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

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

ABSTRACT

As a part of the Symposium "Retinex at 40", this paper recounts 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 will include several modifications of the approach including recent modifications and gamut-mapping applications. This paper emphasizes the need for parallel studies of psychophysical measurements of human vision and computational models of imaging systems.

Keywords: Retinex, model of lightness, pyramid processing

1. INTRODUCTION

In Edwin Land's first Lecture at a Friday Evening Discourse in 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.[1] This 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 one microsecond flash experiments with Nigel Daw showed that adaptation could not account for colors. Color memory could not explain the colors in displays seen for the first time.[2] He knew spatial factors were important, but he did not know how to put the system together. In his process of persistent exploration he made the critical observation that color appearance correlated with the triplet of lightness appearance in long-, middle-, and short-wave light.[3,4] This idea created a halfway point in finding the physical correlation for color appearance. If we found a physical correlation for 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.[5] 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.[6] In assimilation, predominantly black surrounds make grays appear darker, while in contrast, black surrounds make grays appear lighter. Figure 1 shows the R, G, B separations for this effective color assimilation display. 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 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. This is the observation that Land made 40 years ago and named the phenomenon Retinex.

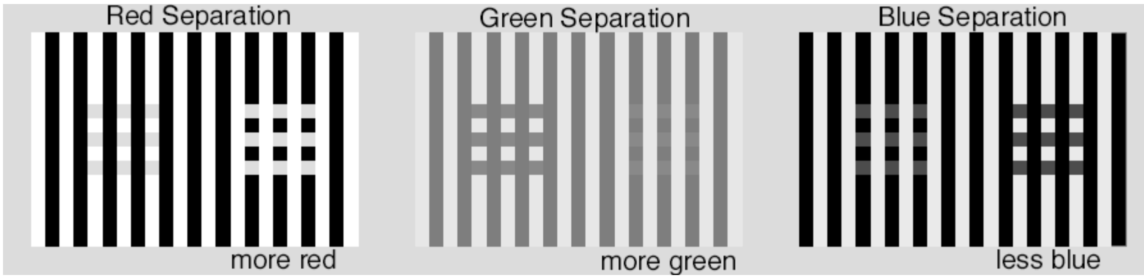

Figure 1 shows R, G, B separation images for a dramatic color assimilation display. The 9 square patches on the center left have the same pixel input as those on the right. The left patches appear bluer; the right patches appear more yellow in the color display. Land's reasoned that the square patches 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 lightner than those on the right.

2. CALCULATING LIGHTNESS SENSATIONS

Retinex made understanding color much simpler, but 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 has done most of the hard work. The influence of 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[7] 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 the discussions leading to the Ratio-Product idea in detail in his second Royal Institution paper.[8]

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[9], 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 cut-out figures used earlier. 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 patent rule applied; namely, the patent must be filed before the talk was given. Usually the 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 of using vision research as the source of image manipulation processes that could be applied to imaging devices fascinating. 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 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[10] 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 that 1000:1[11] 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. 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 scaling 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 to the input. Rather than use an image segmentation approach to search for visually significant boundaries, we introduced the idea of a threshold. Blackwell measured the threshold of edge detection to be three parts in a thousand at high luminance levels.[12] In other words, humans cannot detect edge ratios smaller that 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 30x60 =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 $(.003)^{1800}$ = 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[4]

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.[13] 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 gray; rather they look white. Extensive experiments by Stevens[14], Bartleson and Breneman[15], Bodman[16], Jameson and Hurvich[17] and Gilchrist[18] 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[19], and recently by CIECAM97[20].

Specific experiments demonstrated at Fergus Campbell's FergusFest demonstrated that color constancy uses independent normalization to the maximum in each channel.[21] 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.[22] 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 recently 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

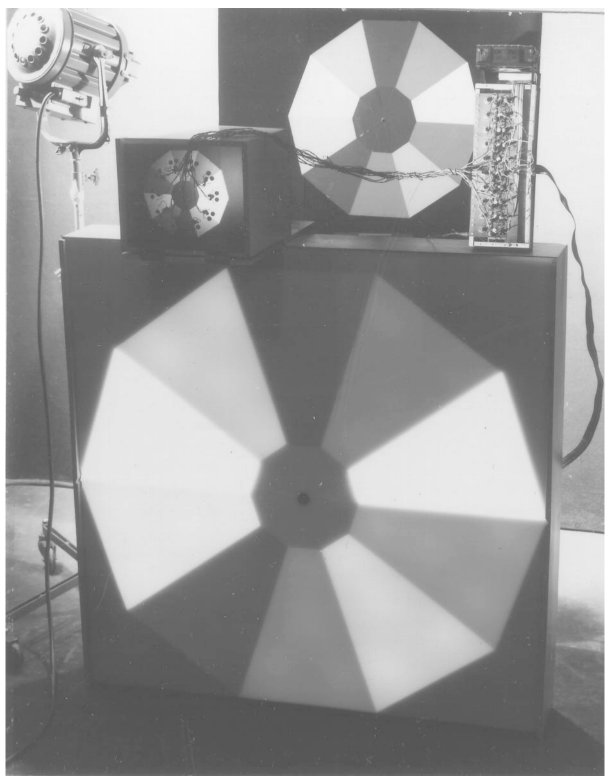

Figure 2 is a photograph of the Retinex camera demonstrated in Land's 1967 Ives Medal address. The wheel of different reflectance papers on the back wall is in the top center of the picture. The movable spotlight illuminator is in the top left. The lightbox display is at the bottom. The display was made 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.

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.[4, 23, 24, 25, 26])

Vision avoids the reflectance asymptote

Although the goal for calculating lightnesses of uniform objects is almost always close to calculating the reflectance, there are some very important discrepancies. 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,[27] this was never the intent of the model.[28] As described in early papers[4,5], 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).[29,30]

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. With this matching data 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 as 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[31]

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[32] and sinusoidal gradients at threshold[33]. To our surprise, there is no single threshold rate of change on the retina. All that matters is size and number of cycles of sinusoid.[34] 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.[35]

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 Fergus Campbell[36], Marr[37], Horn[38] and Stockham[39]. They all looked to filter gradients, but did not have a mechanism to “adapt” the filter to the image, as vision does. The appearance of any particular scene can be calculated by applying a scene specific spatial filter to the input image. The problem is that 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. 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^2S 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^2S 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 I2S 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.[28] (The code and a discussion of the design of Pre and Post LUT parts of the model are included in the paper.)

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 96, 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"[40], in ACM Transactions on Graphics, was published in September 1983.

5. 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"[41] . 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[42,25,43] have reviewed the successful modeling of Color Mondrians, with and without retinal adaptation, Black and White Mondrians with gradient illumination and real-life scenes. In addition these models can account for visual demonstrations of vision experiments, such as Logvinenko 's diamond wall experiment[44] , a variation of the Black and White Mondrian.

6. 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. Colorimetry, even in the most recent standards, allows the input of radiances from only one pixel in the calculations. Since color in humans is a spatial comparison, image processing using spatial optimization makes different colorimetric displays look much more similar. 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

Spatial comparisons were applied to the mismatch of different media, namely the color-gamut problem found between displays and printers. 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.

A familiar gamut mapping process is the evaluation the absolute colorimetry of a pixel see if it is in-gamut, and then replacing it 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.

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.[45,46]

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[47], White's Effect[48], Checkerboard[49] and the Dungeon Illusion. It is difficult to program a computational model that makes grays both lighter and darker than when adjacent to white. We need to understand more about the characteristics of visual mechanism 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.[50, 43] Benary's Cross, White's Effect, Checkerboard and Dungeon Illusion can all be explained by their low-spatial frequency behavior.[51] The Checkerboard illusion is dependent on the number of cycles of checkerboard.[52] All of these observations suggest independent spatial-frequency interactions for each spatial-frequency channel. This is a very similar observation to the one made by Jack Cowan in these proceedings.[53]

7. 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.[54] 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, equivalent to 6 megapixels. 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 rest of 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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*contact: mccanns@tiac.net

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