Color Appearance: A Spatial Computation

John J. McCann*
McCann Imaging
Belmont, MA 02478, USA

Abstract

This paper reviews the argument that color appearance is a biologic spatial computation performed by the human visual system. It shows the progression from Land's Red and White photography, to Retinex, to rod-cone color and models of lightness. It concludes with spatial computations for gamut mapping between different media. It is based on intra-image comparisons (different pixels in the same media image), rather than inter-image comparisons (the same pixel in different media images).

Introduction

Helmholtz initiated two branches of color vision: first, he laid the ground work for modern colorimetry based on receptor quanta catch; and second he introduced the idea that humans are able to discount the illumination, so the appearance of objects corresponds to their reflectance. Both colorimetry and appearance models using "discount of illumination" attack the problem one pixel at a time. This paper describes the family of experiments showing that color appearances are the result of spatial comparisons between different pixels, rather than the response of single pixels.

Red and White Photography

In the late 1950's Edwin Land, founder of Polaroid, repeated James Clerk Maxwell's three-color-projector experiments. Late one evening, as Land and colleagues were leaving, someone shut off the blue projector and removed the green filter, leaving a red and white projection on the screen. Meroe Morse asked Land " Why were the colors still there? Land replied, "Oh, that is adaptation" and went home to bed. At three o'clock in the morning, he woke from a sound sleep and said, "Adaptation! What adaptation?" He returned to the lab in the middle of the night to re-examine Red and White projections.[1] This talk is a summary of the experiments directly tied to that night and Land's insatiable curiosity about images. By that time he had about half of his 350 US patents, mostly on imaging. What fascinated him the most about human color vision was that it was completely different from photography, and video imaging. The mechanism for these color reproduction systems depends only on light at each pixel, the same as in colorimetry. Human vision uses information from the entire image to calculate color appearance. Color appearance comes from spatial comparisons.

Land and Nigel Daw published a series of papers on Red and White and other two color projections.[2] The colors seen in Red and White images were more variegated than those in colored shadows. Land described these colors in a plot of "% Available light in white light" vs. % Available light in red light". This was an attempt to describe color appearance in terms of its physical stimulus. In this plot, the absolute amount of light at a pixel was not important. What was important was the amount of light in the red record compared to its maximum and the amount of light in the white record compared to its maximum.

Retinex

It was forty years ago that Land modified his thinking about the formation of color appearances.[3] He was a voracious observer, always studying the properties of things. He observed that the color appearance always correlated with the triplet of apparent lightnesses in long-wave, middle-wave, and short-wave visible light.[4,5] It did not matter what visual mechanism (contrast, assimilation, edge effects, crispening) caused the apparent lightness, colors always correlated with the triplet of lightnesses. A good example of this was a paper using a colored Cornsweet effect.[6]

Color Constancy and Mondrians

To illustrate the Retinex idea Land experimented with displays of papers and controlled illuminations. The Color Mondrian experiments were a particularly dramatic demonstration of color constancy.[5] Subsequent experiments measured the color appearance of each Mondrian area in five different illuminants.[7] These measurements showed that color appearance correlated with three reflectances measured with sensors having the spectral sensitivities of human cones. Further experiments showed that adaptation to the average-scene radiances had no effect on color constancy.[8,9]

Rod / Long-wave Cone Color

A series of experiments showed that colors produced by the interactions of rods and long-wave cones were consistent with Retinex theory.[10] The rods interacted among themselves to form an image in terms of lightness. All the historical evidence that supported "Duplicity Theory" now support the idea that spatial interactions between rods form independent lightness images. Similarly, interactions between long-wave cones produce a different independent set of lightnesses. Color in these experiments correlated with the pair of Retinex lightnesses, regardless of the quanta catch of the receptors. In a rod/L-cone color experiment, observers reported saturated red and cyan colors from different areas with identical stimuli in the same image.[11]

Models of Lightness

Retinex simplified predictions of color appearances, but made models capable of calculating apparent reflectance much more important. Our model of lightness began with the *Black and White Mondrian* experiment in which a white area and a different black area sent the same amount of light to the eye.[4] This topic has been reviewed recently in a symposium called *Retinex at 40*.[3] It included 9 papers describing a variety of different spatial models of color constancy, dynamic-range and color-gamut compression. Each of these computational models used spatial comparisons of the input values of different pixels to calculate a new improved image.

Color Gamut

Recent experiments have demonstrated that spatial comparisons can be used to calculate the best compromise in color gamut mismatch. This process compares all pixels in an image with all other pixels in the same image (intra-image comparisons) to make the smaller gamut image. Most color mapping algorithms examine each pixel by itself. It transforms the value of a pixel in the source image to be within the limits of the second media. If the color of that pixel is out of gamut, then its value is replaced by a color that is within the gamut (inter-image comparisons). Such transforms create problems because they change the ratios between different pixels. The Retinex color gamut calculation creates a new image such that the smaller gamut image preserves the edge ratios of the larger gamut image, thus preserving color appearance. The average colorimetric error is larger than conventional color gamut transformations, but the color appearance is much better.[12,13]

Summary

This paper reviewed the argument that color appearance is a biologic spatial computation performed by the human visual system. It discussed the negative experimental results in experiments designed to measure the effects of adaptation on color constancy. It included a variety of examples of spatial comparisons as the basis of successful models of color constancy, dynamic range compression and gamut mapping.

References

* <mccanns @ tiac. net>

[1] 1 E. H. Land "The Case of a Sleeping Beauty or a Case History in Industrial Research", in *E. H. Land's Essays **III***, M. A. McCann, ed., IS&T, Springfield, VA, 4-5, (1955).

[2] J. J. McCann, J. L. Benton, S. P. McKee, "*Demonstration of Red/White Projections and Rod-Lcone Color", in Human Vision and Electronic Imaging VII,* B. E. Rogowitz and T. N. Pappas, ed., Proc. SPIE, **4662-39**, in press, 2002.

[3] J. J. McCann, "*Capturing a Black Cat in Shade: The Past and Present of Retinex Color Appearance Model"*, in *Human Vision and Electronic Imaging VII*, B. E. Rogowitz and T. N. Pappas, ed., Proc. SPIE **4662-39**, in press, 2002.

[4] E. H. Land, "The Retinex", *Am. Scientist*, **52**, 247-264 1964.

[5] E. H. Land and J. J. McCann "Lightness and Retinex Theory", *J. Opt. Soc. Am.*, **61** 1-11, 1971.

[6] E. H. Land, "Smitty Stevens' Test of Retinex Theory", in: *Sensation and Measurement, Papers in Honor of S. S. Stevens,* H. Moscwitz et. al. Ed., Applied Science Publishers Ltd., London, 363-368, 1974.

[7] 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.

[8] J.J. McCann, "Color Mondrian Experiments Without Adaptation", *Proceedings AIC, Kyoto,* 159-162, 1997.

[9] J.J. McCann, "Magnitude of Color Shifts from Average-Quanta Catch Adaptations", *Proc. IS&T/SID Fifth Color Imaging Conference*, 215-220, 1997.

[10] J. J. McCann, J. L. Benton, S. P. McKee, "Demonstration of Red/White Projections and Rod-Lcone Color", in *Human Vision and Electronic Imaging VII*, B. E. Rogowitz and T. N. Pappas, ed., Proc. SPIE **4662-39,** in press, 2002.

[11] J. J. McCann, "Rod-Cone Interactions: Different Color Sensations from Identical Stimuli", *Science*, **176**, 1255-1257, 1972.

[12] J.J. McCann, "Using Color Constancy to Advantage in Color Gamut Calculations, *Proc. Third IS&T, PICS Conference*, 3, 169-176, (2000).

[13] J. J. McCann, "Color Gamut Mapping Using Spatial Comparisons", in *Color Imaging: Device Independent Color Hardcopy and Graphic Arts*, R. Eschbach and G. Marcu, ed., Proc. SPIE, 3648, 68-82 (2001).