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Assessment of VINO filters for correcting red-green Color Vision Deficiency

MIGUEL A. MARTÍNEZ-DOMINGO,* LUIS GÓMEZ-ROBLEDO, EVA M. VALERO, RAFAEL HUERTAS, JAVIER HERNÁNDEZ-ANDRÉS, SILVIA EZPELETA, ENRIQUE HITA

Department of Optics, University of Granada, Spain
**martinezm@ugr.es*

Abstract: In our ongoing research on the effectiveness of different passive tools for aiding Color Vision Deficiency (CVD) subjects, we have analyzed the VINO 02 Amp Oxy-Iso glasses using two strategies: 1) 52 observers were studied using four color tests (recognition, arrangement, discrimination, and color-naming); 2) the spectral transmittance of the lenses were used to model the color appearance of natural scenes for different simulated CVD subjects. We have also compared VINO and EnChroma glasses. The spectral transmission of the VINO glasses significantly changed color appearance. This change would allow some CVD subjects, above all the deutan ones, to be able to pass recognition tests but not the arrangement tests. To sum up, our results support the hypothesis that glasses with filters are unable to effectively resolve the problems related to color vision deficiency.

1. Introduction

Some of the people with Color Vision Deficiency (CVD) search for solutions to mitigate their color confusions due to the importance of color coding in our visual world. In some cases, CVD subjects can undergo daily life handicaps and consequently they may be disqualified from several professions [1]. Solutions for people suffering from CVD have proliferated in recent years.

CVD affects 8% of the Caucasian male population and 0.5% of the female [2] and currently there is no effective treatment for humans, although gene therapy has been tested on primates [3].

These congenital deficiencies are classified in three types: anomalous trichromacy (3 types of cones in the retina), dichromacy (2 types of cones), and monochromacy (1 type of cone). According to the type of cone affected the following classification is used: protan (L cones are affected), deutan (M cones are affected), and tritan (S cones are affected). Combining both classifications, the deficiencies are classified as: 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). Both protan and deutan cause a red-green color vision deficiency, whilst tritan causes a yellow-blue color vision deficiency. Among the two types of deficiencies, the red-green is the most frequent in humans [2,3].

As far as solutions for improving color vision in CVD subjects are concerned these are classified in two types, active and passive. The active types [4] change the appearance of the objects (i.e. recoloring images) through image processing algorithms which increase the contrast between colors that are indistinguishable for the user. Therefore, these solutions require a display to show the image to the subject, such as, for example, prototypes of smart glasses [4].

Passive tools are based on colored filters that people can wear (nowadays even with their corresponding optometric prescription) such as tinted glasses or contact lenses. The first idea (for a historical review read [5]), proposed by Seebeck, was to look first through a red and

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then through a green filter [6]. Later Maxwell [7] modified this idea by “a pair of spectacles constructed with one eye-glass red and the other green”. One hundred and twenty years later, in the later 1960s, two companies exploited the idea of just filtering one eye (usually the non-dominant eye) for people exhibiting deuteranomalous color vision: “X-Chrom Color Deficient Contact Lens” [8] and “ChromaGen lenses for Color Blindness and Dyslexia” [9], which are still available on the market today. In 2008 X-Chrom was rebranded to Zeltzer X-Chrom. The difference is what area of the eye is covered by each lens: the X-Chrom tinted lens covers the iris and the pupil, whereas ChromaGen tinted lens only covers the pupil. Several filters are available for these two models, although usually the single lens is red.

Users criticized these color filters because they reduce the perception of other, normally unaffected, colors [5]. Some analysis has been done on X-Chrom and ChromaGen contact lenses [10–12], reporting an improvement on recognition tests and a worsening on color arrangement tests. This leads to disadvantages that have to be considered: their use can be dangerous for activities such as driving and flying at low light levels, visual acuity is reduced, distortions of apparent velocity, visual distortions, such as the Pulfrich effect, and impairment of depth perception. In 2001 Swarbrick *et al.* [12] analyzed 14 CVD observers, after wearing ChromaGen contact lenses for 2 weeks, with three tests: the Ishihara, Farnsworth Munsell-15 and Farnsworth Lantern. They found a slight improvement for Ishihara test, particularly for deutan observers, and for the Farnsworth Munsell-15 test, but no effect for the Farnsworth Lantern. In agreement with other papers, the observers reported poor vision in dim light because of the dark-tinted lenses. The authors concluded that ChromaGen lenses do not provide a true color hue perception.

Recently, other companies have marketed glasses with color filters fo both eyes, among them Enchroma [13] and VINO [14]. In our ongoing research on the effectiveness of different passive tools we have recently studied [15] the Cx-65 model for indoor use produced by the EnChroma company with 48 CVD observers. Our results, which agree with other studies [16,17], show that this model of glasses introduces a variation in the perceived color, but neither improves results in the diagnosis tests nor allows the observers with CVD to have a more normal color vision. Almutairi [18] used the Cx-14 model by EnChroma in his study with a digital version of the Ishihara test (ColorDx) and an online Farnsworth-Munsell FM 100 test. He concluded that this lens had no significant effect on the performance of any of the 10 CVD observers, diminishing the errors in the Ishihara for only two observers.

Although VINO glasses were designed “to enhance the O2 signal from hemoglobin under the skin”, the inventors claim that their technology “aids red-green deficiency” [14]. On their website (June 2019) they use as a marketing message “Our Color Blindness technology corrects red-green color deficiency, based on a scientific understanding of what color vision is for. Our tech does more than simply allow you to pass the Ishihara test” [14]. In addition, VINO states: “VINO Optics comes from the lab behind the 2006 discovery that human color vision is optimized for seeing blood under the skin, something allowing us to sense emotions and health. In light of this, they invented and patented methods for improving our color vision, which led to technology for enhancing veins, and for correcting color blindness.”

Mastey *et al.* [16] and Patterson *et al.* [17] also analyzed the VINO O2 Amp Oxy-Iso model using the same types of tests and the same group of observers as the Cx-65 by EnChroma model. Mastey *et al.* tested these glasses on 27 males with genetically confirmed red-green CVD using a CAD (Color Assessment and Diagnosis) test. According to Mastey *et al.*, contrary to the EnChroma glasses, the VINO glasses improved discrimination along the red-green axis both for deuteranopic and deuteranomalous observers wearing O2 Amp Oxy-Iso glasses. Mastey *et al.* claimed that colored filters can introduce sufficient luminance cues that allow CVD people to “cheat” on color tests based on pseudoisochromatic stimuli, just as the VINO glasses do for deutans. Mastey concluded that CVD people cannot “see new colors” either with VINO or EnChroma glasses. In 2017 Patterson tested the O2 Amp Oxy-Iso VINO glasses on fifteen males with genetically confirmed red-green CVD [17]. With these glasses the dichromats improved their red-green discrimination but for the anomalous trichromats did not. Patterson found a rotation of the confusion axis from protan to deutan for the two protan observers. Patterson concluded that this improvement is achieved by the change in contrast provided by the lenses rather than the change in chromatic sensitivity.

In this study we focus on the "Color Blind Glasses" VINO 02 Amp Oxy-Iso by the VINO company, but without focusing on the enhancement of the O_2 signal from hemoglobin under the skin application. Two strategies are used for this purpose. The first is to perform an objective study (Section 3) with a larger set of observers (52 CVD people) using three classical color tests: recognition (Ishihara), arrangement (Fansworth-Munsell) and discrimination (Oculus anomaloscope). In addition, a subjective color-naming test based on X-Rite Color Chart has been added. The second approach is to evaluate the color performance of the filters by modeling the appearance of natural scenes as seen through the filter by different simulated subjects (Section 4). We also compared our results for the VINO glasses with the results obtained for the EnChroma glasses.

Finally, we sum up the conclusions of this research, analyzing the relative efficiency of the most common passive aids that aim to correct CVD after the comparative analysis of the EnChroma and VINO glasses.

2. Materials

Figure 1 shows the spectral transmittance of the O2 Amp Oxy-Iso VINO glasses (purchased in December 2017), from 380 to 780 nm measured by a Thorlabs CCS200 spectrometer with a UV/VIS/NIR BDS130 Edmund Optics light source. In addition, VINO provided us with the spectral transmittance, also shown in Fig. 1. The differences found between these two curves are due to the effect of the curvature and varying thickness of the lenses on the transmittance measurements. In our simulations (section 4) we have used the transmittance provided by the VINO company.

As Fig. 1 shows this transmittance is close to zero from 530 nm to 580 nm, which results in a purplish (or pinkish) color of these glasses contrary to the neutral-bluish color of the EnChroma Cx-65 glasses (see Fig. 3). The low-transmittance region in the VINO glasses, radically affects the subject's perceived luminance or object lightness, since it overlaps with the peak of the human luminous efficiency curve. At the same time, it makes predominantly green-yellowish colors appear very dark, which would not in principle benefit protanopic subjects.

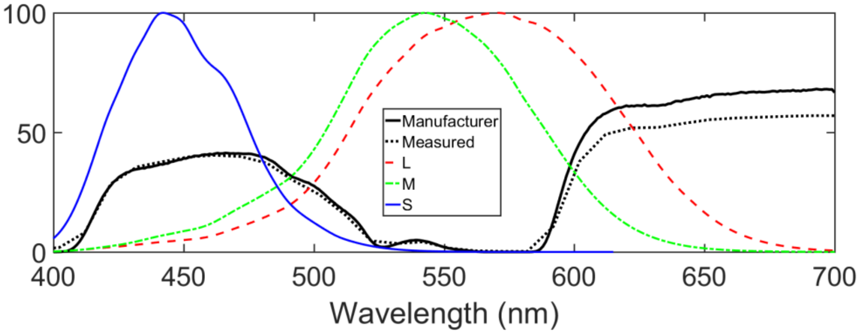

Fig. 1. Spectral transmittance of O2 Amp Oxy-Iso VINO glasses (measured and provided by manufacturer) and LMS cone spectral responsivity of CIE31 2° Standard Observer (relative units) [19].

3. Subjective evaluation

3.1 CVD observers

52 volunteers, 2 women and 50 men with ages between 10 and 64 years and who were aware of their CVD condition, participated in this research. 19 of these observers also participated in the study of the EnChroma glasses [15]. All the participants signed an informed consent for all the research procedures adhering to the tenets of the Declaration of Helsinki.

3.2 Subjective experiment

The subjective experiment consisted of two sessions. The first session was the evaluation of the color deficiency of the volunteers with three different tests: the Ishihara (recognition test) [20], Fansworth-Munsel 100 Hue (FM-100, arrangement test, X-Rite USA) [21], and anomaloscope (discrimination test, OCULUS HMC-Anomaloskop USA). The Ishihara and FM-100 tests were performed in a Verivide CAC 60 lighting booth equipped with a D65 simulator light source located in a dark room.

In addition to these routine tests, we designed a color-naming test with 21 colors from an X-Rite GretagMacbeth Chart. These colors were displayed on a 55x55 mm square patch isolated with a black background on a HP 2510i 25" monitor, calibrated with X-Rite Eye One device. The participants 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) [22]. The answers were compared with the responses from a control group of normal color vision subjects. With a reduced number of subjects (7 CVD observers and 2 with normal color vision) we repeated the color naming test both in the RGB monitor and in the lighting booth with the real chart under a D65 simulator. The average number of changes is kept in both monitor and light booth, with a difference below 1 change. The same trend is found when counting the number of errors with and without glasses. This shows that, even if spectrally the light signals shown to the observers are different comparing the displayed samples in the monitor and the real samples in the lighting booth, the number of changes and errors remain the same doing the experiment in any of the two conditions.

During the second session, performed at least 2 weeks after the first one to minimize the effect of memory, the observers repeated the Ishihara, FM-100 and color naming tests, after wearing the VINO glasses for 30 minutes (adaptation time). We have to mention that the anomaloscope was not used in this second session because the combination of the filters of the glasses and the monochromatic lights of this device resulted in incongruous results.

3.3 Subjective evaluation results

Table 1 shows the results of the first (VINO glasses off) and second (VINO glasses on) sessions. The classification of the observers has been made based on the result of the anomaloscope, which is the best test, amongst all the others, to classify CVD [23,24]. This method classifies the observers into four categories (first column of Table 1): 23 protanopes, 19 deuteranopes, 4 protanomalous, and 6 deuteranomalous in our study.

The third column shows the number of fails (the number of plates that the observer failed to identify correctly) in the Ishihara test, which is a widely used test for screening but is not very reliable for diagnosis [25].

Columns four to seven show the four most relevant parameters for quantifying the severity of a CVD provided by the FM100, although this test does not give a reliable diagnosis of the type of CVD [26]. The first parameter is the *SQR* which is the square root of the total number of errors in the test. The other three 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, the 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 $SI = 1.28$.

The eighth column shows the results for the color-naming test as the number of fails, which are the number of patches for which the observer gave a different name than that given by the normal-observers panel.

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

Classification [a]	VINO	Ishihara	FM100				Color-naming
		Fails	*SQR*	*Angle*	*CI*	*SI*	Terms changed
Deuteranomaly	OFF	20.33 (5.72)	12.78 (2.05)	23.68 (17.78)	2.16 (0.56)	1.30 (0.24)	6.17 (1.17)
	ON	1.67 (1.86)	16.97 (3.76)	41.02 (22.53)	3.53 (1.29)	1.79 (0.52)	9.50 (4.04)
Deuteranopia	OFF	23.15 (1.01)	14.74 (2.73)	11.38 (6.92)	2.68 (0.54)	1.52 (0.26)	7.68 (2.93)
	ON	1.05 (0.91)	18.61 (2.14)	35.92 (5.93)	4.11 (0.54)	2.02 (0.25)	9.37 (1.64)
Protanomaly	OFF	23.75 (0.50)	11.34 (1.78)	22.67 (15.19)	1.94 (0.27)	1.44 (0.11)	7.75 (2.63)
	ON	15.75 (4.19)	15.16 (1.26)	13.91 (8.84)	2.94 (0.40)	1.51 (0.30)	12.00 (0.82)
Protanopia	OFF	22.96 (1.52)	12.51 (2.60)	23.74 (9.84)	2.29 (0.53)	1.57 (0.30)	8.13 (2.42)
	ON	17.48 (4.20)	16.66 (1.76)	19.01 (6.11)	3.36 (0.34)	1.66 (0.21)	10.00 (1.93)
All Observers	OFF	22.79 (2.33)	13.27 (2.75)	19.52 (11.97)	2.39 (0.56)	1.51 (0.28)	7.71 (2.54)
	ON	9.52 (8.65)	17.29 (2.37)	27.33 (13.33)	3.62 (0.69)	1.80 (0.33)	9.87 (2.16)

Comparing the results wearing or not the VINO glasses, Table 1 shows that the number of fails in the Ishihara test has decreased ($p = 1{,}3974\text{x}10^{-35}$); while the results of the FM100 and color naming tests have worsened. This is explained by the *SQR*, *CI* and *SI* parameters. They indicate a more severe degree of CVD in the second session ($p_{sqr} = 1{,}5799\text{x}10^{-9}$, $p_{CI} = 1{,}1183\text{x}10^{-13}$, $p_{SI} = 7{,}5\text{x}10^{-5}$). This result can be interpreted considering that the VINO glasses are able to produce a darkening of the greenish colors and an increase in chroma for the reddish colors at the same time. This transformation breaks the working principle of the pseudoisochromatic plates, revealing the hidden figures and the traces that are meant to be confused by the red-green CVD subjects. Regarding the FM100 results, the *CI* and *SI* values indicate that the observers find it more difficult to carry out the ordering of the samples with the VINO glasses on. Regarding the *Angle* parameter, there is a counterclockwise rotation for deutan observers and a clock-wise rotation (decreasing angle values) for the protan observers. This basically means that both groups are more clearly separated with the VINO glasses ($p<0{,}001$ in all cases).

These results suggest that VINO glasses are able to improve only the results of the Ishihara test. This is mainly due to their transmittance spectra decreasing the lightness of the green colors and not because the observers' color vision is more similar to a normal subject when he or she wears the VINO glasses. This fact is supported by the results of the color naming and color arrangement tests.

4. Evaluation using simulations

4.1. Databases, CVD model, and CIECAM02 computations

As we intend to simulate as much as possible the color vision of normal and CVD observers, under two conditions: without and with VINO glasses, the analysis of the simulations was carried out using CIECAM02 color attribute values computed for two data sets (D1 and D2). Data set D1 is composed of 124 reflectances from three different sets of samples: X-Rite Color Checker chart, FM-100 test, and the CRI set for computing Color Rendering Indices. Data set D2 is extracted from 5 natural scenes from a hyperspectral database of urban scenes [27], and comprises 565500 reflectances. A complete description of these two data sets can be found in [15].

The lightness (*J*), chroma (*C*) and hue angle (*h*, with values between 0 and 360) attributes were computed using the CIECAM02 model, the latest color appearance model recommended by the International Commission on Illumination (CIE), for the seven different vision conditions (normal, protanopy, deuteranopy, mild and medium protanomaly and deuteranomaly), with and without the VINO glasses.

A color appearance model simulates the color vision, considering chromatic adaptation and many other visual effects, better than any basic colorimetry system. The set of parameters considered in CIECAM02, depending of the viewing conditions, have been optimized for each data set, simulating different situations. On the one hand, samples in data set D1 have been simulated to be observed in a lighting booth VeriVide CAC under a D65 simulator. On the other hand, the images in data set D2, have been simulated to be observed in the real viewing conditions of the capture moment. The white point and luminance of the background have been measured in the lighting booth for samples in data set D1, and estimated in each of the images of the data set D2. Table 2 shows the parameters for each case: the absolute luminance of the adapting field (L_a), the relative luminance of the background (Y_b), the relative tristimulus value of the white point, and the degree of adaptation to the white point (*D*). As we will compare later VINO and EnChroma glasses, the optimized parameters for EnChroma glasses have also been estimated.

As it is shown, the parameters change when any of the glasses are worn. In general, the absolute luminance of the adapting field decreases, and of course, the white point changes, more in the case of the VINO glasses, which are more chromatic than EnChroma's.

Table 2. CIECAM02 parameters for samples in data set D1 and the images in data set D2, for VINO and EnChroma glasses "on" and "off"

	L_a	Y_b	X_W	Y_W	Z_W	D
GLASSES OFF (D1)	55	14	94.45	100.00	110.83	0.903
GLASSES VINO ON (D1)	10	14	185.20	100.00	252.24	0.4
GLASSES EnChroma ON (D1)	35	14	91.32	100.00	122.10	0.4
GLASSES OFF (D2-scene 1)	1200	75	96.26	100.00	85.32	1.0
GLASSES VINO ON (D2-scene 1)	300	80	181.32	100.00	186.53	0.5
GLASSES EnChroma ON (D2-scene 1)	850	75	91.56	100.00	93.97	0.5
GLASSES OFF (D2-scene 10)	4000	60	96.11	100.00	72.64	1.0
GLASSES VINO ON (D2-scene 10)	1000	63	177.99	100.00	151.45	0.6
GLASSES EnChroma ON (D2-scene 10)	2500	58	91.32	100.00	78.99	0.6
GLASSES OFF (D2-scene 13)	2000	43	104.26	100.00	58.12	1.0
GLASSES VINO ON (D2-scene 13)	550	38	188.62	100.00	113.00	0.6
GLASSES EnChroma ON (D2-scene 13)	1300	43	100.89	100.00	64.67	0.6
GLASSES OFF (D2-scene 16)	6400	28	97.25	100.00	57.92	1.0
GLASSES VINO ON (D2-scene 16)	1800	25	180.30	100.00	119.82	0.7
GLASSES EnChroma ON (D2-scene 16)	4500	28	93.22	100.00	63.64	0.7
GLASSES OFF (D2-scene 19)	2600	57	94.38	100.00	102.31	1.0
GLASSES VINO ON (D2-scene 19)	900	57	177.29	100.00	226.91	0.5
GLASSES EnChroma ON (D2-scene 19)	2100	57	89.31	100.00	111.64	0.6

The degree of adaptation to the white point (*D*) deserves a separate comment. It takes into account if discounting the illuminant happens ($D = 1$) in the model. CIECAM02 is intended to be used with nearly neutral illuminants, which is not the case when wearing VINO or EnChroma glasses. Thus, the proposed computation of the degree of adaptation only depends on the level of luminance and not the chromaticity of the adapted white point, but the model is open to estimated values of D [28]. To ensure a better simulation we have estimated the factor D using the "chromatic adaptation factors" (F_ρ, F_γ, and F_β) of the Hunt Color Appearance Model [28], the most extensive one, capable of considering any kind of illuminant. These factors take into consideration not only the level of luminance of the adapting field but also the chromaticity of the illuminant. The chromatic adaptation factors are designed such that chromatic adaptation is always complete for the equal-energy illuminant. Therefore, after computation of the chromatic adaptation factors, based on their values, we have estimated the final value of the factor D (lower D values corresponding to F_ρ, F_γ, and F_β values further apart from 1).

The CVD conditions were simulated using the Lucassen *et al.* model with parameter d = 0.3 for mild conditions, d = 0.6 for medium conditions and d = 1.0 for dichromats [29]. As we are using CIECAM02 framework, the CVD is applied inside the CIECAM02 model, specifically after computation of R',G',B' values in the fundamental cone space. The severity parameter d used is not directly linked to the loss of chromatic discrimination of a CVD observer, as described in [30]. The values used for d = 0.3 and d = 0.6 would correspond to spectral separations between R' and G' in the R',G',B' space of 20 and 10 nm for protanomalous, and 30 and 20 nm for deuteranomalous observers. As a reference, the spectral separation in the R',G',B' space for normal observers is 50 nm. One of the limitations of the approach presented is the fact that the simulation model used did not allow for a direct determination of the severity of the CVD simulated observer based on spectral separation of responsivities in the cone response space, which can be related to color discrimination loss, as shown in [30].

The data distributions with and without the VINO glasses were then compared to determine the effect of adding the filter on the color attributes in the different data sets. The data was analyzed using, according to the data distribution type, either parametric or non-parametric statistical tests, and circular statistics for the h parameter, as described in [15].

4.2 Results of simulations

4.2.1 Results of the normality tests

For data sets D1 and D2, the Jarque-Bera test was performed on the J and C distributions to test for normality, and the Watson's U square test was chosen for the hue distributions, since circular statistics were required in this case (see [20,31]).

For data set D1, the J attribute (lightness) distribution is not compatible with normality for all conditions. For C, in the "glasses off" condition, distributions for all conditions were also not normal, whilst for the "glasses on" condition the normal, protanope and deuteranope conditions (d = 1.0) were not compatible with the normality assumption. For the hue attribute, only two conditions without glasses (normal, and mild deuteranomaly) were not compatible with a distribution of the von Mises type. For data set D2, all the J and C distributions for all the conditions were not normal, and the h distributions for all conditions were von Mises type.

Given that for each condition at least one of the distributions of J and C to be compared is not normal, we have used non-parametric tests to compare the attributes obtained with and without the VINO glasses. For the h parameter, we have used either the Mardia-Watson test or Watson's U square test, depending on the distribution type, as described in [15].

4.2.2 Comparison of lightness values

Table 3 shows the statistical parameters found for each data set and attribute J. The effect of adding the VINO filters on the lightness of the samples in both data sets is a consistent trend of slightly increasing median lightness for all conditions in data set D1, and for all conditions save medium and severe protans in data set D2. The differences are not statistically significant for data set D1 except for the medium and severe protan-type observers (maximum $p = 0.0280$). For data set D2, all the differences are statistically significant (with $p = 0$). The median lightness in data set D2 is higher than in data set D1.

Table 3. Median and standard deviation (SD) for the Lightness (*J*) attribute for VINO glasses "on" and "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	52.30 (10.31)	52.38 (10.35)	52.45 (10.40)	52.53 (10.49)	52.18 (10.25)	52.06 (10.24)	51.86 (10.30)
GLASSES ON D1	53.18 (11.12)	53.21 (11.44)	53.20 (11.75)	53.17 (12.16)	53.25 (10.63)	53.29 (10.21)	53.27 (9.85)
GLASSES OFF D2	61.35 (15.67)	61.41 (15.66)	61.46 (15.85)	61.53 (15.98)	61.25 (15.52)	61.14 (15.39)	60.99 (15.25)
GLASSES ON D2	61.50 (17.63)	61.65 (17.67)	61.78 (18.00)	61.93 (18.27)	61.27 (17.16)	61.00 (16.68)	60.58 (16.25)

4.2.3 Comparison of chroma values

Table 4 shows the statistical parameters found for each data set and attribute *C*. Data set D2 has markedly lower C values than data set D1. The C value decreases for the CVD observers when compared with the normal ones, and progressively decreases with the severity of the condition as well, less noticeably for data set D2. The effect of adding the VINO glasses in both data sets is a noticeable increase in the chroma of the samples. This effect is more marked for normal and protan subjects, and the increase is a bit less for the deutan subjects. For data set D2, this decrease in the effect for deutan subjects is higher than for data set D1. The differences found are in all cases statistically significant (maximum p value of $2\text{x}10^{-6}$ for data set D1 and $p = 0$ for data set D2).

Table 4. Median and standard deviation (SD) for the Chroma (*C*) attribute for VINO glasses "on" and "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	30.43 (13.27)	26.38 (12.26)	23.52 (13.24)	23.09 (15.86)	26.26 (12.16)	22.69 (12.50)	20.54 (14.46)
GLASSES ON D1	59.37 (21.06)	47.54 (15.07)	37.72 (15.91)	32.41 (20.41)	50.79 (16.61)	42.03 (15.58)	32.73 (21.53)
GLASSES OFF D2	13.95 (12.36)	12.05 (9.41)	10.77 (7.80)	10.91 (8.29)	11.95 (9.76)	10.27 (7.64)	9.13 (6.98)
GLASSES ON D2	49.52 (19.47)	37.74 (11.83)	26.96 (7.55)	17.41 (10.40)	41.31 (13.85)	33.02 (8.75)	24.34 (9.77)

It is remarkable that the strongest chroma increase happens for the normal subject. We could then say that comparatively the VINO glasses are less efficient in increasing the chroma for the CVD subjects, and that this attribute will contribute the most to the change in contrast induced by wearing the glasses, since the changes in lightness are much lower due to the effect of chromatic adaptation.

4.2.4 Comparison of hue values

Table 5 shows the statistical parameters found for each data set and attribute h. The effect of adding the VINO glasses on the hue of the D1 data set samples is a large increase in the *h* mean angular direction values, while for the D2 data set the increase appears very slightly only for the normal condition, and there is a slight decrease for anomalous trichromats. Basically, for D1 all mean angular directions are moved to the fourth quadrant, which is consistent with the reddish-magenta appearance of the simulated scenes (see Fig. 2). The mean angular direction of D2 samples is already in the fourth quadrant, which is why the variation in hue is much less noticeable for this data set. Due to the fact that the daltonization is performed within the CIECAM02 color appearance model, the hue of all samples falls along a single line and the mean angular direction distribution is bipolar with two values: 112.25° and 292.25° (both in the same hue line, 180° apart). The hue of a sample is assigned either value depending on the (a_c,b_c) coordinates position: if the sample has negative a_c, the hue angle would be 112.25°, and if the sample has positive a_c value, then the hue angle will be 292.25°. The mean angular direction values can then fall to either 112.25° or 292.25°, since the mean angular direction is not a conventional average. This fact makes pointless the statistical comparison between the hue distributions with and without glasses, and so this comparison is not carried out.

Table 5. Mean angular direction and standard deviation (SD), in degrees, for the hue (*h*) attribute for glasses on and 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	96.37 (112.43)	102.55 (108.67)	110.23 (105.02)	112.25 (111.93)	103.68 (112.38)	105.99 (110.12)	112.25 (106.62)
GLASSES ON D1	328.24 (46.87)	329.30 (47.16)	331.31 (53.02)	292.25 (108.32)	326.24 (73.02)	323.76 (72.43)	292.25 (82.03)
GLASSES OFF D2	339.33 (110.04)	345.75 (113.86)	355.12 (122.90)	112.25 (186.56)	342.52 (111.58)	346.42 (116.89)	292.25 (150.37)
GLASSES ON D2	341.25 (113.86)	338.56 (20.22)	333.86 (27.65)	292.25 (54.68)	335.86 (18.28)	326.97 (20.76)	292.25 (29.37)

All the mean angular variations found for D1 and D2 are statistically significant (maximum p value of 0.001 for data set D1, and 10^{-12} for data set D2).

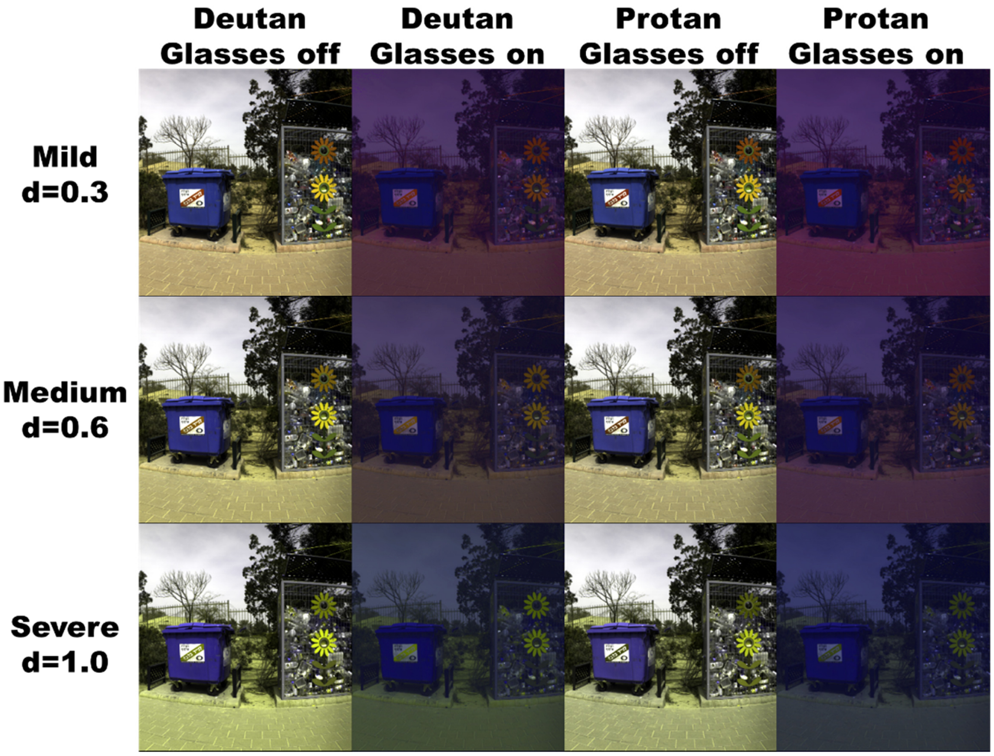

Fig. 2. Example of a simulated scene for mild conditions ($d = 0.3$) in upper row, for medium severity conditions ($d = 0.6$) in middle row and for dichromats ($d = 1.0$) in lower row. Protan and deutan subjects, with VINO glasses off and on in columns.

5. VINO vs. EnChroma

5.1 Filter transmittance curves

The spectral transmittances of the EnChroma Cx-65 and VINO O2 Amp Oxy-Iso glasses are shown in Fig. 3. As described in the previous sections, the VINO filter has near-zero transmittance in the central portion of the visible spectrum, covering the area of maximum spectral response in the luminous efficiency curve (also shown in the Fig. 3). In contrast, the EnChroma Cx-65 transmittance also enhances the perception of bluish or reddish colors, but leaves the green colors mostly unaffected. So, it is expected that both filters will produce radically different effects on any given subject. These differences will be enhanced for the protanopic subjects, which have very little responsivity in the long wavelength portion of the spectrum, and for whom the only available remaining portion of the spectrum would be the blue region with the VINO filter, but blue and green with the EnChroma filter.

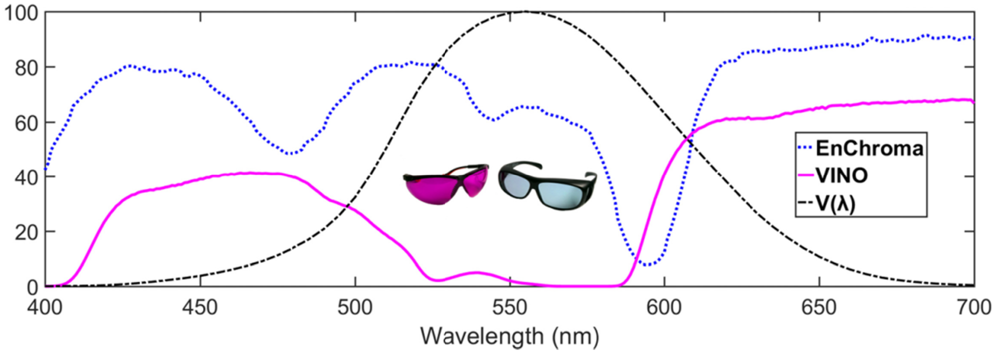

Fig. 3. Spectral transmittances of the two glasses compared VINO O2 Oxy-Iso (magenta) and EnChroma CX-65 (blue). Luminous efficiency curve included (black).

5.2 Subjective evaluation

In comparison with the group of 48 observers that participated in a previous study using the EnChroma Cx-65 glasses [15], the average results of the FM-100 and color naming tests are remarkably similar, although the group of 52 observers that has participated in this study has a slightly higher number of fails in the Ishihara test. This is not very surprising considering that the number of dichromats in the 52-observers group (42 dichromats in VINO study) is higher than in the 48-observers group (30 dichromats in EnChroma study).

If we check the FM100 results, a trend towards a not significant decrease in the *SQR* parameter was found for the EnChroma glasses in [15], but for the VINO glasses the opposite trend is found. In the case of *CI* and *SI* the scores increase markedly with VINO. Regarding the *Angle* parameter, for the EnChroma users there is a clockwise rotation for protan and a counter-clockwise rotation for deutan subjects. The rotation in the case of VINO is much greater producing bigger differences in vision for deutans and protans.

In order to support these results with simulations, the whole Ishihara test was captured using a hyperspectral imaging line scanner model PikaL (Resonon Inc. USA). The spectral images are freely available at http://colorimaginglab.ugr.es/pages/Data. These images were processed with the same simulations performed in section 4.1 (also available in the database). As an example, Figs. 4 and 5 show two plates of the Ishihara test as seen by deutan and protan subjects respectively, with different levels of severity, both without glasses and using either EnChroma or VINO glasses.

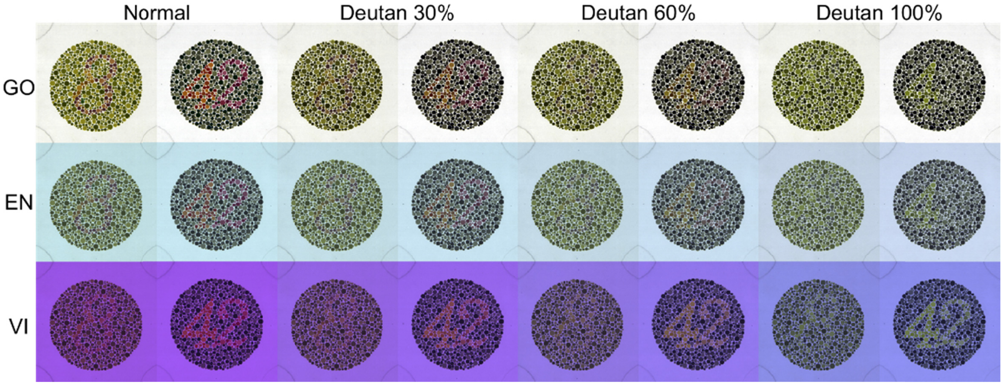

Fig. 4. Simulation of two captured Ishihara plates as seen by deutan subjects with different levels of severity (columns) without glasses (GO), with EnChroma glasses (EN), and with VINO (VI) glasses. Normal subjects included as reference (left column).

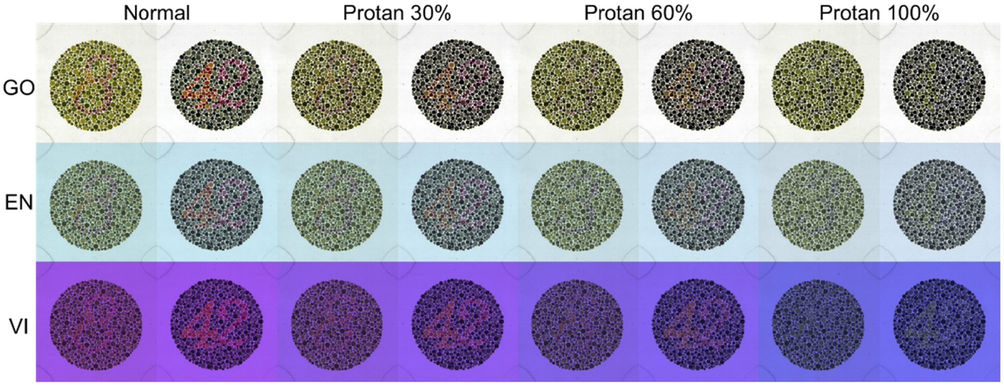

Fig. 5. Simulation of two captured Ishihara plates as seen by protan subjects with different levels of severity (columns) without glasses (GO), with EnChroma glasses (EN), and VINO (VI) glasses. Normal subjects included as reference (left column).

VINO glasses are more effective than EnChroma glasses for passing some of the plates of the Ishihara test, as can be observed in the examples in Figs. 4 and 5, and in Tables 1 and 5. This result is especially evident for deutan subjects, where the contrast of numbers over background is much higher using VINO glasses even for dichromats. As a general result, for protan subjects the VINO glasses could help passing the Ishihara test, especially for mild (30%) and medium (60%) conditions.

There were 19 subjects who participated in both the EnChroma and VINO glasses experiments. For this sub-group, we have compared the results obtained between the two sessions with the glasses on (session 2) as shown in Table 6, taking the EnChroma glasses as reference.

Table 6. Mean difference of the Ishihara, FM100 parameters, and mean number of name changes computed taking session 2 for EnChroma glasses as reference

Ishihara	FM100				Color-naming
ΔFails	Δ*SQR*	Δ*Angle*	Δ*CI*	Δ*SI*	Δ(Terms changed)
−9.45 (7.98)	4.75 (1.79)	5.16 (26.32)	1.34 (0.61)	0.15 (0.31)	3.05 (5.39)

Table 6 shows that in general this group of observers (4 protanomalous, 6 protanopes, 4 deuteranomalous, and 5 deuteranopes) tends to have worse results in the FM100 test wearing the VINO glasses rather than the EnChroma glasses. They also tend to increase the number of errors in the color naming task. However, the number of errors in Ishihara test is much lower with the VINO glasses. This can be explained for similar reasons to those described when interpreting results of Table 1, taking into account that the effect of the EnChroma Cx-65 filter on the color appearance of the samples is much less intense than the effect of the VINO filter, as will be shown in the next section. So, the number of errors in the color naming task increases with the VINO glasses on because of the extreme change in appearance induced by the glasses.

5.3 Simulated data

As explained in section 4.1, the CIECAM02 model computations have been carried out using custom parameters for each scene, and in addition, the daltonization has been performed within the CIECAM02 cone response color space. This makes necessary to re-compute anew the color attributes for the EnChroma Cx-65 glasses to allow for a fair comparison with the VINO filter results, since the values shown in [15] correspond to simulated viewing under only one condition (samples displayed on a monitor screen). The new *J*, *C* and *h* parameter values found for the EnChroma Cx-65 filter are shown in Tables 7, 8 and 9.

Table 7. Median and standard deviation (SD) for the Lightness (*J*) attribute for EnChroma Cx-65 glasses "on" and "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	52.30 (10.31)	52.38 (10.35)	52.45 (10.40)	52.53 (10.49)	52.18 (10.25)	52.06 (10.24)	51.86 (10.30)
GLASSES ON D1	52.24 (10.08)	52.30 (10.09)	52.35 (10.12)	52.41 (10.18)	52.16 (10.09)	52.07 (10.17)	51.92 (10.35)
GLASSES OFF D2	61.35 (15.67)	61.41 (15.66)	61.46 (15.85)	61.53 (15.98)	61.25 (15.52)	61.14 (15.39)	60.99 (15.25)
GLASSES ON D2	61.53 (15.67)	61.59 (15.77)	61.65 (15.88)	61.72 (16.04)	61.43 (15.49)	61.32 (15.33)	61.17 (15.18)

Table 8. Median and standard deviation (SD) for the Chroma (*C*) attribute for EnChroma Cx-65 glasses "on" and "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	30.43 (13.27)	26.38 (12.26)	23.52 (13.24)	23.09 (15.86)	26.26 (12.16)	22.69 (12.50)	20.54 (14.46)
GLASSES ON D1	34.51 (14.41)	29.34 (12.24)	25.20 (12.36)	23.53 (14.74)	29.03 (12.27)	24.19 (11.88)	20.48 (13.76)
GLASSES OFF D2	13.95 (12.36)	12.05 (9.41)	10.77 (7.80)	10.91 (8.29)	11.95 (9.76)	10.27 (7.64)	9.13 (6.98)
GLASSES ON D2	14.54 (14.41)	11.90 (10.04)	9.97 (7.17)	9.45 (7.69)	11.92 (10.88)	9.69 (7.51)	7.74 (5.87)

Table 9. Mean angular direction and standard deviation (SD), in degrees, for the hue (*h*) attribute for EnChroma Cx-65 glasses on and 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	96.37 (112.43)	102.55 (108.67)	110.23 (105.02)	112.25 (111.93)	103.68 (112.38)	105.99 (110.12)	112.25 (106.62)
GLASSES ON D1	172.95 (106.59)	175.00 (109.25)	179.16 (115.43)	202.25 (474.25)	175.24 (125.05)	174.79 (130.85)	112.25 (106.62)
GLASSES OFF D2	339.33 (110.04)	345.75 (113.86)	355.12 (122.90)	112.25 (186.56)	342.52 (111.58)	346.42 (116.89)	292.25 (150.37)
GLASSES ON D2	178.26 (81.45)	180.85 (86.68)	182.33 (96.87)	112.25 (139.57)	178.06 (86.26)	175.62 (95.91)	112.25 (124.51)

Comparing the effect on the *J* (lightness) parameter found for the VINO and EnChroma filters, in both cases the variations in *J* are slight (consistent with a certain degree of chromatic adaptation). The VINO filter tends to decrease *J* values save for D2 and medium-severe protan observers, while the EnChroma filter produces a very slight increase in general for both data sets (the values for the mild and medium protan conditions remain almost stationary). This result shows that the effect of the added filter can be different depending on the CVD condition and the region of the spectrum that the filter is suppressing, but J is the attribute which is less affected by the filters.

Regarding the hue parameter (except for the dichromat conditions), the effect of the EnChroma Cx-65 filter is to shift the mean angular direction towards the 180° axis, both for D1 and D2 samples, while VINO produces a shift towards the fourth quadrant also in both data sets. The amount of the shift is more pronounced for the EnChroma Cx-65 filter, since for data set D2 the mean angular direction was already in the fourth quadrant. The results could also be interpreted in terms of the narrowing of the standard deviation values in the hue distributions, which is found for the VINO filter but not for the EnChroma filter. This means that the VINO filter is shrinking the width spanned by the color samples in the CIECAM02 color space, while the EnChroma filter has not such a noticeable effect in the color distributions, which is expected because the VINO filter produces clearly a shift towards the purple region, while the EnChroma does not produce such a clear effect.

Regarding the C parameter (chroma), for the EnChroma filter there was a rather small chroma increase and it was only found in a consistent way for data set D1 and not for the medium and severe protan observers. With the VINO glasses, the chroma increase is much higher and consistent amongst the data sets and conditions. Since the VINO filter has a lesser transmittance in a longer range of wavelengths than the EnChroma filter, the effects tend to be more marked, making the colors more vivid in comparison with the glasses off condition. Once again, these findings can be explained by considering that the EnChroma glasses will predictably produce a lesser impact on the chroma of the majority of colors present in natural scenes, which have a lesser amount of blue in general, which is the region that is preferably enhanced by the EnChroma filter.

6. Conclusions

The low transmittance in the intermediate region of the spectrum in the VINO O2 Oxy-Iso glasses produces a significant change in color appearance, especially in the chroma attribute. This change allows some CVD subjects, above all the deutan subjects, to pass recognition tests such as the Ishihara but not the arrangement tests such as FM100. Similar conclusions have also been reached by other authors [16–18]. This extreme change in color perception also has a negative effect in the color naming test. The simulations show that the hue angle is compressed and moves towards the fourth quadrant. The chroma increases significantly for all the conditions and the for the two groups analyzed. These effects are much more significant than those produced by the Cx-65 by EnChroma model that we also analyzed using CIECAM02 parameters customized for each scene and data set. Neither of the two models we studied improves the color vision of the CVD subjects to the same level as normal subjects, nevertheless they may facilitate some discrimination tasks. Thus, the VINO O2 Oxy-Iso filters may be useful for some specific applications (like enhancing the O_2 signal from hemoglobin under the skin) as occurs with some color filters used in certain activities such as hunting, shooting, low vision etc [32].

To sum up, our results support the hypothesis that glasses with filters are unable to effectively resolve the problems related to color vision deficiency.

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Disclosures

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