excitation ratios across the D-15 cap set. Improvements in ordering performance therefore are consistent with modified stimulus geometry and cue availability, though colorimetric modelling of filter transmittance against D-15 cap spectra under the test illuminant would be required to quantify the relative chromatic and luminance contributions.

Performance on the D-15 test depends not only on underlying cone mechanisms but also on the geometric distribution of caps within color space, relative luminance differences between caps, and observer strategy. In dichromats, ordering may be strongly influenced by luminance gradients along the confusion axis, whereas in anomalous trichromats residual L–M separation may interact with spectral filtering to alter perceptual separability. Accordingly, D-15 outcomes should be interpreted as task-dependent rather than direct measures of intrinsic chromatic capacity.

The confusion angle data provide additional mechanistic insight when interpreted by CVD subtype. Anomalous trichromats (protanomaly, deuteranomaly) showed modest, relatively stable confusion angle shifts across all three filters, remaining broadly aligned with their baseline protan or deutan confusion axes. This pattern is consistent with filters modulating, but not eliminating, residual L-M chromatic signals in observers who retain both cone classes with reduced spectral separation. In contrast, dichromats (protanopia, deuteranopia) exhibited marked shifts toward larger negative angles, particularly with Lens P, suggesting a qualitatively different perceptual response. In the absence of one cone class, dichromat performance on the D-15 is more strongly influenced by luminance gradients along the confusion axis; filter-induced changes in luminance contrast between caps may therefore produce larger angular displacements than in anomalous trichromats. This

subtype specific differential response is consistent with published colorimetric modelling demonstrating that filter effects depend critically on the observer's cone spectral sensitivities and degree of L/M spectral overlap [25,26]. The substantial inter-individual variability within subtypes reflects known differences in residual cone function and observer strategy and does not undermine the systematic subtype-level pattern. Although the present analysis was not powered for formal subtype × lens interaction modelling, the observed pattern provides preliminary evidence for subtype-specific filter-perceptual interactions that future studies should examine with adequate statistical power.

A key feature of the present findings is the differential effect on error types: crossing errors, which represent major misorderings across the hue circle, were significantly reduced by all ChromaGen lenses, whereas transposition errors did not differ significantly between conditions. This pattern suggests that spectral filtering is more effective in preventing large-scale hue reversals than in refining fine local ordering. This is consistent with findings from previous quantitative analyses of D-15 performance using CDV methods, where indices such as C-index, confusion angle, and TES were particularly sensitive to gross error structure rather than minimal local displacements.

The three ChromaGen filters did not produce equivalent effects. Lens P produced the greatest reductions in all three D-15 error metrics, namely C-index ($d_z = 0.76$), TES ($d_z = 0.81$), and crossing errors ($r = 0.65$), whereas Lenses M and V did not differ significantly from each other on any of these metrics. This pattern is of mechanistic interest because Lenses M and P had similar estimated luminous transmittance (approximately 30%), yet Lens P was superior to Lens M, while Lens M did not outperform the lighter Lens V (approximately 43%). Overall light attenuation alone therefore does not appear to account for the differences between filters, which are more consistent with an influence of the spectral shape of each filter's absorbance profile on the D-15 cap set under the 6500 K LED illuminant. However, this does not exclude luminance-mediated cues: the spectral shape of a filter also alters the relative luminance of individual caps, and because no neutral-density control or luminance-matched condition was included, the relative contributions of chromatic and luminance-mediated cues cannot be separated in the present data.

The spectral differences between the filters are shown in Figure 1. Lens P combines the deepest absorbance band (approximately 460–570 nm) with a steep transition to high transmittance above approximately 580 nm. We hypothesize that this profile may increase the difference in relative L- and M-cone excitation between caps lying near the protan and deutan confusion lines, which could account for its larger effect on global ordering errors (C-index and TES) and large-scale hue reversals (crossings). Lens M attenuates a broader band (approximately 440–565 nm) less deeply, and Lens V attenuates the same region only weakly. These mechanistic explanations should be regarded as hypotheses: cone excitations were not calculated in the present study, and colorimetric modeling of each filter's transmittance against the D-15 cap reflectance spectra under the test illuminant would be required to determine which cap pairs are affected by each filter and whether the effects arise from chromatic contrast changes, luminance contrast changes, or both.

From a clinical perspective, these D-15 results support the role of ChromaGen filters as task-specific aids capable of improving performance on a widely used hue-ordering test in red–green CVD. Consistent confusion angle and defect classification, along with persistent transposition errors, indicate that the underlying cone deficiencies are unchanged, with filters merely remapping available color differences to facilitate certain discriminations. It should also be remembered that color perception is a psychological phenomenon that depends not only on retinal signals but also on the context of the visual scene and on cortical mechanisms, such as memory, attention, and previously learned color concepts, all of which can influence color vision test results. Consequently, clinicians should counsel

patients that while ChromaGen lenses may improve D-15 scores, the present study did not assess other color-dependent tasks, and any benefits are likely to be context-dependent, lens-specific, and insufficient on their own to meet stringent occupational color-vision standards that rely on unfiltered testing. Importantly, because clinical color vision tests such as the Farnsworth D-15 are designed for standardized classification rather than functional enhancement, improvements in test performance with spectral filters should not be interpreted as normalization of color vision status or as evidence of restored chromatic processing in diagnostic contexts.

4.2. Contrast Sensitivity

The results of the PR CS test are measured on a logarithmic scale, wherein a score of 0.15 log units is awarded for each set of letters if the participant correctly identifies at least two of the three letters. The test range extends from 0.00 to 2.25 log units. A score of 2.00 log units indicates normal CS, while a score less than 1.50 log units indicates impaired CS. A score of 2.0 log units implies a 100% CS (the participant correctly identifies letters with 1% contrast). Lower values indicate a reduction in CS. In the present study, the mean CS was 1.92 log units in all four conditions (Table 1), with no statistically significant differences among conditions. All mean differences were below the 0.30 log unit threshold generally considered clinically meaningful for PR testing [53]. The small magnitude of mean differences across lens conditions, together with the narrow standard deviations, further indicates minimal variability between conditions. Because the baseline CS values were already high and clustered near the normal photopic range, and PR scores are assigned in discrete 0.15 log unit steps, a ceiling effect and the limited resolution of the test may have prevented detection of small filter-related changes in either direction under the present testing conditions.

Several visual functions, including VA and CS, depend on the luminance of the visual stimulus [42–45]. CS decreases with reduced stimulus luminance. One hypothesis is that the spectral properties of colored filters have little or no impact on normal broad-spectrum vision, except through reducing retinal illuminance. This hypothesis supports the findings of the current study. The impact of reduced retinal illuminance varies with the overall light levels, being pronounced under low light; it also depends on spatial frequency [54]. Furthermore, Pokorny et al. demonstrated that changing the spectral composition does not affect VA when luminance is matched [55]. These results support the present finding that the spectral composition had no detectable effect on CS under the present conditions. Elliott et al. indicated that statistically significant changes in CS must be at least 0.30 log units [51]. Consistent with the findings of Odell et al. [56], this study revealed that CS remains unaffected by VA until VA declined to 0.1 (20/200). Confounding variables were minimized by ensuring participants had optimal VA prior to testing. Previous studies have established that individuals with CVD often experience challenges, particularly due to their altered color and contrast perception [11–13,18,19,22–29]. Although ChromaGen lenses are designed to modify the spectral composition of light entering the eye, this study found that altering lens color did not produce significant changes in CS under the tested photopic luminance conditions. The relatively young mean age of the sample likely minimized age-related contrast sensitivity variability.

Subjective reports of improvement with colored filters, including ChromaGen lenses, may not always translate into measurable CS enhancements under standardized testing. Prior studies suggest that some users perceive improved visual clarity or comfort due to neural adaptation or placebo effects rather than actual optical benefit [15,17,19,34]. This distinction between objective and subjective outcomes highlights the importance of incorporating both clinical metrics and patient-reported outcomes in future research.

Mahjoob et al. reported that a yellow filter improved CS under glare, particularly in older participants [15], whereas no change was observed in the present study. This difference is likely explained by the different transmission characteristics of yellow filters, the use of glare testing (which depresses CS and leaves more room for improvement), and the young age and normal baseline CS (mean 1.92 log units) of the present participants. Similarly, Eperjesi and Agelis found small, clinically insignificant reductions in VA and CS with increasing yellow-filter absorption under forward light scatter [17], and Samuel et al. found no deterioration in CS with tinted lenses [57]. Differences in filter transmission, ocular status (e.g., cataract), and testing conditions likely account for the variation across studies.

Additionally, the interaction between spectral filtering and visual performance likely involves higher-level perceptual processes not captured by single-frequency CS tests like the PR chart. Filters may influence chromatic contrast and spatial discrimination in complex visual environments, benefits not readily detected under static or highly controlled conditions. Future investigations could utilize multi-frequency tests (e.g., CSV-1000 or qCSF), mobility assessments, or real-world tasks under glare or variable illumination to identify subtle benefits or trade-offs associated with ChromaGen use [14–16]. Furthermore, examining these lenses in populations with ocular conditions such as cataracts or macular degeneration—where contrast loss is more pronounced—may yield different outcomes.

The present findings indicate that the use of three different spectral filters (Lenses M, P, and V) did not lead to substantial improvements in CS across individuals with red–green CVD. Although small variations were observed among filters, overall sensitivity values remained close to baseline levels, suggesting that these lenses do not enhance fundamental visual performance. Deuteranomalous and protanomalous observers showed broadly similar trends with modest changes across filters, whereas deuteranopes demonstrated greater variability and protanopes exhibited the most uniform responses, reflecting differences in the extent of cone function loss between groups. These outcomes are consistent with earlier reports that filters alter spectral input without measurable physiological benefit [51,52]. The stability of CS across baseline and filter conditions indicates that the filters did not produce a detectable change in this measure under the present conditions. While users may perceive subjective improvements in color appearance, the lack of objective gains emphasizes the need for future studies to examine real-world functional outcomes, such as everyday color discrimination tasks and potential adaptation effects with prolonged filter use.

It should be noted that contrast sensitivity was evaluated under a single photopic luminance condition and with a single letter-chart format. Spectral filters alter overall retinal illuminance, and their effects may differ under mesopic or lower luminance conditions where contrast mechanisms are more sensitive to light level changes. Therefore, the absence of significant CS differences in the present study applies specifically to the tested luminance condition and does not exclude the possibility of luminance-dependent effects under different illumination environments or at spatial frequencies other than those sampled by the Pelli–Robson letters. Moreover, no equivalence testing was performed, so the absence of a statistically significant difference should not be interpreted as evidence that CS was equivalent across conditions. Given that baseline CS values were within the normal photopic range, the present findings should be interpreted as indicating no measurable change under these specific luminance conditions rather than absence of potential effects under different testing paradigms.

4.3. Limitations

A key limitation is that overall retinal illuminance was not matched across lens conditions. In the present study, the estimated luminous transmittance of the filters ranged from approximately 30% (Lenses M and P) to 43% (Lens V), so the filters also differed in

the overall light reaching the retina. Spectral filters alter both chromatic relationships and luminance contrasts between cap pairs, and changes in D-15 ordering performance may therefore be partly driven by luminance-mediated cues rather than chromatic remapping alone. No neutral density control lens was included to isolate purely luminance-driven effects; accordingly, the present results should be interpreted as stimulus-dependent changes in spectral input and cue availability, reflecting alterations in both chromatic and luminance contrast between D-15 caps, rather than recovery of intrinsic photoreceptor or post-receptoral chromatic mechanisms.

As described in Section 2, no adaptation period was provided between individual lens conditions. While short-term chromatic adaptation to spectral shifts occurs rapidly, the absence of condition-specific adaptation intervals may have limited full stabilization to each filter's spectral characteristics. Therefore, the present findings primarily reflect immediate task-level effects rather than extended perceptual recalibration.

A further limitation is the possibility of learning effects in repeated D-15 testing. Although the order of all four conditions, including the no-filter condition, was randomized, presentation order was not included as a factor in the statistical analysis; repeated exposure to the cap arrangement task may have modestly improved familiarity with the procedure and thereby influenced performance independently of filter condition [58]. Additionally, participants were not masked to lens condition due to its visible differences in filter tint, which may have introduced expectation-related influences on performance in this subjective arrangement task.

No a priori power calculation was performed. Although the within-subject design provided sufficient sensitivity to detect the medium-to-large D-15 effects observed, the absence of significant CS differences does not establish equivalence. In addition, the CVD subtype groups were unequal in size and small for dichromats (particularly protanopes), and the study was not powered for subgroup or subtype × lens interaction analyses; the subtype-related observations on confusion angle and CS should therefore be regarded as exploratory.

5. Conclusions

Compared with no filter, all three ChromaGen filters were associated with improved performance on the Farnsworth D-15 test in individuals with congenital red–green color vision deficiency, as reflected by reduced C-index, TES, and number of major crossings, with no change in transposition errors or in the classification of the defect. These changes indicate improved performance on a standardized hue-ordering task under filtered viewing conditions, not the restoration of normal color vision.

Although ChromaGen lenses alter the spectral composition of incident light reaching the retina, no statistically significant differences in Pelli–Robson contrast sensitivity were detected between the no-filter and filter conditions. Because scores were near ceiling and testing was limited to a single photopic luminance level and letter-chart format, this finding should not be generalized to other conditions and does not establish equivalence. Because the filters differed in luminous transmittance and no neutral-density control was used, the relative contributions of chromatic and luminance-mediated cues to the D-15 changes remain undetermined, and the proposed role of altered cone excitation should be regarded as a hypothesis. Whether the D-15 improvements translate to other color-dependent tasks was not assessed in the present study.

Future investigations should incorporate quantitative colorimetric modelling alongside luminance-controlled experimental paradigms to directly evaluate the underlying mechanisms. In addition, research employing task-based experimental designs that simulate real-world color-dependent activities (e.g., object identification, signal recognition, or oc-

cupational tasks) under controlled luminance and contrast conditions is warranted. Such approaches would enable direct testing of the hypothesized cone excitation mechanism, facilitate clearer differentiation between chromatic and luminance-mediated effects, and provide a more robust assessment of the functional relevance of spectral filters in applied visual contexts.

Author Contributions: Conceptualization, T.A., A.A. (Ali Almustanyir), B.A. (Balsam Alabdulkader) and M.A.; methodology, formal analysis, investigation, and data curation, A.A. (Amal Aldarwesh), A.A. (Ali Almustanyir), M.A. and N.A.; writing—review and editing, T.A., A.A. (Ali Almustanyir), M.A., H.A. and B.A. (Bader Almagren); supervision, A.A. (Ali Almustanyir), M.A., B.A. (Balsam Alabdulkader) and T.A. All authors have read and agreed to the published version of the manuscript.

Funding: The Deanship of Scientific Research at King Saud University funded this work through the Waed Program (W25-22).

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the King Saud University Office of Research Ethics (E-22-6663).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: The authors would like to extend their appreciation to the Deanship of Scientific Research at King Saud University for funding this work through Waed Program (W25-22).

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CS	Contrast Sensitivity
CVD	Color Vision Deficiency
PR	Pelli–Robson (CS test)
VA	Visual Acuity
C-index	Confusion index
TES	Total Error Score
SD	Standard deviation
CDV	Color Difference Vector

Appendix A. Bonferroni-Adjusted Pairwise Comparisons of C-Index Across Lens Conditions (Repeated Measures)

Condition (I)	Condition (J)	Mean Difference (I–J)	Standard Error	*p*-Value	95% CI Lower	95% CI Upper
No filter	Lens M	0.405 *	0.080	<0.001	0.188	0.623
No filter	Lens P	0.663 *	0.098	<0.001	0.399	0.928
No filter	Lens V	0.318 *	0.062	<0.001	0.149	0.487
Lens M	Lens P	0.258 *	0.079	0.010	0.043	0.473
Lens M	Lens V	−0.088	0.063	0.995	−0.257	0.082
Lens P	Lens V	−0.346 *	0.071	<0.001	−0.539	−0.152

Values represent mean differences in C-Index derived from estimated marginal means of a repeated-measures analysis ($n = 79$). Pairwise comparisons were adjusted using the Bonferroni correction. Positive mean differences indicate higher C-Index values in the first condition relative to the second. $p < 0.05$ indicates statistical significance (*). Lens conditions included no filter, Lens M (magenta), Lens P (pink), and Lens V (violet). C-index, confusion index; CI, confidence interval.

Appendix B. Pairwise Comparisons of Total Error Across Lens Conditions (Bonferroni-Adjusted)

Condition (I)	Condition (J)	Mean Difference (I–J)	Standard Error	*p*-Value	95% CI Lower	95% CI Upper
No filter	Lens M	3.261 *	0.629	<0.001	1.558	4.964
No filter	Lens P	5.661 *	0.784	<0.001	3.538	7.784
No filter	Lens V	2.618 *	0.491	<0.001	1.287	3.948
Lens M	Lens P	2.400 *	0.660	0.003	0.613	4.187
Lens M	Lens V	−0.643	0.545	1.000	−2.117	0.831
Lens P	Lens V	−3.043 *	0.585	<0.001	−4.628	−1.459

Based on estimated marginal means. CI, confidence interval. *. The mean difference is significant at the 0.05 level. Adjustment for multiple comparisons: Bonferroni.

Appendix C. Pairwise Wilcoxon Signed-Rank Comparisons of Cross Scores Across Lens Conditions

Comparison	Z Value	*p*-Value	Interpretation
LM vs. NF	−4.519	<0.001	LM significantly reduced crossings compared to NF.
LP vs. NF	−5.789	<0.001	LP significantly reduced crossings compared to NF (the largest improvement).
LV vs. NF	−4.658	<0.001	LV significantly reduced crossings compared to NF.
LP vs. LM	−3.691	<0.001	LP produced significantly fewer crossings than LM.
LV vs. LP	−4.489	<0.001	LP produced significantly fewer crossings than LV.
LV vs. LM	−1.008	0.31	No significant difference between LV and LM.

LM, Lens magenta; LP, Lens pink; LV, Lens violet; NF, no filter.

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