Color Sensations in Complex Images

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Abstract

Colorimetric measurements are equally influenced by the reflectance spectrum of the object and the illumination spectrum of the light. The 1931 CIE colorimetric measurements are made one pixel at a time; they integrate the radiances at each wavelength with three color-matching functions so as to generate three Tristimulus Values for one pixel. No information from other pixels in the field of view is used in this calculation.

Our everyday experience is that color appearance of objects remain the same, regardless of substantial changes in the spectrum of the illuminant. In other words, everyday experience tells us that an object's reflectance spectrum controls appearance, while its illumination spectrum has little influence.

This paper will review the history of different hypotheses explaining human color constancy and describe techniques for measuring color appearances. It will review important experiments that measure color sensations and new techniques using the introduction of a new patch in a display that destroys color matches.

Human color vision is a field phenomenon. Humans calculate color sensations by comparing pixels across the entire field of view. Global changes in reflectance or illumination cause small changes in appearance: Local changes in reflectance or illumination cause large changes in sensation. The spatial interaction of all pixels in the field of view controls human color appearance.

Color Constancy

Everyone knows that there are two kinds of photographic film: One for daylight, one for tungsten light. Using the wrong film degrades seriously the quality of the prints. Everyone knows that humans are almost totally insensitive to the color of illumination. The color of objects stays the same regardless of sunlight, skylight or artificial light. Measurement of the spectra of these illuminants shows that they can be very different. If they were the spectra of objects they would appear highly colored.

Color Constancy is the name of the phenomenon that makes humans insensitive to the illumination. This paper will review a number of the mechanisms proposed to explain the observations. Further, it will describe experiments that demonstrate the important difference between the human eye and film. It is *spatial* image processing.

Color Constancy Models

There is a physical tradition in color theory that spans Newton, Young and Maxwell and leads directly to modern colorimetry. The most used colorimetry standard is the one adopted by the CIE (Commission Internationale de l' Eclairage) 1931.[1] Colorimetry[2] takes into account the spectral properties of the light source, the spectral-reflectance properties of the objects, the pre-retinal absorbance of the eye, and the sensitivity of the rods and cones in the retina. Although colorimetry was originally based on color matching measurements, Smith and Pokorney[3] have shown that Tristimulus Values correspond to direct measurements of cone pigments sensitivities in the retina. This tradition uses a physical model that is nearly identical to a physical model for photographic film sensitivity. Input to the model is the quanta caught by a single pixel. The evaluation of each pixel is independent of the quanta caught by all other pixels.

Helmholtz, in his encyclopedic Physiological Optics, made the observation that humans "discount the illumination."[4] Von Kries proposed that human vision used an average of the light falling on the retina. If the illuminant was brighter in long-wave light, then the receptors in the retina became less sensitive to those wavelengths. Hecht proposed a biochemical adaptation based on biochemistry of cone pigments. Threshold sensitivity mechanisms begun by Hecht and continued by Wald and Rushton have provided a very precise interdisciplinary understanding of threshold sensitivity for both rod and cones. Color constancy is a different mechanism and has not shown the same degree of understanding. One often hears of the "adaptation of the eye," but one almost never sees the detail describing the spatial and temporal parameters of the mechanism in biophysical measurements. The tradition started by Helmholtz is that color constancy requires additional correction factors, but that these are well within the range of a second order corrections.

There is a very different tradition started by the poet Goethe and established by Chevreul[5] and Hering.[6] The idea is that post-receptor visual mechanisms are spatial. Opponent color ideas say that the contrast of white and black, and of red and green, and of blue and yellow are the basis of vision. Work by Jameson and Hurvich, along with the neurophysiology of Kuffler, Hubel, Wiesel and especially Rus and Karen DeValois and Zeki have built up a massive amount of evidence that post-receptor neural mechanisms are spatial interactions.

The ratio is a measure of the change in radiance between two pixels. Wallach[7] showed that the ratio of radiances correlated with the change in appearance of two adjacent areas. Land and McCann[8] showed that the influence of the spatial mechanism covered the entire field of view. Furthermore, they showed that the normalization required by color constancy was not controlled by an average, but by the maximum. Further they showed that normalization to maximum occurred independently in each receptor type.

Marr[9] and Horn[10] adopted the spatial field ideas, but sought an artificial intelligence solution. They set out to solve the problem of calculating the reflectance spectra of the objects from the 2-D array of radiances at the retina. Horn has shown considerable success in aerial reconnaissance imagery in which there is a single source of known illumination. Petrov, Hurlburt and Poggio[11], Buchsbaum,[12] Brill[13], Maloney and Wandel,[14] are actively working on the separation of reflectance of objects from radiance arrays.

The color constancy problem is well known. The proposed models for color constancy are varied. The objectives of the models are varied. We will review the experiments that measure the phenomena and discuss the need for color constancy models in the practical field of image reproduction.

Search for the General Case

One of the most interesting problems in the theory of color theory and color transformations is the differentiation of the general case of calculating color appearance, from the practical applications of special cases. The general case is the ideal situation in which all the parameters of the complex problem are solved; a model that can calculate the array appearances from the array of quanta caught by retinal receptors. The special cases are situations in which successful solutions to particular problems can be artfully constructed by applying certain powerful simplifying assumptions. A colorimetry model that matches all pixels will be successful when the color gamut of the original and the reproduction are the same. Great confusion comes from mistaking a special case for the general case.

We will pursue the idea that human color sensations are spatial — a field phenomena — derived from sensory input from all parts of the field of view. Colorimetry is bas-ed on information from a single point, or pixel in the image and is a special case that can match pixels with considerable accuracy, but as G. Wyszecki said, colorimetry provides "no direct clue as to the color appearance"[15] of a pixel.

Vocabulary

Color has a wonderful history in art and aesthetics, the psychophysics of sensation and cognition, the colorimetry and biophysics of retinal receptors and the physics of light. Unfortunately these very different fields tend to use the same words with entirely different definitions. Terms, such as color, intensity, saturation, and lightness, have multiple, contradictory definitions. The section will outline four different kinds of color models and will provide a few important definitions that can help us to make important distinctions about the appropriate model to use when calculating color quantities.

The four models are: Color Match, Color Sensation, Color Perception, and Color Aesthetics.[16] Each can be thought of building on the previous. Each successive layer adds more and different disciplines.

Physical Color Match

Colorimetry models of color match are based on physics. Two pixels, or groups of pixels, will match to a human observer, if they are placed side by side and if they send to the eye photons that generate the same quantum catch in the rod and cone cells in the retina. Quantum catch is a physical property of the receptors in the human eye.

The physics of quanta caught by the receptors can produce very large color phenomena. The imaging issues demonstrated by Jay Hannah's paintings[17] show that a vast number of important color changes take place simply by changes of viewing distance. Hannah's paintings show that changes in viewing distance, which change the distribution of light on the retina, contribute to substantial color appearance changes. This is a new and complex phenomenon that is partly, but not entirely, explained by foveal tritanopia and chromatic aberrations of the human visual system.[18]

Psychophysical Color Sensation vs. Cognitive Perception

Color Sensation models are based on spatial interactions of nerve signals; Sensations are measured by psychophysical experiments. Two pixels, or groups of pixels, will appear the same color if they have the same long-, middle- and short-wave lightnesses or appearances. Sensation is a property of neural interactions.

In common usage sensation is incorrectly used as interchangeable with perception. The Scottish philosopher Thomas Reid first defined and contrasted their meaning. The "Handbook of Color" by the Optical Society of America[19] defines *sensation* as a sensory response and differentiates it from *perception* as a sensory response with cognitive influence. The distinction has very important implications for models of vision. To illustrate the significance of the distinction between sensation and perception, McCann and Houston[20] described a swimming float on a New Hampshire lake. The color and amount of light coming from one face of the float are very different from that coming from the other side. The sun illuminates only one face, while the other face is illuminated by very blue skylight.

Radiance—Physical Model

A physical model measures the radiance at each wavelength from each pixel. The sunlit side is bright and has a color temperature of about 4000° K. The sky lit face is 8 times darker and is 20,000° K. *The two faces of the float have very different colorimetric values.*

Sensation—An Appearance Model

The experiment to measure the sensation or appearance of the two faces is to ask people to imagine they are visual artists, fine-arts painters. They are to pick, from a catalog of color mixtures, a sample to match the paint on the float. They select a yellow-white paint for the sunlit face and a darker, blue-gray paint for the face in the shade. In this case they have matched the sensation and chosen *slightly different values.*

Perception—A Cognition Model

Color Perception is based on recognition mechanisms and artificial intelligence. Two pixels, or groups of pixels, are recognized as representing the same material, If the model can emulate the human's ability to recognize objects. Perception/Recognition is a Cognitive Quantity.

The experiment to measure the perception of the two faces is to ask people to imagine they are house painters. They are to pick a sample to match the paint on the float. They selected a white paint for the whole rafts. In this case they have matched the perception and chose *identical values.*

A colorimetry measurements reports that the two faces are *very different*. A model that calculates sensation must report that the two faces of the float are *slightly different*; A successful sensation model must render differences in hue and visible gradients due to illumination. A successful model of perception must report that the two faces of the float are *identical*. Perception models have the goal of calculating the reflectance of the object and should not report appearances due to either illumination or visual phenomena, such as simultaneous contrast. The goals—calculate appearance and calculate reflectances—are very different. Appropriate models for each must have different properties to arrive at different results.

Color Aesthetics

A model of aesthetics is best described as a problem of Fine Arts. Artists assign colors to pixels, or groups of pixels, to generate physical, sensational and perceptual values so as to contribute to the visual intent of the image. In computer graphics we use the term visualization in a very narrow sense to describe the art and science of optimizing displays of information. In fine arts, visualization has a much broader meaning that includes the creation of the visual message. The successful computer model of color aesthetics will be one that calculates the color and tone values for an arbitrary image so as to evoke in humans a particular emotion. There is comparative little work so far in this area. Papers, such as Michael Burger's work on processing images to evoke the feelings of painting, are an interesting beginning. Emotion is an Aesthetic Quantity.

The general case for a model of color vision would be to record the spectra at each pixel in an image and then:

- be able to calculate the colorimetric properties by applying proven physical models of quanta catch at the receptors;
- be able to calculate the color sensation of areas in the field using spatial comparisons;
- be able to recognize objects in the field of view using cognition models;
- be able to predict the emotional message using aesthetic models.

Such a complete model is certainly possible, but in a practical sense it does more things than are needed for many real life problems. Thus the need for efficient special solutions.

Successful Pixel Calculations—The Special Case

A "Pixel Transformation" is special case of reproducing a complex image by:

1. Measuring the Tristimulus Values of each Pixel.
2. Measuring the Tristimulus response function of the reproduction system
3. Transforming the image pixel by pixel so that the reproduced pixel has the same Tristimulus Value as the original Pixel.

There is little doubt that a "Pixel Transformation" is the easiest class of calculation to do. All that is required for input is the three, (R, G, B) or four (C, M, Y, K) values for each pixel. The problem becomes interesting when applied to images, because images now commonly contain millions of pixels. Any computation time performed 106 times in a single processor is tens of seconds long.

If we are to follow the human visual system we need to employ mechanisms that compare each pixel with each other pixel. Millions of pixels, compared with millions of other pixels, computation time becomes prohibitive unless you mimic another human image processing technique – using multi-resolution calculations.[22]

In general, most transforms are performed with only one pixel input. Advanced systems incorporate factors for the surround. Nevertheless, it is interesting to review the situations in which "Pixel Transformation" are successful special cases.

The argument is that, if a reproduction has the same Tristimulus Values as the original at every pixel in the image, then the original and the reproduction will match exactly. If all the pixels match, then all the spatial interactions between pixels are the same. All evaluations, whether by pixel, or spatial, arrive at the same conclusion. When gamut mismatch intervenes, then the pixels that cannot match the original *introduce changes in the spatial relationships*. These spatial changes are the ones that introduce changes in appearance.

An example of a successful application of a "Pixel Transformation" is a Museum Replica®. It is a reproduction that, by means of a calibration procedure, calculates a film positive that when optically printed on Polacolor film generates a final print that matches the original.

Replicas

Oil paintings have a range of lightnesses from white to black and a range and distribution of colors that is equal to or less than print media. A typical process is to begin with a three-dimensional color array of digits. Print the digits using the desired reproduction system on the desired print media to make a three dimensional color test target made from known system digits.

Next, we photograph the original painting and the three-dimensional color test target with a long-range negative film, scan the test target and the image of the original. The test target is a closed loop operation. The target started as an array of triplets of digits, and subsequently became a print, then a negative photograph and finally a scanned triplet of numbers. The output of the scanner is a corresponding array to the start of the loop. One can write a three-dimensional transform to alter the scanned digits to make a reproduction of the test target that is nearly perfect. The target original is the same print system as the reproduction, thus eliminating gamut mismatches.

Poorly Matched Gamuts

A print film and a CRT are an example of poorly matched color gamuts. CRTs have high color purity and demonstrate maximum saturation at high lightnesses. Prints, whether photographic, offset, gravure and non-impact all exhibit maximum saturation at lower lightnesses and have a larger, more controllable range of colors near black. The absolute radiance of the white in the print is unpredictable because it is determined by the value of the illuminance. The black in the print is determined by the surface properties of the media. The black in the CRT is a much more complex function of reflected surface light and the tube's internal light and electron scatter properties. The external reflection is a percentage of incident light, but the internal scatter is image dependent and hence more difficult to calculate or measure. The color gamut of a CRT display is greatest at a relatively-high lightness value. The color gamut of a print film is greatest at a lower lightness value. A small difference in lightness of maximum saturation points generates large volumes of points outside the other systems gamut.

Alan Heff recently measured the volume of overlap in L*a*b* space (print film and a CRT monitor) and found the common volume to be about 50% of the combined volume. This calculation assumed that the whites and blacks were identical. If we transform an isotropic CRT image to a print, at least half of the pixels of that image cannot be successfully mapped. Algorithms must be specified to remap the values of half the pixels. Since at least half of the pixels have to be remapped to non-colorimetric match values, the techniques applied are very important to the outcome of the image. In real-life applications the 50 percent overlap can be significantly reduced by whites and blacks that are not equal.

Human Color Appearance: Experiments in the Spatial Tradition

Human vision is a field phenomenon. Appearances are determined relative to all other pixels in the field. Colorimetry is the physics of the quantum catches of the retinal receptors. Color matching is well understood. The limitation of colorimetry is that, although it has considerable accuracy in describing the match of two adjacent stimuli, it cannot predict the color without spatial information from the rest of the field of view. It is easy to confuse the ability to calculate a color match with the ability to calculate a color, such as red. In fact, the two are completely independent properties. The experiments that prove this concept are described below. They look for the variability of sensations possible from a *constant quanta catch* at the retina.

Quantitative Measurements of Color Sensations

The following group of experiments show that a single quanta catch cab appear white, or black, or red, or blue, or almost any color.

Gelb's Experiment

Observers report that black paper appears white when intensely illuminated and when it is the only thing in the field of view.[24] When a white paper is placed adjacent to the black paper, observers reports the black paper has been reset to black. The white paper appears white and the black paper appears black.

Gelb's experiment is very important for two reasons. First, it demonstrates that a quantum catch at a pixel can appear white or black depending on the other things in the field of view. Second, Gelb's experiment shows that human vision is not symmetrical. Gelb's experiment used a black paper with an intense spot of light to make black paper appear white. The inverse experiment would be to use a white paper with a weak spot of light to make white paper appear black. This does not happen.[25] Human vision resets appearance to the maximum in the field of view.

Black and White Mondrians

Land and McCann's Black & White Mondrian[8] combined the two parts of Gelb's experiment in one field of view. Using a complex array of black white and gray papers and a gradient of illumination, they arranged that a white paper in dim light and a black paper in bright light sent the same radiance to the eye. Despite the identical radiances, the observer reported seeing the sensations white and black. Following this experiment one can easily demonstrate that all possible sensations from white to black can be generated by a single quantum catch at a pixel, and in a single field of view. Other pixels in the field of view change the appearance of a particular pixel from white to black.

Yosemite

McCann's Yosemite experiment combined real life images with the Black-and-White Mondrian. A white card held in the shadow of a tree sends to the eye the same radiance as a black patch in the sun. The shade in Yosemite valley is 32 times less light than the sun. Observers report that identical radiances look white and black in the same real-life scene.

This observation points out important distinctions between the world and paintings. In real images we find both variable reflectance and variable illumination. In many circumstances we can measure illumination ranges in excess of 30:1 The product of reflectance and illumination typically varies from 30:1 to 1000:1 or more depending on the particular scene. The painter can only command the range of reflectances to generate his image. The range of reflectance is 30:1. The limit comes from the surface properties of objects. Painting of outdoor scenes, such as those by Bierstadt, create an image in terms of reflectance that appears the same as the real scene, having 30 times the range of radiances. This situation is the real challenge of being able to calculate sensations. To make a photographic print that reproduces the quanta catch of Yosemite is impossible. To reproduce appearance one must calculate the array of sensations and then write sensations on the print.

Color Mondrians

The Color Mondrian[27] explored the full range of color space. McCann, McKee and Taylor[28] generated five different displays in which the quantum catches at five pixels were identical, yet the observer matched these pixels to standard patches covering the entire range of reflectances in the standard. Almost any color appearance can be generated by a single quanta catch. The parameters that control the color appearance are the spatial relationships to other pixels, not the absolute quanta catch.

Measurements of Human Spatial Normalization

The next critical question in understanding color appearance is the nature of the spatial interactions. If vision is really controlled by averages as suggested by Helmholtz and von Kries, the single values can be derived to represent all the other pixels in the entire image. The consequence of being able to model human vision using a single correction factor for the influence of all other pixels in the field enormously simplifies the problem of computation. The benefits are obvious. Does such a model process information the same as the actual human mechanisms? The following experiment measures important parameters of the influence of other pixels on the appearance of the pixel of interest. These experiments test whether single average parameters can do the job of providing powerful simplifying assumptions.

Measurements "Average Radiance" Influences

The best way to settle the question of the influence of averages of radiance or quanta catch across the field of view is to directly measure them. In the Color Mondrian, a red paper caused the same quanta catch as the gray paper, because the experimenter decreased the red illumination. The illumination decrease caused a decrease in the average quanta catch. One can explain the Mondrian results by either an "average quanta catch hypothesis" or "a normalization hypothesis" In a second paper,[29] the experimenter both decreased the illumination and added a red surround that returned the average radiance to the starting values. Now the illumination changed, but the average had not. The red paper retained its red appearance. Averages of all the quanta caught over the field of view have almost no influence on sensation. The same article showed that local averages cannot provide a mechanism for the Color Mondrian experiments.

Color Properties of Normalization

Models such as R. W. G. Hunt's[30] go significantly beyond colorimetry because they introduce a normalization factor or "white point". Color spaces such as L* a* b* have incorporated in them a scaling factor for the whitest part of the image.

There are two ways to introduce a white point. The first, as usually done, in L* a* b* space is to make a physical measurement of a white paper in the desired illuminant. This is standard procedure in the context of physical colorimetric measurements. This procedure makes little sense in a computational model for the eye.[28,31] An appearance model has to be able to first compute the normalization values from the image data, and then normalize all pixels in the image relative to the appropriate maximum radiance. Measuring the normalization values removes from the model the more interesting part of the problem.

Many models normalize to the spectra coming from a white or close to 100% reflectance paper in the viewing illuminant. Land and McCann's Retinex model specifies that each receptor type normalize the quanta catches independently. In other words, white is the special case, whereas the general case is that long-, middle-, and short-wave cone mechanisms each normalize the quanta catches independently.

Recently, McCann used thin bands of "Reflectance," called "Constancy Test Patches" to test the Retinex normalization hypothesis. First, the experiment uses two pairs of center surround displays. They have different reflectances, but one pair is shifted to the yellow, while the other is shifted to the blue. When these "Reflectances" are combined with specifically chosen yellow and blue "Illuminants" they combine to become physically identical displays. Since they are physically identical *everywhere*, they look identical. This special pair of displays overcomes "Color Constancy".

Second, the experiment adds to the "Reflectance" component new, thin bands called "Constancy Test Patches". The same "Reflectance" is added to both targets. The experiment is to add all types of "Constancy Test Patches": white, blacks, light red, dark red, etc. The results show that the introduction of any "Constancy Test Patch" with *a new maximum quanta catch for any cone destroys* the match observed earlier. The results also show that the introduction of any "Constancy Test Patch" with *less than a maximum quanta catch for any cone does not destroy* the match. The new highest reflectance causes a reset of color appearance. Color Constancy returns when a new reflectance is introduced to one of the "Reflectance" displays. This follows the Gelb model of reset to the maximum in the field of view, but introduces the new feature of reset by cone type.

The "Constancy Test Patch" experiment[32] demonstrates that humans normalize each waveband independently. The results are quite simple. If the Constancy Test Patches are not the highest quanta catch in any waveband, the color match is unchanged. Nothing happens. If the Constancy Test Patches are the highest quanta catch in any waveband, the color match of both the center and the surround is destroyed. The bright red, green and blue "Constancy Test Patches" introduce a maximum for only one of the cone types. The yellow, magenta and cyan Constancy Test Patches introduce new maxima for two of the cone types. The white Constancy Test Patch introduces maxima for all three cone types. In all of these cases, the color matches of the identical quanta catches are destroyed. The introduction of any new maximum causes a reset of color appearance. The introduction of any new maximum turns on the color constancy, or match destroying, mechanism. It follows that the mechanism controlling color constancy uses the individual maxima in each wave band to calculate color sensations. This is the Retinex hypothesis.[8]

Spatial Properties of Normalization

The appearance of a particular quanta catch is determined by comparison with all other areas in the field of view. This comparison is not local; it is not compared to an average; it is relative to the maximum quanta catch in the field of view. The mechanism is a neural calculation that is influenced by spatial parameter such as adjacency, separation, circumference and absolute intensity. In other words, appearance is a complex function of the maximum quanta in the field of view.

Contrast phenomena are a wonderful paradox. Start with a spot of light with no light in the surround. The spot appears a light gray. To decrease the lightness, or make that spot of light look darker, put a higher surround radiance around the spot. The greater the radiance of the surround, the darker the spot appears. The paradox is that the effect on the quanta caught by the retina corresponding to the spot, as the appearance gets darker, is that the radiance increases significantly, due to scattered light.

So the paradox is "The technique to make a spot appear darker is to increase the radiance of the spot." The underlying mechanisms are two fold:

1. When a spot of light is surrounded by a brighter surround, scatter in the human eye significantly increases the quanta catch of the receptors corresponding to the spot.
2. When a spot of light is surrounded by a brighter surround, spatial interactions in the neural system significantly decrease the lightness of the spot.

McCann and Savoy[33] used lightness matching techniques to quantify the effects on lightness introducing surround areas of higher radiance. They had observers match a wide variety of displays to a standard lightness display containing[34] lightnesses between white and black. Each patch in the calibrated test target is equally spaced in lightness. These experiments showed that the spatial influence of the maximum in the field of view depends on the following variables:

- The absolute intensity of the light.
- The separation distance between the maximum radi ance and the area of interest.
- The degree to which the maximum radiance sur rounds the area of interest. Namely, if the maximum surrounds the area on all sides then the area will look darker than if it is surrounded on only one side. This is true when the maximum is contiguous and when there is a separation.

The data showed that the introduction of a new maximum radiance influences all other parts of the image. The amount of influence was dependent on the *extent and the proximity* of the new maxima to an area of interest. The experiments did not show correlation of appearance to either a local or a global average of radiance.

Separating Neural Image Processing from Scatter in the Eye

The McCann and Savoy data gives us the properties of the entire system, but does not address important underlying mechanisms, such as scattered light in the ocular media and spatial interactions in the neural mechanisms. Lightnesses reported by observer are the combination of these two canceling mechanisms—one physical, the other neural. The data of McCann and Savoy, combined them using new scattered light calculations in collaboration with Alan Heff's show this effect quite clearly. After correcting for scattered light, we find that lightness has an even greater dependence on the maximum radiance in the field of view.

Color Models

Model of Sensation

McCann, McKee and Taylor[28] described quantitative experiments that tested Land and McCann's model for lightness and color sensations for Color Mondrians. These experiments showed that the ratio-product-reset model accurately predicted color sensations for all 18 patches in all five Mondrian experiments. Subsequent experiments studied real life images[35] and specially designed Mondrians that tested the importance of averages to the human observer.[29] In all cases the Ratio-Product-Reset model made accurate, quantitative predictions of color sensations.

The important ideas in this model of sensation are:

- Long-, middle- and short-wave radiances are processed independently.
- The *Ratio* step compares radiances at different pixels in order to establish relative values in a field.
- The *Product* step propagates relationships long distances across the field of view. The product propagates information over long distances, but remains an incomplete comparison. This property is necessary to account for the Spatial Properties of Normalization measurements described above.
- *Reset* is the critical element that creates the asymmetry required by the Gelb Experiment and "Constancy Test Patch". It normalizes the long-, middle- and short-wave images so as to account for color constancy.

A good sensation model uses the quantum-catch physics of colorimetry as the input to the appearance model. Any model that did not include the physical properties of the photoreceptors is at a disadvantage in trying to predict metameric colors. After a physical input, sensation models have to have a lightness asymmetry as shown by the Gelb experiment. Models such as those described by Land and McCann, McCann McKee and Taylor, Frankle and McCann, are very accurate predictors of color sensations, as proven by detailed color matching experiments.[28,29,35]

The introduction of new radiances,[36] or Constancy Test Patches[32] has different implications for different models of human vision. For example, let us compare the CIE model of colorimetry[4] and the Frankle and McCann Retinex model[22] The fundamental difference in the models is that colorimetry evaluates a single pixel, whereas a Retinex evaluates all pixels in the field of view. Colorimetry evaluates pixels in a real-life complex image as a set of completely independent points. The Ratio-Product-Reset Retinex model is a field model. Each pixel is evaluated relative to all the other pixels in the field of view. Color sensation is a field phenomenon.

Summary

The most important part of any color calculation is the obvious initial question, "What do I want to calculate?" The answer is not always easy.

How do we synthesize the easy-to-do "Pixel Transformations" with the more complex sensation or perception models. What is a sensible approach to daily problems of color? Do the convenient and easy-to-do colorimetric calibrations work when they shouldn't? Should we continue to ignore the color-constancy mechanisms of vision because it is more complex than pixel thinking? How hard is it to understand human color appearance?

If the goal is to calculate color appearance, the calculation must be a field calculation because human color appearance is derived from spatial relationships in the visual image. Special cases using "Pixel Transforms" can be used in images, just as long as the entire gamut of the original is present in the reproduction medium. As soon as there exists a disparity of gamuts between original and reproduction, there will be a degradation of color match. The mechanism of color degradation is that the spatial relationships between different areas in the field of view change.

As we have seen the "Pixel Transformation" special case of reproducing a picture by colormetric matching each pixel in the image using a transform that uses input data from only one pixel at a time. This "Pixel Transform" works perfectly when all the pixels in the original image are within the gamut of the reproducing mechanism, because all the spatial relationships are matched exactly. When the gamut restrictions enter into the experiment, then each departure from a perfect reproduction of a pixel introduces a new and different spatial relationship. Since human vision is a spatial mechanism it generates color appearance based on the distorted spatial relationships. As soon as color gamuts do not match, the degree of success of"Pixel Transformation" is unknowable unless you set aside the special case analysis tools and analyze the reproduction using the general case, that is use tools based on spatial interactions of human vision.

Color—A Greater Challenge than 1 Bit B&W

We have come a long way to this morning. We have seen color theory, measurement and color spaces. We have ventured even as far as color aesthetics. We have been spoiled in the past because of the great success of 1-bit black-and-white printers. We hope no one believes that color is a simple extension that requiring 23 or 31 more bits to make real complex images on different devices appear identical.

A 1-bit-black-and-white system has, by definition, only a max and a min. It does not matter what the max and the min happen to be. The max and the min can be in arbitrary, radiometric, colorimetric, or psychophysical units. All definitions are equivalent for one bit.

In a continuous tone image it matters a great deal whether a digit value represents *undefined, radiometric, colorimetric,* or *appearance* values. Further, the shape of the function of the values from max to min matters. Today, the system hardware has a much higher demand, a reduced cost and new level of interconnectability. Today, the important idea in all color system components is the demand for interchangeable, interconnected hardware components. The demand is that color be *transportable* from any scanner and electronic camera, to any display device and printer. This requires that equipment be designed to work in systems that can be unique.

All computer users want WSYIWYG to work. Clearly, machines can only communicate with other machines that share the same definition for a signal. Device independent systems are supposed to be made up of components that have precisely the same definition for each digital value. *If the system truly requires WSYIWYG, the colorimetric matches for 30 to 40% of the pixel may not be sufficient.* If we want WSYIWYG to work, as advertised, digits have to be precisely defined to represent Color Appearance not Colorimetry. In such cases, instead of color matches new approaches, using spatial interactions, to generate color sensations or color perceptions are required.

Acknowledgments

I wish to thank Mary McCann for her thoughtful discussions and many contributions.

References

1. CIE Proceedings 1931, p. 19, Cambridge University Press, Cambridge, 1932.
2. G. Wyszecki, and W. S. Stiles, "Color Science: Concepts and Methods, Quantitative Data and Formulae," 2nd Ed, John Wiley & Sons, New York, 1982.
3. V. C. Smith and J. Pokorney, "Spectral Sensitivity of the Foveal Cone Photopigments between 400 and 500 nm," *Vision Res.,* **15**, 161, 1975.
4. H. von Helmholtz, "Physiological Optics," Vol. II, J. P. Southall, Ed., *Optical Society of America*, 264, 1924.
5. M. E. Chevreul, *The Principles of Harmony and Contrast of Colors and Their application to the Arts*, 1854, Republished Reinhold, New York, 1967.
6. E. Hering, *Outline of a theory of the Light Sense*, L. Hurvich and D. Jameson Trans, Harvard University Press, Cambridge, 1964.
7. H. Wallach, *J. Exptl. Psychol.* **38**, 310, 1948.
8. E. H. Land and J. J. McCann, "Lightness and Retinex Theory, " *J. Opt. Soc. Am.*, **61**, 1, 1971.
9. D. Marr, "The computation of lightness by the primate retina," *Vision Res.* **14**, 1377, 1974.
10. B. K. P. Horn, "Determining lightness from an image," *Comp. Gr. Img. Proc.* **3**, 277, 1974.
11. A. Hurlbert and T. Poggio, "Formal connections between lightness algorithms," *J. Opt. Soc. Am. A* **3**, 1684, 1986.
12. G. Buchsbaum, "The retina as a two dimensional detector array in the context of color vision theories and signal detection theories," *Proc. Inst. Elect. Electronic. Engrs.* **69**, 772, 1981.
13. M. H. Brill, "Further features of the illuminant-invariant trichromatic photosensor," *J. Theor. Biol.* **78**, 305, 1979.
14. L. T. Maloney and B. A. Wandell, "Evaluation of linear models of surface spectral reflectance with small numbers of parameters," *J. Opt. Soc. Am. A,* **76**, 1673, 1986.
15. G. Wyszecki, "Colorimetry", in *Color: Theory and Imaging Systems*, Society of Photographic Scientists Engineers, R. Eynard, ed., Washington, 38, 1973.
16. J. J. McCann, "Color Sensations and Color Perceptions," in *Asilimar Proceedings, Signals, Systems in Computers*, *IEEE*, **1**, 408, 1990.
17. J. Hannah, "An Artist's Experiments with Color Perception," *SPIE Proceedings*, **1250**, 212, 1990.
18. J. J. McCann and R. L. Savoy, "Psychophysic Measurements of Hannah Color/Distance Effects", in *SPIE Proceedings, in Perceiving, Measuring and Using color Human Vision, Visual Processing and Digital Display II*, **1250**, 203, 1991.
19. The handbook cites the following definitions—SENSATION: mode of mental functioning that is directly associated with stimulation of the organism. PERCEPTION: mode of mental functioning that includes the combination of different sensations and the utilization of past experience in recognizing the objects and facts from which the present stimulation arises. Optical Society of America, Committee on Colorimetry, *The Science of Color*, **58**, Crowell, New York, 1953.
20. J. J. McCann and K. L. Houston, "Color Sensation. Color Perception and Mathematical Models of Color Vision, in: *Colour Vision*, (Mollon, J. D., Ed.) Academic Press, London, 535, 1983.

21. M. Burger, Digital Photography—first impressions, *Image-Base*, **1**, 1, p. 8, 1993.
22. J. Frankle and J. J. McCann, *Method and apparatus of lightness imaging*, U.S. Patent, 4,384,336, 1983.
23. R. W. G. Hunt, Revised colour-appearance model for related and unrelated colours, *Color Res. Appl.* **14**, 146, 1991.
24. A. Gelb, Die "Farbenkonstanz" den Sehdinge. In *Handbuch der normalen und patholgischen Physiologie*, vol. **12** (ed. Bethe, A.) Berlin, Springer, 1929.
25. J. J. McCann, "Local/Global Mechanisms for Color Constancy," *Die Farbre*, **34**, 1987.
26. J. J. McCann, "Calculated color sensations applied to image reproduction," *SPIE Proceedings*, **901**, 205, 1988.
27. E. H. Land, "The Retinex theory of color vision," *Proc. Roy. Inst. Gr. Britain*, **47**, 23 1974.
28. 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, 1976.
29. J. J. McCann, "The role of nonlinear operations in modeling human color sensations," *SPIE Proceedings*, **1077**, 355, 1989.
30. R. W. J. Hunt, "Revised colour-appearance model for related and unrelated colours," *Color Res. Appl.*, **14**, 146, 1991.
31. D. Marr, Vision, Freeman, 1982.
32. J. J. McCann, "Color Constancy: Small overall and large local changes," *SPIE Proceedings*, *Human Vision, Visual Processing and Digital Display III,* **1666**, 310, 1992.
33. J. J. McCann and R. L. Savoy, "Measurements of Lightness: Dependence on the Position of a White in the Field of view," in *SPIE Proceedings*, in *Human Vision, Visual Processing and Digital Display II*, **1453**, 402, 1991.
34. W. A. Stiehl, J. J. McCann and R. L. Savoy , "Influence of intraocular scattered light on lightness scaling experiments" *J. Opt. Soc. Am.,* **73**, 1143, 1983.
35. J. J. McCann and K. L. Houston, "Calculating color sensations from arrays of physical stimuli," in *IEEE Transactions on Systems, Man, and Cybernetics*, vol. *SMC* **13**, 1000, 1983.
36. J. J. McCann, "Rules for colour constancy," *Ophthal. Physiol. Opt.,* **12**, Apr., 1992.

published previously in the IS&T 1993 Color Imaging Conference Proceedings, page 16