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Do EnChroma glasses improve color vision for colorblind subjects?

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Abstract: The commercialization of EnChroma glasses has generated great expectations for people to be able to see new colors or even correct color vision deficiency (CVD). We evaluate the effectiveness of these glasses using two complementary strategies for the first time. The first consists of using the three classical types of tests — recognition, arrangement and discrimination — with and without glasses, with a high number of individuals. In the second, we use the spectral transmittance of the glasses to simulate the appearance of stimuli in a set of scenes for normal observers and observers with CVD. The results show that the glasses introduce a variation of the perceived color, but neither improve results in the diagnosis tests nor allow the observers with CVD to have a more normal color vision.

1. Introduction

Normal human color vision is trichromatic thanks to a cluster of three types of photoreceptors known as cones. These cones are sensitive to short wavelengths (S), medium wavelengths (M) and long wavelengths (L). Around 8% of men and 0.5% of women in the Caucasian population suffer from some type of congenital color deficiency, which is a sex-linked recessive trait, with the red-green color vision deficiency (CVD) being the most frequent in humans [1] [2]. Red-green CVD is classified into two types: the protan and the deutan. These congenital deficiencies are classified depending on the number and type of affected cones. As far as the number of cones is concerned the classification of CVD is: anomalous trichromacy (3 cones), dichromacy (2 cones), and monochromacy (1 cone). According to the type of cone affected, the following classifications are used: protanomaly (L cones are affected) or protanopia (there are no L cones), deuteranomaly (M cones are affected) or deuteranopia (there are no M cones), and tritanomaly (S cones are affected) or tritanopia (there are no S cones).

People who are suffering from some moderate to strong CVD undergo daily life handicaps (e.g. detecting the ripeness of fruit and vegetables, dealing with the color of LED lights in electronic devices, interpreting maps and graphs, ...) and consequently they are automatically excluded from particular occupations (e.g. airline pilot, firefighter, train driver, air traffic controller, ...) [3].

Apart from new genetic therapy treatments, so far only tested on mice and primates [4], currently there is no effective treatment of CVD in humans [1]. However, available tools have been suggested as aids for people with CVD [5]. These active tools are really interesting for helping CVD observers in their daily life as they change the appearance of the objects through image processing algorithms. However this results in a decrease of naturalness. Among the passive tools, colored filters (or tinted lenses) have recently received an increased interest in the media, with viral videos where people even cry when they wear for the first time the glasses commercialized by EnChroma [6], under the name "Color for the Color Blind". This company was founded in 2010 and the first version of the glasses was launched in 2012, while an improved version appeared in 2014. Currently there are several models available and they can be manufactured for any mount and prescription, even for progressive

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lenses. These glasses block parts of the visible light spectrum through optical filters. The company advertises an improvement in color vision for people with red-green CVD, which includes protan and deutan cases, by extending the range of colors perceived without affecting the colors that are already distinguished without glasses. EnChroma states that their glasses “alleviate red-green color blindness, enhancing colors without the compromise of color accuracy” but claiming that their glasses “may not work” for severe red-green deficiency [6].

One strong claim on the EnChroma website [6] (October 2017) was that their “glasses are designed to improve the everyday experience of color vision”. Recently, however, this claim was substituted by a more subtle sentence: “the glasses are an optical assistive device for enhancement of color discrimination in persons with color blindness; they are not a cure for color blindness.” Other current claims (July 2018) are: “EnChroma does not endorse the use of the glasses to pass occupational screening tests such as the Ishihara test”, “Results vary depending on the type and extent of color vision deficiency per individual”, “EnChroma glasses are usually effective for red-green color blindness and are unlikely to help for tritanomaly or tritanopia (blue-yellow color blindness)”.

Mastey et al. [7] and Patterson [8] studied the effect of wearing EnChroma glasses on red-green CVD observers. Mastey et al. [7] recruited 27 males: ten deuteranopic, eight deuteranomalous and nine protanopic. Patterson [8] recruited fifteen males: seven deuteranopic, six deuteranomalous, one protanopic and one protanomalous. In both papers [7] [8] the authors used the Color Assessment and Diagnosis (CAD) test that provides chromatic discrimination thresholds. The results of Mastley et al. [7] show that EnChroma glasses did not significantly improve the red-green thresholds for either protans or deutans and decreased the blue-yellow thresholds for deutans. Similar results were found by Patterson [8]. Both Mastey et al. [7] and Patterson [8] concluded that their data did not support that EnChroma glasses are the solution for seeing new colors or curing color blindness.

Recently Almutairi et al. [9] recruited 9 males and 1 female (six severe deutans, two moderate deutans, and two severe protans). To assess the effect of EnChroma glasses, as well a red filter and a green filter, the authors used the ColorDx software (which is a digital version of the recognition Ishihara test) on a tablet and the online arrangement Farnsworth-Munsell (FM) 100-Hue test [10] and compared with “placebo” glasses (untinted glasses). Regarding the ColorDx test the EnChroma glasses only produced an improvement in two subjects: from severe protan to moderate protan and from severe deutan to moderate deutan. For the FM100 Hue test EnChroma did not significantly improve the error scores. It is surprising that Almutairi et al. [9] were able to use the anomaloscope to evaluate EnChroma glasses because these Notch filters cause some nearly-monochromatic stimulus of the device to be perceived as too dark thus preventing the color matching experiment.

The potential of dyed contact lenses in wavelength filtering and color vision deficiency has been proved recently by Badawy et al. [11]. Twenty normal color vision observers and fifty with red-green color vision deficiency were tested with the standard Ishihara test as well as looking at their surroundings and commenting if there was a subjective improvement. With the Ishihara test the levels of improvement for the participants affected by CVD was not homogeneous. However all the participants did notice an improvement in the colors of their surroundings when looking through contact lenses. The authors concluded that the dyed contact lenses tested cannot provide those affected with CVD a color vision comparable to those with normal color vision.

In this paper we tackle the evaluation of the possible effectiveness of EnChroma glasses by using two approaches. The first approach is to examine the EnChroma glasses with a larger set of people with color vision deficiencies (Sections 2.1, 2.2 and 3.1) by using the classical types of tests: recognition (Ishihara) and arrangement (Fansworth-Munsell). Taking into account that these lenses could change the color perception without improving the results in tests, a subjective color-naming test based on X-Rite Color Chart has been added. The second approach is to simulate the effect of these glasses not only by taking the spectral transmittance of their lenses on different simulated observers but also modeling the appearance of the stimulus in order to evaluate the color performance of the filters (Sections 2.3 and 3.2). Finally, in section 4, we draw the conclusions of this work.

2. Material and methods

2.1 EnChroma glasses

According to the manufacturer, EnChroma filters tend to decrease the overlap between M and L cones spectral sensitivity. In this study we have used the indoor glasses (EnChroma Cx filter category 1). Figure 1 shows the transmittance measured from 380 to 780 nm by using a Thorlabs CCS200 spectrometer and a UV/VIS/NIR BDS130 Edmund Optics light source.

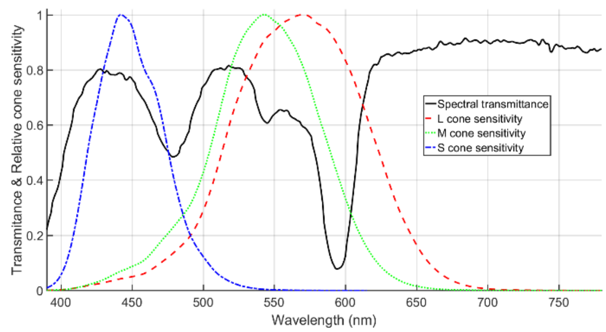

Fig. 1. Spectral transmittance of EnChroma Cx filter category 1 and color matching functions of CIE31 2° Standard Observer [12].

As Fig. 1 shows, this transmittance has three valleys introduced by EnChroma with the intention of lowering the sensitivity where there is possible overlap between L and M cone responsivity, specifically at 594 nm, and they have a higher transmittance where the maximum color matching functions of a standard observer should be. Anomalous trichromats would however have different L (for protans) or M (for deutans) cone responsivities, with an increased overlap between L and M responsivities. Due to the shift between cone responsivity peaks for normal and anomalous trichromats, the position of the valley in transmittance does not guarantee effectivity in decreasing the overlap for all cases. The variability in cone responsivity curves found for anomalous trichromats has not been introduced in Fig. 1 due to the dispersion in results found in different sources and the convenience of presenting graphical results as simply as possible.

2.2 Subjective evaluation experiment

48 volunteers participated in this research. They were all given a recommendation for the use of the glasses by the "EnChroma Color Blindness Test" [6]. Of these 48, four were women and 44 men, with ages between 14 and 64 years. All the participants were aware of their CVD condition.

Each subject was asked to perform two sessions. The first consisted of the evaluation of their color blindness with three different tests: Ishihara (recognition test) [13], Fansworth-Munsel 100 Hue (FM-100, arrangement test, X-Rite USA) [10], and anomaloscope (discrimination test, OCULUS HMC-Anomaloskop USA). Ishihara and FM-100 were performed in a lighting booth equipped with a D65 simulator located in a dark room.

In addition we designed a color-naming test with 21 colors from an X-Rite GretagMacbeth Chart. These colors were displayed in a 55x55mm isolated with a black background in a HP 2510i 25" monitor, calibrated with X-Rite Eye One device. The observers were asked to name the color by using the 11 color names proposed by Berlin and Kay (black, white, grey, red, green, blue, yellow, orange, brown, purple and pink) [14]. The answers were compared with the names that a control group of normal color vision observers used.

In the second session, the observers were requested to repeat the Ishihara, FM-100 and color naming test under the same conditions as before, but after wearing the EnChroma glasses during an adaptation time of 30 minutes. The anomaloscope could not be used because the combination of the filters of the glasses and the monochromatic lights of the device resulted in incongruous results. There were more than 2 weeks between the first and second session to minimize the effect of memory.

2.3 Evaluation using simulations

Simulated data were used to assess the changes induced by the EnChroma glasses quantitatively, and to analyze the differences found for a given set of colors and scenes in the main perceptual attributes of lightness (*J*), chroma (*C*) and hue (*h*), with and without the glasses. Specific parameters for viewing conditions and chromatic adaptation as predicted by a widely used color appearance model, CIECAM02 [15] were taken into account.

Two different data sets containing two groups of samples which varied greatly in composition and the amount of data were used. The effect of using the EnChroma glasses was analyzed with a data set consistent with the colors used in our experiments (data set D1) and with one data set that could be representative of real objects found in different natural viewing scenarios (data set D2).

2.3.1 Data sets

Data set D1 is composed of 124 samples from three different reference charts used in colorimetry and color vision assessment: the X-Rite Color Checker (24 samples), the FM100 samples (85 samples) and the Color Rendering Index [16] reference sample set (15 samples). We measured the reflectance of these samples with a spectroradiometer Spectrascan PR650, in the range from 400 to 700 nm, sampled in 10 nm steps.

Fig. 2. a) RGB rendering of the five scenes selected for data set D2.

Data set D2 includes samples from a public hyperspectral image database acquired with a line-scan device in outdoor scenarios [17] [18]. Five scenes were selected that contained natural and man-made colorful objects (see Fig. 2), and sub-sampled in a 1 over 4 ratio to get a spectral datacube size of 325x348x31 to reduce the huge initial number of colors. Therefore, each pixel from the 325x348 scene contains spectral information from 400 to 700 nm, sampled in 10 nm steps. The full data set, D1 and D2, contains 565.624 colors.

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2.3.2 Simulation of anomalous color vision conditions

For each data set, the CIECAM02 values were computed for normal vision and simulated six anomalous color vision conditions using Lucassen et al. model [19]. This model introduces varying amounts of weighting of L and M cone responses in the anomalous observers, modulated by a parameter called d. For instance, a mild deuteranomalous condition modifies the L and M cone responses introducing a 0.3 contribution of the cone L into the M cone response. A deuteranope would be simulated using a d parameter value of 1. The six conditions modeled [19] are: mild (d = 0.3), medium severity (d = 0.6), and severe (d = 1.0) for protan and deutan types. See Fig. 3 for some examples of a scene simulated for the different conditions. Including the normal observer vision as well, we then have seven conditions without glasses.

For each condition, we re-computed the CIECAM02 values after incorporating the glasses to the scene by multiplying the spectral transmittance of the EnChroma filters (see Fig. 1) by the color signal of the samples under D65, as described in section 2.3.3.

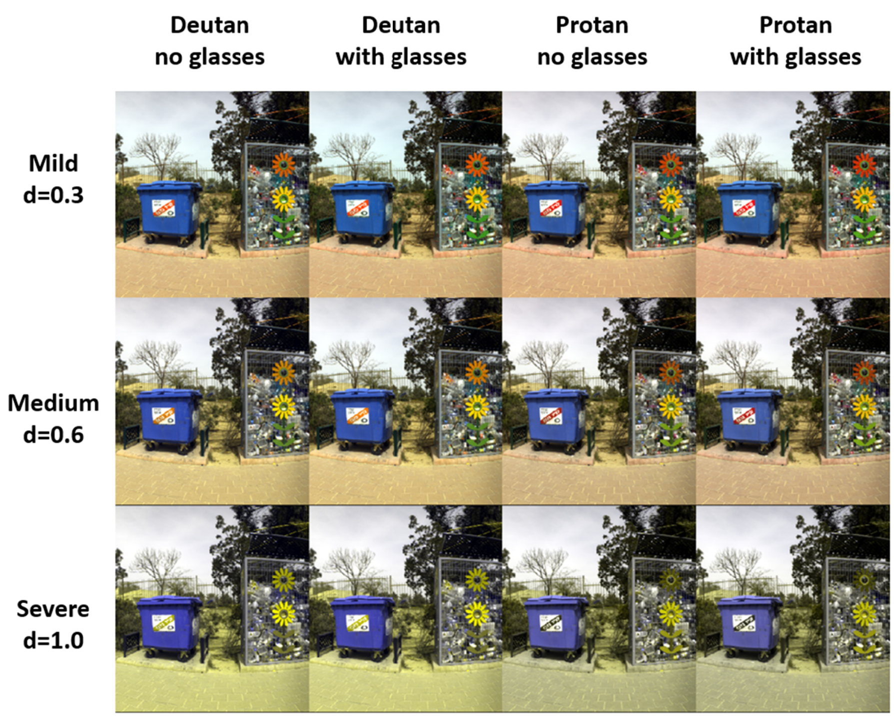

Fig. 3. Upper row: example of a simulated scene for mild conditions (d = 0.3, protan and deutan, with or without glasses); middle row: simulated scene for medium severity conditions (d = 0.6); lower row: simulated scene for dichromats.

To sum up, we then have 14 sets of CIECAM02 values corresponding to the seven vision conditions, with and without the EnChroma glasses.

2.3.3 CIECAM02 computation

We first obtained the CIE1931 XYZ values of the samples included in each data set, under a D65 standard illuminant, using the spectral information contained in each sample's spectrum. Then, we simulated the viewing of the samples in our calibrated monitor. The parameters used for CIECAM02 were: X_w = 97.10, Y_w = 100, Z_w = 111.062, corresponding to the white of the monitor; L_a = 23 cd/m^2, the absolute luminance of the adapting field; Y_b = 28, the relative luminance of the background; and F = 0.9 (degree of adaptation), c = 0.59 (impact of

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surround), and N_c = 0.9 (chromatic induction factor) as correspond to a "dim" surround. Finally we have consider D = 0.84 (discounting the illuminance) as we are using displayed samples [15]. We obtained the following data after our computation: lightness J, chroma C, hue angle h and chromaticity (a_c, b_c) values.

The a_c-b_c plots of data sets D1 and D2 can be seen in Fig. 4. They differ in the amount and distribution of the samples.

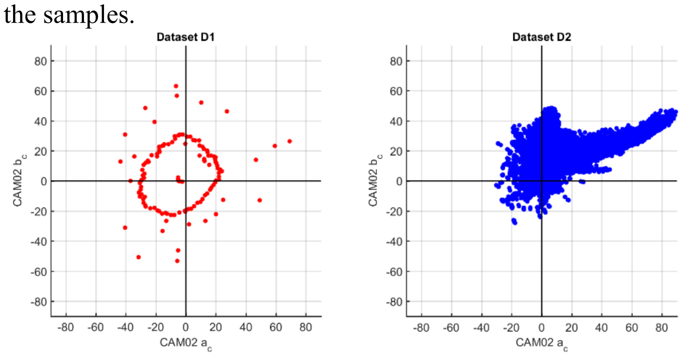

Fig. 4. CIECAM02 a_c-b_c plot of the two data sets used in the simulation experiment.

3. Results

3.1 Subjective evaluation

Table 1 shows the results of the first session. Some considerations must be taken into account; firstly, the Ishihara test is a widely used test for screening but is not very reliable for diagnosis [20]. Secondly, Vingrys [21] analysis for FM100 provides many parameters in order to quantify the severity of a CVD, but it does not give a reliable diagnosis of the type of CVD. Among these parameters, *SQR* is the square root of the total errors in the test, increasing with the number of errors. The other parameters are obtained after analyzing the color coordinates of the chips in CIELUV color space: the confusion index (*CI*) describes the severity of a color loss, scatter index (*SI*) quantifies the randomness of cap arrangement and *Angle* identifies the orientation of the cap arrangement. As a reference, a perfect arrangement has a *CI* = 1 and *SI* = 1.28. In Table 1, the results of the Ishihara test are provided as the number of plates that the observer failed to identify correctly. For the color-naming test, the number of patches for which the observer gave a different name than a normal observer are registered as fails.

Whilst a dichromat accepts the same matchings as a normal observer does, because the dichromat is missing one of the cone responsivities but the other two are left unchanged, an anomalous trichromat does not accept the matchings made by a normal observer, since one of the responsivities is different from the normal and this would cause a different matching set for the same stimulus presented to normal and anomalous trichromats, as long as this stimulus resulted in the anomalous cone excitation. Therefore, given that the only test that allows us to examine an observers' color match settings directly is the anomaloscope, which is also the best test for CVD classification (diagnosis). According to this device, the 48 observers were classified into the following groups: protanope (19), deuteranope (11), protanomalous (12) and deuteranomalous (6).

Table 1. Mean values and standard deviation (*SD*) of the Ishihara, FM100 and color naming tests results without glasses for the different groups

Anom[a]	FM100				Ishihara	Color-naming
	SQR	*Angle*	*CI*	*SI*	Fails	Fails
Deutly	12.35 (1.79)	30.64° (13.59)	2.16 (0.47)	1.47 (0.27)	16.83 (3.54)	6.00 (1.26)
Deutpia	14.05 (2.51)	12.01° (7.18)	2.55 (0.47)	1.50 (0.16)	19.45 (0.69)	7.00 (4.10)
Protly	12.20 (2.22)	26.05° (12.84)	2.07 (0.42)	1.44 (0.17)	18.58 (2.02)	7.00 (1.71)
Protpia	13.95 (2.76)	23.11° (9.41)	2.47 (0.53)	1.56 (0.19)	18.68 (1.49)	8.79 (3.26)
All	13.33 (2.64)	22.24° (12.29)	2.35 (0.53)	1.50 (0.20)	18.60 (1.95)	7.58 (3.09)

[a]Anom: Amomaloscope, Deutly: Deuteranomaly, Deutpia: Deuteranopia, Protly: Protanomaly, Protpia: Protanopia, All: All observers.

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Table 2 shows the results of the second session, where the same observer classification is kept. A comparison of FM 100 results between both sessions shows an apparent decrease in *SQR* and *CI* and two rotations. The angles of the deutan observers move towards protan and the angles of the protan observers move towards deutan. However, these changes are not relevant due to the following reasons. Firstly, there is an increase of *SI*, which means that globally the randomness of the order of the color chips set by the observers is higher with the EnChroma glasses. Secondly, an ANOVA analysis of the data shows no statistical differences between the two conditions for *SQR*, *Angle* and *CI* ($p_{SQR} = 0.094$; $p_{angle} = 0.492$; $p_{CI} = 0.548$), but *SI* parameter increases significantly ($p_{SQR} = 0.005$). These trends are similar for each type of color blindness subgroups. Overall, there is not much difference between both sessions based on the Ishihara and color-naming test results. The angle parameter is defined, according to Vingrys, as "...the axis angle producing the minimum moment of inertia" when the chips are represented in the CIELuv color space [21], so, this angle could not be considered to have a direct relationship with the confusion axes.

Table 2. Mean values and standard deviation (*SD*) of the tests results with glasses for the different groups

[a]Anom	FM100				Ishihara	Color-naming
	SQR	*Angle*	*CI*	*SI*	Fails	Fails
Deutly	11.34 (2.01)	24.08° (19.46)	2.08 (0.31)	1.54 (0.11)	16.71 (4.92)	7.67 (6.83)
Deutpia	13.10 (2.10)	8.87° (5.83)	2.42 (0.47)	1.67 (0.22)	19.27 (1.35)	7.32 (2.84)
Protly	11.57 (3.12)	34.19° (9.55)	2.13 (0.54)	1.58 (0.17)	17.75 (2.53)	6.33 (1.97)
Protpia	12.83 (1.96)	31.46° (9.50)	2.39 (0.40)	1.73 (0.28)	18.95 (1.68)	8.32 (3.87)
All	12.93 (2.47)	26.04° (14.64)	2.29 (0.47)	1.66 (0.24)	18.46 (2.60)	7.41 (3.80)

[a]Anom: Amomaloscope, Deutly: Deuteranomaly, Deutpia: Deuteranopia, Protly: Protanomaly, Protpia: Protanopia, All: All observers.

The previous results show that the glasses do not improve the color vision of the red-green CVD, based on the averaged values of the whole subgroups. To tackle this question the difference of each one of the parameters from FM100 hue test was computed taking session 1 as reference. In addition, from the color-naming test the number of terms that were changed between sessions has been calculated (see Table 3).

Table 3. Mean difference of the FM100 parameters and mean number of name changes computed taking session 1 as reference

	FM100				Color-naming
	Δ*SQR*	Δ*Angle*	Δ*CI*	Δ*SI*	Terms changed
Deuteranomaly	−1.01 (1.26)	−6.57° (8.29)	−0.08 (8.29)	0.07 (0.31)	9.00 (5.48)
Deuteranopia	−0.95 (2.05)	−3.14° (7.27)	−0.13 (0.58)	0.18 (0.24)	8.27 (2.87)
Protanomaly	−0.62 (1.89)	8.14° (17.53)	0.06 (0.26)	0.14 (0.14)	6.75 (1.76)
Protanopia	−1.12 (1.92)	8.34° (13.09)	−0.11 (0.38)	0.18 (0.37)	9.05 (3.67)
All Observers	−0.94 (1.91)	3.80° (14.39)	−0.07 (0.42)	0.15 (0.30)	8.23 (3.43)

Table 3 shows that the change in the arrangement of the color chips in the FM100 test is slight. Although the average change in the angle suggests a clockwise rotation for protan and a counter-clockwise rotation for deutan observers, the standard deviation values show that this change is not homogeneous amongst observers.

A remarkable result is that the high values of standard deviation confirm our impression during the sessions that CVD observers have a different perception related to their color vision. Therefore, a common solution for all subjects is a very difficult challenge.

In our opinion an interesting result is shown in the last column of Table 3: the number of terms changed from the first to the second session have a very similar value to the number of fails in both sessions, meaning that the observers failed in different colors, so the filters seem to help in some color recognition to the detriment of failing in other colors.

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3.2 Analysis of color variations induced by the EnChroma glasses using simulated data

To complement the subjective evaluation of observers described in the previous section, a comparison between simulations of images seen by normal and CVD subjects without filters and the same images seen through the filters was carried out. The different conditions simulated can be found in section 2.3.

To analyze the influence of wearing the EnChroma glasses with simulated data, first a statistical test (the Jarque-Bera normality test [22]) was performed to determine if the distribution for *J* or *C* for the reference condition ("glasses off") could be treated as normal. The *p*-parameter obtained in the comparison test marked the level of significance of the differences found between *J* or *C* values in each condition. *p* values below 0.05 meant that the difference found was statistically significant. For both Data sets D1 (set of 124 discrete color samples) and D2 (real scenes), the results of the Jarque-Bera test were negative in all cases for *J* and *C* attributes. So the Wilcoxon signed rank test [23] was used in all cases to compare between the medians of the "glasses off" and "glasses on" conditions. The *p*-parameter obtained in the comparison test marked the level of significance of the differences found between *J* or *C* values in each condition. *p* values below 0.05 meant that the difference found was statistically significant. As the Jarque-Bera tests indicated that the distributions were not normal, the median and standard deviation were computed to visualize the trends found when the glasses were incorporated into the simulated data.

Since the *h* data are angles, circular statistics were used to analyze them. First, we tested the data for fitness to a von Mises distribution (the analog of the normal distribution for circular data) using Watson's U square test as implemented in the Oriana software package [24]. We have computed the mean angular direction and standard deviation for all data [25]. To test for the effect of introducing the EnChroma glasses on the hue angle, we then used the Multivariate Watson test [26] if the distributions were of the von Mises type, and we used the non-parametric analog (Mardia-Watson as described in [27]) if the distributions were not of the von Mises type.

3.2.1 Comparison of lightness values

Table 4 shows the statistical parameters found for each data set and attribute *J*.

Table 4. Median and standard deviation (*SD*) for the lightness *J* attribute for glasses on or off and for each simulated CVD condition (data sets D1 and D2)

	Original	D_0.3	D_0.6	D_1.0	P_0.3	P_0.6	P_1.0
GLASSES OFF D1	54.54 (10.00)	54.39 (9.98)	54.23 (10.03)	53.99 (10.18)	54.81 (10.14)	55.03 (10.46)	55.26 (11.17)
GLASSES ON D1	54.23 (9.74)	53.86 (9.63)	53.47 (9.60)	52.91 (9.68)	54.89 (10.09)	55.49 (10.65)	56.19 (11.71)
GLASSES OFF D2	56.72 (13.79)	56.81 (13.83)	56.89 (13.85)	57.02 (13.93)	56.55 (13.84)	56.37 (13.92)	56.07 (14.17)
GLASSES ON D2	56.55 (13.71)	56.44 (13.74)	56.33 (13.75)	56.19 (13.82)	56.73 (13.83)	56.88 (14.00)	57.01 (14.45)

The effect of adding the EnChroma filters on the lightness of the samples in both data sets is a slight decrease in the median values for normal and deuteranomalous/deuteranope observers, and a slight increase for protanomalous/protanope observers. The effect of adding the glasses is slight because the *J* values are computed after the chromatic adaptation. The differences are statistically significant for data set D1 (maximum *p* value of 0.000363) except for the mild protanomalous condition (p = 0.1648). For data set D2, all the differences are statistically significant (with maximum *p* of $1.97\text{x}10^{-9}$), very likely due to the high cardinality of this data set. The median lightness in data set D2 is slightly higher than in data set D1.

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3.2.2 Comparison of hue values

Table 5 shows the statistical parameters found for each data set and attribute *h*.

Table 5. Mean angular direction and standard deviation (*SD*), in degrees, for the hue *h* attribute for glasses on or off and for each simulated CVD condition (data sets D1 and D2)

	Original	D_0.3	D_0.6	D_1.0	P_0.3	P_0.6	P_1.0
GLASSES OFF D1	131.53 (109.11)	125.71 (112.83)	72.07 (120.03)	25.74 (88.91)	112.28 (107.4)	72.55 (101.02)	36.96 (76.61)
GLASSES ON D1	170.53 (102.24)	174.81 (112.01)	188.36 (128.84)	359.79 (92.72)	162.70 (109.05)	136.56 (125.43)	25.52 (81.40)
GLASSES OFF D2	84.18 (28.93)	81.98 (24.71)	78.01 (21.44)	75.88 (23.05)	81.24 (24.67)	76.83 (20.46)	77.16 (16.10)
GLASSES ON D2	118.71 (42.17)	110.32 (41.29)	93.42 (41.50)	55.09 (40.79)	106.40 (37.27)	89.25 (30.40)	69.67 (21.14)

Regarding the statistical analysis, the results of the Watson's U square test show that the distributions of Von Mises type are the Original, d_03 and p_03. The effect of adding the EnChroma glasses on the hue of the D1 data set samples is an average increase in the mean angular direction for normal and mild-medium anomalous trichromats (counter-clockwise rotation), while the mean angular direction decreases (clock-wise rotation) for the severe conditions. The amount of variation in the mean angular direction is not uniform across conditions. However, the results of the tests for comparing the two distributions indicate that these differences are not statistically significant (minimum p value of 0.05 for the p_06 condition.).

For data set D2, the Watson's U square tests confirmed that all the distributions cannot be fitted by a von Mises function. Regarding the mean angular direction results, the same trends as in the data set D1 are found. The amount of angular rotation in this case is more uniform across conditions than for data set D1, and all the changes in the mean angular direction are found to be statistically significant ($p<10^{-12}$). The slight difference between both data sets can be explained by the fact that data set D2 contains a denser distribution of hue values, and so the behavior when the filter is added is less erratic.

3.2.3 Comparison of Chroma values

Table 6 shows the statistical parameters found for each data set and attribute *C*.

Table 6. Median and standard deviation (*SD*) for the chroma, *C* attribute for glasses on or off and for each simulated CVD condition (data sets D1 and D2)

	Original	D_0.3	D_0.6	D_1.0	P_0.3	P_0.6	P_1.0
GLASSES OFF D1	28.58 (12.18)	24.66 (11.18)	21.59 (11.54)	20.55 (12.67)	24.20 (11.34)	20.46 (11.41)	17.86 (12.03)
GLASSES ON D1	32.00 (13.59)	27.13 (11.24)	22.97 (10.94)	21.01 (12.53)	26.33 (11.53)	21.38 (11.26)	18.11 (11.82)
GLASSES OFF D2	14.83 (12.16)	13.58 (9.33)	12.98 (7.95)	13.37 (8.14)	13.76 (9.79)	12.82 (7.19)	11.81 (4.97)
GLASSES ON D2	15.00 (13.28)	12.04 (9.82)	9.83 (8.35)	10.52 (7.92)	12.67 (10.84)	10.92 (8.03)	9.96 (4.76)

The effect of adding the EnChroma glasses in data set D1 is a slight increase in the median chroma values for all conditions, which is lower for the dichromat observers. The difference is statistically significant for all conditions (maximum p value of 0.00036) except for the dichromat observers ($p = 0.0555$ for deuteranopes and $p = 0.38$ for protanopes). These results would then be in agreement with the claims of the manufacturers of EnChroma glasses.

For data set D2 the trends found are opposite to those in data set D1. There is a clear trend for a decrease in chroma values with glasses, except in the normal color vision condition (for which the chroma increases slightly). The differences are statistically significant in all cases.

This difference in the trends found for the chroma attribute is due to the different distribution of the two sample population data sets. Analyzing separately the samples that result in a chroma increase and a chroma decrease, it is apparent that most samples with negative values of b_c (bluish hues) belong to the group that increases chroma. This is not unexpected, since the spectral transmittance of the EnChroma filter (see Fig. 1) is relatively high in the blue region of the spectrum. Since the average percentage of samples with negative b_c is much higher in data set D1 (41.24% *vs* 2.53% in data set D2), then this factor alone may account for the opposite trend found in the chroma shifts in both groups. However, for the other color attributes there is no clear dependence on the sign of the shift with a_c or b_c values, and the trends found are very similar across the data sets.

4. Conclusions

EnChroma glasses are designed considering the cone responsivity of normal color vision observers as a reference. Using a notch filter that decreases the overlap between the L and M normal cone responsivitiy does not necessarily produce improvements in color discrimination for anomalous observers. Dichromats are missing one type of cone, so decreasing the overlap is not a solution for them and anomalous trichromats do not have the same cone responsivity as normal observers, so the design is not optimal for them either.

Nevertheless, designing a customized filter for each CVD observer is not a solution as the observer will not see new colors, but rather will see colors in a different way. Whereas previously colors were confused it is possible that with a filter observers will be able to distinguish some colors, but to the detriment of others. This is reflected in the differences in the values of the FM100 parameters (*SQR* does not change, but the value of *SI* increases) and the results of the color-naming test (they confuse the same number of colors, but for different stimuli). In the results with the simulations, the variation of the three attributes of color appearance is reflected. To sum up, the use of a colored filter may change the appearance of colors (depending on the shape of its spectral transmittance), but will never make color vision more similar to a normal observer's vision. This effect is similar for certain specific uses (shooting, hunting, low eyesight etc. [28]) where the use of colored glasses helps to perceive certain stimuli better thanks to an increased contrast with the surroundings. For example, Corning filters are used both for observers with poor eyesight and for archery [29].

On the other hand, when session 2 ended the observers were asked to look at their surroundings with the glasses and to assess subjectively the possible improvement. None of the participants noticed any improvement to the colors of their surroundings when looking through the glasses, except for just one female participant with very mild deuteranomaly.

The results show that the glasses specifically used in this study have not revealed any improvement in the two types of color blindness tests: recognition and arrangement. Therefore, the glasses cannot help in cheating in professional screening tests.

All our results complement the results of other authors such as Mastey et al. [7] and Patterson [8], who use a more specific test (CAD) and a smaller group of observers (27 and 15 respectively). They also found that for EnChroma glasses there is some non significative "small rotation" but they use CAD test which measures thresholds instead of the FM100 test which measures sorting. Almutairi et al. [9] use some digital versions of the same standard tests as us and a much smaller group of observers (10). Moreover, the simulations (to the best of our knowledge the first published) allow us to conclude that there is a change in the perceptive attributes and that the effect of the lenses is so low that only a change in contrast is perceived for certain colors present in nature.

We believe that our results allow us to cast doubt on the real effectiveness these devices have on the color vision of observers with CVD.

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Disclosures

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