Second Annual TI Digital and Analog MEMs Symposium
AT&T Conference Center, UT Austin Campus
April 23, 2010

DMD Applications in Color Vision Science: Observations of the Abney Effect in Direct and Peripheral Viewing

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Early Involvement in Vision Research

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Objectives

- Need to improve models for understanding the neural basis for color vision capacities
- Percept of color dimensions (hue, saturation, brightness) typically well predicted by standard color vision models per relative activity of the three cone classes (L – long, M – medium, S – short; 570nm, 543nm and 442nm)
- But there are cases where it fails: "unique hues," (colors that appear "pure" and without other hues) and of which mixtures constitutes "pure white"
- Evidence of spectral properties of the environment greatly shape the percept of hue

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Applications of Color Vision Research

- Medical
  - Effects of Stress, Aging and Link to Color Deficiencies
- Automotive and Aerospace
  - Understanding Limits of Visibility
  - Human Factors
  - Design of Lighting
  - Accident Reconstruction
- Product development and quality
  - Pigments and paints
  - Textiles

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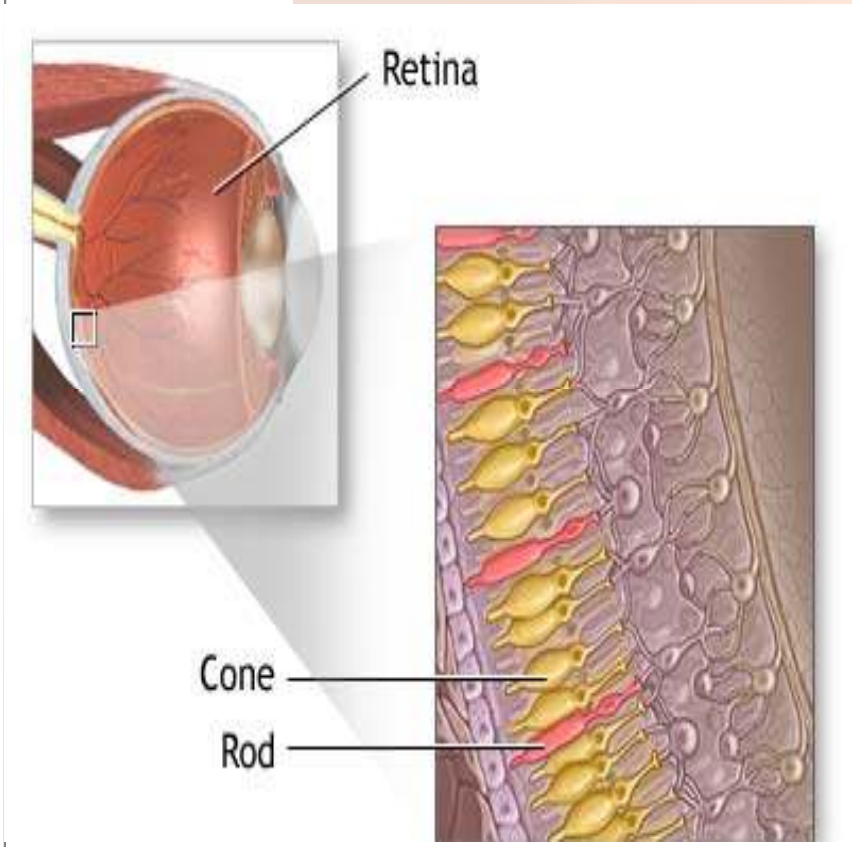
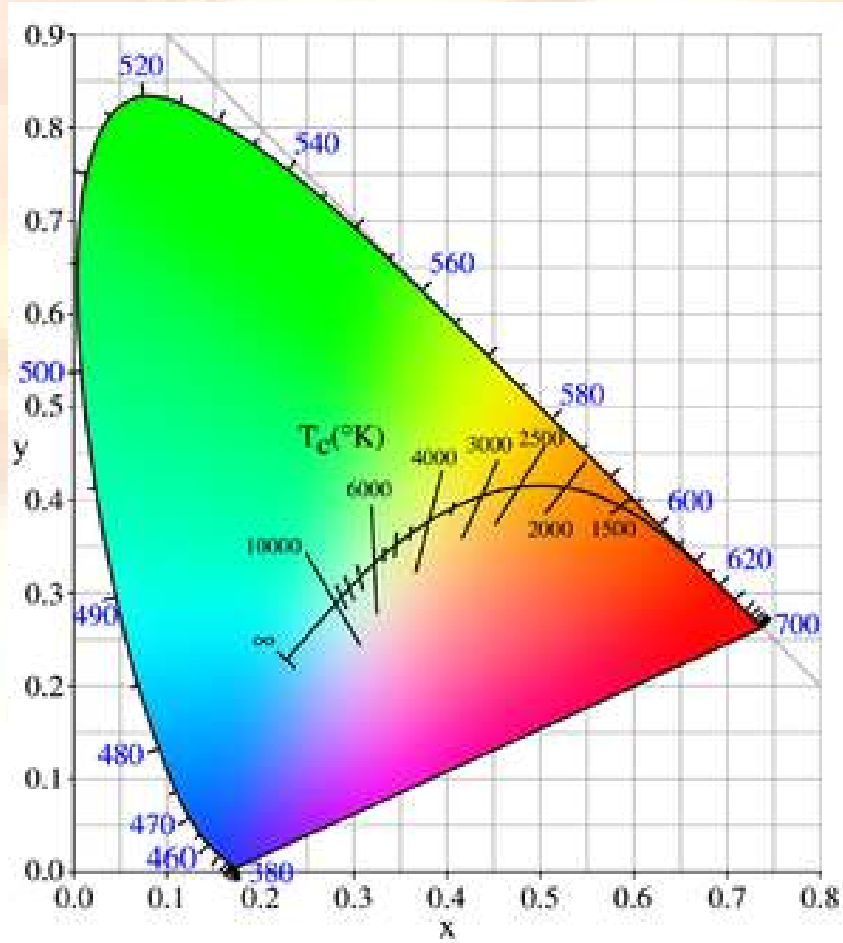
The Eye and CIE Color Map





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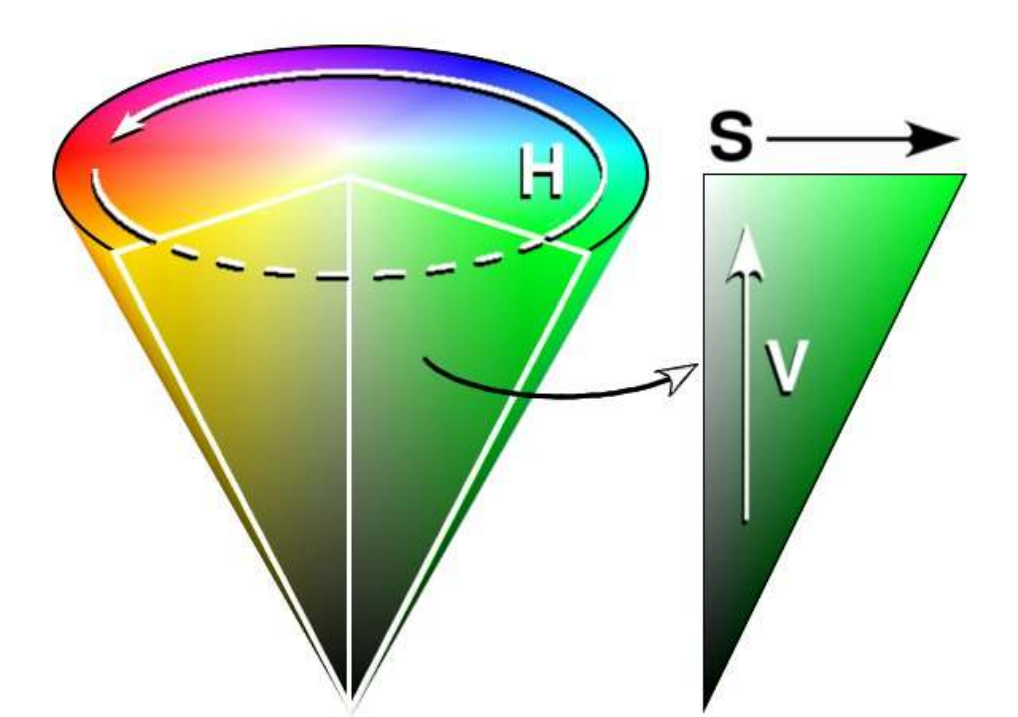
Hue, Saturation, and Brightness



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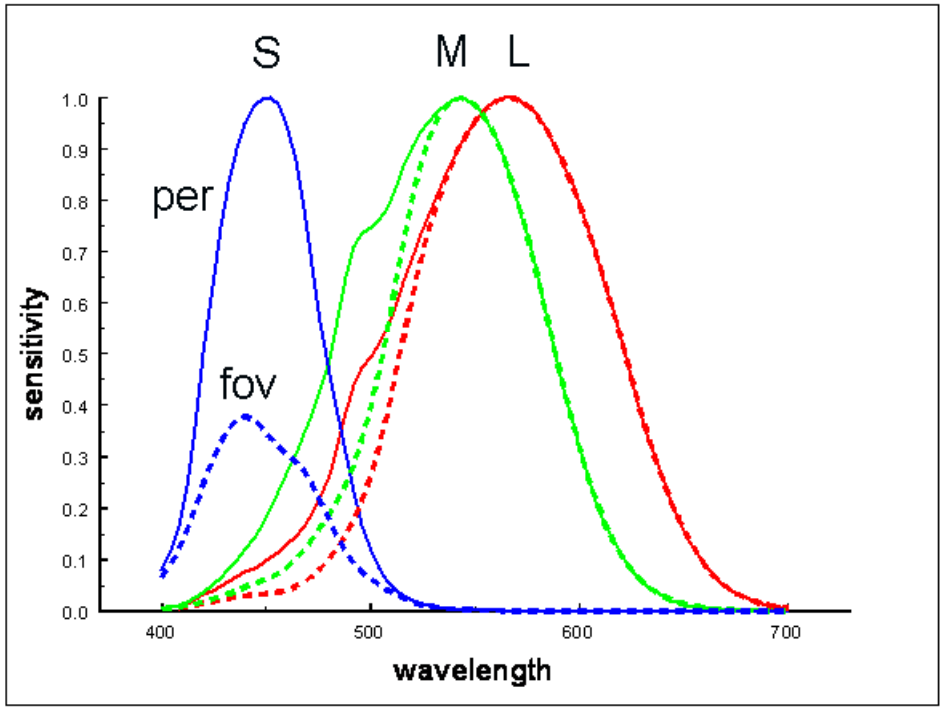
Pigments and Receptors in the Eye



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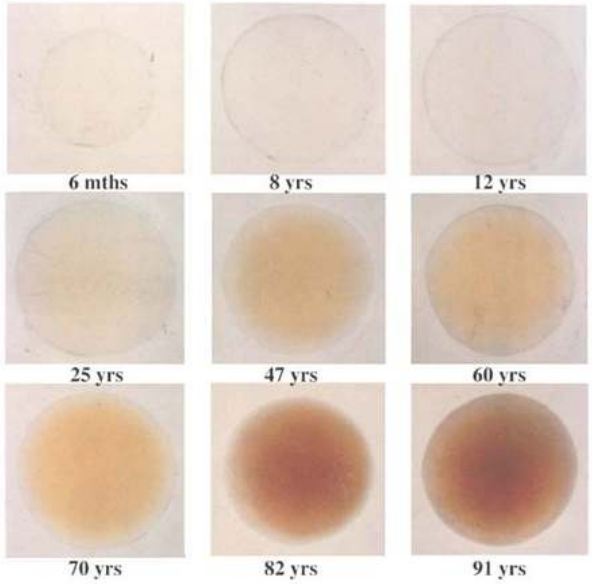
Lens Pigment Increases with Age



Werner and Schefrin JOSA A (1993)

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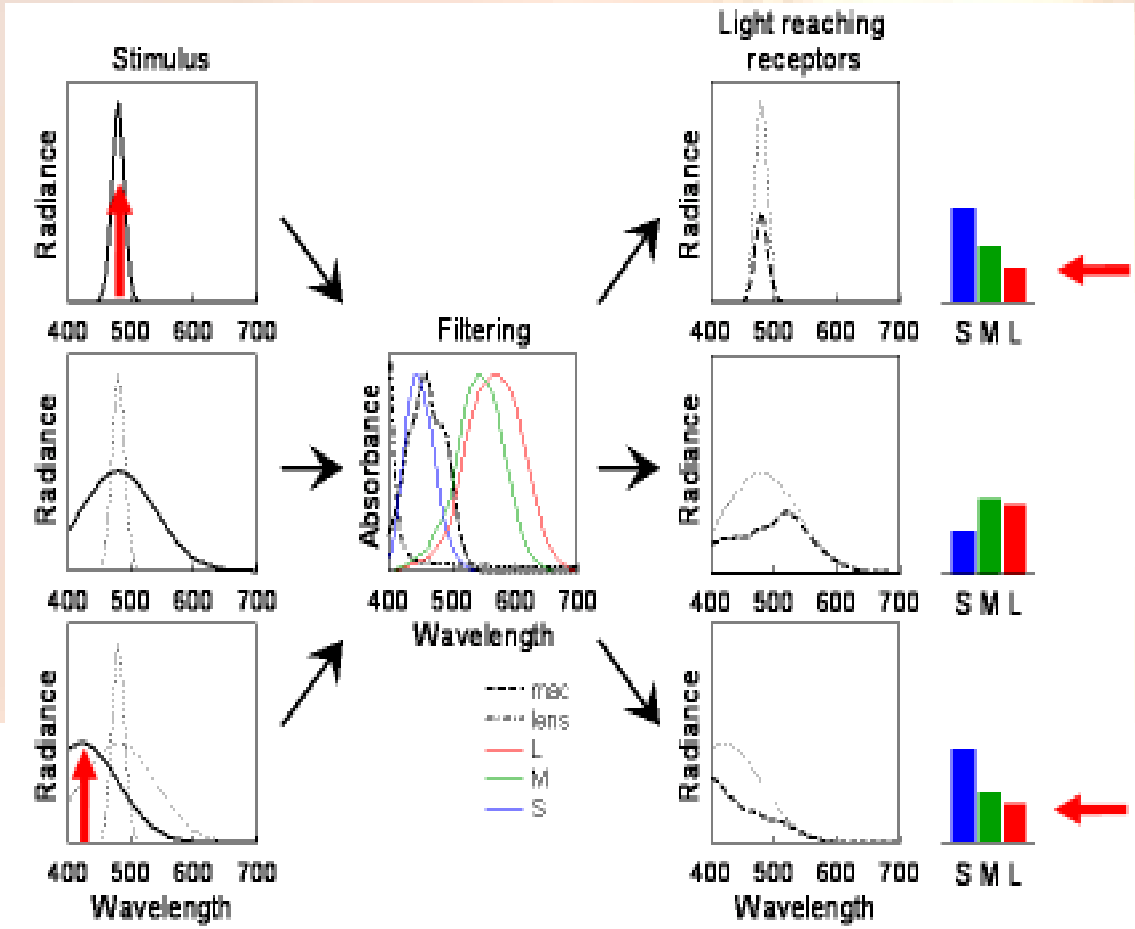
Background

- Most surfaces in the natural environment reflect light over a large part of the spectrum
- In laboratory experiments the chromaticity of the light is controlled by relatively narrow band sources (i.e. monochromator or medium-band RGB sources)
- Suggested that human color vision system retains constant hues/judgments of white by implicitly assuming stable natural spectral properties "learned" during long-term exposure
- When tested in laboratory settings, failures in hue judgments due to violations in the assumptions (i.e. Abney Effect)

Constant Cone Ratios *(Varying Stimulus)*



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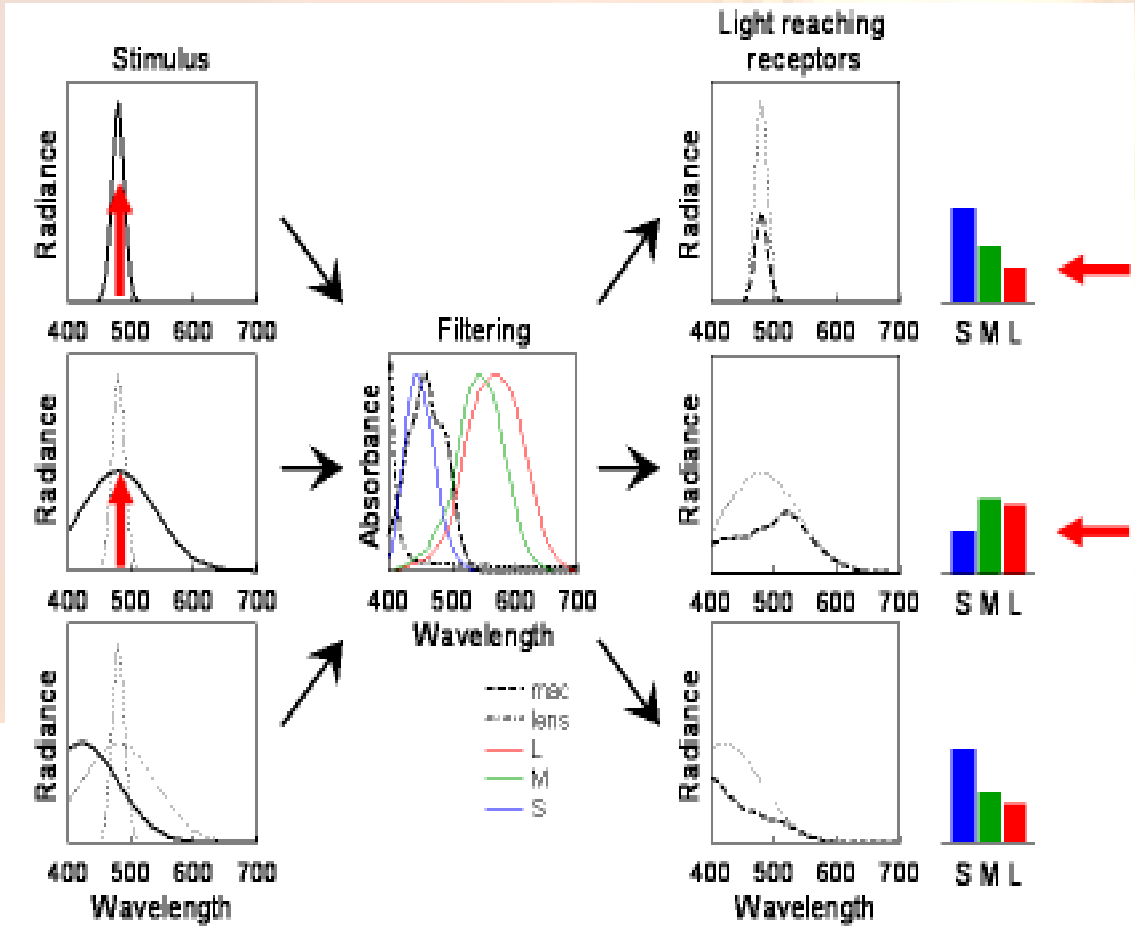
Constant Stimulus Peak *(Varying Cone Ratios)*



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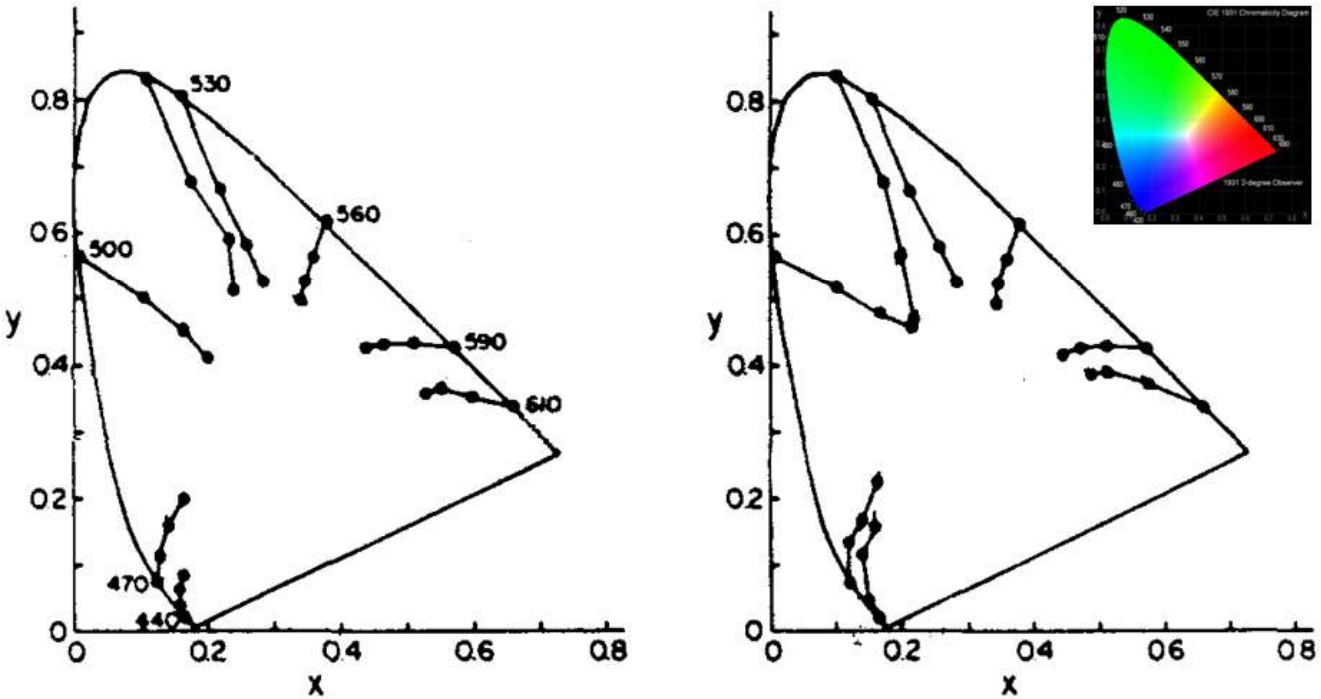
The Abney Effect: Perceived Hue Changes with Spectral Purity *(Abney, Proc Roy Soc, 1910)*



Burns, Elsner, Pokorny & Smith, Vision Research, 1984

Experimental History

- Past researchers combined LCD technologies with broadband sources, wavelength dispersing elements such as gratings
- Produced approximations to natural distributions
- Limited in contrast, temporal resolution, and precision
- Digital Light Processor (DLP) micro-mirror technology provides for rapid and precise spectral shaping of visual stimuli at intensity and precision levels previously unattainable

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Methodology

- Desirable to precisely control the spectral content of light stimuli in vision and color research
- Require replicating or producing novel complex spectral illumination
- Complex spectral distributions, common in the real world; difficult to replicate in the lab
- Present a sample application consisting of data from color vision experiments designed to probe the visual systems differential response to narrow versus broad band color stimuli

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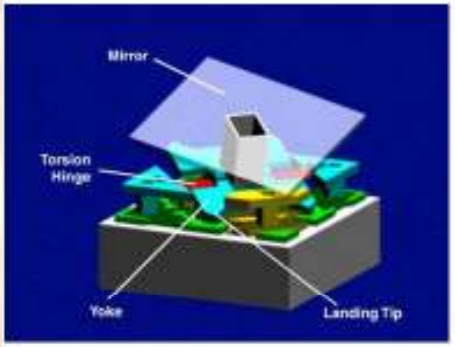
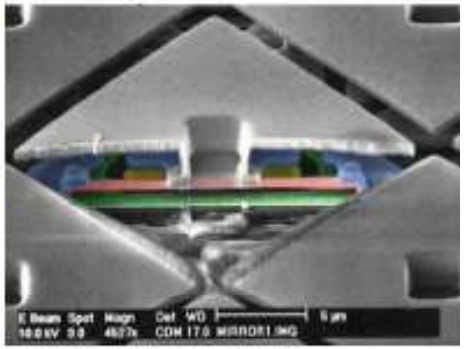
Texas Instrument DLP® Digital Light Projection Chipset

- The building block - MEMs pixel: Mirrors are ~ 10 microns square
- Formed by photolithography + etching + chemical processing
- Two stable states where a corner is "grounded," one floating state



Schematic of a DLP pixel



SEM picture

A packaged DLP "engine"
Available in SVGA (800x600)
or in XGA (1024x768)

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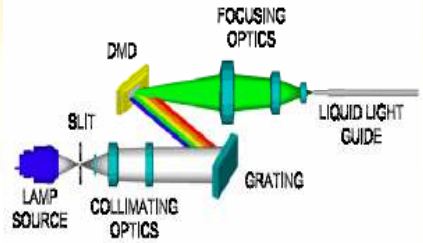
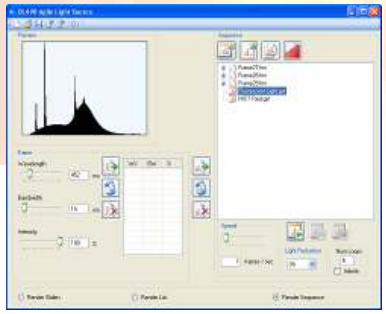
OL 490 Agile Light Source

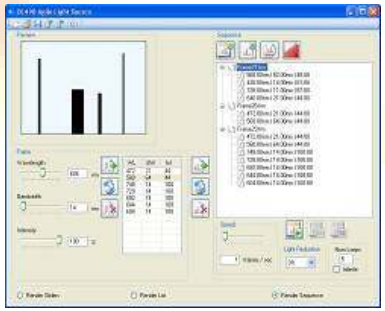
- Utilizes Texas Instruments' innovative Digital Light Projection technology to offer a programmable and variable high intensity and high resolution spectral light source



OL 490 Specifications

Output Intensity (10 nm HBW, 3 mm LLG)	200 mW
Highest Spectral Resolution	< 5 nm (150 µm slit)
Spectral Range	380 – 780 nm
Spectral Accuracy	1 nm
Intensity Control Levels	up to 49, 152 levels
Max Spectral Scan Rate	12,500 spectra/s
Max Modulation Freq	6.25 kHz
Out of Band Rejection	1000:1
Output Spot Size	3 mm via liquid light guide
External Triggering	Yes





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Methodology/Procedure

- Light guide was connected to the input port of an 8 inch integrating sphere
- The output port of the integrating sphere was 5 cm in diameter – stimulus field for hue judgments
- Participants seated ~57 cm from sphere and viewed the exit port in darkened room
- Viewing field was ~5 cm and 2°, therefore viewing distance was about ~143 cm.
- Made hue judgments between two stimuli presented in temporal sequence
- Reference stimulus composed of light with Gaussian spectral distribution, fixed peak wavelength, and bandwidth (full-width at half-height) of 75 nm

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Methodology/Procedure

- Test light spectrally distributed as a Gaussian with a bandwidth of 25 nm at half-height
- Reference light appeared for 1 second followed by a dark period of 0.5 seconds; the test stimulus for 1 second
- To make a hue match, the peak wavelength of the test was adjusted using a two-alternative, forced choice procedure with 2 interleaved staircases
- Hue judgments were made using reference lights from 450 nm to 650 nm in 20 nm intervals

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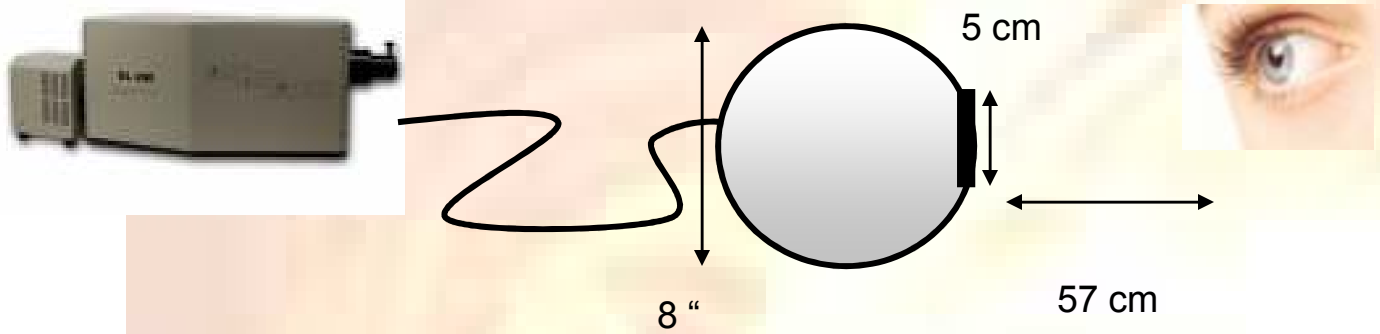
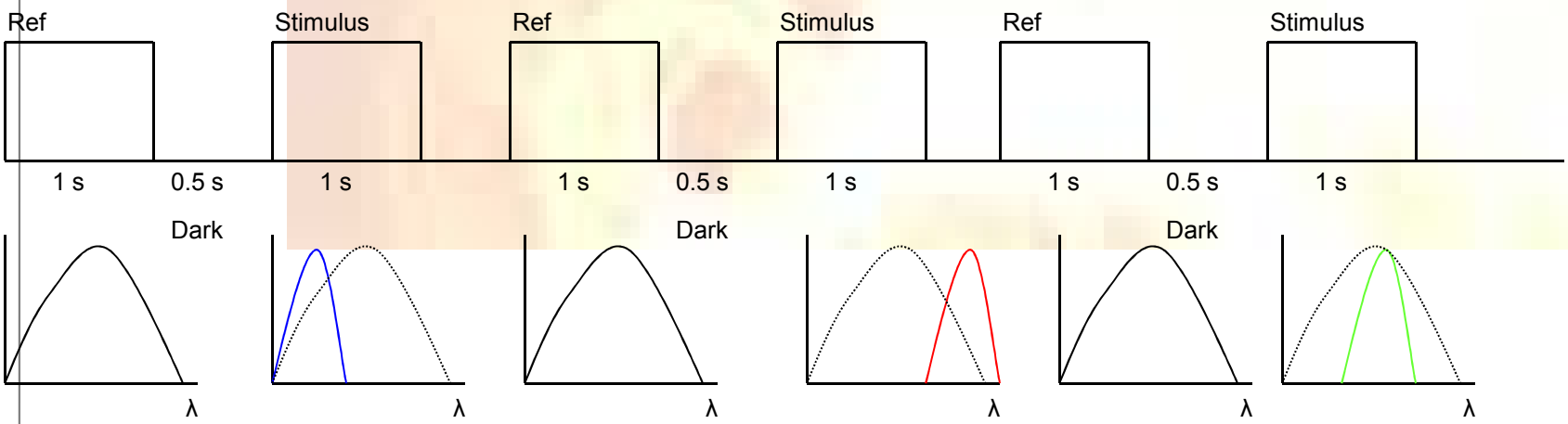
Methodology/Procedure





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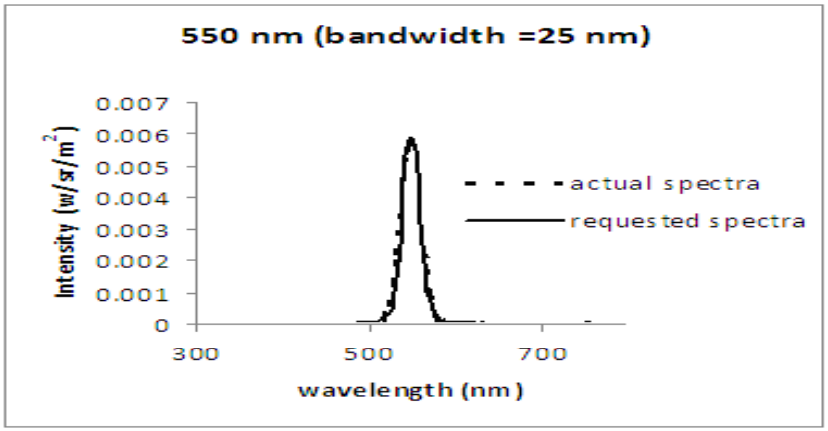
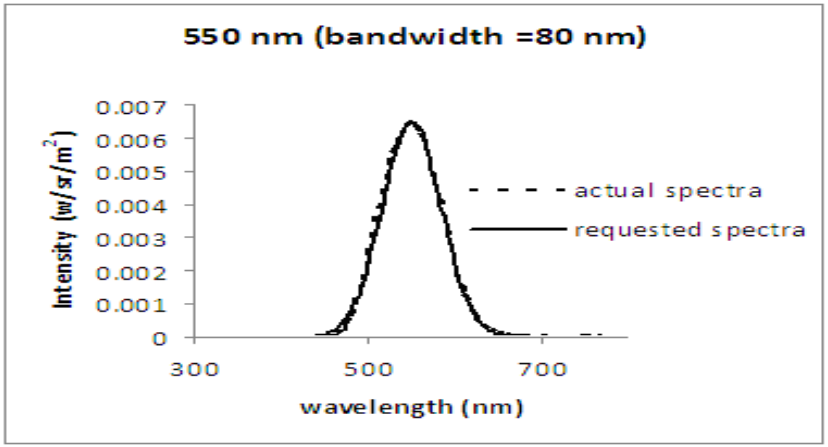
Results and Discussion

- Data for a Gaussian spectrum with a peak at 550 nm and a bandwidth of 25 nm (top)
- Data for a Gaussian spectrum with a peak at 550 nm and a bandwidth of 80 nm (bottom)
- Both requested distributions and actual distributions shown





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Results and Discussion

- 9 observers tested under all conditions/criteria thus far
- Narrow and broad stimuli matched in hue when their peak wavelengths were equal in the blue and blue-green region of the spectrum (≤ 510 nm) and near yellow (~ 570 nm)
- Stimuli subtended at 2°, fixated directly and periphery at 8°
- Matching peaks differ in the yellow-green (~ 550 nm) and in the orange and red regions of the spectrum (≥ 590 nm)
- Results thus fall in between the predictions for either complete compensation, so that hues are tied to a constant peak (flat line at 0) or the predictions for no compensation such that the hue is determined by constant ratios of the cone excitations (line shown as linear prediction)

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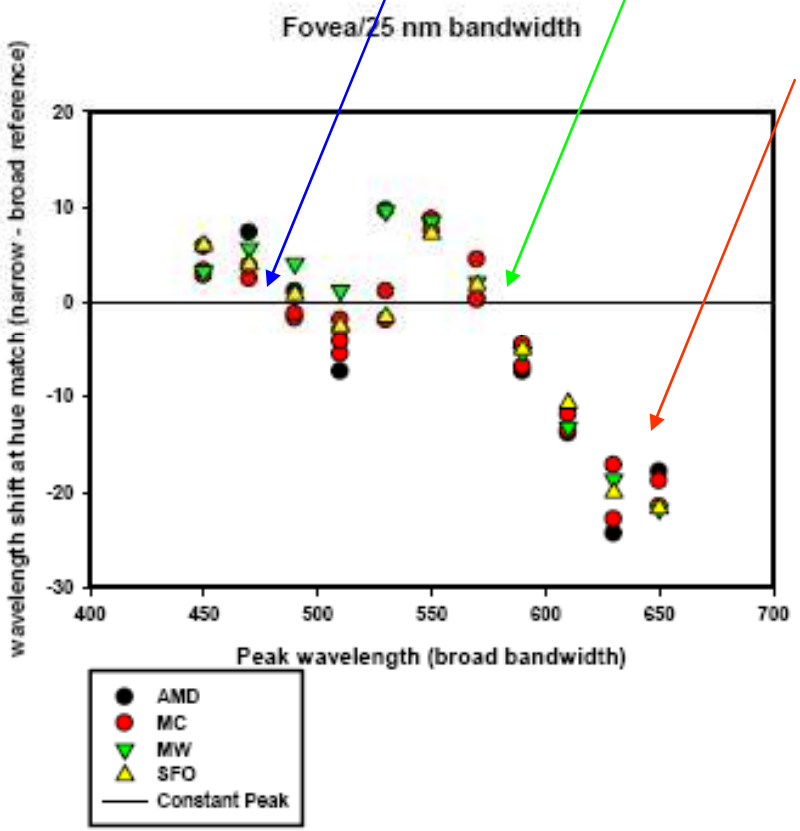
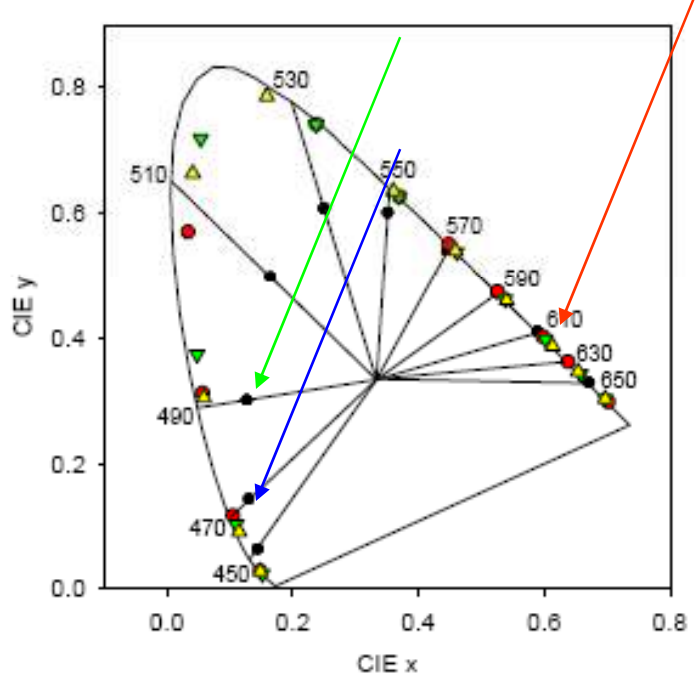
Shifts in Wavelength Vs. Chromaticity – Fovea





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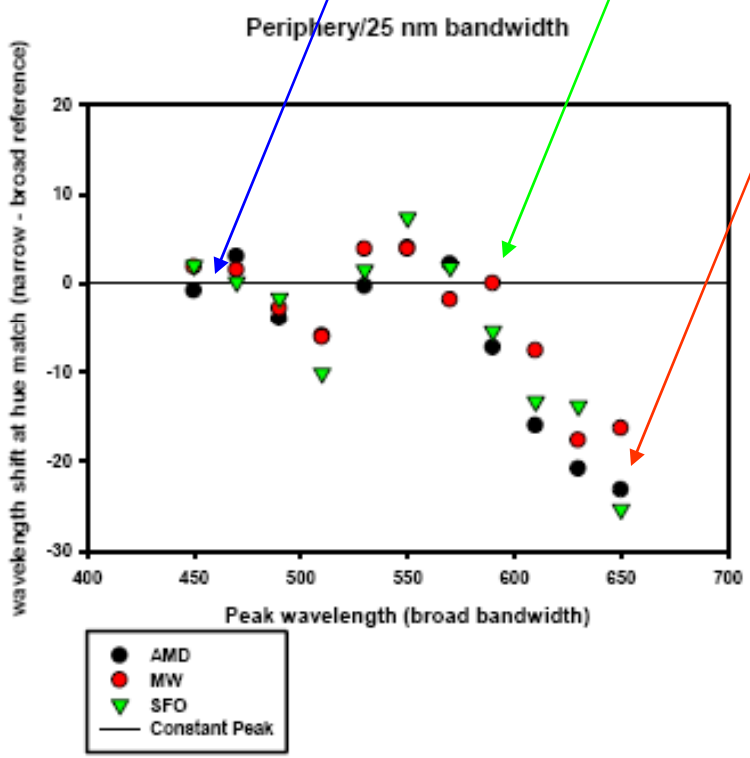
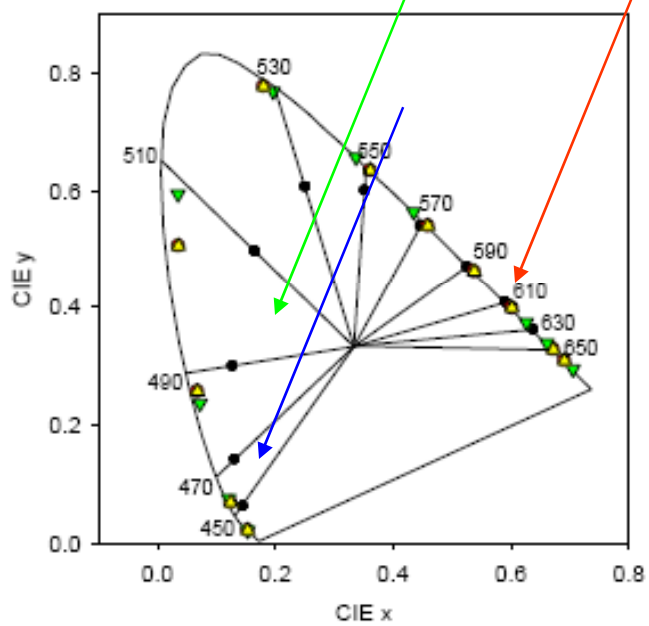
Shifts in Wavelength Vs. Chromaticity - Periphery





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Results and Discussion

- Matching chromaticities for narrow (open symbols) and broad (closed symbols) spectra do not fall on common lines over most of the spectrum
- Confirms strongly nonlinear relationship between hue and saturation (i.e. Abney Effect)
- Nonlinearity may reflect a functional adjustment in color coding so that hues tend to match when properties of the physical spectra (e.g. their peaks) match
- May be advantageous in color vision – allows hue percepts to more clearly convey information about the spectral qualities of the stimulus than the spectral sensitivity limits of the observer

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Results and Discussion

- At shorter wavelengths, almost complete compensation for perceived hue – peak wavelengths match even though the cone ratios must therefore vary
- At longer wavelengths (not previously tested) only partial compensation – equivalent hues do not reflect equal peaks in the spectra, BUT matches are still shifted away from constant cone ratios in the direction of constant peaks.
- Unclear why the effects measured in terms of peak wavelength are asymmetric at shorter and longer extremes of the visible spectrum – nonlinearities of the Abney Effect appear similar at either end

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Results and Discussion

- Possibility is that sensitivity at shorter wavelengths is limited by very different factors (the inert screening pigments in the lens and macular region of the retina) rather than sensitivity at the red end of the spectrum (i.e. L and M cones)
- OR failures at longer wavelengths due to region of the visible spectrum which is visible only to the L and M cones and not to the short-wavelength sensitive (S) cones
- Could indicate the visual system can only learn and compensate for some of the factors that constrain spectral sensitivity and that the spectral peak assumption or the assumption of Gaussian profiles is too simplistic – hue percepts correspond to some other inference that the visual system is making
- <u>Pattern of matching is similar for fovea and periphery</u>
- <u>Indication that additional processes exist that help maintain this constancy</u>

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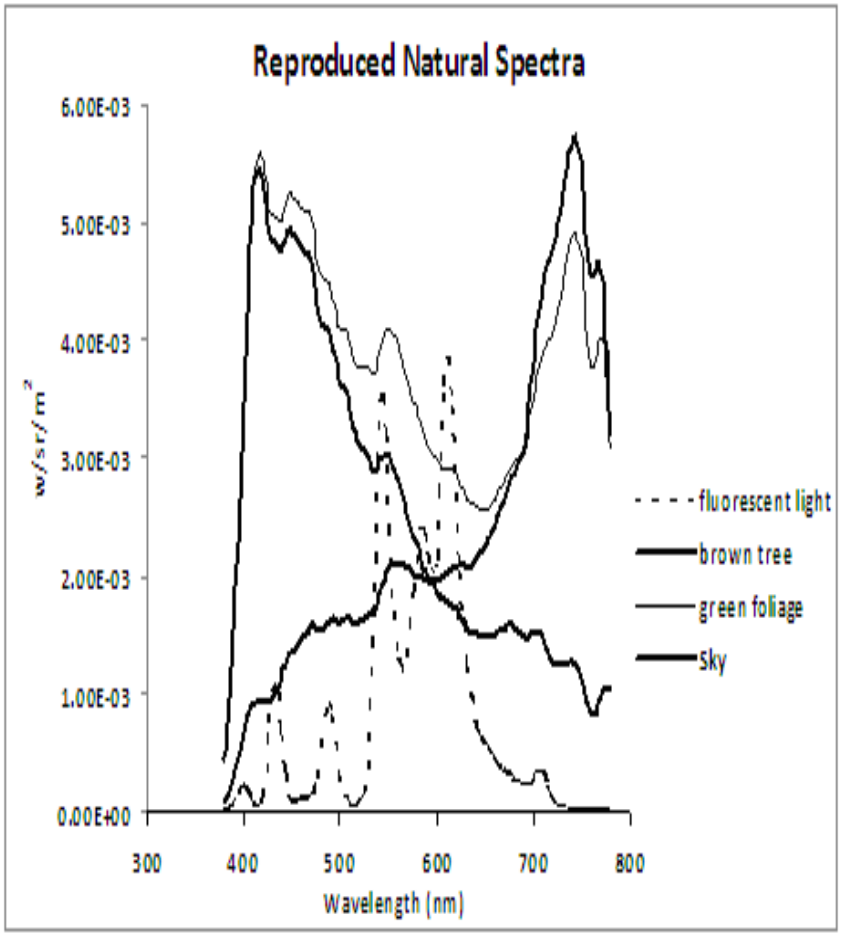
Results and Discussion

- Measuring how individuals respond to different spectra important for exploring mechanisms of color coding and understanding color rendering across illuminants and media
- How the visual system responds to the complex and broadband spectra that characterize natural illuminants and surface reflectances
- Such spectra are typically complex and thus difficult to simulate with traditional technologies



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Summary and Next Steps

- Demonstrated utility of using a DLP-based system to shape the spectrum in research on human color vision
- OL 490 produced spectral lights that closely matched those of the model (Gaussian)
- Precision of control over the spectral bandwidth of test stimuli reveals effects of spectral composition on the perception of hues
- These percepts are not easily modeled by relative cone activations and require additional explanation

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Summary and Next Steps

- Data supports the proposal that hue percepts may be more closely tied to properties of the natural environment (e.g. broad-band spectra) than to actual relative cone excitations
- Raises question of which properties and to what extent color vision is matched to the color environment
- Precise control over the temporal properties of the output provided by the OL 490 complements the spectral capacities of the device and further enhances its potential applications

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References

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- *Schefrin, B. E. and Werner, J. S. "Loci of spectral unique hues throughout the lifespan", Journal of the Optical Society of America A, Optics and Image Science, 7, 305-311 (1990).*
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- *Maloney, L. T. "Surface color perception and environmental constraints", [Colour Perception: Mind and the physical world], Oxford University Press, Oxford , 279-300 (2003).*

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Q & A

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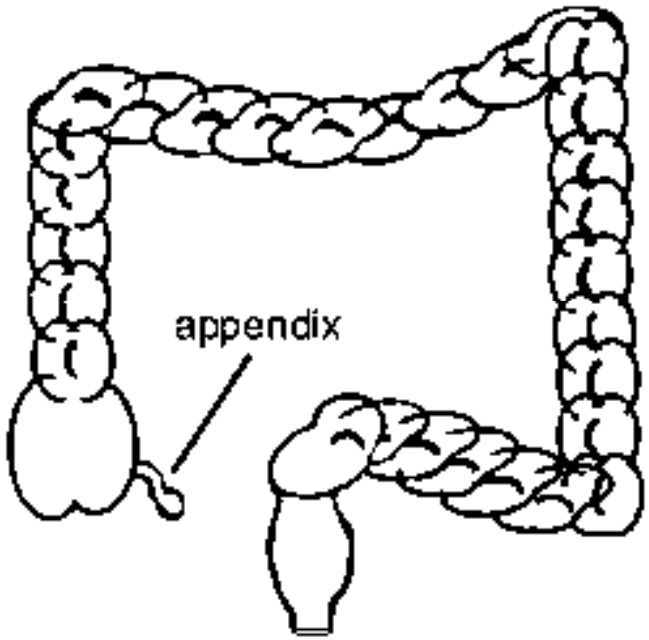
Appendix



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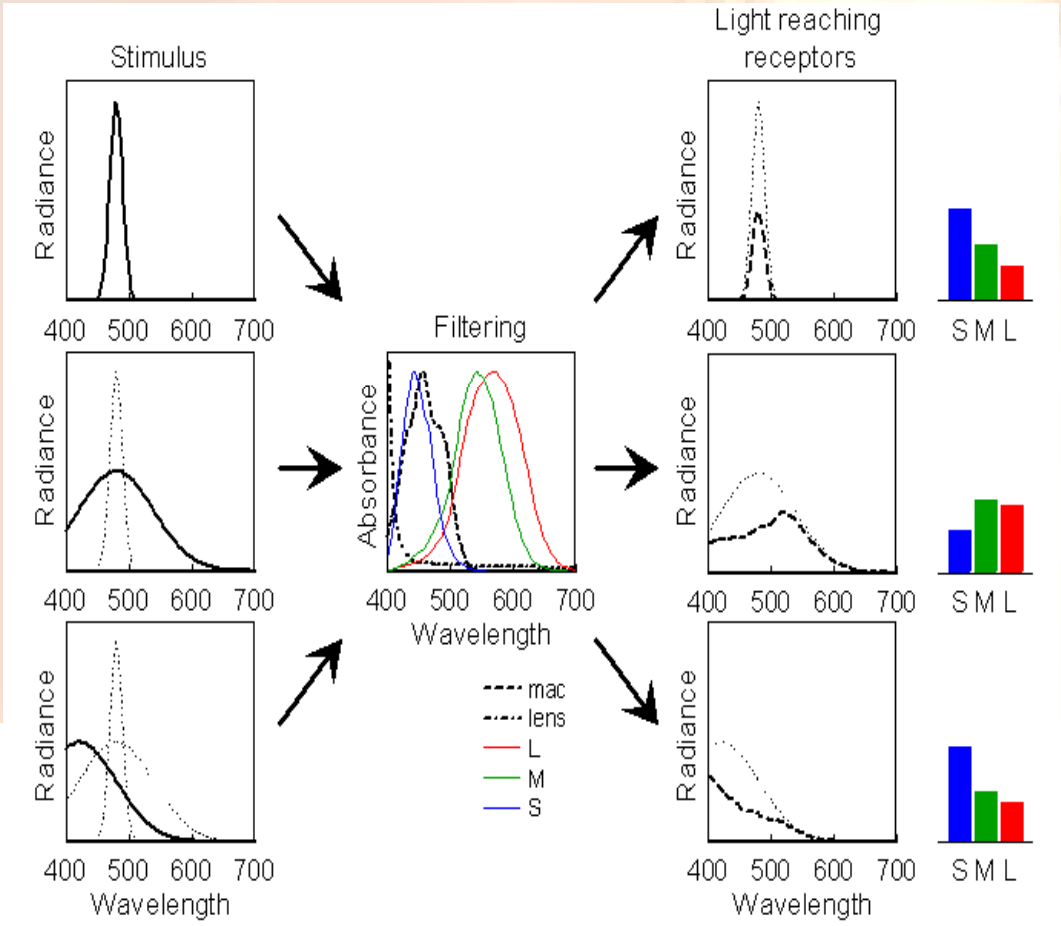
Cone Responses to Narrow and Broadband Stimuli



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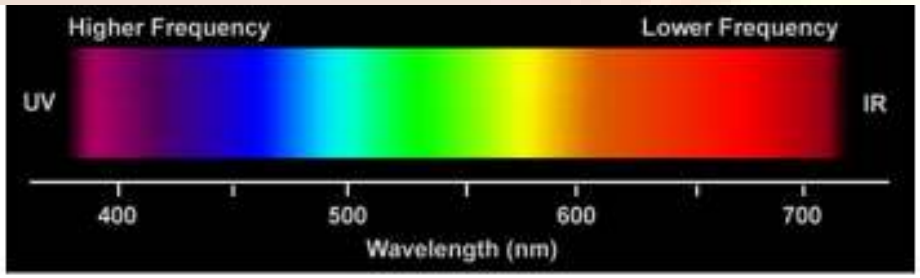
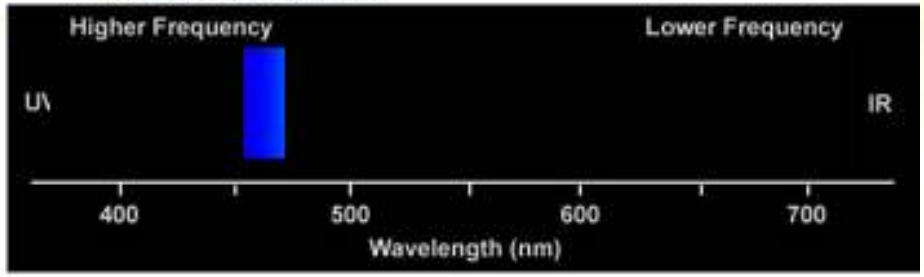


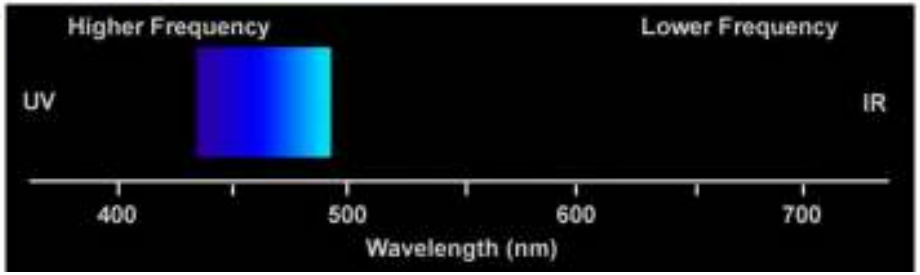
narrow bandwidth

percept



broad bandwidth

percept



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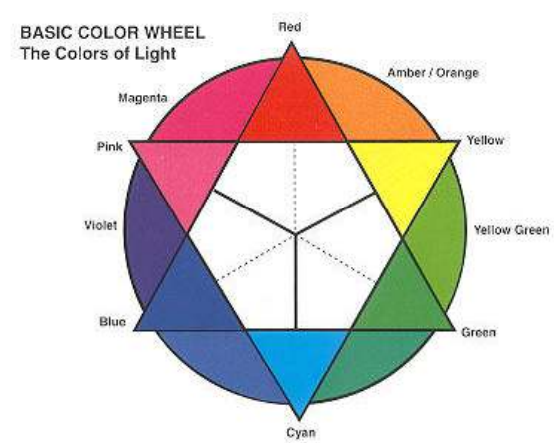
Colorimetry Introduction

- Colorimetry is the science of measuring colors
- Cones - Human eye has three type of color receptors
- Color Wheels around since Newton
- CIE has defined a standard observer with conditions for performing color matching measurements
- The Standard Observer - Defined by the amounts of the additive primary colors of light needed to match solar light at each wavelength in the visible spectrum (red, green, blue)
- Tri-stimulus – White light is the result of "Additive Color Mixing" of three primary colors (Red, Blue, Green - RGB†)



† Printers use Cyan, Magenta and Yellow inks on white paper to produce color - CMYK

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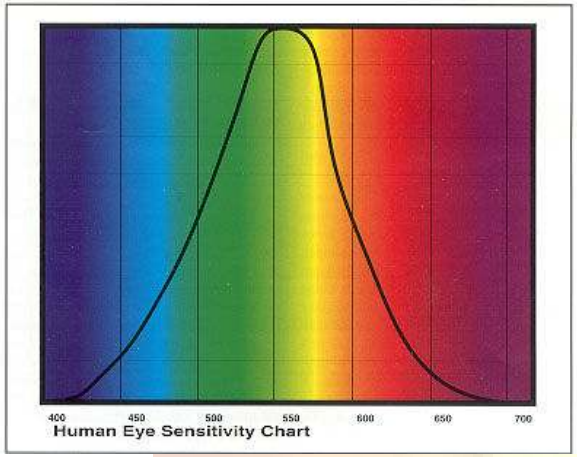
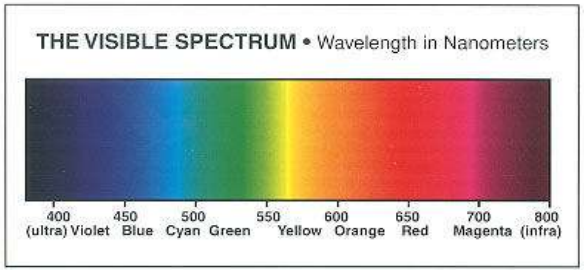
CIE† Chromaticity Chart





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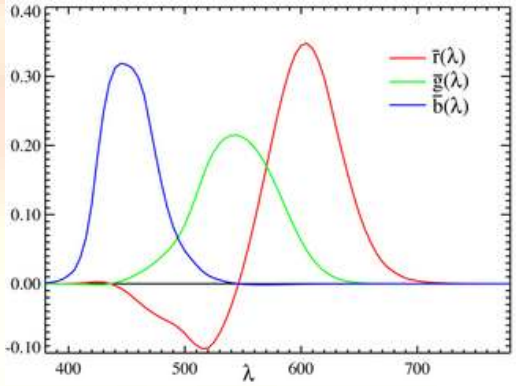
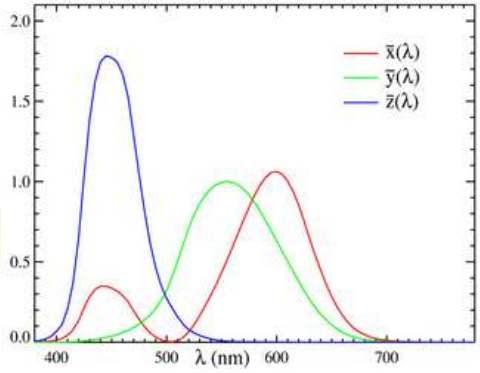


Color Matching Functions (Wright and Guild)



CIE Standard Observer

†Commission International de l'Eclairage

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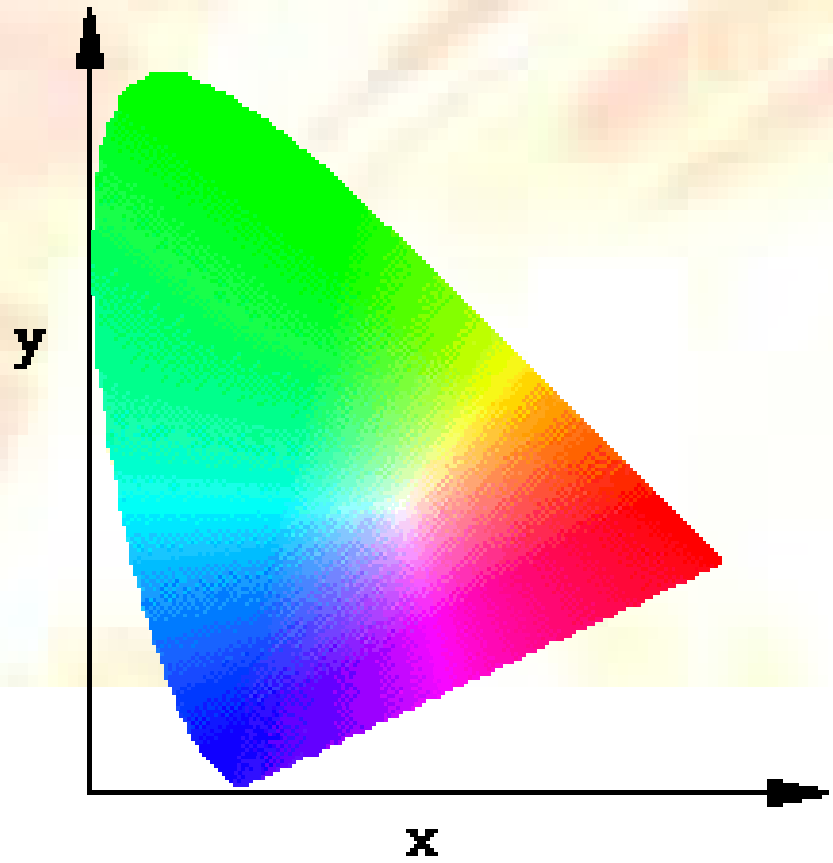
CIE 1931 Chromaticity Chart

- aka CIE “Tongue”, “Shark Fin”
- Color space model only, ignores saturation levels
- The standard observer can be plotted as spectral irradiance curves, designated x, y, z in the CIE Diagram
- Boundary represents maximum saturation for the spectral colors, and the diagram forms the boundary of all perceivable hues (wavelengths)
- Purple boundary is straight line connecting blue to red
- Outlining border, or "Arch" represents any color in it's most pure form
- If a line is drawn between two "Complementary Colors" it will always travel through the "White Point Axis“
- Gamut is a subset of the color space



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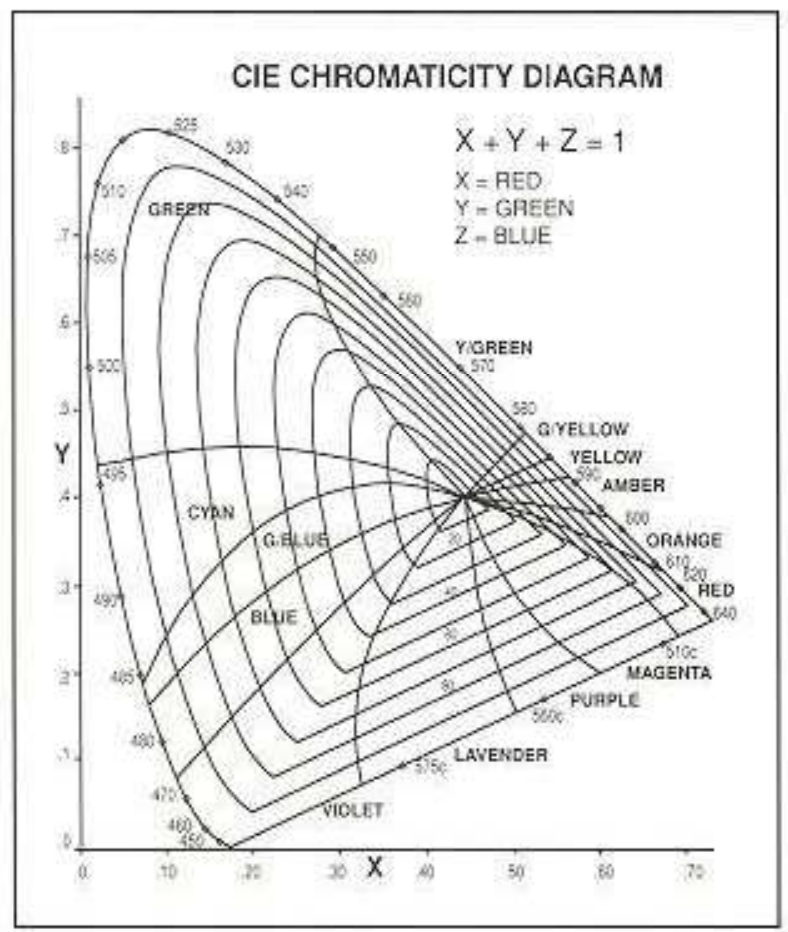
CIE 1931 Chromaticity Chart

- Dominant wavelengths follow the outside curve of the chart where they are numbered
- An imaginary straight line ran between two dominant wavelengths result in mixing
- This line is referred to as a minus, or a complimentary number
- Colors can be designated by their XY coordinate
- The Y axis represents green, the X axis represents red, and the three numbers must add up to one
- The Z axis is blue



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CIE 1931 Chromaticity Chart

- Formulae:
  - *x = X/(X+Y+Z) or x = Red/(Red + Green + Blue)*
  - *y = Y/(X+Y+Z) or y = Green/(Red + Green + Blue)*
  - *Since (x + y + z) =1, the third axis, z = 1 – (x + y)*
- Luminance calculated by adding the values of the 3 primary colors and dividing by 3

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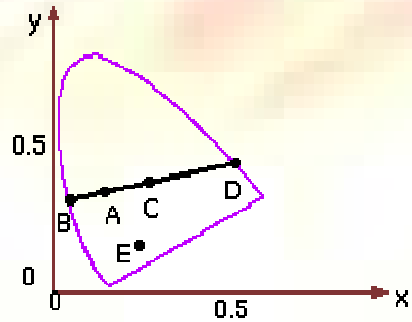
CIE 1960 and 1976 Chromaticity Chart Revisions

- Revisions sought to address shortcomings in 1931 model in 1960, 1967. All three contain the same information, just scaled differently.
  - CIELUV–Attempts to make the chromaticity plane more visually uniform
    - A perceptually uniform color space is a color space in which the distance between two colors is always proportional to the perceived distance (i.e. CIE XYZ color space and the CIE chromaticity diagram are not perceptually uniform)
    - Good for emitted color (i.e. CRT monitors, displays)
  - CIELAB – Attempts to make the luminance scale more perceptually uniform
    - Distance between points on the diagram is approximately proportional to the perceived color difference
    - Good for subtractive primary color mixing, e.g., printing inks and computer printer/plotter output



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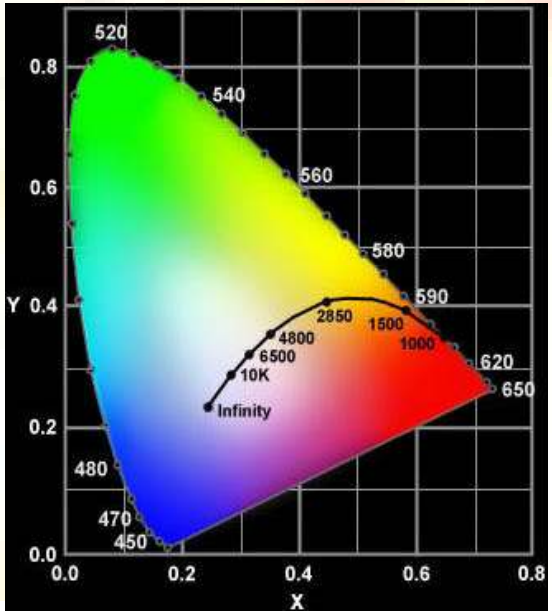
Color Temperature and CCT

- All objects emit light when sufficiently hot - the apparent color of an object changes as the temperature increases (i.e. brightness and color of the light emitted is a function of temperature)
- Glowing or "incandescent" sources that emit radiation with 100% efficiency are called "Black Body Radiators" or Planckian Sources
- Describes broadband source spectral profile with respect to theoretical black body temperature with equivalent emission – BUT – Degrees Kelvin can only be attributed to a black body radiator where spectral color balance is predictable as the black body radiator's temperature rises (ratio of blue to red shifts in a predictable fashion
  - Although the black body radiator is a theoretical device, sunlight, carbon arcs and incandescent (Tungsten filament) lamps are very good black body simulators
  - Discharge lamps such as fluorescent, Xenon and Hg vapors aren't black body radiators

Color Temperature and CCT

- Correlated Color Temperature (CCT) of a source is the temperature of the blackbody radiator which has the chromaticity most similar to that of the light source
- Black body locus is the curved line – indicates what happens to a black body radiator as its temperature is raised
- Points are designated along the black body locus for incandescent, daylight and other frequently used light sources



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Color Rendering Index (CRI)

- CRI is a subjective method of determining how well a light source renders color to the average observer.
- Based on the average the response of a group of human subjects as to how accurately the colors appear when compared to the same colors under either Tungsten or daylight sources.
- Ratings are 0 to 100. By definition, daylight and Tungsten are 100 and everything else is measured from that point down.
  - 100 doesn't always mean good rendering – measured with respect to reference source
  - Supposed to work at different CCTs but does not.
  - For poor sources can be negative!
  - Based on spectral power distribution so can be 'manipulated' to produce higher CRI values (i.e. fluorescent lamp manufacturers manipulate emission points)
  - In general, > 80 good for indoor and >90 good for visual inspection, differences < 5, negligible

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Glossary

- The Standard Illuminant - this refers to a light source, such as an incandescent lamp, the sun, overcast daylight or colored lighting
- Chromaticity Coordinates - These are x and y coordinates corresponding to each hue in the CIE system. The coordinates are comprised of 3 components that correspond to the Color Dimensions (hue, value, chroma):
  - Dominant Wavelength - The dominant wavelength corresponds to hue. The x,y location of a coordinate defines a specific hue in the CIE system.
  - Purity - Purity is the physical CIE counterpart to Chroma, defined on a scale of 0 (achromatic, or the purity of the illumination source) to 100 (full purity of the spectral hue of the dominant wavelength).
  - Luminosity - Luminosity is the lightness or darkness of a hue and corresponds to Value (Y Value). It is measured as the luminous reflectance of the color.
- Metameric Colors - Colors that look the same under one light source but different under another. They look different because the spectral energy of the two colors are different.

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X, Y, Z Tristimulus Calculations for Sources

$$X = \sum_{\lambda=380}^{780} E(\lambda)\bar{x}(\lambda)\Delta(\lambda)$$

$$Y = \sum_{\lambda=380}^{780} E(\lambda)\bar{y}(\lambda)\Delta(\lambda)$$

$$Z = \sum_{\lambda=380}^{780} E(\lambda)\bar{z}(\lambda)\Delta(\lambda)$$

Where:

$E(\lambda)$	=	Spectral values of the data file
$\bar{x}(\lambda)$ $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$	=	CIE 1931 spectral tristimulus values
$\Delta(\lambda)$	=	Wavelength interval of the data file [nm]

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X, Y, Z Tristimulus Calculations for Objects

$$X = k \sum_{\lambda=380}^{780} \overline{E}(\lambda) R(\lambda) \overline{x}(\lambda) \Delta(\lambda)$$

$$Y = k \sum_{\lambda=380}^{780} \overline{E}(\lambda) R(\lambda) \overline{y}(\lambda) \Delta(\lambda)$$

$$Z = k \sum_{\lambda=380}^{780} \overline{E}(\lambda) R(\lambda) \overline{z}(\lambda) \Delta(\lambda)$$

$$k = \frac{100}{\sum \overline{E}(\lambda) \overline{y} \Delta\lambda}$$

Where:

$\overline{E}(\lambda)$	=	Relative spectral power of an illuminant
$R(\lambda)$	=	Spectral Reflectance or transmittance data
$\overline{x}(\lambda)$ $\overline{y}(\lambda)$ and $\overline{z}(\lambda)$	=	CIE 1931 spectral tristimulus values
$\Delta(\lambda)$	=	Wavelength interval of the data file [nm]

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Chromaticity Calculations

$$x = \frac{X}{X + Y + Z}$$

$$y = \frac{Y}{X + Y + Z}$$

$$z = \frac{Z}{X + Y + Z}$$

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U,V Calculations

The UCS 1960 u, v coordinates are calculated:

$$u = \frac{4x}{12y - 2x + 3} = u'$$

$$v = \frac{6y}{12y - 2x + 3} = \frac{2}{3}v'$$

The UCS 1976 u' and v' coordinates are calculated:

$$u' = \frac{4x}{12y - 2x + 3} = u$$

$$v' = \frac{9y}{12y - 2x + 3} = \frac{3}{2}v$$

$$m = \frac{3}{2}m'$$

Where: m and m' are the isotemperature line slopes for 1960 and 1976, respectively.

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LAB Calculations

$$L^* = 116\left(\frac{Y}{Y_n}\right)^{1/3} - 16$$

$$a^* = 500\left[\left(\frac{X}{X_n}\right)^{1/3} - \left(\frac{Y}{Y_n}\right)^{1/3}\right]$$

$$b^* = 200\left[\left(\frac{Y}{Y_n}\right)^{1/3} - \left(\frac{Z}{Z_n}\right)^{1/3}\right]$$

Here X_n, Y_n and Z_n are tristimulus values of the reference white.

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