# Colors before and after cataract surgery:
# A study of color constancy and discrimination

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## Abstract

*Cataract surgery replaces the aged human lens with a transparent silicone implant. The new lens removes optical distortions and light scattering media, as well as a yellow filter. This talk describes the appearances of natural scenes before and after cataract surgery. While Color Constancy experiments showed small changes, color discrimination experiments had large changes. These results provide a mechanistic signature of Color Constancy and Discrimination.*

## Introduction

This paper describes the appearances of natural scenes before and after cataract surgery. It uses three different experimental techniques using complex scenes, with special emphasis on observations with one eye with an Intraocular Lens (IOL) implant, and one un-operated eye with a "ripe" cataract. The first experiment measured the appearance of scenes in PreOp, and Post Op eyes using color matching. The second experiment, Titration, selected the color filter that changed the appearances of the PostOp eye to match those of the PreOp eye. The third experiment used the Farnsworth-Munsell 100-Hue Test[1] to measure color discrimination in both PreOP and PostOp eyes.

The vision literature on aging describes many changes in vision with age. Oyster[2] cites 21 different age related changes. Boettner and Wolter measured the transmittance of enucleated lenses from 53 and 74 year patients[3], and Weale measured cataract transmission.[4] Knoblauch et al. studied the effects of age on Farnsworth-Munsell 100 Hue Tests. They showed a decrease in performance scores with age.[5] Wuerger has studied the effect of age on Unique Hues selections.[6] Ikeda [7, 8] and Warner [9] studied lens transmission and color matching changes. Farnand et al. described changes in appearance following IOL implant surgery.[10]

The research described below is a part of a two-year study of many different properties of each eye using two observers; before, during, and after bilateral cataract surgeries. These experiments measured an age 80 female (Obs80); and an age 76 male (Obs76). The 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[11], and changes in appearance caused by cataract surgery. This article describes a subset of data which includes three assessments of color: color appearance, color-balance titration matching, and color discrimination.

Further, this paper reviews these measured results with respect to the role of visual adaptation to natural scenes. The cataract transmission approximates a photographic filters that changes an equal-energy spectrum to tungsten light.[12] A cataract filters light on the retina in a way that mimics a Color Constancy experiment. The Titration and the 100 Hue data show that complex scenes and discrimination tasks are insensitive to chromatic adaptation.

## *Exp.1 Matching Appearance*

One day after IOL implant surgery, that eye's appearances were foggy, brighter, and bluer. The foggy quality disappeared quickly. The intraocular scatter's fog decreased rapidly over the first week. and was minimal after one month.

Figure 1 shows a pair of matches of an indoor/outdoor scene. The matching image on the left was made 1 day after surgery of the left eye. The image on the right was made the same day with the right eye. It had an IOL implant 100 days earlier.

*Figure 1 compares the appearances using Obs76's left eye (Left) one day after surgery with right eye (Right) 100 days after surgery.*

The observer sat in front of the real scene, holding a laptop computer with a photograph of the scene open in Photoshop®. Using only the right 100-day PostOp eye, the observer adjusted every image segment of the photograph to match the scene's appearances.(Figure 1 Right) For Figure 1 (Left) the observer looked at the real scene with the 1-day PostOp eye. He adjusted every image segment of a second photograph on the laptop using the 100-day PostOp eye. All matching adjustments for both photographs were made using the 100-day PostOp eye. The real scene was viewed with only the 1-day PostOp eye for the left match; and with the 100-day PostOp eye for the right match.[12]

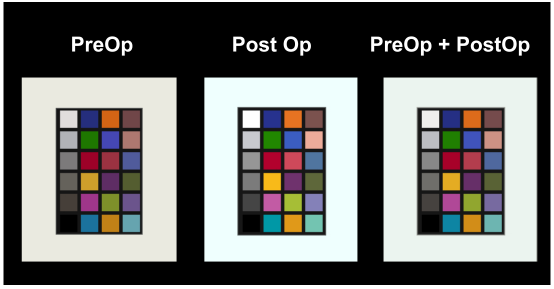

*Figure 2. ColorChecker's® changes in appearance with cataract surgery.*

Figure 2 renders the appearances of a ColorChecker® using PreOP, PostOP and both eyes, 30 days after right eye surgery. By then the observer reported the fogginess had disappeared. All matching adjustments for the three photographs were made using the 30-day PostOp eye. The scene was viewed with only the PreOp eye for the left match; and with the the 30-day PostOp eye for the middle match, and both eyes for the right match. The ColorChecker was observed in a 6200°K daylight lightbox. Consistent results are reported for these and other matched scenes.[12]

The PostOp sensations were brighter, and bluer than those of the PreOp eye. Binocular observations were between the PreOp and PostOp sensations.

## *Exp.2 Filter Titration over the Post Op eye*

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 color balance shift between the PreOp and PostOp eyes was measured several times a week until the second surgery: 77days for Obs80, 99 days for Obs76. The filters available for this color titration were Kodak Wratten, Edmund Scientific and Rosco filters. Wratten Color Compensating (CC) photographic filters are designed to make small corrections to the spectral illumination They use a constant dye varying from very low to high dye concentration. Both observers felt that the Wratten CC Yellow family was the right hue. They used that family of 10Y, 20Y, 30Y 40Y, and 50Y filters to find the best matching filter for the PostOp eye.

Both observers selected the Wratten CC 40 Yellow as the best filter. More important, that filter was repeatedly selected over the entire period. The brighter and bluer differences between the first PostOp eye and the remaining PreOp eye were constant over the nearly 100-day period.[12]

Weale measured the transmission of human lenses from a 13 and a 63 year old eyes.[4] We took the ratio of [63yr /13yr] transmissions for each wavelength reported as the spectra of the additional aging filter in the 63yr eye. That plot is shown in Figure 3 as yellow/red circles.

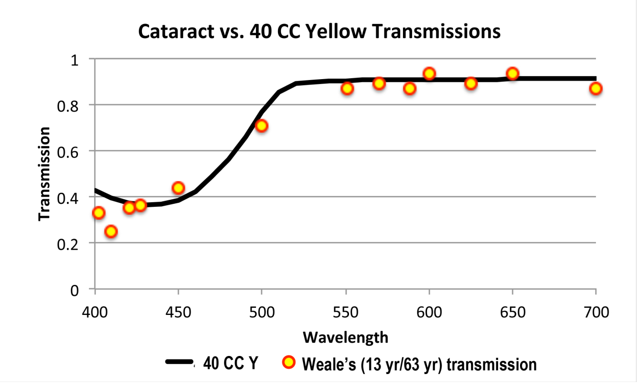

*Figure 3 plots the transmission of the 40 CC Yellow (solid black line). The circles plot the transmission of the additional filter in the 63yr aged eye.*

The transmission of 40 CC Yellow superimposes on Weale's age filter transmission namely the ratio of [63-year old observer / 13-year old eyes]. We used Weale's 13 yr transmittance as the lens's baseline before aging. By dividing the 63yr data by the 13yr data we calculated the change in spectral transmittance caused by the aged lens.

## *Exp. 3 Temporary Tritanopia*

Figure 4 shows the Farnsworth-Munsell 100 Hue Test scores for Obs80 comparing the PreOp and PostOp results for the left eye. The standard 100 Hue polar plot is shown in the upper left. Farnsworth used Dominant Wavelength as the circumference of this plot, and error score as the length of the radius. [1]

In Figure 4 the top-left polar plot suggest the Obs80's left PreOp eye has no S-cones. The polar plot is nearly identical to Farnsworth's results for a tritanopic dichromat.[1] The IOL implant in that eye restored discrimination to normal Tritanopia. Clearly, the cataract did not disable Obs80's S-cones. The implant did not recover them. However, this data shows that the change in filtration plotted in Figure 3 has substantial effects on color discrimination. While Experiment 1 reported modest changes, Experiment 3 reported substantial ones. This paper analyses color mechanisms to help understand these results.

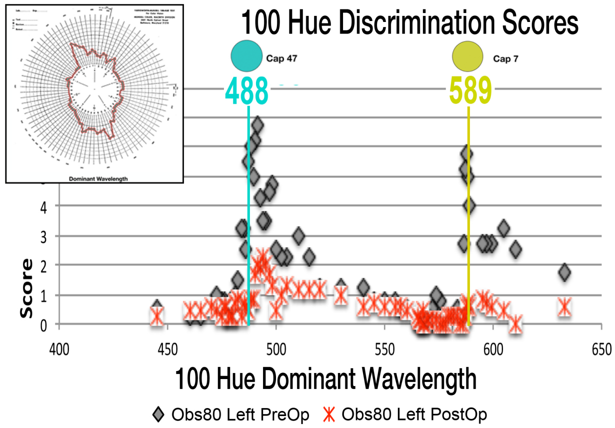

*Figure 4 describes the change in Color Discrimination after cataract surgery for Obs80. The upper left box plots Obs80 data using the standard polar plot with Dominant Wavelength as circumference, and error score as radius. The main graph is linear plot of Dominant Wavelength vs. error score. The poorest discrimination zones are found near cap 47 (488 nm), and cap 7 (589 nm).*

## Color Mechanisms: Quanta Catch and Neural Comparisons

In the second half of the 19th century, Ewald Hering and James Clerck Maxwell took color along two very different paths. Hering made constancy, and the role of illumination in appearance, an important topic.[13] Hering thought about the appearances in complex scenes. In contrast, J.C.Maxwell's color matching experiments[14] laid the groundwork for Colorimetry. Maxwell thought about the molecular physics of the quanta catch.

Land thought about both molecular physics and Color Constancy. His Retinex Theory[15] and his Double Mondrian experiments[16] demonstrated the power of constancy. Land's experiment changed the spectrum of spatially uniform illumination on a flat 2-D paper display. He showed that a particular L,M,S cone quanta catch can appear any color (any Hue, Lightness and Chroma). The spectral illumination causes small shifts in the color appearance of scene segments. Those same changes in light reaching the retina cause very substantial changes in the quanta catch of retinal receptors. Further, these substantial changes in quanta catch result in very substantial changes in the appearance of spots of light in a no-light surround. The appearance of spots of light are simply the result of local molecular physics in the receptor's outer segments. However, the appearances of image segments in complex scenes are the result of the cascade of spatial comparisons made in the retina, along the optic nerve, and in the cortex. Each neural layer is making spatial comparisons among neighboring responses along the pathway. Hubel and Wiesel showed this with the cascade of simple, complex, hyper-complex cells, and columns of neurons.[17]

Color has two sequential stages: first, receptor quanta catch defined by molecular physics; and second, spatial comparisons defined by neural processing. With the exception of the boundary of the spot of light adjacent to the constant no-light surround, the spot stimulus is edgeless. Appearance of spots responds to the molecular physics of quanta catches.

Land's Retinex theory proposed that following the molecular-physics stage, a second, a series of spatial comparison stage controls color appearance in real natural scenes. Ratios at edges are almost indifferent to spectral changes in uniform illumination. The ratio of radiances for each wavelength across edges is nearly constant. Human color constancy follows the L-cone ratios, M-cone ratios, and S-cone ratios at edges.[18, 19 ] Retinex theory also predicts the departures from perfect constancy.[20, 21] Experiments with edges in illumination, caused by shadows, show the erosion of Color Constancy in High-Dynamic-Range scenes.[19]

While Color Constancy experiments showed small changes, Color Discrimination experiments had extreme changes. These results provide a mechanistic signature of Color Constancy and Discrimination.

## *Exp.1 Color Constancy Appearances*

In many ways cataract replacement surgery is a Color Constancy experiment. The change in spectra shown in Figure 3 converts an equal energy spectra to a tungsten lamp spectra. Introducing the 40 CC Y filter in a color matching experiment requires substantial adjustments to a match. After all, it reduces the 400-480 radiances to 40% of their original value. However, the change of equal energy to tungsten is too small to be dramatic in Color Constancy experiments. Only small, subtle changes in appearance are reported there.

Color constancy, whatever its mechanism, is unresponsive to substantial spatial uniform changes in cone quanta catch. IOL implants change scene appearances consistently, making them brighter, and subtly bluer. IOL implant data is consistent with the changes in spatial ratios across edges of each cone quanta catches.

## *Exp.2 Filter Titration Matches*

The Figure 3 comparison of 40 CC Y filter to Weale's aged lens data is consistent with the molecular physics of cone quanta catch. Whether uniformly changing the illumination of the scene, or the filter in the human lens, they both should have the same effect on cone quanta catches. With identical cone quanta catches everywhere in the scene we must expect the same appearances. These matching results follow the fact that the 40 CC Y filter is very similar to the aged lens transmission.

While the titration match is not surprising, the observation that the best filter remains constant from the 1st day to the 100th day is surprising. All neurons adapt. Receptor outer segments adapt. The expected change-with-time of titration match was not observed. The PostOp eye was always brighter and bluer than the PreOp eye. With two PostOp eyes, the two eyes showed no yellow-blue shift. Whites were the same color, neither bluish, nor yellowish. With IOL implants in both eyes, after the fogginess disappeared, both observers reported identical color sensations in both eyes.

Spectral adaptation has been hypothesized as a mechanism of Color Constancy for more than a century. We observe cone adaptation in afterimages, and in entering a dark room. Nevertheless, we do not find that adaptation plays a role in IOL implants, as it does not in most measurements of Color Constancy in complex scenes.[22]

## *Exp.3 100 Hue Color Discrimination*

Unlike the subtlety of results in Experiments 1 and 2, we find that the IOL implant has caused very substantial changes in Color Discrimination. These extreme changes occur at Cap 7 (589 nm Dominant Wavelength) where the IOL has not changed the transmission spectra. Further, the IOL has that same transmittance at 550 and 625 nm dominant wavelength at which the cataract eye has normal Color Discrimination.

As well, the poorest Color Discrimination is found at Cap 47 (488 nm dominant wavelength). At that wavelength the 40 CC Y filter transmits 60%. The observers have normal discrimination at 475 and 525 with filter transmissions of 50% and 90%. Calculations of quanta catches of L,M,S cones, with and without a CC 40 Y filter, do not explain these discrimination results. We must look to other models of color vision that involve the neural spatial calculations after the molecular physics of cone quanta catches.

There are three essential sets of spectral sensitivities used in color today:

- First, the CIE X,Y,Z color matching functions can predict when two spectra will match when observers look at a spot. However, these functions cannot predict the color appearance of that match.[15, 23]
- Second, the L,M,S spectral sensitivity functions are made from measurements of cone absorption spectra.[24] When combined with the spectral transmissions of the eye and macular pigment, the L,M,S sensitivities allow us to calculate the spectral light imaged on the retina from Low-Dynamic-Range scenes. Another calculation is necessary to find the amount of light falling on the retina from High-Dynamic-Range scenes. Scene radiances need to be convolved with the Glare Spread Function of the eye in almost all outdoor scenes with shadows. [25, 26]
- Third, an industrial standard, called Status A, is an empirically established triplet of sensitivities that optimize spectral color channel separation. Figure 5 plots the desired sensitivity functions of color films. Although designed for film, these same spectral response goals are currently used in all electronic cameras, displays, and projectors.

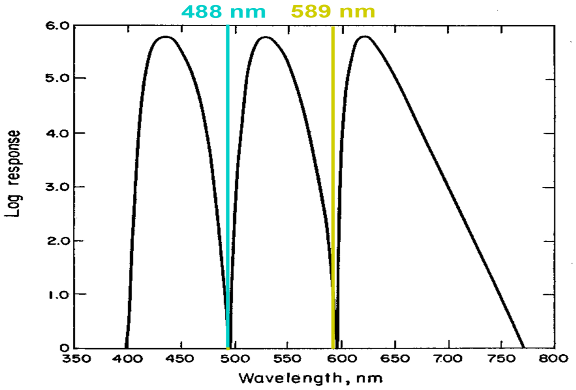

*Figure 5 plots imaging's ideal spectral channels (Status A sensitometry). These spectral channel curves are used in all cameras (silver-halide and electronic) and displays. The troughs between sensitivity functions are at 488 and 589 nm.*

Voglesong described Status A sensitometry spectral measurements. He wrote that Status A "has become a standard metric by historical record alone. This response is carefully controlled by filter selection and by spectrally trimming the densitometer. The response is intended to be free of crosstalk; i.e., red, green and blue measurements do not overlap as they measure the sample, ... Status A may be considered a form of abridged spectrophotometry." [27]

This Status A standard is very simple. The R-separation image should respond to light above 589 nm. Any response to shorter wavelengths degrades the chromatic purity of that separation image. The B-separation image should respond to light below 488 nm. Any response to longer wavelengths degrades chromatic purity. The G-separation responds solely to the light between R and B. This standard made the best color pictures. Small shifts of these cutoff minima to longer, or shorter, wavelengths degrades color reproduction dramatically.[28]

Standard A implies that 488 nm should have equal, and minimal spectral sensitivity in the G and in the B record. That wavelength contributes equally to both separations. Thus, that wavelength does not help the separation of chromatic channels. It just adds equal crosstalk to both. Cap 47 has 488 nm as its Dominant Wavelength. Poorest discrimination falls at Cap 47 because it is the perfect storm: It has maximal 488 nm light at maximum crosstalk. The result is the poorest Color Discrimination. The same argument applies to Cap 7 at 589nm: The crossover of R and G color separation channels. While this is purely an empirical explanation, it provides some important clues about vision's image processing.

IOL implant surgery adds another set of data that can help us understand the mechanisms of color vision. There is an apparent paradox that 40 CC Y causes small changes in constancy and large changes in discrimination. These results are consistent with many previous observations. Nevertheless, the matching and 100 Hue data on the same observers, in the same time period is novel. Further, the observation that appearances were constant with one PreOp and one PostOp eye is important. No temporal adaptation was observed. While the spectral properties of vision's molecular physics is well established, more work modeling the spatial transformations of color is needed. Spatial color enhancement of chromatic separations began in 1889.[29] and is used in all electronic media. Detailed computational models of neural interactions are needed to understand this second stage of color vision reported here before and after IOL surgery.

## Summary

One day after IOL implant surgery, appearances were foggy, brighter and bluer. The foggy appearance disappeared quickly. The intraocular glare decreased rapidly over the first week and was minimal after one month. The brighter and bluer differences between the first PostOp eye and the remaining PreOp eye were constant over the 100-day period.

Cataract removal is very similar to Color Constancy experiments in that both have large spectral changes that is spatially uniform over the entire scene. Just as in constancy experiments, observers reported small appearance changes of individual color segments. These color shifts were adaptation free, namely, constant over the 100 day period. Titration experiments used a wide selection of different optical filters over the observer's Post Op eye. The observer selected the filter that made a real scene appear identical in both PreOp and PostOp eyes. Over the 100 day period, both observers chose the same Kodak 40 CC Yellow filter.

Farnsworth-Munsell 100 Hue measurements provide a markedly different perspective. Both observers, over decades had "Superior normal " 100 Hue Color Discrimination scores. Prior to their surgeries their Color Discrimination matched that of Tritanopic observers. Surgery returned their vision to "Normal".

Experiments 1 and 2 are simply another example of Color Constancy's response to spatially uniform changes in illumination. Experiment 2 adds to the literature supporting the idea that temporal adaptation is not the underlying mechanism controlling Color Constancy. Experiment 3 adds to the literature that L,M,S cone separation crosstalk is present in a manner similar to R,G,B crosstalk in cameras. Neural, post quanta catch, mechanisms control the L,M,S channel information, that in turn controls color appearance and discrimination.

## Acknowledgements

We want to thank John Sexton for his report of his Color Correction filter observations prior our surgeries. We want to thank Dr. Donal Korb, OD, and Dr. Bradford Shingleton, MD, for sharing their scientific knowledge, and their medical care.

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## Author Biography

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