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Research article

A mathematical approach to assess the ability of light filters to improve color discriminability of color vision deficient persons☆

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A B S T R A C T

Color vision deficiency (CVD) is a frequent condition that alters color perception to such an extent that many people encounter serious difficulties on their everyday lives. In this work, we present a strategy to analyze the effectiveness of light filters aimed to improve color discriminability of persons with CVD. The calculations are based on a simple model of color discrimination which has been successfully applied to several animal species. We first tested the calculations on three well-known commercial lenses designed for persons with CVD. In agreement with results of clinical studies, the calculations show that the highly colored lenses (VINO® and X-Chrom®) enhance chromaticity contrasts between problematic colors, whereas the more neutral Enchroma® do not provide any benefit. Also, we predict that two light filters proposed in recent works for novel lenses would not improve the performance of the commercial ones. Since the mathematical approach presented in this work enables predictive filter assessment, it opens the door to future research on the design of more effective lenses to improve color discriminability of persons with CVD. The calculations allow for large-scale screening of numerous light filters and different colored stimuli, CVD conditions, light sources, etc.

1. Introduction

"Color blindness", best referred to as *color vision deficiency* (CVD), is a frequent condition that affects the ability of people to perceive colors, as opposed to individuals with "normal" color vision. Congenital CVD incidence may be as high as 8–9 % in men, thus being the most frequent X-linked condition [1, 2]. For severe cases, CVD may have an important impact on people's daily lives, impeding them to perceive the world as observers with normal color vision do. People with CVD experience difficulties with everyday tasks such as clothing, cooking, or driving. They also find problems at their jobs whenever they have to make decisions based on color perception, and are often precluded from certain occupations, such as those related to the army or transport (where communications often rely on color signals), or those related to electronics or telecommunications (where decision making is often related to color) [3, 4].

The photoreceptor cells responsible for color vision are the cones. These are located mainly in the macula, a region of the central retina; the highest density of cone photoreceptors occurs in the fovea, a depression within the macula. Humans have three types of cones: S, M, and L (Figure 1A), named after the wavelength of maximum spectral sensitivity of their photopigments: short, medium and long [5]. When light enters the retina, these cells undergo differential excitation depending on the spectral distribution of the stimulus and on the sensitivity of each type of cone to light of different wavelengths. The rates of light absorption at each photoreceptor (represented by the photoreceptors' *quantum catches*) are further processed and transduced by other specialized cells located at inner layers of the retina (the *post-receptoral processing*). Briefly, retinal bipolar cells collect, process and transduce the photoreceptor's signals to the retinal ganglion cells at the innermost layer of the retina, and ultimately to the brain through the optic nerve [6], rendering the impressions we know as colors [1].

Most of the congenital CVD conditions occur because of mutations that alter the spectral sensitivity of one photoreceptor type. When three functional types of cones are present but the response curve of one of them is shifted compared to a normal observer, the condition is known as *anomalous trichromacy*. It may also happen that the retina completely lacks functional cells of one of the three types of cones; in this case, the

☆ Dedicated to the memory of Professor Lelia E. Dicelio (1946-2021).

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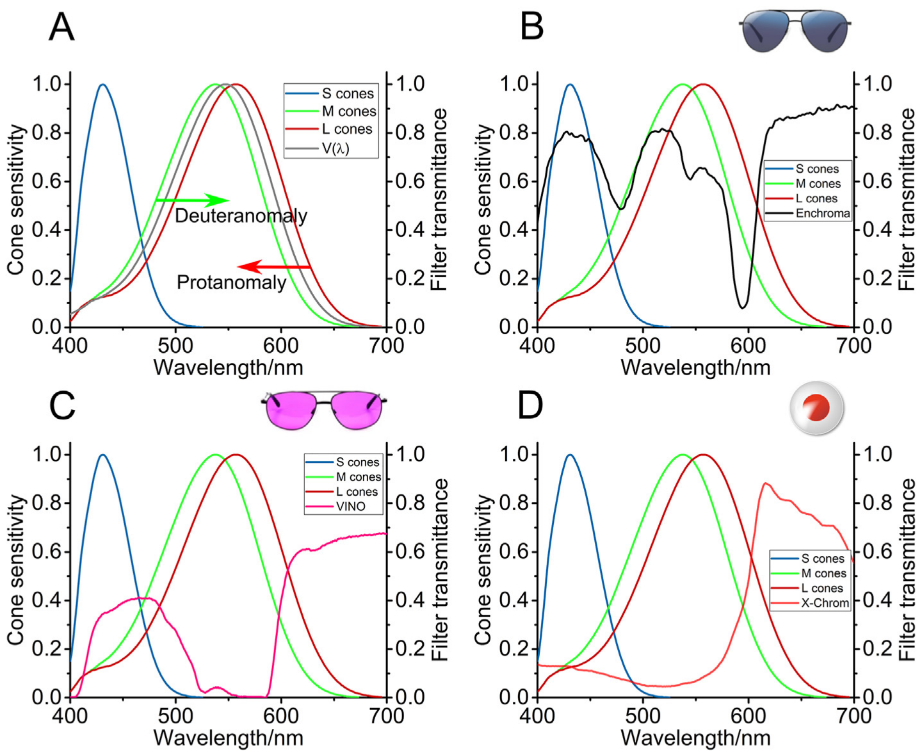

Figure 1. (A) Normalized spectral sensitivity of the three types of human cones. V(λ) represents the luminous efficiency (or photopic luminosity) function. The arrows indicate the shifts responsible for the two most common types of anomalous trichromacy (deuteranomaly and protanomaly). (B), (C), (D) Spectral transmittance of the three commercial filters analyzed in this work: (B) Enchroma (https://enchroma.com/) reprinted with permission from [17] © The Optical Society. (C) VINO (https://www.vino.vi/) reprinted with permission from [16] © The Optical Society. (D) X-Chrom, reprinted with permission from [14] © John Wiley & Sons.

condition is referred to as *dichromacy* [7]. Either of these situations causes that, after the incidence of colored light on the eye, the excitation of the defective cones is different from that of normal observers, thus sending "anomalous" signals to the brain and causing a "misinterpretation" of color, which may vary on severity depending on the condition.

The most common conditions are the *red-green CVD*, which are related to either the M or L cones, and account for most of the cases; the S-cone related CVD are very rare. Red-green CVD includes both dichromats (*protanopia*, in which only S and M cones are present, and *deuteranopia*, in which only S and L cones are present) and anomalous trichromats (*protanomaly*, in which the L cones are shifted towards the blue, and *deuteranomaly*, in which the M cones are shifted towards the red, as shown in Figure 1A). Deuteranomaly is the most common of them, accounting for more than 50 % of the CVD cases, with protanomaly, protanopia and deuteranopia rising to ~12–15 % of the total each [1, 7]. People with any of these four conditions have difficulties discriminating shades of red/orange from green, although there is a wide range of severity among anomalous trichromats [8]. Due to their high rate of incidence, this work is aimed at red-green CVD.

To the date, congenital CVD has no cure. Gene therapy protocols seem to be the only possible option in the future. Although there have been some successful attempts performed in animals [9], it seems unlikely that these procedures will be available for humans anytime soon. On the other hand, it has become quite common the use of interactive tools for electronic devices [10, 11] and of tinted light filters aimed to enhance the discriminability between problematic colors [1, 12]. Several companies provide such filters as commercial contact lenses or glasses, which are available in the market. Their performance has been studied by using color vision tests [13, 14, 15], such as the Ishihara test (Figure S1), and by calculations based on perceptual models of color vision [16, 17]. Although it is not possible to restore normal color vision, in occasions the filters improve discriminability of certain pairs of problematic colors, albeit with mixed results and not without drawbacks (such as the distortion of the appearance of perceived colors and important losses on total luminance due to filtering by the lens) [16].

To our knowledge, there are no predictive methods that provide an indicator of the expected performance of light filters on color discrimination. We believe such predictive methods are necessary to guide future efforts in the development of novel filters that perform better and have less drawbacks than those available in the market. In this work, we propose a calculational method based on the Receptor Noise Limited (RNL) model [18], which has been extensively used in visual ecology [19, 20, 21, 22]. The model predictions have been able to match experimental data of threshold spectral sensitivities for both trichromatic and dichromatic humans [23]. This model is based on the assumption that the ability of individuals to discriminate between two colors is limited by noise from the photoreceptors [23]. Its main advantage is its simplicity and therefore its generality, since only one parameter per photoreceptor is required (three in the case of humans); these parameters have been determined experimentally and used extensively [24].

First, we tested the ability of the model to account for the color contrasts perceived by people with different color vision conditions. Then we analyzed the performance of three commercial filters available in the market: Enchroma, VINO, and X-Chrom (Figure 1). The first one is a *multi-notch* filter designed under the basis that by filtering regions of overlap of the M and L cones the confusion of certain colors may be mitigated. In this case, the glasses are somewhat "neutral", whereas the other two are highly colored filters. There are many clinical studies available for these filters, which provide a good source of empirical information on their effectiveness to compare with the calculations of the RNL model. We then predicted the performance of two new filters proposed in recent works as candidates that are not available as commercial devices yet. Finally, we tested whether the use of these filters may have any effect on luminance contrast between colors, rather than on chromaticity.

Human color perception is a complex phenomenon, which cannot be approached by a simple model that provides a single indicator of color discrimination. Here we aim to provide quick and straightforward calculations that allow to assess whether a certain filter is a potential candidate for further exploration. Due to its simplicity, these calculations can be applied to examine thousands of candidate filters at the same time.

2. Materials and methods

2.1. Model and strategy

We used the Receptor Noise Limited (RNL) model [18, 23] to analyze whether the use of different light filters improves the discriminability between pairs of problematic colors for different vision conditions (normal color vision, protanomaly and deuteranomaly). In this model, a colored stimulus is indicated by a point in a three-dimensional space whose axes are the *quantum catches* (q_i), which represent the excitation of each photoreceptor type by a certain stimulus. The separation of two stimuli in this color space is indicated by their *chromatic distance* (ΔS), which can be calculated according to the model. The outcome of the calculation is compared to a certain threshold: for any pair of colors, if $\Delta S < \Delta S^t$ ("t" stands for threshold), the observer is not expected to be able to discriminate them. Above this threshold, as the separation of the two colors in the color space increases, the probability of discrimination rises [19]. It is common practice to consider $\Delta S^t = 1$ (provided that the parameters of the model have been chosen correctly); however, higher thresholds have been used as more conservative values, especially if there is no behavioral data available [20, 25].

Since many clinical studies of the performance of these filters on persons with CVD are based on their responsiveness to the Ishihara test, and given that it is common practice to use this test for diagnosis, we decided to base our method on its colors. For selected Ishihara plates, the color spots were classified as "signal" (if they compose the pattern the person has to identify, a number) or "background" otherwise. For each plate, ΔS was calculated for all the possible pairs of signal-background color spots. The comparation of the ΔS values for "with" and "without" filter situations allowed to evaluate the effect of the different light filters on color discrimination.

2.2. Model calculations

According to the model, the spatial coordinates for any stimulus (i.e., the quantum catch for receptor i under the stimulus j, q_i^j) are given by:

$$q_i^j = k_i \int I(\lambda) R^j(\lambda) T(\lambda) S_i(\lambda) d\lambda \tag{1}$$

where $I(\lambda)$ is the spectral distribution of the light that illuminates the stimulus, $R^j(\lambda)$ is the normalized reflectance spectrum of the stimulus, $T(\lambda)$ is the normalized transmittance spectrum of the filter placed between the stimulus and the eye ($T(\lambda) = 1$ if the calculation does not involve any filter), $S_i(\lambda)$ is the normalized spectral sensitivity of the photoreceptor, and k_i is a normalization constant.

Integration was performed between 400 nm and 700 nm, which are approximately the limits of human color vision. For most calculations, the light source was considered to be the CIE standard illuminant D65 [26], which represents approximately the spectral distribution of the average daylight. Alternatively, the CIE standard illuminant A [27], which corresponds to the spectral distribution of a typical tungsten filament, was used to test the effect of the filters in an "indoor" situation. The spectral distribution of both light sources is shown in Figure S2. The spectral sensitivities of human cones (Figure 1A) were calculated using a reported template for the absorption of A1 photopigments [28]. The λ_{max} of human pigment absorbance used for the calculations were obtained from the literature [29]. Filtering by ocular media and macular pigment was considered by including both normalized transmittance spectra in the calculations [30]. To account for red-green CVD conditions, protanopes and deuteranopes were modelled as dichromats lacking either the L or M cones, respectively; the same spectral sensitivities as observers with normal color vision were used for the remaining two cone types. Protanomaly and deuteranomaly were calculated by introducing a shift on the spectral sensitivities of the L (towards the blue) or the M (towards the red) cones, respectively [31] as shown in Figure 1A; besides this shift, the same spectral sensitivities as observers with normal color vision were used. Shifts of less than 1 nm to as much as 20 nm (which corresponds to a situation of almost complete superposition of M and L cones) have been reported [32]. We decided to work with a shift of 10 nm both for protanomaly and for deuteranomaly, which can be considered as an intermediate situation. Results of calculations performed using shifts of 5 nm and 15 nm were consistent (Table S1).

For each stimulus (j), the signal of each receptor f_i^j, (i = S cones, M cones, L cones), can be defined according to Weber-Fechners law [18]:

$$f_i^j = \ln\left(q_i^j\right) \tag{2}$$

Thus, the signal difference caused by two stimuli (for example, j_1 = Green (G) and j_2 = Orange (O)) on each photoreceptor can be computed as:

$$\Delta f_i^{G-O} = \ln\left(q_i^G\right) - \ln\left(q_i^O\right) = \ln\frac{q_i^G}{q_i^O} \tag{3}$$

The normalization constant k_i (Eq. (1)) is cancelled when the quotient of quantum catches is calculated.

The chromatic distance (ΔS^{G-O}) is defined as the Euclidean distance between the two points representing the colored stimuli in the three-dimensional photoreceptor color space. Therefore, its calculation must include the inputs of the three types of cones. The model assumes that luminance contrast does not affect color perception (although a luminance contrast can be calculated; see below), and that discriminability (i.e., "distance in the color space") is limited by noise from the photoreceptors [18]. According to the model, the chromatic distance for trichromats can be calculated as:

$$\Delta S^{G-O} = \sqrt{\frac{e_S^2\left(\Delta f_L^{G-O} - \Delta f_M^{G-O}\right)^2 + e_M^2\left(\Delta f_L^{G-O} - \Delta f_S^{G-O}\right)^2 + e_L^2\left(\Delta f_M^{G-O} - \Delta f_S^{G-O}\right)^2}{\left(e_L e_M\right)^2 + \left(e_L e_S\right)^2 + \left(e_M e_S\right)^2}} \tag{4}$$

In Eq. (4), e_i represents the noise of each photoreceptor channel; these are the only parameters of the model. It can be shown that $e_i \approx \omega_i$, where ω_i is the Weber fraction of the Weber law [18, 24]. We considered the reported values of $e_S = 0.08$, $e_M = 0.02$, $e_L = 0.02$ [33]. It is important to point out that our calculations are valid under bright-light illumination (that is, when the Weber law and therefore these values for the parameters are valid).

For dichromats the calculation is:

$$\Delta S^{G-O} = \sqrt{\frac{\left(\Delta f_{L/M}^{G-O} - \Delta f_S^{G-O}\right)^2}{\left(e_{L/M}\right)^2 + \left(e_S\right)^2}} \tag{5}$$

In this case, we considered the same photoreceptor spectral sensitivities as for the individuals with normal color vision, that is, the S and M cones (protanopia) or the S and L cones (deuteranopia). We used the same e_i as before.

The model also allows the calculation of *achromatic distances*, accounting for differences in luminance between stimuli. A single input needs to be considered in the case of humans, represented by the luminous efficiency function (the $V(\lambda)$ curve, shown in Figure 1A). The quantum catches of the two stimuli are calculated by replacing $S_i(\lambda)$ by $V(\lambda)$ in the quantum catch formula. Since there is a single achromatic input, the achromatic distance is given simply by the contrast between the two stimuli:

$$\Delta S_{achrom}^{G-O} = \left|\frac{\Delta f_V^{G-O}}{e_V}\right| = \left|\frac{1}{e_V}\ln\frac{q_V^G}{q_V^O}\right| \tag{6}$$

The bars in the formula represent absolute values. The $V(\lambda)$ curve was calculated in all cases considering the inputs from the M and L cones, as: $V(\lambda) = 1{,}55\, S_L(\lambda) + S_M(\lambda)$, where $S_L(\lambda)$ and $S_M(\lambda)$ represent the spectral sensitivities of the L and M cones, respectively [34]. For anomalous

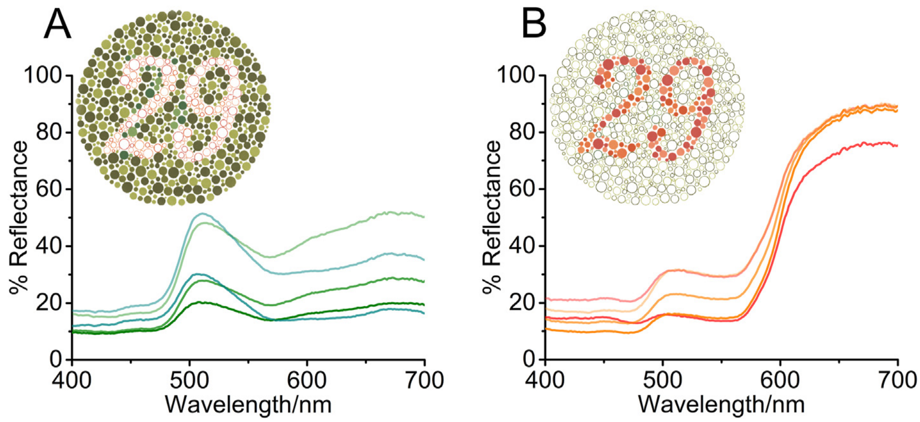

Figure 2. Reflectance spectra of spots corresponding to (A) green (background), and (B) orange (signal) colors of plate 3 of the Ishihara test. This plate contains 5 different shades of green and 5 different shades of orange.

trichromats, the 10 nm-shifted spectral sensitivities were considered for this calculation. The achromatic noise was $e_V = 0.125$, an average of the previous reported values of 0.11 [35] and 0.14 [36].

2.3. Selection of Ishihara color spots

Taking into consideration the instructions of the 24 plate edition of the Ishihara test [37], we selected three plates which represent green-orange contrasts (plates 3, 4, and 8), and plate 1 which is a control plate designed to be read by all non-monochromatic observers (Figure S1). We identified by visual inspection the different colors of each plate. For each color, spots of different sizes and locations within the plate were selected and their reflectance spectra were recorded.

2.4. Reflectance spectroscopy

The reflectance spectra of the color spots were acquired using a Shimadzu UV-3101PC spectrophotometer equipped with an integrating sphere (ISR-3100, Shimadzu) and UVProbe 2.33 software. The scans were performed between 350 and 750 nm, every 1 nm, with a bandwidth of 0.5 nm. To adjust for 100 % reflectance, both reference and sample positions of the sphere were occupied by a barium sulfate standard. After this correction, the 18 mm diameter sample position was completely covered with spots of the same color excised from each of the four Ishihara test plates analyzed in this study. In the sphere, the incidence angle to the sample position is set to 0°, therefore excluding the specular component of the reflected light, and allowing the determination of the diffuse component of the reflectance. For each color, the procedure was repeated three times and the three spectra were compared. In case they were considered similar, the average spectrum was used for further analysis; otherwise, the dissimilar spectrum was discarded and the average calculated with only two spectra (Figure S3).

2.5. Filter transmittance

Five colored filters designed for persons with CVD were tested: three of them are commercially available, while the other two were proposed in recent publications. The transmittance spectra (Figure 1 for the commercial filters and Figure S4 for the proposed filters) are publicly available either from the manufacturers, or from articles that have performed previous analyses: Enchroma Cx1 [17], VINO [16], X-Chrom [14], Functional Reflective Polarizer (FRP) [38], and Rhodamine [39].

2.6. Calculations, data treatment and statistical analysis

For each Ishihara plate, both chromatic (Figure 3) and achromatic (Figure S5) ΔS were calculated between all the possible pairs of “signal” (number) and “background” color spots. The calculations were preformed using a spreadsheet program. For each plate, an average signal-background ΔS was calculated (ΔS_{avg}), both for chromatic (Table S2) and achromatic contrasts (Figure S5). Afterwards, for each condition (k = protanomaly, deuteranomaly) the difference in chromatic distance (ΔΔS) between the person with CVD and the observer with normal color vision was calculated for each signal-background pair of color spots as follows:

$$\Delta\Delta S_k = \Delta S_k - \Delta S_{normal} \quad (7)$$

The results were represented as box plots (Figure 3) indicating the median and the 25th and 75th percentiles.

To assess for the effect of wearing the lenses on anomalous trichromats' vision, for each lens (l = Enchroma, VINO, X-Chrom, FRP, Rhodamine) the difference in both chromatic and achromatic distances (ΔΔS) between “with” and “without” lens situations was calculated for each signal-background pair of color spots as follows:

$$\Delta\Delta S_l = \Delta S_{with} - \Delta S_{without} \quad (8)$$

The mean and standard deviation of each data set were calculated both for chromatic (Figure 4) and achromatic (Figure 5) distances. For all these data sets, one sample hypothesis t-test for the mean with null hypothesis: Mean = 0 (i.e. there is no significant effect of wearing the filters), and alternate hypothesis: Mean ≠ 0, were performed. All the datasets accomplishing the alternate hypothesis at a significance level of 0.05 are indicated with * in the figures.

3. Results

3.1. Chromatic distance values for normal color vision and CVD

Reflectance spectra of the color spots from plate 3 of the Ishihara test for CVD diagnosis (Figure S1) are shown in Figure 2; spectra from the other plates are shown in Figure S3.

For each Ishihara plate, the chromatic distance (ΔS) was calculated for all the pairs of “signal” and “background” color spots considering observers with normal color vision (Figure 3, first column). The average value for plate 3 was $\Delta S_{avg,normal} = 6.39$ (n = 25). The results for the other plates were similar (Table S2).

The same calculations were performed for observers with red-green CVD, both dichromats and anomalous trichromats (Figure 3, first column). As expected, for all the conditions the ΔS values are lower than those of observers with normal color vision. The average values for plate 3 were: $\Delta S_{avg,protanomaly} = 4.06$, $\Delta S_{avg,protanopia} = 2.75$, $\Delta S_{avg,deuteranomaly} = 4.29$, $\Delta S_{avg,deuteranopia} = 2.22$. The results for the other plates were similar (Table S2). Also, for anomalous trichromats the ΔS values become smaller as the shift of the sensitivity curve (and therefore the superposition of the M and L cones) increases (Table S1).

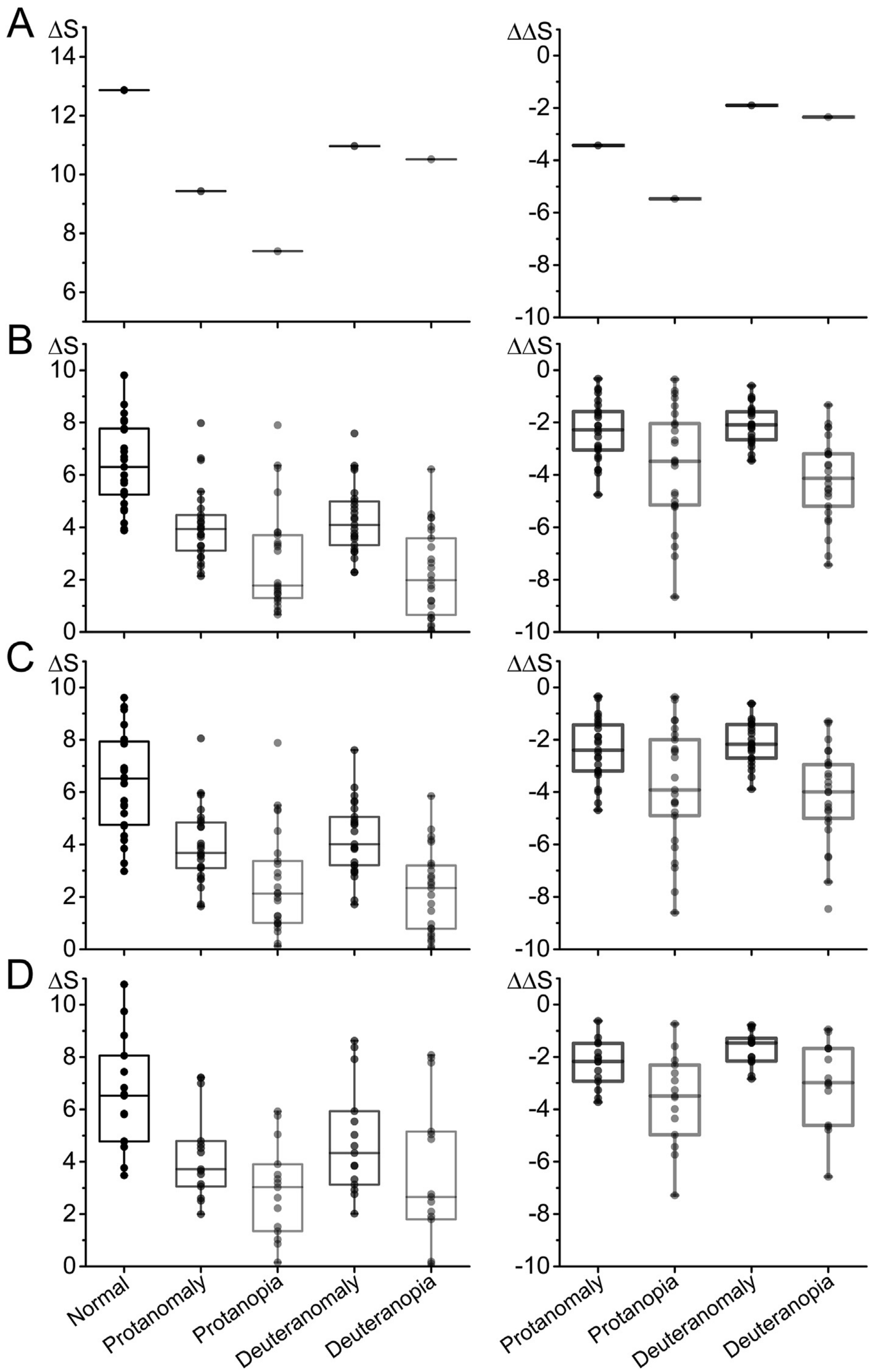

Figure 3. (First column) Chromatic distances (ΔS) of signal-background color pairs calculated according to the RNL model for individuals with normal color vision and for persons with different CVD conditions. (Second column) The same results expressed as the difference (ΔΔS), for each specific pair of green-orange spots, relative to normal color vision. For both columns, each point represents a green-orange pair, and the median and 25th and 75th percentiles are indicated. (A) plate 1 (n = 1), (B) plate 3 (n = 25), (C) plate 4 (n = 25), (D) plate 8 (n = 15).

Since the ability to discriminate between green and orange is reduced in persons with red-green CVD, not only the average values, but also ΔS for any pair of colors, should be lower than that of persons with normal color vision. To account for this fact, the results were plotted as the difference in chromatic distance (ΔΔS), for each specific signal-background pair of spots, between individuals with CVD and persons with normal color vision (Figure 3, second column). All the color pairs are less discriminable both for the anomalous trichromats and for the dichromats compared to observers with normal color vision (i.e. all the differences are negative; the average decrease for plate 3 was $\Delta\Delta S_{avg,protanomaly}$ = -2.33, $\Delta\Delta S_{avg,deuteranomaly}$ = -2.10, $\Delta\Delta S_{avg,protanopia}$ = -3.64, and $\Delta\Delta S_{avg,deuteranopia}$ = -4.17). These results indicate that the values of ΔS calculated by the model are consistent with the lower ability of individuals with different CVD conditions to discriminate between pairs of colors of green-orange compared to normal color vision, and with decreased ability with increased severity of the condition.

As stated in the Materials and methods section, usually at the threshold of discriminability it is $\Delta S^t = 1$. However, actual discriminability may be poor and two colors with $\Delta S \approx 1$ or slightly above may not be discriminable, depending on the conditions of observation [20]. Also, the results of the calculations are strongly dependent on the choice of the parameters [40]. If accurate values for the parameters are not available or if there are no

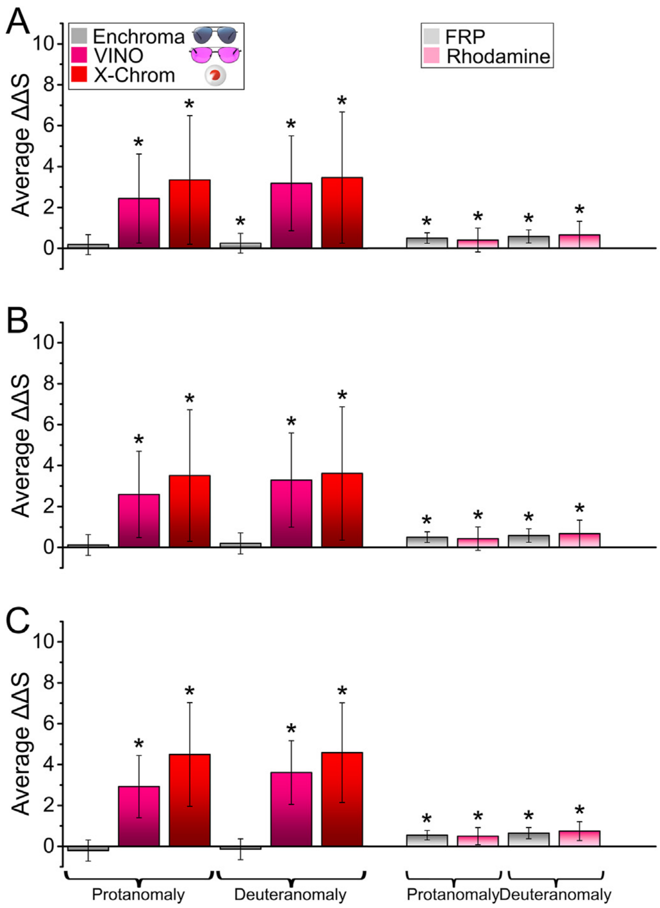

Figure 4. Average differences in chromatic distances ($\Delta\Delta S_{avg}$) for individuals with protanomaly or deuteranomaly wearing filters aimed to help persons with CVD, relative to the corresponding condition without filter. Each bar represents the average of all the green-orange spots in each plate; the standard deviation is also shown. Asterisks indicate those data sets which are different from zero at a significance level of 0.05. (A) plate 3 (n = 25), (B) plate 4 (n = 25), (C) plate 8 (n = 15).

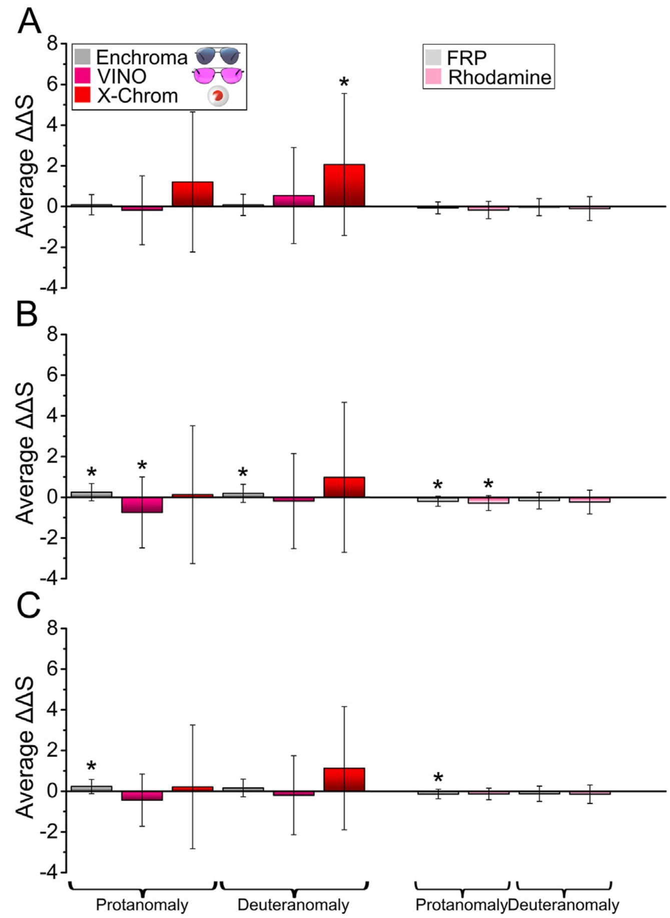

Figure 5. Average differences in achromatic distances ($\Delta\Delta S_{avg}$) for individuals with protanomaly or deuteranomaly wearing filters aimed to help persons with CVD, relative to the corresponding condition without filter. Each bar represents the average of all the green-orange spots in each plate; the standard deviation is also shown. Asterisks indicate those data sets which are different from zero at a significance level of 0.05. (A) plate 3 (n = 25), (B) plate 4 (n = 25), (C) plate 8 (n = 15).

behavioral experiments to determine the actual thresholds of color discrimination, more conservative values such as $\Delta S^t = 3$ have been considered [25]. Also, empirical values of $\Delta S^t > 1$ have been reported based on behavioral experiments [41, 42, 43]. It is therefore important to point out that we will use ΔS values as a comparative measure between different conditions ("glasses on" vs. "glasses off", as we will discuss in the following sections), and not to predict absolute discriminability.

As a control, we calculated ΔS for plate 1, which is designed in such a way that any person who is not monochromatic should be able to read the number. This plate contains a single pair of signal-background, orange-gray spots (Figure S1). The lower value, corresponding to protanopia, is $\Delta S_{protanopia} = 7.39$ (Table S2). We have also calculated *achromatic* ΔS (Figure S5), which account for the luminance contrast between the spots (see the following sections for details). The Ishihara test is designed in such a way that people should not be able to identify the pattern based on luminance contrasts, but rather based on chromaticity only. There are no significant differences between normal color vision and anomalous trichromats, as opposed to the results of chromatic ΔS, which agrees with the rationale of design of the test. Overall, these observations provide another level of validation to the calculations. Finally, it should be noted that the plates are designed for people with mild/intermediate CVD to confuse the number but not to completely hide it. For instance, for plate 3 normal observers read "29" whereas red-green anomalous trichromats often read "70". Therefore, many of the color pairs remain discriminable even for persons with CVD.

3.2. Effect of commercial filters for CVD on chromaticity

We then analyzed the effect on color discriminability of different commercially available lenses aimed to help persons with CVD. We focused our study on the less severe conditions, the anomalous trichromats, with a 10 nm shift on their photoreceptors. The effect of "wearing the lenses" was simulated by introducing the transmittance spectra of the filter in the calculations of the quantum catches. Therefore, the incident light (CIE standard illuminant D65 spectrum) is reflected on the color spots (reflectance spectrum) and the spectral distribution of the light that reaches the S, M or L cones (spectral sensitivity curve) is modulated by the filter (transmittance spectrum). The calculations were performed for three brands of commercial devices: Enchroma, VINO, and X-Chrom (see Figure 1 for the transmittance spectra; the first two are provided as glasses whereas X-Chrom are contact lenses). Afterwards, for each specific signal-background pair of spots ΔΔS was calculated as the difference between the "filter on" and "filter off" situations (positive values indicate an increase in discriminability as a result of wearing the filters). The results are presented in Figure 4 as the average of all the ΔΔS for each plate. Both strongly colored filters, VINO and X-Chrom, induce a significant improvement on the ability of individuals with both types of anomalous trichromacy to discriminate green from orange, up to values of discriminability close to that of normal observers. However, the neutral Enchroma glasses have no apparent effect on the signal-background contrast. These results are consistent with clinical studies of patients wearing the filters [15, 16, 17, 44] (see the Discussion for more details).

Care must be taken when interpreting the values of standard deviation of these data sets, since each average includes ΔS from different color pairs, and therefore some variability within each plate is expected (Figure 3, first column).

3.3. Effect of filters proposed for future devices on chromaticity

Some articles have proposed filters which have not been implemented as commercial devices yet as putative aids for persons with CVD. We analyzed two of these filters in the same way as the commercial lenses, in order to predict if they could provide a better result than those available in the market. FRP [38] is a multi-notch filter similar to Enchroma, since its rationale is to minimize the transmission of light on regions of superimposition of the spectral sensitivities of the M and L cones. Rhodamine [39] is a contact lens designed recently which contains rhodamine as a chromophore; as VINO and X-Chrom, it is a highly-colored filter. The transmittance spectra of these filters are shown in Figure S4, and the results of the calculations are shown in Figure 4. Although both filters provide a statistically significant improvement and perform slightly better than Enchroma, the effect is much less noticeable than that of the already available VINO and X-Chrom. Therefore, we predict that these two filters are not good candidates to design commercial devices.

3.4. Effect of the filters on luminance

Previous works have proposed that VINO and X-Chrom filters may affect luminance differences between colors [16, 45] rather than chromaticity. Discrimination based on differences of luminance can be considered using the RNL model by taking as input the luminous efficiency function (V(λ)) [34] shown in Figure 1A, instead of the spectral sensitivities of the three types of cones. This function represents the sensitivity of the human eye to light under photopic conditions, that is, relatively high photon flux (when cones are functional). In this way, the calculation of an *achromatic distance* which accounts for the contrast in luminance, is very similar to the calculation of the chromatic ΔS we have been analyzing so far, which accounts for the chromatic contrast.

The achromatic ΔS_{avg} between signal and background spots was calculated for observers with normal color vision and for people with CVD (Figure S5). For normal color vision the values are much smaller than those of chromatic ΔS for all plates. Furthermore, there is no difference on luminance contrast between normal and CVD. This result is in line with the rationale of Ishihara plates, which are designed to be discriminated by chromaticity but not by luminance differences between signal and background.

The average difference of achromatic distance ($\Delta\Delta S_{avg}$) for individuals wearing filters relative to individuals without filters is shown in Figure 5. The dispersion of the data (in terms of standard deviation/mean) is considerably higher than in the case of the chromatic ΔS; this causes that in most cases, the $\Delta\Delta S_{avg}$ values are not different from zero at a significance level of 0.05. Therefore, the analysis of achromatic ΔS is less concluding than that of chromatic ΔS, and does not allow supporting the idea that the filters might work through an achromatic mechanism, as previously proposed.

3.5. Effect of the illuminant on the performance of the filters

The calculations presented so far were performed using the CIE standard illuminant D65, which represents approximately the spectral distribution of daylight. This corresponds to an "outdoor" situation. To gain some insight into the performance of the filters in an indoor situation, we repeated the calculations for plate 3 using the CIE standard illuminant A as the light source (Figure S2). This illuminant represents a typical domestic tungsten-filament lighting. The results of these calculations are shown in Figure 6.

Even though for observers with normal color vision and for anomalous trichromats the absolute values of ΔS are higher than those obtained using daylight conditions (compare Figure 3B, left panel, and Figure 6A), the model provides ΔS values which are consistent with the color vision limitations of each observer. The results of the effect of the filters on chromatic distance are similar to those obtained with the D65 illuminant (compare Figure 4A and Figure 6B). A slight improvement of the performance of Enchroma, FRP and Rhodamine was observed under the indoor condition; however, they are still greatly outperformed by the highly tinted VINO and X-Chrom filters, as observed for the daylight illumination condition. These results suggest that addressing the effect of the illuminant will be important in future works aimed at the development of better filters.

4. Discussion

The RNL model allows focusing on color discriminability rather than on "absolute" color perception, the latter being the focus of the most recent works on Enchroma and VINO glasses [16, 17]. It is now agreed that the use of colored filters cannot return normal color vision to people with CVD; thus, the best expectation for these devices is to enhance discrimination between certain colors. This potential should not be underestimated, since it could significantly improve the performance of persons with CVD on specific tasks. Furthermore, new devices could be developed based on the existing work on the field if an accurate method to assess and predict the effect they have on color discriminability is developed.

Our results show that the values of the chromatic ΔS provided by the RNL model account for the capability of persons with different degrees of CVD, both dichromats and anomalous trichromats, to discriminate between pairs of colors. We defined a ΔΔS indicator that allows for

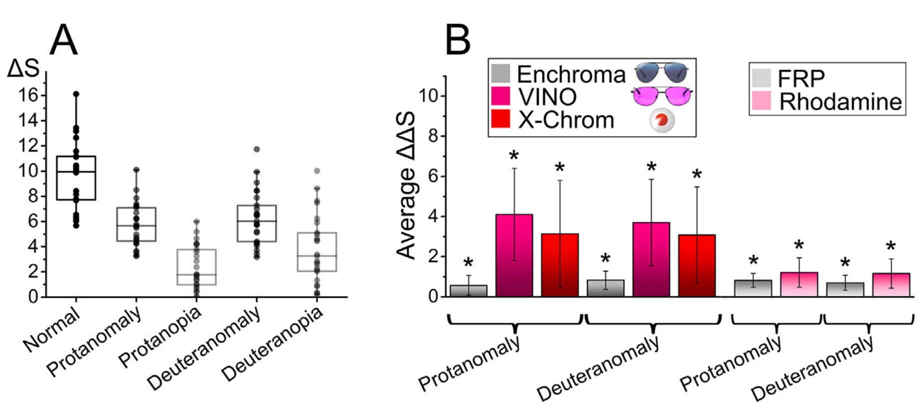

Figure 6. Calculations for plate 3 of the Ishihara test using the CIE standard illuminant A as a representative of indoor lighting. (A) Chromatic distances (ΔS) of signal-background color pairs calculated according the RNL model for individuals with normal color vision and for persons with different CVD conditions. Each point represents a green-orange pair, and the median and 25th and 75th percentiles are indicated. (B) Average differences in chromatic distances ($\Delta\Delta S_{avg}$) for individuals with protanomaly or deuteranomaly wearing filters aimed to help persons with CVD, relative to the corresponding condition without filter. Each bar represents the average of all the green-orange spots in this plate (n = 25); the standard deviation is also shown. Asterisks indicate those data sets which are different from zero at a significance level of 0.05.

quantitative prediction of the improvement in discriminability provided by the filters. The results obtained using this indicator agree with previously reported clinical studies. This approach could be useful in exploratory research of candidate filter selection for the design of lenses to be tested on clinical studies.

We surveyed three commercial filters: Enchroma, VINO, and X-Chrom; the first one is more greyish-neutral, whereas the other two are highly tinted (purple and red respectively). In principle, Enchroma is expected to be more appropriate for daily use for two reasons. First, its overall transmittance is much higher, whereas for the tinted lenses the total amount of light that reaches the eye is considerably less; this may be problematic under dim light, when total luminance is low. Second, highly-tinted lenses induce more distortions in the perception of the "real" appearance of colors [16].

Many recent works have addressed the performance of Enchroma [15, 17], VINO [16], X-Chrom (or very similar filters) [14, 44, 45, 46] and the ChromaGen [13, 47] glasses (which are also highly-tinted filters that were not studied here), on the basis of responsiveness of persons with CVD to color vision tests. Some general conclusions from that works are:

- The tinted filters are a better option to improve color discrimination. It was found unanimously that Enchroma provides no significant improvement in any color vision test.
- In almost all cases the tinted filters improved the performance on pseudoisochromatic plate tests (such as the Ishihara test). Results of tests in which persons are asked to arrange a set of similar colors according to its hue (such as the Farnsworth-Munsell D-15 test) were mixed: the performance of some individuals improved with the use of lenses, whereas others worsened. No improvement was observed on color naming tests (such as the Fansworth Lantern test) which are used to assess color vision for certain occupations. These observations reinforce the idea that, even though contrast between certain colors is improved by using tinted lenses, the perception of "real" color does not.
- Deutan individuals tend to obtain more benefit from the use of the lenses than protans, with varied degrees of improvement among individuals. This indicates that universal solutions may be rather difficult to develop; instead, more personalized lenses could be searched for.
- Often the authors of these works argue that the use of the lenses generates an enhancement of luminance contrast, thus "cheating" the Ishihara test.

Based on our analysis, both VINO and X-Chrom significantly improve color discrimination of persons with CVD, while Enchroma did not induce any improvement; these results agree with the reported literature. On the other hand, our data seems to support the idea that the improvement provided by both tinted lenses occurs through a chromatic mechanism, whereas the effect on luminance is unclear due to the high dispersion of the data; this observation contrasts the observations made by of some authors.

In recent years, Zhu et al. [38] and Badawy et al. [39] have proposed two filters for CVD assistance: a rhodamine-based contact lens, and a multi-notch filter Functional Reflective Polarizer (FRP), which was inspired by the Enchroma concept. Our results indicate that, although statistically significant, the performance of these two proposed filters is far less impressive than the already available VINO and X-Chrom. The strategy of designing "universal" glasses that filter regions of superimposition of the M and L cones sensitivity curves does not appear successful so far. Future solutions should have sharp absorption bands in the correct location within the visible spectrum to avoid too much luminance loss and to maximize color discriminability. To be functional, a varied set of filters could be available to be chosen by each particular person for the specific task they intend to perform.

We have also tested the effect of using an illuminant with a spectral distribution corresponding to a standard indoor illumination. The results for this situation were similar to those obtained for standard daylight illumination. It is important to point out that both situations correspond to high illumination intensities, where the Weber law is valid. Further work is required to assess the effect of the filters under low-light illumination, where dark noise is important for color discrimination.

Beyond the assessment of already known filters for improving color discrimination of people with different CVD conditions, the approach presented here provides a mathematical tool for the future design of new filters. Indeed, "customized" filters could be designed to achieve a desired degree of discrimination between colors, based on knowledge of the type and severity of the observer's CVD condition, and on the task the person intends to perform.

Declarations

Author contribution statement

Nicolás González Bardec: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

María Gabriela Lagorio: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

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References

[1] M.P. Simunovic, Colour vision deficiency, Eye 24 (2010) 747–755.
[2] J. Birch, Worldwide prevalence of red-green color deficiency, J. Opt. Soc. Am. A. 29 (2012) 313.
[3] J.M. Steward, B.L. Cole, What do color vision defectives say about everyday tasks? Optom. Vis. Sci. 66 (1989) 288–295.
[4] A. Tagarelli, A. Piro, G. Tagarelli, P.B. Lantieri, D. Risso, R.L. Olivieri, Colour blindness in everyday life and car driving, Acta Ophthalmol. Scand. 82 (2004) 436–442.
[5] S.G. Solomon, P. Lennie, The machinery of colour vision, Nat. Rev. Neurosci. 8 (2007) 276–286.
[6] R.H. Masland, The neuronal organization of the retina, Neuron 76 (2012) 266–280.
[7] L. Hofmann, K. Palczewski, Advances in understanding the molecular basis of the first steps in color vision, Prog. Retin. Eye Res. 49 (2015) 46–66.
[8] J. Barbur, M. Rodriguez-Carmona, S. Evans, N. Milburn, Minimum color vision requirements for professional flight crew, Part III: recommendations for new color vision standards, Civ. Aviat. Auth. Rep. 50 (2009).

[9] K. Mancuso, W.W. Hauswirth, Q. Li, T.B. Connor, J.A. Kuchenbecker, M.C. Mauck, J. Neitz, M. Neitz, Gene therapy for red-green colour blindness in adult primates, Nature 461 (2009) 784–787.

[10] P. Melillo, D. Riccio, L. Di Perna, G. Sanniti Di Baja, M. De Nino, S. Rossi, F. Testa, F. Simonelli, M. Frucci, Wearable improved vision system for color vision deficiency correction, IEEE J. Transl. Eng. Heal. Med. 5 (2017).

[11] E. Tanuwidjaja, D. Huynh, K. Koa, C. Nguyen, C. Shao, P. Torbett, C. Emmenegger, N. Weibel, Chroma: a wearable augmented-reality solution for color blindness, UbiComp 2014 - Proc. 2014 ACM Int. Jt. Conf. Pervasive Ubiquitous Comput. (2014) 799–810.

[12] L.T. Sharpe, H. Jägle, I used to be color blind, Color Res. Appl. 26 (2001) S269–S272.

[13] H.A. Swarbrick, P. Nguyen, T. Nguyen, P. Pham, The ChromaGen contact lens system: colour vision test results and subjective responses, Ophthalmic Physiol. Opt. 21 (2001) 182–196.

[14] V. Diaconu, D. Sullivan, J.F. Bouchard, V. Vucea, Discriminating colors through a red filter by protanopes and colour normals, Ophthalmic Physiol. Opt. 30 (2010) 66–75.

[15] N. Almutairi, J. Kundart, N. Muthuramalingam, J.R. Hayes, K. Citek, S. Aljohani, Assessment of enchroma filter for correcting color vision deficiency assessment of enchroma filter for correcting color vision deficiency, Coll. Optom. 21 (2017) 1–48. http://commons.pacificu.edu/opt/21.

[16] M.A. Martínez-Domingo, L. Gómez-Robledo, E.M. Valero, R. Huertas, J. Hernández-Andrés, S. Ezpeleta, E. Hita, Assessment of VINO filters for correcting red-green color vision deficiency, Opt. Express 27 (2019) 17954.

[17] L. Gómez-Robledo, E.M. Valero, R. Huertas, M.A. Martínez-Domingo, J. Hernández-Andrés, Do EnChroma glasses improve color vision for colorblind subjects? Opt. Express 26 (2018) 28693.

[18] M. Vorobyev, R. Brandt, D. Peitsch, S.B. Laughlin, R. Menzel, Colour thresholds and receptor noise: behaviour and physiology compared, Vision Res. 41 (2001) 639–653.

[19] A. Siddiqi, T.W. Cronin, E.R. Loew, M. Vorobyev, K. Summers, Interspecific and intraspecific views of color signals in the strawberry poison frog Dendrobates pumilio, J. Exp. Biol. 207 (2004) 2471–2485.

[20] S.A. Kane, Y. Wang, R. Fang, Y. Lu, R. Dakin, How conspicuous are peacock eyespots and other colorful feathers in the eyes of mammalian predators? PloS One 14 (2019) 1–35.

[21] P. Olsson, O. Lind, A. Kelber, Bird colour vision: behavioural thresholds reveal receptor noise, J. Exp. Biol. 218 (2015) 184–193.

[22] K.L. Cheney, N.J. Marshall, Mimicry in coral reef fish: how accurate is this deception in terms of color and luminance? Behav. Ecol. 20 (2009) 459–468.

[23] M. Vorobyev, D. Osorio, Receptor noise as a determinant of colour thresholds, Proc. R. Soc. B Biol. Sci. 265 (1998) 351–358.

[24] P. Olsson, O. Lind, A. Kelber, Chromatic and achromatic vision: parameter choice and limitations for reliable model predictions, Behav. Ecol. 29 (2018) 273–282.

[25] G. Pérez i de Lanuza, J. Ábalos, A. Bartolomé, E. Font, Through the eye of a lizard: hue discrimination in a lizard with ventral polymorphic coloration, J. Exp. Biol. 221 (2018).

[26] T.M. Goodman, International standards for colour, in: Colour Des, second ed., Woodhead Publishing, 2017, pp. 417–452.

[27] R.W.G. Hunt, M.R. Pointer, Appendix 5: relative spectral power distributions of illuminants, in: Meas. Colour, John Wiley & Sons, Ltd, 2011, pp. 355–378.

[28] V.I. Govardovskii, N. Fyhrquist, T. Reuter, D.G. Kuzmin, K. Donner, In search of the visual pigment template, Vis. Neurosci. 17 (2000) 509–528.

[29] H.J.A. Dartnall, J.K. Bowmaker, J.D. Mollon, Human visual pigments: microspectrophotometric results from the eyes of seven persons, Proc. R. Soc. London - Biol. Sci. 220 (1983) 115–130.

[30] G. Wyszecki, W.S. Stiles, Visual thresholds, in: Wiley, Sons (Eds.), Color Sci. Concepts Methods, Quant. Data Formulae, second ed., 2000, pp. 525–544.

[31] M. Lucassen, J. Alferdinck, Dynamic simulation of color blindness for studying color vision requirements in practice, in: CGIV 2006 - 3rd Eur. Conf. Colour Graph. Imaging, Vis., 2006, pp. 355–358.

[32] L.T. Sharpe, A. Stockman, H. Jägle, J. Nathans, Opsin genes, cone photopigments, color vision, and color blindness, in: K. Gegenfurtner, L.T. Sharpe (Eds.), Color Vis. From Genes to Percept., Cambridge University Press, 1999, pp. 3–51.

[33] W.S. Stiles, Color vision: the approach through increment-threshold sensitivity, Proc. Natl. Acad. Sci. 45 (1959) 100–114.

[34] L.T. Sharpe, A. Stockman, W. Jagla, H. Jägle, A luminous efficiency function, VD65* (λ), for daylight adaptation: a correction, Color Res. Appl. 36 (2011) 42–46.

[35] U. Griebel, A. Schmid, Brightness discrimination ability in the West Indian manatee (Trichechus manatus), J. Exp. Biol. 200 (1997) 1587–1592.

[36] T.N. Cornsweet, H.M. Pinsker, Luminance discrimination of brief flashes under various conditions of adaptation, J. Physiol. 176 (1965) 294–310.

[37] S. Ishihara, Ishihara's Tests for Colour-Blindness, Kanehara Shuppan, 1972. https://books.google.com.ar/books?id=rug6nwEACAAJ.

[38] R. Zhu, G. Tan, J. Yuan, S.-T. Wu, Functional reflective polarizer for augmented reality and color vision deficiency, Opt. Express 24 (2016) 5431.

[39] A.R. Badawy, M.U. Hassan, M. Elsherif, Z. Ahmed, A.K. Yetisen, H. Butt, Contact lenses for color blindness, Adv. Healthc. Mater. 7 (2018) 1–7.

[40] O. Lind, A. Kelber, Avian colour vision: Effects of variation in receptor sensitivity and noise data on model predictions as compared to behavioural results. Vision Res. 49 (2009) 1939–1947.

[41] K.L. Cheney, N.F. Green, A.P. Vibert, M. Vorobyev, N.J. Marshall, D.C. Osorio, J.A. Endler, An Ishihara-Style Test of Animal Colour Vision, 2019, pp. 1–8.

[42] A. Sibeaux, G.L. Cole, J.A. Endler, Success of the receptor noise model in predicting colour discrimination in guppies depends upon the colours tested, Vision Res 159 (2019) 86–95.

[43] O. Lind, Colour vision and background adaptation in a passerine bird, the zebra finch (Taeniopygia guttata), R. Soc. Open Sci. 3 (2016).

[44] D.P.K. Sodhi, Are X-chrome lenses an occupational succor for the colour vision defectives? J. Adv. Res. Med. Sci. Technol. 1 (2017) 1–6.

[45] K. Sato, T. Inoue, S. Tamura, H. Takimoto, Discrimination of colors by red-green color vision-deficient observers through digitally generated red filter, Vis. Neurosci. 36 (2019).

[46] H.M. Paulson, The X-chrom lens for correction of color deficiency, Mil. Med. 145 (1980) 557–560.

[47] C. Ilhan, M.A. Sekeroglu, S. Doguizi, P. Yilmazbas, The effect of the ChromaGen contact lens system on visual performance, Clin. Exp. Optom. (2019) 1–6.