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What scene information is needed for Models of Color Appearance in the Natural World?

Scene input for Color Appearance Models (short title)

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ABSTRACT

Colorimetry is an essential tool in every part of color. This article looks over our shoulders at the color research of Maxwell, Wright, Land and Wyszecki to build a framework for color. Then, the article looks forward to the needs of digital imaging's future. Color is the fusion of today's imaging technology with our understanding of color. Molecular physical chemistry describes the light-matter interactions, while human color is controlled by neurons that compare light from the entire scene, covering a nearly 180° visual angle. This article's question asks about the information required by a future Model of Color Appearance that is able to predict any scene: all natural scenes and any experimental display.

1. INTRODUCTION

The research of four color scientists form the corners of a framework that discusses the “Challenges and Open Problems in Colorimetry”. The four scientists are: James Clerk Maxwell, David Wright, Edwin Land, and Gunter Wyszecki.

James Clerk Maxwell (1831-1879) invented Colorimetry. There are many different three-channel color sensitivity functions. They fall into two distinct groups. First, narrow, minimally-overlapping curves used by photographic makers; and second, broad, overlapping curves derived from characterizing human vision. James Clerk Maxwell described both in the 1860s. Maxwell, with Thomas Sutton, made the first color photograph.[1,2] As well, Maxwell wrote the first color matching equations, from matches made using a spinning disc. His human sensitivity functions were derived from monochromator color matching data. Figure 1 shows Maxwell’s Color Matching Functions (CMF).[3] These CMF preceded CIE colorimetric standards by 7 decades.

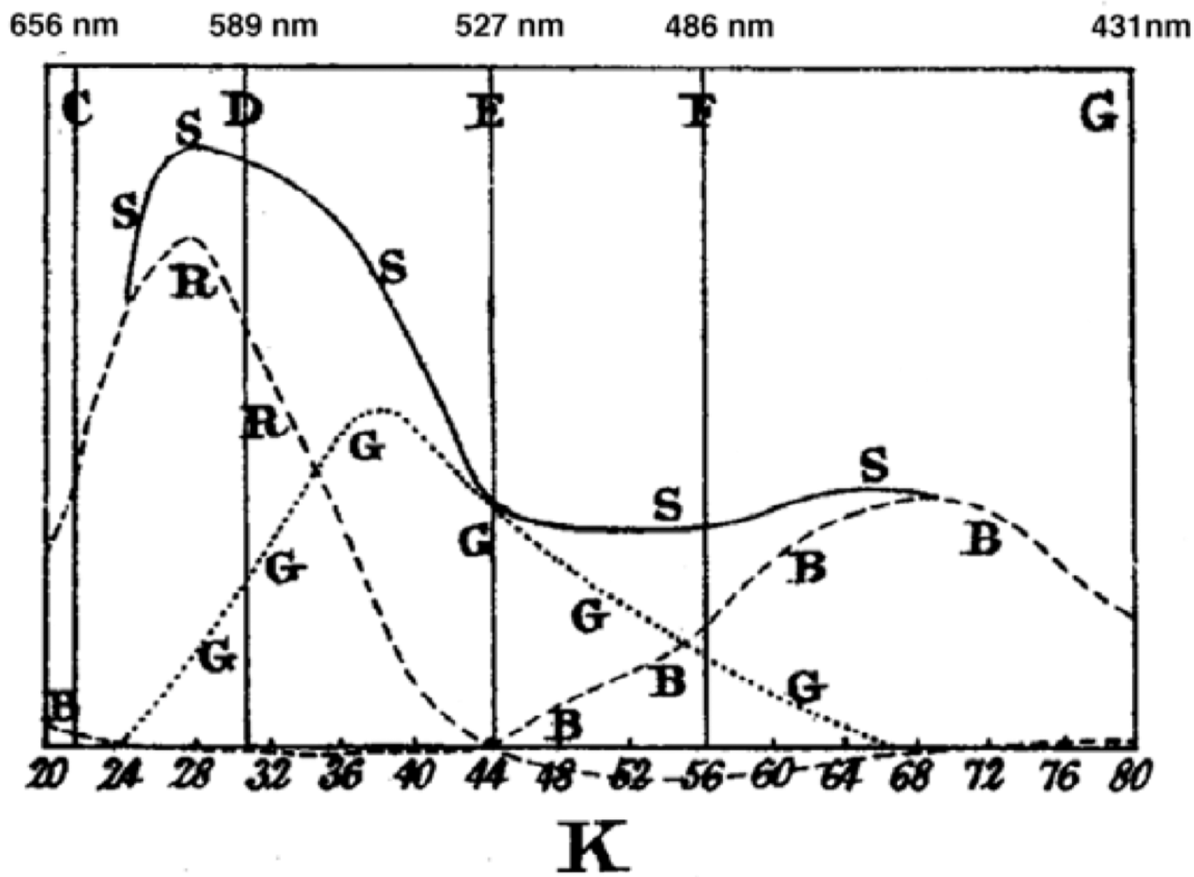

Figure 1 plots Maxwell’s color matching functions R, G, B for observer K. Observe that these curves are very broad and show significant spectral overlap. Note that Maxwell’s plot is calibrated using the Fraunhofer spectral lines. Hence, the horizontal axis plots longer to shorter wavelengths (calibrated at the top).

David Wright (1906-1997) studied color vision and color-vision deficiencies. He produced much of the fundamental data[4] incorporated in the standard observer of the CIE system for colorimetry used since 1931. Wright was professor of physics at the Imperial College, London, and served as the first president of the AIC.

Edwin H. Land (1909-1991) was a scientist and inventor. He founded Polaroid Corporation in the late 1930's and served as Chairman, President, and Director of Research until the 1980's. He invented inexpensive sheet polarizers, Polaroid instant photography, and the Retinex theory of color vision. His 1930's research in polarizing sheets led to Vectographs, 3-D projections and prints using polarized glasses. That led to Polaroid instant photography in the late 1940's. While developing instant color film in the late 1950's, an accidental observation made him change his previous understanding of color. He was startled by the range of color appearances in two-color (red and white light) projections. Up until then, he had accepted the common notion that human vision mimicked silver-halide photography, namely that human color vision was limited to light/matter interactions.

Land's study of Red and White Photography [5,6] led to Color Mondrians. At his OSA Ives Medal lecture in 1967 Land demonstrated that, in the same complex field of view at the same time, a single XYZ triplet could appear any color (white to black, red to cyan, and yellow to blue).[7] That demonstration of color constancy led to his Retinex theory in which vision's three separations are not receptor quanta catch, rather they are independent appearance arrays, that result from spatial interactions.[7] Land used Retinex - the contraction of retina and cortex - to emphasize that the specific neuroanatomy was then, and still is unknown.[8, 9,10]

Gunter Wyszecki (1925-1985) was an expert in all areas of color science. He is well known for his co-authorship of outstanding books, e.g "*Color in business, science and industry*" (with D. B. Judd), and "*Color science: concepts and methods, quantitative data and formulas*" (with W. S. Stiles). Wyszecki was president of the CIE, and led the Colorimetry Committee for many years.

2. FRAMEWORK

My forward-looking note on the future of Colorimetry begins with David Wright's 1987 note in *Color Research and Engineering*. He wrote:

> "Where does colorimetry end and appearance science begin? An interesting question. My short answer would be that colorimetry ends once the light has been absorbed by the colour receptors in the retina and that appearance science begins as the signals from the receptors start their journey to the visual cortex. To elaborate a little, tristimulus colour matching is governed solely by the spectral sensitivity curves of the red-, green-, and blue-cone receptors (if we may be allowed to call them that), whereas the appearance of colours is influenced by all the coding of the signals that takes place along the visual pathway, not to mention the interpretation of the signals once they arrive in the visual cortex." [11]

Here, David Wright splits CIE Color standards into its two topics: Colorimetry, and Appearance. *Colorimetry* is the study of the Molecular Physical Chemistry of light /matter interactions. The spectral sensitivities of the cones are the input to vision. After that *Appearance* is the study of the cascade of neural interactions that begin with the signals from rods and cones, and travels down the optic nerve and throughout the brain. Wright's clear dichotomy between Colorimetry (light/matter interactions) and Appearance (comparison of neuron responses) is the beginning of our framework for the future.

2.1 Light/Matter Interactions

Color is both practical and scientific. The practical part is the art of coloring the world; namely, making colorants, light emitters, pictures, as well as the technology of reproducing colors. The scientific part is the interaction of light and matter. Physics provides understanding of electromagnetic visible light (wavelengths between 400 and 700 nm). Some molecules (colorants) modify the wavelength distribution of the illumination's light. Other atoms and molecules emit light. All of color physical chemistry happens at a sub-microscopic, atomic/molecular scale. More important, these light/matter interactions at each location in the scene are independent of light from all other parts of the scene. In other words, *Molecular Physics* describes hyper-local events. The physical dimensions for light/matter events are measured in Angstroms. The light/matter variables are molecules and their shape, the energy of quanta (frequency/wavelength), and the number of quanta, as well as interference and diffraction of light.

2.2 Neural Spatial Comparisons

As David Wright suggested, practical Color is different. It uses the human's entire visual system as the second part of the process: whether synthesizing a colorful dye, painting a landscape, or making firmware for a camera. The picture's appearance is the output of the viewer's neural comparisons of all scene elements. Appearance depends on the interactions of all of human vision, and the entire scene. In other words, human vision uses light from all parts of the scene to make the appearance of each scene element. While local Molecular Physics events are the essential first step, vision requires neural spatial comparisons made across the entire scene to make Appearances. Neurophysiologists have shown that the visual pathway is a cascade of spatial comparisons starting with the receptor's output and continuing at every stage throughout the brain. We know this because two identical spots of light can appear different colors in the same real-life scene at the same time.[7]

Picture Making's biggest challenge is rendering the real-world's High Dynamic Range (HDR). Painters met that challenge in 1500 AD with chiaroscuro scene renditions. Painters learned to create spatial relationships in low dynamic range paint on canvas that appeared to match HDR scenes. Today physics-based technology is struggling with capturing real HDR natural scene radiances.[12] Questions about Colorimetry's future include defining the most essential variables used in human vision for viewing all possible scenes. Essential variables are well defined in Molecular Physics, but they remain elusive in vision research. What is the scene input needed for Color Appearance Models?

3. COLORIMETRY

Computational models have shown remarkable growth in the past 60 years in the wake of computers' digital revolution. In my early days at Polaroid in the late 1960's, I had to justify to Polaroid Corporation's Treasurer a $16,000 purchase order. That order would double the amount of hand-wound computer core memory in Polaroid Research's central computer. Just think, that was 8kb of pre-chip memory.

Today, my 2 Terabyte of laptop memory costs $0.001/Kb. My laptop has a billion times more byte memory than Polaroid research's 1970 mainframe computer. Further, that memory costs only 1 part in 2 million. That is a [benefit/cost] improvement for computer memory of 10^{14} for [memory size/(cost/byte)].

Going forward with today's state of the art in imaging and computational power, what is the information needed to model appearance? The answer is different for different problems. Some color problems are solved entirely in the domain of Molecular Physics. Finding a new paint that is an exact match of an existing paint on any object is a good example. That problem can be solved easily in the Molecular Physics domain. It is accurate, and easy to do, and works extremely well in all parts of the world.

Paint matching is a practical application of Colorimetry as standardized by the CIE in 1931. It uses a chain of steps that follow a well-established practice designed to restrict it to Molecular Physics.

The steps are:

1. Bring a sample of the surface to a paint supplier with color matching system.
2. Place the flat sample in the surface reflectance measuring device
3. The device illumination has:
   - Uniform light over a single, small spot
   - Constant luminance
   - Constant visible spectrum
   - Enclosure to remove stray and scattered light
   - Special optics that illuminates the surface at one angle, and reads reflected light at a different angle. These optics exclude unwanted surface reflections.
4. Three-channel light metering system to measure CIEXYZ color separation values.
5. Computational software that finds the best paint match formula using spectral data of the components used in that paint mixture system.
6. Paint supplier implements best match formula to make and deliver your matching paint.

This is a very reliable system that has remarkable success. It success is due to the excellent design of the entire system. Rather than imposing unnecessary burdens, the system introduced *limiting specifications* so that the problem could be solved easily by available computers and photonics.

The limiting specifications in the system design removed most of the problems that normal human vision has to solve. Recall the long list of limiting specifications: small spot of light falling on a flat reflective surface in perfectly uniform illumination of constant intensity, and spectral content using special enclosures and optics to remove stray and scattered light, and surface reflections. Our eyes in the natural environment do not have any of these restrictions.

The reason these instruments have this design is to provide the three-channel light measurement data about the colorants in the paint below the top surface. The problem of *buying a paint that matches* has been skillfully restated to be measurements of *three spectral integrals* of the subsurface colorant. These paints do not match spectra, rather they match CIEXYZ values.

These paint matching systems make the case that CIE XYZ can match paints using the above list of restrictions. This is to be expected when we recall the design of the experimental data used to derive CIEXYZ. Wright and Guild repeated and improved James Clerk Maxwell's measurements of three Color Matching Functions. The stimulus was a single spot of light, divided into two independent semicircles (a constant target half, and an adjustable matching half). Although these matches used light, not reflected light, they used a fixed spot size, constant, uniform, pure spectral light in a dark room on a no light background to remove stray and glare light. These are almost identical restrictions as those in the paint matching system. Observers adjusted the variable light side of the spot until it matched the constant side. The observers found null matches for the majority of measurements by adjusting three narrowband variable lights on one half to match a constant single narrowband on the other half. For technical reasons, some wavelength matches required that one adjustable waveband be combined with the constant side, rather than the adjusted side. Null match became possible, but it altered the appearance of the "constant" half. Null matches do not measure, nor provide any information about color appearance. They only provide identity data for a human observer. That was Maxwell's great insight. Today's photonics were not available. He could not measure, nor emit single wavelengths of light. Maxwell was unable to measure the spectral sensitivity of actual human cone visual pigments. That had to wait until 1963 (Brown and Wald [13], Marks, et al.[14]). Color matching data of highly unnatural, restricted, zero-glare scenes has been used for a century as a means of estimating a substitute transformation of human cone sensitivity functions.

Maxwell used the powerful tool of his era - the null match. He used his human vision system as an identity meter. He did not measure the color, its appearance, hue, chroma, lightness. He just measured the match to approximate a transformation of human cone sensitivities. This great invention allowed him to calculate the first color matching functions shown in Figure 1.

All human light/matter interactions take place in the retinal rod and cone outer segments (and ganglion cells). The red ellipse at the top of Figure 2(left) identifies the only site of light/matter cone interactions. The only scene data allowed in all CIE calculations (Colorimetry and Color Appearance Models) is the estimated CMF responses from a single small spot of light on these receptors.[15] That CMF data is an estimate of a transformation of cone response to a single spot of light. Everything that happens in CIE Color is limited to the spectral response of a small spot with all of the above restrictions. Fig 2(left) illustrates this fact.

David Wright's statement that: "colorimetry ends once the light has been absorbed by the colour receptors in the retina". All of cone vision's light/matter interactions take place inside the red ellipse (white background). That red ellipse is Wright's stop sign. The neural (non-colorimetric) interactions in the retina begin in the gray area. Colorimetry predicts matches from the spectral radiances of single spots of light.

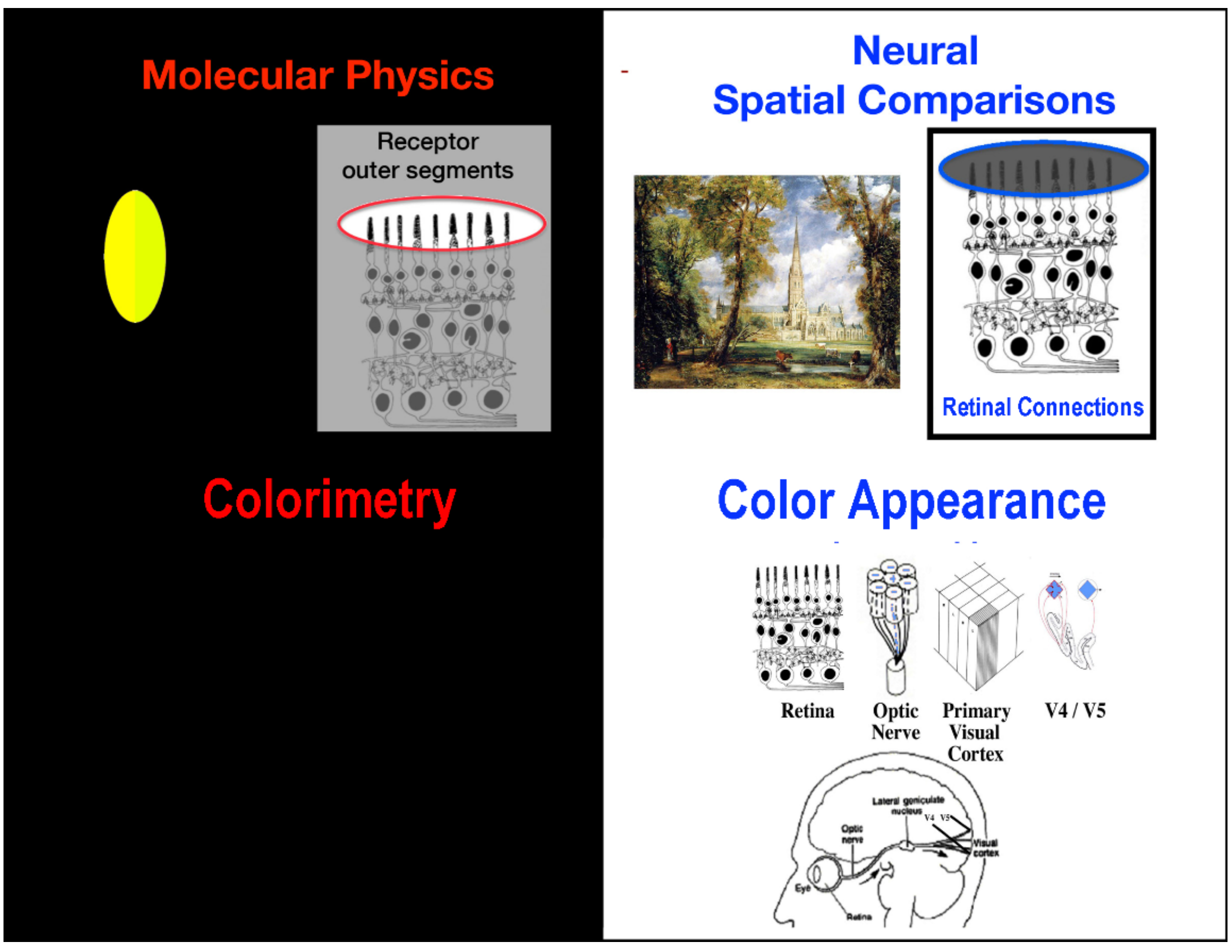

Figure 2 (left) illustrates David Wright's end of Colorimetry, and (right) the beginning of Color Appearance Science. The light stimuli icon for Colorimetry is a spot of light composed of two hemi-fields of light that are adjusted until the appear identical. The stimulus for Color Appearance is a painting of a natural scene.

4. APPEARANCE SCIENCE

Neural Spatial Comparisons

Today's challenge in Appearance Science is to calculate all elements in a scene from the light it sends to the eye.

Figure 2 (right) illustrates Wright's statement that "appearance science begins as the signals from the receptors start their journey to the visual cortex". Constable's painting is an icon representing the natural scene in natural illumination. Color Appearance Science (white background) uses receptor's outer-segment quanta-catch (blue ellipse) as input to the retina's complex spatial comparisons (box). The bottom illustration shows different types of neural spatial comparisons, and their location along the visual pathway.

In Figure 2 (right) the natural scene is represented by John Constable's HDR painting "Salisbury Cathedral from the Bishop's Garden". It illustrates the Bishop, his cathedral in sunlight, and his garden in shade. It is a rendition of what Constable saw - his appearances - made from this typical real-world HDR scene.

The white half of Figure 2 illustrates Wright's neural "journey to the visual cortex" and beyond. It illustrates the work of Dowling, Kuffler, Daw, Hubel, Wiesel, and Zeki. Neurophysiologists have shown that vision uses neural spatial comparisons at every stage along the visual pathway. They have shown that the visual pathway is a cascade of spatial comparisons starting with receptor's output synapses and continuing at every stage throughout the brain. Dowling's retinal connections are magnified at the top and shown again below in the map of the entire visual pathway. (From retina to optic nerve, to primary visual cortex and beyond (V4,V5 etc.).[16] Understanding the neurophysiology of vision, so as to know the mechanisms of Neural Spatial Comparisons, is an essential question in the future of color.

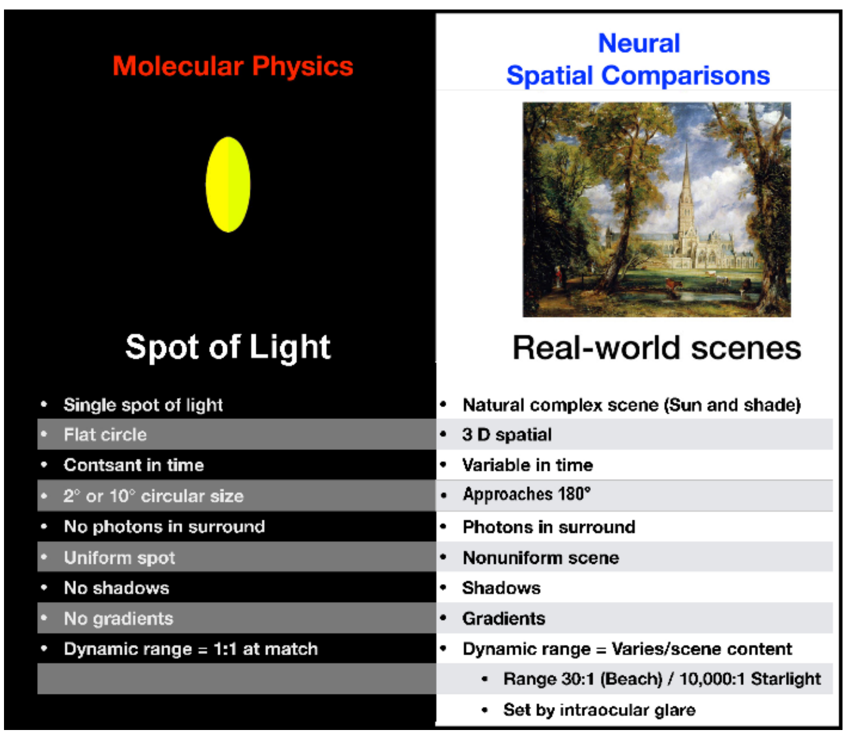

Figure 3. List of parameters in Colorimetry and Appearance Science. The limiting specifications from the colorimetric paint matching application are nearly identical to Maxwell"s color matching restrictions. Color Appearance parameters are different from those of Colorimetry. A model of vision must include all possible scenes to have that name.

Figure 3 is a list of the parameters of Colorimetry and Appearance Science. On the left it shows the limiting specifications of Wright's color matching experiments, and CIEXYZ Colorimetry. On the right it shows the absence of the limitations. While matching a paint sample embraces these limiting specifications to achieve its goal, Appearance Science needs to embrace all possible scenes and experimental stimuli. By definition, Appearance Science has no limiting specifications. 20th century neurophysiology has shown that post-quanta-catch vision is a complex net of multi-resolution spatial calculations. Color Appearance's mechanism is a neural net connecting all parts of the human field of view. That neural net cannot be studied, or predicted with a single spot of light. Everything in the field of view becomes the stimulus. All parts of the scene play a role in controlling every color appearance. In 1967 Land and McCann proposed a Retinex model for Lightness to calculate each color channel's appearances everywhere in the scene.[7] They proposed that future photography would mimic human vision by calculating appearances, and writing appearances (not radiances) on film and other media. Calculated appearances allows cameras to render scenes in the way fine-art painters do.

21st century Appearance Models need everything in the field of view as input. While such assumptions were completely impractical before digital imaging, implementation today is easy and inexpensive. Multiresolution image processing, mimicking that in the visual cortex, exponentially increases the efficiency of processing large input images.[17][18]

Using the entire field of view as input removes Colorimetry's limiting specifications for single spot, flatness, size, and uniformity of spatial and spectral illumination. Further, it introduces multiple illuminations, light patches, shadows, gradients and the dynamic range of scene and retinal luminances. Dynamic range is the final item on the list. In our analysis of the future, the range of light in the stimulus has some of the most interesting consequences. Constable's painting of sunlight on the cathedral and shade on the garden appears familiar and natural. The painting is remarkable because it renders the appearance of a very bright day that we can see in any light level. Based on my measurements of similar scenes,[19] the actual scene's range was about 4 log units. Constable rendered those appearances in paint's range of 1.5 log units.

Constable used his own Color Vision to learn how to spatially manipulate his paints on the canvas to generate the appearances of this HDR scene in his low range oil paints. This success demonstrates the power of neural spatial mechanisms.

Recent work on HDR imaging has shown that actual range of luminances never reaches the retina. Intraocular glare redistributes the light from every pixel to every other pixel as a function of the pixel's intensity, and the angular separation between emitting pixel and receiving pixel. The CIE Glare standard uses Vos and van den Berg's Glare Spread Function[20] . A MatLab program converts scene luminance to retinal luminance.[21] Using this program to calculate light on the retina for three 6 log unit HDR scenes showed markedly different ranges of stimuli on the retina. For a scene with black background (5.4 optical density), and with white (0.0), the range of light on the retina was 4 log units. By replacing the black background with white, the retinal range reduced to only 1.5 log units. For a background that was half-white/half-black the retinal range 2.0 log units.[21]

Replacing a spot of light with a real natural scene changes everything. Maxwell's and Wright's no-light surround eliminated intraocular glare. Intraocular glare causes a major spatial transformation of scene luminance to retinal luminance across the image of the scene. Starry night scenes have 4 log units of retinal range, while beach scenes have a 1.5 log unit range. The range of appearances from white to black is best on the beach, despite the glare-degraded retinal image. The eye's response function, namely the plot of apparent lightness vs. log retinal luminance, has a slope of 56.3 with 100 white background, and 26.7 with 0% white background.[21] This doubling in the slope of the eye's response to light in 100% white surround reveals that the neural spatial mechanism counteracts glare. The very high-slope response function for a beach scene compensates for the very low-dynamic-range retinal image. The study of intraocular glare show that vision does not have a single response function to retinal quanta catch! Rather, the neural processing response to light varies with the content of the retinal image.[21]

Glare distortion of the retinal image turns out to be an important feature of human vision. Colorimetry is fortunate that there is no light surrounding its spot. Nevertheless, glare in the natural scene is a major issue in the study of Appearance Science. The question/problem that glare poses for Colorimetry is simple: How can we use glare-free data to predict appearances in natural scenes with abundant glare? The corollary question is: How do we relate natural scenes with abundant glare to pure spectral matches without glare?

5. COLOR TRANSFORMATIONS, CALCULATIONS, and MODELS

In the 95 years since the standardization of XYZ Colorimetry, the number and variety of color calculations has exploded in many parts of science and engineering. Figure 4 provides a general framework for organizing these calculations for four different color topics listed in rows.

The three columns are organized using the limiting specifications described above. The black column shows calculations for matching spots of light. The white column shows calculations using the light from all parts of the field of view. The intermediate gray column shows hybrid calculations extending XYZ measurements to address color appearance using Chromatic Adaptation.

Topic	Matching Spots	Natural Images with Matching's Restrictions	Natural Image Input=Entire Scene
Position in Color Space	CIEXYZ, 1931 CMF		Retinex-LMS Channels Apparent Lightness predicts color, 1963
Uniform Color Space		CIELAB,CIELUV 1976 Cube root of L* a*b* Amplification	Intaocular glare causes cube root LMS Opponent Color fit to Munsell Book
Color Constancy		CIECAM 1997, 2002 Partial Chromatic Adaptation	Retinex, 1963 Spatial Comparison 1971
Spatial: Contrast Assimilation		CIECAM 1997, 2002 Fixed Transforms of XYZ + c, Nc,F	Matching Colors in Complex scenes with unrestricted matching

Figure 4. (rows) Framework of color topics: Position in Color Space; Uniformity of Color Space; Color Constancy; and Spatial: Contrast and Assimilation - difficult complex scenes.

Figure 4 (columns) Approaches to Color: single Matching Spots - shown on black; hybrid of applying XYZ with spot restrictions to unrestricted images - shown on gray; and entire scene calculations without restrictions - shown on white.

Position in Color Space

The first row shows the topic of calculation; namely, the calculation of a spot of light in a 3-D color space. XYZ,1931, in the black column, uses light/matter interactions from Color Matching Functions. (Described above).

In the white column, neural spatial comparisons build up a color space from the image on the retina using the entire image. In 1963, Edwin Land's studies of Color Constancy demonstrated the importance of the content of the entire scene. Land showed that a particular triplet of L, M, S cone-quanta catches, or XYZ values from an image segment spot, could appear any color. So, Land proposed that position in color appearance space was best predicted by three L,M,S apparent Lightnesses. Color in complex scenes correlated with lightnesses in L, M, S appearance separations.[7 22]

Uniform Color Space (white column)

In 1982 Stiehl et al. showed that Lightness's cube root function is the direct result of intraocular glare from a uniform white, or gray, background.[23] Intraocular glare added proportionally more light to darker lightness test patches. Stiehl et al. used Vos and Walraven and Van Meeteren's glare spread function[24] to show that Lightness retinal response function is proportional to log luminances. While Lightness is proportional to the cube root of Scene Luminance, Retinal Luminance is proportional to Log Luminance. Since 1932, many physiologists have measured that receptor output is proportional to log luminance.[25,26] This simplifies the mechanism of Lightness. It is simply proportional to actual receptor output.

Log Retinal luminance is easily calculated by the convolution of all scene radiances with CIE's Glare Spread Function using a MatLab program.[20,21]

Best-fit calculations have been used to develop a model for Uniform Color Appearance Space. D'Andrade, et al. [27] started with an established Uniform Space, namely the Munsell Book. First, they put all Munsell chips into two 3-D spaces. One was the uniformly spaced coordinates of the Munsell Book - the goal. The second 3-D space was the actual cone quanta catch coordinates. They were calculated by the product of each chip's reflectance, illumination, intraocular absorption, and LMS cone sensitivities. Given the coordinates of the uniformity goal, what 3-D spatial transformation of cone quanta catches is the best fit to the Munsell Book coordinate? They used an opponent color model very similar to L*a*b*. It used the same cube-root function of luminance, and the same 200% amplification of the yellow-blue color axis. However, they report that the red-cyan color axis requires a 700% amplification, compared with 500% in L*a*b*. This is consistent with the much greater spectral sensitivity overlap of L and M cone sensitivities compared to that of X and Y CMF.

If ***LC*** long-wave cone***, MC*** middle-wave cone***, SC (***short-wave cone) are the normalized (white paper) three cone responses (log Retina Quanta Catch), D'Andrade's best fit results become very simple in principle. Using cone responses, Munsell Space is fit by the linear algebraic formulae:

$$Value = 0.5 * \left(LC + MC\right)$$
$$RtoBG = 7 * (LC - MC)$$
$$YtoPB = 2 * (-LC + 2MC - SC)$$

D'Andrade, et al. space has many advantages. It is very simple. This space has actual color-appearance uniformity that equals the Munsell book, rather than an approximation. It is linear. It uses the actual cone spectral sensitivities with much more spectral overlap from L and M cones. Future research is needed to see when, and if, models of retinal physiology are more useful than color matching data in the analysis of color.

Color Constancy [white column]

The next topic in the white column is Color Constancy. Land's Retinex was built using observations of color constancy of complex, but flat, arrays of colored papers in variable spectral illuminations. Experiments that measured all Mondrian radiances, and matched (Munsell Book) all Mondrian patches, tested the Spatial Comparisons model. Observer matches in varying spectral illuminations showed approximate color constancy to surface reflectance, but with systematic departures from perfect constancy. That data showed better correlation with Scaled Integrated Reflectance using Paul Brown's cone sensitivity functions.[13]

A computational model used Brown's cone-response array of all Mondrian image pixels as input. The lightness model [7,17,18] emphasizes edges and minimizes gradients. Using Spatial Comparisons it calculated the L,M,S independent apparent lightnesses for model output. The model predicted observed matches accurately, by predicting the small departures from reflectance constancy.[22,] Additional discussion of Spatial Models are available. [16, 18, 28, 29]

The above flat Mondrian experiments seem to agree with the Helmholtz/vonKries observations about the reflectance/illumination dichotomy. In color adaptation theory, appearance correlates with reflectance because illumination is recognized, and then discounted. Four sets of Mondrian experiments fail to support this reflectance/illumination approach. Instead, they suggest the important dichotomy is between two spatial properties: edges and gradients.[34]

New experiments used 3-D Mondrians made of wooden blocks with many crystal-like facets. Observers were instructed that certain red(R) facets had the same paint on their surface. When viewed using a spot light with sharp edges in illumination those constant R reflectance surfaces had very different appearances. As well, the experiment used G,B,Y,M,C and 5 neutral paints with analogous observations. When the illumination has sharp edges, Color Constancy is substantially weakened. The correlation of appearance with Scaled Integrated Reflectance is limited to some specific scene elements in 3-D scenes with edges in illumination.[30]

Goethe used afterimages in his attacks of Newton. Today, we think of afterimages as the Molecular Physics's dark-adaptation, and the Neural Comparison's light adaptation.[31] Alpern and Campbell showed that bleached photopigment initiates signals out of the retina that constrict the pupil, until the the retina regains dark adaptation.[32] Daw studied afterimages viewed on a projected background. In the control, Daw made afterimages by light-adapting observers to a colorful scene using a fixation point, and viewed it on a uniform projected white background. In the experiment, the afterimage was viewed on a projected black & white photo of the scene. When observers used the same fixation point that formed it, the afterimage appeared the same as on a white background. Moving the fixation to a different point in the scene made the afterimage disappear. Re-fixating on the original point, made the afterimage reappear. Repetitions caused the same results until the afterimage faded away.[33] Daw's experiment shows that the bleached photopigment signal (Molecular Physics) is blocked by conflicting current stimuli with conflicting contours (Neural Comparisons). Afterimages are a second example of bleached photopigment sending signals out of the retina. The disappearance of afterimage in complex stimuli with conflicting contours raises doubts that they play a role in the Color Constancy of natural scenes.

An alternative to building Color Constancy up from edges and gradients is Helmholtz/vonKries color adaptation. Modeling the combination of bleached photopigment and its neural suppression is extremely complex, and remains in uncharted waters. Alternatively, a number of experiments have looked for the consequences of vonKries adaptation mechanism in complex scenes. They include: attempting to cancel chromatic adaptation using adjustments in average scene content; Constancy's on/off switch (modifications of scene maxima); and matches using 27 illuminants to study incomplete adaptation. All these experiments fail to find evidence that Color Constancy Appearances are responsive to chromatic adaptation.[34]

Spatial: Contrast and Assimilation [white column]

The final topic in the white column is vision's unique spatial image processing, often categorized as visual illusions. Since Leonardo daVinci, a very long list of null experiments has been compiled. They all use identical stimuli that have different appearances.

Neural spatial modeling uses a two-step procedure to evaluate its spatial models. First, all image segments in any null illusions are matched to a constant complex standard, such as the Munsell Book in a complex scene. Second, spatial models calculate that match. This procedure is distinctly different from the image processing of a picture of the illusion, and visually inspecting the calculation. One cannot look at a processed image to evaluate the success of a vision model. Spatial models have successfully predicted many visual illusions.[19] There are innumerable spatial imaging algorithms that either calculate appearance, or improve the appearance of digital images. Too many to discuss here. The important point is that the extremely rich data contained in the image on the retina provides input, that when properly processed can, very likely, predict all appearances in all illusions.

Hybrid: Relative ColorimetryTransformations [gray column]

The gray column, between black and white in Figure 4, lists three relative Colorimetry standards that transform XYZ values with limiting specifications, so as to apply them to natural scenes that have no restrictions.

The hybrid calculations use XYZ measurements of a single spot of light, along with a measurement of either the illuminance falling on the spot, or reflected light from a standard white placed in front of the spot, or a maximum scene radiance. This normalization step changes absolute XYZ to Relative Colorimetry.[35]

The Helmholtz/vonKries chromatic adaptation proposal suggests that humans discount illumination, to recognize an object's reflectance. Normalized CIEXYZ is helpful to partially compensate for variations in amounts and different spectral content of uniform illuminations.

CIELAB & CIELUV Uniform Color Spaces and Color Difference Formulae -1976 [gray column]

Many color scientists have studied the uses of distance in ***X,Y,Z*** color space. All agree that ***X,Y,Z*** is not linear in appearance. If a scientist wants to calculate an average appearance error throughout the entire color space, the ***X,Y,Z*** has to be transformed to a more uniform space. Distances in color space must be proportional to color appearance differences, so as to use them in linear arithmetic averages.

In 1976 CIE introduced a pair of standards to transform nonlinear ***X,Y,Z*** space to a uniform color space. The transformation normalized ***X,Y,Z*** [36], so as to minimize the effect of intensity, and spectral content of illumination. Further, it transformed the lightness axis with a cube root of luminance, and stretched opponent R to BG, and Y to PB chromaticity axes by different functions. Both shared the identical Lightness function ***L****, while ***a*,b**** and ***u*,v**** are different chromaticity functions. The ***L**** value for a sample with ***Y*** luminance is the scaled cube root of the ratio $[Y/Y_n]$, when Y_n is the nominal white object-color stimulus.[36]

These standards have much better color space uniformity than ***X,Y,Z***. However, the transforms are different, and they generate different color spaces, as seen by 3-D plots of the spectrum locus. Both color uniformities are approximate. Given that the Munsell Book is a Uniform Color Space, the ***L*a*b**** average ***a*,b**** delta E error in C is 27% of the Munsell's C value.[37]

CIECAM Color Appearance Models [gray column]

Fairchild's book "Color Appearance Models", describes the single spot-of-light models of Nayatani, Hunt, Fairchild, Guth, Luo models leading to the 1997 CIECAM.[35] Moroney et al.'s further modifications led to 2002 CIECAM[38].

Color Constancy [gray column]

Using reflectances and illuminants, CIELAB, CIELUV, and CIECAM transform the ***X,Y,Z*** color space of the scene radiances into the equivalent of relative reflectances. These models use a pixel's scene radiance and that pixel's illumination to calculate positions in their spaces. If two pixels from different parts of a scene have the same reflectance, but different illumination, then CIELAB, CIELUV and CIECAM predict identical outputs. These models predict that sensations always correlate with surface reflectances, but equal reflectances always predict equal sensations. There is no mechanism here to generate different appearance predictions caused by constant surface reflectances, such as 3-D Mondrians with edges in illumination.[30]

Spatial: Contrast and Assimilation

Contrast, assimilation, and thousands of visual illusions use pairs of identical stimuli that have different appearances. CIECAM models require their users to visually interpret the contents of the scene to assign three scene-dependent coefficients: c (viewing condition parameter), Nc (chromatic surround induction factor), and F (surround parameter). These parameters have to be set by inspecting the scene.[38,39] They are not calculated from the array of scene radiances. Attempting to model all visual illusions (using identical patches) with a few parameters, such as those in CIECAM (c, Nc, F) is a daunting task. Much more information about the contents of the image on the retina, and background knowledge of vision's multiresolution mechanisms makes modeling all illusions more tractable.

Summary of Relative Colorimetry [gray column]

CIELAB, CIELUV, CIECAM models predict appearances of single spots using the principle discounting the illumination. They require measurements of the light coming from the scene, and a normalization factor. In the reflection/illumination case the models measure illumination, rather than deriving it from scene's radiances. These models calculate the reflectance of the object and scale its relation to white. These models measure the X, Y, Z radiances to calculate reflectances of individual pixels and transform them into a new color space. There is nothing in the calculation that can generate different outputs from identical scene reflectances. These models predict the same color appearance for all image segments with the same reflectance, in every illumination. While useful in analyzing appearances of flat scenes in uniform illumination, such as printed test targets, it does not predict appearance in real three-dimensional scenes.

In the future, Color Appearance Models will increase in importance. There needs to be greater attention to the properties of the color spaces we use. Absolutely accurate uniform color spaces are essential. Color Appearance Models need to shed the limiting specifications of paint matching systems. The struggle that relative Colorimetry has to face is most obvious in digital image processing. Although this paper has regarded the capture, synthesis, rendering, printing, enhancing of digital images beyond its scope, those digital applications dominate Colorimetry's applications today. Digital imaging needs Colorimetry to move beyond the XYZ's color matching's restrictions.

6. WYSZECKI'S WARNING

Gunter Wyszecki gave a tutorial talk "Colorimetry" in *COLOR: Theory and Imaging Systems* in 1973. Near the end of the tutorial he warned us, "...the tristimulus values and thus the chromaticity of a color stimulus do not offer any direct clues as to what color perception will be perceived."[40] Additional variables, such as the other colors in the field of view, the state of adaptation of the receptors, and spatial relationships in each scene determine the color appearance. In order to measure appearance one needs to match a test color to a sample in a library of standard colors in a constant complex scene.

In the "*COLOR: Theory and Imaging Systems "*proceedings Wyszecki wrote: "Sometimes we encounter beautifully colored chromaticity diagrams intended to display the color world in a way we are considered to perceive it. The whites in the center, the reds in the right corner, the blues in the left corner, the greens at the top, and so on. Although these are often masterpieces of painting, they can be quite misleading as to the real purpose of the chromaticity diagram".[40]

What he said in his talk was more direct.

He said: "Whenever you find a colored chromaticity diagram: Burn it !"

Gunter Wyszecki, the man who made colorimetry and color science so accessible, to so many people, realized along with David Wright and Edwin Land that Tristimulus Values X, Y, Z are the signature of Colorimetry's Matches, but not the signature of Color Appearances.

Maxwell's experiments on color matching were done early in his career. After that he turned his attention to electromagnetic fields. Edwin Land often quipped that the study of color vision would have been very different had Maxwell studied color matching after he had studied fields. Maxwell analyzed colors with the assumption that color vision works, as film does, using a pixel-based mechanism, as shown by his Royal Institution demonstration of color photography. Maxwell, the man who wrote the equations to describe electromagnetic fields, never discussed the idea that color was a field phenomenon.

The combined work of Maxwell, Wright, Land, and Wyszecki built an interesting, diverse framework of understanding human color. Even though they worked on color separately, over a 140 year period, their ideas show remarkable overlap. Using their contributions as the framework of Colorimetry's future is a good idea. Going forward, much more information about all the scene radiances, everywhere in the field of view is needed to calculate appearances in real, natural scenes. One sample of the scene radiances, out of millions falling on the retina, is not enough.

Our predecessors lacked our Photonics, and our computational power. Today's computers with recent universal improvements (e.g. memory = $>10^{14}$) opens the doors to scene-dependent calculated Color Appearance Models to include millions of retinal radiances in that calculation. With the possibility of using the entire scene as input to the model, we could address the problem of predicting Color Appearance in real natural scenes without any restrictions.

7. QUESTIONS

What scene information is needed for Models of Color Appearance in the Natural World?

In summary, Colorimetry is the result of molecular physics taking place locally at the atomic scale. As David Wright commented, Colorimetry's input data is limited to the light from a single local region of the scene. Colorimetry success is due to Maxwell's insight of a Null Match.

Color Appearance is processed throughout the rest of the neural visual system that makes spatial comparisons at every stage. Color Appearances depends on all the spatial information in the entire field of view.

Appearance models have two branches:

- Chromatic Adaptation - Given illumination data, these models discount illumination - to estimate surface reflectances. But, adaptation has no mechanism for predicting appearances of scenes with edges in illumination, and the appearances of illusions.
- Edges and Gradients - Building appearance from edges in scene content, in order to calculate the appearances in Natural World's scenes. Spatial vision emphasizes edges and

minimizes gradients to compress the range of scene radiances. That compression varies with the patterns of light in the scene (beach scene vs. starlight).

A Model of Vision needs to predict the Appearances of all scenes. What scene information is needed to calculate the Appearance of all parts of all scenes? We need to consider:

- How many input samples are needed to represent the Natural World's HDR scenes, and difficult illusion targets? Camera digits do not represent scene radiances; they have their own camera generated glare.
- Which spatial pattern of light does the model use: the light from the scene, or the glare-transformed light on the receptors?
- Does the Appearance Model use the standard CIE Color Matching Functions, or the actual spectral sensitivities of receptor photopigments?

These complex Questions are examples of remaining challenges in our simple goal, namely predicting what we see using the light from the scene.

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