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Color Discrimination and Chromaticity Shifts Associated with O2AMPTM Lenses

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Doctoral Candidate(s)

5/1/15

Date

COLOR DISCRIMINATION AND CHROMATICITY SHIFTS ASSOCIATED WITH O2AMP ™ LENSES

by

Joshua Byers & Jacob Clark

This paper is submitted in partial fulfillment of the
requirements for the degree of

Doctor of Optometry

Ferris State University
Michigan College of Optometry

May, 2016

COLOR DISCRIMINATION AND CHROMATICITY SHIFTS
ASSOCIATED WITH O2AMP ™ LENSES

by

Joshua Byers & Jacob Clark

Has been approved

_____ May, 2016

APPROVED: [redacted]

Faculty Advisor:

ACCEPTED: [redacted]

Faculty Course Supervisor

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ABSTRACT

Background: The Oxy-Iso lenses (produced by the O2AMP^{TM} company) are currently marketed as a "treatment" for red-green color deficiency. It is postulated to enhance the transmission of those visible wavelengths that are poorly discriminated by individuals with Deutan and Protan color defects. Intuitively, such a design principle predicts the emergence of a blue-yellow color defect with perhaps a shift of the chromaticity co-ordinates of confusable colors away from the Deutan and Protan confusion axes. This study measured the shift in the chromaticity co-ordinates of color caps comprising the D-15 and FM-100 hue arrangement tests caused by the Oxy-Iso lenses. **Methods:** The chromaticity co-ordinates of the hue caps comprising the D-15 and FM-100 arrangement tests were measured with and without Oxy-Iso lenses using the Minolta CS-100A chromometer. All tests were conducted under standard lighting approximating the Illuminant C light source. Chromaticity coordinates for each cap were plotted on the CIE-xy chromaticity diagram. Ellipses were fit to the resulting hue contours to extract geometric indices that characterized the shifts of the hue contours of the D-15 and FM-100 with and without the lenses. **Results:** The chromaticity co-ordinates for the D-15 and FM-100 that were plotted on the CIE-chromaticity diagram showed a shift toward the Deutan co-punctal point when comparing measurements first without and then with the Oxy-Iso lenses. In addition, greater discrimination along the Deutan axis was observed. **Conclusions:** The results of the testing suggest that Deutan defectives would derive the most benefit from the Oxy-Iso filter. Testing in this study with a color anomalous individual agreed with the obtained results. Additional testing with color anomalous individuals should be conducted to further confirm these effects in a real-world setting.

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CHAPTER 1

INTRODUCTION

Since the proposition of the Trichromatic Color Theory, pioneered by Thomas Young and Hermann Helmholtz in the 18th century,[1] much research has been done uncovering the various causes and mechanisms behind color deficiencies, yet there is still no "cure." Instead, research has resulted in a variety of lenses designed to increase color discrimination. Recently, several color vision aid spectacle and contact lenses have been seen on the market, including ChromaGen, X-Chrom and Oxy-Iso. Naturally, these lenses are marketed to color deficient people; especially those working in positions requiring color discrimination, such as police officers, electricians, graphic designers, firefighters, and pilots among others. Several studies of similar color-vision enhancement lenses suggest that these lenses induce or enhance luminance differences between confusable hues,[2] selectively enhance transmission of wavelengths within a spectral region of poor wavelength discrimination in color anomalous individuals, or enhance hue contrast. [3]

The Oxy-Iso lenses were originally developed for medical personnel. The lenses allowed for better visualization of the effects of blood vessels dilating beneath the skin. This was accomplished as the lenses create a greater contrast between the skin and the red vessels. Later it was realized that it also has significant benefits for enhancing color discrimination in color anomalous individuals.[4] It has since been marketed as a corrective option for color anomalies. Despite its commercial success, the underlying process by which it imparts this benefit has not been elucidated at this point. This knowledge is extremely relevant to eye-care professionals because they are often the first to diagnose color anomalies, and are also involved closely in determining optimal management options, especially when patients request such assistance.

Therefore, the current study attempted to elucidate the principle of hue discrimination associated with the Oxy-Iso lenses by measuring and analyzing shifts in chromaticity coordinates of the D-15 and FM-100 arrangement tests within the CIE 1931 chromaticity diagram induced by the Oxy-Iso lenses.

A chromaticity diagram is a versatile method of representing color. Any color visible to the human eye can be described by 3 metrics: The relative amount of the 3 primaries (X, Y, and Z) in a mixture required to match any one color are expressed as chromaticity coordinates (x, y, z). Furthermore, within the color space bound by the regions of the CIE plot, there exist confusion lines along which hues appear identical or indistinguishable to dichromats. Each type of dichromat (Protan, Deutan, Tritan) has different confusion lines. Furthermore, the test hues comprising various color vision tests (such as the Pseudoisochromatic plates and arrangement tests) can be represented within the CIE color space, and all 3 confusion lines traverse their hue ellipses. Consequently, the loci of their constituent test hues can be evaluated relative to each of the dichromatic confusion lines.

The D-15 and FM-100 hue arrangement tests comprise color caps whose chromaticity coordinates form an approximate ellipse relative to a standard reference lighting source (Illuminant C). All 3 color confusion axes (Protan, Deutan and Tritan) cross through the hue ellipse. Therefore, the utilization of these color tests represents an informative method by which to investigate the effects of any colored filter on the hue representation of colors within the color space. Therefore, the current study investigated the hue discrimination properties of the Oxy-Iso lenses by evaluating its effect on chromaticity co-ordinates of 2 commonly used arrangement tests (D-15, FM-100). This method allows various characteristics of the filter to be analyzed which includes its effect on the perception of colors within the normal color space, quantification of the shift it induces in the chromaticity coordinates of hues relative to dichromatic confusion lines, and its effects on the shape parameters of the hue ellipses of clinical color vision tests.

CHAPTER 2

METHODS

Chromaticity coordinates for each of the caps of the D-15 and FM-100 color arrangement tests were measured using the Minolta CS-100A chromometer. All testing was done under standard lighting approximating the Illuminant C light source using the DayLight^{TM} Illuminator. Testing was repeated with an Oxi-Iso lens placed over the chromometer. A +5.00 diopter lens was placed over the objective lens of the chromometer which allowed the extent of the color cap to fall within the measuring area of the chromometer at the closer measuring distance. Chromaticity coordinates of the FM-100 and D-15 were plotted on the CIE chromaticity diagram with and without the filter (shown in Figures 1 and 2), and a best-fit ellipse was fit to the coordinates using the least-squares minimization method utilizing Matlab^{TM}. The following parameters were derived from the best fit ellipse to the chromaticity coordinates:

i) Shift ratio: The ratio of the distance from the respective Dichromatic copunctal point to the geometric center of the best fit ellipse with and without the Oxy-Iso filter. The smaller the ratio, the greater the shift of the ellipse (with filter) toward the respective copunctal point

ii) Vertical Ratio: The ratio of the minor axis of the best fit ellipse with filter to the minor axis of the best fit ellipse without filter. The smaller the number the greater the "contraction" of the ellipse along its minor axis.

iii) Horizontal Ratio: The ratio of the major axis of the best fit ellipse with filter to the major axis of the best fit ellipse without filter. The smaller the number the greater the "contraction" of the ellipse along its major axis.

iv) Axis: The angular subtense between the major axis of the best-fit ellipse and the major confusion line. The smaller the angle, the more parallel are the two axes to each other.

v) Major confusion line: A line connecting the copunctal point of the respective dichromat to the chromaticity co-ordinate of Illuminant C (reference illumination source).

The factor decrease in luminance through the Oxy-Iso lens was also derived by taking the ratio of the Y value with filter and without filter (Figures 3 and 4).

CHAPTER 3

RESULTS

The ellipse parameters showing the shift in the coordinates for the best fit ellipse in comparison to the copunctal points can be seen in Table 1. Table 2 shows changes for additional indices of the best fitting ellipses. The effect that each parameter has on color vision discrimination is summarized below.

Horizontal and vertical ratio: For both the D-15 and FM-100, the vertical ratio of less than one shows a decrease in the relative differences in excitation purity between chromaticities along the vertical axis. The horizontal ratio of greater than one shows an increase in the relative differences in excitation purity between chromaticities along the horizontal axis. Relative to the major confusion axes, this shift appears to benefit the Deutan the most, but also the Protan and Tritan, to a lesser extent.

Shift ratio: The smaller the shift ratio, the closer the ellipse moves toward a given copunctal point. In the absence of any other change, the closer the shift toward a copunctal point, the greater the discrimination between adjacent color caps. This is because their chromaticity coordinates will fall on a different confusion axis. Based on these indices (see Table 1), the Tritan would appear to benefit more than the Protan or Deutan, which both had similar ratios.

Axis: The closer angular subtense between the major axis of the best-fit ellipse and the major confusion line, the lower the chromaticity discrimination is for the given deficiency. Conversely, the closer the angular subtense between the two is to ninety degrees, the better the chromaticity discrimination. To simplify the data, Table 2 shows the smallest equivalent axis (i.e. θ_{NF} Deutan axis of 77.61 degrees as shown in Table 2 is equal in the magnitude of difference from 180 degrees as the actual value of 102.39 degrees listed in figure 2), so that the closer the value is to 90 degrees, the more discriminable it will be. Results from the D-15 suggest that the Deutan will benefit from the tilt toward 90 degrees, while the Protan shifts away from 90 degrees. Even though the Tritan achieved the greatest shift toward 90 degrees, the ellipse remains very close to parallel to the Tritan axis. For the FM-100, the lens appears to tilt the ellipse away from the perpendicular axis for the Protan and Deutan, and towards 90 degrees to the Tritan axis. Once again, based on the tilt indices, the lens appears to be of least help to the Protan, and while shifting the ellipse the most toward 90 degrees relative to the Tritan axis, the ellipse remains very close to 90 degrees for the Deutan.

In summary, Deutan defectives will derive the most benefit from the Oxi-Iso lenses based on the horizontal ratio. While the Tritan appears to benefit from the shift ratio and axis tilt with the filter, the direction of the shift most towards the Deutan and the tilt remaining closest to 90 degrees favors the Deutan. The combined downward shift and the increase in horizontal ratio will jointly shift chromaticity coordinates away from all three confusion contours, thereby allowing for increased hue discrimination.

The decrease in the vertical ratio decreases the purity of the hues. This will decrease the discriminability between these hues; however, as mentioned earlier, the non-uniform changes in luminance may counteract this disadvantage to a certain extent.

The change in luminance with filter increases the luminance difference between adjacent hues, providing an additional cue for chromaticity discrimination. As seen in

Figure 3, the factor decrease in luminance is non-uniform. The D-15 without filter had an average luminance of 31.98 and variance of 1.47. With the Oxy-Iso filter, the average decreased to 8.44cd/m2 and the variance increased to 1.62 cd/m2. Thus, with the filter, there is a greater difference in luminance between neighboring hues, which may provide the patient with a stronger signal to differentiate adjacent hues.

The overall hues shift towards the non-spectral purple axis, suggesting that while the Oxy-Iso lenses may improve hue discrimination for Deutan and Protans, it does not improve hue naming or identification. Therefore the wearer may experience increased success at discriminating hues that appeared similar without the filter; however, these patients will not likely experience increased identification of hues beyond what was previously identifiable to them.

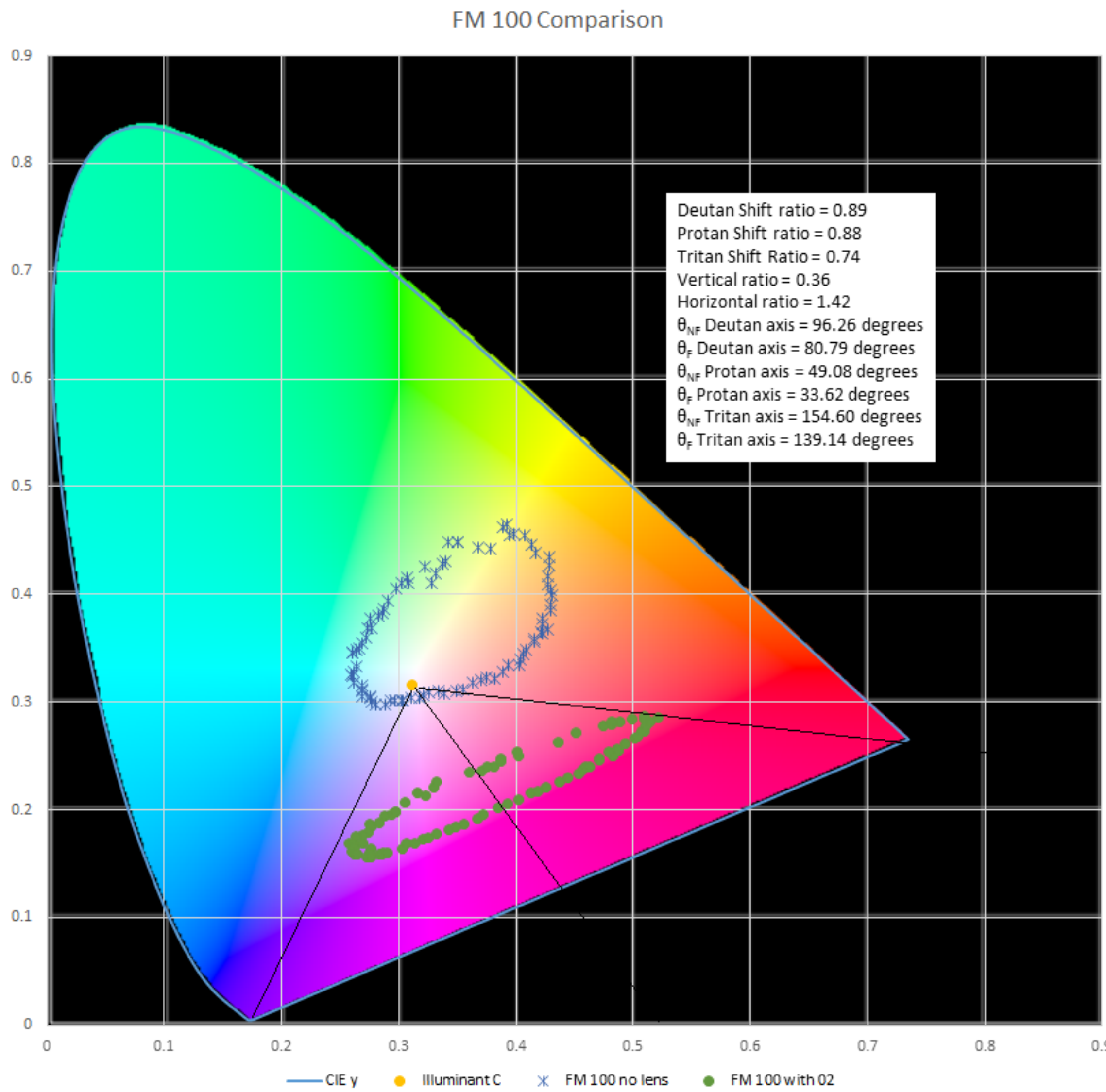

Figure 1. 1931 CIE-xy Chromaticity diagram with chromaticity coordinates for FM100 color cap set with (F) and without (NF) Oxy-Iso lenses. Solid lines represent the major confusion axes which connect the Deutan, Protan and Tritan copunctal points to the chromaticity coordinates of Illuminant C.

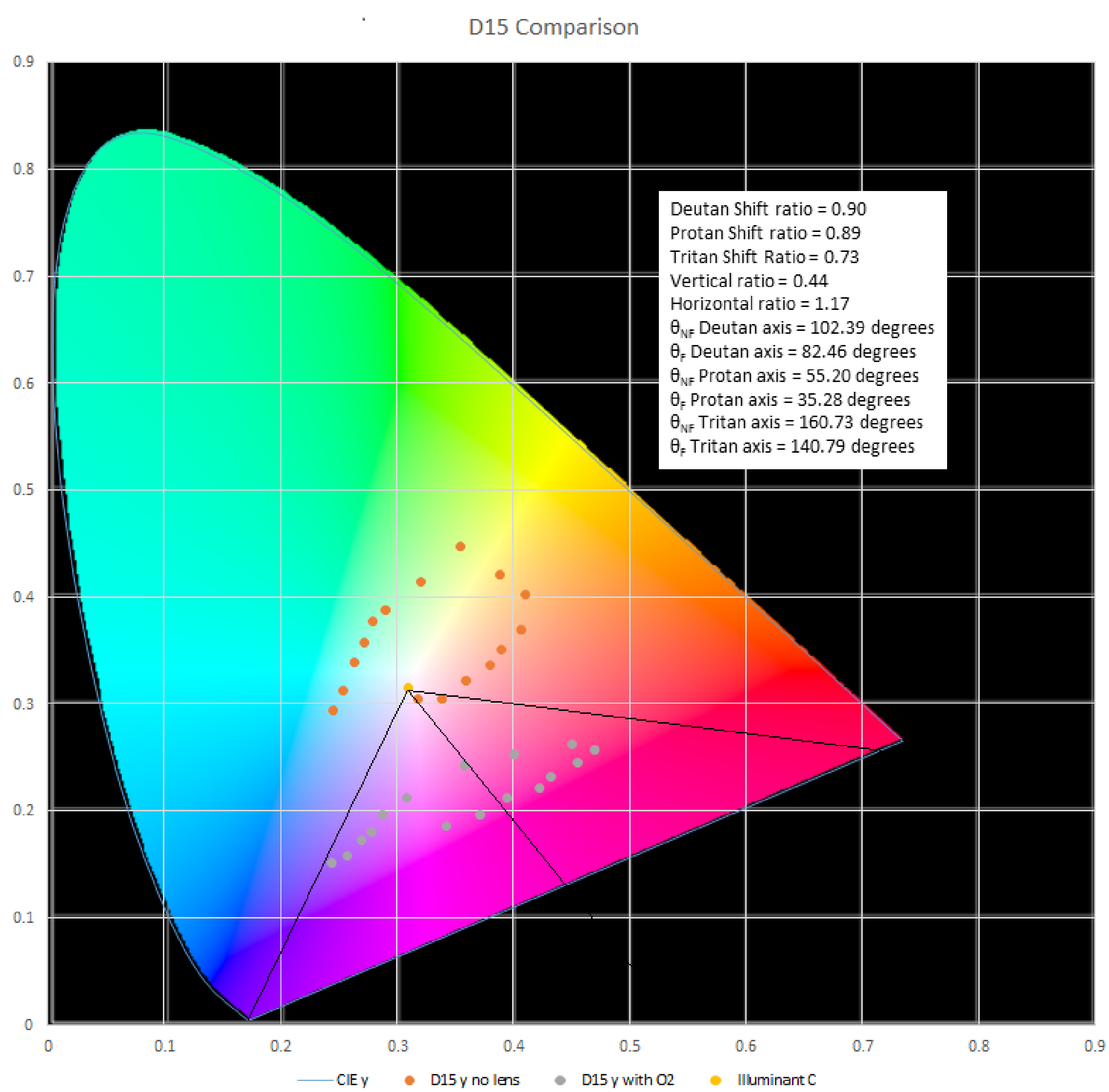

Figure 2. 1931 CIE-xy Chromaticity diagram with chromaticity coordinates for D15 color cap set with (F) and without (NF) Oxy-Iso lenses. Solid lines represent the major confusion axes which connect the Deutan, Protan and Tritan copunctal points to the chromaticity coordinates of Illuminant C.

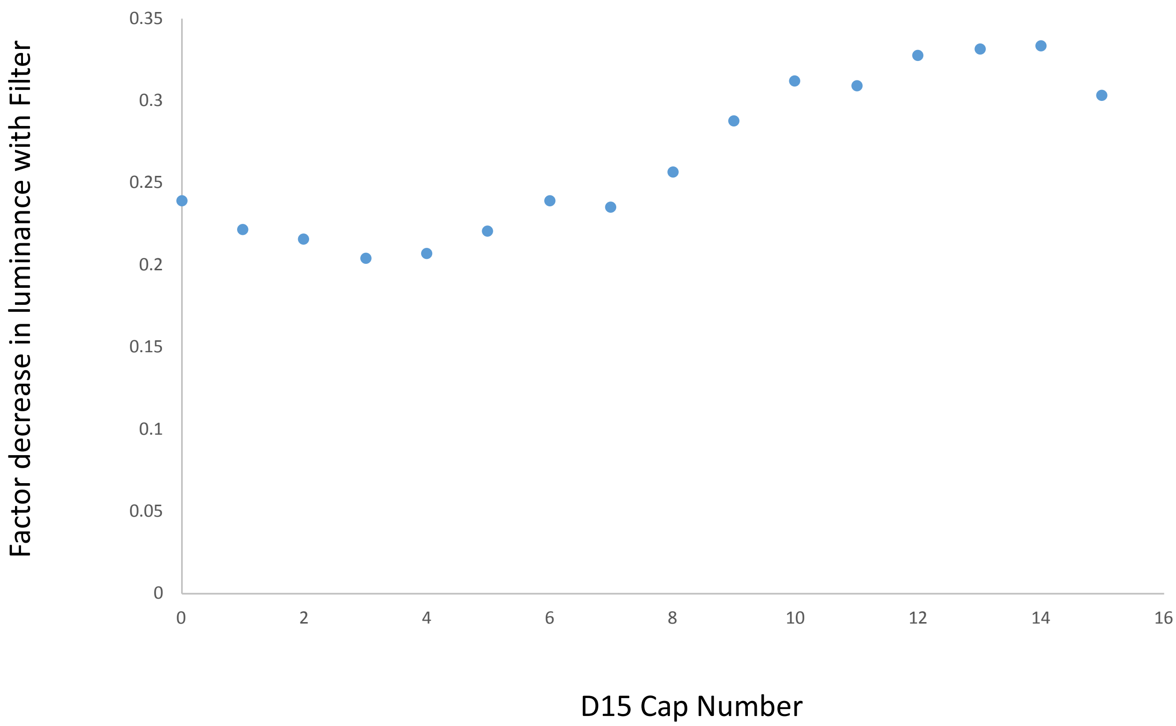

Figure 3. Factor decrease in luminance of D15 caps with filter in place plotted against the D-15 cap number. An abscissa value of 0 represents the reference cap.

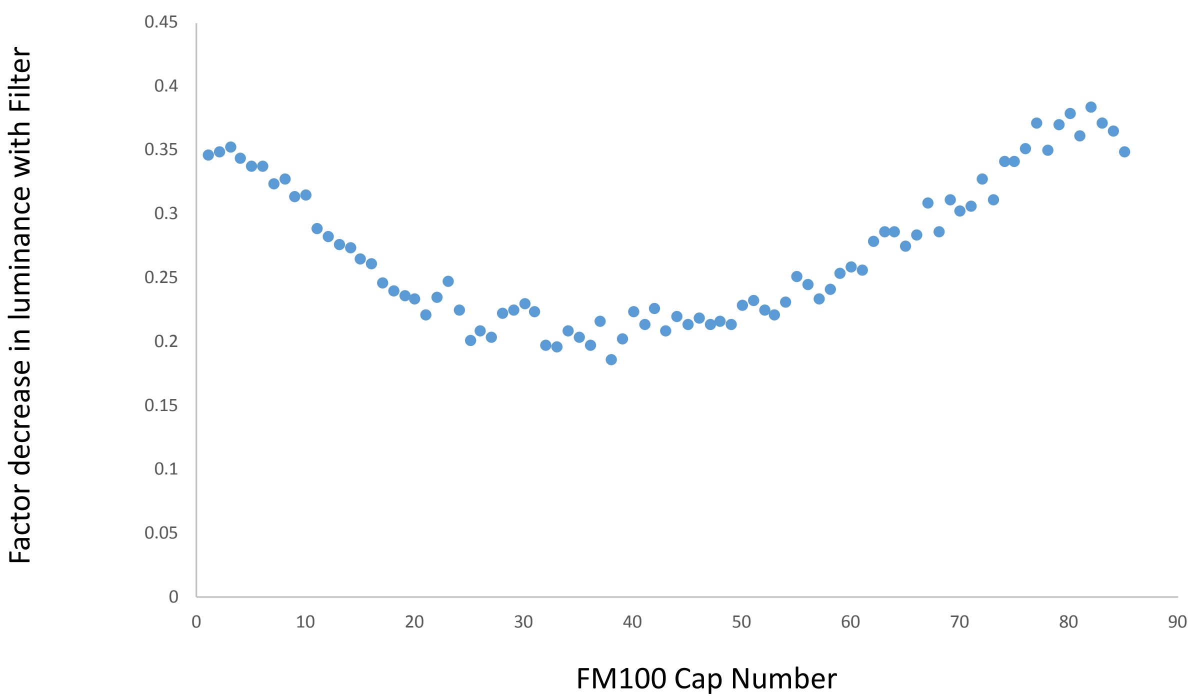

Figure 4. Factor decrease in luminance of FM100 caps with filter in place plotted against the FM-100 cap number. An abscissa value of 0 represents the 1st reference cap.

	X	Y
Deutan Copunctal Point	1.080	-0.800
Protan Copunctal Point	0.747	0.253
Tritan Copunctal Point	0.171	0.000
Illuminant C Point	0.310	0.316
D-15 Center (no lens)	0.334	0.365
D-15 Center (with lens)	0.366	0.219
FM-100 Center (no lens)	0.350	0.375
FM-100 Center (with lens)	0.381	0.222

Table 1. Coordinates for the center of the best-fit ellipse without and with the Oxy-Iso lens.

	D-15	FM-100
θ_{NF} Deutan axis (deg.) (+/- 0.45)	77.61	83.74
θ_{F} Deutan axis (deg.) (+/- 0.79)	82.46	80.79
θ_{NF} Protan axis (deg.) (+/- 0.44)	55.20	49.08
θ_{F} Protan axis (deg.) (+/- 0.79)	35.28	33.62
θ_{NF} Tritan axis (deg.) (+/- 0.44)	19.27	25.40
θ_{F} Tritan axis (deg.) (+/- 0.79)	39.21	40.86
Deutan Shift Ratio (+/- 0.001)	0.90	0.89
Protan Shift Ratio (+/- 0.014)	0.89	0.88
Tritan Shift Ratio (+/- 0.014)	0.73	0.74
Vertical Ratio (+/- 0.018)	0.44	0.36
Horizontal Ratio (+/- 0.04)	1.17	1.42

Table 2. Parameter changes to the D-15 (+/- 95%CI) and FM-100 best-fit ellipses. All indices represent significant changes with the filter ($p < 0.001$, paired t-test).

CHAPTER 4

DISCUSSION

The results from this study agree with previous studies performed on similar filters, showing primary benefits for Deutans. A 1984 study by Richer and Adams[2] developed an experiment with the X-Chrom lens, in which the subjects arranged a series of pairs of caps from the D-15 from greatest to least difference between pairs. The pairs were chosen in such a way that ordering based on chromaticity would be different than ordering based on luminance. Results from the study revealed that discrimination by dichromats predominantly differentiated based on chromaticity. In subtests of discriminating based on chromaticity and luminance, a one-tailed T-test showed that deuteranopes and protanopes used both chromaticity and luminance cues, with deuteranopes benefiting more than protanopes. A later study on a filter similar to the X-Chrom lens, tested the ability of four protanopes using the D-15 and HRR tests, and the ability to identify red, green, and yellow monochromatic light stimuli when luminance was randomized.[3] In this study, Diaconu et. al. discovered that a red filter improved the ability to detect lights in the long wavelength area, and proposed that the filter modifies the luminance mechanism for the protanope, in which adaptation of M cones aids in transforming chromatic contrast into luminance contrast. In this study, the four protanopes tested initially as severe Protan on the HRR, however all subjects shifted to moderate Deutan using the red filter.

Swarbrick et. al. tested the ChromaGen contact lens system, which consists of a range of colored filters, in which users subjectively pick the one that works best for them.[5] For the red-green anomalous subjects in this study, filters used ranged from orange, pink, magenta, to violet (categorized by peak transmission). The lenses also are available in multiple transmission strengths, but all subjects in that study chose the darkest option. In that study, testing was conducted using the Ishihara, D-15, and Farnsworth Lantern. Deutans gained greater benefit from the lenses, but interestingly, Protans rated subjective improvement in color appreciation higher than Deutans. Oriowo also found that Deutans achieved greater improvement than Protans using the ChromaGen system.[6] Swarbrick suggests that achromatic luminance cues are the primary aid, with results that showed improvement on the D-15 and Ishihara, but no improvement with Farnsworth Lantern testing.[5] The non-uniform luminance decrease found in our study shows that the Oxy-Iso lens may aid discrimination of easily-confused hues that happen to be adjacent to each other. Just as a light source other than the standard illuminant can aid in performance on pseudoisochromatic testing, the filter will aid in differentiating hues by adding luminance cues after transmission through the filter.

In another study of a red filter on red-green anomalous subjects, York and Loop developed a "Red-sensitivity test" which measured luminance threshold (cd/m^2) to a stationary 2 degree red light stimulus.[7] Results from this study showed that Protans had much lower sensitivity than Deutans, attributed to the shift of the long wavelength photopigment shift toward shorter wavelengths. An interesting result of this study was that the three worst performers on the red test achieved the top three scores (number correct) on HRR testing. The D-15 performance in this study did not correlate to red sensitivity.

The ideal color vision product would increase hue identification and discrimination with minimal impact on luminance. The Oxy-Iso lens does fall short of ideal. Designed for surgeons to wear in order to improve hue discrimination for visualization for blood vessels, it meets these needs through greater hue and luminance differences. It does so, however, at the cost of shifting the perceived hue of the target. Furthermore, the improvement in hue discrimination is achieved at the expense of luminance.

Despite its shortcomings, the Oxy-Iso lens does provide color discrimination benefits. For occupational and career needs emphasizing discrimination vs. identification, the use of this lens may meet the needs of a color-anomalous subject, such as its advertised use identifying veins for surgeons. In some situations, such as identifying colored wires for the electrician, signal lights for the police officer or pilot, subjective occupational testing should be done to assess its effectivity.

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APPENDIX A

IRB APPROVAL FORM

FERRIS STATE UNIVERSITY

Institutional Review Board for Human Subjects in Research

Office of Academic Research, 220 Ferris Drive, PHR 308 · Big Rapids, MI 49307

Date: August 12, 2015

To: Dr. Avesh Raghunandan, Joshua Byers and Jacob Clark
From: Dr. Joshua Lotoczky, Interim IRB Chair
Re: IRB Application #150705 *(Color Discrimination and Chromaticity Shifts Associated with O2AMPTM Lenses)*

The Ferris State University Institutional Review Board (IRB) has reviewed your application for using human subjects in the study, "*Color Discrimination and Chromaticity Shifts Associated with O2AMPTM Lenses*" (#150705) and determined that it meets Federal Regulations *Expedited-category 2D*. This approval has an expiration of one year from the date of this letter. **As such, you may collect data according to the procedures outlined in your application until August 12, 2016**. Should additional time be needed to conduct your approved study, a request for extension must be submitted to the IRB a month prior to its expiration.

Your protocol has been assigned project number (#150705), which you should refer to in future correspondence involving this same research procedure. Approval mandates that you follow all University policy and procedures, in addition to applicable governmental regulations. Approval applies only to the activities described in the protocol submission; should revisions need to be made, all materials must be approved by the IRB prior to initiation. In addition, the IRB must be made aware of any serious and unexpected and/or unanticipated adverse events as well as complaints and non- compliance issues.

Understand that informed consent is a process beginning with a description of the study and participant rights with assurance of participant understanding, followed by a signed consent form. Informed consent must continue throughout the study via a dialogue between the researcher and research participant. Federal regulations require each participant receive a copy of the signed consent document and investigators maintain consent records for a minimum of three years.

As mandated by Title 45 Code of Federal Regulations, Part 46 (45 CFR 46) the IRB requires submission of annual reviews during the life of the research project and a Final Report Form upon study completion. Thank you for your compliance with these guidelines and best wishes for a successful research endeavor. Please let us know if the IRB can be of any future assistance.

Regards,

Ferris State University Institutional Review Board
Office of Academic Research, Academic Affairs

Version 1.2015

APPENDIX B

SUBJECTIVE TESTING

Color vision was assessed for a color anomalous individual using the D-15 standard and FM-100 color arrangement tests, and the HRR Pseudoisochromatic Plate test. Testing was performed under lighting approximating the Illuminant C light source, first without, then with O2AMP™ lenses.

The initial HRR Pseudoisochromatic plate trial without lenses revealed that the subject had a strong Deutan deficiency. Likewise, the FM-100 test confirmed that the patient trended toward a Deutan defect (shown in Figure 5). The HRR Pseudoisochromatic plate trial after the lenses were in place did not appear to show a decrease in Deutan defect, but rather gave a broader non-specific defect. When the patient wore the lenses while repeating the FM-100 test, the defect shifted away from a Deutan defect and toward a Tritan defect (shown in Figure 5).

The total error score (TES) across the 4 boxes of the FM-100 for this individual was 136 without the filter, The TES increased to 448 with the use of the filter. This was consistent with a study by Hovis,[8] who found that a long-pass filter caused severe Deutan and Protan subjects to average a TES greater than 400. A TES greater than 400 indicates that the caps are randomly arranged. Hovis suggests that the filter superimposes a blue-yellow defect over the initial red-green defect, thus reducing overall color discrimination. He states that the improved contrast is primarily due to luminance differences increasing contrast in the yellow and red spectrum. Further testing on color identification should be done to elucidate additional mechanisms and effectivity of the Oxy-Iso lenses.

Both eyes together (OU)

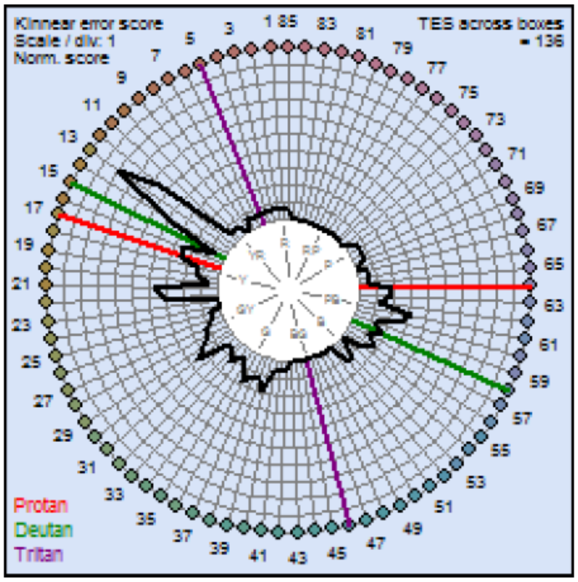

Figure 5. FM 100 Test results without O2AMP™ lenses in place

Both eyes together (OU)

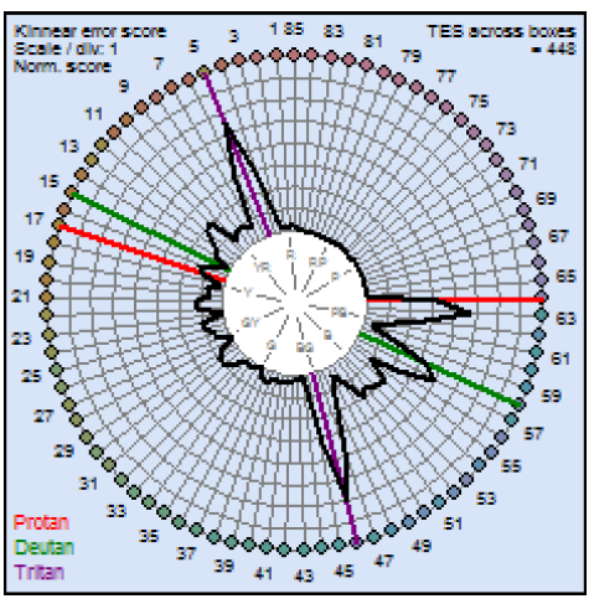

Figure 6. FM 100 Test results with O2AMP™ lenses in place