Retinex Algorithms: Many spatial processes used to solve many different problems

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Abstract

There are many different Retinex algorithms. They make different assumptions, and attempt to solve different problems. They have different goals, ground truths and output results. This "Retinex at 50 Workshop" session compares the variety of Retinex algorithms, along with their goals, ground truths that measure the success of their results. All Retinex algorithms use spatial comparisons to calculate the appearances of the entire scene. All Retinex algorithms need observer data to quantify human vision, so as to evaluate their accuracy. The most critical component of all Retinex experiments is the observer matches used to characterize human spatial vision. This paper reviews the experiments that have evolved as a result of Retinex Theory. They provide a very challenging data set for algorithms that predict appearance.

Introduction

Edwin Land coined the word Retinex in 1963. He used it to describe the theoretical need for three independent color channels to explain human color constancy.[1] The word was a contraction of "retina" and "cortex". A "Retinex" is a theoretical color channel that makes spatial comparisons so as to calculate lightness sensations, namely the range of appearances between light and dark.

Land had enthusiastically experimented with two-color projections in the late 1950's and early 60's.[2] By that time, he had hundreds of patents on many different photographic systems. He was well aware of the possibilities, and limitations, of silver halide photography. Before his Red and White light projection experiments, he accepted the standard explanation of color. Namely, color was the result of the local quanta catches of receptors with different spectral sensitivities. Human color vision was thought to behave the way that color film did; in that color was a local phenomenon that resulted from spectral responses within each very small image segment. The quanta catches of the triplet of retinal cones in a small retinal region generated color appearances.

An accidental observation made a colleague in a late-night experiment changed all. The colleague remarked that there was more color than expected from mixtures of photographic separations using red and white lights. Land responded: " Oh yes, that is adaptation." At two o'clock in the morning, Land sat up in bed, and said : "Adaptation, what adaptation?" He immediately returned to the lab to repeat the experiment. For the rest of his life, human color vision was a favorite research area.

What was it that Land had seen, so briefly, that made him return to the lab in the middle of the night?

Human Trichromatic Color Theory and film have always been linked. When Thomas Young made his famous suggestion of human trichromacy in 1802, his colleague at the Royal Institution, Humphrey Davy, was studying a black and white photographic system. Young was the editor of the Institutions journal that described the work.[3] Young was well aware of silver halide's response to light.

That night, Land realized there was nothing he could do with a <u>locally-responsive</u> silver-halide system to make film behave the way that vision did. The color appearances in those projections could not be understood from the quanta catches of receptors in a tiny local region. Human color appearances are fundamentally different. It is spatial comparisons that control color sensations.

Silver halide film uses quanta catches in a very small area which includes a small fraction of all the light-sensitive grains. Distant objects cannot influence the film's response to its quanta catch of each tiny segment.

Figure 1 illustrates the human visual pathway that begins with the visual pigments located in the distal tips of the cone and rod receptors in the retina (red ellipse). The quanta catch of these visual pigments initiates the spectral response to light. The receptors provide only the first response to the image on the retina. Appearance is the result of spatial processing along the entire visual pathway.

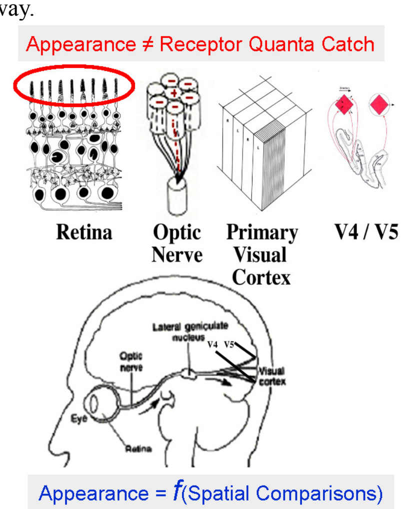

Figure 1. Illustration of the many stages of spatial comparisons in the visual pathway.

John Dowling, greatly expanded the work of Hecht and Wald, by describing the complex retinal spatial interactions.[4] Berson has recently shown spatial modulation from Melanopsin photopigment in ganglion cells.[5] In 1953, Kuffler [6] and Barlow [7] showed ganglion cells in the optic nerve make spatial comparisons. Hubel and Wiesel [8], DeValois [9] found spatial comparison cells in the cortex. Semir Zeki [10] found color constancy cells in V4 cortical cells. The dominant theme in research on the human visual pathway over the past 80 years has been the documentation of human spatial mechanisms at every stage along the visual pathway. level. Vision is a spatial process.

Vision's Ratio-making Sense

In 1974 Land wrote in his Friday Evening Discourse at the Royal Institution: "*This Discourse is about a generally unrecognized animal sense-the ratio-making sense. It is the ratio-making sense which processes the radiation reaching our eyes in such a way as to discover the constant properties of objects in relation to the radiation falling on them.*"[11]

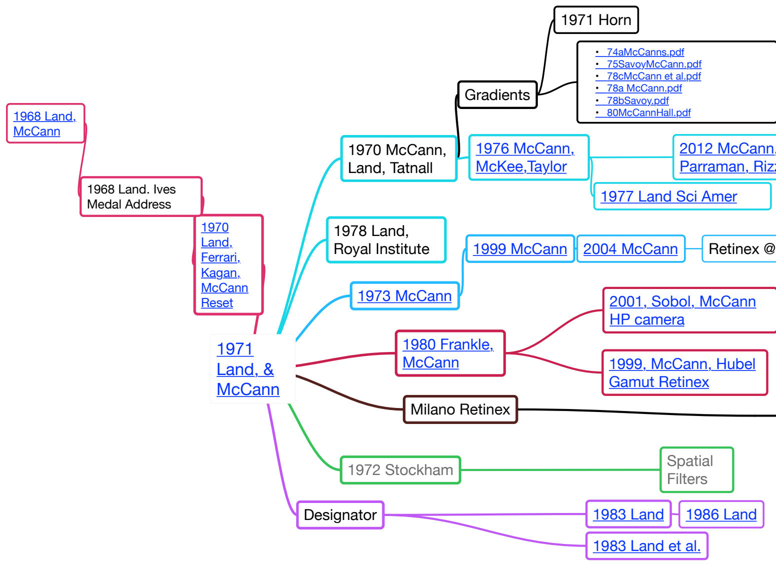

Figure 2 illustrated the papers surrounding the "Lightness and Retinex" article.Use reference [12] for download with links to papers.

Land put forward the idea that spatial comparisons, not receptor quanta catch, were the important stimulus for vision. Of course, quanta catch, as the first input step, plays a role, but ratios of quanta catches play a much more fundament role in synthesizing appearance.

Perhaps Land's greatest contribution to vision research is the remarkable legacy of fascinating, simple but elegant, experiments. His Red and White projections, Color and Black & White Mondrians changed the requirements of vision theories. Scenes required fundamentally different mechanisms than quanta catch models. This paper will review Land's and others experiments that help us understand human's unique spatial vision.

Many Spatial Algorithms

The best description of the original spatial algorithms that calculated lightness are found in the original literature:

- Land and McCann, J. opt. Soc Am, 1971 [13]
- Land, Royal Institution, 1974 [11]
- McCann, Land and Tatnall, 1970 [14]
- McCann, McKee and Taylor, Vis Research, 1976 [15]
- Land, Scientific American, 1977 [16]

Each of these articles describe important aspects of the model. In order to predict lightness in the B&W Mondrian and other test targets, the model varies the number and direction of paths. It included a gradient threshold; and a reset step that introduces normalization. Experiments showed that the reset step is the most interesting. Reset is key to the successful compression of HDR images. Frankle and McCann's 1983 patent [17] replaced paths with an array processor that calculated ratio, product, reset and average using a multi-resolution algorithm. This algorithm could calculate lightness predictions for a 512 by 512 image in seconds in 1980. This led to the algorithmic Zoom Processing [18] with O(N) computational efficiency. It is an extremely fast computational model, and is even more efficient when combined with special purpose hardware. Sobel's modification [19] was incorporated into a line of digital cameras. Review papers document the advances in the original Retinex algorithm over the past 50 years.[20, 21, 22]

Figure 2 lists the related papers and patents that incorporate the ratio-product-reset algorithms described in Land and McCann.

Two Distinct Problems: Model Vision and Make Reproductions

From the very beginning, the Retinex algorithm had two distinct, but related parts:

- First, develop a model of human vision that was based on many detailed measurements of human sensations from complex real-life scenes.
- Second, use that model as the basis of calculating human sensations and writing those sensations on film. Cameras have many problems that humans do not have. Namely, to reproduce what humans see, the camera needs to have color constancy and HDR scene compression.

A successful model of spatial color vision can calculate color constancy in HDR scenes, and write those sensations on LDR media. However, color photography research has shown that people prefer enhanced sensations over accurate reproductions, so color-masking and tone-scale enhancements are needed to meet consumer preferences.

Over the past 5 decades of growth in digital imaging, there has been a parallel growth in spatial image processing. This paper serves as an historical introduction to the *Retinex at 50 Workshop*. This workshop aims to provide the attendants with a novel and comprehensive look at the Retinex theory of color vision, and other spatial imaging algorithms. It will discuss the different goals, different definitions, and different degrees of success of the many variants of spatial algorithms. This paper reviews the experiments that characterize spatial vision to serve as ground truth for models.

Color Mondrians and Color Constancy

The Retinex algorithm began as a model of color vision. It's three independent (L, M, S) spatial color channels were needed to explain Land's Color Mondrian experiments.

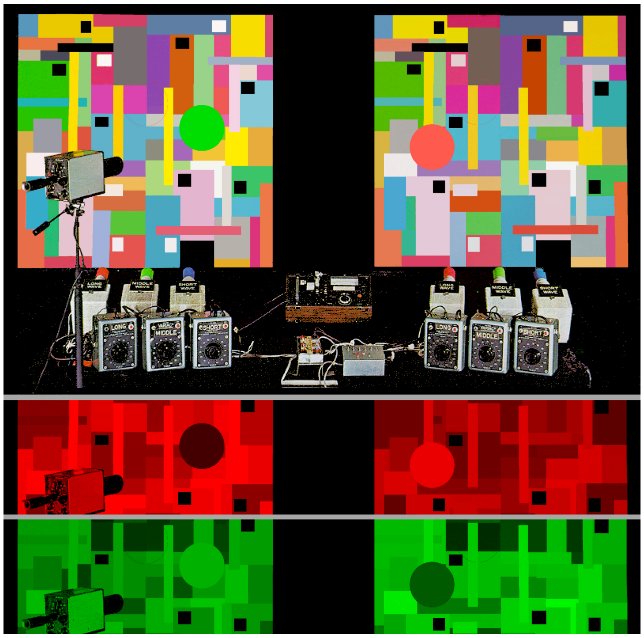

Figure 3. (Top) Illustration of Land's Double Mondrian experiment. By adjusting the two sets of L,M,S illuminants he sent identical triplets of radiances to the observer from green and red circular papers. Despite identical quanta catches, observers reported red and green sensations. (Middle) View of a part of the Mondrians in Long-wave(L) illumination. The green-circular paper on the left Mondrian has higher L illumination than that on red-circular paper on the right Mondrian. The illuminations were adjusted to make the L radiances from both circular papers equal. Nevertheless, the green circular paper looks dark, and the red circular paper looks light in L-Illumination. (Bottom) In Middle-wave(M) light the green paper on left looks light, and the red paper on the right looks darker despite equal M radiances. The green and red appearances correlate with L and M lightnesses.

Figure 3 illustrates Land's Double Mondrian experiment. He used this demonstration in his Ives Medal Address to the Optical society of America in 1968. At the top is a photograph of the two side-by-side, identical Mondrians, and the two independent sets of long-, middle-, and short-wave illuminating projectors with adjustable intensities. The circular papers are the areas of interest: green in the left-, and red in the right-Mondrian.

Land adjusted the overall uniform illumination on each side so that the green paper in the left Mondrian and the red paper in the right had identical radiances. Although these stimuli had identical quanta catch by the photopigments in the receptors (start of the visual pathway), the circle in the left-Mondrian appeared green and the circle in the right-Mondrian appeared red. Appearance did not correlate with quanta catch.The expended experiments showed that a single triplet of quanta catches can appear any color, at any location in the Color Mondrian.[11,12]

To understand how human vision does this, Land studied the Mondrians in each waveband. Figure 3(middle) illustrates a portion of the two Mondrians in long-wave illumination. The circular green paper in the left Mondrian has the same radiance as the circular red paper in the right Mondrian. The green paper reflects a smaller percentage of long-wave light than the red paper. To make the left-green circle have the same the long-wave radiance as the right-red circle, the L illumination on the left has to be increased.

Figure 3(middle) illustrates more long-wave illumination on the left. Land recognized that a common, everyday phenomenon was happening here. We all have observed that when a cloud passes in front of the sun we have less light falling on that scene. Nevertheless, the appearance of that scene changes only a small amount. The middle illustration shows a small darkening of all papers on the right caused by the less illumination. The lightnesses of corresponding Mondrian papers in both Mondrians are nearly constant.

The green paper appears dark, and the red paper appears light in long-wave illumination when they have identical radiances.

In Figure 3 (bottom) the green paper on the left Mondrian reflects more middle-wave light than the red paper on the right. In this case, the right Mondrian has increased middle-wave illumination. Again, increased uniform illumination of corresponding Mondrian papers makes very small increases in apparent lightness for all papers. Again, the lightnesses of all corresponding Mondrian papers in middle-wave light are nearly constant in variable illumination. The spatial relationships of the appearances of the two Mondrians is nearly constant. The green paper appears lighter, and the red paper appears darker in middle-wave illumination when they have identical radiances.

Color Appearance	Appearance in L- light	Appearance in M- light	Appearance in S- light
Red	light	dark	dark
Yellow	light	light	dark
Green	dark	light	dark
Cyan	dark	light	light
Blue	dark	dark	light
Magenta	light	dark	light
White	light	light	light
Black	dark	dark	dark

Table 1. Correlation table of color appearances and the apparent lightnesses in L, M, S illumination.

These observations explained to Land why vision has color constancy, while film does not. Color appearance correlates with the relative visual lightness in long-, middle-, and short-wave light. The Retinex is a theoretical independent channel that calculates the apparent lightness of each image segment, for each spectral waveband. Color appearance correlates with three Retinex lightnesses.

Table 1 is a list color appearances and their underlying triplets of lightness.

McCann, McKee and Taylor [14] measured color sensations in these color constancy experiments. They showed that in uniform illumination color sensations correlated with the paper's reflectance, using cone spectral sensitivities. See Figure 4 (left). Further, they successfully modeled color sensations using the spatial Retinex algorithm. This quantitative study provides important data on the limits of color constancy.

Additional color matching experiments showed that receptor adaptation cannot explain color appearance. [23, 12(Chapter 27)] These Color Mondrian experiments modified the surround to compensate for changes in scene averages caused by adjustments in overall illumination. Not only did the different color samples have constant radiances, but also they had constant average scene radiances. Receptor adaptation cannot account for color constancy.

Figure 4 illustrates the three different Color Mondrian experiments. Observers reported different degrees of Color Constancy. Fig. 4(left) 17-Area 2-D (flat) Mondrian in uniform illumination. Observers reported color constancy. Measurements of color appearance show correlation of appearance with cone-based reflectance with crosstalk limits. Fig.4(middle) 3-D Mondrians in LDR, partially uniform illumination. Observers reported that many surfaces have color constancy. Fig.4(right) 3-D Mondrians in HDR (sharp shadows) illumination. Observers reported some color constancy, but it was rare.

Another interesting experiment shut off color constancy in a complex scene. As proposed by Vadim Maximov, the experiment made two sets of papers with correlated reflectances, shifted in color space. The experiment used illumination with spectra that shifted the combined radiances to be identical. This complex scene made by the combination of reflectances and illuminations create two displays with identical quanta catch. Identical quanta catches over the entire field of view generated identical sensations. Even though we should expect color constancy in a complex scene, these two complex displays shut constancy off. Introducing new maxima turned constancy back on. [21(Chapter 28)]

McCann, McKee & Taylor's [14] quantitative measurements of color appearance also documented the limits of color constancy. Figure 4 (left) shows the 17-Area Mondrian matched by observers. These departures from perfect constancy provide a distinctive signature of its underlying mechanism. This work showed that spectral crosstalk between cone receptors determined the limits of constancy. McCann made extensive measurements of changes in color appearance with changes in spectral content of 27 illuminations. [24] The experiments used R, G, B LEDs inside a diffusing hemisphere dome. Each illuminant was generated by having experimenter turning on either 1, or 2, or 4 LEDs in each spectral band. Three spectral LEDs at three light levels made 27 different combinations of illumination.

Observers matched two chromatic and one achromatic samples in all illuminants. Observers reported that the achromatic paper was nearly constant in all spectral illuminants. However, the chromatic samples showed a small, but distinctive shift in appearance matches to the Munsell Book. That signature shift correlates with changes in spatial edge ratios due to the overlap in spectral sensitivity of cone photopigments.[25] That signature was distinctly different from predictions made by an incomplete adaptation model. [26]

Color Mondrians in illumination with edges

All of the Color Constancy experiments described above used flat Mondrians in uniform illuminations. Recent experiments [27] measured appearances in nonuniform illuminations that had sharp shadows, that created edges in illumination. Human vision treats edges in illumination the same way it treats edges in reflectance.

3-D Mondrian experiments used of blocks of wood (See Figure 4 middle, right). All the facets had one of 11 paints (R,G,B,Y,M,C,W,GL,GM,GD,K). The observers were informed that all blues had the same blue painted surfaces, etc. They were asked to measure changes in appearances of individual facets compared to a ground truth sample. The set of facets included each paint, in nearly uniform (LDR), and in directional (HDR) illuminations. They were asked to quantify the degree of color constancy in more real-life illuminations. Figure 4(center) used an integrating illumination box (LDR illumination), that attempted to make uniform illumination. Observers reported that many facets with the same paint appeared nearly constant. Others did not.

Figure 4 (right) used two different white lights hitting the 3-D Mondrian from different directions (HDR illumination). These illuminants created sharp shadows. In HDR illumination observers reported many large departures from color constancy. Color appearance correlates with the edges in the retinal image, not with the reflectance of each painted surface.

Carinna Parraman made a unique contribution. She painted the appearance of the two 3-D Mondrians in watercolors. She made two paintings by painstakingly reproducing the appearance of each facet (matching its sensation) in uniform illumination while viewing the entire scene and the entire reproduction. She quantified her matching sensations of each scene segment by painting it, and then by measuring its reflectance.[27]

In summary, these experiments measured the limits of color constancy. While departures from ideal (perfect) color constancy are very small in uniform illumination, constancy erodes with the increase of spatial structure in illumination. Color sensations of identical surface reflectances change in real world illumination. Edges in illumination are processed in the same manner as edges in reflectance. Cone quanta catch cannot identify radiances modified by reflectance from radiances modified by illumination.

This body of work provides an extensive dataset for ground truth information for color constancy models. The experiments provide observer data for models of human vision that include:

- Quantitative matches (Munsell Book) for Color Mondrians[14]
- Quantitative matches (Munsell Book) for Color Mondrians in constant average radiances[23]
- Mondrians that destroy color constancy [21(chapter 28)]
- Quantitative matches (Munsell Book) in 27 spectral illuminants [23]
- Quantitative matches (Magnitude estimation) 3-D Mondrians in illumination with edges[27]

In retrospect, this quantitative data on the limits of observer color constancy is very important. One cannot just assume perfect color constancy when modeling human vision. If vision is assumed to be part of a model, then that model needs to account for the fact that color constancy varies with scene content. Edges in illumination have the same visual impact as edges in reflectance.

Black & White Mondrians - Lightness Constancy

When Land realized that human vision was a spatial mechanism, that led him to approach image reproduction in a new way. He thought that a better process would be to incorporate a model of vision in the reproduction process.[28] The idea evolved to the sequence of capturing scene information; then, spatial processing to calculate visual sensation; then, writing sensations on film.[29, 30, 21(Chapter 33)]

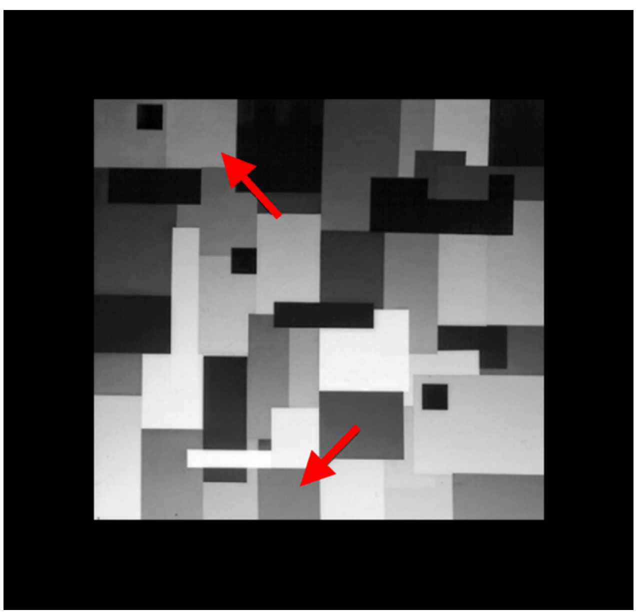

Figure 5, Land's Black and White Mondrian experiment. At the tips of the red arrows, White and Black papers had identical radiances, and hence identical digital image values.

In 1968 Land and McCann extended the Retinex algorithm to more realistic scenes using the Black and White Mondrian experiment.[12] Here gradients of illumination made near-white and near-black papers have the same retinal luminance. Despite equal cone quanta catches, the white paper looked white and the black paper looked black. The Retinex Algorithm added thresholds and reset normalization to its spatial comparison mechanism. Spatial comparisons successfully modeled sensations.

Land and McCann studied appearances of papers in HDR illumination. In Land's Black and White Mondrian experiment, the range of nonuniform illumination was equal to the range of the paper's reflectances. They used a gradient of illumination arranged so that a white paper in dim light had the same radiance as a black paper in bright light. In the experiment illustrated in Figure 5, the near-white paper behind the top arrow and the near-black paper behind the bottom arrow have identical radiances. Nevertheless, the papers still looked black and white.

The Black and White Mondrian experiment makes a number of important points about human vision.

- White and black reflectances can have identical radiances in non-uniform illumination.
- Identical radiances can have any sensation (white to black).
- In a complex scene, radiance cannot predict appearance.
- . The appearance of an area cannot predict the radiance of that area.
- Tone scale maps, using single pixels, cannot improve HDR images. Tone scales can only improve regions of an image. If white and black reflectances have the same digital value, a single-pixel tone scale map cannot make changes in different directions. It cannot make the white area lighter, while making the black area darker. Improving an HDR scene reproduction requires spatial modifications.

The Black and White Mondrian also points out a serious concern. One can never look at a picture to evaluate the success of an algorithm's output. Algorithm analysis requires study of the output numbers. When we look at an output image (Visual Inspection), human spatial image processing transforms radiance information into sensations. Since radiance does not correlate with appearance, a pixel's appearance tells you nothing about the numerical content of the output image. One cannot evaluate the computational success, or failure, of an algorithm by inspecting a processed image on a display. Human vision, while inspecting the display image, adds its own spatial transformations. Obviously, one has to use human observers to measure observer preferences for the most desirable camera images, but the analysis of computational imaging requires the analysis of the numerical output values.

Extending Measurements of Appearance

One of Edwin Land's greatest talents was his unique ability to think of critical experiments. His experiments tested the fundamental principles of an hypothesis or theory. As described above, Land used Color and Black and White Mondrian experiments as an exploration of the imaging properties of vision. These simple combinations of measurements of reflectance, illumination and human sensations made an essential contribution to our thinking about appearance.

Can we add to Land's experiments with additional tests, that inform us about the fundamental mechanisms of vision, and provide additional ground truths for our models? Can we use the quantitative measurements of human responses to scenes to better test our models?

Surrounds and Averages

What are the important properties of an image? Should we look to scene averages, contrast ranges, or other metrics of scene content?

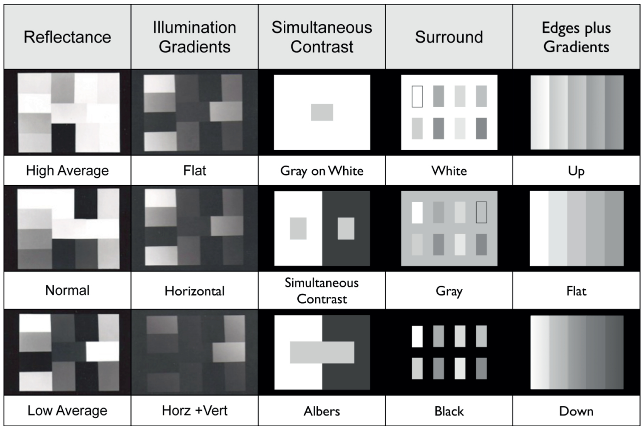

Fig. 6 shows lightness test targets used to study spatial comparison models.

Following the modeling protocol described in the 1960's, [13] we measured the appearances of lightnesses using many types of scene contents. This set of targets included variations in reflectances, uniform and gradient illuminations, and visual phenomena in order to study vision's spatial properties. It is essential to include test targets in which appearances did not correlate with reflectances. Figure 6 shows a series of 15 black-and-white test targets used to evaluate lightness models. The targets were transparencies with a dynamic range of 1,000:1, with angular subtends of 30° by 25°. The targets included variations in scene average luminance, gradients in illumination, variations of Simultaneous Contrast, extremes in background, and combinations of edges and gradients with the same luminance changes. We carefully measured the scene luminances of all areas in the field of view. The entire scene is the input to a spatial vision model. Observers matched the lightness of all the areas in all targets. Models of appearance calculated sensations using scene radiances as input. We compared calculated sensations for all image segments with observer matches.

We studied the effects of model parameters on each area in each display as individual events. Although time consuming, it gives a good sense of parameter properties for all parts of the test target. We measured observed appearance; calculated sensations; and compared them, area by area. The important point here is that these evaluations of a model looked for correlations of measured matching lightness with calculated lightness. Observer inspection and observer preferences were not part of the evaluation. We just compared calculated and observed lightness sensations.

Our results showed that all these design parameters have small influences on matching sensations. We were able to fit all these experiments using a single set of model parameters. The fit of Simultaneous Contrast, Albers and Gradients with Edges data was the most sensitive to these model parameters.

Spatial Relationships vs. Image Statistics (Histograms)

Figure 7 top shows the spatial arrangement of 6 scenes made from identical pixel populations.[31] The 30° x 25° displays had constant 2.5° dark-gray square at the center. The background around area T was constant with the exception of the addition of a fixed number of maximum luminance pixels in a variety of spatial arrangements.

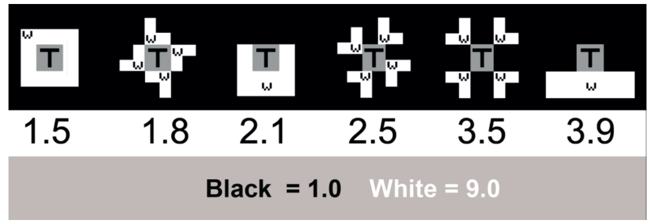

Figure 7 illustrates six targets (top row): matching lightness values for area T (middle row); and the quantitative scale of the standard Lightness display used by observers (Black = 1.0: White = 9.0). All targets have identical local radiance histograms. nevertheless, the sensations vary by 30% of the entire range of lightness (white to black).

Figure 7 (middle) shows the measurements of the variable appearance from identical pixel populations. The same pixel population is just rearranged in their spatial locations. All six targets had the same-size constant luminance central square area, labeled T.

In Figure 7 (left target), all the maximum radiance pixels surround the test square. Observers matched T to Lightness 1.5, nearly black.

In Figure 7(right target) All the maximum radiance pixels are adjacent to test square on only one side. Observers matched the test square to Lightness 3.9, near to middle gray (Lightness 5.0). Others spatial arrangements gave intermediate matches. Despite identical histograms, lightness varied over 30% of the range from white to black.

The set of six targets have different spatial positions of maximum luminance pixels, and different adjacent stimuli. Asymmetry, contiguity and enclosure are important. There is no simple rule that explains this spatial data. The only direct conclusion is that the local population of luminances, and their local scene histograms, do not control appearance.

There are a number of studies than provide a challenge to models of vision using local statistics. One study measures the appearance of a central gray square with a surround of 8 surround squares. Half of the surrounding squares are white; the other half black. The experiments measure the sensations of the central gray in all combinations of spatial arrangements. The matches vary from exhibiting contrast to assimilation.[32] All of these detailed studies [21(Chapters 20-25)] point out that the spatial organization of boundaries are in control of sensations. Image statistics cannot account for observer matches.

Retinal Contrast

Simultaneous Contrast is the familiar demonstration that surrounds affect appearance. Figure 8 illustrates the test target. This simple experiment uses two identical gray papers on white and black surrounds. Observers report that gray on white appears darker than the same gray on black. What makes the experiment more interesting is the fact that the retinal stimulus of the darker square is higher than the other. When we consider intraocular glare, the white surround scatters light into its gray square, yet it looks darker. Why does more light look darker? Two powerful spatial mechanisms, intraocular glare and post-receptor neural contrast tend to cancel each other. Neural contrast is slightly stronger than glare for this target. It overcompensates glare, making the Gray-in-White darker.

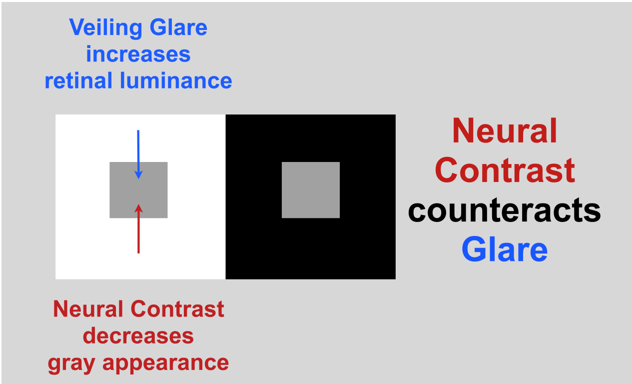

Figure 8 illustrates Simultaneous Contrast. Two identical reflectances in uniform illumination have different sensations. The Gray-in-White appears darker, even though intraocular glare makes it have higher retinal luminance.

The effects of intraocular glare are hard to see, except in severe clinical cases. Nevertheless, it limits the range of light that reaches our retinas. Depending on the scene, amounts of glare can very from vary small to very large amounts. A scene composed of just stars at night has little glare, while a beach scene will have an extremely low range of light on the retina. Despite this limit of range, we see the richest, deepest blacks under these conditions - high luminance and high glare.

To understand the role of intraocular scatter, we made a set of HDR test targets with almost 6 log units of dynamic range. The test targets have different backgrounds covering maximal to minimal glare. Using Vos and van den Berg's Glare Spread Function [33] it is possible to calculate the radiance image on the retina (Figure 9). The target has a dynamic range of 6 log units; the calculated retinal range has only 2 log units.

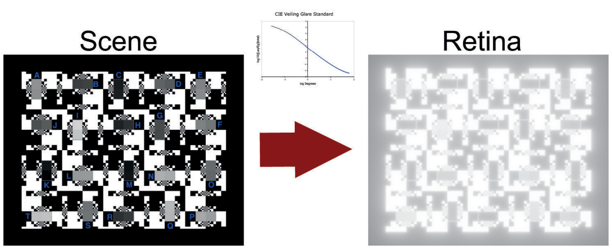

Figure 9 illustrates (left) the array of scene radiances; (center) Vos and van den Berg's Glare Spread Function; (right) the resulting calculated retinal image.

Young observers, with low levels of intraocular glare, were asked to make magnitude estimates of appearance of the target in Figure 9. Given the endpoints of sensations (White = 100, and = Black =1), the observers estimated the appearance of each gray square. The vertical axis in Figure 10 is the magnitude estimates of Lightness. The plots of the retinal response functions (retinal luminance vs. lightness appearance) show markedly different functions depending on scene content. The half-White/half-Black surround shown in Figure 9 has an intermediate contrast response function. The White to Black range of sensations requires a contrast of 2.0 log units on the retina (Grey Squares in Figure 10). [21(Chapters 14-19)]

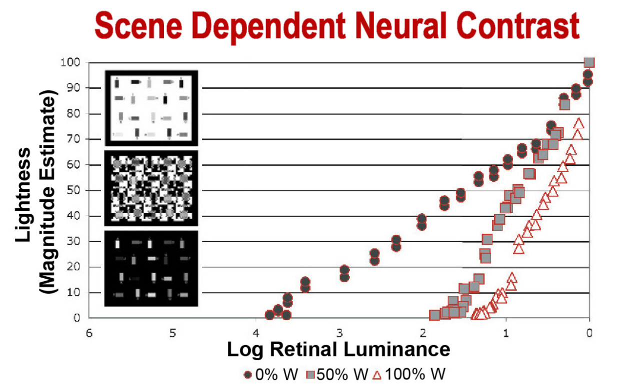

Figure 10 plots the apparent lightness of test samples vs. log retinal luminance for three different backgrounds. All three targets had a dynamic range close to 6 log units. All three plots cover the range of sensations from White to Black (Lightness 100 to 0). In maximal glare, the range of retinal luminances for the entire apparent lightness range (White to Black) is 1.5 log units (white triangles). The half-Max and half-Min surround has a range of retinal luminance of 2.0 log units (gray squares). In minimal glare, the range of retinal luminance is 4.0 log units (black circles).

The data in Figure 10 shows very large effects of surround on the range of the dynamic retinal image.

- •In maximal glare (white surround) - the dynamic range of retinal luminance is 30:1
- •In half-Max and half-Min surround - the dynamic range of retinal luminance is 100:1
- •In minimal glare (black surround) - the dynamic range of retinal luminance is 10, 000:1

The envelope of Visual Response Functions is measured by these experiments. There is no single Visual Response Function to light. The response varies with the specific scene content.

Intraocular glare causes extraordinary changes in the dynamic range of light on the retina as the result of scene content. This is illustrated in Figure 11. The first powerful spatial process is optical. Glare from all parts of the scene reduces the retinal range on the beach scene to very low levels. Nevertheless, apparent contrast is highest when retinal range is lowest.

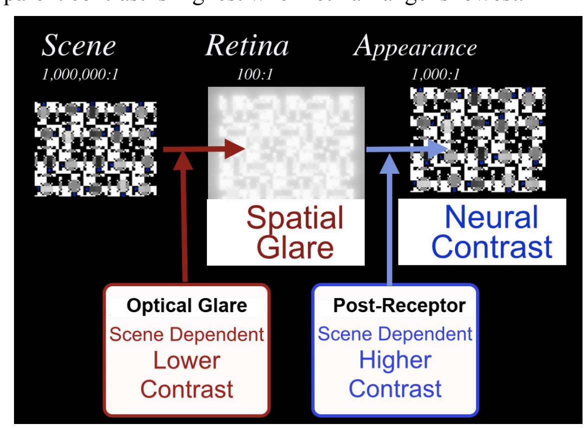

Figure 11 illustrates the two powerful scene-dependent spatial processes in human vision. Optical veiling glare reduces the scene-contrast range of the image on the retina. Subsequent post-receptor neural processes use variable contrast response functions depending on scene content. Glare reduces image contrast; neural processing increases apparent contrast.

The second powerful spatial process is neural; it is performed by post-receptor spatial processes. The combination of these processes is a cancelation of scene-dependent glare by scene-dependent Neural Contrast. The first spatial mechanism introduces significant changes to the optical image, and the second mechanism transforms the neural response. Remarkably, the resulting sensations are without the effects of intraocular glare. They show only small residual differences in appearance. Objects appear more constant because of the powerful post quanta-catch spatial neural processing. Figure 11 illustrates the two independent spatial mechanisms: glare and neural spatial processing.

Along with many vision scientists, we believed that models of human vision should use measurements of scene radiance as the best input to our models of vision. We always made the assumption that young observers with 20/20 vision had very low levels of intraocular glare. Glare was so low that we could assume that scene radiance was linearly proportional to retinal radiance. The only significant optical transformation was transmission losses. As measured in Figure 10, we were wrong to think that glare was unimportant. There glare reduced the scenes's dynamic range by 4.5 log units in making the retinal image (white triangles). Observers with normal vision do not notice this very large distortion of the retinal image.

Remarkably, post-receptor processing is an effective antidote to glare. However, we need to ask ourselves about the practice of trying to design models of human sensation using a one-step algorithm to describe a two-step process. It is unfortunate that all of CIE Colorimetry allows us only single pixel input data. That severely limits our ability to predict color appearances. Do we have the same problem here? Does it make sense to model the combined output sensation, when they are controlled by obviously different scene dependent mechanisms? Shouldn't we use two independent models?

Summary

Land initiated the idea that we needed a model of spatial vision to make better reproductions. That model needed to capture the wide range of scene radiances as input, spatially compare them to calculate sensations, and then display them.

The problem is that the spatial algorithm, that mimics vision by introducing color constancy and dynamic range compression, resides in the middle of the scene-reproduction processing pipeline. Assuming that the model successfully calculates sensations, we still have the practical problem of transforming that 2-D array of sensations into the appropriate signal for the reproduction media device. The print or display device needs an image that is calibrated for its conversion process from digits to light, viewed by the observer. That post-spatial process also requires chroma and tone-scale enhancements to suit consumers' preferences.

Unfortunately, it can be much more convenient to take a shortcut. If the goal is simply to make a better scene reproduction, one can take a photograph of a scene, apply a spatial algorithm and send that processed image to the output device. This shortcut removes two tedious tasks:

- First, it omits camera calibration to capture accurate radiance information,
- Second, it replaces the tedious task of matching sensations with just asking the observer to evaluate the output. Which image looks best? Or, does the image appear to have the desired improvement?

Many authors have used this approach. There is no doubt that their algorithms have made improved renditions of the images that they selected. But, are these algorithms successful models of vision? Do these algorithms provide a general solution to the problems of scene reproduction? Or, are they simply singular examples of trial-and-error image manipulations.

The biggest problem with visual inspection technique is that it does not include a discussion of the role of human vision in the algorithm's evaluation process. If vision is a powerful spatial image processing mechanism, what are the specific effects of using vision to measure success? Looking at the algorithm's output image means that the observer is applying those same spatial image processing mechanisms a second time in the experiment.

The big mistake is using observer preference techniques to evaluate vision model principles. It fails to separate the model's spatial processing from the subsequent human spatial processing. It makes it likely the subsequent human processing is the source of the improvement, rather than the initial algorithmic processing.

The important principles to evaluate models of vision are:

- Use calibrated input data, instead of easily available pictures. That way we can calculate the light receptor's quanta catch.
- Calculate sensations
- Measure the observer's sensations (matches and magnitude estimates)
- Compare vision model predictions with observed sensations
- Evaluate the vision model using a collection of challenging scene contents.

The Challenge

The challenge becomes how do we develop a set of data to document vision's spatial mechanisms. The actual quantitative measurement allows us to get beyond simplifying principles of vision, such as color constancy and HDR range compression. This challenge led to experiments that measured sensations created by challenging scene content; color constancy, gradients in illumination, constant spatial statistics, and illumination with edges. Each of these scenes provide a different challenge for a model of human vision. A successful model of vision should be able to predict observer matches in all these scenes using only the array of scene radiances.

HDR-Cancelation of Glare by Neural Contrast

Dynamic range compression is much stronger than one can observe. Optical veiling glare reduces the range of light falling on the retina, followed by a very strong change in neural response from scene content. This is hard to believe because we observe a very constant world. Neural contrast cancels glare, so we simply do not see it.

Spatial Relationships not Scene Statistics

Measurements of matching sensations show that targets with constant scene statistics (local histograms) have variable appearances. The properties of size, retinal position, contiguity, and enclosure must be an integral part of a model of vision.

Color Constancy erodes with Edges in Illumination

Colorimetry is an interesting example of an experimental technique based on unspecified assumptions. CIEXYZ, CIELAB, and CIECAM use color matching data as the basis of their models. Curiously, these color matching experiments are unique in the study of vision, in that there is almost no effect of scattered light on the retina. The scene presented to observers is two semicircles of light in a no light surround. The observers' task is to adjust the mixtures of light so that the semicircles match. At the match point all the light in the field of view generates the same quanta catch in retinal receptors. There are no additional sources of glare in the scene. The important underlying assumption is that equal quanta catch is a necessary and sufficient explanation of color.

As well, the color matching experiment reduces the stimuli to a single edge in the field of view, namely, the uniform circle of light in the middle of a no-light surround. This stimulus removes the information needed for post quanta-catch Neural processing. Colorimetry makes the unspecified assumption that spatial processes are absent from vision. While everyone agrees that quanta catch is necessary in a model of vision, no one should argue that it is sufficient. Human color vision is a spatial process.

There is an equally bad underlying assumption, namely that objects appear constant in all complex scenes. Here the pendulum has swung to the opposite extreme. The underlying assumption is that a surface's reflectance controls its appearance. Unfortunately, many authors mistakenly cite Land's experiments as evidence for this idea. Some even cite Land's experiments as evidence that spatial image processing can "discount the illumination", so as to separate illumination from reflectance. Retinex does not do that. That notion is incompatible with Land's writings:

- The last sentence in Land's Ives Medal Address: "the function of retinex theory is to tell how the eye can ascertain reflectance in a field in which the illumination is unknowable and the reflectance is unknown." [12]
- The discussion of the "biological correlate of reflectance" [11, 13,15(Chapter 32)] Land cited many examples of test stimuli in which lightness did not correlate with physical reflectance.

Just as we cannot think that quanta catch can predict color, we cannot think that all objects always appear constant. Both these unspecified assumptions are incompatible with measurements of vision.

In order to navigate between these extremes we need to measure sensations. When we do, we find that color constancy works very well in uniform illumination falling on flat scenes. However, if the illumination has sharp shadows (edges), those edges are processed by the visual system the same way that edges in reflectance are processed. In these conditions, found in all natural scenes, the principle of color constancy erodes. Measurements of appearance are much more helpful in understanding vision complexity than extreme assumptions.

The Retinex Idea

The origin of the word "Retinex" was the observation that color appearance in complex scenes correlated with the triplet of apparent lightnesses. Regardless of the cause of the lightness changes, when two identical physical objects look different, color appearances correlate with their L,M,S lightnesses.[21(Chapter 27)]

Figure 12 (top left) shows two identical sets of nine red squares. When the same sets of 9 squares are surrounded by yellow and blue stripes, the left and right sets no longer have the same color (top center). On the left side, the red patches fall on top of the yellow stripes; and on the right side, they fall on 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.

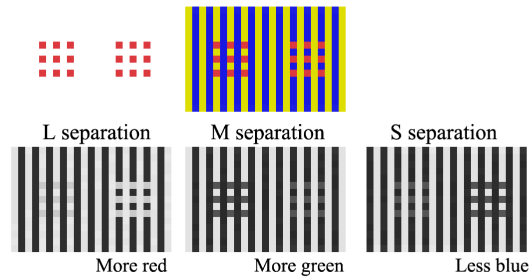

Figure 12 (top) Color squares change in appearance in Color Assimilation backgrounds. (bottom) L, M, S separation images. Changes in color appearances correlate with L, M, S lightness changes.

In Figure 12 (bottom) the apparent lightnesses of the sets of red squares are different:

- In the L separation, the squares are lighter on the right;
- In the M separation, these squares are lighter on the right;
- in the S separation, the squares are darker on the right.

Land's Retinex predicts that whenever L and M separations are lighter and the S separation is darker, then that patch will appear more yellow. Whenever the S separation is lighter, and L and M separations are darker, then those square will appear more blue. Colors correlate with L, M, S lightnesses.

Land's Retinex predictions of color in complex scenes still stands.

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Biography

John McCann received a degree in Biology from Harvard College in 1964. He worked in, and managed, the Vision Research Laboratory at Polaroid from 1961 to 1996. He has studied human color vision, digital image processing, large format instant photography, and the reproduction of fine art. His publication and patents have studied Retinex theory, color constancy, color from rod/cone interactions at low light levels, appearance with scattered light, and HDR imaging. He is a Fellow of the IS&T and the Optical Society of America (OSA). He is a past President of IS&T and the Artists Foundation, Boston. He is the IS&T/OSA 2002 Edwin H. Land Medalist, and IS&T 2005 Honorary Member.