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"Calculated Color Sensations Applied to Image Reproduction",

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CALCULATED COLOR SENSATIONS APPLIED TO IMAGE REPRODUCTION

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ABSTRACT

The ideal color photograph is one that captures what we see. This implies that photographic film should record human color sensations. Ordinary photography responds to the amount of light coming from the world in front of the camera. There is a large variety of scenes that have a greater range of light intensities than can be reproduced on a print. These scenes can be printed by capturing the data from the world, calculating color sensations, and writing those color sensations on a print.

1. INTRODUCTION

The human visual system has a remarkable range of response to variable light intensities. Hecht, Shlaer and Pirenne[1] showed that humans, when asked "Can you see the light ?" are able to respond reliably to 4 to 7 photons. Bartley[2] reported that the ratio of the radiance from snow on the top of a mountain to Hecht, Shlaer and Pirenne's threshold of detectability is equal to ten billion to one or $10^{10} : 1$. Nevertheless, humans could not see such a wide range of radiances in a single scene, if such a scene existed, because of intraocular scattered light.[3, 4] The range of discrimination in an image is roughly 3 log units.

One of the objectives of this paper is to describe the range of radiances found in a variety of real life scenes. Of particular interest is the comparison of the range in real world scenes with the range that can be recorded on reflection images such as photographic and electronic imaging prints on paper.

2. MEASUREMENTS OF RADIANCE RANGE IN IMAGES

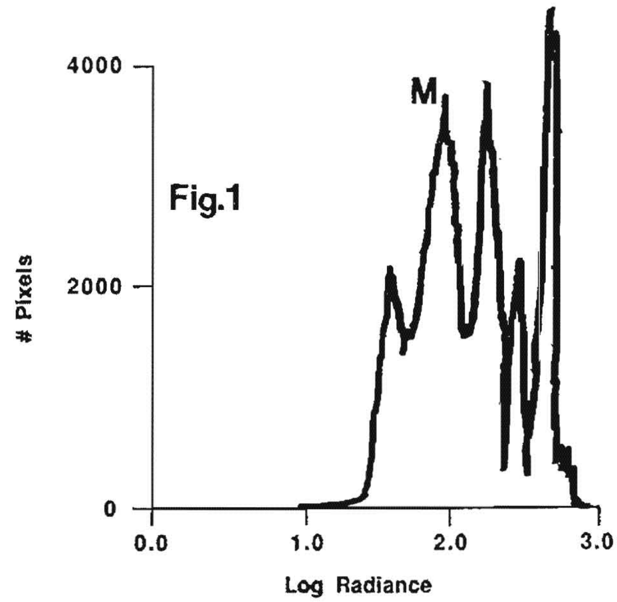
The classic work in this area was done by L.A. Jones and H.R. Condit [5] of Kodak in 1948. They measured the luminances and luminance ranges of 126 outdoor scenes with a portable, telescopic visual photometer. The advance made by Jones and Condit was to improve the range of measurable intensity by reducing the stray light in the optical system and hence find lower luminances in images. They reported the average scale or luminance range of 160 : 1 (2.2 log units). The smallest range was 28 : 1 (1.4 log units); the largest range was 780 :1 (2.9 log units). Condit later found sunlit scenes with ranges greater than 1000 : 1 (>3.0 log units).

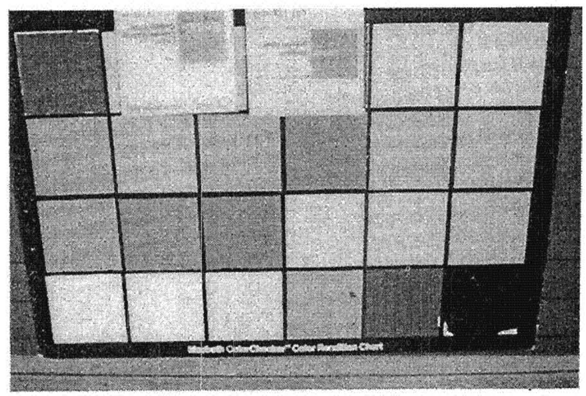
We were interested in determining the range of intensities in a wider variety of scenes than reported by Jones & Condit. We wanted to measure the amount of light coming to the film at each point in the image, even though the camera flash was the principal light source. As well, we were interested in measuring the relative spectral shifts due to variable illumination.

We used a photographic film as the light capturing medium. We used Ektachrome 5071 Slide Duplicating film.[6] It has a characteristic curve slope very close to 1.0. Slope 1.0 means that the optical densities in the film are proportional to the log radiance coming to the camera lens. The film's three sensitizing dyes integrate radiance in long-wave (580-710 nm), middle-wave (490-590 nm), and short-wave (380-490 nm) visible light. The film's characteristic curves give us the data to transform optical densities in the film back to radiances in the world.

The photographs were made on 35 mm film, using a variety of cameras. The color balance of the film was adjusted to daylight with appropriate filters such as a 60Y CC. The 35 mm transparencies were digitized on an Itek 200-S graphic arts scanner. Each image was subdivided into 512 by 512 pixels. The scanner was set up so as to represent three log unit radiance range as an 8 bit digital word for each waveband. Calibration of the scanner gives us the data to transform scanner digit back to optical densitiy in the film, which in turn is traceable back to radiance in the world.

We scanned the 35 mm transparency and accumulated the histogram of the number of pixels measured as a function of log radiance between 0 and 3.0. Fig. 1 shows the histogram of the middle-waveband of a close-up image of the





MacBeth Image Checker. A black-and-white photograph is shown to the right of the histogram. The figure plots the log radiance recorded on the film along the horizontal axis. The scanner digitizer was normalized so that log radiance 3.0, in all three wavebands, was set to highest radiances in this image. The number of pixels in the 512 x 512 array with a particular log radiance is plotted along the vertical axis. M stands for middle-wave radiance. The original scene was recorded in daylight, uniform in spatial distribution.

An important observation can be made from the histogram. The dynamic range of radiances is about 1.5 log units. This corresponds to the range of reflectance possible in a print. High reflectance papers approach 100% reflectance as a limit. The amount of light reflecting off the surface of the paper determines the lower limit reflectance. Surface reflectances are of the order of 1 to 5% depending on the surface character (matte, glossy, etc.) and the optical geometry of the measuring instrument. The digitization histogram of a reflectance target in uniform illumination gives results consistent with other means of measurement.

In order to evaluate the types of images that people take, we used survey data accumulated by Millard[7]. This data is specific to a particular camera system; nevertheless it is very helpful in identifying meaningful types of images. The images are subdivided into ambient and flash illumination. The percent distribution of each type of image is shown in Table 1.

Photographic Conditions	**% Images**
Flash	
Background equal	29%
Background dark	22%
Background light	10%
Ambient	
Bright sun (side,top,front)	19%
Cloudy / Open Shade	16%
Dawn or Dusk	3%
Bright sun (back)	2%
Total	100%

We chose example images from the major categories. We digitized images and show their histograms in the Figs. 2-7.

Fig. 2 is the histogram of a difficult flash image. A young man holding a birthday cake is wearing a white shirt. His mother is standing behind him. Further behind him is a fairly low reflectance wood panelled wall. Visual inspection of the transparency shows that there is structure in the flames on the candles, detail in the specular reflections from the mother's glasses, and detail in the man's white shirt. As well, there is detail in the darker parts of the image, namely, the wood panel, the book case, and the picture hanging in the next room (far right of the image). The histograms show that the image contains radiance information over the entire 3.0 log unit range. L stands for long-wave radiance; M stands for middle-wave radiance; S stands for short-wave radiance. Since the image fills the entire range of the measurement window, there exists the possibility that the actual range in the original image exceeds the data reported here. Further work is necessary to evaluate whether the original image, the film, or the scanning apparatus and procedure are truncating the range.

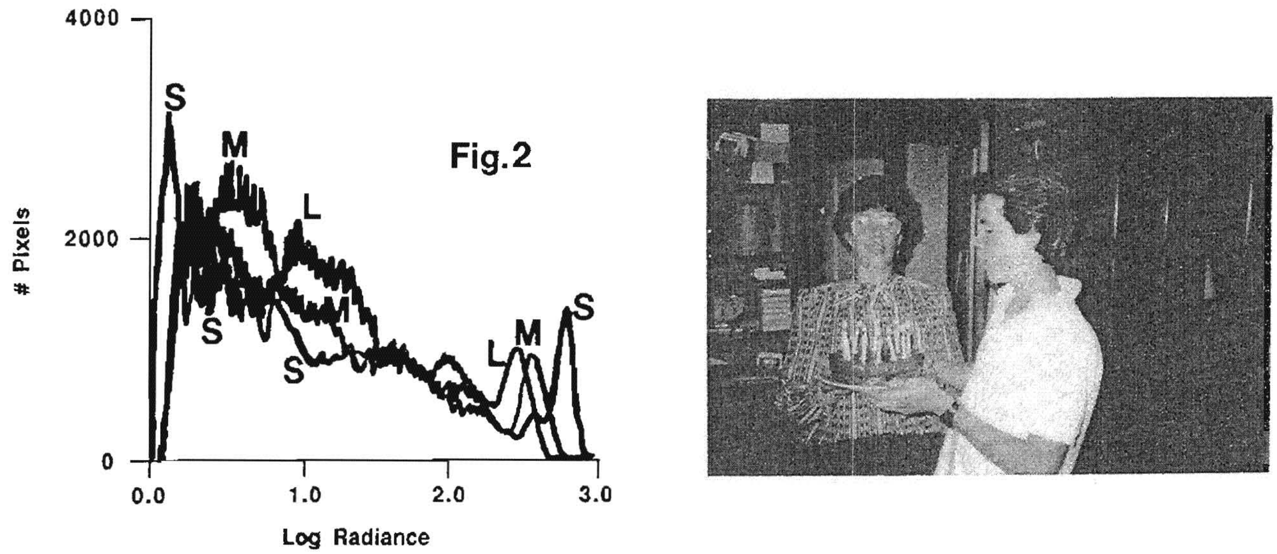


Fig. 3 is the histogram of an outdoor backlit scene. A grandmother is reading on her back porch in the late afternoon. The sun is reflected off the water in the pond. Visual inspection of the transparency shows that there are ripples in the water and detail in the leaves. As well, there is detail in the darker parts of the image, namely, in the cushion on the chair on the far left. The histograms show that this image contains radiance information over a range of slightly less than 3.0 log units. The highest radiance part is the water. The rest of the image spans about 2.0 log units.

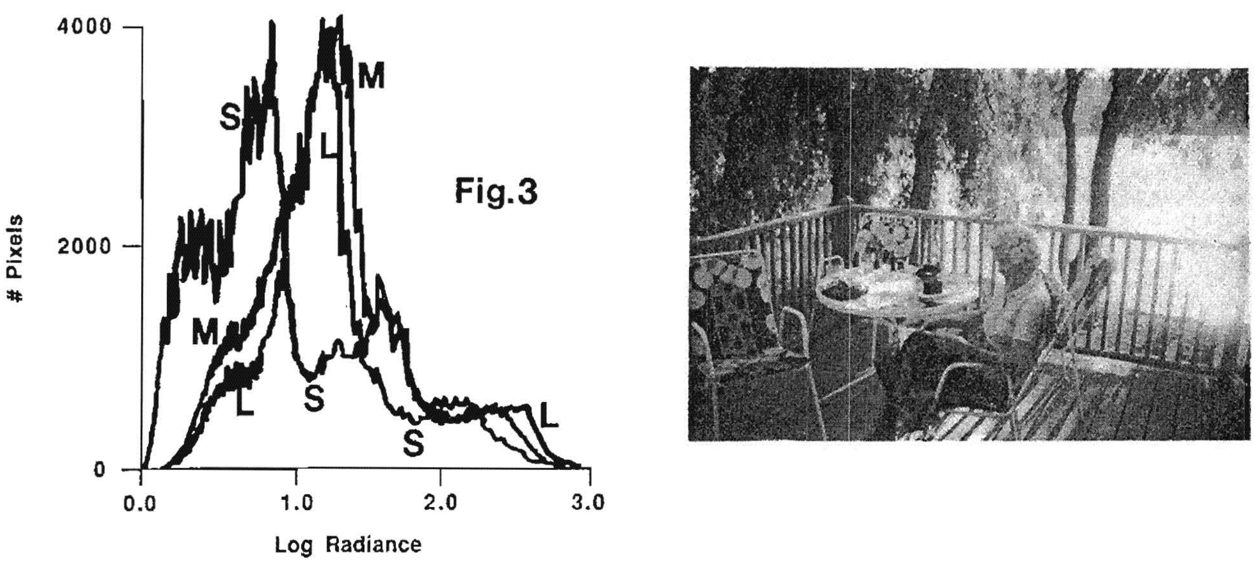
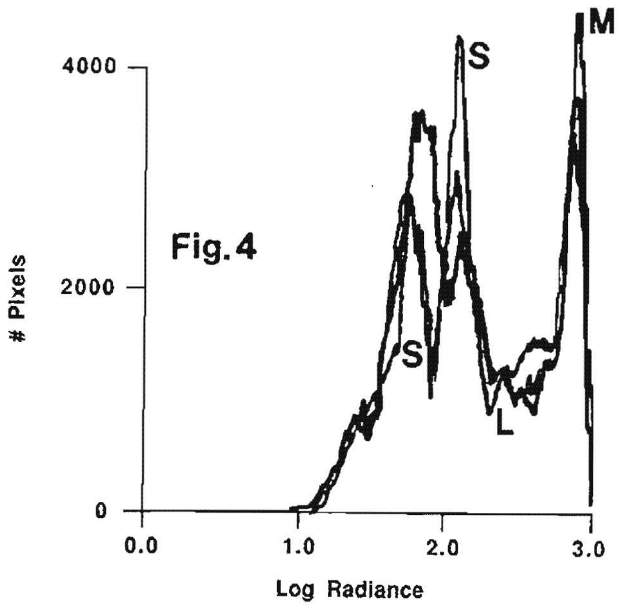


Fig. 4 is the histogram of an outdoor scene that contains both sun and shadow. One man is standing in the sun, the other in the shade. Visual inspection of the transparency shows that there is detail everywhere in the image. The histograms show that this image contains radiance information over a range of slightly less than 2.0 log units .



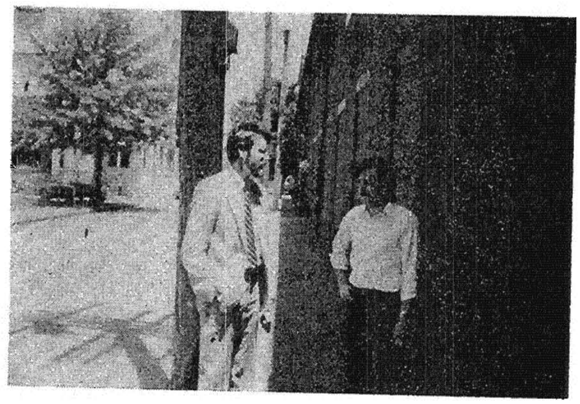


Fig. 5 is the histogram of a sunset image taken at dusk. The sky is filled with multicolor clouds, the tree is silhouetted against the sky and the foreground is filled with green grass bespeckled with small white flowers. Visual inspection of the transparency shows that there is detail in the reflections from the surface of the pond, in the sky and in the grass in the foreground. The histograms show that this image contains a relatively small number of pixels between 2.3 and 3.0 log units. The majority of the sky has radiances between 1.3 and 2.3 log units and the grass in the foreground has radiances below 0.6 log units .

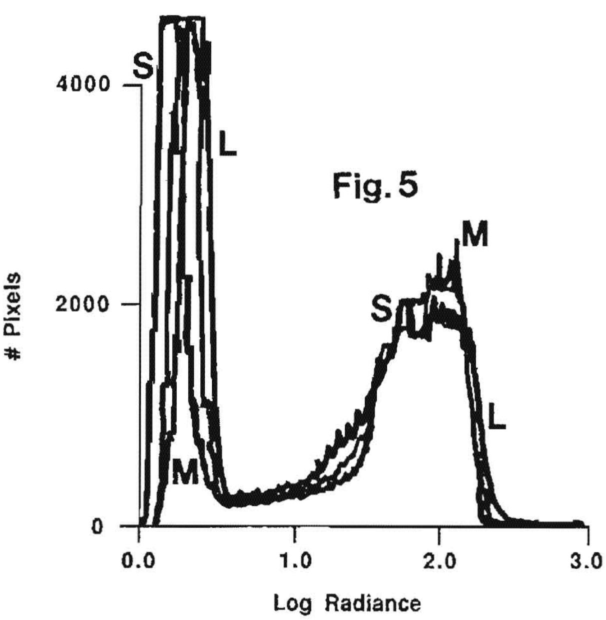
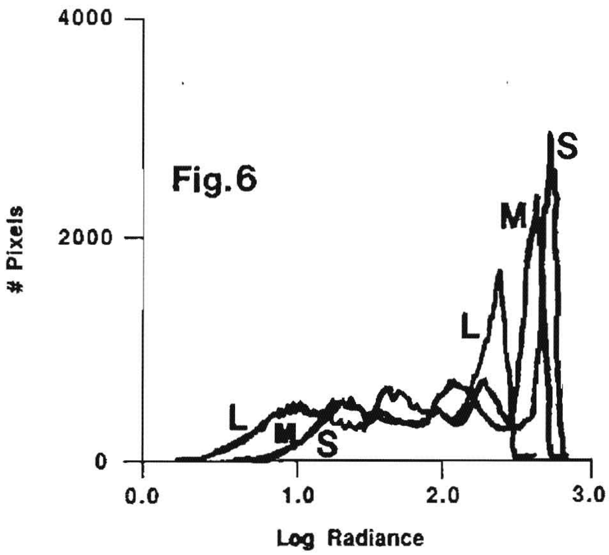


Fig. 6 is the histogram of an outdoor scene that contains mostly shadow. The sun has passed over the hill behind the photographer. The foreground is a yellow sandy beach with palm trees. There is a patch of sunlit rock on the far side of the bay. Visual inspection of the transparency shows that there is detail everywhere in the image. The histograms show that this image contains radiance information slightly more than 2.0 log units. Of particular interest in this image is the spectral shift. The histograms are very similar in shape, yet the short-wavehistogram is shifted toward higher radiances by 0.4 log units compared to the long-wave histogram.



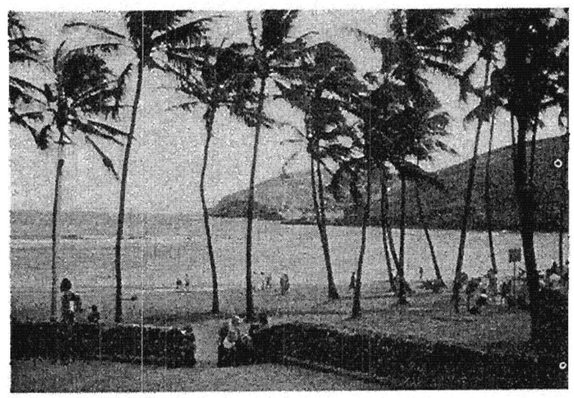
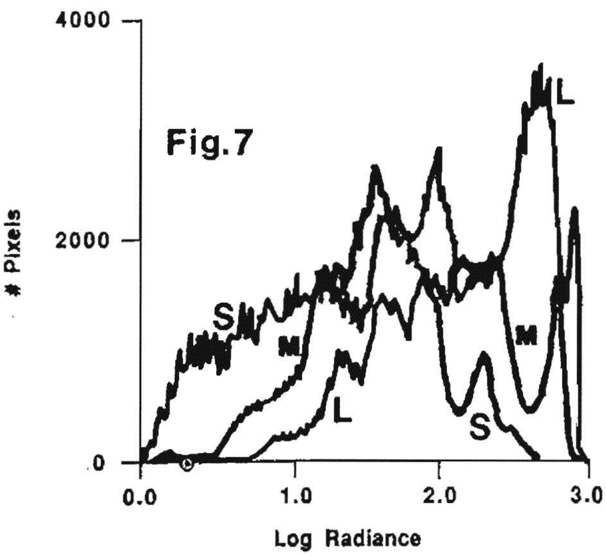


Fig. 7 is the histogram of an indoor scene taken in incandescent light. Visual inspection of the transparency shows that there is detail everywhere in the image. The histograms show that this image contains radiance information over a range of slightly more than 2.0 log units. Here the spectral shift is in the opposite direction from that in Fig 6. The histograms are similar in shape, yet the short-wave histogram is shifted toward lower radiances by 0.4 log units compared to the long-wave histogram. The range of spectral shifts from shade to tungsten light was about 0. 8 log units.



These images are some examples of the types of still pictures people take. They do not represent an exhaustive collection or a statistical study of the ranges found in any of these types. They should be considered individual examples. There are two general conclusions. First, there are many images in everyday life that exceed the radiance range of 1.5 log units. That wider range is created, by the ubiquitous presence of spatially non-uniform illumination. Furthermore, there is substantial variability of the spectral composition of different illuminations. Second, reflectance prints, because they are limited in radiance range by surface properties, need radiance range compression in order to portray the image as the original scene appeared to human observers.

3. STRATEGIES FOR RADIANCE-RANGE COMPRESSION

The problem in making images on paper begins with a fundamental mismatch in radiance range. The usable reflectance range of a print is limited by surface reflection. The range of many photographic scenes is between 2.0 and 3.0 log units. Simply stated, the situations in which ordinary photography works best are those situations in which the illumination approaches uniformity and the range of reflectances of the print recreates the range of reflectances of objects in the scene. The absence of nearly uniform illumination conditions, the reproduction of the image must have some type of radiance-range compression so as to be able to fit the scene onto the limited range of the print. In the next part of the paper we will discuss a variety of different approaches to computing reduced range images for reflection prints.

3.1. Paintings

The first extremely good solution to this problem was found many centuries before the problem was discovered. Namely, the solution to the problem of encoding a scene with an very wide intensity range in the narrow range of reflectances can be found in any number of paintings, watercolors, drawings and etchings. Visual artists have recorded the appearance of objects in their illumination environment. These paintings provide a superb role model for a computational algorithm for image range compression, because there is an absolute minimum of local contrast distortion. Details in highlights and details in shadows do not suffer from contrast compression because they are near the extremes of high and low reflectances.

The disadvantage of such a model is that it does not provide any clues about how to construct a mathematical function that embodies the painter's process. The descriptions of the painter's process do not lead directly to numerical functions.

3.2. Linear compression

An extreme alternative to a strategy embodying what a painter does is one that simply applies a linear compression to intensities in the world. The numerical process is straightforward. Simply take, for example, a 3 log unit scene intensity range and reduce the local contrast everywhere in the image so that the print range is only 1.5 log units. The advantage of this approach is that it is easily implemented. It spreads the distortion of local contrast uniformly throughout the range from white to black. The disadvantage is that it reduces the contrast of the image everywhere. In the 3 log unit example, it reduces all contrast in half. In effect it portrays objects as they appear in a dense fog - another way to reduce contrast in an image. The effects of contrast reduction are particularly apparent in saturated colors. By definition green objects have a higher reflectance in middle-wave light than they do in both long- and short-wave light. The saturation is determined by how different the middle-wave record is from the others. Contrast reduction of the scene data has a double effect. It moves both the middle-wave record and the other two records closer together - giving much less color saturation. It is for this reason that all commercial print film and video systems incorporate contrast enhancement, not contrast reduction. This contrast enhancement make green objects, such as grass, look in the print greener than they are in real life. Although linear compression is easily implemented, it very often has highly undesirable effects on images.

3.3. Nonlinear compression

Nonlinear compression is the technique used in color photography. Here the middle of the range from white to black is expanded. The contrast is enhanced because the films' characteristic curves have slopes between 1.5 and 2. Despite this expansion in the middle of the white-to-black scale, the image records information over nearly 2 log units of scene intensities in the print. The way this is achieved is by having slopes much lower than 1.0 in both the highlight and the shadow regions of the image. Contrast within whites is compressed, contrast within grays is expanded and contrast within blacks is compressed. This is an excellent example of a compromise strategy. Color saturation in the midtones is enhanced. Recognizable detail in highlights and shadows is also maintained with only the loss of actual contrast in those regions. Without the power of electronic image processing to compute the appropriate range compression for each image and each image segment, nonlinear compression is probably the optimal solution.

3.4. Calculated Perception

Edwin Land's 1967 Ives Medal Address to the Optical Society of America introduced three important ideas to the computational approaches to vision.[8] The first was the experiment of the "Black-and-White Mondrian", emphasizing the appearance of objects in non-uniform illumination. The second was the experiment of the "Color Mondrian", emphasizing the appearance of objects in different spectral illumination. The third was the original computational approach for calculating appearance, using only the radiometric information in the image. McCann, Land and Tatnall[9] defined a technique measuring human response for comparison with mathematical models. McCann, McKee and Taylor[10] developed a computational algorithm based on the ideas of Land and McCann.[8] They also made quantitative measurements of observer responses to "Color Mondrian " experiments. The McCann, McKee and Taylor data showed that the observer choices of matching appearance corresponded to the scaled integrated reflectances of the patches in the Mondrian.

Over recent years there has been increasing interest in algorithms that set out to calculate the actual physical reflectances of objects in real life scenes. There are many different approaches reported in the literature. Marr[11], Horn[12] and Buchsbaum[13] developed algorithms that calculated the illuminant, then divided the scene radiances by the calculated illuminant to get the reflectances of objects in the scene. Wandell and Maloney[14] sought to solve the problem by assuming that all reflectances can be fit well by a small number of basis functions. Hurlburt and Poggio[15] have developed learning algorithms that seek to solve for the illuminant. Brou, Sciascia, Linden and Lettvin[16] have used a normalization factor, Brill[17] has used the overall average and Worthey[18] has used opponent processes. Lee[19] has written programs to embody specular highlight recognition ideas. Each of these approaches represents an interesting formulation of the problem of calculating the reflectances of objects in the scene. Many of these approaches only address a limited portion of the problem we are discussing here.

In the above papers, the objective is to have the computation report the <u>reflectances</u> of the objects in the scene. This is an important computational problem, but an inappropriate objective for making the optimal color print, or for modeling human color matches. The reason it is inappropriate for the optimal print is that if the algorithm succeeds in calculating reflectance, then all trace of the illumination will be removed from the computed image. As long as the objective is defined to be a computed version of what a painter would do, namely record the object's appearance in the illumination environment, then an image of calculated reflectances is undesirable. What is needed is an image that is made up of matches to what human observers see -- color sensations. The computed image must include the record of the illumination environment.

3.5. Calculated Sensation

The most desirable goal for the calculated image to be written on reflection media is the record of the appearance of objects. The goal is to calculate a match to what observers see. Sensation, by its OSA definition,[20] refers to primary response of sensory mechanisms. An operational definition of measuring sensations is to ask observers to match appearance. The goal of calculating sensation is clearly differentiated from the goal of finding the reflectance of objects.[21]

The essence of the sensation / perception distinction is seen in the practical embodiment. If one chooses the goal of calculating the physical reflectance there is not enough information to arrive at a proper solution.[22] If one states that the goal of the calculation is to obtain the appearance of an object, then there is adequate information in the two-dimensional array of radiances. The problem is simpler. One no longer has to differentiate gradients in illumination from gradients in reflectance or edges in illumination from edges in reflectance; they are treated the same. Both illuminants and reflectance are incorporated in color matches. There is sufficient information to calculate a color match-color sensation, even though there is not enough information to solve the reflectance / illumination - color perception or color recognition problem.

Classical CIE colorimetry can calculate a color match in a bipartite field. That calculation tells you the colorimetric specification of the stimuli that will match it. These colorimetry calculations will not offer any direct clues as to the color appearance of the stimuli.[23, 24] Color sensation calculations [10,25] tell you the appearance, that is the tristimulus values, that observers will choose as a match. This match includes the effects of the illumination environment and simultaneous contrast.[26] This calculation will not tell you the albedo of the object in the field. This calculation will not isolate objects from illuminants. It simply calculates a match to the human visual system for each pixel in a real image.

There are three advantages to the calculated sensation approach :

1. It is computationally efficient. [25, 27]

2. These simple and efficient algorithms have been shown to predict color sensations as measured in quantitative experiments.[10,25]

3. As a model of the human visual system, this approach can be used to precalculate color constancy effects and thereby simplify the the perceptual computational problem of how to recognize objects. By this strategy the input fields to the recognition computations are calculated matches or sensations. The triplet of color values exhibits color constancy. In other words, the effects of illumination have been greatly reduced and simultaneous contrast has been introduced. [26]

4. CONCLUSIONS

Computed color sensations are the ideal goal for image reproduction systems. They make the reproduction a record of what we see. They are in fact the closest thing to the painter's transformation of the image in the external world to the reflectance image. Calculated color sensations can be used to reduce the very large radiance range found in reflection prints. The advantage of the technique is that it does not create lightness distortions due to radiance compression.

5. ACKNOWLEDGMENTS

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