Capturing a Black Cat in Shade:
The Past and Present of Retinex Color Appearance Models

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ABSTRACT

As a part of the Symposium "Retinex at 40" [1], this paper recounted the research on capturing real-life scenes, calculating appearances and rendering sensations on film and other limited dynamic-range media. It describes: the first patents, a hardware display used in Land's Ives Medal Address in 1968, the first computer simulations using 20 by 24 pixel arrays, psychophysical experiments and computational models of color constancy and dynamic range compression and the Frankle-McCann computationally efficient Retinex image processing of 512 by 512 images. It includes several modifications of the original approach including recent models of human vision and gamut-mapping applications. This paper emphasizes the need for parallel studies of psychophysical measurements of human vision and computational algorithms used in of commercial imaging systems.

Keywords: Retinex, model of lightness, pyramid processing, color constancy

1. INTRODUCTION

In Edwin Land's first lecture at a Friday Evening Discourse at the Royal Institution, London on April 28, 1961 he used real papers as a part of a series of experiments including red and white projections.[2] For Land, it was the turning point from photographic projections to experiments with controlled reflectance and illuminants. More important it was the turning point from the dimensionless coordinate system as a physical description of the stimulus to the psychophysical quantity lightness as the determinant of color. Up until this lecture Land had been trying to correlate the colors he saw with the physical stimulus. He knew that colorimetry was of little help beyond calculating quanta catch of receptors. His experiments with Nigel Daw showed that adaptation, specifically, the change of receptor sensitivity in response to light, could not account for color appearance. They projected red and white images of ambiguous objects to naive observers using 1 microsecond duration flashes. Color memory and adaptation could not explain the colors in ambiguous displays seen for the first time with so few photons.[3] Land knew spatial factors were important, but he did not know how to put the model of human color vision together. In his process of persistent exploration he made the critical observation that color appearance correlated with the triplet of lightness appearances in long-, middle-, and short-wave light.[4,5] This idea created a halfway point between the physical measurement of cone quanta catch and color appearance. If we found a physical model whose output correlated the appearances ranging from white to black, then that mechanism could be used three times in parallel to predict colors. This observation transformed the study of color to a need for understanding how the eye sees whites, grays and blacks.

Land's observation still stands. The triplet of apparent lightnesses correlates with color. The observation is important because a variety of different phenomena can influence lightness, such as simultaneous contrast, the Cornsweet effect, assimilation, and spatial blur of the retinal image. Regardless of the cause of the lightness shifts, when two identical physical objects look different, color appearances correlate with their L, M, S lightnesses.[6,7] In an effective color assimilation display there are two sets of nine square red-brown patches on a yellow and blue striped background. On the left the red-brown patches fall on top of the yellow stripes and on the right they fall on the blue stripes. The left patches appear a purple red, while the right ones appear a yellow orange. In other words, the left patches appear more blue and the right ones more yellow. Color assimilation displays exhibit larger color effects than color contrast.[8] In assimilation, predominantly black surrounds make grays appear darker, while in contrast, black surrounds make grays appear lighter. Figure 1 shows the color display and the R, G, B separations for this effective color assimilation display. Identical square patches appear different colors. In the R separation the corresponding patches are lighter on the right; in the G separation the patches on the right are lighter; in the B separation the patches are darker on the right. Whenever

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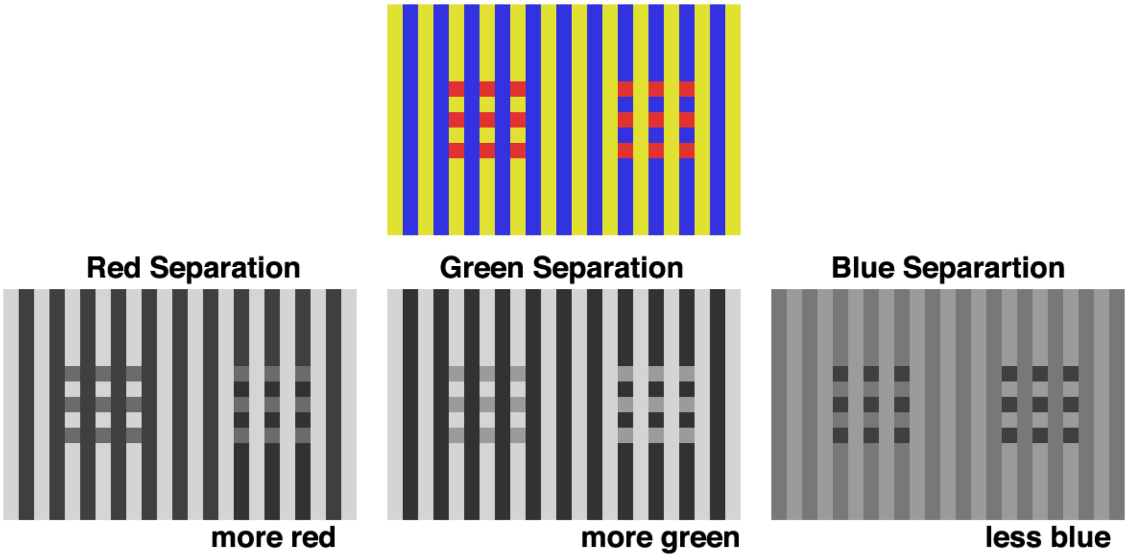

Figure 1 shows a dramatic color assimilation display on top and the R, G, B separation images below. The 9 square patches on the center left are identical (the same pixel values) as those on the right. The left patches appear bluer; the right patches appear more yellow in the color display. Land's reasoned that the square patches on the right look more yellow because they are lighter in both the long-wave and the middle-wave separations . The opposite is true for the left patches. They appear more blue because the squares in the short-wave cones are lighter than those on the right.

R and G separations are lighter and B separation is darker, then that patch will appear more yellow. Whenever B separation is lighter and R and G separations are darker, then that patch will appear more blue. Colors correlate with R, G, B lightnesses.[7] This is the theory that Land proposed 40 years ago and called it Retinex.[4]

2. CALCULATING LIGHTNESS SENSATIONS

Retinex made understanding color much simpler, and made the mechanism of how humans generate lightness more important. The black and white Mondrian with a gradient of illumination became the "problem to be solved". The same radiance, and hence same receptor quanta catch, appears white in one patch and black in another in the same arbitrary scene. The experimental design, using a single display with arbitrary shapes of unrecognizable objects in a gradient of illumination, has done most of the hard work. The influence of retinal adaptation, object memory, visible location of the light source and unconscious inference were minimal or absent. The only likely candidate for an underlying mechanism for generating lightnesses was spatial comparisons. Wallach's[9] classic paper had introduced the idea that the ratio across edges was important. The Mondrian with gradient illumination showed that ratios alone cannot predict lightness. Ratio-Product became the next hypothesis. The ratio of two pixels gave the relationship of two nearby pixels, but their relationship to distant pixels could be propagated by multiplying all the ratios along a path, from here to there. The ratio-product model was able to incorporate interactions from distant parts of the same scene. Land described our discussions leading to the Ratio-Product idea in detail in his second Royal Institution paper.[10]

Ratio-Product Calculation

Land had a very special relationship with Optical Society of America. Many of his closest scientific colleagues were active members. He first demonstrated instant photography at the Annual meeting in 1947. When he received the 1967 Ives Medal[11] , he wanted to make the traditional address something special. A lot of work went into the talk. The demonstrations were bigger and better. Color Mondrians replaced the animal cutout figures used earlier[4]. For the first time, the Ratio-Product Threshold model was described and the Ratio-Product-Threshold-Reset model was demonstrated.

Along with the preparations for the talk and the demonstrations I had my introduction to patent law. The universal corporate patent rule applied; namely, the patent must be filed before the talk was given. Usually patent lawyers hold speakers hostage until filing. Since Land was the speaker he held Polaroid's Patent Attorney Bill Roberson hostage to get the patent filed before the talk. Bill's problem was that Land was too busy to explain the patent. Bill found the idea fascinating, namely that one could use human vision research as the source of image manipulation processes. These processes, in turn, could be applied to imaging devices.

The frantic preparation of the first Retinex patent led to a long and valuable friendship with Bill and a lot of good stories. Land and I had left for Detroit ahead of the talk as a snowstorm moved up the East Coast of the United States. Bill and the patent application were trapped in Boston. Ever resourceful, Bill walked through the blizzard from Cambridge to Boston to a Western Union office and telegraphed the ten-page application to Washington for filing just ahead of the talk. Bill often told the story of a subsequent meeting with the patent examiner in which he had to explain that he understood that telegrams were not the accepted format for US Patent submissions, and that he would never do it again.

The patent application[12] was the first description of the ratio-product model for lightness. It described the problem of calculating lightness in terms of differentiating between a black cat in the sun and a white cat in the shade when they both sent to the eye and the camera the same amount of light. The algorithm described a technique that made equal radiances appear at opposite ends of the lightness scale. But, in retrospect, the search for the black cat in the shade is an even more difficult problem. It requires physical measurements of the scene to accurately record image content over a range of more than 1000:1[13] without distorting the information in the very low radiance region. Further, it requires a means of scaling the radiance information in equal logarithmic steps for meaningful image processing. Nonlinear scaling of the captured image means that the same pair of papers in the sun and in the shade will have different radiance ratios. In order to generate the same appearance in both sun and shade these pairs of papers have to be rendered with constant radiance ratios. We preferred scaling the image in log radiance for two reasons. First, an 8-bit log image can represent any dynamic range, while an 8-bit linear image is limited to a range of 256:1. Second, the computation of ratios of pixel values is much more efficient using digital subtraction, than using digital division. In the late 70's high-dynamic range images were synthesized by scaling and combining together different video images. In the 1980's, it was possible to scan low-slope photographs of real scenes.[13] In the 1990's expensive digital cameras with 16-bit output became available. However, it is important to remember that the number of bits only refers to the number of digital levels; it is quite independent of the actual dynamic range in the final digital image. The camera's tone scale function used in rendering the digital image controls the image content. Capturing and preserving the actual relative radiances of the black cat in the shade remains one of the biggest challenges in digital photography.

Threshold

It was Bill Roberson who raised the issue that the ratio-product calculation was incomplete. If you take the ratio of pixels at each of the visually significant boundaries between distant patches on a Mondrian, you can calculate the ratio of the first patch to the last by multiplying all the edge ratios. Bill's concern was with the pixels between the boundaries. In the case of the Mondrian in gradient illumination, the product of the ratios of all pixels would calculate an output equal

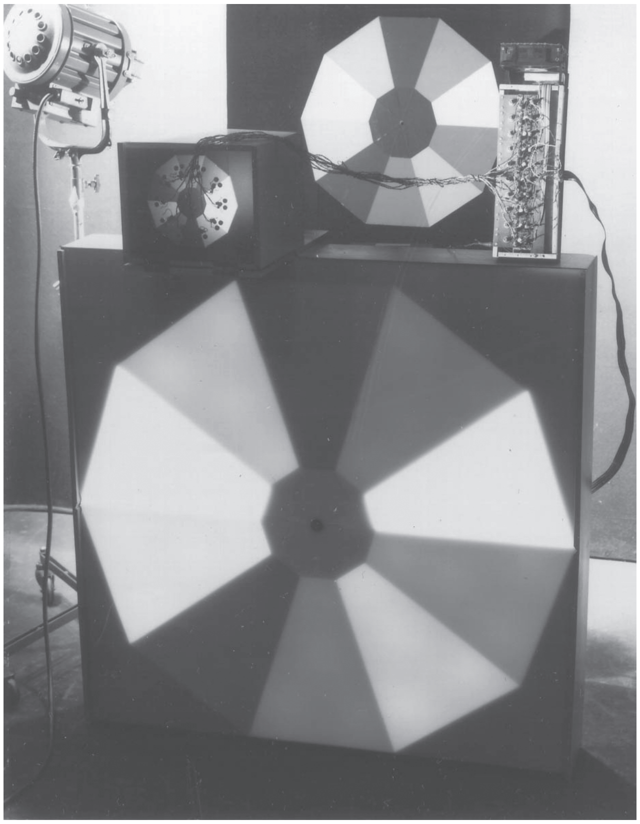

Figure 2 is a photograph of the Retinex camera demonstrated in Land's 1967 Ives Medal address. The wheel of different reflectance papers on the back wall is in the top center of the picture. The movable spotlight illuminator is in the top left. The lightbox display is at the bottom. The display was made up of 10 individual, pie-shaped boxes with independently controlled lamps in each box. The camera sits on top of the left side of the display. Pairs of photocells are inserted in holes drilled in the camera's ground glass. Theses pairs measured the ratio of radiances in the camera's focal plane. The ten edge ratios were sent by wires to the processor on the right. This electronic package multiplied the ratios to form a product. That product was the signal sent to control the brightness of the individual light boxes in the display. Regardless of the direction, the nonuniformity and overall intensity of illumination, the ratio-product display was constant.

to the input. Rather than use an image segmentation approach to search for visually significant boundaries, we introduced the idea of a threshold. Blackwell had measured the threshold of edge detection to be three parts in a thousand at high luminance levels.[14] In other words, humans cannot detect edge ratios smaller than 1003/1000, or 1.003. If the Black and White Mondrian subtended 30 degrees of visual angle, and if individual foveal receptors subtend one minute of arc, then there are 30 x 60 =1800 receptors in the image height of the Mondrian. If the threshold for each pair is 1.003, then the gradient it could remove is $(1.003)^{1800}$ = 219. Such a threshold applied to a 30 degree image can remove gradient of over 200:1, while the gradient on the Mondrian is only 20:1. The threshold replaced ratios close to 1.0 with exactly 1.0. Using this threshold made the model responsive to edges and insensitive to gradients. This idea played an important role in the Ives Medal Address and the subsequent paper by Land and McCann.[5]

Following demonstrations of Color Mondrians, Black and White Mondrian in gradient illumination, and a description of the Ratio-Threshold-Product model, Land demonstrated the first Retinex camera. Figure 2 is a photograph of the system. The demonstration consisted of moving the spotlight to change the direction, uniformity and intensity of the illumination and observing that the lightbox display gave constant output despite the wide range of inputs.

This demonstration was in fact an embodiment of the Ratio-Product-Reset process before it was invented. Sometime after the lecture Kagan and Ferrari pointed out that the device they built should not have worked as it was described. The signal passed from one ratio detector to the next and formed a circle. They reasoned that the loop should have gone into oscillation. The existing circuit did not, so they looked further to understand its stability. The amplifier circuit, which sent the product signal to drive the lamps in the pie area display, acted as a reset step before sending the old product to be multiplied by the new ratio. This observation led to a lot of analysis. A computer model needed a more explicit mechanisms for establishing the particular lightness from white to black for a given ratio product. This work led to the second Retinex patent.[15] The Ratio-Product steps provided the long-distance interactions, but did not provide normalization. Since adaptation and grayworld, associated with camera electronic exposure devices, seemed inappropriate, we pursued the idea of reset to maximum radiance. Early arguments for normalization to the maximum were as simple as the fact that Ganzfelds do not look middle gray; rather they look a dirty white. Extensive experiments by Stevens[16], Bartleson and Breneman[17], Bodman[18], Jameson and Hurvich[19] and Gilchrist[20] all show dramatic shifts in lightness function when a new white is introduced. Normalization to white is used by CIE L*a*b*, CIE Luv[21], and recently by CIECAM97.[22]

Specific experiments demonstrated at Fergus Campbell's "FergusSpiel" demonstrated that color constancy uses independent normalization to the maximum in each channel.[23] The experiments followed Maximov's suggestion of making two identical Mondrian stimuli using two different illuminants and two different sets of reflectances to offset the spectral shift of the illuminant. Maximov's idea was that identical retinal stimuli from different sets of reflectances must shut off "color constancy". Adding new papers could test the underlying mechanism by identifying the set of stimuli that turned "color constancy" back on. Although difficult to make, each area in first Mondrian must match the corresponding area in the second, because all the quanta catch from all the corresponding pixels are the same everywhere in the image. Once this difficult control is achieved, introducing new areas to the Mondrians provides opportunities to probe the color constancy mechanism. Introducing a white paper to both Mondrians destroys the match, but introducing a black or a gray paper to both Mondrians does not. A second set of experiments made the case that color constancy uses independent normalization to the maximum in each channel. Any new paper with a new maximum in any of the long-, middle-, or short wavebands will destroy the match.[24] This is strong direct evidence for the Retinex hypothesis of independent LMS normalization.

3. PROCESSING IMAGES

The Ives Medal display required a camera focal plane with holes drilled for the pairs of receptors and segmented lightboxes for each area of the pie. Land's close friend Ed Purcell, had become fascinated with computer programming. He wrote the first Retinex simulation program. He made two arrays that were 24 pixels wide and 20 pixels high. The first array was the radiance of the input scene. The second was the Old Product initialized to the maximum value of 1.0. It randomly selected the first pixel of a path. Then it selected an adjacent pixel. It divided the radiance of the second pixel by the radiance of the first to make the ratio. It multiplied the Old Product for the first pixel by the Ratio to form the New Product for the second pixel. If the value of the new product was greater than 1.0, it was reset to 1.0. The New Product was stored in the Old Product array at the location of the second pixel. In a pseudo-random manner the program selected the third pixel, multiplied the Old Product of the second pixel by the Ratio of the third divided by the second, reset and stored in the Old Product array. The process was repeated until the path reached its specified length. Multiple paths were used up to the program variable number of paths. The output was stored in the Old Product array for the next iteration. (Papers describing the details of the computation are found in the literature.[5, 25-28])

Vision avoids the reflectance asymptote

The physical definition of reflectance, used to characterize objects, is the fraction of incident light that is reflected. Although the goal for calculating lightnesses of objects in uniform illumination is usually close to calculating the reflectance of objects (using human cone sensitivities), there are some very important departures from visual reflectance. Simultaneous contrast is an excellent example. Here, a gray in white looks the same as it does in a complex scene. The gray in black looks about 10 % lighter. A model that successfully calculated the reflectance of the gray patch fails to calculate the apparent lightness seen by observers. The ratio-product-reset model prediction approaches reflectance with increased processing. With many long paths the output of the model approaches the input as an asymptote. Despite an analysis to the contrary,[29] this was never the intent of the model.[30] As described in early papers,[5,6] the goal is to mimic the sensation lightness, not calculate physical reflectance. The sensation lightness does not correlate with the radiance of a pixel divided by the radiance of the pixel with maximum radiance in the image. Rather, lightness correlates with a spatial normalization process that is sensitive to the amount and position of the maxima in the image. In particular, it is sensitive to enclosure (number of adjacent sides with maximum radiance) and separation (distance from maximum).[31-32]

Using the local processing associated with a few short paths, the ratio-product-reset model prediction for the gray in the black surround can be white, or close to white. The model resets to the maximum. With a few short paths the spatial interactions are limited to the vicinity of the gray and black papers. The gray is the local maximum and is assigned to white. Greater spatial interaction is required to have the distant white paper influence the model prediction for the gray in black. This display is a sensitive litmus test for spatial comparisons in vision and helps to define model parameters. Short paths make the gray in black too light; long paths make it too dark.

In the study of how to optimize the parameters of the model we first had to establish a goal. The idea was to perform matching experiments on a series of lightness displays to find what human observers saw. The procedure for quantifying lightnesses is described in a paper by McCann, Land and Tatnall.[33] With this matching data as quantitative goals for the model we could optimize the path length and the number of paths. The most sensitive test for the model was a simultaneous contrast display. With short path lengths the model reported that the gray-in-black patch was white, because it was the maximum in the set of comparisons reached by the short path length. With very long path lengths the model reported the gray-in-black patch as equal to the gray-in-white patch, because the output approaches the input as a limit. Observers report that the gray in black is 10% lighter than gray in white. Path lengths of 100 to 200 successfully modeled this result. Some of the data from these early experiments are reported in another paper in these proceedings.[34]

The Rise of Reset and the Fall of Threshold

We undertook a major effort to understand the visibility of gradients. We felt we needed better data on the rate of change of radiance on the retina that was at detection to improve our model. We measured the magnitude of both continuous[35] and sinusoidal gradients at threshold[36] . To our surprise, there is no single threshold rate of change of luminance on the retina. All that matters is size and number of cycles of sinusoid.[37-40] About the time we were trying to understand our gradients measurements, we found out that reset had the same effect as a gradient threshold. Using reset we could eliminate the threshold step and get equivalent good predictions of the Black and white Mondrian with gradient illumination.[27]

We became fascinated with reset because it could model simultaneous contrast in addition to auto-normalization. Even more important was the idea that reset provided a mechanism for calculating a low-spatial frequency filter that was image dependent. This was the important differentiation from the work of Fergus Campbell[41], Marr[42] , Horn[43], Stockham[44], Wilson[45], as well as much later variations by Pattanik et. al.[46] and Fairchild and Johnson.[47] They all looked to apply spatial filters to receptor images, but did not have a mechanism to independently “adapt” the filter coefficients to each image. Human vision generates a scene depend low-spatial-frequency filters. Patches in a white surround need no filtering, patches in a gray surround need some filtering, and patches in a black surround need strong filtering.

4. COLOR CONSTANCY

The modeling of black and white lightness phenomena in collaboration with Tom Taylor was the stepping stone to modeling color constancy. Along with Suzanne McKee, John Hall and Tom Taylor, we performed a wide range of observer measurements and computer modeling experiments with the goal of understanding the role of spatial comparisons and adaptation in color constancy.

The first paper[25] in the series had three sections. The first made quantitative measurements of color sensations in color constancy experiments. Observers matched color appearance to the Munsell Book in constant illumination. The target was a small Mondrian of 17 areas and a gray surround made of Munsell papers and illuminated it with narrowband 656, 530 and 450 nm light.

The experiment repeated Land's Color Mondrian demonstration[4] using gray, red, green, yellow and blue papers. The steps were:

1. Match all 18 areas in the Mondrian in the initial illumination
2. Measure the 656, 530, 450 nm radiances from the gray paper
3. Adjust the irradiances from the three projectors so that the gray-paper radiances came from the red paper
4. Match all 18 areas in the Mondrian in the red paper illumination
5. Repeat steps 3 and 4 for green, yellow and blue papers.

This procedure generated 5 papers in 5 different illuminants that sent identical radiances to the eye. The observers matched these identical stimuli to 5YR6/1, 5R6/6, 2.5PB6/4, 10GY7/4, 5Y8/8 in the Munsell Book. Five identical stimuli generated five very different color sensation. The Munsell designation of the papers making up those areas in the display were N 6.75/, 10RP6/10, 2.5PB6/8, 2.5 GG7/6 and 5Y8.5/10.

Despite the fact that the cones' quanta catch are identical the matches are very close to the paper designations. The average distance between original paper and equal-quanta-catch match in Munsell Chips is 0.6 chips in hue, 0.25 chips in lightness and 1.3 chips in chroma. When we look at the results in terms of color constancy, color sensations are nearly constant with variable illumination.

When we look at the results from in terms of the mechanism that moves identical quanta catches to predicting color sensations, the magnitude of the spatial influence on color appearance must be great. The distance in color space between the matches caused by a single stimulus is large. There are ten distance combinations between each of five matches (Gy-R, Gy-Gr, Gy-Y, Gy-B, R-Gr, R-Y, R-B, Gr-Y, G-B, Y-B). On average the sensation distances are 10.8 pages in hue, 1.0 chip in lightness and 2.2 chip in chroma. The maximum distance was between yellow (5Y 8/8) and blue (2.5PB 6/4) patches. They are 16 pages in hue, 2 steps in lightness and 2 steps in chroma. The average distance is 11.3 chips in Munsell Space. The small separation in lightness is due to the that the original paper lightnesses were 6.75, 6, 6, 7 and 8.5. In summary, the mechanism that predicts color constancy at a pixel must move the output away from the input the order of 10 Munsell chips on average to account for experimental measurements.[25]

The second part of the McCann, McKee and Taylor paper tested if the color matches correlated with the reflectances of the papers. As expected, matches showed little correlation with quanta catch of cone receptors. Reflectance measurements were made with a telephotometer using three filter sets which converted the meter spectral sensitivity to match human cone pigment sensitivities. The experimenter measured each paper in each illumination. The term "integrated" described the use of a meter with cone spectral sensitivities . The term "integrated reflectance" described the ratio of the response for each paper to the response for the white paper in the Mondrian. Matches showed good correlation with L-, M-, S-wave integrated reflectances. The plots showed greater observer variability near white than near black. R. Clark Jones suggested that these reflectances should be scaled by a lightness function, since equal increments of reflectance do not generate equal increments of sensation. The term "scaled integrated reflectance" described integrated reflectance scaled by lightness. The plot of observer data and physical measurements using scaled integrated reflectance showed excellent correlation. Whatever the mechanism used by human vision, it is able to generate "scaled integrated reflectance" from receptor quanta catch in these Mondrians.[25]

In addition the five different experiments provided 5 x 18 matches for quantitative analysis of different color constancy experiments. This information is of particular importance because it quantifies the departures from perfect constancy. Photographic films have R, G, B emulsion sensitivities adjusted for specific color illuminants. Nevertheless, it is possible to take pictures in tungsten light with daylight film using spectral filters that attenuate the blue and green light the appropriate amount. With these filters the colors are the same as those made using tungsten film. In other words, film/filter combinations have nearly perfect color constancy. Human color constancy is different. It shows a small but systematic departure from perfect color constancy. These measurements provide a signature of human vision that helps to understand the underlying constancy mechanism.[25]

The McCann McKee and Taylor (MMT) data showed a dependence on long-, middle-, and short-wave matches on absolute light intensity. The stronger the illuminant the lighter the match. This effect is small but significant. A control experiment was designed to measure the effect on match from varying the overall illumination. In one control, the Mondrian was half the gray conditions radiance, and in the other, twice the radiance for all three wavelengths. When compared to the gray condition Mondrian matches, the L-, M- S-average match in the control with twice the radiance was 0.5, 0.5 and 0.3 scaled integrated reflectance units lighter. The L-, M- S-average match in the control with half the radiance was 0.3, 0.3, 0.3 scaled integrated reflectance units darker. Similarly, the data from the 5 color experiments showed the same small shifts in matching lightness as a function of overall illumination.

The purpose of Retinex constancy model is show that color constancy can be predicted by spatial comparisons, without requiring adaptation of the sensors to the spectral composition of the image. Most color constancy models, including all of the many CIE appearance models require independent measurement of the target radiance, target irradiance and the reference irradiance for all pixels. In other words, the answer to the question is contained in the question. The goal of Retinex model was to calculate the color sensations from the input image without a priori information of the spectral distribution of the illumination.

The third part of the McCann, McKee and Taylor paper showed that spatial comparisons can predict color constancy. They used the Land and McCann model for each of the L, M and S channels. The three inputs were the L, M, S radiances measured with the cone sensitivity telephotometer. The maximum lightness in each channel and each experiment was scaled for absolute radiance. The correlation between computed lightness and observer matches was excellent.[25]

Although McCann, McKee and Taylor paper showed that spatial comparisons can predict color constancy, it did not exclude "von Kries" type chromatic adaptation as possible explanation. The von Kries chromatic adaptation hypothesis assumes that some type of average measure of the input image provides the signature of the illuminant. This signature provides the information for the receptor circuits to adapt sensitivity to compensate for change in illumination. Imagine a uniform, gray field of view in daylight. If the light source is changed to tungsten, then the gray field will have relatively less blue and green light. It is possible that the increase in blue and green light will bleach more visual pigment and that the sensitivity to blue and green will decrease. It is possible that bleached pigment and a neural feedback loop could generate the same gray sensation from both daylight and tungsten. Beyond uniform fields, these adaptation assumptions become less credible. The mechanism requires that all scenes have the same average value. This "gray world "hypothesis seems unlikely when looking at the sky, the ocean, or going skiing. Nevertheless, it remains a popular hypothesis. As Land and Daw did with Red and White projections[48], Hall and McCann explicitly tested the global-, and local-average adaptation hypothesis. We found, as they did, no experimental support for von Kries adaptation as a controlling mechanism for color constancy.

We repeated the McCann, McKee and Taylor experiments using different carefully selected surrounds. The original experiment changed the illumination everywhere to make a red paper have radiance previously measured from a gray paper. Using an ideal von Kries adaptation mechanism, the sensitivities of sensors could change in proportion to the global average change in illumination. If true, then the observers should report perfect color constancy. In order to repeat the experiment without adaptation, it is possible to change the surround paper to change the global average back to the initial value. In order to send the same radiances from the red paper as the gray paper, the experimenter decreased the 656 nm and increased the 546 and 450nm irradiance. That decreased the long-wave cone average response and increased the middle- and short- wave cone responses a specific calculable amount. By measuring the cone responses to hundreds of papers, it is possible to select a paper for the particular surround area that changes the global average back to that of the gray illumination and the gray surround. Changing the irradiance changes the average; changing the surround paper changes the global average back to the initial state. (See Figure 3, left.) In other words, there is no global adaptation present in these measurements. The results without adaptation show no significant difference from the MMT experiment with global adaptation.49-52

Additional experiments measured the adaptation associated with MMT illuminants. Using constant illumination equal to the reference Munsell book, we introduced papers that changed the global average as much as measured in MMT. In other words, we found surround papers that exactly compensated the global average adaptation state created by the MMT illuminants. Color constancy was still observed despite the fact that the scene was free of von Kries adaptation. In still further experiments, we used the surround to change the adaptation state in constant illumination. We found no significant change in color appearance caused by changes in the global adaptation state.[49-52]

All of the above experiments were repeated using local surround. In this set of measurements new Mondrians were made with each Mondrian area separated from its neighbors so that the surround was visible in all the open spaces. Think of it as a kind of exploded parts diagram that displays

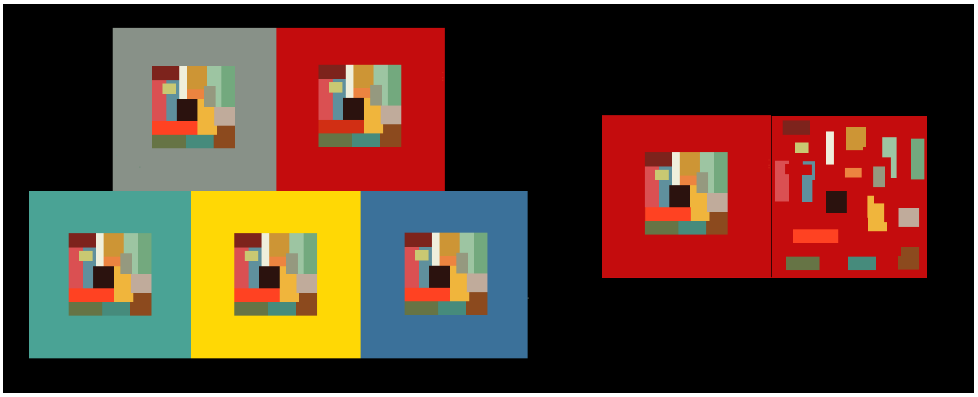

Figure 3 (left) shows the five MMT displays that have no change in average cone catches. The surrounds were selected to compensate for changes in MMT illumination. Figure 3 (right) shows the Red experiment with constant local surround. Local surround experiments were conducted for Green, Blue and Yellow experiments as well.

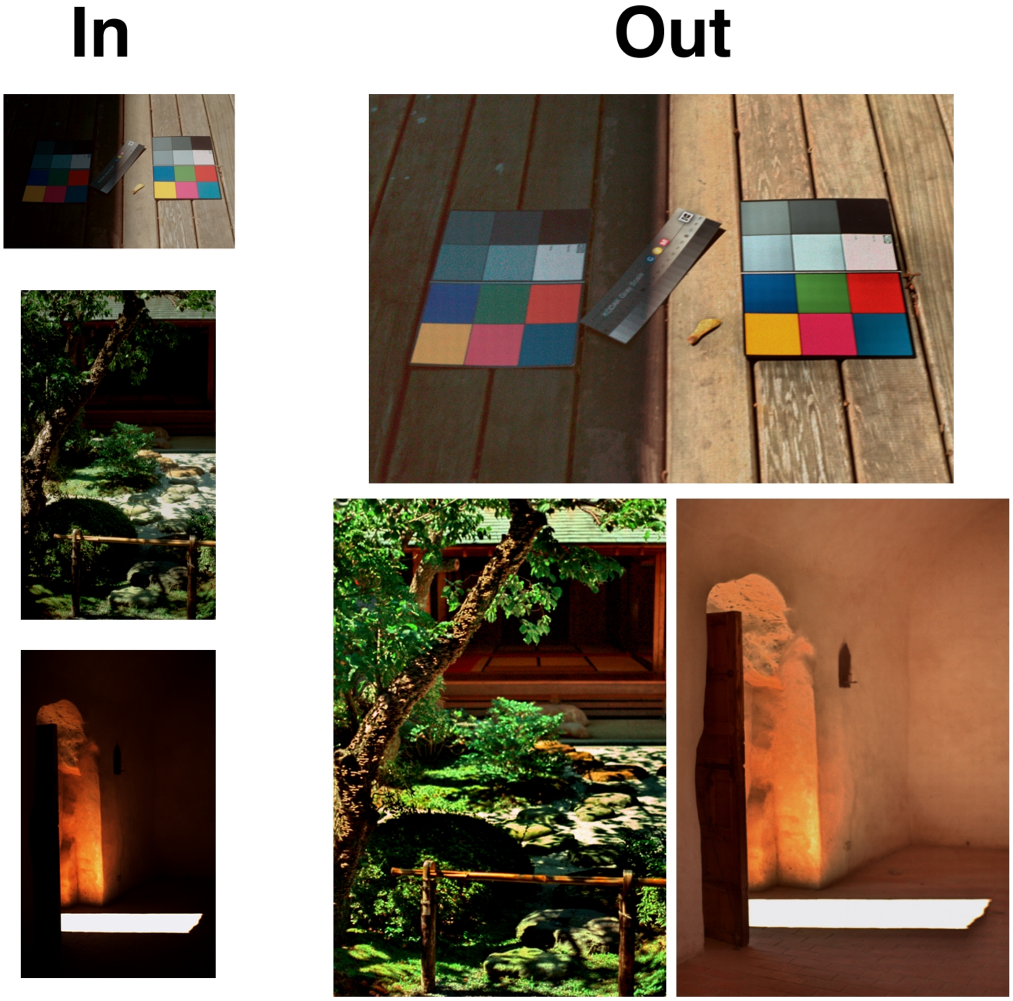

Figure 4 shows three pairs of images. The left column has small unprocessed control images. Here digits are proportional to log radiance in the scene. These images were printed normally. Note that the test target in the sun appears normal. The same test target in the shade is much darker. The larger Retinex images on the right have been spatially processed to compress the dynamic range of the image then scaled to fit the printer dynamic range. Again, the output images are not colorimetric reproductions, rather they preserve the edge information and the relationships of all parts of the image.

each component separately (See Figure 3, right). By making this translation of Mondrian elements the local average is significantly changed. Despite such large changes in local surrounds, the changes in sensation are small.[49-52] Surrounds can change the appearance matches a few Munsell chips in these experiments. Color constancy experiments show the same cone quanta catch generate matches that are very different, namely average distance 11.3 Munsell chips. Clearly the changes in color sensations in Mondrians caused by different surrounds are far smaller than those generated by color constancy.

In summary, despite many different attempts, we were unable to find any correlation between average cone responses and color constancy. That statement is true for both global and local averages and for variable illumination without constant adaptation and constant illumination with variable illumination. Land's query "Adaptation. What adaptation?" remains as important in color constancy as it was in understanding Red and White Projections.[48] All our attempts to measure the role of von Kries adaptation in color appearance have failed. Color sensations are consistent with a mechanism based on spatial comparisons.

In addition, color constancy experiments were performed using real images. In 1982 McCann and Houston[53, 54] reported color matching experiments using a computer generated real complex image. The experiments were similar to the above Mondrian experiments with the new feature that the images were real complex images presented on a computer controlled display. Further, the calculated color appearances were generated from the digital real images sent to the display. Psychophysical experiments using digital images are common today, but were unusual at the time. The results with real images were very similar to those found using Mondrians and much smaller digital arrays. The hardware and image processing are described below. The L, M, S data showed excellent correlation between computed lightness and observer matches.

Psychophysical measurements remain the key to understanding the mechanism used by the human visual system. Recent experiments by Hurlbert and Wolf study the relationship of local and global cone-contrasts to color appearance.[55] J. Barbur, deCunha, Williams, and Plant have studied instantaneous color constancy.[56] Westland, O. Da Pos and C. Ripamonti have shown that invariant cone-excitation edge ratios correlate with the appearance of transparency.[57] Transparency and color constancy appearances both show that observed appearance correlates with mechanisms using spatial correlation.

5. EARLY PYRAMID PROCESSING

By the mid-1970's digital imaging had progressed from 20 by 24 pixels to 512 by 512 pixels in special hardware. The Polaroid's Vision Research Laboratory purchased an I^{2}S image processing system. Spatial interaction algorithms appropriate for 20 by 24 pixel image were hopelessly slow for 512 by 512 images in our new Digital PDP11/60 computer. We developed a series of very efficient multiresolution techniques to make spatial comparisons across the entire image, using the specialized I^{2}S hardware. One technique compared individual pixels half the image width away, then one quarter the image width, then one eighth, etc. The early stages introduced significant artifacts in the developing image; they disappeared when the comparisons approached one pixel separation.

A second process, that was called zoom, has come to be known as pyramid processing. It averaged the full resolution into a set of smaller pixel arrays, made spatial comparisons in the smallest array, used these results in processing the next larger array, and repeated the process until full resolution. The idea was that very long distance interactions could be calculated extremely efficiently using the very small number of pixels in the smallest "zoomed" image of the scene. The long-distance interaction calculations were the most time consuming part of the earlier path-based model. The zoom or pyramid multiresolution techniques replaced the most computationally intensive processes with the least intensive (smallest array) processes. The Frankle and McCann patent, "Method and apparatus of lightness imaging",[26] provides the most complete description of the process. It provides complete FortranIV code for the I^{2}S image processor and a description of the pre- and post-lookup tables (LUT). In today's world the 15 pages of Fortran code can be replaced by a half a page of MATLAB code. The code and a discussion of the design of Pre and Post LUT parts of the model are included in the paper.[28]

The patent was written by Hugo Liepmann and Bill Roberson in three layers and had 86 claims, far more than the 17 claims in the first Retinex patent. The first layer is the specific implementation of the multiresolution ratio-product-reset average. In claim 76 the ratio product step is described as "… providing, for each pairing of segmental areas, at least one measure of transition in said radiance information between the paired areas, said measure conforming to the equation

log ip(x,y)= log op(0,0) + log r(x,y)-log r(0,0) ..."

In claim 74 a broader embodiment of ratio-product is claimed as "…providing, for each pairing of segmental areas, a comparative measure of said radiance information at the paired areas,". In claim 84, an extremely broad restatement, claims "… A. receiving information responsive to the radiance values defining an image field, and B. deriving from said information a lightness field containing final lightness values for predetermined segmental areas of said image field..."

Claim 2 describes the generic multiresolution or pyramid concept: "Image processing apparatus for determining a field of accumulating measures of image lightness in response to information identifying optical radiance associated with arrayed sections of an image field, said apparatus having the improvement comprising A. means for sequentially determining a comparative measure of the radiance information for each segmental area of said image field relative to said information for each of plural other segmental areas, said means (i) providing a new intermediate value of each such measure in response to the product of a ratio function of the radiance information associated with each first-named segmental area and with each second-named segmental area and of a like measure previously determined for the second-named segmental area, and (ii) determining a sequentially new value of each said measure in response to a selectively weighted averaging of said new intermediate value and a like measure previously determined for said first-named segmental area, and B. means for the prior measure for each first-named segmental area in response to said newly-determined value, thereby to determine each measure in the field thereof in response to an accumulating succession of said measures."

This multilayer structure of claims was adopted because we realized the power of multiresolution image processing. It was a timely publication in the development of multilayer or pyramid processing. The Frankle and McCann patent "Method and apparatus of lightness imaging", was filed on August 28, 1980 and published on May 17,1983. A well known reference in multiresolution imaging by Burt and Adelson, "A Multiresolution Spline with Application to Image Mosaics"[58], in ACM Transactions on Graphics, was published in September 1983.

6. ELECTRONIC IMAGE PROCESSING DEVICES

In the early 1980's the cost of digital imaging electronics was very high. The desire for consumer products competitive in price with silver halide photography was not possible. The approach we took was to find ways of incorporating the advantages of digital image processing without the expense of full resolution electronics.

An example is the patent by Kiesel and Wray " Reconstitution of Images"[59]. Here a full resolution radiance field is captured and averaged to form a coarse image field comprising a small fraction of the number of the full resolution pixels. The coarse field image is processed using small affordable image processing hardware to produce an improved coarse image. The improvement was isolated by comparing the coarse input image with the coarse improved image. The improvement is interpolated to full resolution and applied to the full resolution input. This could be a second scan of the input image corrected by the scaled improvement. Such techniques require very small digital storage and small processors, but provide significant improvements to images by adjusting their low-spatial frequency components.

Dynamic-range Compression and Model of Vision

The model for lightness works well in a wide of circumstances. Recent papers[60,27,61] have reviewed the successful modeling of Color Mondrians, with and without retinal adaptation, Black and White Mondrians with gradient illumination. In addition these models can account for visual demonstrations of vision experiments, such as Logvinenko's diamond wall experiment,[62,27] a variation of the Black and White Mondrian.

Examples of capturing a wide-dynamic range image, compressing it using ratio-product-reset-average processing are shown in Figure 4. A number of papers in this symposium have studied real life scenes.

Jobson, Rahman and Woodell generated a lot of interest in Land resetless Retinex. They show how effective it can be in a wide variety of images.[63] Funt, Ciurea and McCann, provided Matlab code for Frankle and McCann and pyramid processing Retinex[28]. Bob Sobol detailed different parameters at different spatial channel levels of the process, as well as assigning limits to the magnitude of the ratios.[64] Ted Cooper analyzes reset and its spatial implications.[65] Funt, Ciurea and McCann[66] compared model responses to psychophysics experiments to define optimal processing parameter values. A. Rizzi, C. Gatta and Marini[67] describe an Automatic Color Equalization (ACE) process that merges white and gray world normalization. Marini, Rizzi and Rossi[68] examine Retinex and other spatial imaging processes using synthetic images. Rodney Shaw has use center/surround spatial comparisons[69] and Kimmel, Elad, Shaked, Keshet, Sobel used illumination estimation tech-

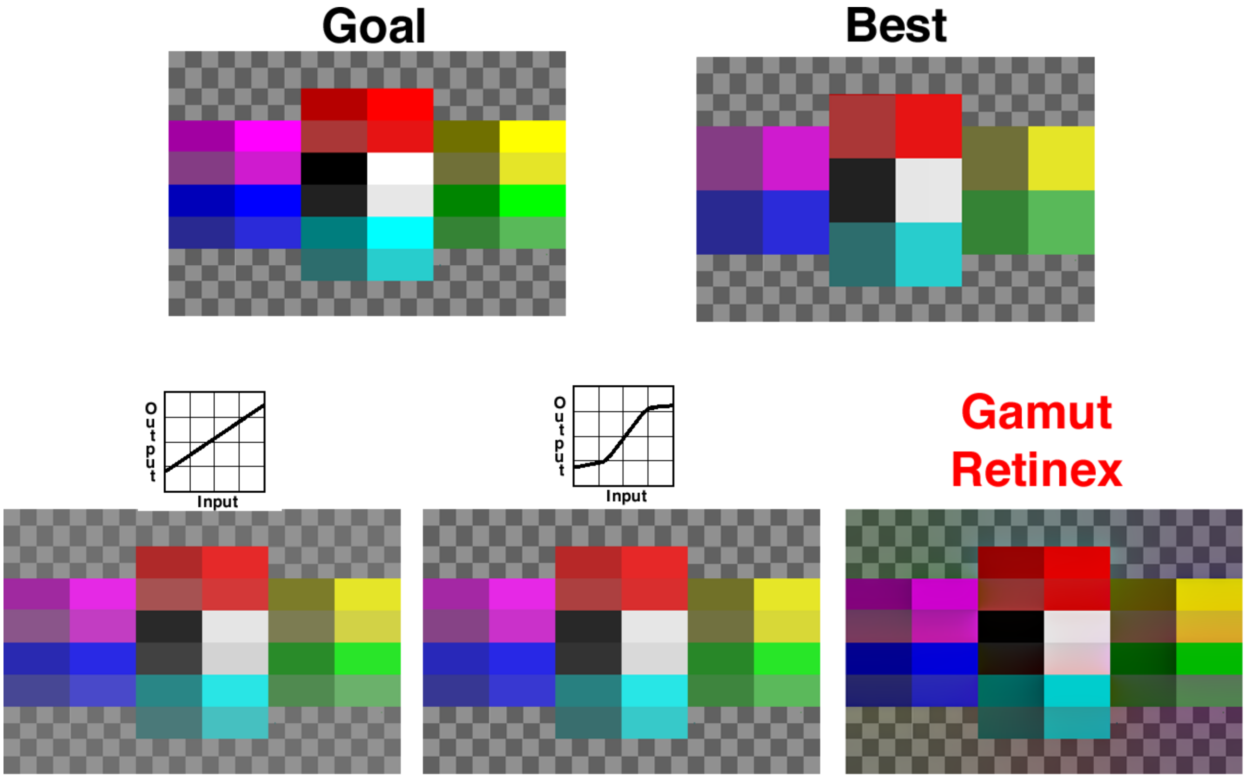

Figure 5 illustrates the use of spatial comparisons applied to media with different color gamut. The top row shows a large gamut original image (Goal) on the left, and a smaller gamut reproduction on the right (Best). Extra-gamut colors are simply reproduced as the nearest in gamut color. The Goal image is made up of pairs of rectangles. The outer rectangles are selected from color on the gamut boundary of the large, original color space. The inner rectangle are selected from colors on the smaller reproduction gamut boundary. When the Goal image is reproduced in the Best color gamut, the rectangles become squares because the outer rectangles are all out of gamut. The bottom row illustrates a variety of color gamut transformations. The left image uses linear compression of the Goal image into the Best Gamut. It applies the same linear Lookup (LUT) table to R, G, B channels. The result improves the image because the rectangle boundaries are clearly visible. The problem is that all the edges have been uniformly reduced in contrast. The image is a foggy reproduction of the Goal image. The S-shaped LUT image (center) illustrates the approach most commonly used in photography and the graphic arts. It changes the values close to the gamut to differentiate the rectangle edges, while it distorts, as little as possible, the colors that are far from the color gamut. It is a better reproduction. The gamut retinex picture uses spatial comparisons to generate a new image using iterative calculations. The process takes the ratios from the Goal and resets to the Best. The resulting image has the largest colorimetric errors and is the reproduction. Gamut retinex image looks most like the Goal image.

niques as spatial processes[70]. Hawley Rising III used wavelets to analyze the multiresolution structure and iterative update properties of the process.[71] All of the Retinex based papers described above show the importance of spatial mechanisms in image processing. As well, R. Eschbach, R. Bala, R. L. de Queiroz showed other spatial operations that are efficient and most valuable in image reproduction.[72]

7. RECENT WORK

Spatial comparisons are at the heart of two developing computational models. The first calculates the best color compromise for the problem of color gamut mismatch between print and display media. The second is the detailed study of contrast and assimilation to determine the human spatial processing mechanisms well enough to propose a joint model.

Spatial Color-Gamut Calculations

Color gamut transformations are usually based on Colorimetry. Tristimulus Values the basis of Colorimetry uses the radiances from only one pixel in the entire input scene. CIELAB and CIELUV normalized Tristimulus Values using independent means to measure illumination at each scene pixel. CIECAM models modify the response to a single pixel with external measures of illumination, coefficients responsive to viewing conditions, and background. CIE calculation combine tristimulus values of the scene radiance with other external measurements of the illumination falling on each pixel and generalizations of the scene.

As described above spatial comparison models start with a smaller subset of data. They restrict all input to the set of radiances falling on the retina. All information about reflectance, illumination, direction of illumination, sun and shade have to be derived from the retinal input image.

By the retinex theory, color in humans is generated by a spatial comparison process. Can color gamut calculations, using spatial comparisons, make colorimetrically different displays and printers appear much more similar to each other? An area of current interest is the mismatch in appearance of displays and printers. Recent experiments[73] applied spatial comparisons to the mismatch of different media. This approach minimizes the spatial errors introduced by limited color gamut and employs human color constancy mechanisms, so as to reduce the color appearance differences caused by limited color gamut.

Many familiar gamut mapping processes evaluate the colorimetric values of each pixel.[74] If the pixel is in-gamut, it is unchanged. If out of gamut, it is replaced with the nearest in-gamut color. This process distorts color appearance. Take two areas next to each other. Let us assume that one area is in-gamut and the other is not. If we leave the in-gamut pixel value unchanged, while changing the out-of-gamut pixel, we have replaced the ratio of these two areas with a new ratio and a new color relationship. It is better to change both pixel values, so as to leave the spatial comparisons constant. The best reproduction is the one that preserves the most spatial relationships.[75-77] Figure 5 illustrates this point. It contains a large-gamut original image made up of rectangles and a smaller-gamut reproduction. The smaller-gamut medium cannot reproduce all the colors in the original and reproduces the pairs of rectangles as uniform squares. Conventional color gamut transforms make global substitutions treating all pixels with the same R, G, B values the same regardless where it is in the image. (Such transforms are shown in Figure 5, the bottom row, left and center). Gamut Retinex lets pixel values change arbitrarily, but attempts to preserve the ratio values between pixels. The reproduction using Gamut Retinex reproduction looks most like the Goal image.[76]

Retinex calculations extended to the problem of gamut-limited reproductions show promise. Global shifts in color, similar to those found in color constancy, produce much smaller changes in appearance than local individual color shifts. Further, this paper argues that color-gamut transformations using spatial comparisons can generate in-gamut reproductions that look more like the original, because it employs the benefits of human color-constancy processing. These reproductions have a greater colorimetric difference between original and reproduction, but look better. Human color constancy uses spatial comparisons between different parts of the image. The relationships among neighboring pixels are far more important than the absolute differences between the colorimetric values of an original and its gamut-limited reproduction. If all the pixels in an image have a reproduction error in the same direction (red, green, blue, lightness, hue, chroma), then our color constancy mechanism helps to make large colorimetric errors appear small. However, if all the errors are randomly distributed, then small colorimetric errors appear large.[75-77]

A Joint Model for Assimilation and Contrast

There is no single model that predicts both assimilation and contrast. In complex scenes the same constant reflectance grays appears the same in different parts of the scene. In simple displays, grays vary in lightness with surround. “Contrast” is the name of the mechanism that makes grays look darker in a white surround than in a black surround. Assimilation is the name of the mechanism with the opposite effect; grays with adjacent white look lighter than the same gray with adjacent black. Examples are: Benary’s Cross[78], White’s Effect[79], Checkerboard[80] and the Dungeon Illusion. It is difficult to program a computational model that makes grays both lighter and darker when adjacent to white. We need to understand more about the characteristics of visual mechanisms in different spatial frequency channels to make a comprehensive model of both assimilation and contrast. We do know several important clues. White's effect can be modeled by combining each layer of the pyramid independently, instead of the usual interpolation to full resolution. In other words, the zoom model interpolated the smallest level of the image for comparison with the next higher layer. In order to model White's effect, the output for each layer needs to be retained as an independent channel, as well as passed on for further computations. The combination of these independent spatial-frequency reports can predict White's effect, while the standard zoom process cannot.[81,62] Benary's Cross, White's Effect, Checkerboard and Dungeon Illusion can all be explained by their low-spatial frequency behavior.[82] The Checkerboard illusion is dependent on the number of cycles of checkerboard.[83] All of these observations suggest independent spatial-frequency interactions for each spatial-frequency channel. This is a very similar observation to those made by Jack Cowan.[84] and Blakeslee and McCourt.[85] Recent experiments show that the average values in a spatial channel- Suburb Averages, rather that global Grayworld correlates with lightness matches.[86]

The integration of psychological experiments and mathematical models into the fabric of physiological data is another most important aspect of understanding color vision. Unfortunately, it is beyond the scope of the present paper. Nevertheless, Zeki has performed intracellular recordings from V4 from alert monkeys and has shown that V4 cells exhibit color constancy. His book, "A Vision of the Brain", provides an excellent discussion of the subject. [87] Y. G. Ichihara et. al. have studied color constancy using fMRI.[88]

8. DISCUSSION

Models for calculating lightness have two distinct applications. First, they can be used as a model for vision. Second, they can be a method for calculating sensations and writing them on film.[89] The vision problem needs to have psychophysical data to define the objectives of the model. The better camera problem has different goals, because cameras do not reproduce the scene, but render it to optimize customer preferences. Further, the better camera problem is highly constrained by hardware costs and marketing constraints. Nevertheless, the interplay between the study of vision and the practical matters of image making are highly synergistic. One can learn a lot from each activity, and even more from studying both.

In the 1980's hardware costs were so high for making a digital camera, that even inexpensive image processing was considered a luxury. Today that is not the case, but the desire for higher and higher resolution still makes costs higher than necessary. For the past 50 years the standard in imaging has been a sharp 8 by 10 inch print, the requirement for 35 mm cameras. However today, the standard image is the 100k jpeg file for the web. Soon people may lose their fascination with number of pixels and turn their attention to the pixels' content. The papers in the "Retinex at 40' session are leading the way. They all demonstrate exceptional work on improving image content, better rendition of high-dynamic range scenes and improving the appearance of gamut mismatch.

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REFERENCES

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1. J. J. McCann, chair, "Retinex at 40 Symposium", in *Human Vision and Electronic Imaging VII*, B. E. Rogowitz and T. N. Pappas, ed., *Proc. SPIE* **4662**, 278-439, 2002.
2. E. H. Land, "Colour in the Natural Image", *Proc. roy. Inst. Gt. Britain*, **39**, 1-15,1962.
3. E. H. Land, and N. W. Daw, "Colors Seen in a Flash of Light", *Proc.Nat.Acad.Sci.*, **48**, 1000-1008, 1962.
4. E. H. Land "The Retinex", *Am. Scientist*, **52** pp.247-264 1964.
5. E. H. Land and J. J. McCann "Lightness and Retinex Theory", *J. Opt. Soc.* [illegible]**1** 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, " When do We Assimilate in Color" in Proc. 10th IS&T/SID Color Imaging Conference, Scottsdale, Arizona,10-16, 2002.
8. S. K. Shevell, "Chromatic Variation: A Fundamental Property of Images", in *Eighth Color Imaging Conference: Color Science and Engineering Systems, Technologies, Applications,* IST&SID, Scottsdale, Arizona, 8-12, 2000
9. H. Wallach, "Brightness constancy and the nature of achromatic colors", *J. Exptl. Psychol,* **38**, 310-324, 1948.
10. E. H. Land, "The Retinex Theory of Colour Vision", *Proc. Roy. Institution Gr. Britain*, **47**, 23-58, 1974.
11. E. H. Land, "Lightness and Retinex Theory", J. *opt. Soc. Am* 57, 1428A, 1967; For citation see J. *opt. Soc. Am.* **58**, 567, 1968.

12. E. H. Land and J. J. McCann, “Method and system for reproduction based on significant visual boundaries of original subject”, *U.S. Patent* 3,553,360, June 5, 1971.

13. J. J. McCann “Calculated Color Sensations applied to Color Image Reproduction”, in *Image Processing Analysis Measurement and Quality*, Proc. SPIE, Bellingham WA, **901**, 205-214, 1988.

14. H. R. Blackwell, “Contrast thresholds of the human eye”, *J. Opt. Soc. Am*. **36,** 624-643, 1946.

15. E. H. Land, L. A. Ferrari, S. Kagen and J. J. McCann, “Image Processing system which detects subject by sensing intensity ratios”, U.S. Patent 3,651,252, Mar. 21, 1972.

16. J. S. Stevens and S. S. Stevens, “Brightness functions: Effects of adaptation,” *J. opt. Soc. Am*. **53**, 375-385, 1963.

17. C. J. Bartelson and E. J. Breneman, Brightness perception in complex fields, *J. Opt. Soc. (A),* **57**, 953-957, 1967.

18. H. W. Bodman, P. Haubner and M. A. Marsden, “A unified relationship between brightness and luminance” *in CIE Proceedings, Kyoto, 1979*, CIE Central Bureau, Paris, 99-102, 1980.

19. L. M. Hurvich D. H. Jameson and L. M. Hurvich, Complexities of perceived brightness, *Science*, **133**,174-179, 1961.

20. A. Gilchrist, Ed. *Lightness, Brightness and Transparency*, Lawrence Erlbaum Associates, Hillsdale, 1994.

21. G. Wyszecki and W. S. Stiles, *Color Science: Concepts and Methods Quantitative Data and Formulae*, *2nd Ed*, John Wiley & Sons, New York, 164-169, 1982.

22. M. Fairchild, *Color Appearance Models*, Addison Wesley , Reading, 1998

23. J. J. McCann, “Rules for Colour Constancy” *Opthal.Opt*. **12** 175-177, 1992.

24. J. J. McCann, “Color Constancy: Small overall and large local changes”, in *Human Vision Visual Processing and Digital Display III,* B. Rogowitz ed., Proc. SPIE, Bellingham WA, **1666**, 310-321, 1992.

25. 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.

26. J. Frankle and J. J. McCann “Method and apparatus of lightness imaging”, *U. S Patent* 4384336, May 17, 1983.

27. J.J. McCann, “Lessons Learned from Mondrians Applied to Real Images and Color Gamuts”, Proc. IS&T/SID Seventh Color Imaging Conference, 1-8, 1999.

28. B. Funt, F. Ciurea and J. J. McCann, “ Retinex in Matlab” in Proc. 8th IS&T/SID Color Imaging Conference, Scottsdale, Arizona, 112-121, 2000.

29. D. H. Brainard and B. A. Wandell “Analysis of Retinex theory of color vision” J. Opt. Soc. Am. A, **3** 1651-1661, 1986.

30. J. J. McCann “The role of nonlinear operations in modeling human color sensations”, in *Human Vision, Visual Processing and Digital Display*, B. Rogowitz et. al. Ed, SPIE Proc., Bellingham WA, **1077**, 355-363, 1989.

31. J. J. McCann and R. L. Savoy, “Measurement of Lightness: Dependence on the position of a white in the field of view”, in *Human Vision ,Visual Processing and Digital Display II,* B. Rogowitz ed., Proc SPIE, Bellingham WA, **1453**, 402-411, 1991.

32. J. J. McCann, “Scene Normalization Mechanisms in Humans”, Proc. IS&T/SID Second Color Imaging Conference, IS&T, Scottsdale, Arizona, 5-8, 1994.

33. J. J. McCann, E. H. Land and S. M. V. Tatnall, “A Technique for Comparing Human Visual Responses with a Mathematical Model for Lightness”, Am. J. Optometry and Archives of Am. Acad. Optometry, **47(11)**, 845-855, 1970.

34. B. Funt, F. Ciurea and J. J. McCann, “Tuning Retinex parameters”, in *Human Vision and Electronic Imaging VII*, B. E. Rogowitz and T. N. Pappas, ed., *Proc. SPIE* **4662-43**, 358-366, 2002.

35. J. J. McCann, R. L. Savoy, J. A. Hall and J. J. Scarpetti, “Visibility of Continuous Luminance Gradients”, *Vis. Research*, **14**, 917-927, 1974.

36. R. L. Savoy and J.J. McCann, Visibility of low spatial-frequency sine-wave targets: dependence on number of cycles, *J. opt. Soc. Am*.**,** **65**, No. 3, 343-350, 1975.

37. J.J. McCann and J. A. Hall, Jr. “Effects of average-luminance surrounds on the visibility of sine-wave gratings”*, J. opt.Soc. Am.*, **70**, 212-219, 1980.

38. J. J. McCann, R. L. Savoy and J. A. Hall, Jr. Visibility of Low Frequency Sine-Wave Targets, Dependence on Number of Cycles and Surround Parameters, *Vis. Research*, **18**, 891-894, 1978.

39. J.J. McCann, “Visibility of gradients and low-spatial frequency sinusoids: Evidence for a distance constancy mechanism”, *J. Photogr. Sci.Eng.*, **22**, 64-68, (1978).

40. R. L. Savoy, Low Spatial Frequencies and Low Number of Cycles at Low Luminances, *J. Photogr. Sci. Eng*., **22**, 76-79, 1978**.**

41. F. W. Campbell and J. G. Robson, “Application of Fourier analysis to the visibility of gratings”, J. Phyiol. (Lond.) **197**, 551-566, 1968.

42. D. Marr, “The computation of lightness by the primate retina” *Vision Res.* **14**, 1377-1388, 1974.

43. B. K. P. Horn, “Determining lightness from an image”, Comp. Gr. Img. Proc. **3**, 277-299, 1974.

44. T. P. Stockham, “Image Processing in the Context of a Visual Model”, *Proc. IEEE,* 60, 828-284, 1972.

45. H. R. Wilson and J. R. Bergen, “A four mechanism models for threshold spatial vision”, Vision Res., **26**, 19-32, 1979.

46. S.N. Pattanik, J. Ferwerda, M. D. Fairchild, and D. P. Greenburg, A Multiscale Model of adaptation and spatial vision for image display”, in *Proc. SIGGRAPH* 98, 287-298, 1998.

47. M. Fairchild and G. M. Johnson, “ Meet iCAM: A next generation Color Appearance Model”, in *Proc. 10th IS&T/SID Color Imaging Conference*, Scottsdale, Arizona, 33-38, 2002.

48. J. J. McCann, J. L. Benton and 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* **4662-35**, 324-330, 2002.

49. J. J. McCann, “Local/Global Mechanisms for Color Constancy”, Die Farbre,34, 275-283, 1987.

50. J.J. McCann, The Role of Simple Nonlinear Operations in Modeling Human Color Sensations, in *Human Vision, Visual Processing, and Digital Display*, B. E. Rogowitz and T. N. Pappas, ed., in *Proc. SPIE,* **1077***,* 355-363, 1989.

51 J. J. McCann, “Color Mondrian Experiments Without Adaptation”, in *Proceedings AIC, Kyoto,* 159-162, 1997.

52. J. J. McCann, “ Magnitude of Color Shifts from Average-Quanta Catch Adaptations”, in Proc. 10th IS&T/SID Color

Imaging Conference, Scottsdale, Arizona, 215-220, 1997.
53. J. J. McCann and K. L. Houston, “Color Sensation, Color Perception and Mathematical Models of Color Vision,” in: *Colour Vision* , J. D. Mollon, and L.T. Sharpe, ed. , Academic Press, London, 535-544, 1983.
54. J. J. McCann and K. L. Houston, “Calculating color sensation from arrays of physical stimuli,” IEEE SMC-13, 1000-1007 1983.
55. **.** A. C. Hurlbert, C. J. L. Wolf, “Contribution of local and global cone-contrasts to color appearance: a Retinex-like model”, in *Human Vision and Electronic Imaging VII*, B. E. Rogowitz and T. N. Pappas, ed., *Proc. SPIE* **4662-36**, 286-297, 2002.
56. J. Barbur, D. deCunha, C. B. Williams, G. Plant “Experimental studies of instantaneous color constancy: dynamic color matching under rapid changes of illuminant “**,** in *Human Vision and Electronic Imaging VII*, B. E. Rogowitz and T. N. Pappas, ed., *Proc. SPIE* **4662-37**, 298-314, 2002
57. S. Westland, O. Da Pos and C. Ripamonti, “Conditions for perceptual transparency “**,** in *Human Vision and Electronic Imaging VII*, B. E. Rogowitz and T. N. Pappas, ed., *Proc. SPIE* **4662-38**, 315-323, 2002.
58. P. Burt and T. Adelson, “A Multiresolution Spline with Application to Image Mosaics, ACM Transactions on Graphics, **2-2,** 17-36, 1983.
59. K. C. Kiesel and W. R. Wray, “Reconstitution of images”, U.S. Patent 4,649,568, Mar. 10, 1987.
60. J. J. McCann, “Color Theory and Color Imaging Systems: Past Present and Future*”, J. Imaging. Sci. and Technol.,* **42**, 70, 1998.
61. J. J. McCann, “Calculating lightnesses in a single plane”, *J. Electronic Imaging***, 10**, 112-122, 2001.
62. A. D. Logvinenko “Lightness Induction Revisited” Perception 28 803-816, 1999.
63. Z. Rahman, D. J. Jobson and G. A. Woodell, “Retinex processing for automatic image enhancement”, in *Human Vision and Electronic Imaging VII*, B. E. Rogowitz and T. N. Pappas, ed., *Proc. SPIE* **4662-47**, 390-401, 2002.
64. R. Sobol, “ Improving the Retinex algorithm for rendering wide dynamic range photographs”, in *Human Vision and Electronic Imaging VII*, B. E. Rogowitz and T. N. Pappas, ed., *Proc. SPIE* **4662-41**, 341-348, 2002.
65. T. J. Cooper, “ Modifications to Retinex to relax RESET nonlinearity and implement segmentation constraints “, in *Human Vision and Electronic Imaging VII*, B. E. Rogowitz and T. N. Pappas, ed., *Proc. SPIE* **4662-42**, 349-357, 2002.
66. B. V. Funt, F. Ciurea and J. J. McCann, “ Tuning Retinex parameters “, in *Human Vision and Electronic Imaging VII*, B. E. Rogowitz and T. N. Pappas, ed., *Proc. SPIE* **4662-43**, 358-366, 2002.
67. A. Rizzi and C. Gatta,, “ Color correction between gray world and white patch”, in *Human Vision and Electronic Imaging VII*, B. E. Rogowitz and T. N. Pappas, ed., *Proc. SPIE* **4662-44**, 367-375, 2002.
68. D. Marini, A. Rizzi and M. Rossi, “ Post-filtering for color appearance in synthetic images tone reproduction”, in *Human Vision and Electronic Imaging VII*, B. E. Rogowitz and T. N. Pappas, ed., *Proc. SPIE* **4662-45**, 376-384, 2002.
69. R. Shaw, “Perceived image quality basis for image enhancement techniques”, in *Human Vision and Electronic Imaging VII*, B. E. Rogowitz and T. N. Pappas, ed., *Proc. SPIE* **4662-48**, 402-408, 2002.
70. R. Kimmel, M. Elad, D. Shaked, R. Keshet, I. E. Sobel, “Variational framework for Retinex”, in *Human Vision and Electronic Imaging VII*, B. E. Rogowitz and T. N. Pappas, ed., *Proc. SPIE* **4662-49**, 409-418, 2002.
71. H. K. Rising III, “Analysis and generalization of Retinex by recasting the algorithm in wavelets”, in *Human Vision and Electronic Imaging VII*, B. E. Rogowitz and T. N. Pappas, ed., *Proc. SPIE* **4662-50**, 419-427, 2002.
72. R. Eschbach, R. Bala, R. L. de Queiroz, “Simple spatial processing for color mappings”, in *Human Vision and Electronic Imaging VII*, B. E. Rogowitz and T. N. Pappas, ed., *Proc. SPIE* **4662-46**, 385-389, 2002.
73. J. J. McCann and P. M. Hubel, “Image processing”, European Patent, PN EP1049324A, 2000; J. J. McCann and P. M. Hubel, “In-gamut image reproduction method using spatial comparison”, Japan Patent, PN JP 2000350050, 2001; J. J. McCann and P. M. Hubel, “In-gamut image reproduction method using spatial comparison”, US Patent, PN US 6,516,089, 2003.
74. J. Morovic and R. Luo, “Developing algorithms for universal color gamut mapping”, in *Colour Imaging: Vision and Technology*, Ed. L. W. MacDonald and M. R. Luo, Wiley & Son Ltd., Chichester, p. 253-283, 1999.
75. J. J. McCann, “Using Color Constancy to Advantage in Color Gamut Calculations, Proc. Third IS&T PICS Conference, 3, pp. 169-176, 2000.
76. J. J. McCann, “Color Gamut Mapping Using Spatial Comparisons”, in *Color Imaging: Device-Independent Color, Color Hardcopy, and Graphic Arts VI*, Proc. SPIE, 4300, pp.126-130, 2001.
77. J. J. McCann, “A Spatial Color-Gamut Calculation to Optimize Color Appearance”, in *Colour Image Science: Exploiting Digital Media*, Ed. L. W. MacDonald and M. R. Luo, Wiley & Son Ltd., Chichester, p. 213-233, 2002.
78. W. Benary, “The influence of Form on Brightness”, in *A Source Book of Gestalt Psychology*, W, Ellis trans. Kegan, Paul, Trench, Truber & Co. Ltd., London, 104-108, 1950.
79. M. White, “A new effect of pattern lightness”, *Perception*, **8**, 413-416, 1979.
80. R. L. DeValois and K. K. DeValois, *Spatial Vision*, Oxford University Press, New York, 1988.
81. J. J. McCann, “Calculating The Lightness Of Areas In A Single Plane”, in *Human Vision and Electronic Imaging V*, B. E. Rogowitz and T. N. Pappas, ed., *Proc. SPIE*. **3959**, 243-253, 2000.
82. J. J. McCann, “ Image Processing Analysis of Traditional Gestalt Vision Experiments”, AIC Proc., Rochester, 375-378, 2002**.**
83. J. J. McCann, “ Assimilation and Contrast” in Proc. 9th IS&T/SID Color Imaging Conference, Scottsdale, Arizona, 91-96, 2001.
84. J. D. Cowan and P. C. Bressloff, “Visual cortex and the Retinex algorithm”, in *Human Vision and Electronic Imaging VII*, B. E. Rogowitz and T. N. Pappas, ed., *Proc. SPIE* **4662-35**, 278-285, 2002.
85. B. Blakeslee and M. E. McCourt, “A multiscale spatial filtering account of the Wertheimer-Benary effect and the corrugated Mondrian” *Vision Res*. **41** 2487-2502, 2001.
86. J. J. McCann and A. Rizzi, “ The Spatial Properties of Contrast”

in Proc. 11th IS&T/SID Color Imaging Conference, Scottsdale, Arizona, in Press, 2003.
87. S. Zeki, *A Vision of the Brain*, Blackwell Scientific Publications, Oxford, 1993.
88. Y. G. Ichihara, S. Nakadomari, H. Takeuchi, S. Miyauchi, and K. Kitahara, "Retinex processing from the fMRI study on V4", in *Human Vision and Electronic Imaging VII*, B. E. Rogowitz and T. N. Pappas, ed., *Proc. SPIE* **4662-51**, 428-439, 2002.
89. J. J. McCann, " The Application of Color Vision Models to Color and Tone Reproductions" in Proc. Japan Hardcopy '88, 196-199, 1988.

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