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Limits of Color Constancy: Comparison of the signatures of chromatic adaptation and spatial comparisons

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Abstract

Color Constancy has two hypothetical mechanisms: Chromatic Adaptation and Spatial Comparisons. These mechanisms have different fundamental properties. Adaptation models work with small individual scene segments. They combine radiance measurements of individual segments with the modeler's selected parameters that scale the receptor's cone quanta catches. Alternatively, spatial models use the radiance map of the entire field of view to calculate appearances of all image segments simultaneously. They achieve independence from spectral shifts in illumination by making spatial comparisons within each L, M, S *color channel. These spatial comparisons respond to color crosstalk caused by the overlap of spectral sensitivities of cone visual pigments. L, M, and S cones respond to every visible wavelength. Crosstalk causes the spatial comparisons of cone responses to vary with changes in spectral illumination. Color Constancy works best in spatially uniform, and variable spectral illumination. Measurements of Color Constancy show systematic departures from perfect constancy. These limits of Color Constancy are predicted by spatial comparisons with cone Crosstalk. These limits do not correlate with Chromatic Adaptation models. This paper describes cone Crosstalk, and reviews a series of measurements of the limits of Color Constancy in variable spectral, spatial and real-life illuminations.*

Introduction

In 1872 Hering wrote about the approximate constancy of appearances of objects in different illuminations.[1] 1872 was 147 years ago - a long time. Victoria was Queen of the British Royal Empire, Ulysses S. Grant was president of the United States; five years earlier the United States purchased Alaska from Russia for 7.2 million dollars; Napoleon III had just been exiled, Bismarck was the Chancellor of the German Empire; and Taiwan was under Japanese rule.

Although many problems have been solved since then, the mechanism controlling Color Constancy remains a matter for debate. There are two main threads that fall onto a persistent debate between bottom-up vs. top-down hypotheses. Figure 1 identifies the *"Discount Illumination"* and the *"Synthesize Appearance from Edges"* threads. The nineteenths century top-down idea assumes that it is possible for human vision to recognize the color of the illumination. With that knowledge, it is straight forward to scale the cone quanta catch values to be proportional to the object's surface reflectance. These *"Discount Illumination"* calculations are modeled on tiny image segments, one at a time. The history of this thread begins with Helmholtz [2]; and continues with von Kries [3]; Hunt [4]; Nayatani [5], Fairchild [6] , and Moroney et al. CIE Color Appearance Models (CIECAM)[7]. The input to CIECAM models calculation is the spectral radiance from a tiny scene segments; four assigned parameters; and the illumination spectral radiance. Although CIECAM calculations require measurements of the illumination, von Kries proposed earlier that Chromatic Adaptation as a visual mechanism for Discounting Illumination. It suggests that the L, M, S cone sensitivities automatically adjust to the scenes spectra content. Hurvich wrote: "Chromatic Adaptation refers to the changes in the eye sensitivity when it is exposed to chromatic stimulation. Here the changes in sensitivity tend to compensate for the spectral quality of the light rather than the changes in its overall level." He describes von Kries idea that the strength of chromatic adaption responds inversely to the cones activation.[8]

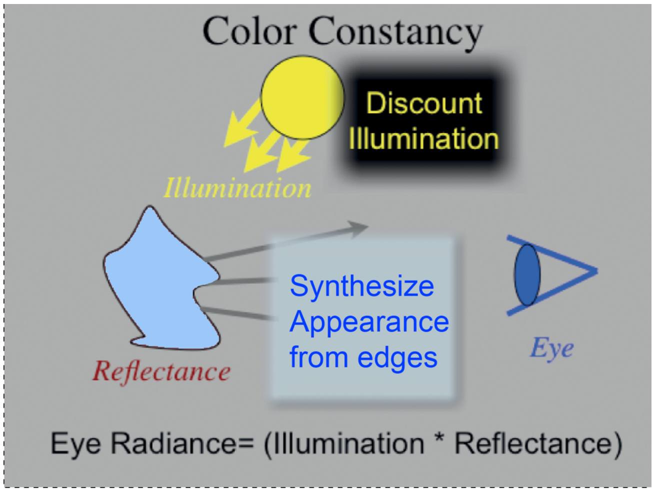

Figure 1 illustrates the Color Constancy debate. The light from the illuminant (yellow in illustration) falls on the reflective surface (blue in illustration) so as to modify the spectrum of the light reaching the observer's eye. The top-down hypothesis requires finding the spectra of the illumination, so as to "discount" it. That approach predicts that the eye responds to the surface properties of the object at each tiny scene segment. The alternative approach compares cone quanta catches from all of the scene segments in the field of view. Appearance results from the relative, spatially-compared cone quanta catches, not the absolute quanta catch values at each tiny segment.

The second approach requires the accurate cone-quanta-catch measurements from the entire field of view in front of the observer. The Spatial Comparisons output is largely indifferent to the absolute quanta catch at any individual scene segment. Spatial comparisons across the entire scene calculate the relative appearance of every scene segment simultaneously. It is an approach built around the study of scenes, not pixels. This bottom-up approach synthesizes appearance from spatial comparisons.[9]

Resolving the Color Constancy debate

Land's color vision experiments [10] moved the Constancy discussion from the general use of color names to the quantitative evaluation of the retinal rods and cone responses from real scenes. Land's Double Color Mondrian experiment [11] showed that two identical stimuli (with identical triplets of radiances), viewed in the same room at the same time, appeared very different colors. Figure 2 illustrates that experiment.

Land showed that a particular triplet of Long-(L), Middle-(M), Short-(S) Wave cone responses can appear any color. The rest of the observers' field of view determines the appearance of cone responses. [12,13]

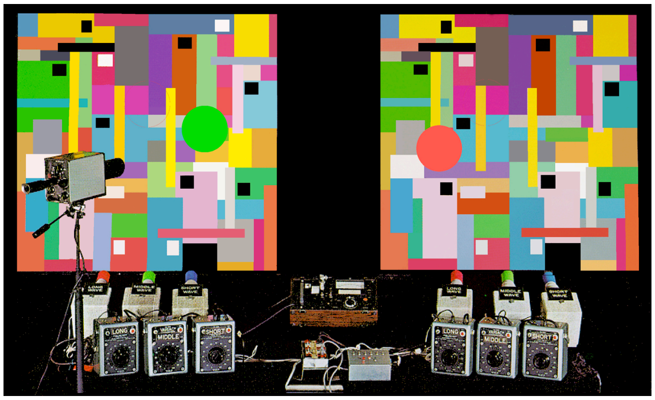

Figure 2 illustrates that Land's Double Mondrian. It showed a green paper (circular) in the left Mondrian that appeared green, despite the fact it had identical cone as the red circle in the right Mondrian in different illumination. This illustration does not reproduce the experiment.

Land's Color Mondrian experiments provided strong evidence in support of bottom-up spatial comparison mechanisms. However, it did not demonstrate that chromatic adaptation hypothesis could not be responsible for Color Constancy. The theme of this paper is to review experiments that measure the limits of Color Constancy. Those limits provide signatures of the underlying constancy mechanisms, and helps us resolve the debate.

Links to < Double Color Mondrian>

Figure 3 is a flow chart of a sequence of quantitative color measurements to study the debate. The idea is to find a series of signatures of the underlying physiological mechanisms to test the constancy hypotheses. Figure 3 provides links to the publications of 5 sets of quantitative color experiments designed to identify the signatures of Color Constancy (blue links).

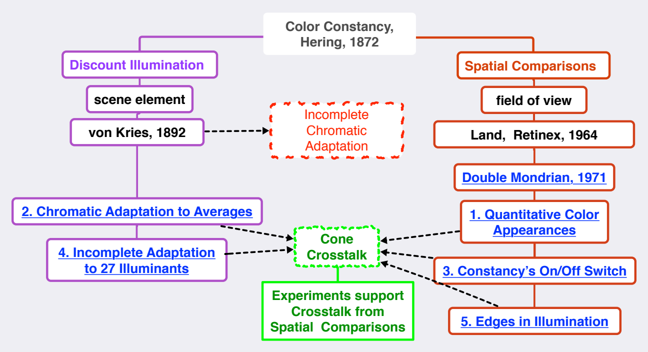

Figure 3 is an outline of the experiments designed to identify the physical limits of Color Constancy. The purple line illustrates the "Discount Illumination" thread of Helmholtz, von Kries, Hunt, Nayatani, Fairchild, Moroney and CIECAM models. The orange line illustrates the "Spatial Comparisons" thread of Land and McCann. Download Figure 3 for a copy of the .pdf file with links to references (blue underlined boxes)

Downloaded Links <Fig3 Constancy>

<http://mccannimaging.com/Review_CC/Constancy_files/Fig3%20Constancy.pdf>

1. Quantitative Color Appearances

Using the McCann, McKee and Taylor (MMT) smaller "*17-area Mondrian*" (Figure13,left), observers matched the appearances of all areas to chips in the Munsell Book.[14] Both the Mondrian and Munsell Book were illuminated by the same mixture of 630, 540 and 450 nm narrowband light, but in separate lightboxes (Mondrian-left/MunsellBook-right eye). The first control experiment, began with measurements of the 630, 540 and 450 nm radiances (***L, M, S***) coming to the eye from a middle-gray Munsell N/6.75 paper. Observers matched all 17 areas in that spatially uniform illumination equal to that on the Munsell book. In the second experiment, the amounts of the three illuminants were uniformly adjusted so that the radiance triplet ***L, M, S*** came from the red Munsell 10RP 6/10 paper in the Mondrian. Observers matched all 17 areas in the second illuminant. In the next 3 experiments the illuminants were adjusted for 2.5PB 6/8, 2.5G 7/4, 5Y 8.5/10 Munsell papers in the Mondrian.

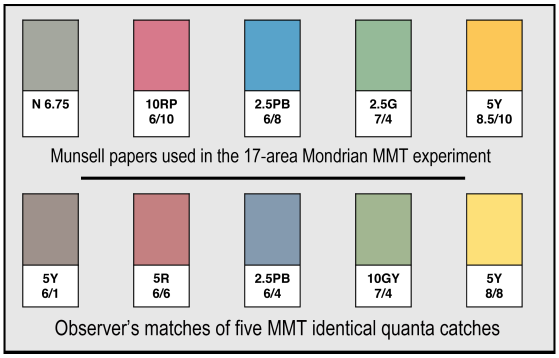

Figure 4 is an illustration of the five Munsell papers, and their matches, in the five MMT experiments. Starting with the control gray N 6.75, they measured **L, M, S** *radiances coming to the observer's eye. In the next four experiments they individually adjusted the illumination so that* **L, M, S** *came from 10 RP 6/10, then 2.5PB 6/8, 2.5G 7/4, 5Y 8.5/10 Munsell papers (Figure 4, top row) in 5 substantially different illuminants. With individually adjusted illuminants, the papers had identical cone quanta catches. Observers matched those 5 papers to the Munsell Book in constant illumination to 5YR 6/1, 5R 6/6, 2.5PB 6/4, 10GY 7/4, 5Y 8/8 (Figure 4, bottom row). The observed matches showed strong Color Constancy. The data correlated with the paper's Scaled Integrated Reflectance, rather than its cone quanta catch.*

In total 5 papers, in five different illuminants, sent identical ***L, M, S*** radiances to the eye. Observers's average matches to those 5 stimuli are shown in Figure 4.

The expanded study of all 17 papers' matches in the five illuminant mixtures revealed two important properties:

- Changes in the absolute radiance levels of illuminants changed matching appearances slightly.
  - More illumination correlated with higher lightness.
- Changes in the mixture of illuminants introduced small, systematic shifts in matching colors.
  - These shifts correlated with the overlap of cone spectral sensitivity (Crosstalk).

This set of quantitative data provides important information about the limits of Color Constancy. As with Land's Mondrians, these targets are made of spatially uniform reflective paper illuminated in spatially uniform illumination. There are no spatial gradients, or edges in these illuminants, unlike natural scenes. Nevertheless, there is clear evidence that constancy has finite limits. One can change the spectral composition by large amounts resulting in small shifts in appearance. However, when the illumination changes become too large, then constancy with illumination degrades quickly.

By design, Mondrian experiments used spatially uniform illumination and uniform reflectance papers. As a consequence, there is a direct correlation of illumination changes and scene average values. Color corrections in color photography simply use the average spectral radiance from the entire scene (or spectral radiance of the scene's illumination) to balance photographs for the most pleasing appearance. Color Constancy in these Mondrians is extremely easy to model using chromatic adaptation. Changing illuminations shifts all scene radiances by a constant factor.

Land's Color Mondrians demonstrated that identical ***L, M, S*** radiances generated any color sensation. McCann, McKee, and Taylor (MMT) showed that observers' matches were predicted by Scaled Integrated Reflectance (SIR) calculations. The SIR value for a sample is the edge ratio of that sample's radiance to an adjacent white paper's radiance - a spatial comparison - using a human cone sensitivity function. At the boundary, the illumination is equal on both sides. The L-SIR is the edge ratio using the broadband L-cone spectral sensitivity function. L-SIR represents the reflectance ratio measured by L cones on both sides of the edge. MMT scaled that L-cone reflectance using a cube-root function to convert from reflectance to Lightness (appearance).[15] As well, M-SIR, and S-SIR calculations used M- and S-cone spectral sensitivity functions. Physics-based reflectance is the ratio of radiances [Sample/Reference] using the narrowest possible band of wavelengths. It represents the surface of the paper. Human cone sensitivities are extremely broad (Figure 5). [16] In order for humans vision to calculate reflectance-like data it must use spectral sensitivity filters that are 100's of nanometers wide.

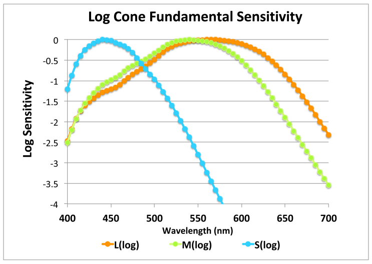

Figure 5 plots Stockham and Sharp's Cone Fundamentals.

Even narrowband illumination will excite two or more cones. L and M cone sensitivities are so similar that the 540 narrowband illumination becomes a substantial fraction of L-cone response. While the 630 nm illumination cares the 630 relative reflectance information, the 540 nm light carries very different information about the surface reflectance. The combined L-cone response is the sum if 630 nm and 540 nm information. L-cone Crosstalk is the unwanted addition of 540 and 450 nm reflectance information to the L-cone response. While color photography uses spectral sensitivities with extremely small color channel crosstalk, human vision has massive Crosstalk.

The Color Mondrian experiments use adjustments of the relative amounts of 630, 540, 450nm illuminations. These adjustments alter the amounts of crosstalk responses of the ***L, M, S*** cones. Crosstalk accounts for the departures from perfect constancy with changes in spectral illumination, and determines the limits of Color Constancy.

Link to <1. Quantitative Color Appearances>

2. Chromatic Adaptation to Averages

Does human vision mimic the color balancing mechanism that works for photographic cameras? The Chromatic Adaptation hypotheses (purple thread in Figure 3) are very similar to photographic color balancing techniques. The analysis of the spectra of the illumination, or the average radiance from all parts of the scene (Gray-World Assumption), provides a global correction factor for all scene segments. The following experiments measure human vision response to changes in the average radiance.

Figure 6 illustrates experiments that tests the role of the Chromatic Adaptation hypothesis in three parts. Observers matched the papers in three variants of the MMT experiment:

1. Matched the ***L, M, S*** radiances from a Gray paper in the control.
   - The averages from the entire scene = ***AVL, AVM, AVS***.
2. Matched the ***L, M, S*** radiances from a Red paper in the new illumination (adjusted average radiance).
   - The averages from the entire scene = ***AVL, AVM, AVS.***
3. Matched the radiances from a Red paper in the new illumination with a compensating surround.
   - The new surround canceled the illumination adjusment's effect on the average.
   - The averages from the entire scene = ***AVL, AVM, AVS.***

The design of the original MMT Mondrian experiments changed the average radiances in Step 2. This new experiments measured the magnitude of that change in average ***AVL2, AVM2, AVS2*** values. Then, in Step 3, it found a new background red paper that changed the average values back to those of the initial control experiment (***AVL, AVM, AVS***).

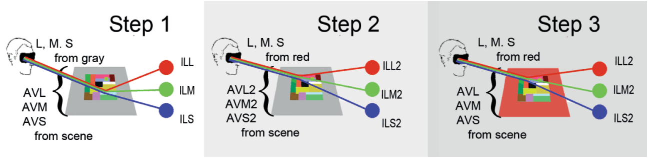

*Figure 6 shows control radiances **L, M, S** from the N6.75 paper, and average radiances from the entire scene **AVL, AVM, AVS** in Step 1. Changing the illumination in Step 2 sent **L,M,S** from 10RP 6/10, and alters the scene averages. Step 3 shows that the new red surround paper changes the scene averages back to the control values (**AVL, AVM, AVS**). In Step 3, 10RP 6/10 paper had both radiances and average radiances equal to those in Step 1.*

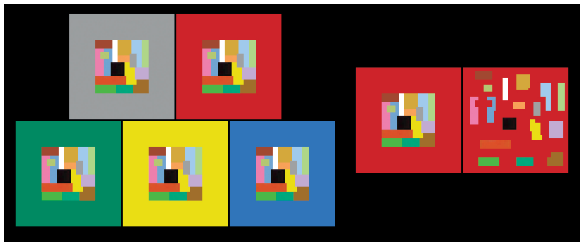

Figure 7 left) Five Step 3 Mondrians with different color surrounds that compensate for changes in scene averages caused by changes in illumination; (right) Global and Local Surround Mondrians.

Figure 7 illustrates the 10 Surround Mondrians designed to measure the effects of average scene radiance on color matches. Figure 7 (left) illustrates the 5 different surround papers added to the MMT 17 area Mondrian. Each surround cancelled the average effect of the illumination for one of the MMT experiments.

Incomplete Adaptation theorists do not provide computational spatial models of how the scene's content, local and global, affects adaptation. Figure 7 (right) illustrates one of 5 "Local Average Surround Mondrians". These 5 Mondrians were made of the identical sets of papers. Only their placement was altered. One of this pair looked for the average effect over the entire Mondrian; the other looked for local average effects. Observers' matches were very similar to those in the original MMT experiment for all 10 altered surround experiments. Both global and local surrounds made very large changes in average scene radiances, but those changes caused minimal changes in observer matches. [17]

These surround experiments tried to shut off Color Constancy using the principles of Chromatic Adaptation. Observers matched the Step 3 Mondrians papers for identical ***L, M, S*** radiances in five Mondrians with the same total average radiances (***AVL, AVM, AVS***) for the entire scene. If the average Mondrian radiance controlled the hypothetical *Discount the Illumination* mechanism, then we should have shut off Color Constancy in this experiment.

All five papers with constant radiances and average radiances should have identical appearances. These Mondrians showed the same Color Constancy found in the MMT data. The matching data showed the effect of very large shifts in average radiances caused tiny changes in appearance. There is no evidence that the scene average (Chromatic Adaptation) controls human Color Constancy.

Links to <2. Chromatic Adaptation to Averages>

3. Constancy's On/Off switch

The search for a way to shut off Color Constancy in complex images is a very important idea. If we really understand the underlying mechanisms, then we should be able to turn on, and turn off, constancy. When do identical ***L, M, S*** values look the same in different illuminations in a complex scene ?

Imagine that we have two scenes that are viewed sequentially. Assume that the state of adaptation for both scenes is constant. If the second scene has identical stimuli everywhere in the field of view, it must appear identical to the first. The array of cone quanta catches are identical. Vadim Maximov, proposed making two shoeboxes with different illuminations and carefully selected papers that combined to make two identical visual stimuli.

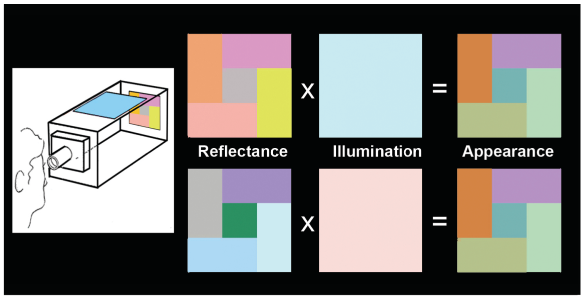

Figure 8 (left) Maximov's Shoe Box; (right) Color Constancy shut off with identical stimuli. Tatami A (top) used a 40 CC cyan filter, and Tatami B (bottom) used a 40 CC red filter.

Identical stimuli everywhere in the field of view have to look the same. Although these two sets of papers are difficult to make, it is possible, if one can manufacture exactly the colored papers required. The results show that Color Constancy in complex scenes can be shut off. The experiments study whether additions to the scene can restore Color Constancy.

Exact Color Constancy is achieved by exactly equal quanta catches everywhere in the field of view. It is difficult to argue against identical stimuli causing identical appearances. The *difficult* part is engineering a full set of papers that exactly compensate for the two different color balancing filters on the shoebox lid. When this challenge is achieved, then the two sets of different reflectances appear the same. We shut off constancy when viewing an array of reflectances - a complex image! [18]

The *interesting* part of this experiment is the study of the conditions that restore Color Constancy. The results showed that L, M, S, maxima all play a special role in appearance. Color Constancy spatially normalizes sensations to the maxima in the field of view; it does this for each waveband separately (Retinex). The experiments introduced a wide range of test patches with pairs of identical reflectances to both shoe boxes. New maximum quanta catch for any of the L, M, or S cones causes a reset of color appearance.[19] The introduction of any new L, M, or S maxima turns the Color-Constancy mechanism back on. It follows that the mechanism controlling Color Constancy uses the individual maxima in each waveband to calculate color sensations.

Link to <3. Constancy's On/Off Switch

4. Incomplete Adaptation to 27 Illuminants

CIE Color Appearance Models present the hypothesis that Color Constancy is controlled by Chromatic Adaptation. The limits of Color Constancy is modeled by calculating "Incomplete Adaptation" described by Nayatani.[20] Figure 9 illustrates the Incomplete Adaptation idea.

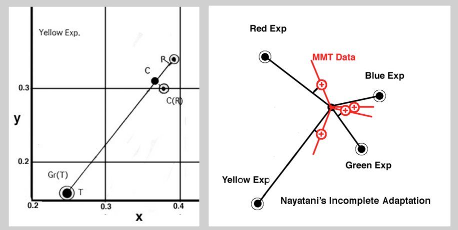

Figure 9 illustrates the incomplete adaptation idea. (left) From Nayatani [20]: The chromaticity plot of MMT's yellow paper's stimulus Gr(T); MMT match C(R); incomplete adaption C; and perfect constancy R. (right) From Nayatani's data: MMT matches shown in red; papers' stimuli chromaticity shown in black.

In Figure 9 (right), the central black dot represents the CIE ***xy*** chromaticity of the McCann, McKee and Taylor (MMT) gray paper N6.75 in the control illumination. The circled black dots plots the chromaticities of the 10RP 6/10, 2.5PB 6/8, 2.5G 7/4, 5Y 8.5/10 Munsell papers in the control illumination. The red + circles plot the MMT matching data. Nayatani argues that MMT's change in illumination controls Chromatic Adaptation resulting in Color Constancy. If adaptation were complete, then all MMT data should fall on the central black dot. Nayatani argued that adaptation is incomplete, so that Color Constancy approaches, but does not reach absolute constancy. Each change in illumination has its own unique chromatic adaptation vector in color space that results from scene's cone activations (controlled by changes in illumination).

The following experiments measured the effect of 27 different illuminants on observers' color matches of three constant papers. The illumination inside a diffusing plexiglass hemisphere consisted of red, green and blue LEDs. Mechanical switches determined whether the R illuminant had 1, or 2, or 4 equal output red LED's turned on. For G and B, other switches turned on either 1, or 2, or 4 green LED's; and 1, or 2, or 4 blue LED's. All possible combinations of the the three colors and three intensities gives 27 different narrowband illuminants. Their *CIE* ***x,y*** chromaticities are plotted in Figure 10.

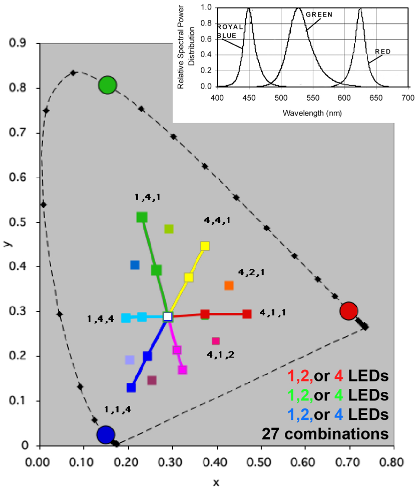

Figure 10 plots the chromaticities of the 27 illuminant combinations used in the matching experiments. All illuminants had either 1, 2, or 4 LEDs turned on in each color. Red, Green, and Royal Blue LED spectra shown in top right.

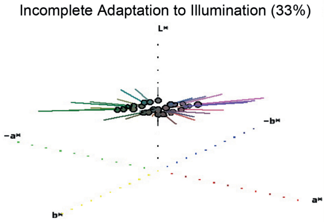

*Figure 11 illustrates a 33% incomplete adaptation hypothesis. The line represents the change in CIEL*a*b* space caused by adaptation. The sphere at the end of each line represents predicted color appearance in each illuminant. The range of Nayatani's predicted color matches using 27 illuminants is the cloud of spheres.*

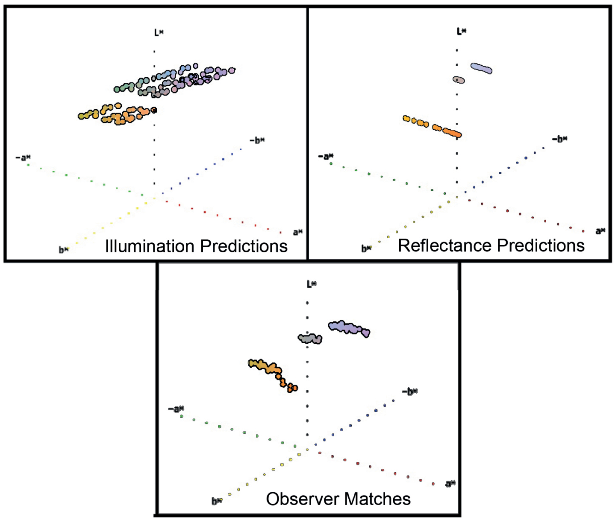

Figure 12 plots (top-left) predicted matches using the top-down Incomplete Chromatic Adaptation hypothesis that is solely dependent on illumination on the scene. All three papers have the same size cloud that is displaced by the papers different reflectances. (top-right) Predicted matches using the bottom-up Cone Crosstalk that is dependent on scene radiances. (bottom-center) Actual matches.

The observers' matches confirm the Crosstalk hypothesis in two distinct ways. First, the chromatic yellow and purple papers do not form the clouds predicted in Figure 10. Instead color matches fall on two distinct lines predicted by the Crosstalk model. Second, the Incomplete Adaptation model predicted the same size cloud for the neutral gray paper as for the chromatic ones. The Crosstalk model predicts no change in appearance for grays. The edge ratio of [Sample/Standard] is constant for all wavelengths for a gray paper. Although cone Crosstalk does take place with the gray papers, the Crosstalk information is constant for all three illuminations. The predicted colors are a single point in L*a*b* space. Observed matches for the gray paper overlapped in all illuminants. Yellow and purple matches formed different lines through color space. These matches were predicted by the Crosstalk model.

There was no evidence to support the Incomplete Adaptation hypothesis in the *27 Illuminant experiment*.

Links to <4.Incomplete Adaptation to 27 illuminants>

5. Edges in Illumination

So far, the study of Color Mondrians has been limited to flat displays in uniform illumination. The following experiments use two identical 3-D Mondrians made with wooden blocks painted with only 11 paints. One Mondrian uses nearly-uniform illumination (Low Dynamic Range), the other in highly directional, mixed spectral light illumination (High Dynamic Range). Observers are asked to measure the appearances of constant reflectances in variable illumination (Figure 13) . [21]

Figure 13 (left) shows the 17 area MMT Mondrian; (center) 3-D Mondrian in nearly uniform LDR illumination; (right) identical 3-D Mondrian blocks in nonuniform HDR illumination.

These experiments used two identical arrays of 3-D objects; one in nearly uniform illumination, and the other used spotlights that caused shadows. They were viewed in the same room at the same time. All flat facet objects have been painted with one out of a set of 11 paints. Two different techniques were used to measure the appearances of these constant reflectance surfaces. First, observers made magnitude estimates of changes in Munsell Notation. Second, an artist painted a watercolor rendition of both scenes. The watercolor paintings' reflectances were used to quantify the artist's sensations generated by the two scenes.

Figure 14 shows Carinna Parraman's pair of watercolor paintings in LDR (left) and HDR illumination (right). Both watercolor paintings were made in uniform illumination. The paintings recorded the artist's sensations. She quantified those sensations by measuring the spectral reflectance of every facet in the watercolor painting. [21,22]

Both magnitude estimates and watercolor reflectances showed the same results. The results failed to show any general rule based on reflectance, illumination, or discounted illumination. Rather, measurements showed a great many individual departures from perfect constancy. MMT data measured that Color Constancy worked. It showed that appearance correlated with Scaled Integrated Reflectance (Figure 13, left). In nearly uniform illumination, many samples appeared close, or equal, to ground truth reflectance data (Figure 13, center). However, in complex HDR illumination with sharp edges in illumination, constant reflectances seldom have constant appearances (Figure 13, right). Departures from perfectly uniform illumination generate departures in appearances from physical surface reflectance. If an image-processing algorithm Discounted Illumination perfectly, then that algorithm would not predict appearances of real-life scenes with complex non-uniform illumination.

The major disruptor of Color Constancy is sharp edges in illumination, such as sharp shadows cast by objects in a real scene. Despite its long history, reflectance and illumination perceptions are not important in vision. The limits of Color Constancy described above provide strong evidence that the perception of illumination is not a fundamental process in human vision. The dichotomy of edges and gradients [23] is much more important in how we see. The degradation of Color Constancy by edges in illumination adds to this realization.

Link to MMT data <5. Edges in Illumination>

Conclusions

This review covers many experiments on Color Constancy in complex scenes relevant to real world conditions. The review compares two central themes (Figure 3): first it describes the 19th century, top-down "*Discount Illumination*" thread, including chromatic adaptation; second the bottom-up Retinex "Spatial Comparisons" thread that includes cone Crosstalk. The experimental results showed that:

- A scene segment with ***L, M, S*** cone quanta catch can appear any color.
- Scene Averages of cone quanta catch have minimal effect on appearances.
- Scene maxima control color appearances in complex scenes. (***L, M, S*** maxima are independent. A white object is not necessary)
- Limits of constancy correlate with crosstalk, not with incomplete adaptation.
- Reflectance correlation is scene dependent. Constancy works best with flat Mondrians in uniform spatial illumination.
- Edges in illumination have the same effect on appearance as edges in reflectance.

None of the experimental data supported the Discount Illumination thread (red box- left branch of Figure 3). All of the experimental data (green boxes - both branches of Figure 3) showed the role of cone Crosstalk in defining the limits of Color Constancy. The Crosstalk signatures provide strong support to the Spatial Comparisons thread. Color Constancy experiments are synonymous with changed illumination. Cone crosstalk from changed illumination is the unique signature of independent L, M, S color channels (Retinexes). Adaptation models do not incorporate those edge ratios, the source of cone crosstalk. Those ratios represent the relative quanta catch at boundaries with uniform illumination. By ignoring the illumination Retinex does not need to find the illuminations actual values. Crosstalk's constancy limits provide the signature of the underlying color mechanism, namely, independent L, M, S color channels.

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Author Biography

John McCann received a degree in biology from Harvard College (1964). He worked in, and managed, the Vision Research Laboratory at Polaroid from 1961 to 1996. He has studied human color vision, digital image processing, large format instant photography, and the reproduction of fine art. His publications and patents have studied Retinex theory, color constancy, color from rod/cone interactions at low light levels, appearance with scattered light, and HDR imaging. He is a Fellow of IS&T and the Optical Society of America (OSA). He is a past President of IS&T, and the Artists Foundation, Boston. He is the IS&T/OSA 2002 Edwin H. Land Medalist and IS&T 2005 Honorary Member. He has participated in EI Meetings since 1988 in many capacities, and was General Co-Chair of Electronic Imaging in 2000.

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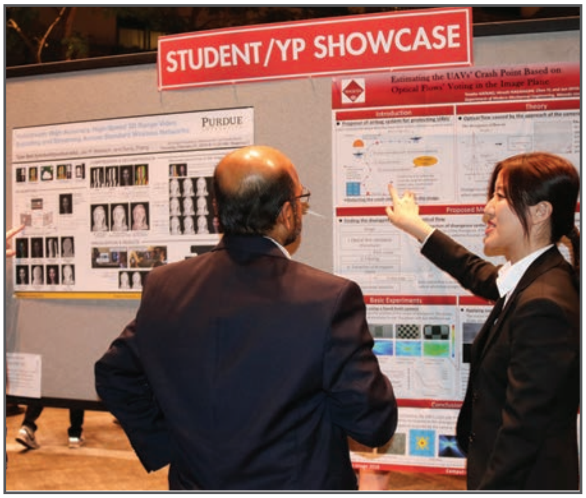

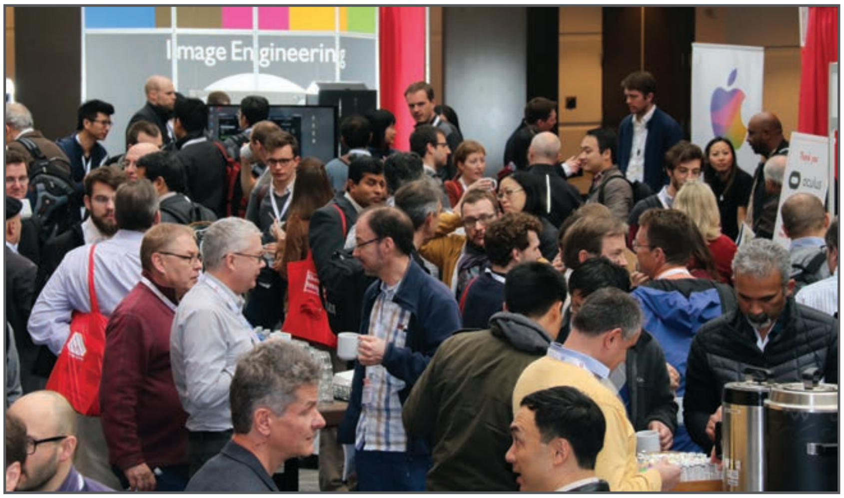

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