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Color Vision Differences Following Retinal Detachment and Subsequent Cataract Surgery

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Abstract. *In September 2017, the first author suffered a rhegmatogenous retinal detachment. This experience included a series of remarkable, sometimes unsettling visual phenomena, which included visible differences in the color vision between her two eyes during the recovery from retinal detachment, as a cataract developed, and following cataract surgery. Her right eye is now equipped with a new lens, replacing one that had yellowed from years of exposure to ultraviolet radiation, which provides a cooler view of the world than before retinal detachment, with slight distortions, and occasionally with sparkles early in the morning. In this review, the color vision changes that were experienced are quantified and detailed. While this does not represent a typical study with a hypothesis and testing of various participants, we hope that it inspires others to ask interesting questions that lead to increased consideration of the relationships between perception and visual health and that it raises awareness of the warning signs of retinal detachment.* © *2019 Society for Imaging Science and Technology.*
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1. RETINAL DETACHMENT

In September of 2017, the first author rather suddenly felt like something was in her eye, like water. It was nothing terribly irritating, just barely noticeable, but persistent. In retrospect, the only warning sign was a few new "floaters"—the shadows cast on the retina by microfibers in the vitreous humor [1]. Calling them floaters, though, gives the wrong impression. They were actually more like dancing missing pixels or luminance-inverted fireflies flashing tiny spots of darkness. They seemed harmless enough, but they were a sign that the vitreous humor was tugging on the retina.

Vitreous floaters occur when the vitreous gel mass that fills the space behind the lens and in front of the retina liquefies as the eye ages. This liquefaction occurs more readily and rapidly after age 50, but can start occurring as early as age four for those who are highly near sighted or myopic, have suffered ocular trauma, have undergone intraocular surgery, have genetic predisposition to such reorganization at earlier ages due to abnormalities in collagen, or have retinal vascular pathology [1].

Such macroscopic fibers cause light scatter and can appear as dark due to the shadow cast on the retina by the reorganized collagen and are often seen in greater number against a bright background and over time along with the more rapid reorganization of the vitreous. Movement of the vitreous body causes these floaters to move across the visual field along intravitreal currents, which may produce a "glass noodle" or "spider web-like" appearance [1].

Seeing a few floaters is likely benign, but seeing hundreds of new spots or flecks in one's vision, often described as seeing a flock of birds or swarm of bees is more serious and may signal the presence of a retinal tear. A retinal tear can lead to a retinal detachment and ultimately vision loss if not timely detected and treated with barrier laser to seal off the tear. The presence of flashing lights or fireworks especially in one's peripheral vision may also harbinger a retinal tear or a developing symptomatic posterior vitreous detachment or PVD that can be associated with a retinal tear or detachment. This visual phenomenon is caused by traction on the retina leading to stimulation of the retina and the perception of light. A PVD occurs in the aging liquefying vitreous when the cortical vitreous separates from the internal limiting membrane of the retina due to the reorganization and enzymatic breakdown of collagen [2]. A PVD eventually occurs in all adults, with most adults over the age 60 years having had a PVD [3].

In most cases a PVD is asymptomatic. However, a symptomatic PVD is associated with a retinal tear in 20% of cases per population studies as the pulling or separation of the vitreous occurs in a way to cause dynamic tugging or pulling of the retina that has a higher chance of causing a retinal tear [3]. Thus, anyone who experiences a significant increase in floaters, flashes of light, or a veil or shadow over one's vision should see an eye doctor within 24 hours for a detailed examination of the retina with dilation of pupil.

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Figure 1. Illustration of the disappearing field of view on the steps of the Royal Palace in Oslo, Norway.

The need for immediate attention is critical. The loss of retinal attachment to the retinal pigment epithelium, or RPE, separates the photoreceptor cells from their blood supply. This diminishes the functioning of the photoreceptors and results in the person with a retinal detachment experiencing shadows or veils over their vision, known as scotomas. If the macula or the center of the retina responsible for the sharpest vision is detached, the visual acuity can decline to the legally blind level. In fact, even if repaired with prompt retinal reattachment within three to seven days, a macula involving retinal detachment can lead to permanent blindness with 20% to 40% regaining a visual acuity of 20/50 or better [4]. By three days after a retinal detachment, 20% of the photoreceptors permanently die. These lost photoreceptors are mostly the rods at first and then the cones. Although they may be foreshortened, photoreceptors are still viable on attachment of the retina to the RPE, their outer segments do regenerate and allow the photoreceptor to regain function. Reattachment of the retina stimulates photoreceptor axonal growth to counter lost axons when the retina was detached. Another cell type of the retina, Muller cells remodel during a detachment and grow into the subretinal space, often forming scar tissue and disorganization of the retinal architecture, making successful reattachment difficult. Timely reattachment limits scar formation. Thus, repair of a retinal detachment is necessary as soon as possible preferably before the macula is involved to ensure the best preservation of vision and avoidance of permanent scotomas [5].

For the first author, while wandering the streets of Oslo after the conference had ended, a white crescent began to appear on the far-left side of field of view in her right eye, Figure 1. This was the start of a rhegmatogenous (from the Greek word *rhegma*, meaning rupture or fissure) retinal detachment, Figure 2. Figure 3 illustrates the relationship between these key components. This happens to approximately 1 in 300 people in their 50's as their vitreous humor liquifies and shrinks, causing it to pull away from the retina and, occasionally, pulling the retina with it. That night, the guidance was that there was little that could be done to mitigate the damage and that it was best to return home for immediate treatment.

The following morning, and until after surgery to repair the detachment, the white area appeared like a filmy, sheer curtain, letting some visual information through, Figure 4. The information was distorted, though, somewhat like looking through antique glass or water, like the retina was floating. A NIH website on retinal detachment provided for non-ophthalmic medical professionals suggests that patients experience a "dark curtain or shadow, appearing first in the periphery and moving to the center" on the opposite side of the detachment due to the optical inversion [6]. The experience of a white crescent and white curtain was not the most common manifestation of a retinal detachment, but it is not considered unusual either. A retinal tear formed by the vitreous humor pulling on a flap of retina allows for the liquefied vitreous to track underneath the neurosensory retina separating it from the retinal pigment epithelium (RPE), thus causing a retinal detachment. While the retina is detached, its photoreceptors are still being activated by vitreous attachments and white blood cells moving in the rental vessels. This activation sends signals to the optic nerve and eventually to the visual cortex where they proceed to sight, which can result in "seeing light," sometimes in white sheets or pin points of light. This sensation of light without any light actually being present is referred to as an entopic phenomenon [5].

Entopic phenomena may be present at other times during a retinal detachment. The pink and green color fringing that the first author experienced might have involved diffraction, but it is more likely another entopic phenomenon occurring along the detached region of the retina relative to the signal processing in the attached retina. Additionally, some patients experience bright flashes like sparklers prior to and immediately following a detachment, Figure 5. If one experiences this type of flashing, contacting an ophthalmologist is warranted. Many patients also experience light sparkles well after surgery.

Treatment of a retinal detachment is based on the extent of the detachment and location of the tear(s) and related retinal pathology. If a retinal detachment is small, spanning only a few clock hours, with only one retinal tear in the superior hemisphere of the globe, a pneumatic retinopexy can be performed. In this procedure, a bubble containing octafluoropropane, an inert gas that is different from the propane that runs the grill but is chemically related, is placed in the eye to tamponade the retina [7]. The retinal tear is either lasered or "frozen" closed with a liquid nitrogen cryotherapy probe. A more extensive retinal detachment may need a band or scleral buckle to support the retina and assist in relieving the pulling or traction of the vitreous and/or a vitrectomy or removal of the vitreous humor and relief of vitreous traction on the retinal tear or break precipitating the retinal detachment. These two procedures are performed in the operating room [8, 9]. For the first author, pneumatic retinopexy was the preferred approach.

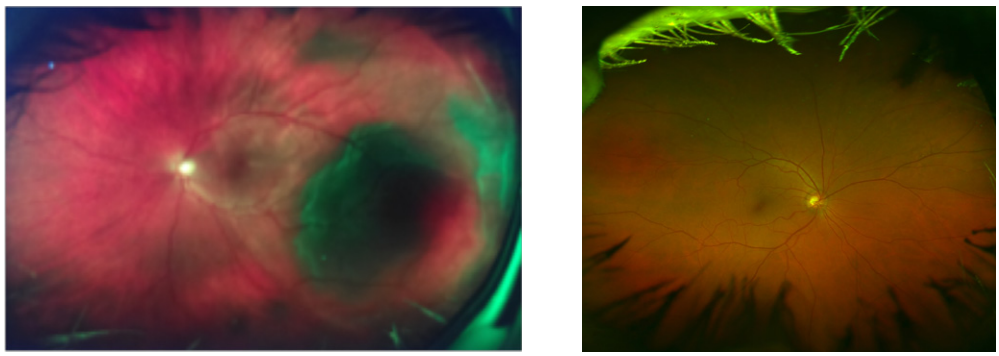

Figure 2. Image of the first author's right eye with partial retinal detachment, left, and an image of a normal left eye taken with the same model device—an Optos wide field of view camera. In these images, green is closer to the camera and red is further away.

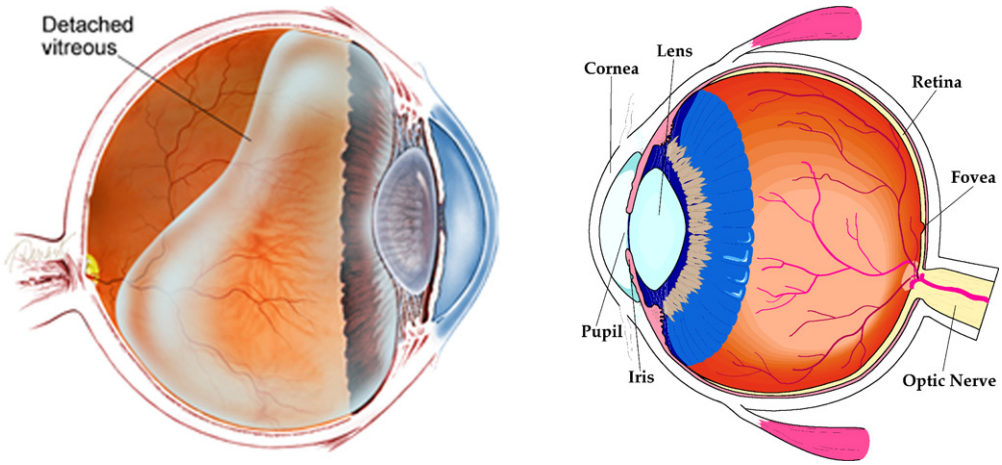

Figure 3. Schematic of a detached vitreous, left. On right, a schematic of an eye. Note the foveal region. For further information on retinal detachment, the NIH has an informative website: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2405853/

Figure 4. After the retinal detachment and before the procedure to repair it, the vision in the left field of the right eye had the appearance of looking through a sheer curtain (left). It also gave the impression of looking through water (center) or antique glass, though not quite as old as the window glass from a building in the Rural Section of the Maihaugen Museum, Lillehammer, shown at right. (Photo credits, Farnand).

Following surgery, the patient is required to lay on her side for about twenty hours per day for a week—three quarters of every waking hour. The gas bubble is reabsorbed by the eye over the course of a month or two, but does expand if one goes up in elevation and thus flying with a gas bubble is not possible as that would increase the pressure in the eye causing pain and blindness.

In a seminar discussion at the Rochester Institute of Technology (RIT) of interesting IS&T Color Imaging Conference talks, including Cohen-Duwek & Spitzer's (2017) paper detailing a model predicting positive and negative after-image effects, Figure 6, the first author noticed that viewing after-images did not work well [10]. The lack of a clear border made the patch ill-defined and the visual

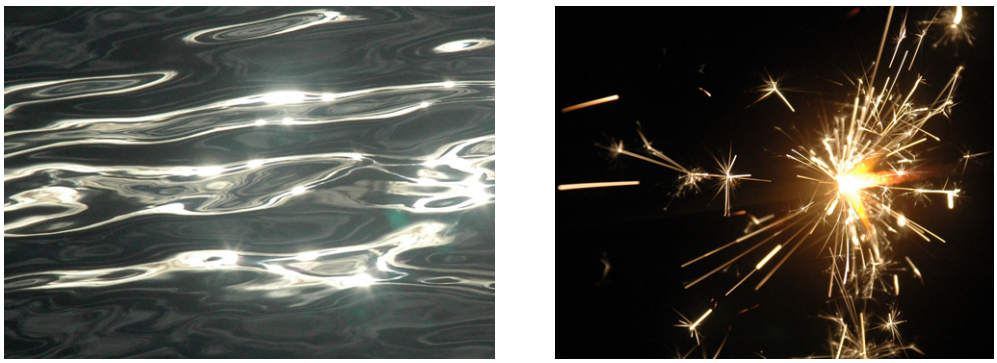

Figure 5. The appearance of flashes, like those given off by sparklers (left), can be a sign of an impending retinal tear. Sparkles like sun on water (right) can occur as part of the healing process after laser repair of a detached retina (Photo credit, Farnand).

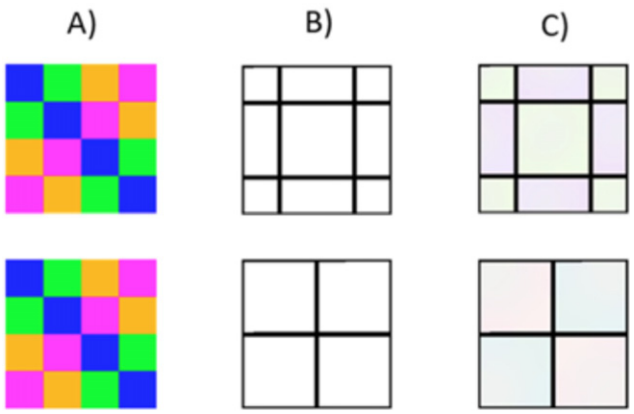

Figure 6. After-image demonstration described by Cohen-Duwek et al., 2017.

distortions made it difficult to fixate. Objects in the middle to far distances, anything beyond about 150 cm, appeared distorted. These distortions do not appear as blur, as they would for a presbyopic eye. Rather, the edges of objects were not straight. They appear more like a misregistered print, or like the Photoshop® wave distortion filter had been applied, Figure 7, producing an effect something like a Van Gogh painting. Retinal reattachment can stimulate formation of the epiretinal membrane, a sheet like structure, at the vitreoretinal interface that may be asymptomatic or cause metamorphopsia, which is a wavyness like visual distortion of straight lines or objects, especially if it causes dragging of the photoreceptors [4, 5]. For the first author, these distortions persisted for many months, but are now largely imperceptible. The author has likely adapted to the distortions in much the same way that humans adapt to the blur inherent in the optics of their eyes [11].

2. COLOR DIFFERENCE EVALUATION

About three and a half weeks post-procedure, as the bubble shrank and vision started to return, color differences, were noticeable both between the top and bubble regions, and between the top of the field of view in the right eye and the eye. The top region looked like it was covered with a greenish filter, especially outdoors, causing red and yellow stimuli to lose some of their chromatic appearance relative to other areas of the visual field. To evaluate the magnitude of this effect, the color of a patch, adjusting in Photoshop, that was needed to produce a match for the first author's two eyes was determined, Figure 8. The patches were presented on a black background. With a viewing distance of about 18″, the patches covered about 5° of visual angle. The color patches as seen by the left eye were adjusted to match the appearance for the right eye. Only one eye was used at a time. The experiment was conducted in a darkened room in the Munsell Color Science Laboratory at RIT on the display of a MacBook Pro having a luminance level of 88 cd/m^2. While not the ideal display for visual testing, the consistency of the unadjusted patch was verified. The observer adapted to the darkened conditions for two minutes before beginning the experiment. The patches were evaluated in random order. The resulting patches were then measured with a PR655 spectroradiometer and the ΔE_{00} difference calculated using the display white point.

The color differences are plotted as a function of time in Figure 9. ΔE_{00} was selected as the metric since the stimuli were generally highly chromatic patches—red, yellow, green, blue, purple, plus gray. The high chroma level warranted ΔE_{00} rather than ΔE^*_{ab}. Further, patch stimuli being compared under identical viewing conditions do not generally require a color appearance metric. In the first measurement, which occurred between three and four weeks after the retinal repair, the color difference between the eyes was easily discernible, with an average difference of over ΔE_{00} 12 units. This quickly dropped for all colors, although the differences were higher for purple, blue, and gray stimuli. The red patch had the subtlest difference. The blue and gray patch differences continued to drop over time such that, by about three months after the retinal repair, all of the differences were in the 2–4ΔE_{00} range, except for purple, which continued to measure around 8ΔE_{00}. It is evident from the graph in Fig. 9 that the initial difference would be quite perceptible to the average, color-normal observer and that the difference gradually diminished along with the gas bubble.

Figure 7. Van Gogh's Olive Trees with yellow sky and sun (left) and Wavy distortions applied to an image taken during a walk in the hills above Lillehammer (Photo source: https://commons.wikimedia.org/wiki/File:Van_Gogh_-_Olivenb%C3%A4ume_mit_gelbem_Himmel_und_Sonne.jpeg left; Farnand, right).

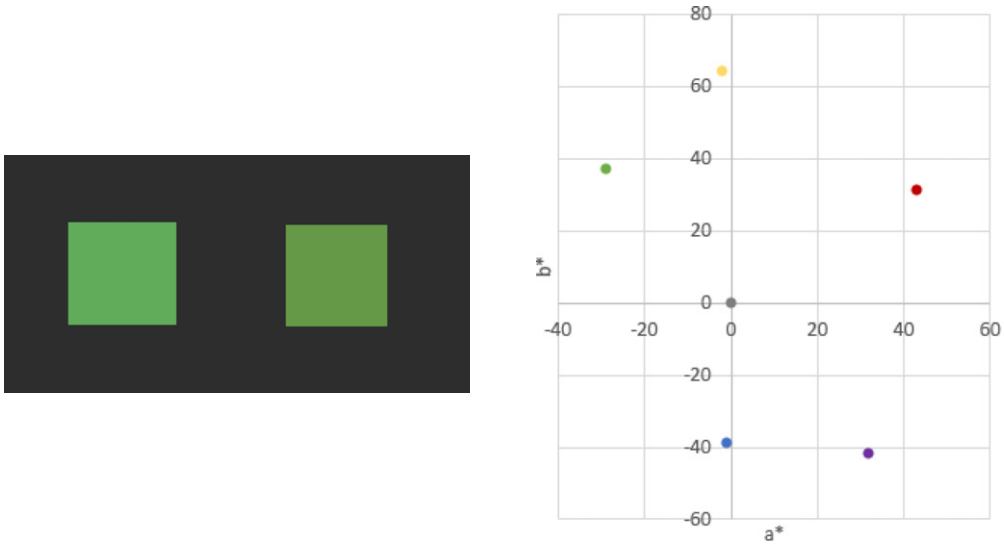

Figure 8. Example stimulus for determining color difference between the two eyes (left). The left patch represented the color needed for the left eye to match how the right eye was 'seeing' the right patch. The a* and b* values of the patch stimuli used (right).

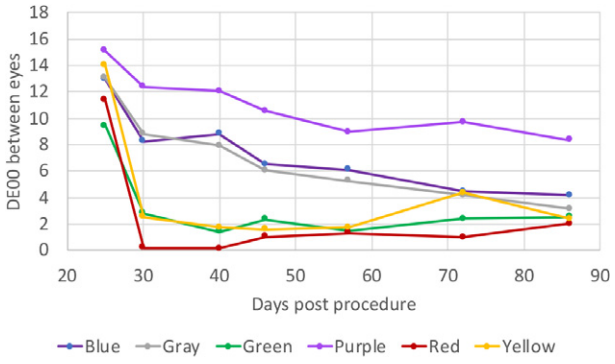

Figure 9. CIEDE2000 between color patches that appeared to match to my left and right eyes.

3. CATARACT

Four weeks after surgery, the ophthalmologist commented that a change in the shape of the lens had occurred, which could indicate the start of a cataract. About four months after surgery, with the bubble was gone, rather than all of the color differences decreasing to imperceptibility, the purple, blue, and gray differences remained clearly discernible and the yellow difference started to increase again. Along with rainbow halos around headlights, candle flames, and some light bulbs, a developing cataract elicited new and somewhat different color differences. After a vitrectomy, about 60–70% of patients develop a new or worsening of an existing cataract that is visually significant enough to require cataract surgery [12]. Due to the added glare, cataracts also negatively impact distance vision. To evaluate the spatial vision effect, the ISO 20462-3 Quality Ruler method was used [13]. Briefly, the Quality Ruler method comprises a series of ruler stimuli of increasing degradation in sharpness. The test stimulus is compared to the ruler stimuli until a quality match is determined. In this evaluation, it was found that the ruler image needed to match what the right eye was seeing was a 24. Figure 10 gives some idea of the difference, although the viewing conditions are considerably different and not as required for an accurate representation. The visual degradation experienced continued to be distortion rather than blur.

Figure 10. The degree of blur needed (right) as compared to the original (left) for the degradation seen by the left eye to match what the right eye was seeing at distances greater than about 50 cm.

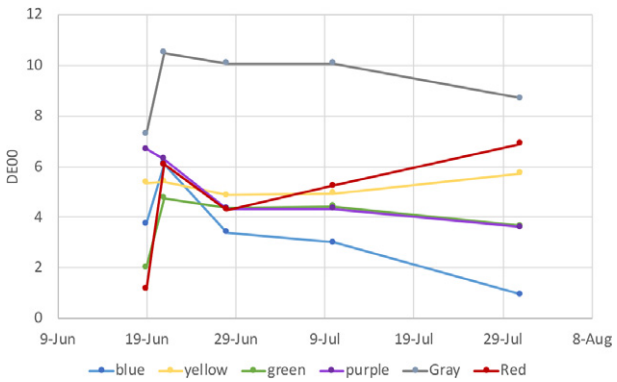

Figure 11. CIEDE2000 between color patches that appeared to match to my left and right eyes before and after cataract surgery, which took place on 20 June.

It is well known that the lens yellows as a result of exposure to ultraviolet radiation causing a reduction in transmission at the short wavelength end of the spectrum, making a distinct shift toward the visual world being perceived as bluish following cataract surgery expected [14, 15]. Indeed, research indicates that, while humans adapt rapidly to changes in color stimuli, this shift in apparent color may persist [16, 17]. Knowing that lens replacement would likely lead to yet another perceived color difference between the author's two eyes, this difference was quantified before and after the surgery. To do this, the procedure of adjusting color patches as seen by the left eye to match the right eye was repeated. The same anchor images were used. The procedure was conducted on an EIZO ColorEdge CG248 sRGB-calibrated display with a luminance of 112 cd/m^2 in the Visual Perception lab at RIT. The results are shown in Figure 11.

The measured differences shown in Figure 12 were quite large the day following cataract surgery and, although they diminished with time, they persist to the time of this writing (May, 2019). In his report on his experience with lens replacement, Granville reported "surprisingly large" differences between colors [15]. He reported differences specifically with morning sky, asphalt, and white. Similar differences were noticed, particularly the difference in white surfaces and gray pavement, which look quite yellowish with the left eye and slightly blue-violet with the right eye. With both eyes open, these surfaces have a neutral appearance. This experience is reflected in the data plotted in Fig. 12, with the largest difference occurring for the gray patch followed by the red and yellow stimuli. The relatively large differences in blue and purple stimuli seen before surgery were diminished after surgery.

In addition to this color matching procedure, the eyes were evaluated using the D&H metamerism ruler. This task was performed under D65 lighting in the Spectral Reproduction lab at RIT. The results are included in Table I and depicted in Figure 13, which show the differences in the spectra of the metameric matches for the left and right eyes before and after surgery. The matches for the left eye were consistently around H9-I9, which falls on the line near the top of the range for D65 lighting found by Billmeyer and Saltzmann in their study of 72, mostly younger, observers, Figure 14 [18]. The right eye, in contrast, had a match of about K11-L11, again falling on the line, but considerably higher than the match points of the young observers and actually approaching the border between the daylight and horizon light matches for the young observers. Following surgery, the match for the left eye was unchanged while the right-eye match point fell to F8, approximately the average match point for the young observers under D65 lighting conditions. These results support the apparent blue shift in the color vision for the right eye and are in general agreement with previous work [15].

Finally, to check color discrimination, the Farnsworth–Munsell 100 hue test was completed with each eye under the daylight setting in the viewing booth of the Visual Perception lab at RIT. In completing the Farnsworth–Munsell 100 hue test, both eyes had flips in the green-to-blue region 45–49, both before and after surgery. Neither eye had difficulty outside of this region either before or after surgery. With the left eye, 48 and 49 were flipped one day before surgery and 46 and 47 one day after surgery. With the right eye, the 44–50 caps were placed in the order: 44, *46, 47, 45, 49, 48*, 50. After surgery, the order was: 44, 45, *48, 47, 46*, 49, 50. While it is

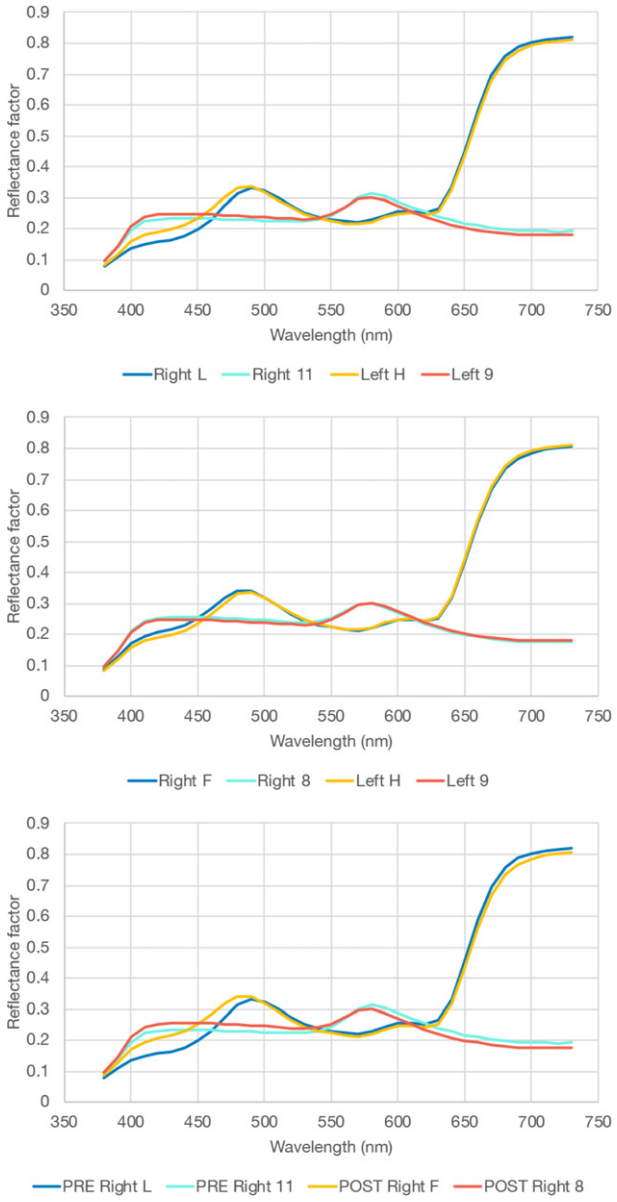

Figure 12. Reflectance spectra of D&H ruler patch matches before and after cataract surgery. The graph at top right depicts the spectra of the matches for my two eyes prior to surgery, the top left shows the matches after surgery, and the bottom shows the right-eye matches before and after surgery. Note the differences in the shorter wavelengths in the top left and bottom graphs.

interesting that the only region that proved difficult was the green to blue, these results do not indicate any meaningful change in color discrimination from before to after surgery.

For a few months following cataract surgery, a rapid flicker in central vision was experienced that resembled a black and white fallout shelter sign, Fig. 14. This diminished to an infrequent occurrence of a black and white grating-type pattern, but it can still be distracting. A clouding or opacity is developing in the capsule that holds the lens implanted in my eye during cataract surgery, which is a common occurrence especially in younger individuals as cells grow over the thin capsule. This cloud, called a posterior capsular opacity, will require an in-office laser procedure to correct [12].

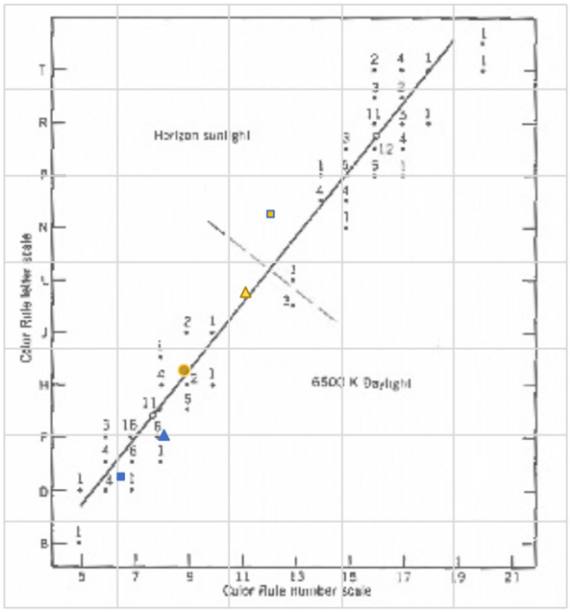

Figure 13. The first author's matches before and after cataract surgery are plotted relative to Billmeyer & Saltzmann D&H ruler match data for daylight (below the dotted line) and horizon (above the dotted line) lighting conditions. The right-eye matches are marked by the yellow (before) and blue (after) triangles. The left eye matches were unchanged (yellow circle). (After Billmeyer & Saltzmann, 1980).

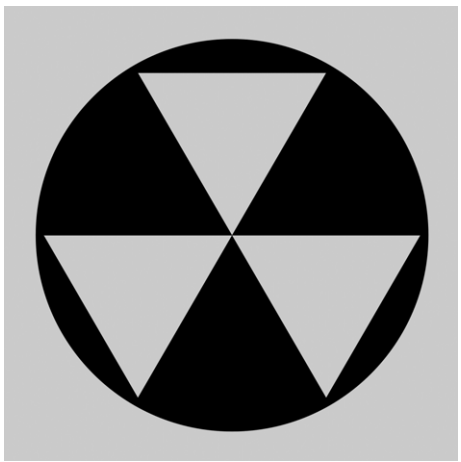

Figure 14. Following cataract surgery, the first author periodically experienced a rapidly flickering black and white pattern that resembled a fallout shelter sign.

4. CONCLUSION

The first author's color vision changed substantially through the process of recovering from retinal detachment, development of a cataract, and subsequent cataract surgery. These differences were quantified. Differences in purple, blue, and gray stimuli were the most significant during recovery from retinal detachment and during the development of the cataract. These differences were likely due to the gas bubble and then the developing cataract increasing the level of light scattering within the eye. The differences were significant enough that, if someone was developing a cataract in only one eye, they would be clearly perceptible.

Table I. D&H ruler results.

Date	Eye	D&H
June 6	Right	K-L11
	Left	H9
June 19	Right	L11
	Left	I9
June 21	**Right**	**F8**
	Left	**H-I9**
July 23	**Right**	**F8**
	Left	**H-I9**

Before and after cataract surgery, the differences in gray, red, and yellow stimuli were the largest due to the removal of the yellowed lens and replacement with a substantially clearer lens implant. At the time of this writing (May, 2019), the differences in neutrals are still apparent when viewing with each eye alone. The brain has adapted to the color information coming from the two eyes such that perception of the world with both eyes is neutral, rather than the bluish-purple seen in the days following cataract surgery.

Retinal detachment is a serious visual health issue affecting roughly 1% of the general population [19]. It is important to take unusual flashes and darting floaters seriously. Prompt medical attention is critical to avoiding permanent visual damage.

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