Temporary Tritanopia: Effects of cataract surgery on color

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Abstract

This pilot study made a wide variety of visual measurements before, during, and after bilateral cataract surgery. This article describes the changes in color discrimination and color appearance resulting from cataract implants. It used the F-M 100 Hue Test, color matching of real scenes, and color-balance titration measurements. The pre-surgery data indicated that the previously normal color observers had severe tritanopic anomalies. Lens replacement restored normal color vision.

Introduction

The vision literature on aging describes many changes in vision with age. Oyster[1] cites 21 different age related changes. Knoblauch et al. studied of the effects of age on Farnsworth-Munsell 100 Hue Tests. They showed a decrease in performance scores with age.[2] Wuerger has studied the effect of age on Unique Hues selections.[3] Ikeda [4, 5] and Warner [6] studied lens transmission and color matching changes. These studies look at a single visual property using as large a group of observers as possible.

This article's two-year study measures many different properties of each eye using two observers; before, during, and after bilateral cataract surgeries. These experiments measured two observers' performance: (female: age 80 (Obs80); and male: age 76(Obs76)). This pilot study emphasizes measurement of differences in appearances of real scenes observed with one PreOp and one PostOp eye. The entire study measured optical acuity, optical glare, dynamic range of appearances, performance in night driving simulations, and changes in appearance caused by cataract surgery. This article describes a subset of data includes three assessments of color appearances: color discrimination, color appearance, color-balance titration matching.

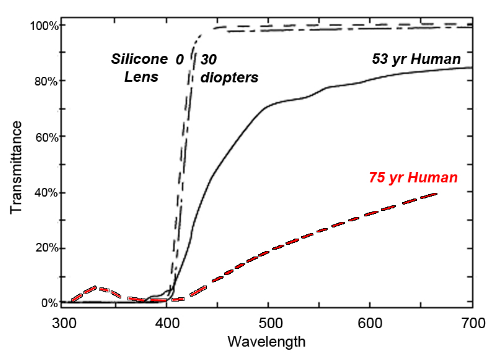

Figure 1 plots Boettner and Wolter's transmittance of human lenses at ages 53 and 74. Also, it plots the range of transmissions of Bausch and Lomb SoftPort® IOL (0 and 30 diopters) silicone lenses.

Cataract Spectral Transmission

The light reaching the eye decreases with age. Between 400 and 700 nm the light loss is greatest at 400 nm. Figure 1 plots the transmittances of Boettner and Wolter's enucleated lens measurements of 53 and 75 year old humans [7], and silicone lens implants. [8] For Boettner and Wolter's data, the implant doubles the projected transmittance at 700 nm. The implant increases transmittance by 10 times at 445 nm (maximum sensitivity of short-wave cone fundamentals). [9]

Color Measurements

Both observers had PreOP acuities that ranged from 20/30 to 20/20. Both observers reported concerns about night driving, and the loss of the ability to see stars at night. Obs76 reported multiple images of the new moon against a dark sky. Obs80 and Obs76 were observers in a night driving simulation experiment over a period of one year before surgery.[10] Obs80 had her first surgery on her left eye (Implant of B&L SoftPort IOL LI1AO). She had surgery on the right eye 77 days later. A second seventy-six year old observer (Obs76) had the surgery on his right eye first; 98 days later he had surgery on the right eye. All four surgeries occurred in a span of 98 days, and used the same IOL implant.

1. F-M 100 Hue Test

Knoblauch et al. [2] tested 75 normal volunteers (20-78 yr) using the Farnsworth-Munsell 100-Hue Test [11] at 5 illuminance levels. All observers had ophthalmological exams and color blindness screening. Any individual with fundus abnormalities or unclear optic media was excluded from the group, as well as anyone with a protan or deutan defect. Knoblauch's analysis showed a similarity between tritan-like defects in older groups and those of younger groups at lower illuminance levels. The number of errors increased with increasing age and with decreasing illuminance. In addition, the errors were not randomly distributed about the hue circle, but progressively became bipolar oriented along a tritan axis. The cataracts of Obs80 and Obs76 would have excluded them from the Knoblauch et al. study.

100 Hue Procedure

Prior to cataract surgery observers performed the original Farnsworth-Munsell (F-M) 100 Hue Test using actual Munsell papers mounted in black plastic caps. Farnsworth [11] reported that results vary with the spectra of the illumination. The measurements reported here used filtered incandescent light similar to Farnsworth's illumination. The caps with Munsell papers were viewed in a lightbox using three 100W tungsten lamps. Four walls of the lightbox had white walls (floor, and three sides). The 37 by 56 cm floor of the lightbox had ample room for the wooden cap display units. The bulbs were mounted on the top above large Lee Filters (#201 plus #202) that converted the 3800° tungsten to 6200° daylight (measured by a K-M CS100 colorimetric telephotometer). The floor of the lightbox measured a luminance of Y = 167 Cd/m²; x,y = (0.314, 0.335). Luminance converts to an illuminance of 525 lux. These chromaticity values fall on a blackbody color temperature of 6200° K.

100 Hue test results

Figure 2 plots the 100 Hue error distribution for one trial of Obs80's left PreOp eye using the F-M 100 Hue polar plot.

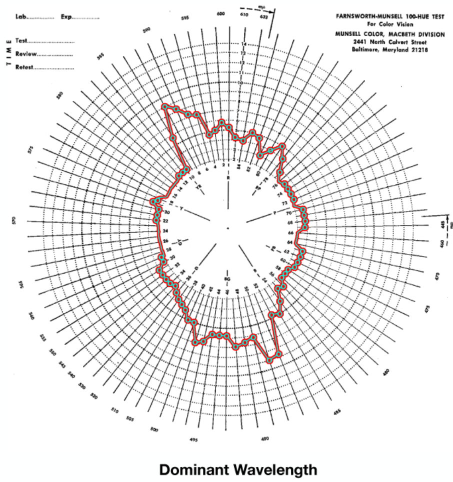

Figure 2 plots a single 100 Hue's polar graph of one Obs80's left eye PreOp trials. Errors scores are plotted on the radius; Cap numbers on the circumference.

Both observers performed the 100Hue Test four times on both PreOp and Post Op eyes. The average values are shown in Table 1. The most severe loss of color discrimination was measured by Obs80's left eye, with an average score of 146.5. Obs80's errors are concentrated in two color regions: caps (37 to 54) and (78 to 8). The maximum average PreOp error score was 7.9 for cap number 47 (Munsell designation 10 BG 5/4). On the opposite side Cap 7 has error score of 5.8 (Munsell designation 2.5 YR 6/6). These errors are very similar to the Farnsworth's plot from a known tritanopic observer. [11] Obs80 and Obs76 had no indications of tritan deficiency prior to the onset of cataracts.

Figure 3 plots Obs80's average data for PreOP and PostOp eyes. It replaces Farnsworth's polar plot with linear error coordinates. PreOP data uses gray diamonds. The average PostOp score (30 or more days following surgery) uses red crosses.

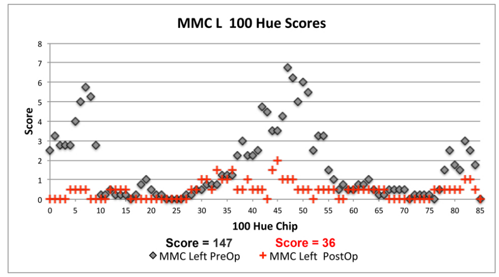

Figure 3 plots Obs80's left eye PreOp average data using linear coordinates for cap numbers (gray diamonds). The plots adds the average PostOP left eye data (+).

Cataract surgery has restored Obs80's F-M 100 Hue designation to normal color vision. Hence, this article title's reference to temporary tritanopia. The PreOp score of 147 changed to 36. Although the F-M 100 Hue data for cataract discoloration resembles that of genetic Tritanopic observers, the underlying mechanism must be different because of the near complete return to the normal vision recorded decades earlier.

Figure 4 plots the PreOP and Post Op results for both observers, both eyes. Table 1 lists both observers' PreOp and PostOp scores. The results show that the cataract discolorations had variable strengths in PreOp eyes, varying from 146.5 to 61.7. All eyes showed a consistent improvement of color discrimination. These improvements put all four eyes in the F-M 100 Hue categories of normal. Farnsworth described scores of <16 as having Superior color discrimination found in 16% of his observer population.

Cataract implants restored normal color discrimination for both observers.

Table 1 list the average scores from monocular tests

	Obs80 Left	Obs80 Right	Obs76 Left	Obs76 Right
PreOp	146.5	96.0	61.7	62.3
PostOp	35.5	38.7	16.0	11.2

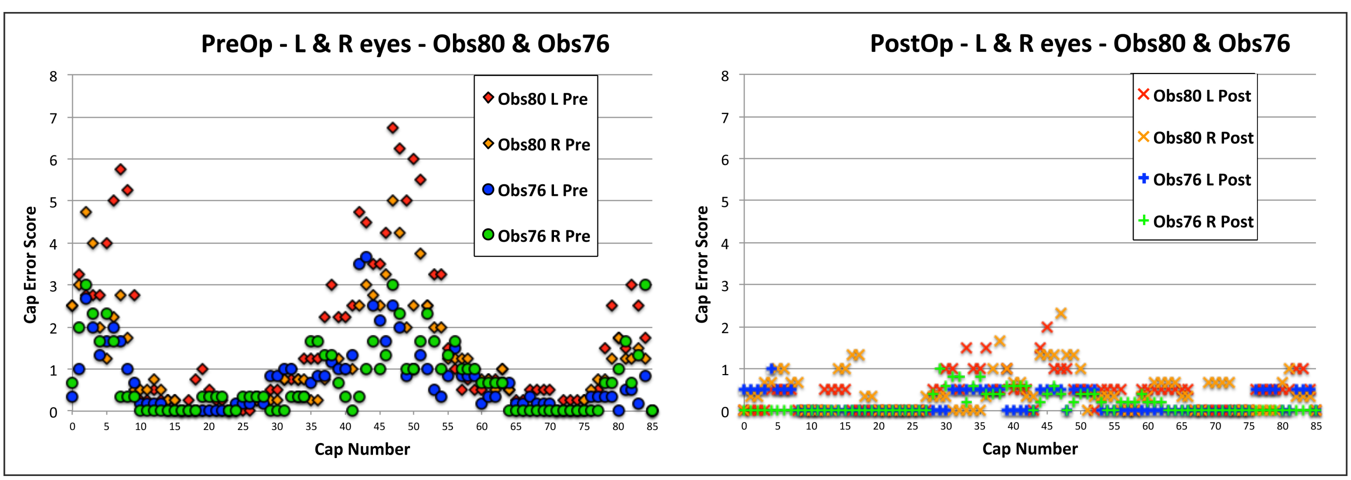

Figure 4 plots all 100 Hue data. (left) PreOp data indicating tritanopic confusion. (right) PostOp data indicating normal color vision.

2. Color appearance by matching

Painters have used their skills to synthesize images, real and imaginary for centuries.[10] Carinna Parraman used her watercolor painting skills to measure color appearance in real scenes. First, she reproduced the scene's color sensations in a watercolor painting made in uniform illumination; second, she measured the CIE (Y,x,y) reflectance values (meter readings) of each watercolor segment. Her rendering intent was to accurately reproduce her color sensations produced by changes in illumination on a real three dimensional scene. Her painting is a reflectance record of the visual system's response to those reflectances and illuminations in the actual 3-D scenes.[12] The following section describes a series of color matching renditions comparing PreOp and Post Op sensations performed by Obs76.

ColorMatching with PreOp & PostOp eyes

Obs76 made two identical photographs of a real life scene. Next, the task was to modify one photograph to reproduce the PreOp eye's scene appearances; and the other photograph to reproduce the PostOp eye's appearances. The assumption is that appearance using the PostOp eye (one month after surgery) was ground truth because the PostOp eye had restored normal color discrimination (Section 1).

First, using the tools in Photoshop®, Obs76 adjusted the "PostOp photograph" to match the scene's PostOp eye color sensations. Obs76 improved the camera's reproduction of the scene by matching and adjusting. Obs76 adjusted the reproductions' appearances both locally and globally (Table 2).

Table 2 list the Photoshop® tools and their effect on the image.

Tool	Effect on image
Levels	Set max, min, and contrast range
Curves	Set tonal response function
Hue/Sat	Adjust colors
Color Balance	Global color adjustment
Selective Color	Local color adjustment

Second, Obs76 adjusted the "PreOp photograph" to match the other eye with a cataract. Now the task was to study the actual scene with the PreOp eye, and adjust the "PreOp photograph" using the Post Op eye. Iterate this procedure until the entire "PreOp photograph" matches the scene using the eye with a cataract.The results are pairs of photographs that render to a normal observer PreOp and PostOp appearances of real scenes.

ColorMatching Results

Figure 5 (left) matches the scene's/photo's's appearances one day after surgery. Figure 5 (right) is the appearance 99 days after surgery.. Ground truth is the PostOp eye's appearances of the scene. Photoshop adjustments of each rendition were made using the PostOp eye (restored normal color vision). The left image used diffusion filters (Rosco CHB & 4 polyethylene sheets) in front of the camera lens to reproduce the apparent fog of the first day.

Figure 5 (left) compares the appearances using Obs76's left eye one day after surgery with (right) 100 days after surgery.

Immediately after surgery the scene appears brighter, more foggy and bluer.

Figure 6 renders the appearances of a ColorChecker using PreOP, PostOP and both eyes, 30 days after right eye surgery. The ColorChecker was observed in the 6200°K daylight lightbox (Section 1). Again, the PostOp sensations were brighter, and bluer than those of the PreOp eye. Binocular observations were between the PreOp and PostOp sensations.

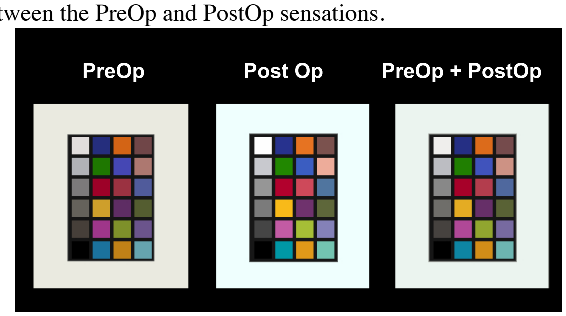

Figure 6 i ColorChecker's® changes in appearance with cataract surgery.

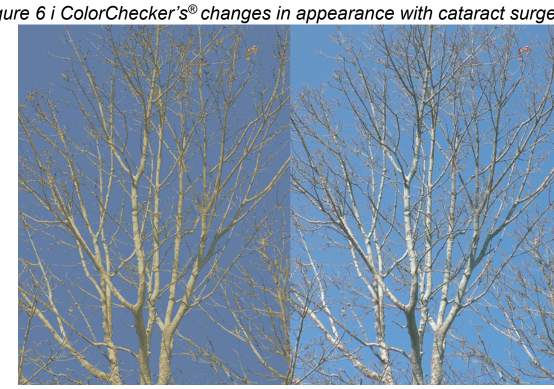

Figure 7 Change in appearance based on intraocular matching.

On a clear winter day, 96 days after right eye surgery, Obs76 made matches of tree branches against a blue sky. Figure 7 shows that the PostOp eye sees a brighter whiter lichen on the branches, and a lighter, bluer sky. (See also Figure 8)

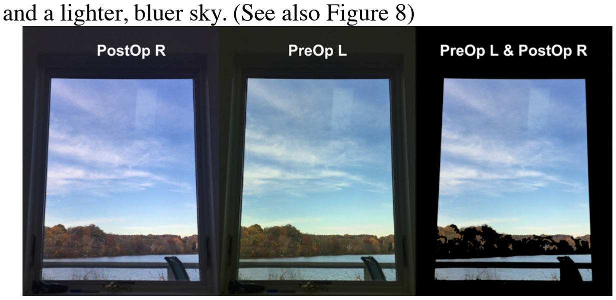

Figure 8 Change in appearance based on intraocular matching.

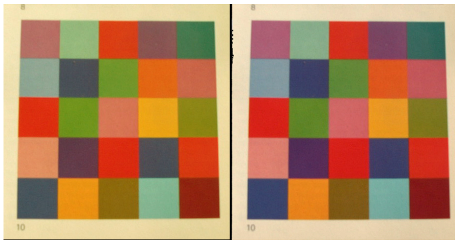

Figure 9 illustrates the change in appearance based on intraocular matching using a color harmony demonstration.

All color matching scenes show similar changes in color appearances. A cataract makes white sensations darker and yellower. Blue sensations are darker and less blue. Other colors have added darkness and smaller but consistent color shifts. Binocular combinations have intermediate appearances.

3. Color-balance titration between surgeries

The filter titration experiment began immediately after the observer's first surgery. In the first week both observers reported the three major differences between the PreOP and PostOp eyes, namely, appearances were substantially brighter, more foggy, and bluer. These differences are illustrated in Figure 5. The apparent fog dissipated quickly in a week, and was gone after four weeks.

Color Titration Procedure

Observers were asked to select a colored filter that made their PreOp and PostOp eyes generate the same color sensations when viewing a variety of natural scenes. The filters available for this color titration were Kodak Wratten filters, Edmund Scientific Filter book, and Rosco filter set. Wratten Color Compensating (CC) filters use a constant dye varying from very low to high dye concentration. These photographic filters are designed to make small corrections to the spectral illumination. Both observers felt that the Wratten Yellow family was the right hue. They used that family of 10Y, 20Y, 30Y 40Y, and 50Y filters to find the best balancing filter for the PostOp eye. The color balance shift between the PreOp and PostOp eyes was measured several times a week for about until the second surgery (77, 99 days).

Color Titration Results

Both observers selected the Wratten CC 40 Yellow as the best filter. More important, that filter was repeatedly selected for the entire period. Figure 10 compares 40 CC Yellow with Weale's cataract transmission [22], namely the ratio of [63 year old observer / 13 year old observer]. We used Weale's 13 yr transmittance as the lens's baseline before development of a cataract. By dividing the 63yr data by the 13yr data we calculate the change in spectral transmittance caused by the aged lens.

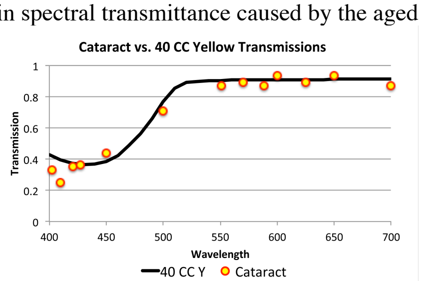

Figure 10 plots the transmission of the 40CC Yellow (solid black line). The circles plot the transmission of the cataract .

Figure 10 show that the overall hue appearance changes are a direct result of the removal of the yellowish aged lens. More important the results show that the 40CC Y filter is an accurate predictor for normal observers to use as a simulation of the appearance changes caused by an aged lens.

Observers looked for subtle changes in appearances in these titration experiments. Both observers reported that all natural scenes looked nearly identical in both eyes before any surgery; and after both surgeries. By making comparisons between one PreOp and one PostOp eye, these experiments measure the lightness and hue changes in appearance cause by cataract surgery (lighter and bluer). The observers looked for changes in appearances with time. However, the lighter/bluer color shift from a single cataract surgery was constant over the 100 day period. The change in retinal stimulus from cataract surgery is very similar to changes of tungsten to equal energy illumination. We saw no evidence for chromatic adaptation in response to the change in retinal stimuli. The appearance differences in PreOp and PostOp eyes were immediate and constant. The second surgery immediately removed all lightness/color differences.

Discussion

This entire project is an unusual pilot study of the effects of cataracts because it attempts to survey the widest scope of visual effects. There were many observations on many topics on four eyes. The topics cover acuity, color discrimination, color appearance, color matching, optical glare, retinal radiances, dynamic range of appearance, and night driving simulations. This article describes three different assessments of how color appearances change with cataract surgery.

Immediately after surgery, scenes appear are brighter, more foggy and bluer. The rates of change during the 100 days of mixed PreOp and PostOp vision. The appearance of fog abates quickly during the first week, and is gone after 30 days. The increase in apparent brightness, and the spectral shift equivalent to the removal of a 40CC Y filter has an immediate and constant change. The color appearance differences in retinal images caused by cataract removal did not adapt away.

Both Color Constancy and color after cataract surgery are the same experiment. Namely, they both observe the change in appearance with change in illumination-like spectra. The difference is the question we ask the observer. In Color Constancy demonstrations, observers report: "The green paper still looks green" after an illumination change. However, there are 374 chips that the Munsell book calls green. Using color matching to measure Color Constancy reduces tolerances to single Munsell chips.[13] Asking the observer to perform the 100 hue test requires even greater color discrimination. Cataract surgery changes the L, M, S cone quanta catches, but it does not change any color names of scene elements. Nevertheless, it causes very large changes in color discrimination: As large as genetic tritanopia. A 100 Hue Test in variable spectral illuminants provides a robust signal-processing signature of the human color process. It provides a data set for a model of color constancy.

Adaptation vs. Spatial Comparisons Models

Color Constancy theory has two branches. One is based on receptor response (adaptation of quanta catch). The other is based on spatial comparisons. Color matches in Color Constancy experiments show that there are limits to perfect constancy. Although a green paper remains green in different illuminants, observers match those greens to different, nearby, Munsell chips. Departures from perfect constancy provide an appearance signature to the underlying physiology of constancy mechanisms.

Adaptation and Spatial Comparisons have different color matching signatures. Adaptation models are based on von Kries [14] and implemented in CIECAM models[15].

- Adaptation models restrict input to one radiance measurement of a small scene segments. The model then combines the single radiance measurement with modeler-selected parameters to scale the cone-quanta-catch responses.
- Incomplete Adaptation is the predicted cause of departures from perfect constancy. Complete adaptation would adjust one illuminant's response predictions to be the identical to another illuminant's. Departures from perfect constancy are modeled by assigning a completion percentage. Incomplete Adaptation model' predictions do not agree with observer matches.[16,17] Adaptation's signature amplifies of cone responses to a small scene segment.

Spatial Comparison models are based on Land's Retinex theory[18], and implemented in multiresolution calculations. [19]

- Spatial Comparisons use a radiance map of the entire field of view as input to models that calculatie the appearances of all image segments simultaneously.
- L, M, an S cone spectral sensitivities are so broad that they respond to all visible" light (400-700 nm). Their spectral sensitivities have substantial overlap. At the peak sensitivity of the M-cones, the L-cones are half as sensitive.
- At every visible wavelength there is a L-cone, a M-cone and a S-cone response. In other words, the M-cone response is the sum of the *wanted* M-cone response to middle-wave light, and the *unwanted* M-cone responses to the long- and short-wave light.
- Illumination changes the edge information for L,M,S cone images, that changes calculated color appearances. [16,17] Spatial Comparisons predict departures from perfect constancy that are very different from those of adaptation. Spatial Comparison's signature is based on edge ratios controlled by the sum of *wanted* and *unwanted* spectral information, namely the relative cone responses at edges. Spatial Comparison's predictions agree with observer data.

McCann [20] reviewed experiments measuring the changes in appearances in color constancy experiments. That review includes a detailed explanation of how illumination like changes control departures from perfect constancy.

Modeling 100 Hue Data

The brighter and bluer appearances in the PostOp eye are consistent with the changes in lens transmission. It is more difficult to understand the slow development of "100 Hue Tritanopia" over 50 years, and its instant remission. Figures 4 shows the color confusion with cataracts is grouped around Munsell 10 BG 5/4 (dominant wavelength 491) and Munsell 10R 5/5 (dominant wavelength 589). As well, Figure 4 shows ranges of excellent color discrimination centered at Munsell 2.5P 5/4 (dominant wavelength reciprocal of 567 nm) and Munsell 10Y 5/5 (dominant wavelength 573 nm). Cataracts cause color confusion only around 491 and 589 dominant wavelengths. Note the peak of color confusion at is 589 nm and excellent color discrimination is at 573 nm. Also note that the transmission of cataracts and CC40Y are flat in that spectral region.(Figure 10)

The comparison of these very-narrow color-confusion spectral regions with the smooth cataract transmission curves in Figure 10 does not suggest any simple quanta-catch-based explanation. Amplification (adaptation) of cone responses (broad spectral sensitivity) cannot introduce very-narrow-spectral confusion regions found in 100 Hue data.(Figure 4) Further, there was no change in appearance over time. There was no change in the filter titration experiment over 99 days. After the second operation the overall color of the scene in PreOp and PostOp were identical at first light (removing the bandage covering the closed eye). It is difficult to find an Adaptation mechanism consistent with the 100 Hue and Color Constancy data sets.

Spatial comparison models are more promising. They build appearances up from the spatial spectral ratios. The full spectral integral that calculates the cone response is not important. The edge ratio of cone integrals for adjacent areas is important.

Color photography and displays use 3 different spectral sensitivities (R, G, B): and 3 different light modulators (dyes or emitters). An ideal color system's goal is to isolate the scene's spectral information into three non-overlapping channels, called separations. Then, make the output image using three non-overlapping spectral modulators. Ideally, the R channel has 100% response to light above 589 nm (R-light); and the G channel has 100% response to light between 589 nm and 488 nm (G-light), the B channel has 100% response to light below 488 nm (B-light). [21] These are the *wanted* spectral responses. There are practical limits, so the actual G separation is a mixture of *wanted* G-light information, and *unwanted* R+B light information (channel crosstalk). R separation is a mixture of *wanted* R-light + *unwanted* G-light information. B separation is a mixture of the *wanted* B-light +*unwanted* G-light information. In photography and displays the *unwanted* crosstalk is small.

Human cones respond to all wavelengths across the visible spectrum. Their spectral sensitivities have extensive overlap that leads to considerable *unwanted* spectral responses. L,M,S cone's responses are the sums of *wanted* and substantial *unwanted* spectral information. The unwanted spectral responses hamper color discrimination required in the 100 Hue Test. Voglesong's selection of 589 and 488 as the ideal no-response wavelengths [21] was based on the empirical development of photographic films, that in turn required many human observations. It is interesting to note that the peaks in our 100 Hue color confusion are at cap #7 Munsell 5YR 6/6 (dominant wavelength 589); and at cap #47 Munsell 10 BG 5/4 (dominant wavelength 491). These two spectral regions has the highest sensitivity to *unwanted* spectral responses, that modify edge ratios, that modify color appearances.

Neural comparisons are needed to model 100 Hue and Color Constancy data. Color-opponent and double-opponent neurons help compensate for crosstalk. Just as in the analysis of Color Constancy measurements[17,18,19], unwanted crosstalk plays a central role in 100 Hue color discrimination. The 100 Hue data provides the data set needed to make a quantitative model of Color Constancy. The study is ongoing. The analysis and modeling of the observed changes in retinal stimuli, spectral discrimination are in progress.

Conclusions

Two observers, who have intermittently performed the Farnsworth-Munsell 100 Hue Test since 1967, analyzed their current scores before, during, and after bilateral cataract surgery. Cataract surgery replaced a low-transmission yellow lens with a clear IOL. The observed brighter and bluer appearances in the PostOp eye are consistent with the changes in lens transmission.

Prior to the development of cataracts, their scores were always in Farnsworth's "superior" category with all scores below 16. With the development of cataracts both observers had markedly higher scores. Pre-surgery the average scores of Obs80 was 146.5 (left), 96.0 (right); Obs76 was 61.7 (left), 62.3 (right). These score plots have the same spectral discrimination profile as Farnsworth's Tritanopic observer. These plots show very poor color discrimination for 100 Hue caps near #47 dominant wavelength 491 (10 BG 5/4) and #7 dominant wavelength 589 (2.5 YR 6/6). All four eyes gave consistent results. All eyes had errors concentrated in the same spectral regions, thus categorizing them all as tritan impaired.

Cataract implants restored normal color discrimination: All eyes were categorized as normal. The average scores of Obs80 35.5 (left), 38.7 (right); Obs76 was 16.0 (left), 11.2 (right). The 100 Hue PostOp linear plots are nearly flat. Hence, cataracts cause temporary tritanopia. Tritanopia is the genetic abnormality associated with the short-wave cone pigment. Cataracts reduce the radiances around the peak of the short-wave cone fundamental by a factor of ten. Despite different underlying mechanisms, tritanopia and cataracts produce almost identical distortions of normal color discrimination results.

Obs76 used Photoshop® to reproduce the PreOP, PostOp, and binocular color sensations. These image match real scenes, and describe of the color effects of cataract replacement.

With one PreOp and one PostOp eye, both observers reported brighter, more foggy, and bluer appearances. The foggy appearances diminished quickly and disappeared in a month. The large change in brightness was immediate. Observers reported that a Wratten CC 40Y filter over the PostOp eye made colors in both eyes appear the same. The cataract introduced a substantial spectral modification affecting cone quanta catch. Comparing the substantial changes in cone quanta catches with the modest changes in appearance suggests the influence of color constancy mechanisms. Nevertheless, color appearances in PreOp vs. PostOp eyes were constant over 100 days. There was no evidence of chromatic adaptation, namely adjustments of relative cone response weightings. Brightness and color appearance changes were immediate and constant.

The 100 Hue data showed color confusion in narrow spectral regions at 491 and 589 nm dominant wavelengths. All color reproduction technologies have minimal spectral overlap at these wavelengths. Minimizing RGB channel crosstalk improves color discrimination. Cataracts increased the unwanted L,M,S channel crosstalk, and caused the loss of color discrimination in at 491 nm and 589 nm. The clear lens replacement restored normal color discrimination.

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