Mechanism of Color Constancy

John McCann
McCann Imaging
Belmont, MA, USA

Abstract

There are two widely held theories of color constancy based on very different mechanisms: *Chromatic Adaptation* and *Spatial Comparisons*. Chromatic Adaptation is based on the change of retinal sensitivity in response to changes in incident light. The Spatial Comparisons mechanism is insensitive to illumination changes because it uses ratios of radiance from different pixels in the image. A spatially uniform increase in long-wave light increases both the numerator and the denominator by the same factor, so that the ratio remains constant. Spatial Comparisons of all pixels in the image synthesize a constant image, when the long-, middle-, and short-wave images are processed independently.

Measurements of color appearance in constancy experiments have shown that there are small consistent departures from perfect constancy. This paper measures the color and magnitude of these departures from perfect color constancy. It tests the hypothesis that these departures provide a signature of the underlying constancy mechanism. Since Chromatic Adaptation mechanism is specific for illumination, then these departures are predicted to be the same, regardless of the color of the paper. Since the Spatial Comparisons mechanism is based on the Integrated Reflectance of the paper, gray papers should show greater constancy than colored papers. In other words, the signature of Chromatic Adaptation is constant departures for each illumination, while the signature of Spatial Comparisons is variable departures for each reflectance. This paper measures the color matches for a yellow, a purple and a gray paper in 27 different illuminants.

Introduction

Human vision demonstrates a fascinating property, namely the color appearance of objects in a complex scene are independent of the quanta catch of the retinal receptors. Changing the spectral content of the illuminant has almost no effect of the color of objects, hence the name color constancy. This constant appearance of colors in changing spectral illumination has been the subject of many models employing Physics, Physiology and Psychophysics.[1-3] This paper compares the expected departure from perfect constancy generated by two types of human color vision models. One type, called Chromatic Adaptation models, is mainly psychophysical.[3,4] These models calculate the appearance of objects and require the measurement of the reflectance and the illumination at each pixel. The other type is mainly physical at the first stages. It calculates the signals generated by receptors acting as sets using spatial comparisons.[2] It only requires the radiances at all pixels falling on the eye.

The Adaptation Model Calculation

Almost all Chromatic Adaptation models use only a single pixel in their calculation. They change receptor sensitivity in response to changes in illumination. It is important to differentiate this adaptation from physiological adaptation involving recovery of visual thresholds with time in the dark (dark adaptation) and changes in neural responses with much brighter lights (light adaptation). Although much is known of these physiological mechanisms,[4] their properties do not correlate with the changes in appearance described here. The technique used in color appearance models is to measure the reflectance and the illumination at each pixel in the field of view. This correction for changes in illumination are made as the first stage of the model calculation. There are many different models based on adaptation with a wide array of different color transforms[3]. For simplicity, in this paper we will discuss the von Kries progenitor transform that changes sensitivity proportional to changes in illumination.

Spatial Comparisons Model Calculation

Spatial models use the light entering the eye from the entire field of view as the input to the model. It measures the ratios of radiances to synthesize an image from all the spatial comparisons found in the image. It keeps separate the long-, middle-, and short- wave information. Color is the result of the comparison of these three spatial calculations. Spatial comparisons do not require any information about changes in illumination and do not employ any changes in sensitivity with different illuminants. Obviously, the documented retinal light- and dark-adaptation processes control the retinal response for the image. The point here is that the hypothetical chromatic adaptation is not required in spatial comparison models of constancy.

Departure from Perfect Constancy

Since these two models have such different characteristics, it seems possible that the departures from perfect constancy can provide a signature of the underlying color mechanism.[5] This paper discusses how the adaptation model and the spatial comparison model can account for the lack of perfect constancy. It uses the size and direction of color shifts as a signature of the underlying mechanism.

The adaptation models use the change in illumination as the operational information to produce color constancy. If we assume that the scene has uniform illumination over the field of view, then adaptation mechanisms will generate a global shift, the same for all colors, in response to uniform changes in illumination.

The proposed mechanism for lack of perfect constancy in the spatial comparison model is crosstalk between light receptors. The long-wave receptor response is the sum of its response to red light (signal), plus its response to green light (crosstalk), plus its response to blue light (crosstalk). Since the response for each component is the product of reflectance and illumination, changes in illumination introduce nonlinear changes in the receptor's combined response. The spatial comparison model takes the ratio of responses for the yellow paper to the response from the white paper to synthesize the relative reflectances. The crosstalk characteristic in the spatial comparison mechanism is dependent on the particular paper and the particular illumination change. The crosstalk model predicts constancy discrepancies that are nonuniform. They are variable in magnitude and color direction. Their size and direction are different for every change in reflectance.

The notable exception is a neutral gray paper that has the same reflectance in long-, middle-, and short- wave light. The unwanted crosstalk components, described above, leave the integrated reflectance unchanged, because the crosstalk contribution is the same as the signal information. Gray papers have constant Integrated Reflectances with variable illumination. Colored papers have variable Integrated Reflectance with variable illumination.[6]

Experimental Procedure

Figures 1 shows three photographs of the experimental apparatus. The observers alternatively looked at a tungsten-lit Munsell Book with the left eye and into the integrating hemisphere with the right. The hemisphere has 12 LEDs mounted on the side. The control switchboard can turn on 1, 2, or 4 LEDs for each of 625 (LXHL-PD01), 530 (LXHL-PM01), and 425 (LXHL-PM01) Lumiled emitters. The power supplies were monitored so that they maintained constant voltage and were not current limited with 1, 2 and 4 LEDs on. This insured that the radiant outputs were factors of 1, 2, and 4. All combinations of three wavelengths and three intensity levels gives us 27 different illuminants. The combinations are quickly generated by the use of a control switch box. The dome integrates the light so that the illumination falling on the papers is very uniform. Figure 2 plots the 1931 CIE chromaticities of all illuminants. Eight combinations share chromaticities with other illuminants. Table 1 shows the 1931 X, Y, Z sensitivities to 625, 530, and 455 and the list of the 27 combinations plotted in Figure 1.

Figure 1 (Top) shows the experimental apparatus. A collection of papers are placed on a white background. Adjacent to the papers is an array of 12 LEDs - four 625nm, four 530nm and four 455nm. The photograph shows the 421 configuration, meaning that all four 625 LEDs are on, two 530 are on and one 455 is on. The relative intensities of long-, middle and short wave illumination is controlled by the number of LED emitters. The black box on the right contains the on/off switches. The constant voltage power supplies for LEDs are in the upper right. The Munsell Book for color matching is shown in the upper left.
(Middle) The device with diffuse integrating hemisphere with viewing window in the top..
(Bottom) View of papers in spatially uniform illumination with opaque dome cover.

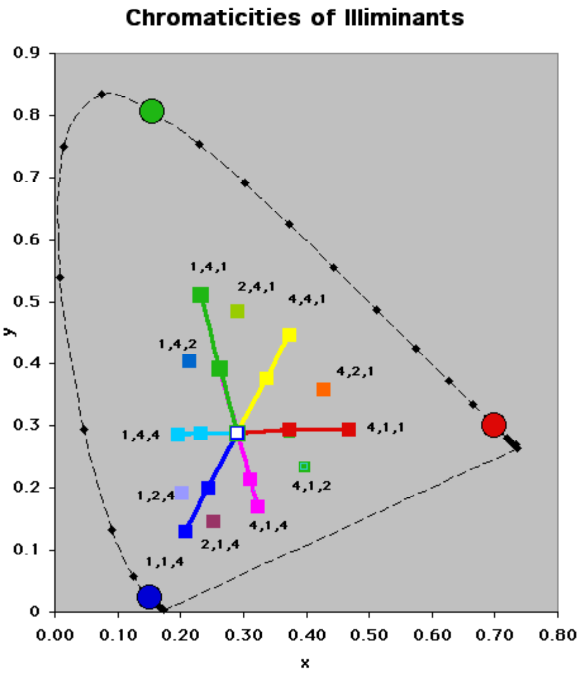
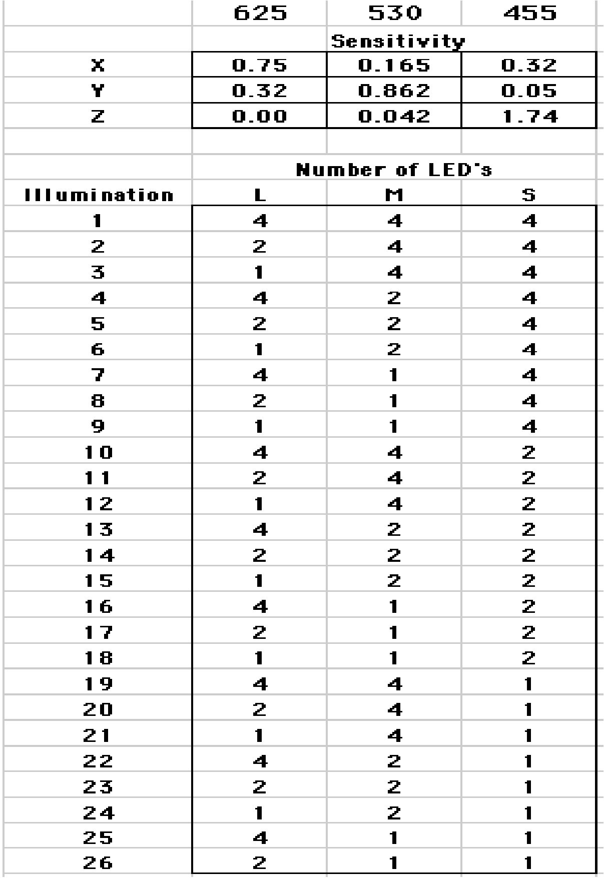


Figure 2 plots the 1931 Chromaticities of the 27 illuminants used in the experiment, The large red , green and blue circles plot the 625, 530 and 455 LED light sources. The red square labeled 4,1,1 is the chromaticity of four 625 LEDs with one 530 LED and one 455 LED. The green square labeled 1,4,1 is the chromaticity of one 625 LED with four 530 LEDs and one 455 LED. The other 25 illuminants are listed in Table 1.



	625	530	455
		Sensitivity	
X	0.75	0.165	0.32
Y	0.32	0.862	0.05
Z	0.00	0.042	1.74
		Number of LED's	
Illumination	L	M	S
1	4	4	4
2	2	4	4
3	1	4	4
4	4	2	4
5	2	2	4
6	1	2	4
7	4	1	4
8	2	1	4
9	1	1	4
10	4	4	2
11	2	4	2
12	1	4	2
13	4	2	2
14	2	2	2
15	1	2	2
16	4	1	2
17	2	1	2
18	1	1	2
19	4	4	1
20	2	4	1
21	1	4	1
22	4	2	1
23	2	2	1
24	1	2	1
25	4	1	1
26	2	1	1

Table 1 lists the X,Y Z sensitivities to the three types of LEDs. It also lists the 27 combinations of 12 LEDs (four 625, four 530, four 455).

The range of these combinations is very large. By varying the amount of each narrow wave band by 4 to 1, we cover an area of the chromaticity plot roughly equivalent to the range of papers in the Munsell Book.

Figure 3 is a photograph of the three papers used in the experiment. They are matte surface Commercial paint chips. *Skyline Steel* (Behr 750E-3^u) is a neutral gray. *Sunburst* (Martin Seymour) 127-5(YE) is a yellow. *Weeping Wisteria* (Behr 650A-3^p) is a purple.

The experiments consisted of four matches for each paper in each illumination with two observers. Both observers have perfect scores in the Munsell 100-Hue test. The data was analyzed for each observer independently. The result were so similar that the data shown is the average of both observers.

Figure 3 is a photograph of the three papers used in these experiments. They are most closely matched to the Munsell Book in tungsten light by N 7.5, 2.5Y7.5/10, and 2.5P8/6.

Sunburst	Aver			Weeping	Wisteria	Aver		Skylight	0	Aver	
0	ML	Ma	Mb	0	ML	Ma	Mb		ML	Ma	Mb
444	78.1	10.9	56.3	444	80.6	12.9	-18.1	444	75.0	0.0	
442	77.5	9.8	56.6	442	79.7	12.5	-21.5	442	75.0	0.0	
441	76.9	11.7	58.7	441	81.6	10.0	-17.0	441	76.9	-0.1	
424	76.3	20.3	62.6	424	78.4	18.6	-26.6	424	75.0	0.0	
422	78.8	18.0	59.8	422	76.9	19.8	-25.7	422	75.0	0.0	
421	78.1	17.8	58.5	421	78.1	17.2	-21.2	421	75.6	0.3	
414	70.6	33.3	62.7	414	74.7	27.1	-29.3	414	75.6	6.4	
412	69.4	29.2	63.4	412	76.9	26.3	-28.2	412	75.0	5.1	
411	71.3	28.1	61.2	411	76.9	28.0	-28.5	411	75.9	8.0	
244	77.5	6.5	57.6	244	78.8	14.5	-25.4	244	75.0	0.3	
242	77.5	3.5	57.8	242	79.4	10.6	-21.2	242	75.6	0.0	
241	77.5	3.5	56.0	241	80.6	9.0	-19.2	241	76.3	-1.1	
224	76.3	9.4	59.3	224	79.4	16.0	-26.7	224	75.0	0.1	
222	78.1	9.8	56.6	222	78.1	15.1	-25.8	222	75.0	-0.1	
221	76.9	13.6	57.0	221	79.4	13.8	-22.3	221	75.0	-0.2	
214	72.5	26.3	65.8	214	76.9	19.4	-26.0	214	75.6	2.0	
212	73.1	22.1	60.5	212	77.8	21.6	-27.5	212	75.0	1.3	
211	71.9	23.6	64.4	211	77.5	19.4	-24.4	211	75.0	-0.3	
144	77.2	-3.7	54.7	144	78.8	8.3	-21.4	144	75.0	-1.1	
142	78.8	-4.5	59.6	142	80.0	9.7	-23.2	142	76.3	-0.5	
141	77.5	-2.9	61.0	141	80.3	5.9	-18.9	141	77.5	-1.5	
124	79.4	1.0	56.2	124	79.7	10.0	-24.8	124	75.0	0.6	
122	77.5	1.2	58.7	122	78.1	10.0	-24.9	122	75.0	0.1	
121	76.3	1.2	56.8	121	79.4	6.8	-18.8	121	76.3	-0.4	
114	75.6	8.6	54.7	114	77.5	14.6	-26.9	114	76.6	2.1	
112	77.5	9.7	54.0	112	78.1	13.8	-27.2	112	75.0	0.0	
111	76.9	9.4	59.3	111	77.5	11.6	-20.6	111	75.0	-0.1	
Average	76.1	11.7	58.9	Average	78.6	14.9	-23.8	Average	75.5	0.8	
Max	79.4	33.3	65.8	Max	81.6	28.0	-17.0	Max	77.5	8.0	
Min	69.4	-4.5	54.0	Min	74.7	5.9	-29.3	Min	75.0	-1.5	
Range	10.0	37.7	11.7	Range	6.9	22.0	12.3	Range	2.5	9.5	

Table 2 lists the average match for both observers in MLAB space. The 27 illuminantes are listed vertically. The three papers are arranged horizontally. The bottom lists the Average, Maximum, Minimum and Range(Max-Min).

Predictions: Chromatic Adaptation

Incomplete Chromatic Adaptation is based on changes in illuminants. It asserts that the visual system adjusts its sensitivity to the changes in illumination, but not completely.[4] It is a psychophysical change that first requires a process that determines the illumination change.

Since it is based on illumination, then we would expect:

- The direction and magnitude of departures from constancy will be the same for all papers
- The hue pattern of results will mimic the pattern of illumination shifts
- Matches will fall on the line from stimulus to perfect constancy.[4]

Predictions: Spatial Comparisons

If the underlying mechanism of constancy is spatial, then overall changes in illumination should result in perfect constancy. The departures observed have a physical explanation. The human sensors have so much spectral overlap that they generate crosstalk between channels. The middle-wave cone response has a substantial contribution from red light. To understand the spatial ratios we need to integrate the each type of cone's response to 625, 530, and 455 illuminants. Scaled Integrated Reflectance is the ratio of a cones response to a particular paper to its response to a white paper. Scaled integrated reflectance is constant for gray papers with changes in illumination. However, scaled integrated reflectance is variable for colored papers with changes in illumination because the paper has different reflectances for 625 and 530.. Spatial Comparisons predicts that departures from perfect constancy correlate with changes in Integrated Reflectance. It is a physical change that can be calculated from measurements of the paper, the illumination, and the sensitivity of the L-, M-, S- cones.

Since Integrated Reflectance is based on integration of reflectance and illumination, then we would expect:

- The direction and magnitude of shifts will be different for gray and colored papers.
- The hue pattern of discrepancies from constancy caused by changing papers and illuminants will mimic the pattern of Integrated Reflectances.
- Matches need not fall on the line from stimulus to perfect constancy.

Matches

Table 2 lists the average matches in MLAB space[7-9], derived directly from Munsell Hue, Lightness and Chroma .

$$ML = \text{Munsell Lightness} * 10.$$

$$Ma = COS\ (\text{Hue angle} * 5 * \text{Chroma})$$

$$Mb = SIN\ \ (\text{Hue angle} * 5 * \text{Chroma})$$

This space mimics the familiar shape of L*a*b* space, but avoids the isotropic distortions introduced by it. [8,9]

The left third of Table 2 shows the matches for Sunburst. The bottom of the table lists the Average, Maximum, Minimum, and Range (Max-Min) for ML, Ma, Mb. The range of matches for ML Lightness is 10, or 1 Munsell chip. The range of Ma is 37.7. The range of Mb is 11.7. In Munsell notation, that is from 7.5YR in 412 illumination to 6.25Y in 144 illumination, nearly 4 pages or 10% of the Hue circle. In Munsell Chroma it is from 12 to 14. In summary, we see a substantial directional shift for the yellow Sunburst paper. The illuminants for the maximum Ma was 412 (magenta) and for the minimum Ma was 144 (the most cyan).

The central third of Table 2 shows the matches for Weeping Wisteria. The range of matches for ML Lightness is 6.9, or less than Munsell chip. The range of Ma is 22.0. The range of Mb is 12.3. In Munsell notation that is from 7.5P in 411 illumination to 2.5P in 141 illumination, 2 pages or 5% of the Hue circle. In Munsell Chroma it is from 8 to 4. In summary, for purple we see a different directional shift from the yellow paper. The illuminants were 411 the most red and 141 the most green.

The right third of Table 2 shows the matches for the gray paper, Skyline Steel. The range of matches for ML Lightness is 2.5, or less than one Munsell chip. The range of Ma is 9.5. The range of Mb is 10.3. In summary, for gray there is nearly no change in match with illumination.

Analysis of Matches

All matches are plotted in Figure 4. The matches for the yellow paper are spread over a wide range of Ma values with a small range in Mb. The matches for the purple paper vary over both Ma and Mb, but over a smaller range. The matches for the gray paper are narrowly distributed around 0, 0. The exception is the matches for 411, 412, 414, that all have Ma values greater than 5.0. There is a small slant from upper left to lower right.

Analysis of Integrated Reflectances

Integrated reflectance is the ratio of a papers radiance to a white papers radiance. L, M, S values were calculating using normalized cone sensitivities.[10] The cone sensitivi-

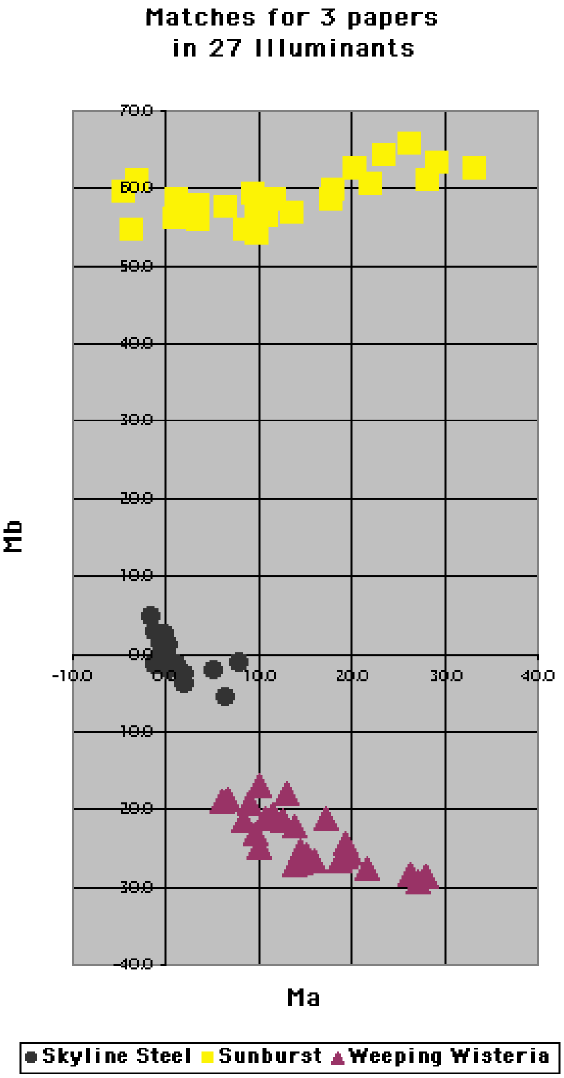


Figure 4 plots in Ma Mb space the average match for all 27 illuminants for three different papers. Sunburst is a low chroma yellow; and Weeping Willow is purple paper; Skyline Steel is a neutral gray.

The matches for the yellow paper (Sunburst) are spread over 37.7 units on the Ma axis and over 11.7 units on the Mb axis. The mean Ma value is 11.7 ± 10.6; the mean Mb value is 58.9 ± 3.1.

The matches for the blue purple paper (Weeping Willow) are spread over 21.8 units on the Ma axis and over 11.8 units on the Mb axis. The mean Ma value is 16.8 ± 6.0; the mean Mb value is -20.4 ± 3.2.

The matches for the gray paper are clustered around 0,0. The mean Ma value is 0.8 ± 2.2; the range 9.5. The mean Mb value is -0.3 ± 2.0; the range 10.3.

ties for each waveband are:

	625	530	455
L cone	50	4	0
M cone	60	95	5
S cone	0	0	100

Figure 5 plots L and M Integrated Reflectances normalized by the sum L+M+S. As described earlier, gray papers show no shift in integrated reflectance because of constant reflectances for all three narrow-band illuminants. The purple paper shows a significant shift in reflectances. The yellow paper shows the largest shift. Again, it is a narrow track of changes quite different from the distribution of changes in illumination seen in Figure 2. All reflectances collapse to a single track for colored papers and to a point for gray.

Detailed Analysis of Sunburst Matches.

The plots of Sunburst matches Ma/Mb are highly overlapped. In order to understand the relationship of effects of reflectances and illuminants we need to track the changes for each illuminant. Figure 6 plots the matches illuminant by illuminant. The red line shows the progression from 411, 422, 211, to 222; Magenta line plots the progression from 414, 424, 212, to 222, etc. The plus sign (+) identifies the 421, 241, 142, 124, 214, 412.

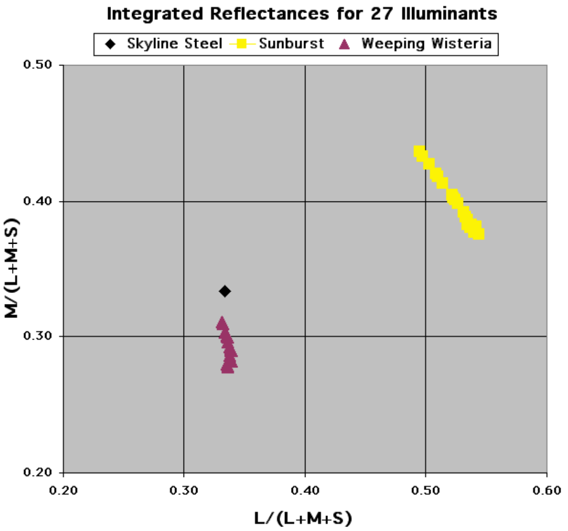


Figure 5 plots the normalized Integrated Reflectance of the three papers as influenced by the 27 illuminants. As described in the text the integrated reflectance for a neutral gray paper is unchanged with spectral shifts of illumination. The yellow paper shows a large unidirectional shift. The purple show a smaller change in integrated reflectance in a different spectral direction.

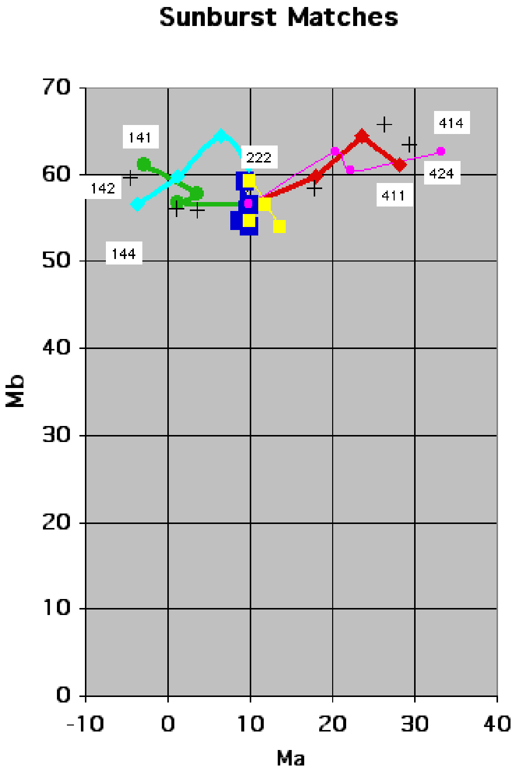


Figure 6 replots the average matches for the yellow paper in Ma, Mb coordinates to identify the different illuminants. The red data starts with 411 (four 625, one 530 and one 455 LEDs) 422, 211. The green data starts with 141 (one 625, four 530 and one 455 LEDs) 242, 121. All lines end at the matches for 111, 222, and 444. The red and magenta matches fall on top of each other, as does the green and cyan data. Blue and yellow data fall on top of the 111, 222 and 444 matches.

The entire range from 441 (yellow) to 114 (blue) are very closely clustered at Ma =10. Neutral 111, 222, and 444 fall in the same cluster. Matches for red, and magentas, and 421, 412, 241 illuminants cover the range from the central cluster to Ma = +30. Matches for cyan and green, and 124, 142, 241 illuminants cover the range from the central cluster to Ma = -5.0.

The observer data from 421 (orange) to 214 (blue purple) all collapse to the same +Ma tract. All observer data from 124 (blue-green-blue) to 421 (yellow green) all collapse to the same -Ma tract. This is exactly the behavior predicted by the Spatial Comparisons hypothesis. Figure 7 plots L Integrated reflectance vs. M Integrated reflectance for all 27 illuminants with the yellow paper. All Integrated Reflectances collapse to a single curve combining the colors on either side of yellow and blue illuminants. The variability in Figure 6 appears to be from the limits of observer matches using the Munsell Book.

Observer matches correlate with the calculated integrated reflectances. Very similar results are found for Weep-

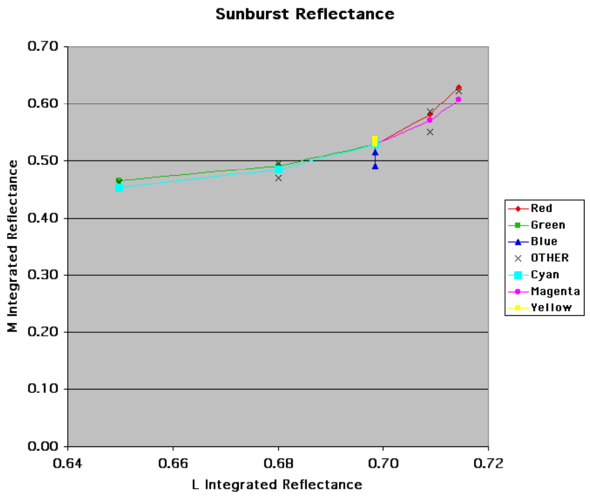


Figure 7 plot the Integrated Reflectance of the yellow Sunburst paper, The L-cone integration is the sensitivity of the L-cones multiplied by the paper's reflectance multiplied by the illuminant. The Integrated reflectance is the ratio of the integration for yellow divided by the integration for the white. Since the cone sensitivities overlap, Integrated Reflectance changes with spectral change in illumination

ing Wisteria. The predictions for gray predict the are that there will be no displacements, only experimental variability.

The predictions for Spatial Comparisons were all observed in the experimental data.

- The direction and magnitude of the departures from constancy were different for gray and colored papers (Figure 4).
- The pattern of discrepancies caused by changing papers and illuminants mimics the pattern of Integrated Reflectances (Figures 6 and 7).
- Not all matches fell on the line from stimulus to perfect constancy.

Discussion

The results of these experiments are consistent with the Spatial Contrast mechanism. Is it also true that these results are inconsistent with the Chromatic Adaptation mechanism?

To provide a reasonable approximation of Incomplete Adaptation we compressed the chromaticities. If the new illuminant moved the chromaticity away from that of 222 a distance x, the compression moved it 2/3 the way back toward 222. The remainder we will call 1/3 incomplete adaptation. We calculated the chromaticities for 1/3 Incomplete Adaptation for all illuminants. The argument described by Nayatani[4] was that incomplete Chromatic Adaptation would confine the color matches to the line between the chromaticities of the original start and the chromaticities associated with the change in illumination.

As described above, the adaptation hypothesis is based on the compensation for change in illumination only. In a complex display involving many papers (including white, black, red, green, blue and other colors) with all present for all experiments, there should be no change in adaptation state with change in experimenter's question. Namely, when the observer is asked to now match the purple paper, instead of the yellow, it should not affect the adaptation state.

If the above hypothesis is correct then the patterns of departures from perfect constancy must be the same for gray, yellow and purple papers. The data does not support this hypothesis. Gray paper showed very little departure from constancy while the yellow showed considerable changes.

Further, we can look at the pattern of departures expected from the incomplete adaptation hypothesis. In Figure 2 plots the array of illuminants in 1931 CIE chromaticity. This is a very convenient reference because of universal familiarity. It has the weakness that it is not isotropic plot color appearance. Throughout the paper we have used either the Munsell notation or MLAB a direct translation that does not distort Munsell space based on millions of observations. We need to evaluate the Incomplete Chromatic Adaptation hypothesis, based on the distributions of illuminants, but we need to translate that into a truly isotropic space.

Stiles and Wysecki[1] provides a table of chromaticities for each Munsell chip. We can use this data table to make the transform the illuminants plotted in Figure 2 from 1931 CIE xy to MLAB. Figure 8 is a plot of all 27 illuminants in MLAB space assuming 1/3 incomplete adaptation. This plot rotates and compresses the CIE chromaticities along the orange-turquoise axis. Nevertheless, the pattern of the illuminants remains. The red-cyan, the yellow-blue and the green -magenta axes divide the space into roughly equal regions. The yellow-blue plot does not collapse on to the 111, 222, 444 matches. The red and magenta data do not collapse on top of each other. The same is true for the cyan and green data. Most striking the fact that the + symbols identifying the 421, 241, 142, 124, 214, 412 illuminants remain distinct from the red and magenta and the cyan and green tracts. This pattern of matches predicted by a general incomplete adaptation model is different from that in the observer matches. More complete adaptation is needed to better approximate observer magnitude of the results for gray. Less complete adaptation is needed for the magnitude of the yellow paper. Elaborate departures for the level of incompleteness are needed to account for the chromatic pattern of matching data.

The three predictions for Chromatic Adaptation did not agree with measurements.

- The direction and magnitude of shifts was not the same for all papers
- The pattern of results did not reflect the pattern of illumination shifts

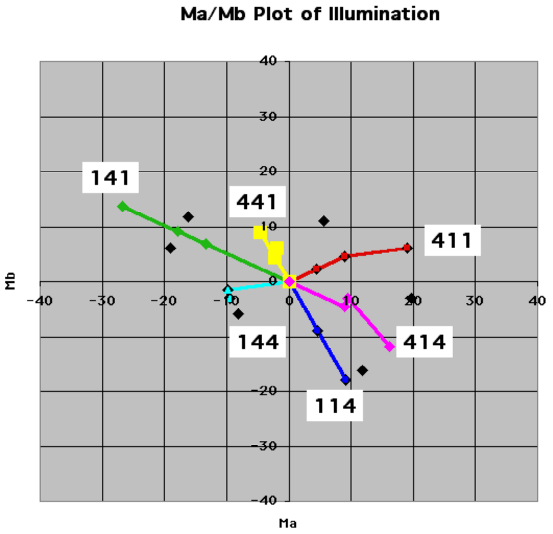


Figure 8 plots the 27 combinations of illuminants in Ma, Mb space. Note the rotation of the green /magenta axis 45 degrees counterclockwise. Also note the compression of the array along the orange/turquoise axis as compared to the plot in Figure 2.

- Matches did not fall on the line from stimulus to perfect constancy

Summary

This paper measures the departures from perfect color constancy using 27 illuminants and three papers. The intent was to compare the predictions from Chromatic Adaptation theory based on illumination with those of Spatial Interactions based on Integrated Reflectance. The results show excellent correlation with Integrated Reflectance. All three predictions agreed with observer data. The results did not correlate with incomplete Chromatic Adaptation. All three predictions were not supported by matches. It is important here to distinguish between Chromatic Adaptation, the psychophysical hypothesis, and light- and dark-adaptations, the physiological entities. The point here is that vision's elegant adaptation mechanism is not used directly by our color constancy mechanism.

References

1. G. Wyszecki and W. S. Stiles, Color Science: Concepts and Methods Quantitative Data and Formulae, 2nd Ed, John Wiley & Sons, New York, pp.117-767, 840-852, 1982.
2. E. H. Land "The Retinex", Am. Scientist, 52 pp.247-264 1964.
3. M. Fairchild, Color Appearance Models, Addison Wesley, Reading, 1998
4. Y.Nayatani, A simple estimation method for effective adaptation coefficient, Color Res. Appl. **20**, 259-274, 1997.
5. J.E.Dowling, "The retina: an approachable part of the brain", Harvard University Press, Cambridge, 1987
6. J. J. McCann S. McKee and T. Taylor "Quantitative studies in Retinex theory: A comparison between theoretical predictions and observer responses to 'Color Mondrian' experiments" *Vision Res*. **16** 445-458, 1976.
7. G. Marcu, "Gamut Mapping in Munsell Constant Hue Sections", in Proc. 6th IS&T/SID Color Imaging Conference, Scottsdale, Arizona, p. 159, (1998)
8. J. J. McCann, "Color spaces for color mapping", *J. Electronic Imaging, **8**, pp. 354-364, (1999);*
9. J.J. McCann, Uniform Color Spaces: 3D LUTs vs. Algorithms, Proc. Second IS&T PICS Conference,**2,** pp. 204-208, (1999);
10. E. H. Land, "The Retinex Theory of Colour Vision", Proc. Roy. Institution Gr. Britain, 47, 23-58, 1974.

Biography

John McCann received his A.B. degree in Biology from Harvard University in 1964. He did research and managed the Vision Research Laboratory at Polaroid from 1961 to 1996. His work concentrated on research in human color vision, large format instant photography and the reproduction of fine art. He is a Fellow of the IS&T. He is a past President of IS&T and the Artists Foundation, Boston. In 2003, he received the IS&T /OSA Edwin Land Medal. He is currently consulting and continuing his research on color vision.