Psychophysical Experiments in Search of Adaptation and the Gray World

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Introduction

Vision research in the first two-thirds of the twentieth century had a rich history of light and dark adaptation. The experiments by Hecht, Pirenne, Wald, Brown, Hubbard, Dowling, Rushton, Campbell and Alpern wove a rich scientific fabric for understanding the first stages of vision. The bleaching of photosensitive visual pigments and the slow regeneration in the dark clearly is controlled by the very first stage of visual image processing, that is, the quanta sensitivity of the rods and cones. If a bright light has adapted the rods and cones, only dark adaptation to less, or no light, can cause the recovery of sensitivity. The range of these phenomena is 10 log units—from the threshold of vision to the luminance of snow on a mountain on a sunny day.

We have all seen demonstrations of a time-dependent loss of sensitivity caused by light. The usual form of the experiment is to "adapt to the stimulus" and then view the "after-image" on a uniform field. There are many good examples of this. One has a cyan, black and yellow American flag with a black dot in the middle. The experiment is to stare at the black dot for about a minute. Then look at a white card, or a projected uniform white field. One sees the red, white and blue negative after-image when looking at the uniform, bright white field; one sees the complimentary colored American flag (positive after-image) when one covers the eyes.

The underlying mechanism is that following the absorption of quanta in the rods and cones, these cells continue to send a signal to the cortex until the rods and cones are fully dark adapted. This fact was demonstrated by an ingenious experiment by Alpern and Campbell[1] in the early 1960's. The observer applied pressure to the side of one eye. That pressure blocked the appearance of a flash of light presented only to that eye. They monitored the response of the pupil in the other eye following release of pressure. The pupil of the closed eye responded the same as control experiments, although the observer "did not see the flash." Clearly the flash initiated a change anterior to the optic nerve block. Clearly that signal was sent out of the retina to higher levels that caused the pupil of the other eye to behave the same as if it had seen the flash.

Sometimes we hear arguments that this bleaching of photopigment in the retina is the underlying mechanism of color constancy. This idea goes back to von Kries in 1899. The question at hand is whether the quantitative aspects of the adaptation mechanism match the quantitative values of color constancy phenomena. McCann, McKee and Taylor[2] measured the range of color sensation produced by a single stimulus at a point using Color Mondrians. They chose 5 colorful papers (not the most saturated in the Munsell book). They began with a gray paper and measured the long-, middle- and short-wave radiances coming to the eye from the gray paper. They asked observers to match that gray paper to paper in a Munsell Book. The average was 5YR 6/1. This paper is a gray with a very slightly warm caste. The experimenter then adjusted the long-, middle-, short-wave illuminants so that now the same irradiances came from the red paper as came from the gray paper. Although the quanta catch by the retinal receptors was the same as from the gray paper, the observer average was 5R 6/6, a red paper. In the next iteration with a different paper, the same quanta catch as from the gray was 5Y 8/8, a bright yellow. In the final two iterations the same quanta catch as from the gray were 10G 7/4, a mid green and 2.5RB 4/6, a mid blue. Quantitative matches of a single stimulus were gray, red, bright yellow, green, and blue. Can we show that adaptation can produce changes this large? Can we establish a quantitative experimental link between adaptation and color appearance?

There is a very dramatic experiment by Nigel Daw that raises the question of whether after-images can affect the color appearance of objects in real-life images.[3] This experiment was done with a red and white projection. There was a still-life image with a large red pillow and a teapot spout placed in front of the pillow. Daw used the tip of the spout as the fixation point. Observer stared at the tip to form an after-image. Daw then occluded the red projection, leaving the black and white color separation in white light on the screen. He asked observers to continue to look at the spout. They reported the expected cyan after-image. What was not expected was that when Daw asked the observers to look at other objects in the projection the after-image vanished. It returned when re-fixated on the spout and re-vanished when looking elsewhere. When one repeats the experiment with the conventional uniform white screen, the cyan pillow is visible for several minutes. Clearly the presence of conflicting contours between the after-image (fixed on the retina) and "live" image caused the visual system to suppress the after-image. The removal of conflict, by looking at the tip of the teapot spout, allowed the after-image to become visible again. This very dramatic experiment raises questions about the influence of after-images and gray-world algorithms on the everyday experience of color constancy. No one can doubt that, at every moment, the rods and cones send signals out of the retina about their state of adaptation. Daw's experiment raises the question whether the color sensation mechanism uses that information in color constancy sensations. When the after-image <u>contours matched</u> the "live" image the after-image was visible; when <u>contours didn't match</u> it was invisible. The

Table 1 lists the Experiments [Column 1], the Gray-World Predictions [Column 2], the Reset Retinex Predictions [Column 3], the Experimental Results [Column 4].

Normalization **Experiment**	**Gray World** Average each waveband **Prediction**	**Reset Retinex** Maxima each waveband **Prediction**	**Result**
Change Average Radiance	Proportional color shift	Second order color shift	Small change
Repeat Color Mondrian Constant average radiances	Failure of Color Constancy	Color Constancy	Color Constancy
Change the maxima without changing the average	Gray the same as White & Black	Maxima restores Color Constancy	Maxima restores Color Constancy

adapted image on the retina is stabilized and undergoes neural inhibition.[4] Does this inhibition prevent adaptation from influencing phenomena such as color constancy? If the state of adaptation and the gray-world algorithms are used by human vision then we should be able to find experimental evidence of adaptation influence in the appearance of colors in complex scenes. Can we find such evidence that after-image, the state of adaptation and gray world can influence color sensations?

Testing For The Normalization Mechanism

A simple description of color constancy is that, if the illumination changes so that there is more long-wave light, then the visual system becomes less sensitive to long-wave light. The idea is that color appearance uses a normalization mechanism. The question is the mechanism of the normalization process. Land and McCann[5] used the maxima in each type of the long-, middle-, short-wave cone and rod receptors to explain the Color Mondrian. The gray world mechanism assumes that the average quanta caught over the entire field of view is used as the normalizing value. Because the illumination was changed everywhere in the Color Mondrian experiment, the Total Average Radiance for the entire display changed. The idea to be tested is, “Does human vision use this information to achieve color constancy?” The gray-world hypothesis has been used in artificial intelligence algorithms[6]. The Color Mondrian experiment by itself might be explained equally well with either hypothesis. New elements need to be added to the experiment to discriminate between ratio-product-reset mechanism and the gray world.

In this paper we will discuss the following questions:

If one changes the average over the field of view, will that change the color appearance?

If one repeats the Color Mondrian with no change of gray-world average, will that observers report the same the color appearances?

If one changes the maxima, without changing the average, will that change the color appearances?

These three questions can be used to form a convincing test of the relative merits of a Reset to Maxima model compared to gray-world model for human vision. (See Table 1).

Change Average Radiance

The first hypothesis is a direct test of the gray world. Doubling the amount of long-wave illumination doubles the long-wave average, and should lead to a dramatic change in color appearance. Alternatively, doubling the area of long wave reflectances will double the long-wave average, and should lead to the same predicted dramatic change in color appearance. Furthermore, both changing the illumination and changing the size of the papers should produce exactly the same effects, because both change the average the same amount.

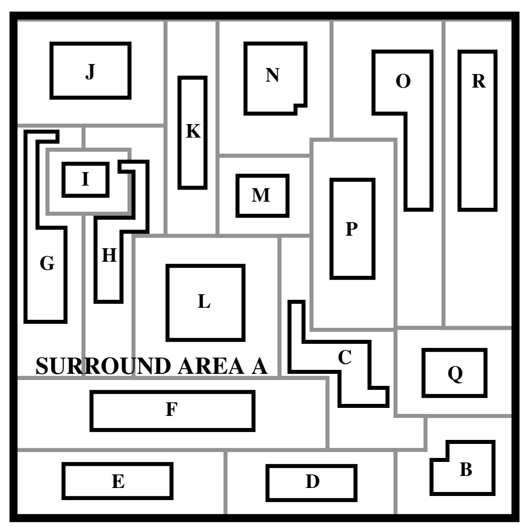

Figure 1 is a Mondrian in which areas B through R are identical to areas in the McCann, McKee and Taylor experiment. They are placed in the center of a proportional Mondrian twice the size (Four times the area). Area A is twice the size of the original display.

One can change the average very easily using Wratten CC or CP filters. Photographers use these filters all the time to shift the color balance of images. If one looks through a series of different CC red filters, starting with CC10 and increasing by 10 each time, one sees an orderly increase in redness. Even with the CC10 one can see that the whites have gotten more “rosy,” with each increase, the entire image shifts more to the red. All colors are effected by the same amount. A CC30 will attenuate the long-wave light by a factor of 2; a CC60 a factor of 4.

We must make a new Mondrian to change the average by a factor of 2 by changing the areas in the display. (See Fig 1.) Here we made the Surround Area A twice the size, in each dimension, as the original Mondrian. All other areas B through R were the same. The Surround A paper was as one of the most saturated red papers available. We placed them so as to completely surround each area of the Mondrian.

Clearly the average has been shifted as much as possible by papers. Observers report that this large red surround has an influence on some saturated colors and some middle values. It has very little effect on the whites and the blacks. Here, as with the CC filter experiment the changes in appearance are very small. Furthermore, the two kinds of average modification produce two different effects.

The Reset-Maxima Retinex hypothesis has different predictions for doubling the illumination and doubling the reflectances of long-wave papers. Doubling the long-wave illumination will create a small overall shift in all colors including the white.[7] Changing the average areas of the long-wave light will not affect the whites: it may have a small effect on colors adjacent to those with larger surround. These experiments which look for the effects of adaptation show small changes. The results of these and many other experiments are that adaptation causes changes in color appearance, but only by small amounts. Grays do not become red, or green, or blue, or yellow.

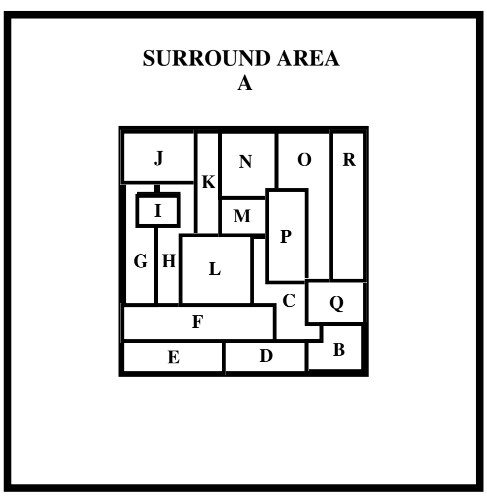

Figure 2 is a Mondrian in which areas B through R are identical to areas in the McCann, McKee and Taylor experiment. They have the same placement. Area A is twice the size of the original display.

Repeat Color Mondrian with Constant Average Radiances

Just as in the earlier Color Mondrian experiments, each experiment uses one of the papers in the display. Again we begin with the gray paper (area P). We measure the triplet of long-, middle-, short-wave radiances.[8] This time we measure the Total Average Radiance of all areas including the Surround A, made up of a Gray 6.25/ paper. (See Fig 2.) This radiance measurement integrates the product of the reflectances at each point and the uniform illumination. We call these average radiances: AVL, AVM, AVS.

Just as in other Color Mondrian experiments, we select a new paper, Red 10 RP 6/10- Area G. This paper has a higher long-wave and lower middle- and short-wave reflectances than the gray Area P. To make the same triplet of radiances come from Area G as Area P, we must decrease the long- and increase the middle- and short-wave illuminants. This change in illuminants changes AVL, AVM, AVS. In order to maintain a constant Total Average Radiance and constant Gray World value we need to change the surround Area A. Quantitative measurements of many different papers was necessary to find papers with just the right reflectances. These measurements showed that replacing N6.25/ with color Aide RVR Hue 2 restored the averages to AVL, AVM, AVS.

The Area P and Area G papers have different reflectances and compensating illuminants. The different surround papers were chosen to compensate for the illuminant. The long-, middle-, and short-wave reflectances of the surround papers were chosen so that the same triplet of average radiances (AVL, AVM, AVS) came from the global average of each targets. Thus we have constructed a pair of displays that have the same average over the entire field of view. Any measure of a global average or gray-world average calculates the displays to be identical. In addition, we have a particular paper in each display that sends to the eye identical triplets of radiances. Just as in the earlier Mondrian experiments, the papers have different reflectances and compensating illuminants.

A gray-world model must predict that the Area P with N6.25/ surround will match Area G with RVR Hue2. It will appear the same because the radiance from each is identical and the average radiance from the entire field of view is the same. In other words, because the gray world averages are the same, color constancy will not hold. With the RVR Hue2 surround, that exactly compensates for the change in illumination, Area G (10RP 6/10) must look gray. Gray World models predict that color constancy will fail.

A Ratio-Product-Reset model predicts that the average radiance will have a small effect, but basically the papers will appear very similar to their appearance in the initial illuminant and initial surround. Both surround and illuminant will change the appearance of the five selected papers, but as measured in previous quantitative experiments, the magnitude of these effects is small. The nonlinear reset is the underlying operation that causes the Ratio-Product-Reset model to behave independently of the average properties of the entire field of view. It normalizes to the maximum in each waveband and is only secondarily responsive to the average properties of the image. Reset Retinex predicts that color constancy will hold.

The experiment consisted of five different areas, triplets of illuminations and surrounds. Table 2 lists the observer color matches for this Total Average Radiance (TARS) experiment in column 2. The data from the original Color Mondrian experiments (MMT) are listed in Column 3. The matches are very close to those measured in the original experiment. The measurements show that color constancy has held. These large changes in the Average radiances have had no significant effect on color appearance.

The results in Table 2 show very little change in appearance due to the presence of a Surround. For both versions of the targets the observers' matches for the gray patch span a range of 0.25 units in value and 1 unit in chroma. The observers' Munsell chip matches for the red patch span a range of 1 page in hue. The observers' matches for the yellow patch span a range of 1 page in hue, 0.5 units in value.

Table 2. Shows the matches in the current experiment with constant Total Average Radiances in the TARS column. MMT matches refer to the original McCann, McKee, and Taylor experiments in which the average radiances varied with the illumination.

	TARS matches	Original MMT matches
Area P- N 6.25/	N6/	5YR 6/1
Area G 10RP 6/10	2.5 R 7/4	5R 7/4
Area C 5 Y 8.5/10	5 Y 8/8	5Y 8.5/8
Area R 2.5 C 7/6	7.5 G 7/4	10 G 7/4
Area H 2.5 PB 6/8	10 B 6/2	2.5 PB 4/6

The observers' matches for the green patch span a range of 1 chip in hue, 1 unit in value and 2 units in chroma. The observers' matches for the blue patch span a range of 1 chip in hue, 2 units in value and 4 units in chroma. The matches do not show significant changes in appearance.

In the MMT experiment the gray-world averages were all as different as the illuminants. In the Surround Targets they were all the same. These experiments did not show a significant dependence on the average of the target. Even then, there was no significant change in the observer's color matches. Table 2 is strong evidence that a model whose goal is to calculate color sensation be essentially independent of averages. The ratio-product-reset model has this property because of its nonlinear reset. The model normalizes the image with respect to its maximum value, not an average.

Change The Maxima Without Changing The Average

The final question is the influence of maxima. Here, we can test to see if maxima shows an influence on color appearances, while the experimental design restricts the average of the entire field of view to stay constant.

The experiments are patterned after those described in the Campbell Spielfest.[9] Two different illuminants are chosen. Two sets of reflectances are chosen such that the product of the reflectances and illuminates produce two images that are equal at all corresponding pixels. This is possible by making the reflectances in the first set differ from those in the second by an amount precisely equal to the ratios in illumination.

As in the previous experiment, there is a clear differentiation between the predictions of adaptation to an average and normalization to maxima [Reset Retinex].

The control experiment creates to sets of reflectance and illuminations whose products are, at corresponding pixels, equal: they must look alike. They do.

The experiment consists of adding new reflectances to the control matching displays. Previous experiments showed that the introduction of a new maxima destroyed the match[10]. Here we need an additionalconstraint, we need to introduce a new maxima while not disturbing the average quanta catch. Here the technique is to add the average condition to the previously described experiments. Here we replace the maxima used to destroy the color match with an area that is half maxima and half minima. The average of this new area is middle gray, or gray world. The question is whether a new maxima can still "reset" the appearance when an equal area of minima is used to hold the average of the scene constant. The average or gray world hypothesis predicts that there will be no change: the Reset Retinex predicts that the new Maxima will destroy the match between the corresponding reflectances.

The result of making these displays is that the new maximas destroy the matches.

Summary

The fourth column in Table 1 summarizes the experimental results. In each experiment, the results support the Reset Maxima hypothesis and fail to support the adaptation to average hypothesis. In all three sets of experiment we fail to find evidence that adaptation is effecting the appearance of objects. Other experiments clearly demonstrate that adaptation to the average amount of light is controlling the overall level of sensitivity of the rods and cones. Nevertheless, Daw's experiment on the visibility of after-images provides an important insight into understanding color appearances. The signals sent from the retina to higher levels are suppressed as stabilized images are suppressed. Color appearance is calculated from the "live image" incident at the moment while the average adaptation of the rods and cones show no significant influence. Perhaps adaptation signals are suppressed, just as Daw's after-images were.

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