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Assessment of Enchroma Filter for Correcting Color Vision Deficiency

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Abstract

Purpose: Color vision deficiency (CVD) especially the Red-Green type (RG), affects 8% of the male and 0.5% of the female population. There is no cure for color deficiency. However, there are specially-tinted lenses marketed to enhance the color contrast for CVD individuals. Recently, EnChroma Filters claim to enhance color perception. The aim of this study was to examine EnChroma Cx-14, red, and green filters subjectively on subjects with RG CVD.

Methods: Nine males and one female (aged 19 – 52 years) with RG CVD were recruited. Five were severe deutans, two moderate deutans, and two were severe protans. Subjective responses to EnChroma were tested using ColorDx software on a tablet and online Farnsworth-Munsell (FM) 100-Hue tests. Error scores of the ColorDx and FM 100 Hue tests with EnChroma CX-14, Red and Green filters were calculated and compared against Placebo (untinted glasses).

Results: In only two subjects , EnChroma filters resulted in CVD improvement from severe protan to moderate protan and from severe deutan to moderate deutan using ColorDx. Neither EnChroma nor green filters improved the mean error scores of ColorDx ($p = 0.39$) and ($p = 1.00$), respectively. However, red filter significantly improved color discrimination from severe deutan to mild deutan in all deutan subjects, and in one subject, from severe protan to mild deutan ($p = 0.013$). Similarly, EnChroma did not significantly improve the error score of FM 100 Hue test. Also, none of the other filters showed significant improvement in the error scores of the FM 100 Hue.

Conclusions: EnChroma Cx-14 filters are multi-notch filters that modify the wavelength transmission to the observer. To our knowledge this is the first study to measure the effectiveness of EnChroma Cx-14 on digital version of Ishihara (ColorDx). Our results showed that the EnChroma filters had no significant effect on the performance of any of the CVD subjects, but improved the error score in only two subjects.

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ASSESSMENT OF ENCHROMA FILTERS FOR CORRECTING COLOR VISION DEFICIENCY

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THESIS

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Nawaf M. Almutairi

MASTER OF SCIENCE IN VISION SCIENCE
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Keywords: Color vision deficiency, Treatment, Filters, Enchroma, Red filter

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INTRODUCTION

1. Theories of Color Vision

Understanding the physiology of normal and abnormal color vision is important in understanding possible color vision deficiency treatments. Color is the sensation that allows us to differentiate between uniform surfaces of equal brightness[2]. Humans can perceive a wavelength of light that spans from about 380 nm to 700 nm. People with normal color vision can distinguish thousands of color shades [3]. Perceptually, human color vision is organized in an opponent manner, with pairs of categories of light and dark, red and green, and blue and yellow. Therefore, color percepts can be characterized in a three-dimensional space (Fig. 1), bridged by color axes conforming to these opponent pairs.[4] Normal color vision is trichromatic in which the observer can match any spectral light to a mixture of the three primary color lights (Blue, Green and Red). The trichromatic theory of vision was first briefly stated by Thomas Young in 1807 and was developed about 50 years later by Helmholtz, according to which color perception depend on three mechanisms with sensitivities in different parts of the electromagnetic spectrum[5,6]. At the receptor level in the retina, trichromatic color vision relies on three classes of cones that receive inputs from the short (S), middle (M), and long (L) wavelength regions of the visible wavelength spectrum that have peak sensitivity lie at about 426 nm, 530 nm, and at 557 nm, respectively [7] (Fig. 2). Perceptually, these wavelength spectrums are associated with the blue, green and red colors, respectively. Therefore, color processing is based on quantum photon that these photoreceptors catch, and a single

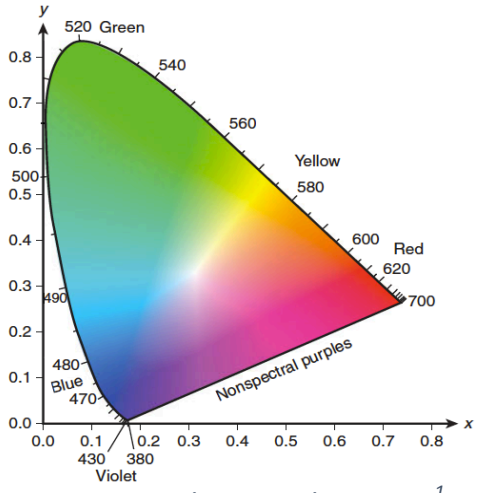

Figure 1 The CIE Color Space [1]

photoreceptor cannot produce color, although photoreceptors may have a peak sensitivity in its absorption spectrum. In fact, all people are colorblind under dim light conditions when there is not enough light to activate the cones, and then are left with only one active class of photoreceptors, the rods. Cone photoreceptor signals are further processed in the Lateral Geniculate Nucleus (LGN) through color-opponent process. LGN has two class of neurons. The first class is referred as red-green color opponent cells which are excited by red light and inhibited by green light, or vice versa. The other class responds to blue-yellow light, which are known as Blue-Yellow color opponent cells. Unlike the opponency system in red-green channel, blue-yellow opponent cells receive input from the S-cones and from the sum of L- and M-cones [8]. The S- cone sends its inputs to the LGN through the Koniocellular pathway which then projected to cytochrome oxidase (CO) blobs in layers 2 and 3 of visual cortex area 1 (V1), while the M and L through cells that synapse in layer 4C beta in V1. Finally, V1 sends its inputs to V2 and then V4.

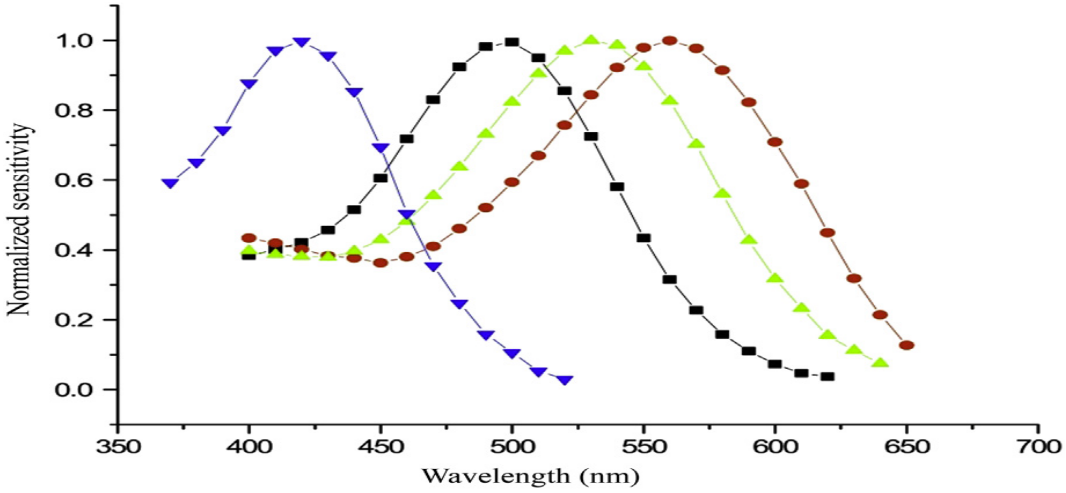

Figure 2. The spectral sensitivities of the 3 classes of cone photoreceptor (S-cones, blue; M-cones, green; L-cones, red) and of the rods (black squares) plotted against wavelength in nm [7].

2. Congenital Color vision deficiency

Congenital color vision deficiency (CCVD) is considered one of the most common inherited disorders of vision, and is the most studied one. The most common type of the CCVD is the red-green defect, a term that comprises protanomaly, protanopia, deuteranomaly, and deuteranopia. CCVD is usually a result of genetic mutations that affect the expression of the long-wavelength (L) or the middle-wavelength (M) cone photoreceptors. Both red (erythrolabe) and green (chlorolabe) photopigments are coded on the X-chromosome. As a result, the prevalence of red-green color vision deficiency is as high as 8% in males and 0.5% in females, as males only possess one X-chromosome, and females have two. Geographically, red-green CCVD is more prevalent among Europeans, while Africans have the lowest rate. [9,10] Although there is an alteration in the cones function either a missing class of cone photopigments in dichromacy, or deficiency in the opsin composition in anomalous trichromacy, the visual acuity remains unchanged. Generally, CCVD can be classified as protan, deutan or tritan, and comes in two forms: dichromatic and anomalous trichromatic forms as a accepted classification for twenty-five years.[11,12]

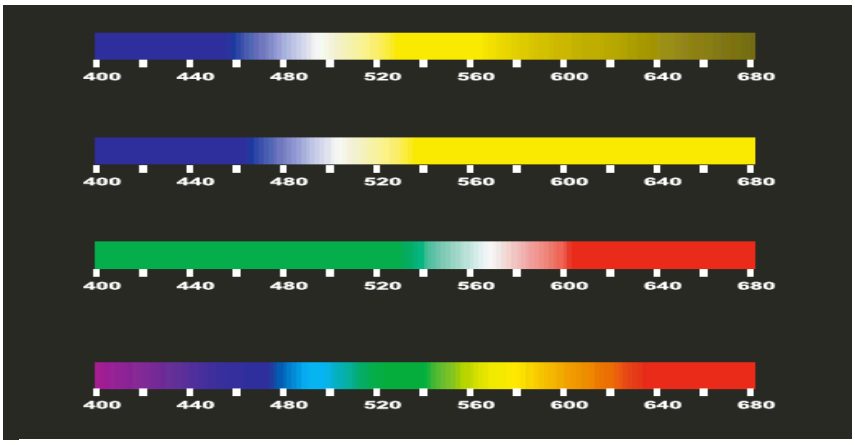

Figure 3. From top to bottom, protanopia, deuteranopia, tritanopia, and normal Trichromat

2.1 Dichromacy

Dichromacy is the severest form of color vision deficiency, and less prevalent than anomalous trichromacy. It is reported to be 1.0% and 1.3% for protanopia and deuteranopia, respectively.[13] The defect occurs when either the *M* opsin (deuteranopia) gene or *L* opsin (protanopia) gene is missing.[13] Consequently, dichromat color vision has a reduced dimensionality in the corresponding missing cone axis. [14] For example, protanopes confuse colors along the red-green axis (Figure 3). The missing photopigment is believed to be replaced by the remaining photopigment. For instance, chlorolabe is replaced by erythrolabe in case of deuteranopia. Similarity, erythrolabe is replaced by chlorolabe in case of protanopia. This process is called the replacement model of dichromacy.[15] The other case scenario is when a portion of the cones contain no visual pigment, and that referred as the empty cones model.[16] Perceptually, individual with protanopia only can distinguish about 21 distinct wavelengths; whereas deuteranopes can only distinguish 31 distinct wavelengths. On contrast, the normal trichromat can distinguish about 150 wavelengths. Generally, red–green dichromat sees only two primary colors in the visible spectrum. [13]

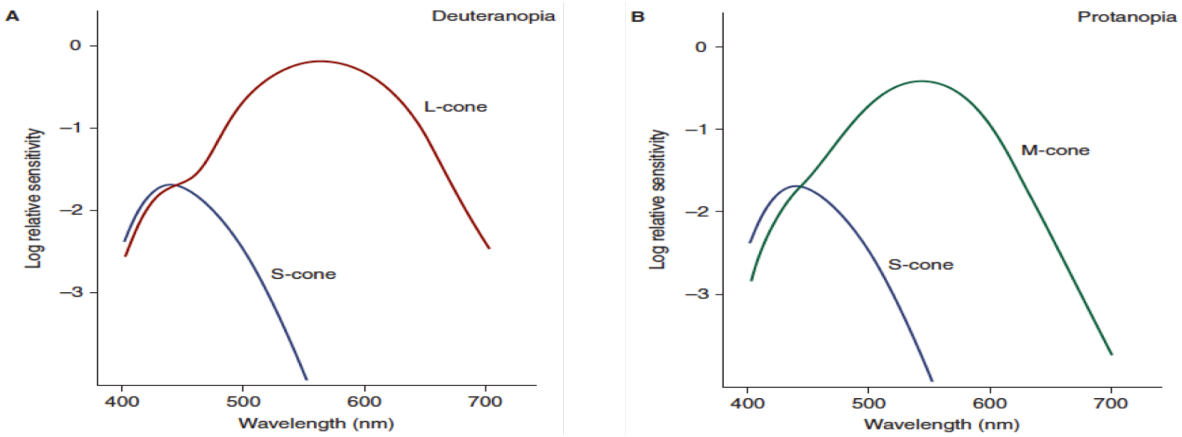

Figure 4. Approximations of the absorption spectra for the remaining photopigments in deuteranopia and protanopia

2.2 Anomalous Trichromacy

As with dichromacy, anomalous trichromacy is an inherited defect of the color vision in which there is an alteration of the spectral sensitivity of one or more cone photopigment. [17] In deuteranomaly which affects around 5% of males, the normal L-photopigment is mostly preserved, whereas the M-photopigment is replaced by an anomalous photopigment referred as L', has a close spectral sensitivity to the normal L-photopigment. [18-20] On the other hand, protanomals (1% of the male population), similarly have a normal-functioning M- cone, and have L-cone photopigment that is replaced by an anomalous M' photopigment. [20] *(Fig. 5)* The magnitude of color vision confusion in either the protanomals or deuteranomals is determined by the amount of peak sensitivity displacement; therefore, the greater the displacement, the more severe the color vision anomaly. [1] Anomalous trichomacy can range from moderate to severe color discrimination loss and many of anomalous trichomats who fall in the category of moderate to mild may not be aware of their color vision loss until they sit for color vision test. [21] Unlike dichromats, anomalous trichromats don't have neutral (white) point, and they can see more than two primary hues in the visible spectrum. [12] On the anomaloscope, their Rayleigh match can be categorized for protanomalous and deuteranomalous, based of the mid-point match and the matching range. Protanomals require adding more red, and therefore, their matching range is significantly displaced to the red. Similarity, deuteranomals have a matching displacement to the green with a narrow matching range. [22]

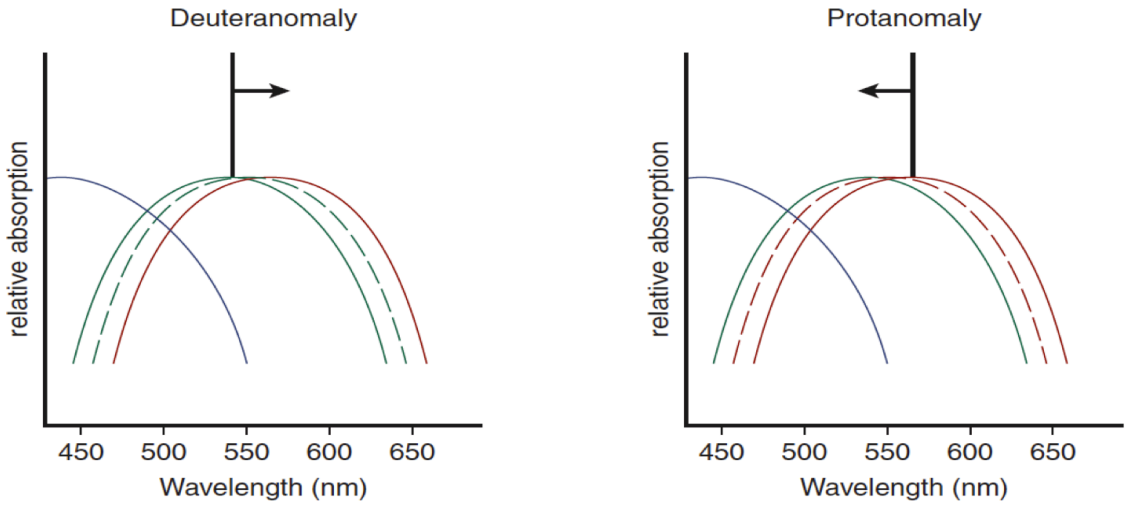

Figure 5. Simplified absorption spectra for anomalous trichromacy

3. Acquired Color vision deficiency

Acquired color deficiency usually arises secondary to ocular and visual pathway diseases. Epidemiologically, the prevalence of the acquired form of color vision deficiency was thought to be about 5% to 15% of the population. However, this prevalence was based on general opinion rather than a large survey. [10] A study conducted in Iran examined 5,102 adults aged 40 - 64 years old using the Farnsworth D-15 test suggested a prevalence of 10.1%. Of those surveyed; 66.1% had an acquired tritan defect, while the remainder had acquired red-green defect. [23]

Clinically, the most common used classification of acquired color vision deficiency was developed by Verriest. [24] His classification scheme was as follows:

1. Type I M-L mechanism (red-green) deficiency with a peak spectral sensitivity shift to shorter wavelengths
2. Type II M-L mechanism deficiency with relative preservation of the spectral sensitivity function

3. Type III S-mechanism (blue-yellow) deficiency in which there is a shift in peak spectral sensitivity to shorter wavelengths, and
4. Ill-defined or unclassifiable.

Recent epidemiological studies suggest that S-mechanism acquired color vision deficiency is more prevalent than M-L mechanism. [23] Schneck, M.E., et al, studied the frequency and type of color vision defects in a group of 865 individuals aged from 58 to 102 years using the Adams desaturated D-15 test. They found that 88% of whom failed the test had blue-yellow defect. [25] The most common of mechanism of blue-yellow acquired color vision deficiency possibly secondary to increase in optical density of the crystalline lens pigments. [26] Diseases such as Vascular retinopathies and papilledema, glaucoma and dominant optic atrophy are most likely to cause tritan acquired color vision deficiency. [27,28] On other hand, diseases such as, optic neuritis, toxic amblyopia, optic atrophy, chiasmal disorders, peripheral chorioretinal degenerations, angioid streaks, myopic choroidal degeneration, and chorioretinitis tend to cause red-green acquired color vision deficiency. [22,29,30] Some other diseases such as diabetes tend to have mixed red-green and blue yellow color vision defects. Barton and colleagues analyzed Farnsworth-Munsell 100-hue test results in 2701 from the Early Treatment of Diabetic Retinopathy Study. Their results showed that 51% of the examined individuals had color vision abnormality; blue-yellow color vision defect represented in 26% of the eyes, whereas the reminder had combined red-green and blue-yellow deficiency. [31] In addition, red-green acquired color vision deficiency tend not only affect the color discrimination, but also affect the spatial vision as opposite to blue-yellow acquired color vision deficiency. [32] Although the precise prevalence of

color vison deficiency is still unknown, the current evidence suggest that it is more common than the congenital color vision deficiency.

4. Color Vision Deficiency Treatment

Red-Green color vision deficiency is considered not a disabling condition, even though many of the affected individuals might disagree. Normal color vision is required for employment to various professions such as those with a commercial drivers license, police officers, pilots, or a firefighters. Over the two centuries, there have been attempts to treat color vision deficiency, yet there no universally established treatment. Among many options that have been tried, a few have shown effect. In 1817, Seebeck was the first to suggest using color filters for color vision deficiency management. [33] Since then, color filters gained a great attention of research. Generally, colored filters enhance color discrimination by tuning the brightness, saturation, and hue through a selective absorption of certain wavelengths. In 1971, Zeltzer developed X-Chrom lenses, a red contact lens places over one eye. [34] The X-Chrom lens is a long-pass filter works by darkening the yellow-green objects and making orange objects appear more red and slightly darker. [35] It was reported be more effective for anomalous trichomats and less for dichromats. [36] Barry et al, examined X-Chrom lens on sixteen color anomalous subjects using AO HRR pseudoisochromatic plates and Farnsworth-Munsell 100-Hue tests. Their results showed a significant improvement on AO pseudoisochromatic error score but not on 100-Hue tests. The JLS is an aqua (blue-green) lenses placed on one eye as in X-chrom lens to manage color vision deficiency. Schlanger tested JLS lens on twenty-five color deficient patients. Of the twenty-four subjects, seventeen showed an improvement with as success rate of 62%, analyzed using chi-square test. [37] He concluded that the perceived

luminosity difference between the two eyes plays a key element in the subjective color discrimination improvement.

In 1996, David Harris, an English optician developed ChromaGen that provided some advantages compared to earlier lenses. ChromaGen comes in a range of tints as soft contact lens that provide more comfort compared to X-Chrom lenses. Patients are instructed to determine the preferred filter or filters from a potpourri of colors ranging from red to violet across the visible spectrum. In addition, only the pupil size is tinted, which provides better cosmesis compared to the fully-tinted lenses. [38] Swarbrick et al., investigated the efficacy of ChromaGen on fourteen color deficient patients using Ishihara, Farnsworth D-15, and Farnsworth Lantern. Patients were administered the tests at baseline, lens dispensing, and after a two-week lens-wearing trial, during which subjective responses were recorded daily using visual analogue scales. Their results showed that ChromaGen significantly reduced the error score of Ishihara test, particularly for deutan subjects. There was also a significant reduction in errors on the D-15 test. Conversely, lens wear had no significant effect on Farnsworth Lantern test performance. Subjectively, patients showed an improved color perception. Although, there was an improvement on some color tests, subjects reported poor vision in dim light because of the dark-tinted lenses. The study concluded that even though there was an improvement in color discrimination, the lenses do not provide a true color hue perception, and has serious implications for the prescription of these lenses for people who are motivated to gain entry to occupations from which they are legally excluded because of their color vision deficiency. [38]

A more recent application of filters is Enchroma lens. Enchroma has variable degrees of tints ranging from indoor (light-blue tinted) to outdoor (dark gray-tinted) filters. The company

states that[39], Enchroma filters use "a Multi-notch filter" technology which selectively filters out parts of the visible spectrum. The targeted wavelength is derived from the basics of anomalous trichomacy i.e. protanomaly and deuteranomaly wavelengths peak sensitivity response curve. For example, in protanomaly, the L-cone peak sensitivity is shifted towards the shorter M-cone sensitivity, creating an overlap between the two classes of cones sensitivities and thus, absorbed spectra would not be discriminable. Therefore, Enchroma exploits this overlap by filtering out the unwanted peak overlapping wavelengths, creating a little difference between the M and L-cones wavelength sensitivities. This mechanism of Enchroma wavelength spectrum modification has never been tested in a clinical trial. However, Enchroma advertises its products by providing patients' written and videoed testimonies in their website (readers are referred to Enchroma website [40]).

The most recent promising therapy for color vision deficiency uses gene therapy to replace and modify the defective or missing chromophore in the photoreceptors. The process of gene therapy involves injecting adeno- associated virus that has a human opsin gene in the sub-retinal layer to the photoreceptor layer. Mancuso et al., examined the effect of gene therapy on two dichromat squirrel monkeys that were missing L-opsin gene. They were trained to perform a computer-based Cambridge Color Test. After about 20 weeks post-injection, the trained monkeys' thresholds for blue-green (490 nm) and red-violet (499 nm) improved, indicating that they gained trichromatic vision and therefore passed the color test . [41] Genetic therapy has not yet been applied to humans. Although, these monkeys have not shown serious side effects two years after the viral injection, scientists remain cautious about translating animal studies to individuals with color blindness.

The aim of this study was to test Enchroma filters on both anomalous trichomats and dichromats. We conducted two separate studies. In the first, we examined Enchroma's spectral transmission and the effect of Enchroma filters on normal color vision subjects, subjectively. In the second study, we tested if Enchroma filters would enable individuals with abnormal color vision to see more colors than conventional filters available on the market using standard clinical color vision testing. Our hypothesis stated that there is no difference between color perception of abnormal color vision individuals with and without Enchroma.

STUDY 1: OBJECTIVE AND SUBJECTIVE TRANSMISSION ASSESSMENT OF ENCHROMA FILTERS

PURPOSE

The aim of this study was to test the overall transmission and wavelength filtering characteristics of EnChroma Gamma II Cx-14 filter objectively and determine if it subjectively changes the color perception in normal trichromats.

METHODS

Subjects

Twenty-five males (aged 20 to 25 years) with normal vision were randomly recruited through email from Qassim University college of optometry students. Inclusion criteria included that participants had to have visual acuity at least 20/40 best-corrected. Participants also had to have normal color vision. Two color-deficit participants were excluded from the study due to having abnormal color vision. Exclusion criteria included individuals with anterior

or posterior ocular diseases that may affect color vision. Twenty-three participants met the study criteria and included in the data analysis.

Materials

Pseudoisochromatic color vision test ColorDx (as an iPad app, Fig. 9) was used only to screen participants' color vision to make sure that they had normal color vision. An Apple Macbook monitor was used to conduct the Online version of Farnsworth-Munsell 100-Hue test (http://www.color-blindness.com/farnsworth-munsell-100-hue-color-vision-test/#prettyPhoto/1/) [42] on all of the participants with and without Enchroma filter. The Macbook calibrated using Spyer5Pro to the ideal color vision testing illumination (Illuminance C, 6400 K). Ocean Optics spectrophotometer was used to measure the spectral transmission of Enchroma Cx-14 glasses.

Data Analysis

Paired t test was used to compare the Farnsworth-Munsell 100- Hue tests error scores and time duration to complete the test the results compared and correlated with and without Enchroma filters, and then correlated to the Ocean Optics spectral transmission curves.

RESULTS

Spectral transmission of Enchroma Cx-14 showed notching of wavelength starting from 450 nm that dipped down close to zero transmission from 475 nm to 500 nm, and from 560 nm to 575 nm. Peak sensitivity was not achieved for the short wavelength of 420-450 nm (Fig. 6). There was a significant ($p = 0.018$) increase in the total mean Farnsworth-Munsell 100-Hue test error scores with a shift towards a defect resembling tritanomaly (mean = 35), 95% CI [-94 to 165] with the Enchroma Cx-14 glasses. The correlation of time taken to complete the FM100 - Hue test with and without EnChroma was stronger ($r = 0.82$) only for the Farnsworth-

Munsell 100-Hue caps that test for confusion in the blue orthogonal axis of the CIE chromaticity diagram, but not significant overall (Fig. 7, 8).

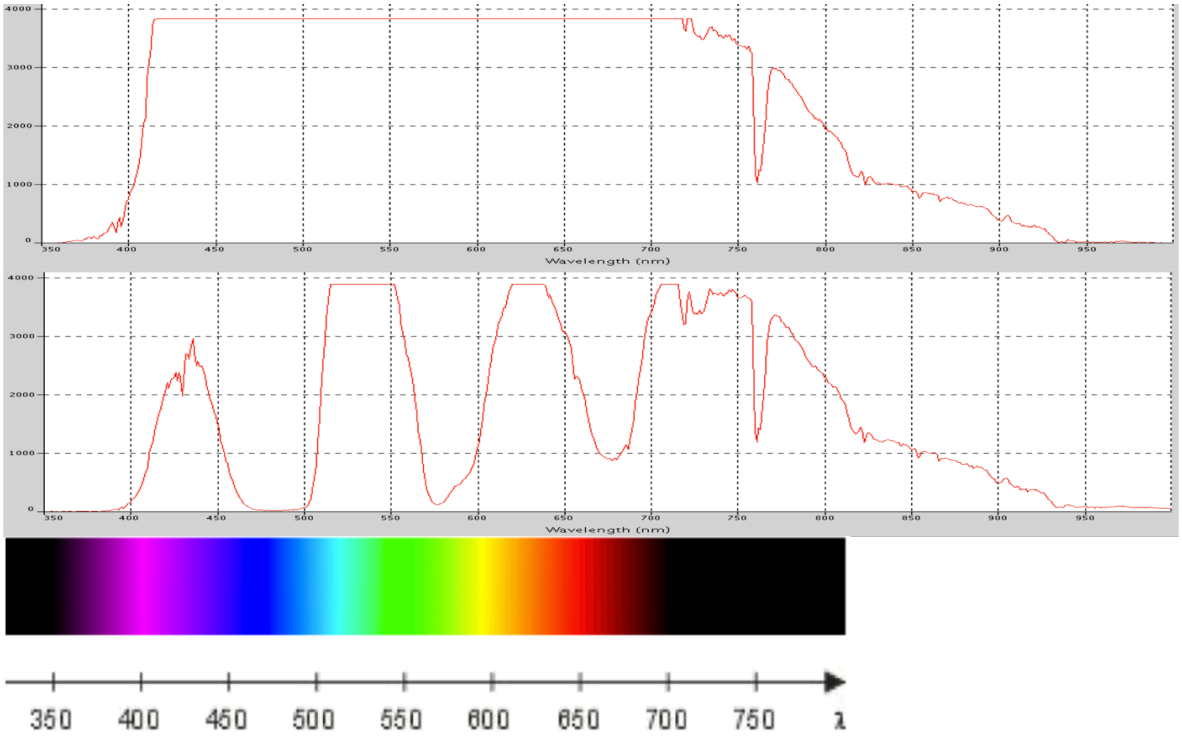

Figure 6. Spectral transmission of Enchroma Cx-14. The upper curve represents light transmission without Enchroma and the lower represents the transmission curve of Enchroma.

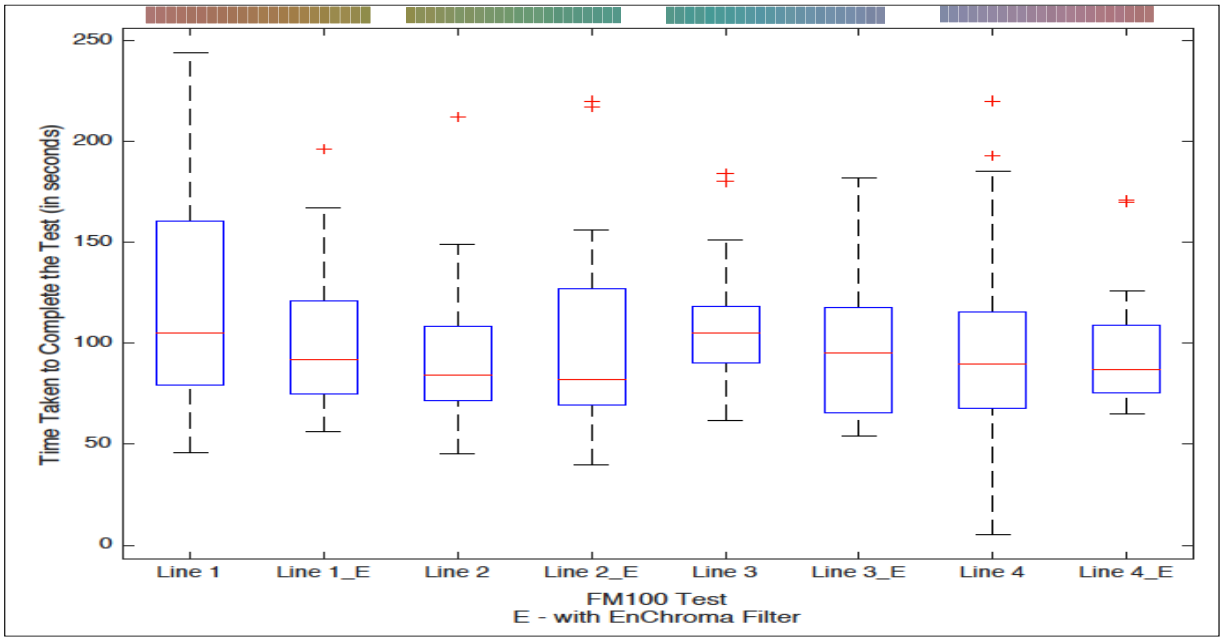

Figure 7. Box plot representing the median time taken to complete the test has decreased with the Enchroma filter in all the four rows of plates

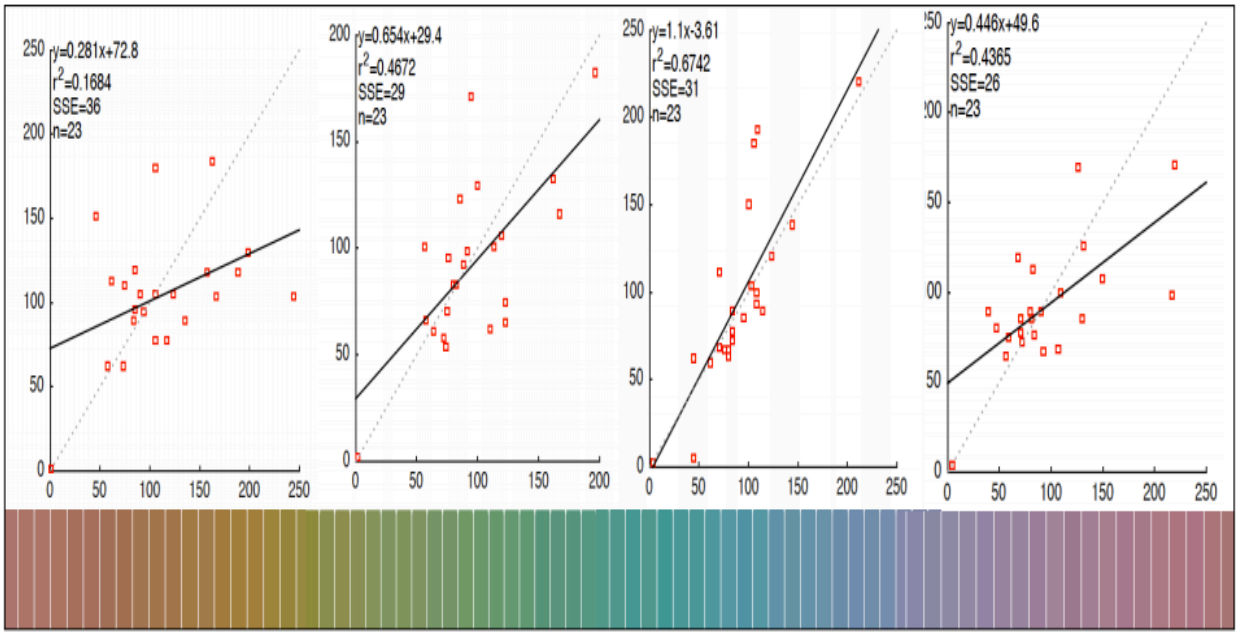

Figure 8. The correlation of time taken to complete the FM100 test with and without EnChroma

DISCUSSION

To our knowledge this is the first study that measures the transmission spectrum of Enchroma Cx-14 lens and its effects on color vision of normal trichromats. EnChroma Cx-14 glasses are multi-notch filters that modify the wavelength transmission to the observer. Our results show that the Enchroma filters notch the blue region of the visible spectrum consistently. As a result, we postulated that this precise notch of the wavelength induces a tritan defect in individuals with normal color vision. The following study was to further investigate whether Enchroma filters improve the color discrimination in individuals with red-green color vision deficiency.

STUDY 2: ASSESSMENT OF ENCHROMA FILTERS FOR THE CORRECTION OF COLOR VISION DEFICIENCY

PURPOSE

The purpose of this study was to test if Enchroma Cx-14 filters would enable individuals abnormal color vision to see colors. In addition, it compared Enchroma Cx-14 to conventional filters available on the market using standard clinical color vision testing.

METHODS

Subjects

This is randomized cross-over study that was conducted in two centers. The first was conducted at Pacific University College of Optometry, in the Visual Performance Institute, and the second parallel portion was conducted at Qassim University, College of Applied Medical Sciences, Department of Optometry Eye Clinics, Buraydah City, Saudi Arabia. The research was approved by both of Institutional Review Boards of Pacific University and Qassim University. Ten

individuals (9 males and 1 female, mean range 19 - 52) with hereditary red-green color vision deficiency were recruited from both Pacific (n=2) and Qassim (n=8) Universities. All subjects had at least 20/20 best corrected visual acuity. There were six severe deutans, two moderate deutans and two severe protans.

Inclusion criteria included subjects with red and green color deficiencies at all levels of severity. Subjects had to be over 18 years old with healthy eyes. All participants underwent a comprehensive eye examination and had best corrected visual acuity of least 20/25 acuity in each eye.

Exclusion criteria included individuals with anterior or posterior ocular diseases that may affect color vision (such as diabetic retinopathy or glaucoma, optic neuritis, among other, rarer conditions). These eye diseases can cause blue-yellow color vision defects, in the case of diabetic retinopathy or optic neuritis, glaucoma, or otherwise alter color perception. Likewise, participants should not be taking any medications that alter color vision, such as thiazide diuretics for high blood pressure, amphetamines, Plaquenil, Viagra, and others.

Procedure

Examiners at both of Pacific University and Qassim University used the same testing conditions, instruments and viewing conditions. Participants underwent screening procedures to determine their eligibility for the study. ColorDx was used as a screening device to determine if a participant had congenital color vision deficiency. After determining the participants' eligibility for the study and signing the informed consent, participants completed testing on Anomaloscope, digital Farnsworth-Munsell 100-Hue and ColorDx (Waggoner Computerized Color Vision Test software) using the Enchroma Cx-14 filter, red-tinted and green-tinted filters and placebo untinted

glasses. The rationale for selection of these devices was that they are commonly used in clinical settings to test people with people with CVDs. Furthermore, the selected tests covered a wide range of color perception tasks including color discrimination (ColorDx) and subtle hue detection (Farnsworth-Munsell 100-Hue). The order of testing was determined by the Latin square randomization technique.

The treatment conditions that were tested in this study were Enchroma Cx-14 filter, Green filter, red filter and untinted lenses. The light transmission for the green and red lens is 13% and 15% as an estimate provided by the manufacturing company. EnChroma (EnChroma, Inc., Berkeley, CA (US)) is a patent pending application. It uses the technology of notch filters in which some of the spectral wavelength is cut out to enhances specific colors *(Fig. 6)*. Green filters are meant to be a balancing condition because they make the color vision test harder to pass. However, the red lenses have been shown to be effective to allow patients with red-green color deficiency to pass pseudo-isochromatic plate tests like the Ishihara or the Hardy Rand and Rittler (HRR) test. All the lenses were coated with mirror coating to conceal the underlying lenses tints from the participants.

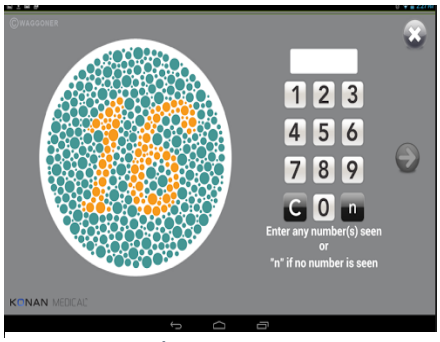

Figure 9. ColorDX

Materials

Participants were instructed to wear each one of the mentioned filters and then they were tested using the following instruments:

The first was Oculus Anomaloscope, which is a microprocessor-controlled device for precision diagnosis of color vision in the red/green (Rayleigh criterion) spectrum and in the

blue/green (Moreland criterion) spectrum with integrated automatic neutral adaptation. The unit is normally controlled using the Windows™ based software and cable from a PC. The program supports incorporation of patients' data and results comparison (https://www.good-lite.com/Details.cfm?ProdID=570). The instrument has a circle divided into an upper and a lower half. The upper half is a mixture of 670 nm red and 549 nm green light with a knob that controls the mixture on a scale units from 1 to 75. A scale of 1 is pure green and a scale of 75 is pure red. The lower half of the circle is a pure yellow light (590 nm) that can be adjusted in brightness with another knob. The examiner changes the upper mixture half and then the subjects were asked match the upper and the lower circles colors using two knobs. Once the subjects made the match as the two circle halves appears identical, we then record the obtained range and midpoint match.

The second test was a pseudoisochromatic color vision test (ColorDx), available at http://konanmedical.com/colordx/ (Fig. 7) [43]. We used the iPad version of the ColorDx which is designed to screen red-green and blue-yellow color vision defects. The test has a randomized series of presented plates that flashed on the iPad I (128 GB) screen for about two seconds and the subjects had to respond by entering the number that appeared in the plates on the screen, or respond by N denoting "nothing". The test consists of four sets. The first set is 24 diagnostic plates. If the subject passes, the application ends. If this set is not passed, the application immediately begins further tests to quantify the defect. This section consists of three sets: 32 plates for protan, 32 plates for deutan, and 12 plates for tritan.

Figure 10. EnChroma CX-14

The third test was the online version of Farnsworth-Munsell 100-Hue arrangement caps test used on an Apple laptop (http://www.colormunki.com/game/huetest_kiosk). Although the

Farnsworth-Munsell 100-Hue test is not designed to screen color vision, we chose it because it tests fine hue discrimination [44].

All the tests were administered under dim lighting conditions. Between each test and the other, the room lights were turned on to adapt subjects to white light and to eliminate the effect of adaptation to the previous tested filter. Both the illumination of the iPad and the laptop were calibrated using Spyer5Pro to the ideal color vision testing illumination (Illuminance C, 6400 K) [45].

Data analysis

IBM SPSS Statistics version 24 was used to perform the data analysis. Repeated measures ANOVA was chosen to test differences among conditions (Enchroma, green-tinted, red-tinted and untinted placebo lenses) color vision tests mean error(s) score. In the case of Farnsworth-Munsell 100-Hue test, we analyzed the total error score for all quadrant. The online version of Farnsworth-Munsell 100-Hue doesn't provide the specific error score for each quadrant. The results of error rates of color vision test using Enchroma, red, and green-tinted lenses were compared to the untinted placebo lenses. A critical p -value of 0.05 was chosen to indicate statistical significance.

RESULTS

Each of the 10 subjects performed all three-color vision tests (ColorDx, Anomaloscope, and digital Farnsworth-Munsell 100-Hue) with each of the randomized treatment conditions filters (EnChroma, red, green, and placebo). There were seven deutans, two protans and one deutan-protan. Table 1 shows the summery of raw data for the 10 subjects and their color vision deficiency diagnosis**.** The Enchroma filters resulted in CVD improvement from severe protan to moderate protan and from severe deutan to moderate deutan in only two subjects on ColorDx, Table 3.

However, the mean difference of error score of EnChroma compared to placebo was not significant (49.6 ± SD 7.8 / vs 50 ± SD 9.34; : t = 0.27, p = 0.791, respectively). Similarly, green filters had no significant improvement on the mean error scores of ColorDx (51 ± SD 8.8 / vs 50 ± SD 9.34; ; t = 0.25 , p = 0.805, respectively), Table 3. Cohen's effect size value for Enchroma and Green filters versus placebo (d = 0.04, d = 0.11 SD, respectively) suggested a lower practical (or clinical) significance. In addition, the mean error score with Enchroma filter did not differ significantly from the green filter (49.6 ± SD 7.8 / vs 51 ± SD 8.8; ; t = - 0.41, p = 0.668, respectively)

The red filter significantly improved color discrimination, particularly the deutan subjects. Improved subjects improved from severe deutan to mild deutan in all deutan subjects and from severe protan to mild deutan in one subject when tested with ColorDx (34.9 ± SD 2.5/ vs 50 ± SD 9.34; ; t = 3.58, p = 0.006, respectively), (*Fig. 10)*. In addition, Cohen's effect size value for the red filter relative to plano (d = 1.7) was a highly clinically significant. In addition, performance with red filter was significantly better compared to Enchroma a (34.9 ± SD 2.5 / vs 49.6 ± SD 7.8; t = 3.81, p = 0.004, respectively) and green filter (34.9 ± SD 2.5/ vs 51 ± SD 8.8; ; t = 3.93, p = 0.003, respectively) ,Table 3.

The raw data of subjects' performance on Farnsworth-Munsell 100-Hue is shown in Table 2. Pairwise comparison of performance on Farnsworth-Munsell 100-Hue revealed that there was a reduction in mean error score with Enchroma compared to placebo (127.9 ± 52.9 SD / vs. 132.2 ± 108.9 SD, respectively), which was not statistically significant (t = 0.17p = 0.866). On the other hand, Subjects significantly performed worse with red filter (mean = 245 ± 104.8, t = 0.4.29, p = 0.002). Also, performance on red filter was significantly worse compared to Enchroma (mean = 127.9 ± 52.9 SD, t = 4.45, p = 0.002) and green filter (mean = 142.1 ± 71.5 SD, t = 4.5 , p = 0.001).

We further tested the performance of the filters on both of deutan and protan groups individually. Neither the Enchroma nor the green filter significantly reduced the error score in deutan subjects (51.38 ± SD 7.8, $p = 0.5$ / vs 51.38 ± SD 9.7, $p = 0.8$, respectively). Figures 13 and 14 show the mean error score for the deutan and the protan subjects when wearing the filters on Farnsworth-Munsell 100-Hue and ColorDx, respectively.

All subjects showed an increase in matching midpoint and decreased matching range values with Enchroma filter compared to when they were wearing the placebo lens (*Fig. 15*). Red and green filters did not have a clear impact on the match mid-point or the range. See Figure 16 and Figure 17, respectively.

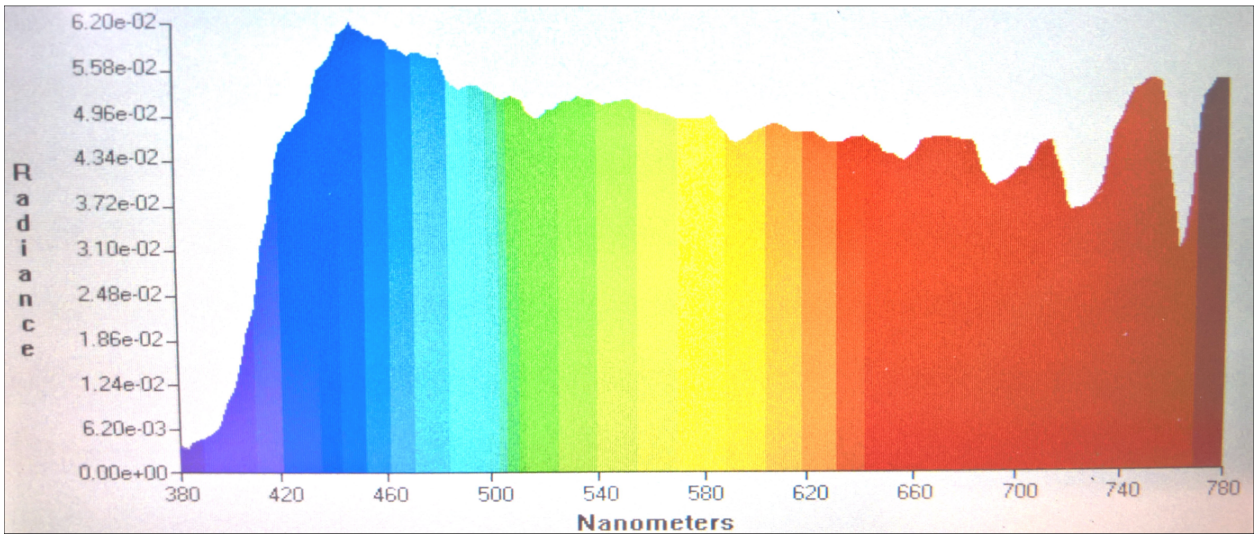

Figure 11. Spectral transmission of the placebo (clear lens).

Subject	Gender	Screening (5)	Protan (32)	Protan Diagnosis	Deutan (32)	Deutan Diagnosis	Tritan (12)	Tritan Diagnosis	General Diagnosis
1	M	0	1	Severe	12	Moderate	11	Pass	Severe Protan
2	M	0	0	Severe	0	Severe	11	Pass	Severe Protan/Deutan
3	M	0	9	Moderate	0	Severe	10	Pass	Severe Deutan
4	M	0	6	Moderate	0	Severe	11	Pass	Severe Deutan
5	F	0	5	Moderate	2	Severe	10	Pass	Severe Deutan
6	M	0	0	Severe	18	Mild	12	Pass	Severe Protan
7	M	0	16	Mild	8	Moderate	12	Pass	Moderate Deutan
8	M	0	9	Moderate	0	Severe	12	Pass	Severe Deutan
9	M	0	1	Severe	17	Mild	12	Pass	Severe Deutan
10	M	0	17	Mild	1	Severe	11	Pass	Severe Deutan

Table 1. Raw data for the subjects screening and diagnosis using ColorDx color vision test. The numbers indicate the correct plates and the severity of CVS. In parenthesis are the total number of plate.

Subjects	Enchroma	Red Filter	Green Filter	Placebo
1	169	334	125	155
2	83	221	75	66
3	172	144	137	103
4	213	388	244	422
5	124	216	165	79
6	106	133	90	55
7	30	115	41	42
8	123	192	162	131
9	96	314	113	129
10	163	393	269	140

Table 2. Raw data of the subjects' error scores for F-M 100-Hue test. The pass criterion is equal or less than 83 error score.

id	Age	EnChroma Filter	Diagnosis EnChroma	Red Filter	Diagnosis Red Filter	Green Filter	Diagnosis Green Filter	Placebo	Diagnosis Placebo
1	21	43	Moderate Protan	39	Moderate Deutan	46	Severe Protan	49	Severe Protan
2	51	45	Severe Protan	49	Moderate Deutan	47	Severe Protan	44	Moderate Deutan
3	22	42	Severe Protan	34	Mild Deutan	53	Severe Protan	48	Severe Protan
4	20	57	Severe Deutan	28	Mild Deutan	62	Severe Deutan	59	Severe Deutan
5	19	54	Severe Deutan	42	Mild Deutan	56	Severe Deutan	55	Severe Deutan
6	19	61	Severe Deutan	33	Moderate Deutan	33	Severe Deutan	65	Severe Deutan
7	19	58	Severe Deutan	35	Mild Deutan	62	Severe Deutan	57	Severe Deutan
8	22	44	Moderate Deutan	21	Mild Deutan	50	Severe Deutan	45	Severe Deutan
9	29	39	Moderate Deutan	39	Moderate Deutan	45	Moderate Deutan	32	Moderate Deutan
10	30	53	Severe Deutan	29	Mild Deutan	56	Severe Deutan	46	Severe Deutan

Table 3. Raw data for the participants' performance on ColorDx with each filter type. The numbers in the filter column represent the number of error plates for the plates that test for the red-green color vision. The total number of plates were 64 plates, 32 plates for protan and 32 platesfor the deutan.

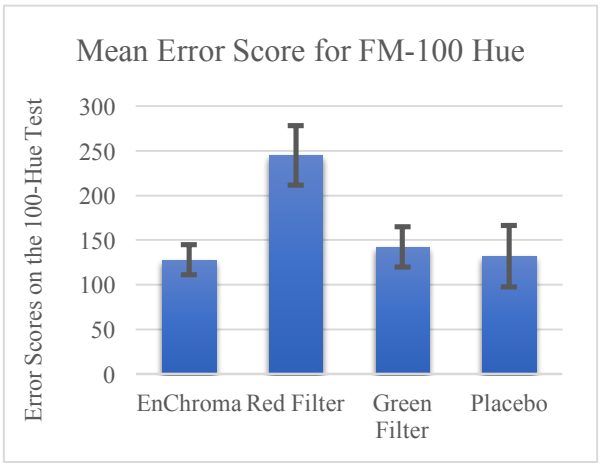

Figure 12. Mean error score for FM-100 Hue. Error bars represent SE of the mean.

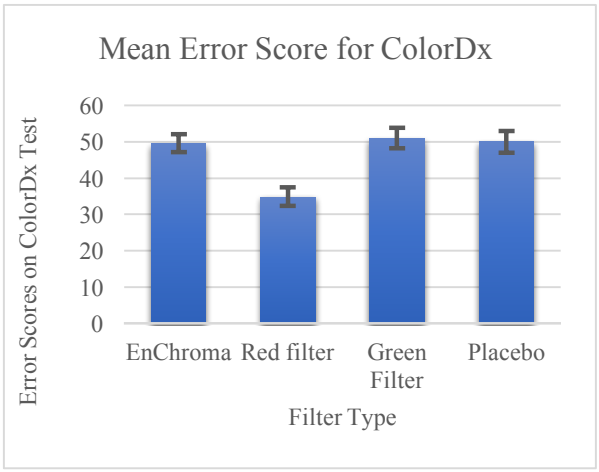

Figure 13. Mean error score for ColorDx. Error bars represent SE of the mean

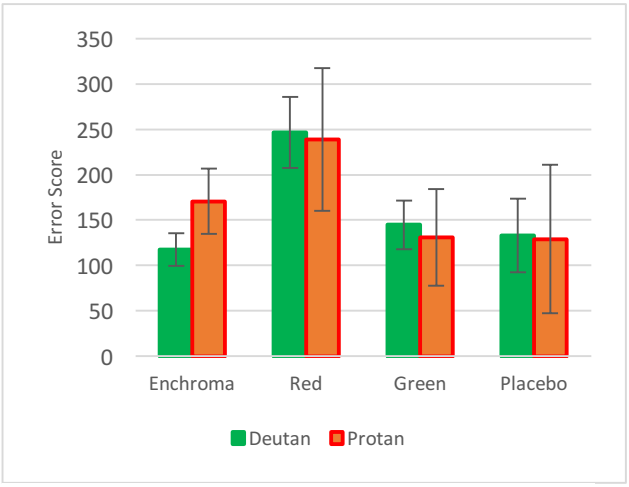

Figure 14. Average Error Score for deutans and protans obrained with the four types of filters using FM 100-Hue. Error bars represent SE of the mean.

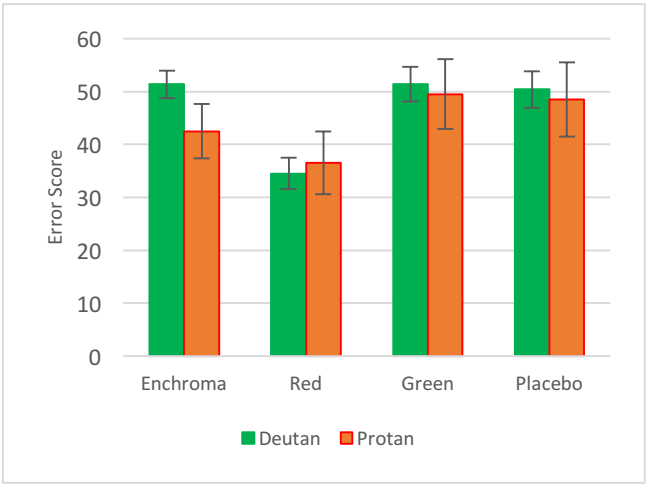

Figure 15. Average Error Score for deutans and protans obrained with the four types of filters using ColorDx. Error bars represent SE of the mean.

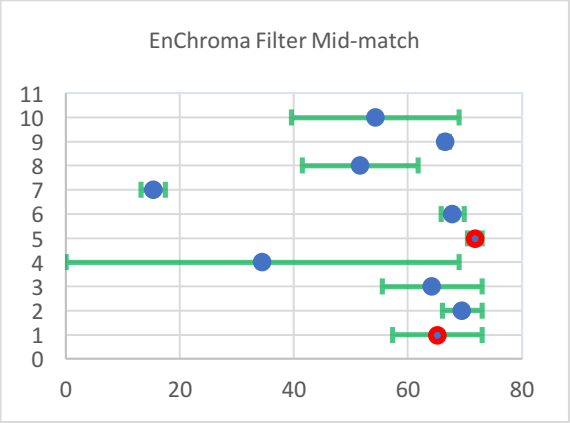

Figure 16. Anomaloscope Mid-point and match range with Enchroma.

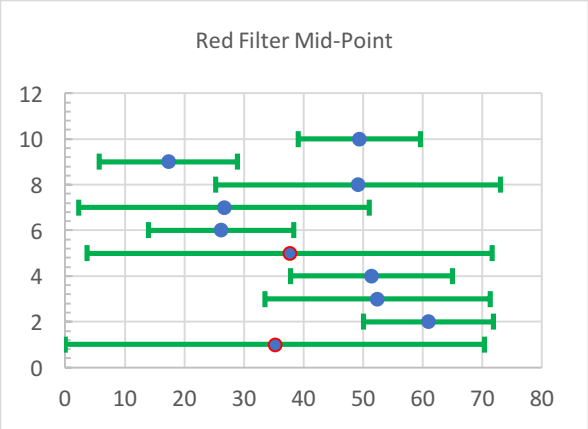

Figure 17. Anomaloscope Mid-point and match range with Red filter.

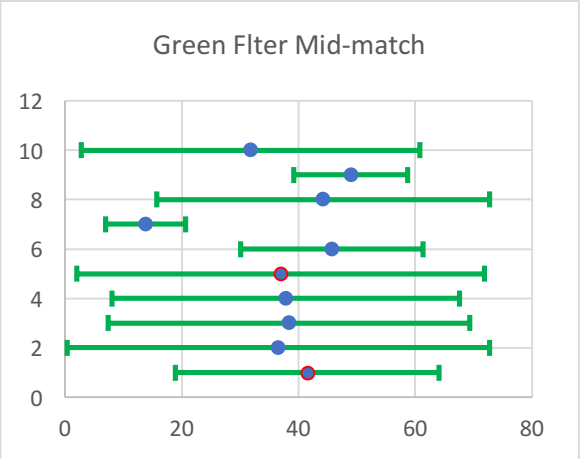

Figure 18. Anomaloscope Mid-point and match range with Green filter.

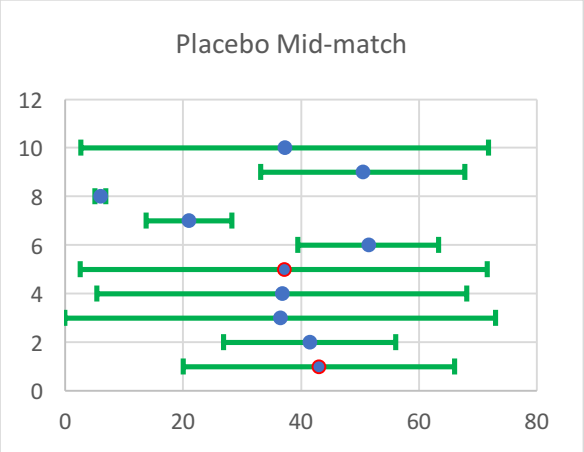

Figure19. Anomaloscope Mid-point and match range with Placebo lens.

DISCUSSION

This study has investigated the performance of the Enchroma, red, green filters in terms of error scores on standard color vision tests that was compared against the transparent placebo lens. Enchroma filters are the most recent advertised filters that claim enhancing color vision in abnormal and normal color vision individuals alike. Our results provide important clinical guidance for Enchroma lens use. The results demonstrated that Enchroma had no significant improvement on our participants' ColorDx test score, even though there were two subjects experienced an improvement CVD: from severe protan to moderate protan and from severe deutan to moderate deutan. Similarly, there was no improvement in color discrimination when tested using Farnsworth-Munsell 100-Hue test. Unfortunately, there are no published studies that test Enchroma's filters claim. However, there were published scientific posters presented at different scientific meetings. In 2016, Loshin and Bi tested Enchroma Cx-65 using Rabin cone contrast test on three subjects who were; a medium deutan, with acquired CVD, and a normal subject. The threshold of the contrast increased from 5% to 35% in the deutan subject, 5% to 30% of the green letters for the subject with acquired CVD and 70% to 90% for the normal subject. The definite limitation of thier study was the small sample size.

In 2015 Mastey et al., investigated the efficacy of Enchroma using Color Assessment and Diagnosis (CAD) test on ten deuteranopic, eight deuteranomalous, and nine protanopic. They found that Enchroma glasses had no significant effect on red-green thresholds for either protans ($p = 0.97$) or deutans ($p = 0.68$). Furthermore, They found that Enchroma resulted in poor blue-yellow discrimination for deutans ($p < 0.001$) which was consistent with our first study [46]. It is possible that Enchroma (as any other filters) can sharpen some colors, but clearly not to the degree of discriminating different wavelengths independently of their brightness intensity.

Red lenses surpassed Enchroma and green filters in terms of error rate reduction on ColorDx color vision test. Our red lens was designed from scratch for binocular viewing condition and the transmittance resembled long wavelength passband as shown in Figure. 17. Although none of our subjects passed the ColorDx test due to wearing the red filter, they made significantly fewer errors compared to when they were wearing placebo lens. These results should not be surprising for those who are acquainted with the literature of studies that have investigated the efficacy of X-Chrom lens. Recall this, red monocular contact lens that was introduced by Zeltzer in 1971 as a filter that can be used to correct color vision deficiency. [47] Zeltzer also reported that it significantly enhanced color perception for those with a color deficiency. [48] Even though subjects improved significantly with ColorDx, this does not indicate that they saw colors, or were able to discriminate different hues. Principally, The ColorDx plates and other pseudoisochromatic color vision tests were developed on the basis that when all the dots in the plate have equal brightness, the normal observer will be able to see the figures if the background and the figure in the foreground will have different colors. However, people with abnormal color vision would not be able to discern the differences of the two colors.

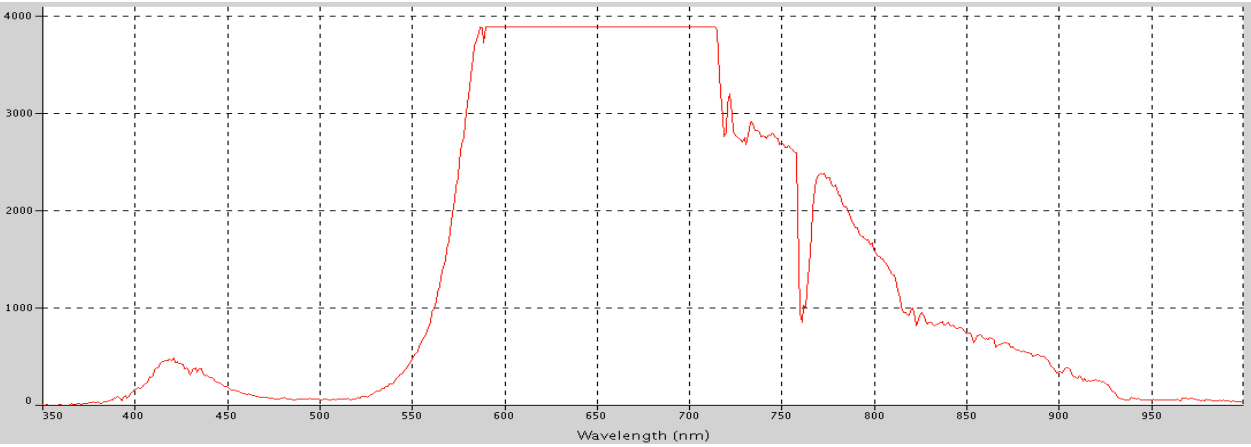

Figure 20. Spectral transmission of the red lens shows a cut-off transmission at 550 nm.

On this basis, a red filter introduces a luminance cue difference between the figure and the background that in turn make the figure in the foreground, or "symbols", distinguishable based on brightness (contrast) alone. [22] This phenomenon also persists when the light color temperature is altered. When the color temperature that is lower than illuminant C (e.g. standard color vision testing color temperature) is used, subjects are likely to make fewer errors on pseudoisochromatic plate tests. The opposite is also true and errors are expected to increase when the color temperature is above the standard illuminance C. [49,50]

Although, our lenses system is based on binocular viewing unlike X-Chrom, the results we obtained were consistent with Hovis's study that assessed the long wavelength pass filters using Ishihara, Farnsworth-Munsell 100-Hue, D-15 and SPP1 color vision tests. With the Ishihara error rate of eight errors, all the subjects passed the test when wearing the long wavelength pass filter and the number of errors made were significantly reduced. [35] On the other hand, our subjects' Farnsworth-Munsell 100-Hue test results worsened with red lens compared to placebo. Because we used an online Farnsworth-Munsell 100-Hue test, we were not being able to get the confusion lines that our subjects made to precisely determine what color axes were confused. However, in 1997 Hovis reported that when his color deficient subjects were wearing the long wavelength pass filter, the increase of Farnsworth-Munsell 100-Hue error score were due to an increase in blue-yellow errors and also a slight increase in the red-green errors. All of our subjects reported a difficulty of discriminating the Farnsworth-Munsell 100-Hue caps colors, and they were able to see only few of them. These observations were also consisted with a previous study, which showed that long wavelength pass or "blue blocking" filters induce a blue-yellow defect in addition to the red-green defect that the red-green color deficient subjects had. [51]

Green filters are known to worsen colors discrimination in normal observers. However, Green filters had no significant change in the mean error score, either when testing using ColorDx or FM 100-Hue. In 1976, Harris et al. examined the effect of multiple PMMA tinted contact lenses, including a green-tinted lens, on color vision. Individuals with normal color vision (Six women and two men) were asked to wear a total of 13 different tinted lenses monocularly, including the green-tinted lens, and their color vision were examined immediately after wearing the lens using Farnsworth-Munsell 100-hue test. There was no significant reduction found in error scores using green-tinted lens. In fact there was a significant increase in error score for the third quadrant of the Farnsworth-Munsell 100-Hue test that is designed to test the blue-yellow confusion axis. [52]

Little data exists about the effect of green tinted lenses on color normals and abnormals. However, generally, tinted lenses that resemble short wavelength cut-off filters usually increase the errors made on Farnsworth-Munsell 100-Hue test, as Grimm et al., reported in their investigation of the effect of color tinted contact lenses on color vision. [53]

Our study's limitation is the small sample size. Most of the investigated subjects in our study were in the severe category of color vision deficiency. Furthermore, most of our subjects had deutan color vision deficiency. Therefore, a much larger sample size is needed to accurately determine the effect of Enchroma filter for the correction of different severities of color vision deficiency.

CONCLUSION

Enchroma Cx-14 filters are multi-notch filters that modify the wavelength transmission of the observer. To our knowledge this is the first study to measure the effectiveness of Enchroma on the digital version of Ishihara (ColorDx. an iPad app). Our results showed that the Enchroma filters had no significant effect on any of the CVD subjects, but improved the CVD diagnosis in only two subjects which was not significant. However, red filter did improve performance on ColorDx

which uses red-green and blue-yellow for the figure and background colors. We believe that the improved performance due to red filter wear was primarily due to luminance artifacts produced by these filters. In addition, performance with red filter worsened the results on the Farnsworth-Munsell 100-Hue. Color vision by definition is the ability to distinguish surfaces of different colors on the basis of the spectral distribution received by the eye independently of light intensity. [32,54] Therefore, Enchroma Cx-14 could enhance certain colors, but using Enchroma Cx-14 for treatment of color deficiency is not supported by our results.

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APPENDIX A
Color Vision Testing Subject Recording Form

Assessment of Enchroma filters for the correction of Color Vision Deficiency

Data Collection Form

Participant Name/Number: _____ Date: ___/____/_____

VA: OD: _____ OS: _____

Initial Screening Diagnosis:

- □ Protanopia
- □ Dueteranopia
- □ Tritanopia
- □ Protanomaly
- □ Deuteranomaly
- □ Tritanomaly

Tests Results:

Glasses / Test	Enchroma	Red	Green	Placebo
Anomaloscope				
ColorDX				
100-Hue				

Diagnosis with the glasses:

Glasses / Test	Enchroma	Red	Green	Placebo
Anomaloscope				
ColorDX				
100-Hue				

CURRICULUM VITAE

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EDUCATION

Pacific University, College of Optometry
Master of Science in Vision Science — **Expected in August 2017**

Qassim University, Department of Optometry
Doctor of Optometry (O.D.) degree — **2006 – 2012**
Thesis: Relationship of Ocular Biometry measured by Pentacam and A-SCAN Ultrasound, with Intraocular Pressure measured by Goldmann Applanation Tonometry

Qassim University, College of Medicine
Pre-Med Year — **2006 - 2012**

AWARDS

Postgraduate Scholarship, Qassim University — **May 2015 – August 2021**

TEACHING EXPERIENCE

Qassim University, Optometry Department
Teaching Assistant — **Holds Position to Date**
Collaborate on Curriculum and exam development, instructed students in optometry clinics, met with students and grades written work for midterms and final exams

RELATED EXPERIENCE

Qassim University, Department of Optometry's Eye Clinics
Director — **2013 – 2014**

King Faisal Specialist Hospital and Research Center
Optometric Intern — **March – August 2013**
Worked in pediatric optometry clinic, managed and treated variety of eye complications and prescribed spectacles and contact lenses

King Saud Medical Complex
Optometric Intern — **January – April 2013**
Worked full time in optometry and ophthalmology clinics

King Khalid Eye Specialist Hospital
Optometric Intern — **July – December 2012**
Worked full time in the Optometry and Ophthalmology clinics

PUBLICATIONS AND PAPERS

"Objective and Subjective Wavelength Transmission Assessment of EnChroma Glasses" — ***2017***
Poster Presented at The Annual Meeting of the Association for Research in Vision and Ophthalmology (ARVO), *Baltimore, Maryland*

"Assessing the Risk factors of Keratoconus in Saudi Arabian population" — ***2017***
Second Author in Poster to be Presented at The Annual Meeting of the Association for Research in Vision and Ophthalmology (ARVO), *Baltimore, Maryland*

"Effect of High Temperature on Tear Film Stability in Bakers" 2016
Second Author in Poster Presented at the Annual American Academy of Optometry, *Anaheim,CA*

CONFERENCES AND WORKSHOPS

The Annual Meeting of the Association for Research in Vision and Ophthalmology (ARVO), *Baltimore, Maryland* The Annual American Academy of Optometry (AAO), *Anaheim, CA* **2016**

The Annual American Academy of Optometry (AAO), *New Orleans, Louisiana* **2015**

The Annual meeting of Vision Science Society (VSS), St. Pete Beach, Florida **2015**

The Annual Saudi Association of Optometry (SAO), *Riyadh, Saudi Arabia* **2013**

LANGUAGES

Arabic – Native Language
English – Second Language

MEMBERSHIPS

American Academy of Optometry (AAO)
Saudi Association of Optometry (SAO)