Pixel and spatial mechanisms of color constancy

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1. ABSTRACT

Color constancy remains an important subject of research on color standards, computer imaging, and human color vision. There are many different theories and algorithms that interpret and predict constancy. This paper analyzes three different approaches that are frequently discussed separately in the literature: pixel-based colorimetric standards of appearance; computer imaging calculations of an object's reflectance; and calculation of appearance using spatial comparisons. This paper compares and contrasts these approaches. Further, it reviews experiments that measure appearance in color constancy in a variety of situations. A pivotal tool in analyzing models of constancy is the correlation of object's reflectance with appearance. Each approach has different interpretation of this correlation. Using measurements of constancy with particular attention to reflectance, illumination, and appearance helps us to see the successes and limitations of each constancy approach.

2. INTRODUCTION

> "*The approximate constancy of the colors of seen objects, in spite of large quantitative or qualitative changes of the general illumination of the visual field, is one of the most noteworthy and most important facts in the field of physiological optics. Without this approximate constancy, a piece of chalk on a cloudy day would manifest the same color as a piece of coal does on a sunny day, and in the course of a single day it would have to assume all possible colors that lie between black and white. Similarly a white flower that is seen under a green arbor roof would show the same color as a green leaf under open sky, and a ball of yarn, white in daylight, in gas light would have to have the color of an orange.*"
>
> Ewald Hering, *Zur Lehre vom Lichtsinne*,1872 [1]

Leo Hurvich was Hering's disciple and translator. Hurvich attributes color constancy to a chromatic adaptation mechanism using "von Kries Coefficient Law".[2] Increases in one spectral band of illumination is hypothesized to cause decreases in sensitivity to that band. Hurvich suggests that this mechanism is the same as that responsible for color afterimages.

Two sets of experiments show that such an explanation is incorrect for color constancy in complex images. Daw showed that afterimages are suppressed when looking at complex images. Afterimages are formed by staring at a single point in a colored image, so as to locally bleach photopigment in the rods and cones. The afterimage is seen clearly by looking at a blank screen that is uniformly illuminated. Such afterimages, that are clearly visible, disappear when observers look at a complex scene. Daw also showed that afterimages reappear if the afterimage fits the contours of the real image. Daw made afterimages appear and disappear by looking around the same scene.[3] Normal viewing of complex scenes suppresses afterimages caused by bleached photopigment in the rods and cones. Suppressed afterimages cannot influence color constancy.

Daw's experiments influenced Edwin Land in the design of his Color Mondrian experiments. He specified that each color area have a different size and shape. It is possible to transfer afterimages of equally sized rectangles from one rectangle to another. It is not possible to transfer afterimages of one Mondrian area to another, because the contours do not fit.

The second set of experiments [4-7], measured directly the changes in color constancy appearances using Mondrians that all had the same average radiance. The average of scene content has no effect in complex Mondrian test targets. These experiments will be described in detail in Section 2.2.

In combination, Daw's experiments and experiments with controlled average properties, make a convincing case that von Kries Coefficient Law does not apply to color constancy in complex scenes.

3. COMPUTATIONAL MODELS

Table 1 summarizes the goals of Retinex, CIE Discount Illumination Standards and Computer Vision. All three describe different aspects of color constancy computations. Retinex [7] and CIELAB [9] /CIECAM [10] models share the same goal of calculating color appearance. Computer Vision [11] calculates reflectance. Retinex and Computer Vision models share the same input information, namely, the radiances of all pixels in the scene. The inputs for CIELAB/CIECAM models are a number of measurements of only the single pixel of interest. The radiance and the irradiance of that pixel are measured and converted to XYZ color space. While Retinex and Computer Vision use the product of reflectance and illumination, CIELB/CIECAM has each available as input.

Color Constancy: 3 Types of Models

Model	Calculation Goal [Output]	Given Information [Input]	Reference
Retinex	appearance	radiance array of entire scene	Land, 1971
Discount Illumination CIELAB CIECAM	appearance	pixel's radiance + pixel's irradiance	CIE, 1976 CIECAM 1997,2002
Computer Vision	reflectance	radiance array of entire scene	Ebner, 2007

Table 1 lists the three computation models of color constancy (output, input, and references).

3.1 Retinex

McCann, McKee, and Taylor (MMT)[12] measured the appearances in Color Mondrians using color matches to a Munsell Book. They found that the matched appearances of the same paper were approximately constant. They found very good correlation of appearance with the paper's reflectances when they were measure with a three-band meter having the same spectral sensitivities as the cones.[13] These experiments were performed with flat Mondrians in uniform illumination. In fact, the Mondrians were inside a large white box that approximated an integrating sphere. The observers viewed the Mondrian through masks that allowed them to see the display, but not the illumination box.

The MMT Mondrian results showed appearance correlated with cone reflectance integrated by human cones. Land and McCann had described earlier a computational model designed to calculate independent L-, M-, and S-cone integrated reflectances from the array of all radiances in the field of view.[8] MMT showed that this model worked well in predicting observer matches, including the departures from perfect constancy.

These experiments were limited to the appearances of flat Mondrians in uniform illumination. These experiments did not eliminate a possible loophole for von Kries models using chromatic adaptation. The MMT experiments used the same display in five different illuminants. Therefore, the average radiance of the entire field of view changed with the illuminant composition. Subsequent experiments held the average illuminations constant by using a carefully selected surround to compensate for the change in illumination [4-7]. In other words, when changes in illumination changed the average radiance, we replaced the surround to change the average back. These experiment held the average illumination constant, thus providing not cause for chromatic adaptation. The observed color constancy data were indistinguishable from MMT data. Chromatic adaptation does not play a role in the appearances of these Mondrians.

The series of Mondrian experiments support the idea that human color appearances are built up from spatial information in the scene.

3.2 CIELAB and CIECAM

In 1976, the CIE issued a standard "L*a*b* Space and Color difference Formula" that could be used to convert color-matching data in a more uniform color space.[9] This extended the work of Adams, Glasser, Hunter and many others.[14] This model requires the user to measure three reflectances of the scene pixel of interest, using CIE standard $\bar{x},\bar{y},\bar{z}$ color matching functions. These reflectances (X/X_w, Y/Y_w, Z/Z_w) are then scaled by the empirically selected cube root. This scaling has been shown to mimic the effect of intraocular scatter.[15] The darker areas in all scenes have lower contrast on the retina than in the scene. The cube root transforms the high contrast scene into a lower contrast retinal, log-radiance, image.[16]

The rest of the CIELAB transformation compares X,Y,Z log retinal reflectances and stretches the differences. In short, CIELAB manipulates and stretches (X/X_w, Y/Y_w, Z/Z_w) reflectances. Since it applies the same operations on all reflectances, it cannot reorder, or rearrange input reflectance values. The L*a*b* values are uniquely linked to their input reflectances. Identical reflectances anywhere in the scene have identical CIELAB output values.

In 1997 and 2002, the CIE standardized CIECAM models[10] Although the transforms are much more complex, they share many of the same design features of CIELAB. The user measures three reflectances of the scene pixel of interest, using CIE standard $\bar{x},\bar{y},\bar{z}$ color matching functions. The user measures absolute luminance and selects 4 scene parameters. These reflectances (X/X_w, Y/Y_w, Z/Z_w) are processed by over 100 equations. In short, CIECAM manipulates and stretches (X/X_w, Y/Y_w, Z/Z_w) reflectances. Again, it applies the same operations on all reflectances, it cannot reorder, or rearrange input reflectance values. The output values are uniquely linked to their input reflectances. Identical reflectances anywhere in the scene have identical CIECAM output values.

If we apply CIELAB and CIECAM to the flat Mondrians in uniform illumination, we find calculated appearances that correlate with both reflectance and appearance.

3.3 Computer Vision

Computer Vision shares the same input requirements as Retinex, namely the spectral radiance at every scene pixel. The measure of success of these algorithms is whether calculated reflectance correlates with the object's reflectance. Ebner reviews a variety of computer algorithms that calculate object reflectances in chapter 6 of his book "Color Constancy".[11]

Computer Vision is distinct from vision, in that its goal is to calculate the reflectance of the surface of the object. It is an ongoing part of artificial intelligence, and pattern recognition research that identify an object's properties from captured scene data. If appearance happens to correlate perfectly with reflectance, then a computer vision model might be applied to human vision problems.

However, Hering talked about the "approximate colour constancy of seen things"[1]. Color constancy is only perfect when two scenes are identical.[17,18] Departures from perfect color constancy provide important signatures for understanding how human color constancy mechanism works.[19,20]

3.4 3-D Mondrians

Although appearance correlates with reflectance for flat, uniformly lit Mondrians, the previous paper in this conference [21] showed that 3-D Mondrians in non-uniform illumination show no such correlation. Even though the illumination cube makes the light as uniform as possible, the LDR watercolor documents changes in appearance because of the soft shadows. The HDR watercolor documents much larger appearances changes with harsh illuminations and multiple reflections.

4. WATERCOLOR PAINTINGS CAPPTURE APPEARANCE

In the previous paper [21] we describe Carinna Parraman's watercolor painting of the side-by-side LDR and HDR 3-D Mondrians. This paper extends previous experiments on 3-D Mondrians.[22-24] This painting, along with the information about the paint reflectances on the blocks, helps us to evaluate the three computational models.

First, by having an artist render the appearances of the LDR / HDR scene we represent appearance in the same easily measurable physical space as the paint on the blocks. The artist's rendition converts the high-dynamic range, caused by illumination, into the set of appearances expressed in the low-dynamic range of the watercolor. The conveniently measured watercolor reflectance is a measure of appearance. These measurements are ideal for evaluating the three computational algorithms.

We set out to analyze specific sections of the scene to help us understand the above models. Figure 1 shows central areas surrounding a dark gray and black block [21].

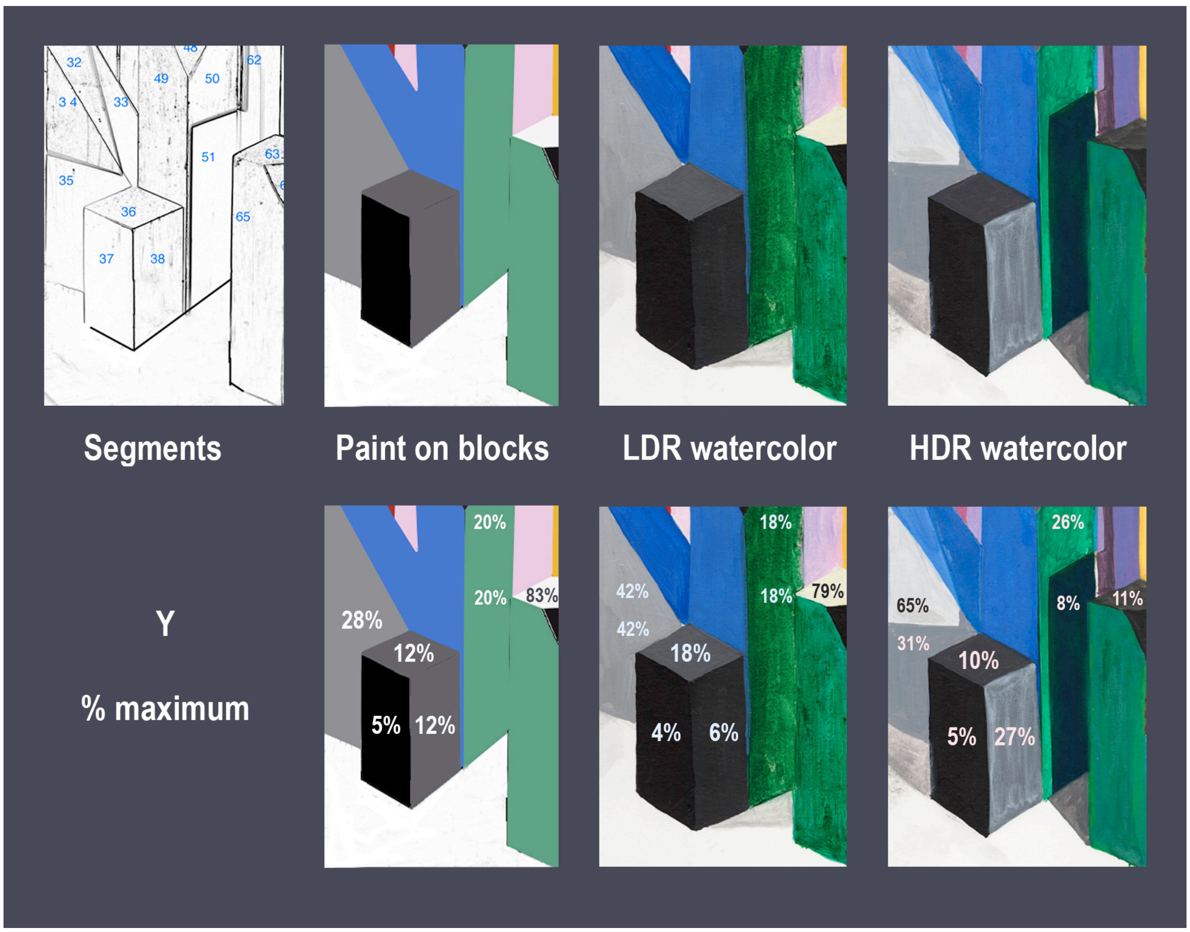

Figure 1 studies a region in the center of the 3-D Mondrians. The top left sketch identifies the image segments. . The top middle-left shows the paint used on the blocks. The top middle-right and right shows these segments in the LDR and HDR watercolor painting. The captured appearances of the LDR and HDR scenes are different from reflectance and each other.

Areas 36 and 38 have the same Gray-Dark (GD) paint. The CIE Y percent luminance measured by the Spectrolino meter is 12% for both. These constant reflectances have different appearances in the LDR and HDR portions of the watercolor. The top (36) is lighter in the LDR (18% vs. 6%), while it is darker in the HDR (10% vs. 27%). See Table 2. for complete X, Y, Z values). The order of the appearances changes with changes in illumination. Area 38 is the lightest of the block's faces (36, 37, 38) in the HDR, and nearly tied for darkest in the LDR. These changes in appearances correlate with the changes in edges caused by the different illuminations.

The Gray-Middle (GM) area on the left side (34 &35) shows equal LDR appearances (42% and 42%); but very different appearances in the HDR (65% & 31%) due to the shadow. The central green block face (50 & 51) appears 18% on top and bottom in LDR, while the top is 28% and the bottom is 8% in HDR in shadow. The area (63) on the top of the green block on the right edge has W paint. It appears 79% in LDR, while 12% in HDR.

Paint	Paint X	Paint Y	Paint Z	Segment	LDR X	LDR Y	LDR Z	HDR X	HDR Y	HDR Z
W	83%	84%	81%	63	79%	79%	64%	12%	12%	11%
GM	28%	28%	29%	34	42%	42%	43%	65%	65%	65%
GM	28%	28%	29%	35	42%	42%	43%	31%	31%	34%
G	13%	20%	8%	50	11%	18%	6%	14%	26%	10%
G	13%	20%	8%	51	11%	18%	6%	6%	8%	9%
GD	12%	12%	13%	36	18%	18%	19%	10%	10%	11%
GD	12%	12%	13%	38	6%	6%	6%	27%	27%	31%
K	5%	5%	5%	37	4%	4%	4%	5%	5%	5%

Table 2 lists the CIE XYZ values (percentage maximum) of the paint, the measured the LDR, and HDR watercolor reflectance, along with the individual image segments.

Figure 2 shows another section of the LDR and HDR scenes [21]. These scene portions have a tall white block face that is influenced by shadows and multiple reflections. The white paint has constant reflectance values (83,84,81) from top to bottom. The LDR appearances show light-middle-gray, and dark-middle-gray shadows (Table 3-center).

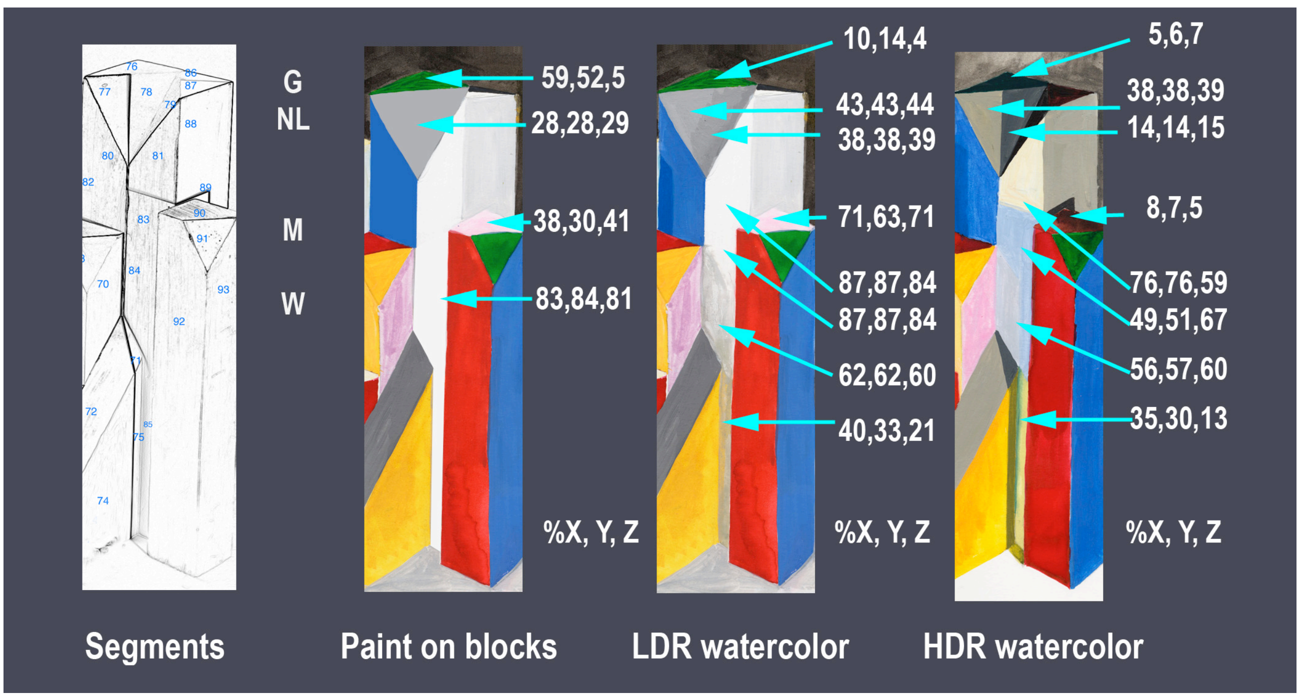

Figure 2 studies a region on the right center of the 3-D Mondrians. The left sketch identifies the image segments. . The middle-left shows the paint used on the blocks. The middle-right and right shows these segments in the LDR and HDR watercolor painting. The captured appearances of the LDR and HDR scenes are different from reflectance and each other.

The HDR appearances show four different appearances. The painting shows: white at the top, a blue-gray shadow below it, a pinker reflection and a yellow reflection below that. (Table 3-right).

Green paint (76) and magenta paint (90) are very close to black in the HDR watercolor. The LDR shows a weak shadow (77 vs.78) on the light gray (NL) paint. The HDR shows a 38% Y vs. 14% Y dark shadow. Shadows and multiple reflections show larger changes in appearance caused by different illumination.

Paint	Paint X	Paint Y	Paint Z	Segment	LDR X	LDR Y	LDR Z	HDR X	HDR Y	LDR Z
G	59%	52%	5%	76	10%	14%	4%	5%	6%	7%
NL	28%	28%	29%	77	43%	43%	44%	38%	38%	39%
NL	28%	28%	29%	78	38%	38%	39%	14%	14%	15%
M	38	30	41	90	71%	63%	71%	8%	7%	5%
W	83%	84%	81%	81	87%	87%	84%	76%	76%	59%
W	83%	84%	81%	83	87%	87%	84%	49%	51%	67%
W	83%	84%	81%	84	62%	62%	60%	56%	57%	60%
W	83%	84%	81%	85	40%	33%	21%	35%	30%	13%

Table 3 lists the CIE XYZ values (percentage maximum) of the paint, the measured LDR, and HDR watercolor reflectances, along with the segment number for each individual image segments.

Both Figures 1 and 2 show significant departures from perfect correlation of appearance and object reflectance. These departures are examples of how the illumination plays an important role in color constancy.

5. DISCUSSION

As one inspects the color appearances in the LDR and HDR watercolors it is evident that these color have a physical correlate. That correlate is not the XYZ values of a pixel. The correlate is the spatial relationship of XYZ values from different pixels. Darker regions of the same reflectance paint have edges created by the illumination. The appearances observed here are consistent with a model that builds colors from image structure.

If we return to the three computational models we discussed in the introduction, we can evaluate how they apply to these experiments. The MMT data show that flat Mondrian appearances correlated with cone reflectances in uniform illumination. The model they tested built those calculated reflectances by spatial comparisons. The intent was to show that it was possible to calculate reflectances without every finding the illumination. If one applies a spatial model to these 3-D Mondrians we would not calculate the paints' reflectances. Instead we would get a rendition of the scene that treated edges in illumination, the same as edge in reflectance. The Retinex spatial model shows correlation with reflectance sometimes, (in MMT Mondrians), but not all the time (in 3-D Mondrians).

The input to both CIELAB and CIECAM are reflectances. These models transform the shape of the color space, but have no computational means to predict that the same paint surface can have more than one appearance. These models predict the same color appearance for all blocks with the same reflectance.

The third class of model, Computer Vision, has the specific goal of calculating the object's reflectance. The question here is whether such material recognition models have relevance to vision. If a computer vision algorithm correctly calculated cone reflectance of the flat Mondrians, then one might argue that such processes could happen in human vision.[11] However, the 3-D Mondrians show divergent interests. If that same computer vision algorithm correctly calculated 3-D Mondrian reflectances, then these calculations are not modeling appearances in 3-D Mondrians. Computer Vision is a distinct discipline from human vision, with very different objectives.

Table 4 summarizes this discussion. The human visual pathway generates appearances that correlate with reflectances some of the time. Spatial models of vision [25] use image structure to calculate appearances. Models that transform reflectance in a color space give constant output for constant input. Computer vision, if successful, calculates reflectance. A priori information about objects' reflectances, and scenes' illuminations, is not available to humans as they view the world. Humans exhibit color constancy using scene radiances as input. The appearances they see are shaped by both illumination and reflectance. Measuring, or calculating reflectance, is insufficient as a model of vision in real complex scenes.

Color Constancy: 3 Types of Models

Model	Calculation Goal [Output]	Mechanism	[Output] = Reflectance
Human Vision	appearance	visual pathway	sometimes
Retinex	appearance	build appearance from edges	sometimes
Discount Illumination CIELAB CIECAM	appearance	measure reflectance stretch	always
Computer Vision	reflectance	estimate illumination to calculate reflectance	always

Table 4 lists human vision and the three computation models of color constancy (goals, mechanism, and outputs correlation with reflectance).

6. CONCLUSIONS

This paper reviews three types of color constancy computations: Retinex, CIELAB/CIECAM, and Computer Vision. We discuss the similarities and differences in their objectives, required input information, and outputs. We discuss the models' characteristics in reference to 3-D Mondrian experiments in LDR and HDR illumination. While flat Color Mondrians in uniform illumination have color appearances that correlate with reflectances, 3-D Mondrians do not. Retinex builds color appearance from the spatial information in the scene, so that appearances that differ from reflectances are not an issue. Retinex treats edges and gradients in radiance the same whether they are caused by reflectance, or illumination. For Retinex the changes in appearance in 3-D Mondrian experiments follow from the changes in spatial pattern of radiances caused by illumination. CIELAB/CIECAM models measure the X, Y, Z reflectances of individual pixels and transform them into a new color space. There is nothing in the calculation that can generate very different outputs from identical inputs. This result is observed in color appearances in 3-D Mondrians. The Computer Vision goal is to calculate reflectances from all the scene radiances. It is skew to color appearance. The success of the algorithm is simply measured by its ability to find reflectances. Human Vision is not involved, and Computer Vision models cannot predict Human Vision.

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