Color

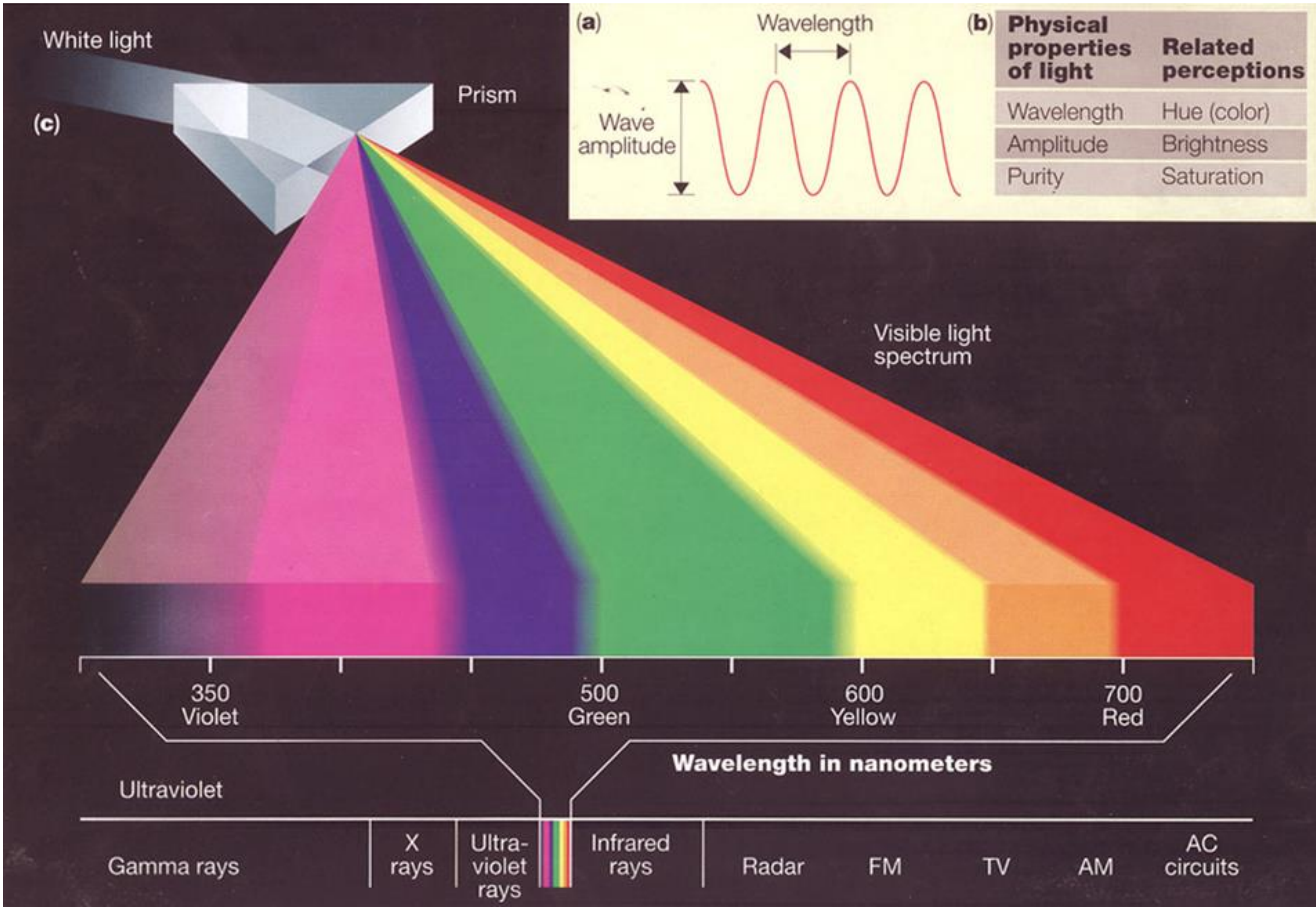
What is 'Color'

Color is a fundamental attribute of human visual perception.

By fundamental we mean that it is so unique that its meaning cannot be fully appreciated without direct experience.

How would you describe color to a person who was blind since birth?

Wavelength → Color Perception



3 Properties of Color Perception

- **Hue**
  Qualitative, easily identified category of visual experience (Colloquially known as 'color'; e.g. 'red', 'green', 'blue'). Differs from black-gray-white.
  Quickly now: Name 10 'colors'…

- **Brightness**
  Intensity of the visual experience (e.g., 'dim', 'bright', 'light', 'dark')

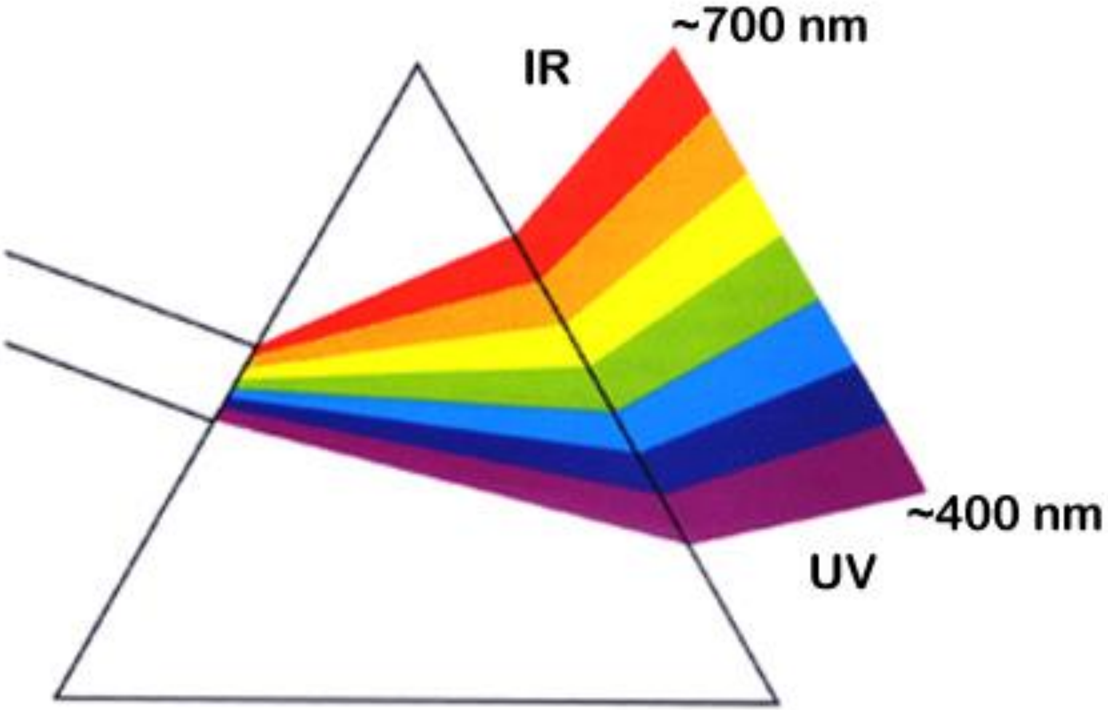
- **Saturation**
  Purity of the hue experience (i.e., relative absence of 'white' or 'gray')
  (reciprocal of 'added white' required for a color-match-to-sample)

Color Stimulus Triad

- <u>Illuminant</u> Spectrum
- <u>Surface</u> Reflectance Spectrum
- Spectral Sensitivity of the <u>Visual System</u>

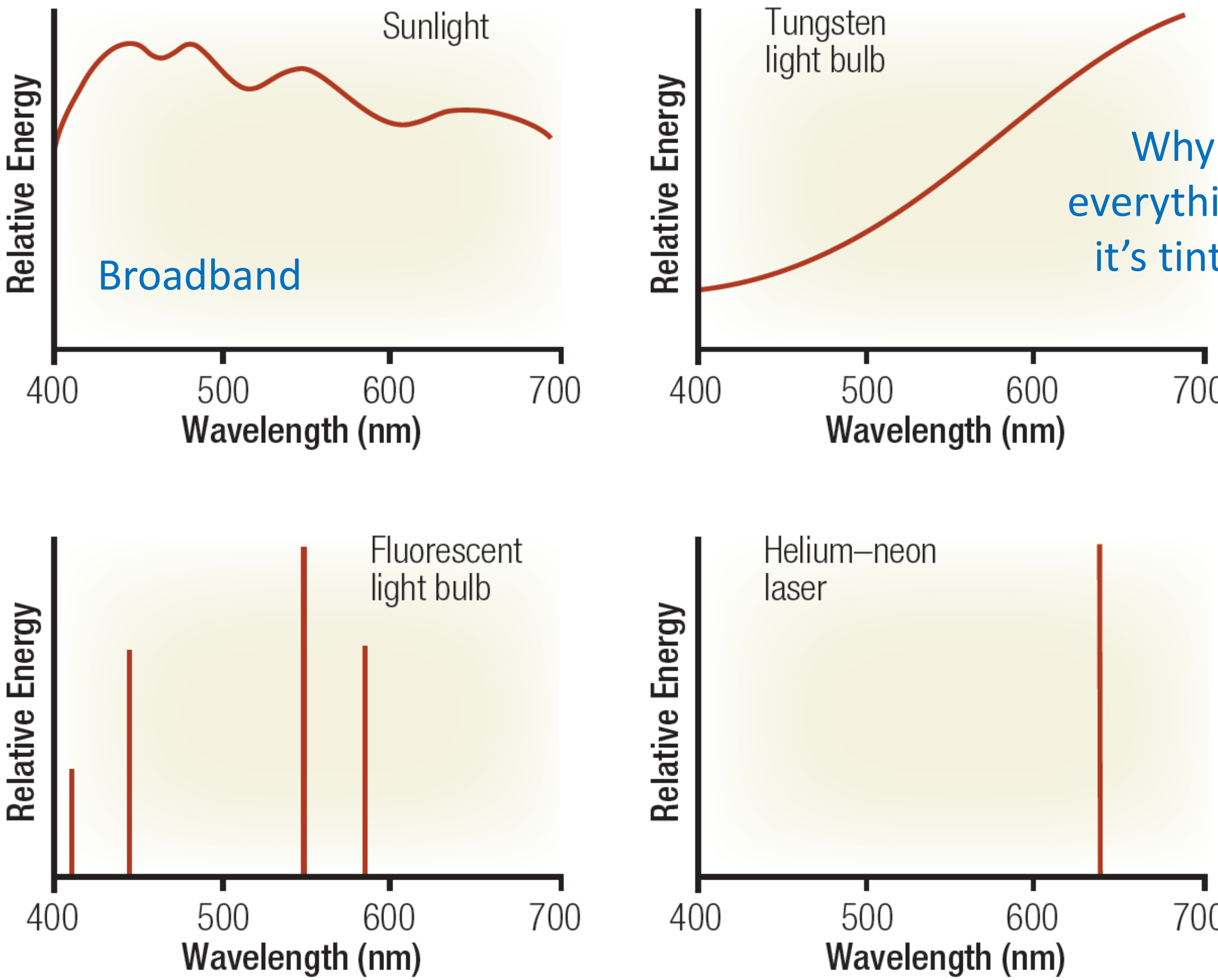
Illuminant
Emission Spectra

“White” Light is a mixture of many different WAVELENGTHS



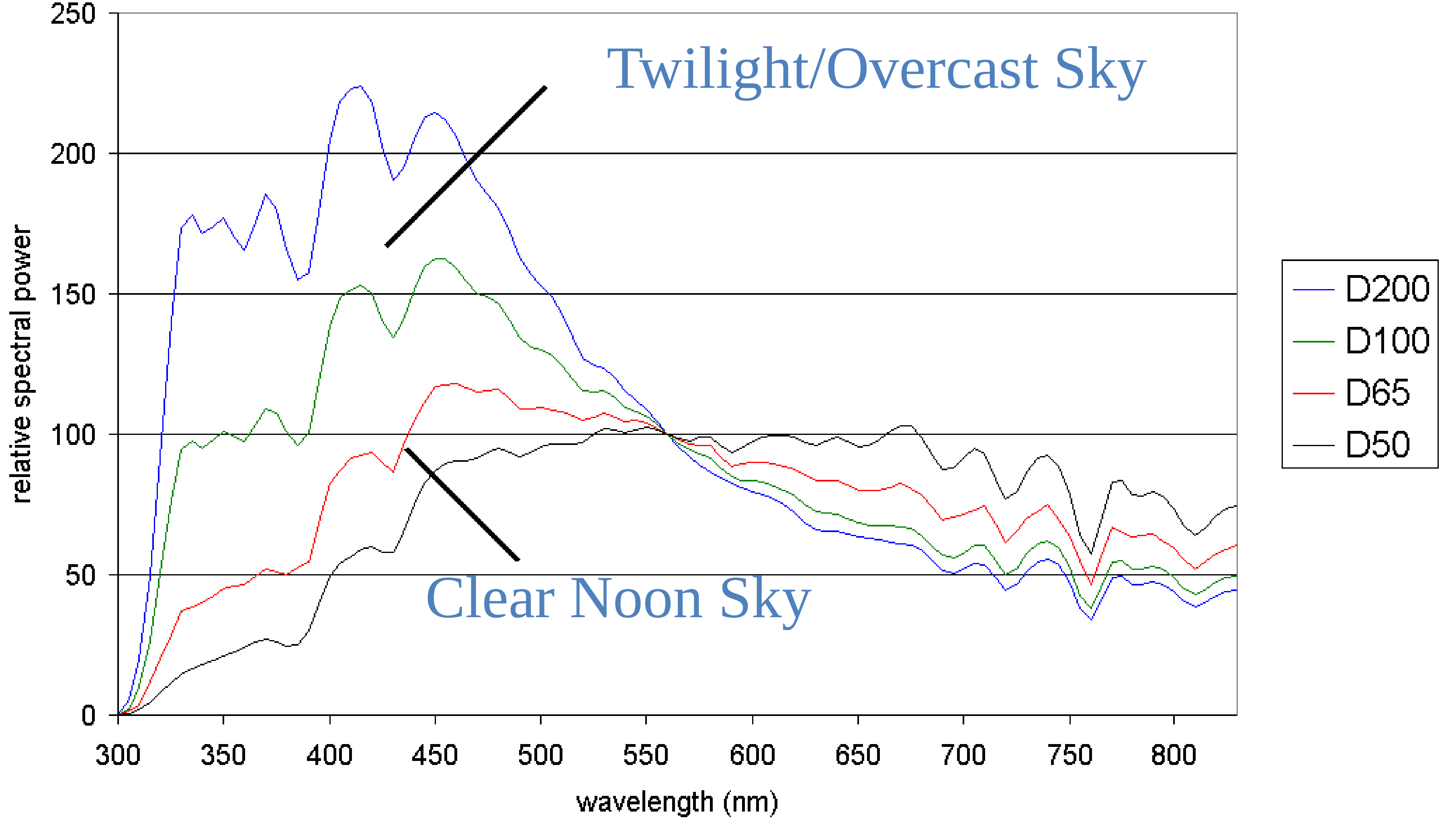
We perceive different wavelengths as different colors

Spectra of Some Common Illuminants



Why doesn't everything look like it's tinted "red"?

Sunlight



Twilight/Overcast Sky
Clear Noon Sky
relative spectral power
wavelength (nm)
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
D200
D100
D65
D50

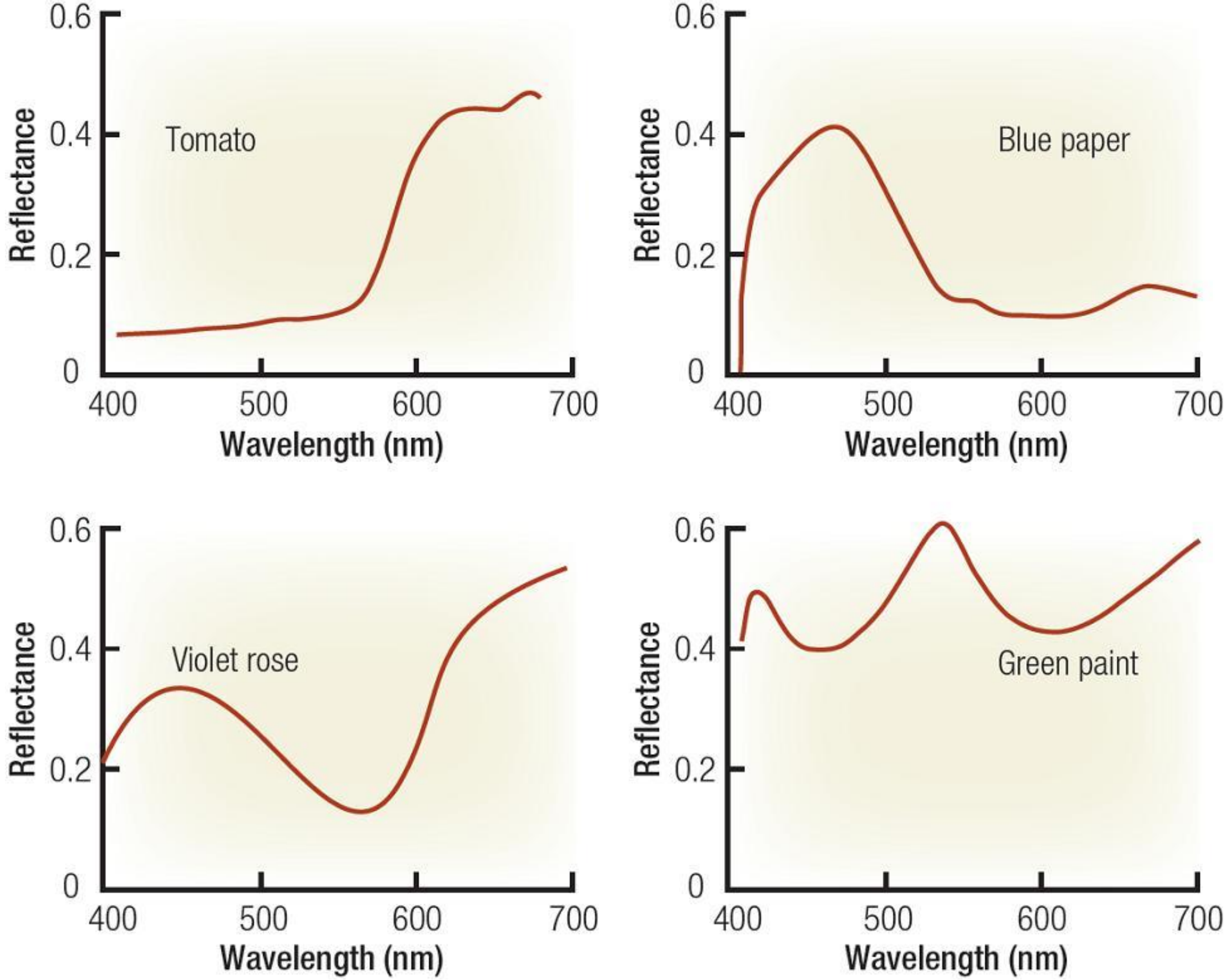
Surface
Reflectance Spectra

Objects REFLECT some wavelengths but ABSORB others….

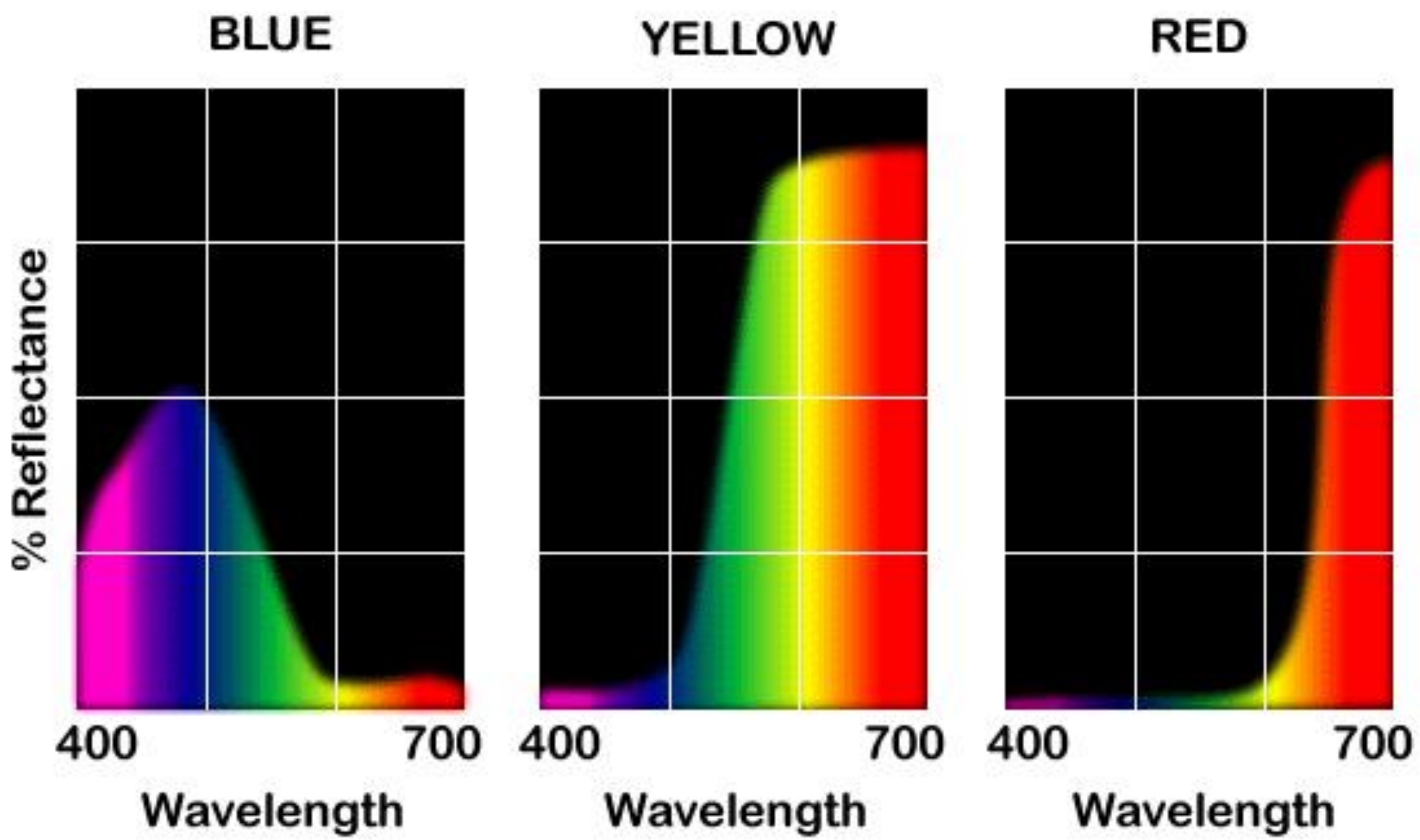
Broadband
“White” Light

“Red” Light

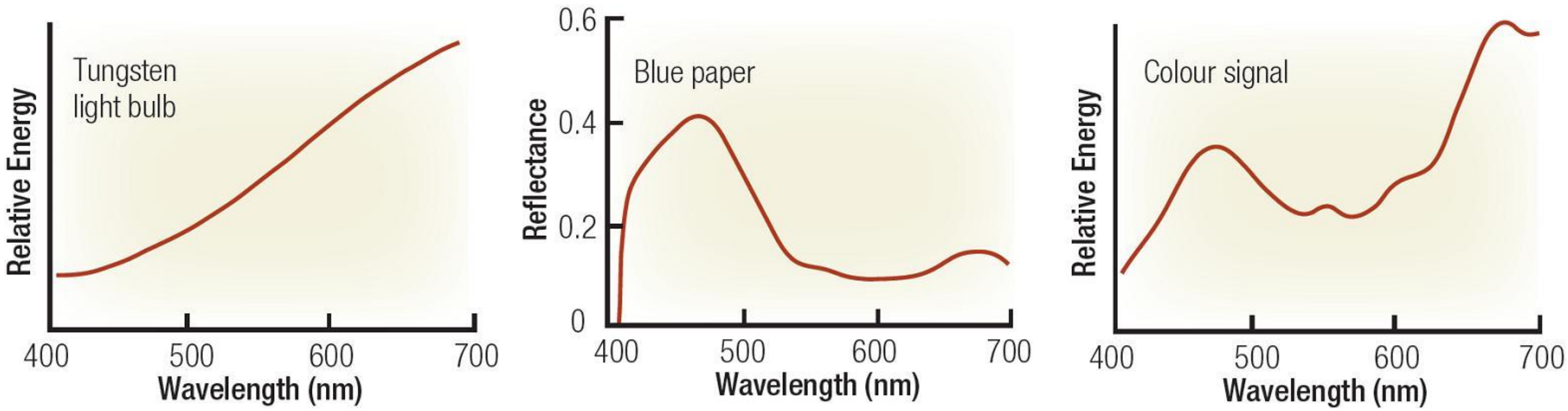
Surface Reflectance Spectra



The Spectral Reflectance Profile is the basic stimulus for Color Vision



Visual Stimulus Spectrum = Illuminant x Surface Reflectance

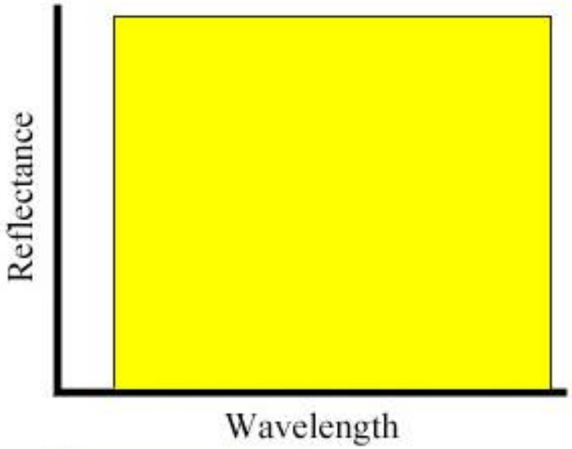


Light spectrum that Reaches the eye

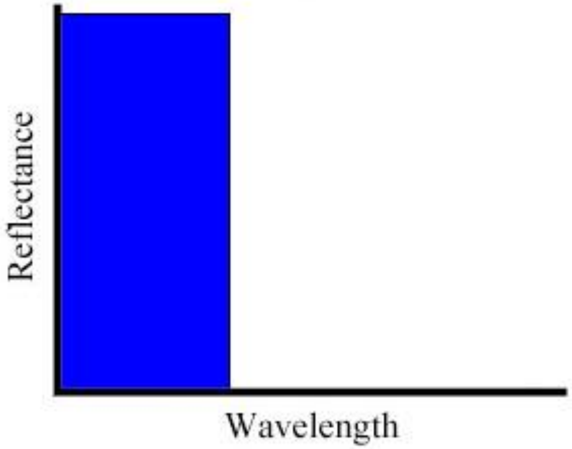
Additive vs. Subtractive Color Mixing

- Color Mixing Demo

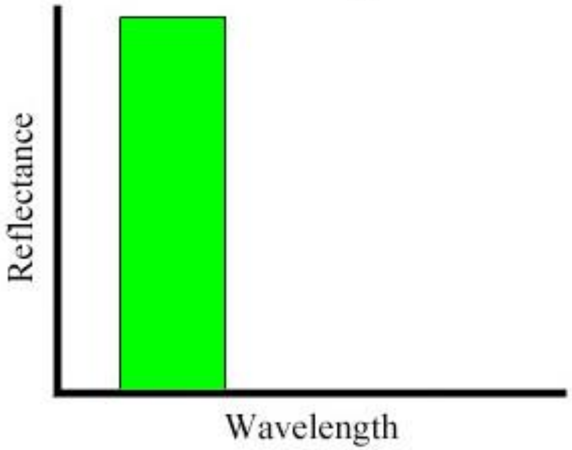
Java Applet
Requires IE11 and Java Plugin



Ideal “Yellow” Pigment



Ideal “Blue” Pigment

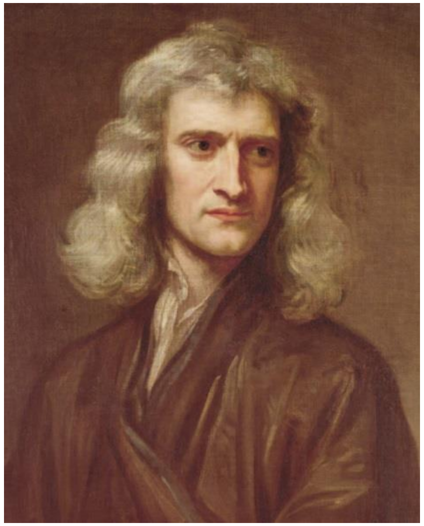


Residual “Green” Pigment resulting from mixing Yellow+Blue

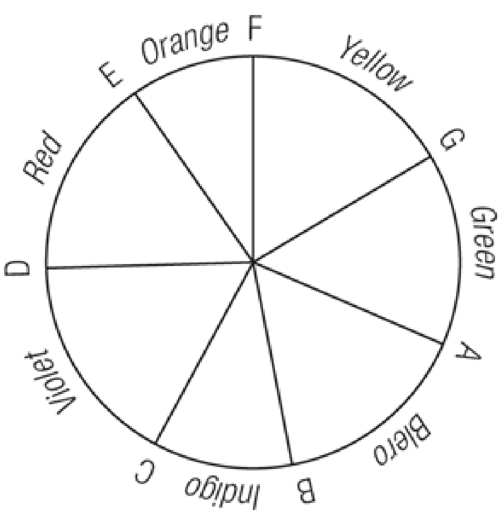
Mixing Color Pigments

Spectral Response of the Visual System

Newton's Color Experiments



Sir Isaac Newton
(1643-1727)

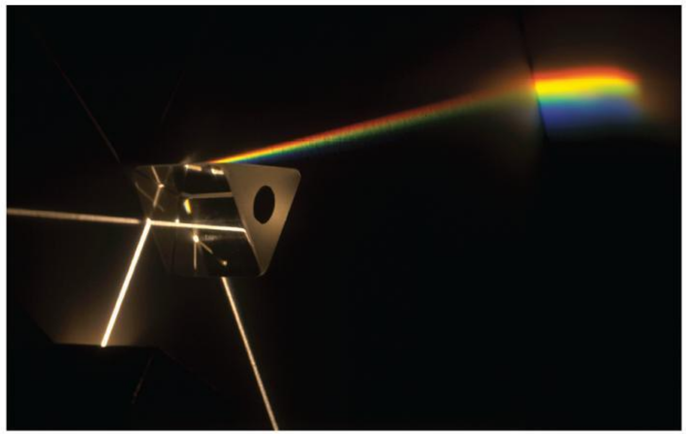


Color Circle

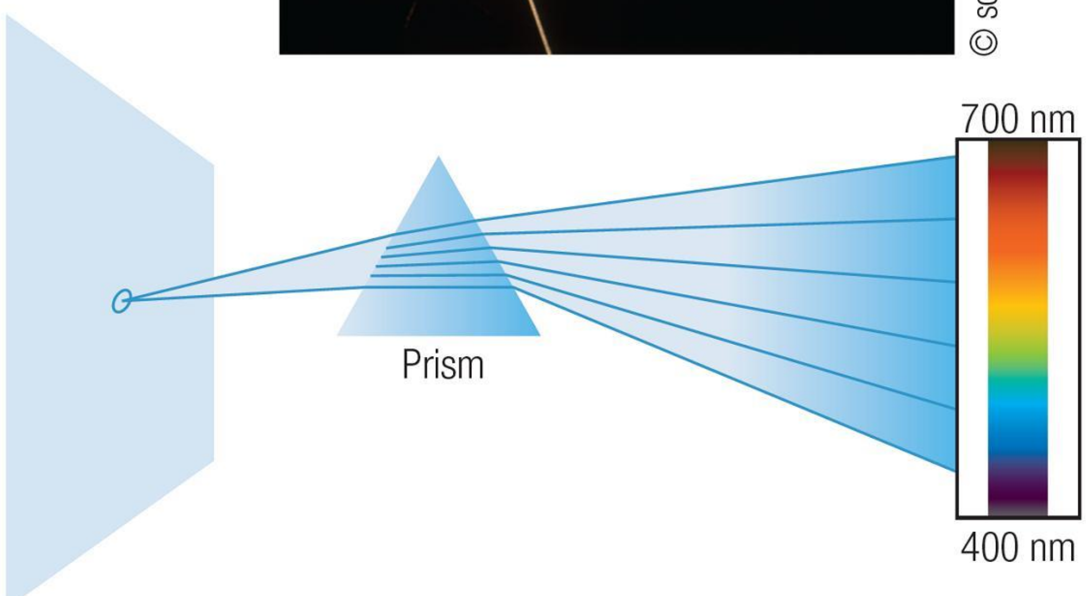
- Found that light was not "pure" but could be analyzed into separate component that appeared different in color [ROY G BIV]
- Combinations of "spectral colors" gave rise to perceived colors not observed in the spectrum
- "Non-spectral colors" were an emergent property of the human nervous system
- "Color wheel" is one of the first <u>psychological</u> theories in the classic scientific literature

Newtonian Light Spectrum

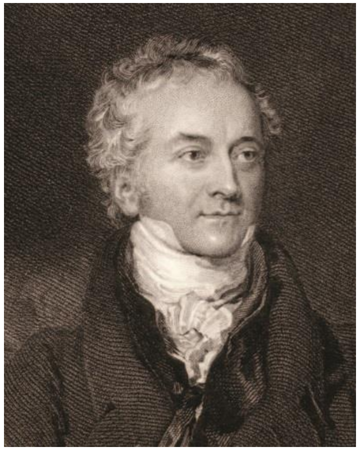
(ROY G BIV)



© sciencephotos/Alamy



Trichromatic Theory of Color



Thomas Young
(1773-1829)

Hermann von Helmholtz
(1821-1894)

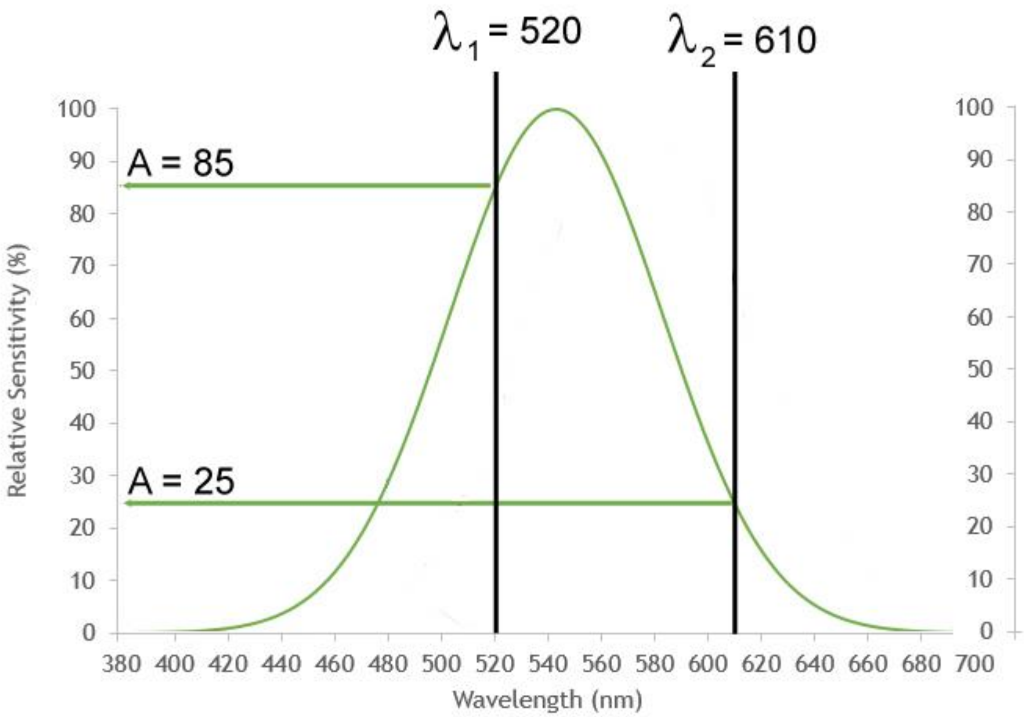
- Color perception emerges from the idiosyncratic discrimination of light wavelength in the retina

- Evidence strongly suggests that the retina must "encode" color based upon more than one type of wavelength-tuned photoreceptor
  [*Univariance Principle*] **Next Slide**

- Additive color matching experiments suggest that three wavelength sensors are required
  [aka Trichromatic Theory]

1-Channel Chromatic Coding System (Univariance Principle)

Stimulus <u>wavelength</u> and <u>intensity</u> are completely confounded.



Bandpass Spectral Response of Light-Activated Molecules

<u>Signal = Activation x Intensity</u>

There is no way of telling how much of the signal represents the intensity of the stimulus versus the wavelength-specific activation of the receptor

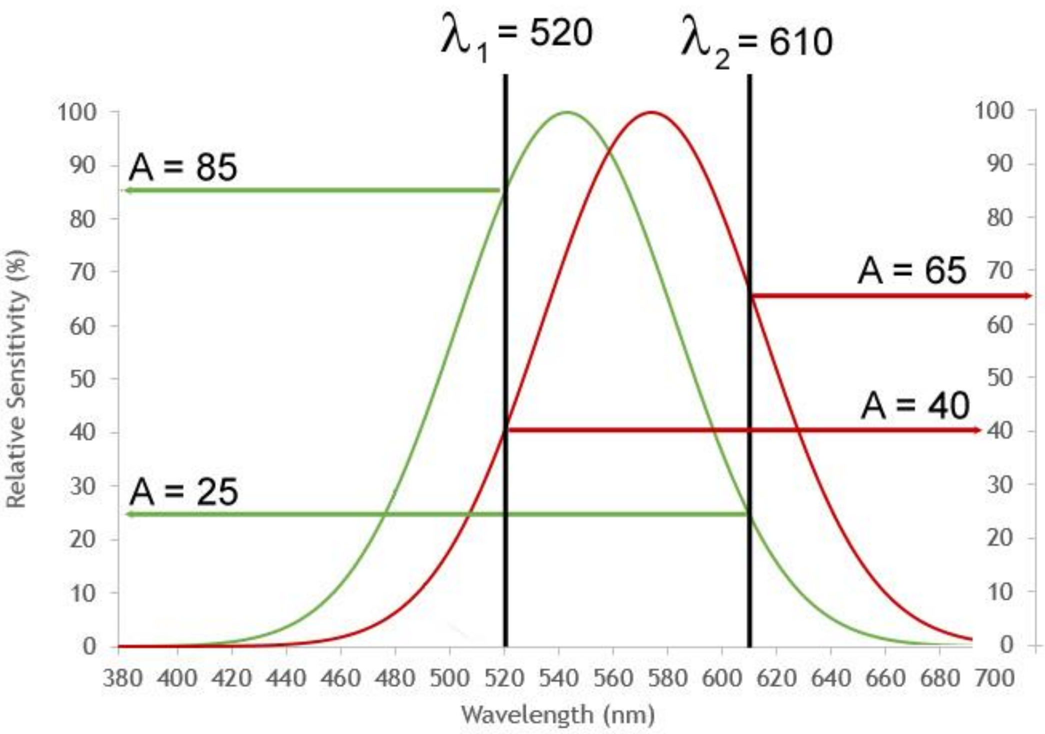
<u>(A x I)Confound Example</u> :

$S_{\lambda 1} = 0.85 \times 2.95 = 2.5$

$S_{\lambda 2} = 0.25 \times 10.0 = 2.5$

2-Channel Chromatic Coding System

Stimulus <u>wavelength</u> and <u>intensity</u> become separable.



Signal = Activation x Intensity

$S_{\lambda 1} = 0.65 \times 2.95 = 1.9$

$S_{\lambda 2} = 0.40 \times 10.0 = 40.0$

2-Channel Chromatic Code

		Channel 1	Channel 2
Wavelength	1	2.5	1.9
	2	2.5	40

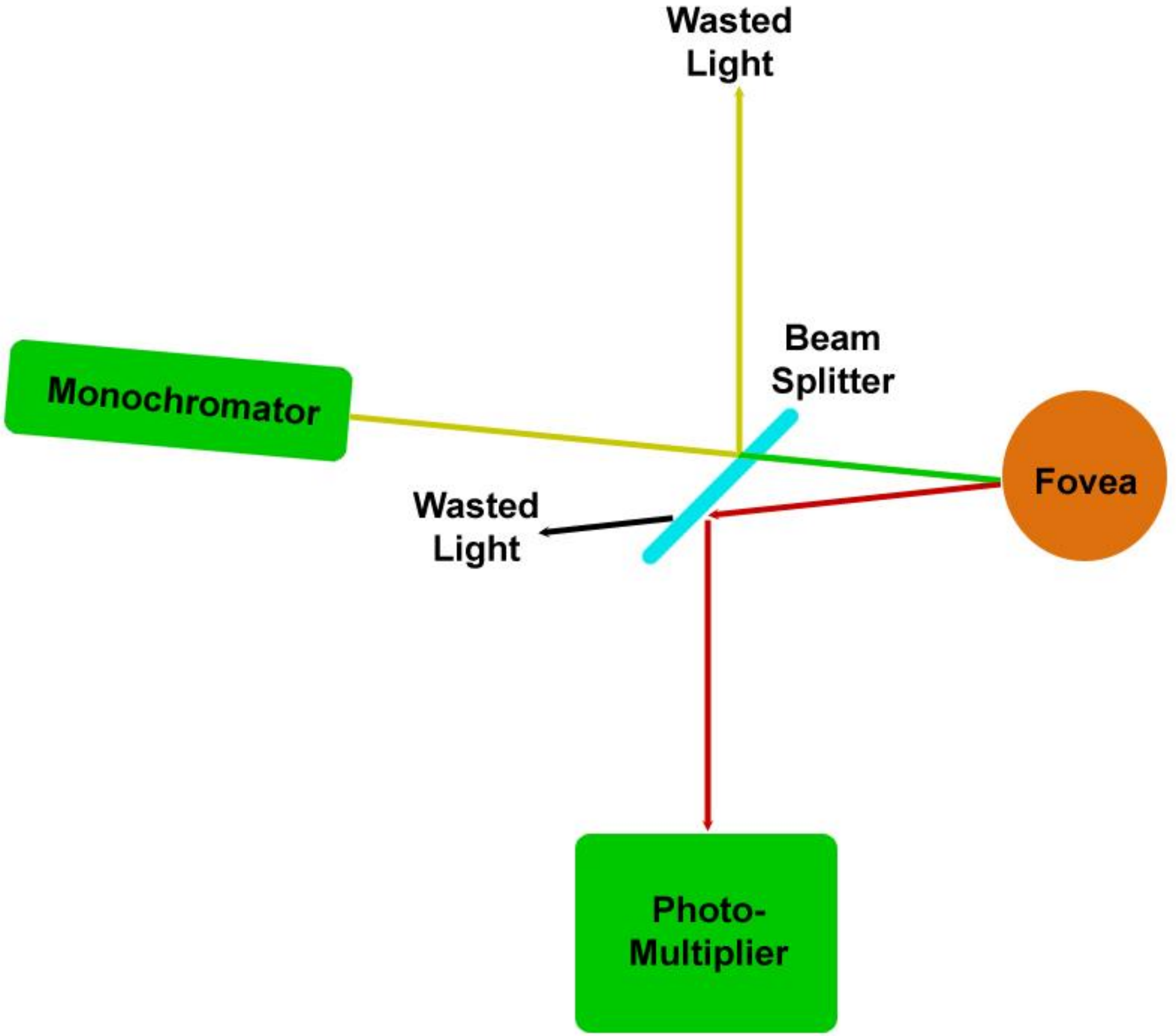
Classic Color Demonstrations Explained by Trichromatic Mechanism

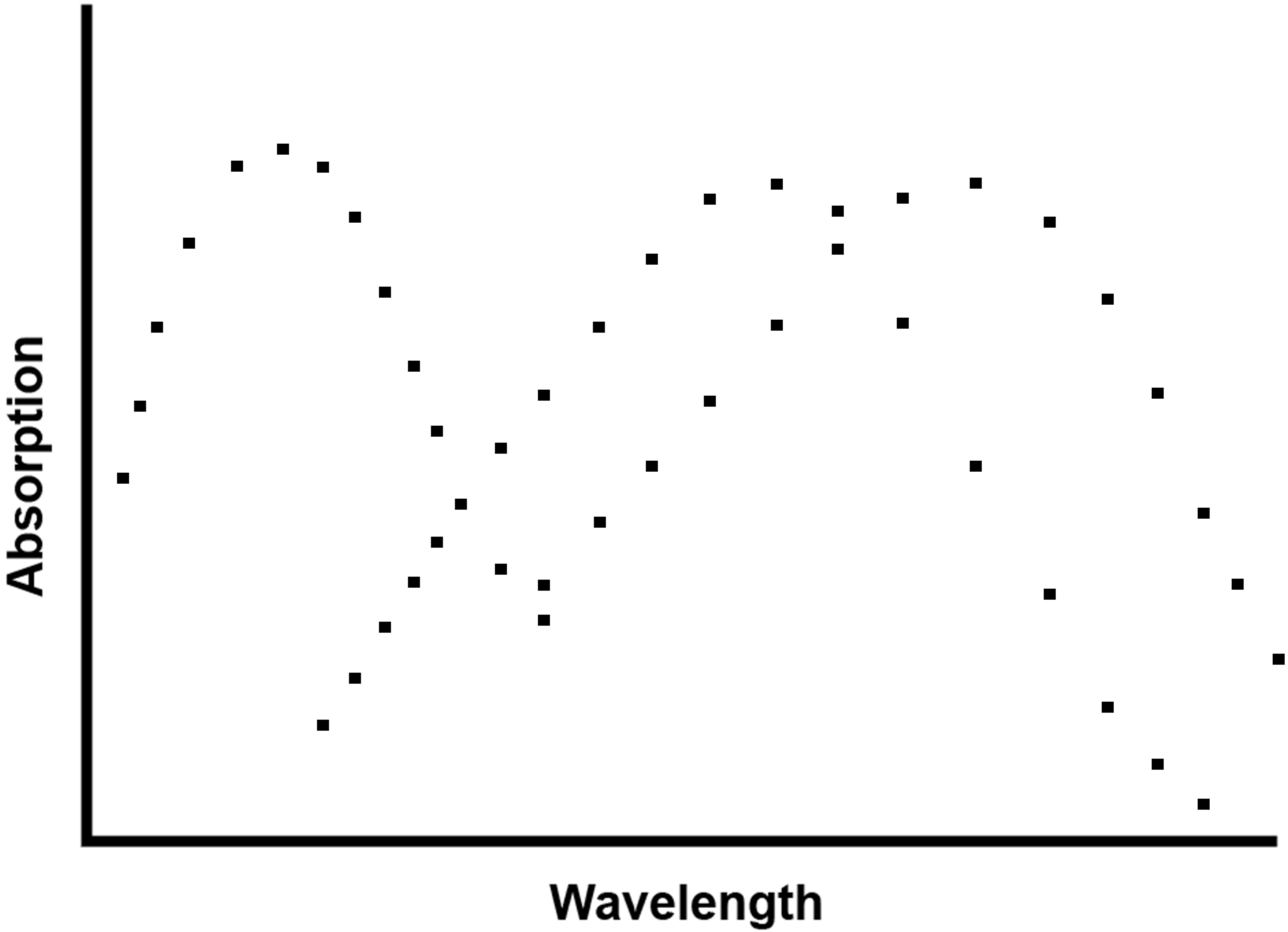
- Tristimulus Color Mixing Findings
  (https://graphics.stanford.edu/courses/cs178/applets/ColorMatching10.swf)
  Maxwell Color Matching

- Fast Color Adaptation
  (http://usd-apps.usd.edu/coglab/coloradapt.html)
  (Basis for **Color Constancy**)

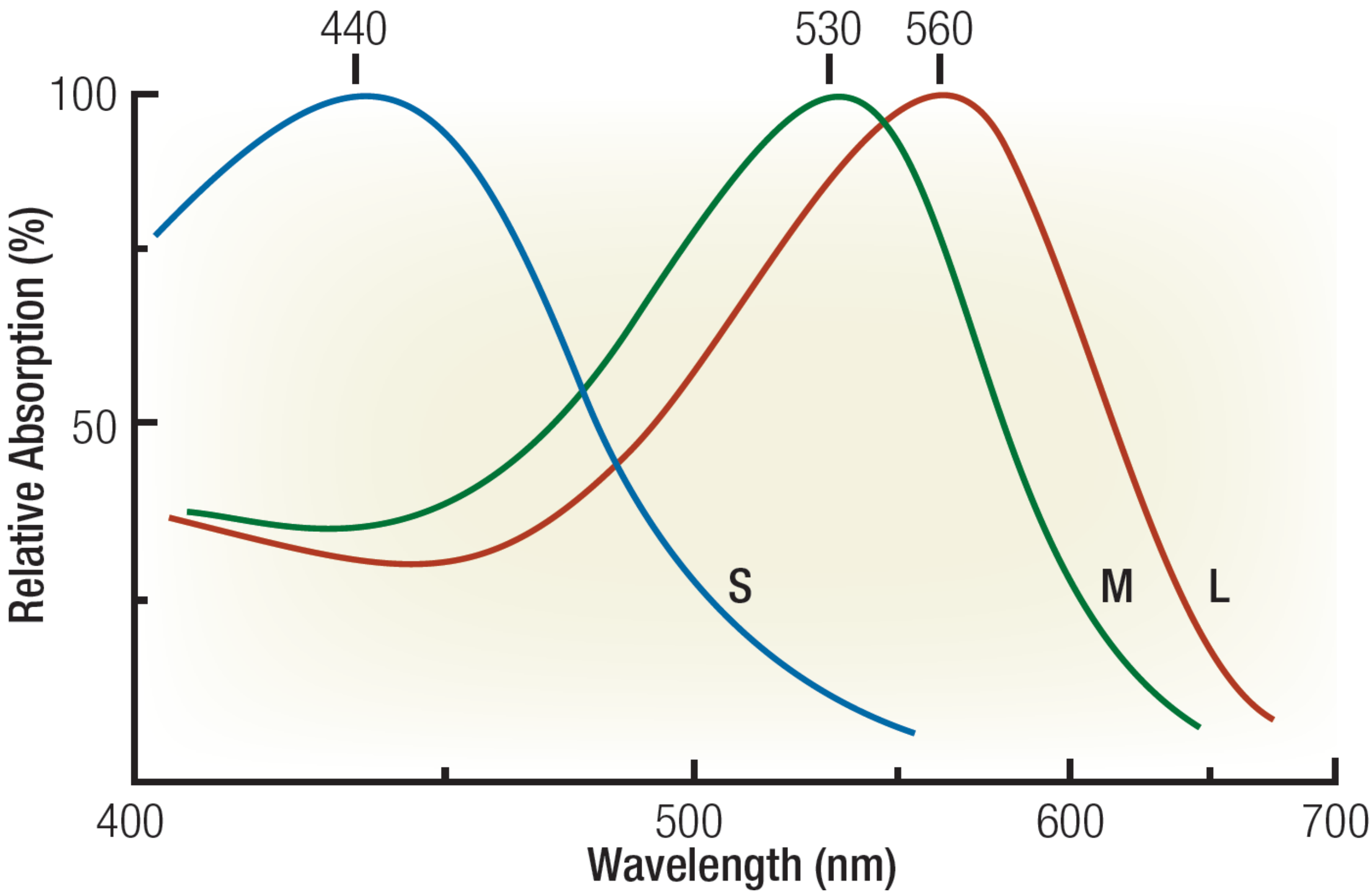
Simulated Microspectrophotometry Analysis of Human Retina

Microspectrophotometer




Absorption
Wavelength

3 Cones Revealed by MSP

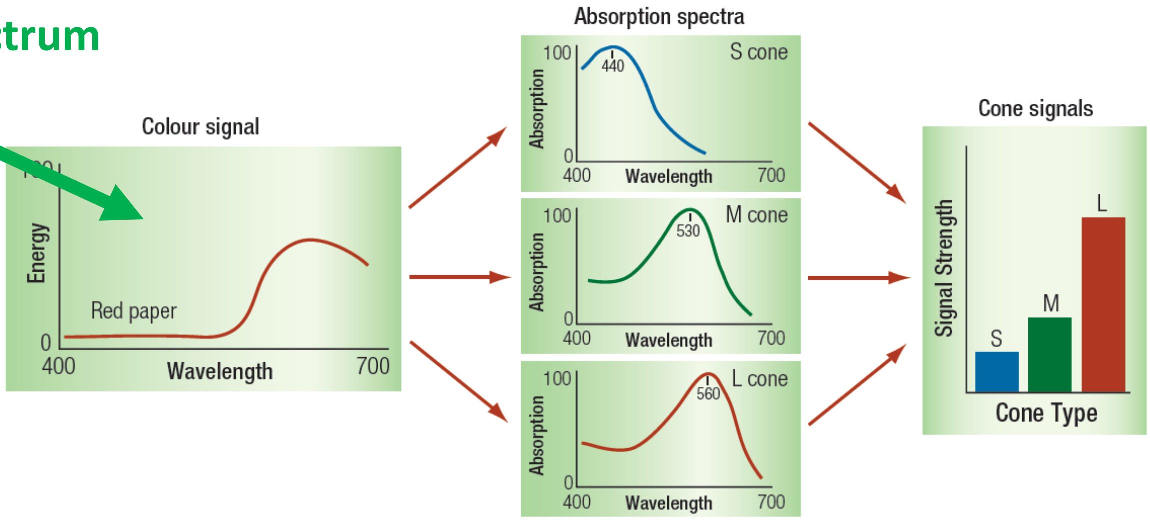


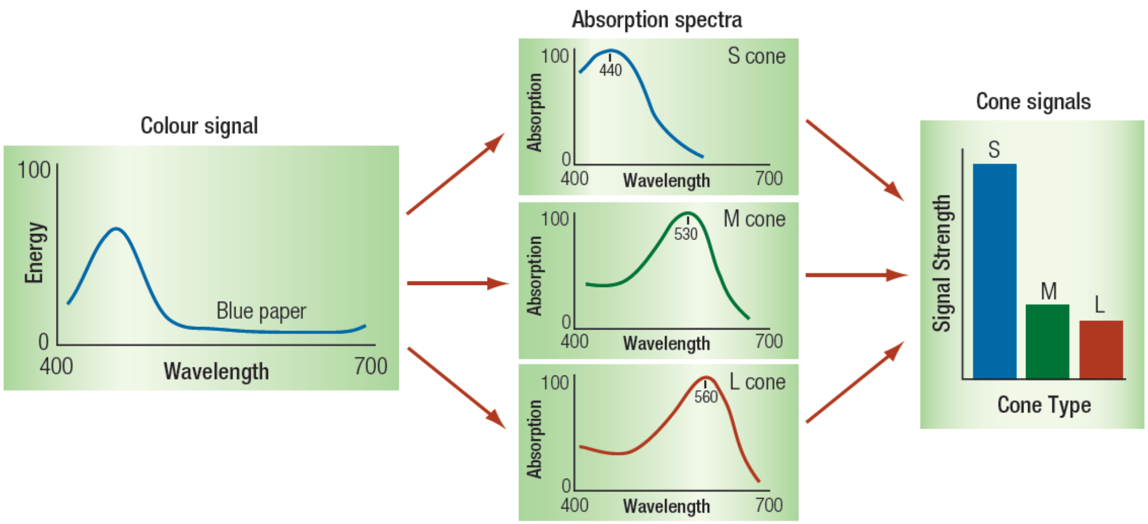
Trichromatic Response to Spectral Stimulus

Illuminant spectrum

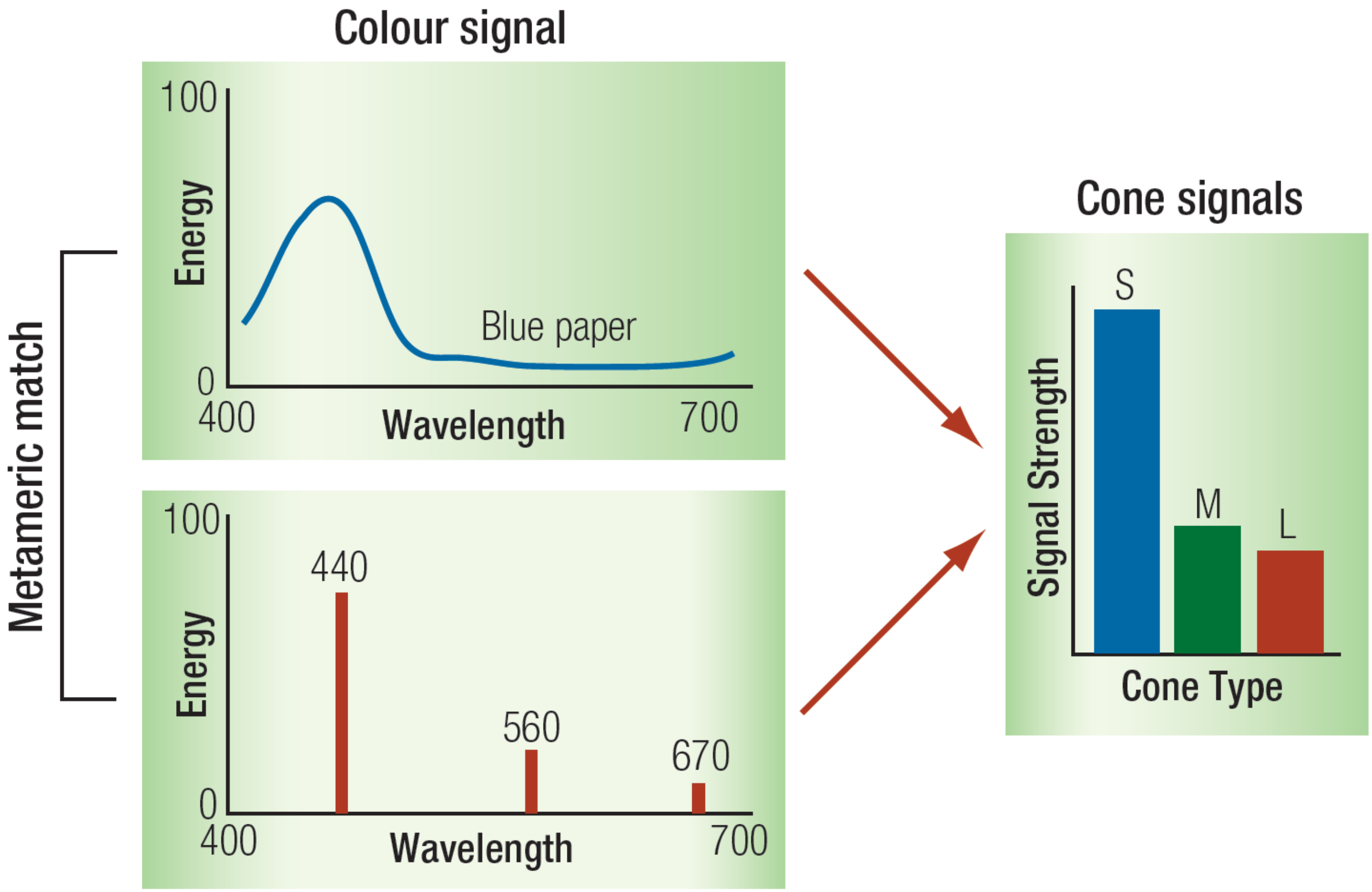
X

Object's reflectance spectrum





Color Metamers



Color Specification Systems
(Hue,Saturation,Brightness)

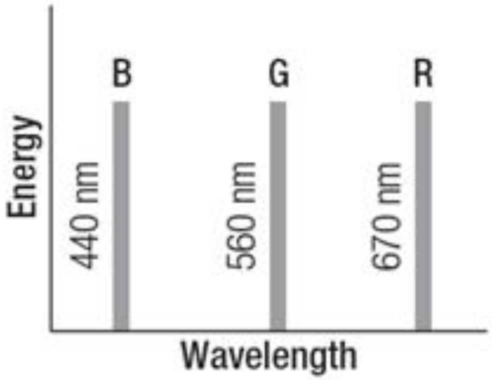
- **CIE (1931) Chromaticity**
  (x,y) captures hue x saturation

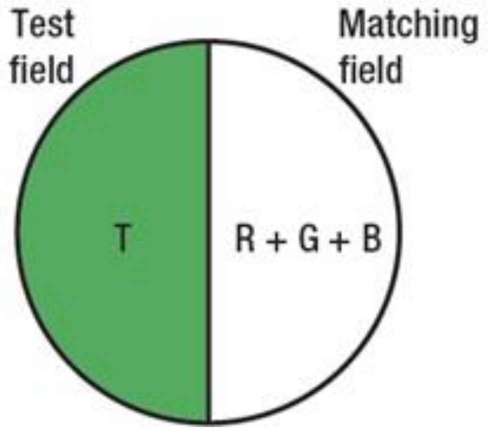
- **Munsell Color System**
  (18 Hues, 18 Chroma; 10 Values)

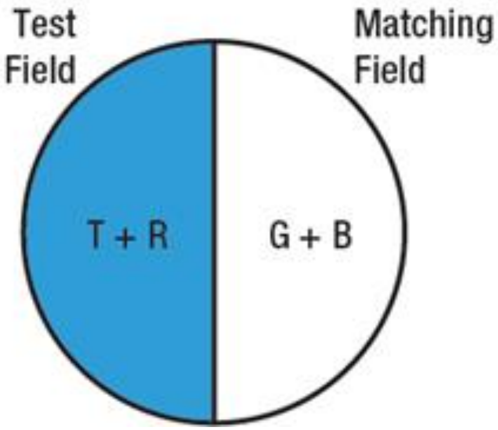
- **Pantone**
  (Proprietary Color Matching Standards)

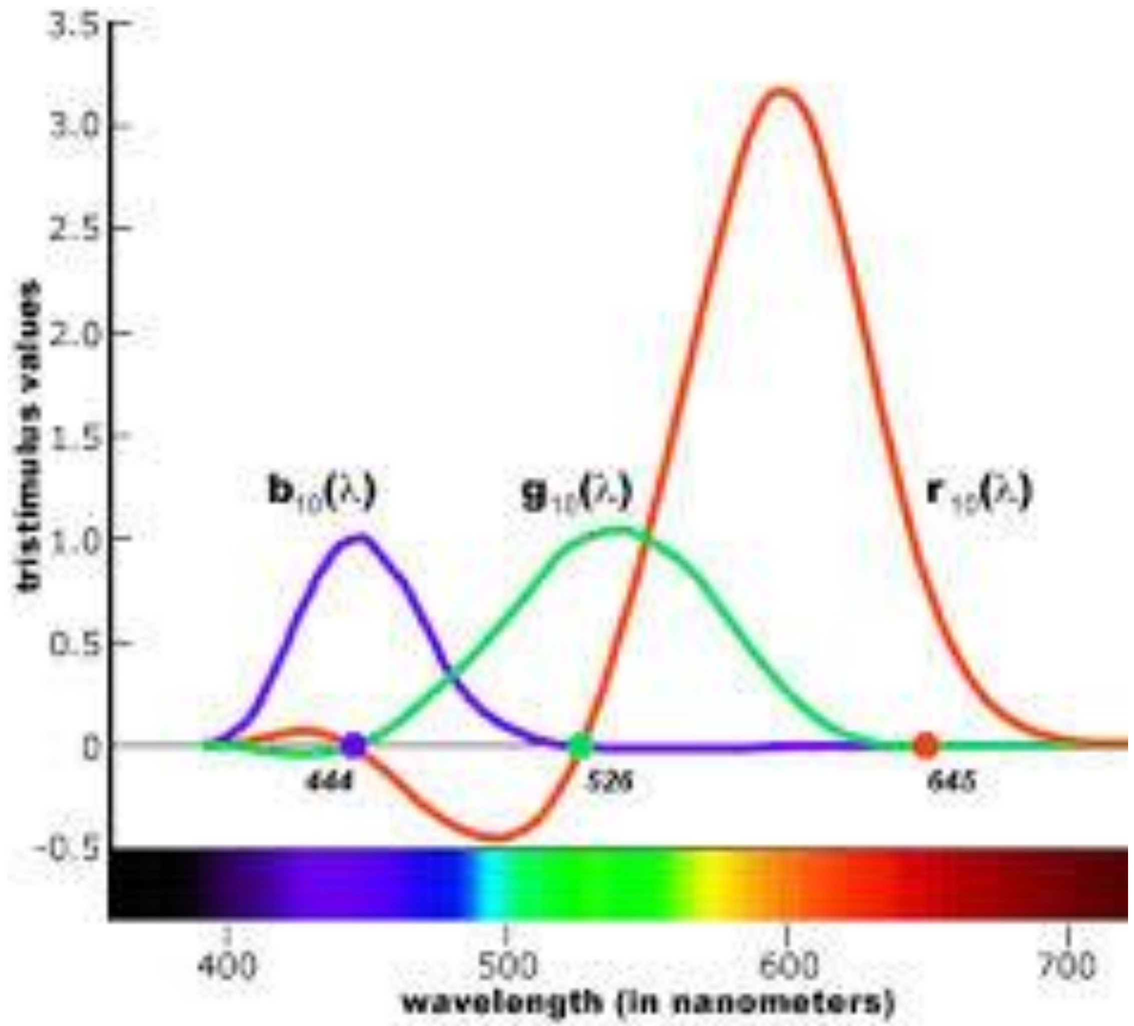
CIE Color Matching Paradigm

(Specifying Tristimulus Values)

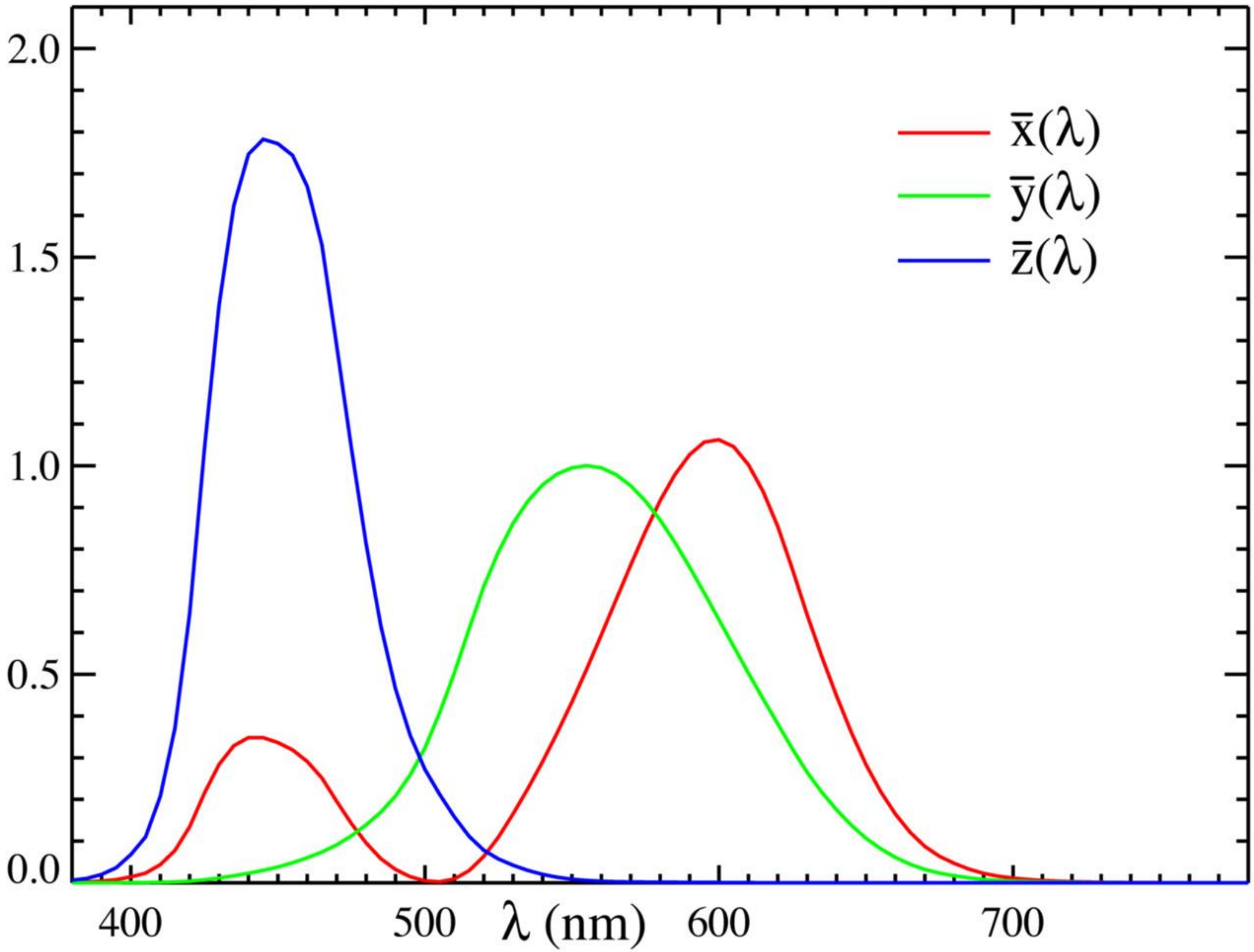








CIE Maxwellian **Color Matching Functions**



CIE (1931) Standardized Tristimulus Color Matching Functions

(1) Y function transformed to recapitulate the CIE Vλ function

(2) X and Z functions transformed to eliminate "negative" values

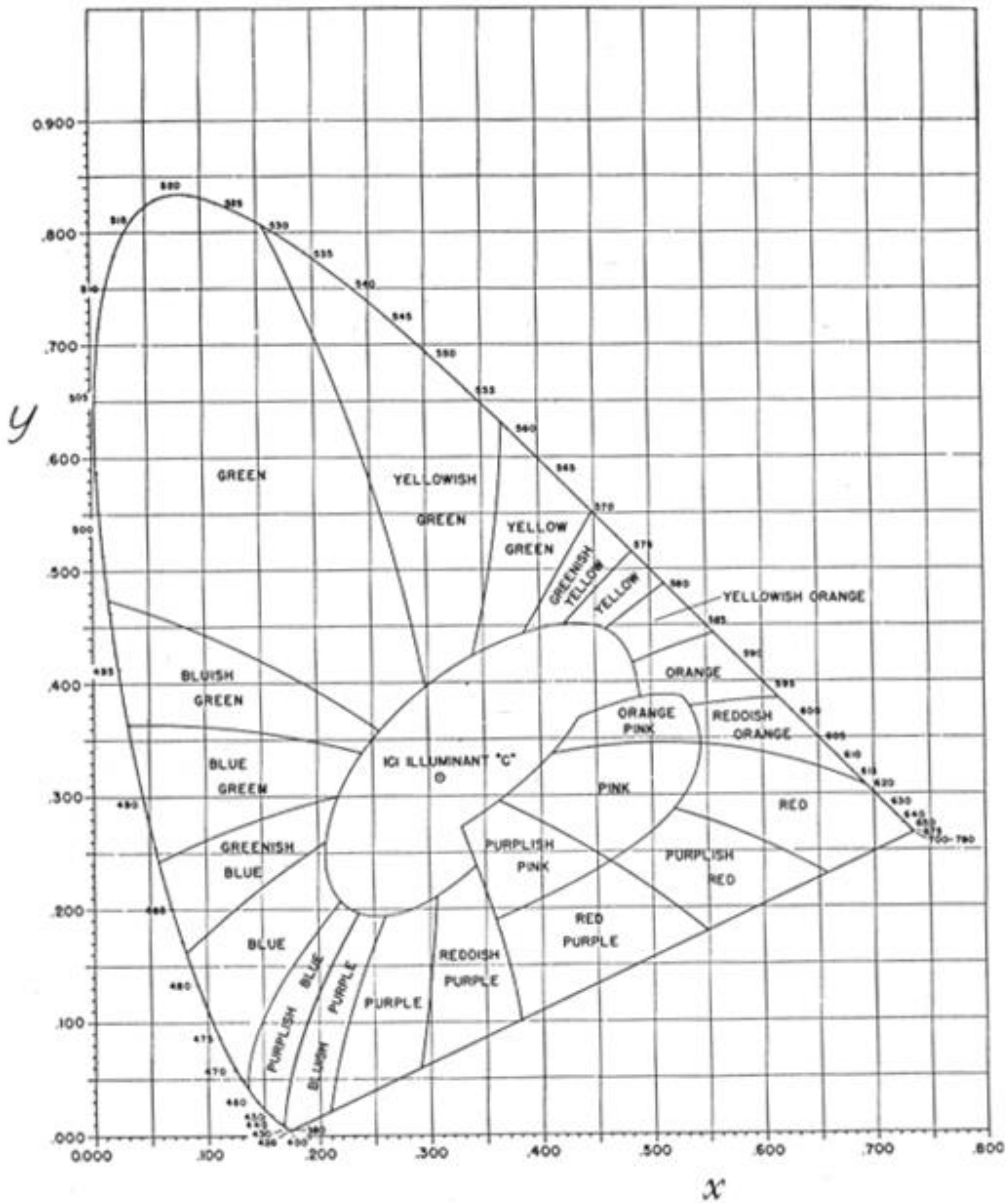


Fig. 4-6. CIE 1931 chromaticity diagram showing color designations for lights, by K. L. Kelly. (From *J. Opt. Soc.* **33**, 627, 1943).

CIE (1931) Chromaticity Diagram

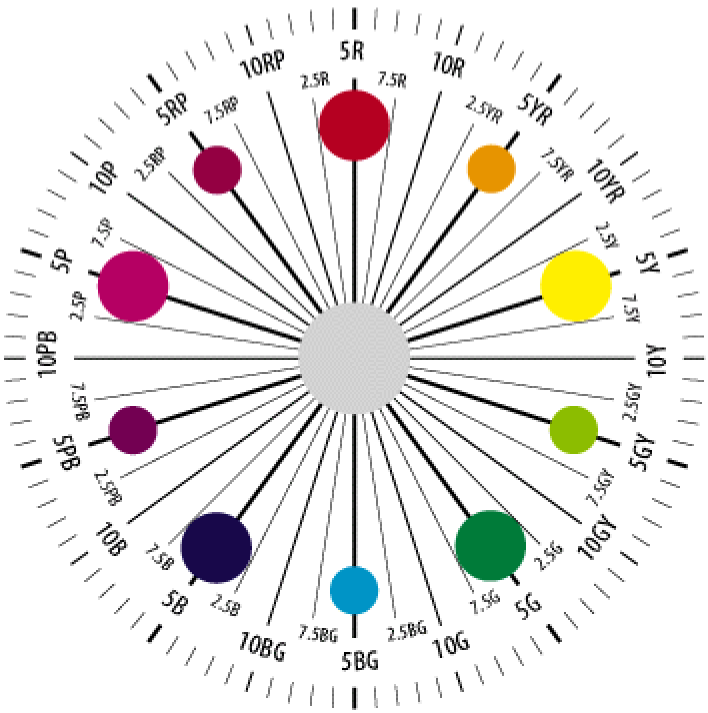
<u>TRISTIMULUS VALUE</u> = X,Y,Z

Normalization of XYZ into
(x,y) Chromaticity Coordinates:

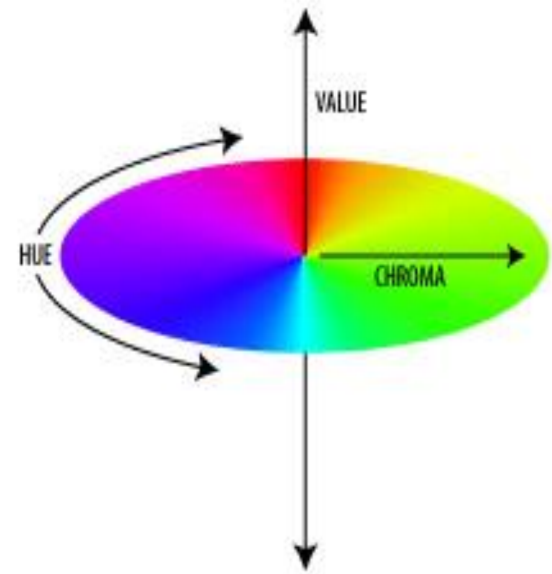
x = X / (X+Y+Z)
y = Y / (X+Y+Z)
z = Z / (X+Y+Z)

Since z = 1 – x – y then XYZ can
be fully specified in the (x,y) plane

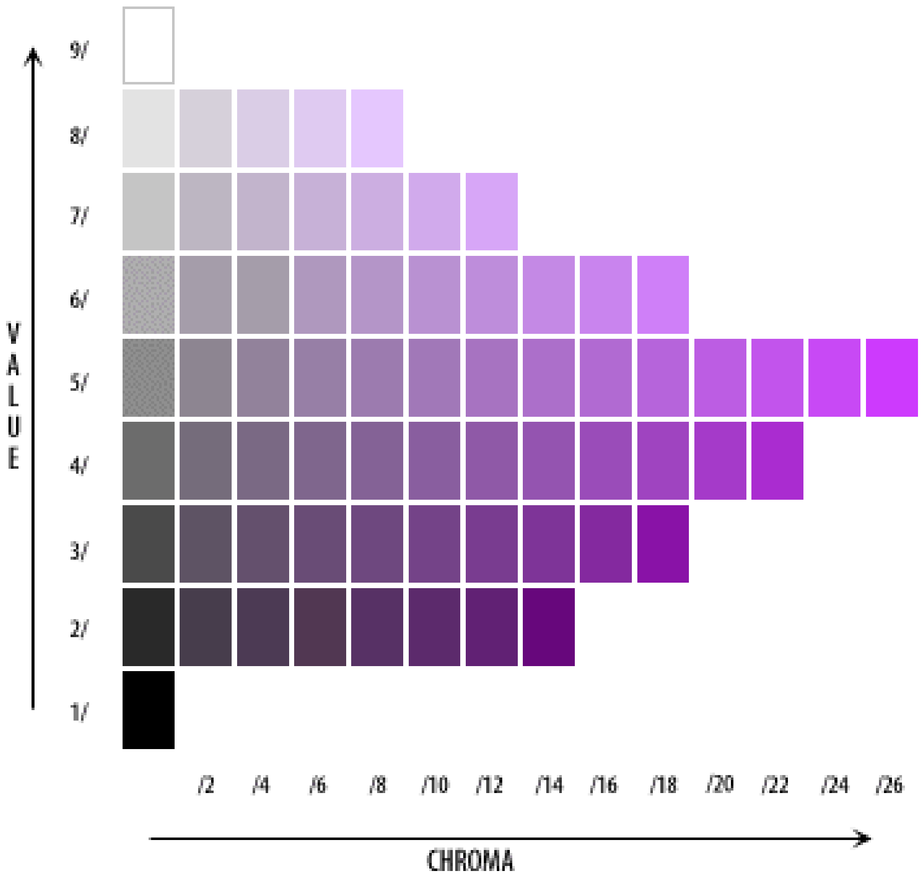
Munsell = (Hue,Value,Chroma)



Munsell Hues



Munsell Book of Colors



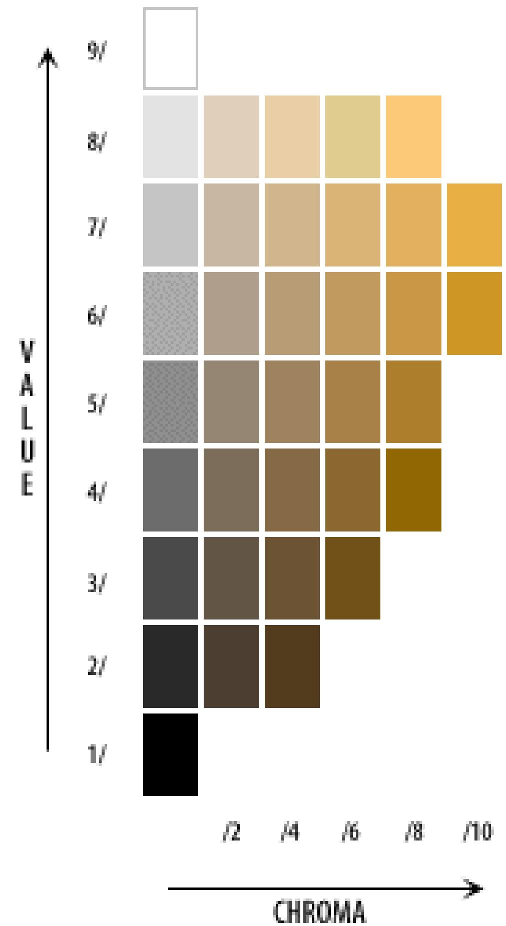
Hue 5RP (Red-Purple)

(Most saturated: 5RP 5/26)

Hue

Value

Chroma



Hue 10YR (Yellow-Red)

Problems for Trichromatic Theory

- Hue Cancellation Effects (Hurvich & Jameson)
  Red+Green → Yellow (not reddish-green)
  Yellow+Blue → White (not yellow-blue)
- Complementary Color Afterimages
- Complex Color Contrast Effects (Land)
- “Blue” light discounted in Brightness Perception

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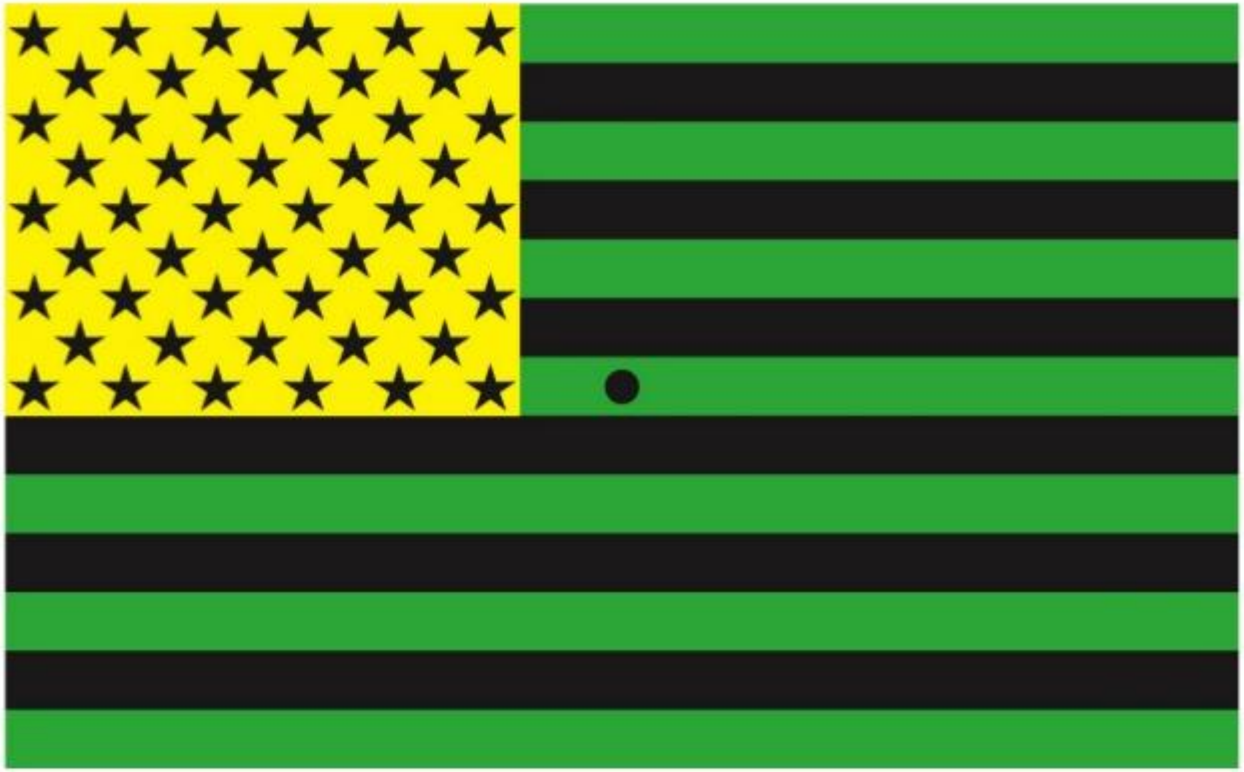
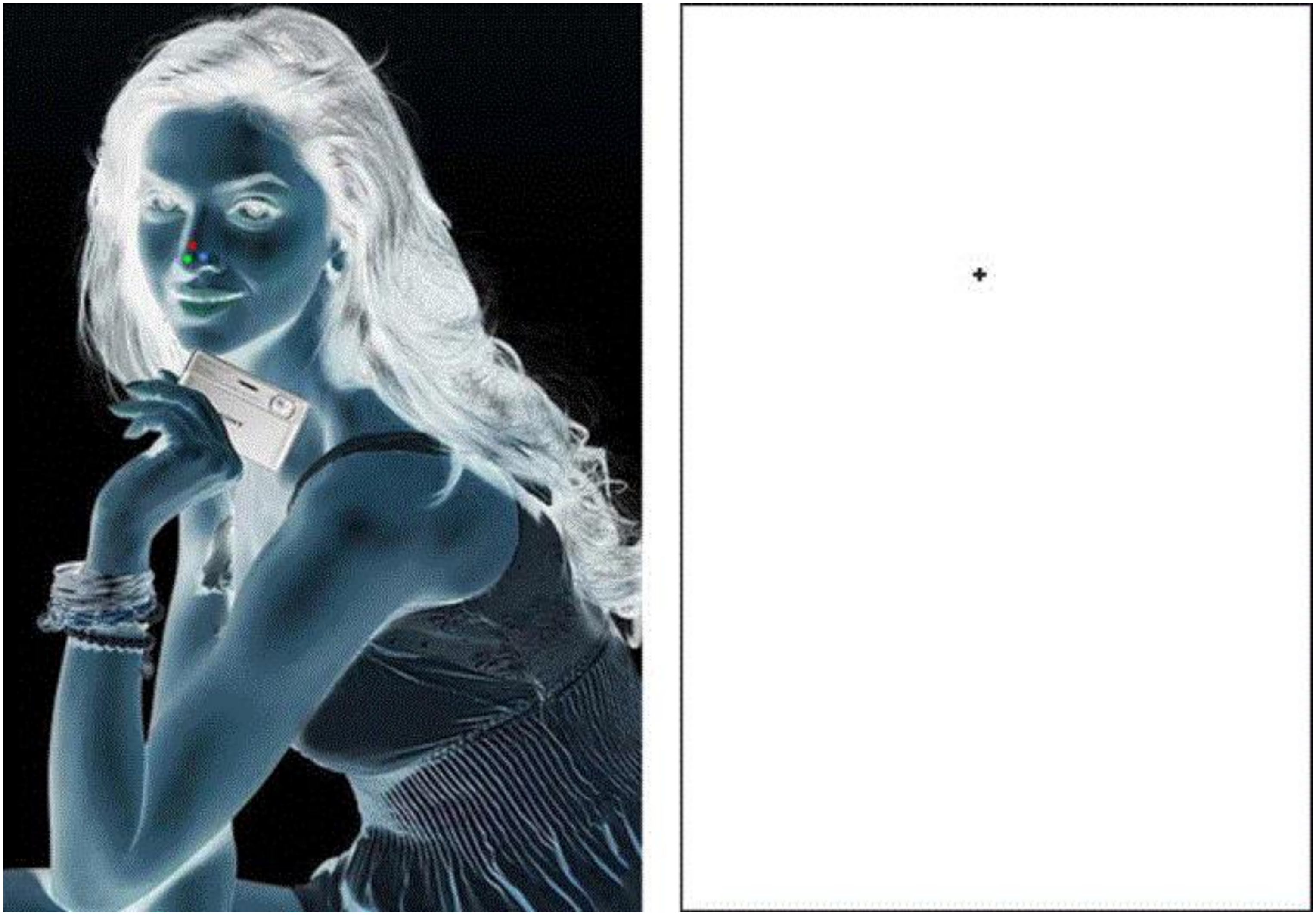
Complementary Color Afterimages

Challenge for Simple Trichromatic Theory





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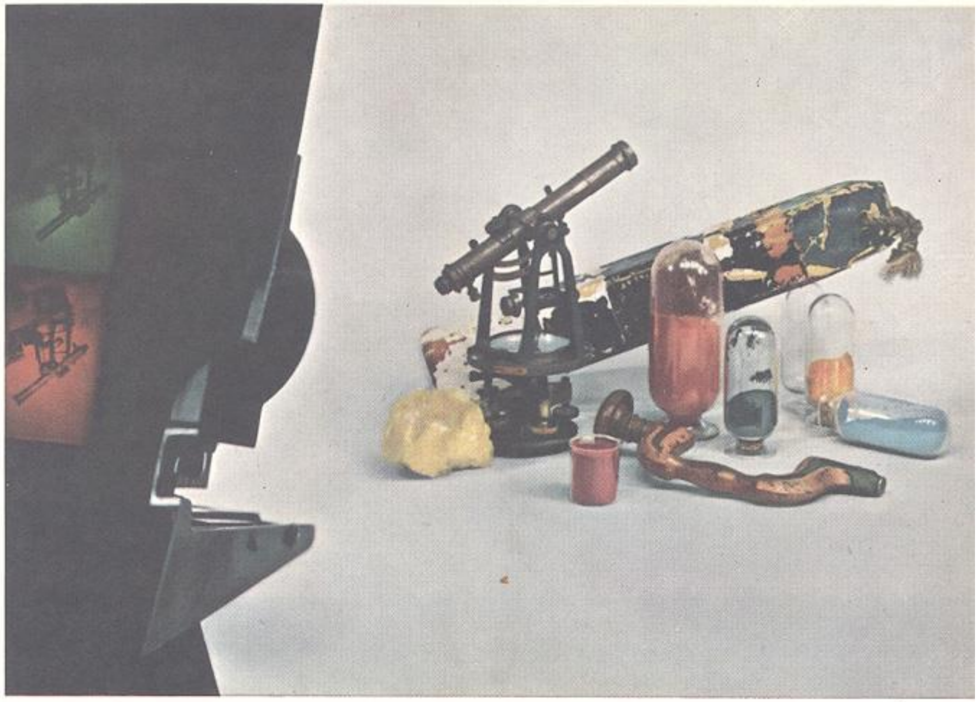
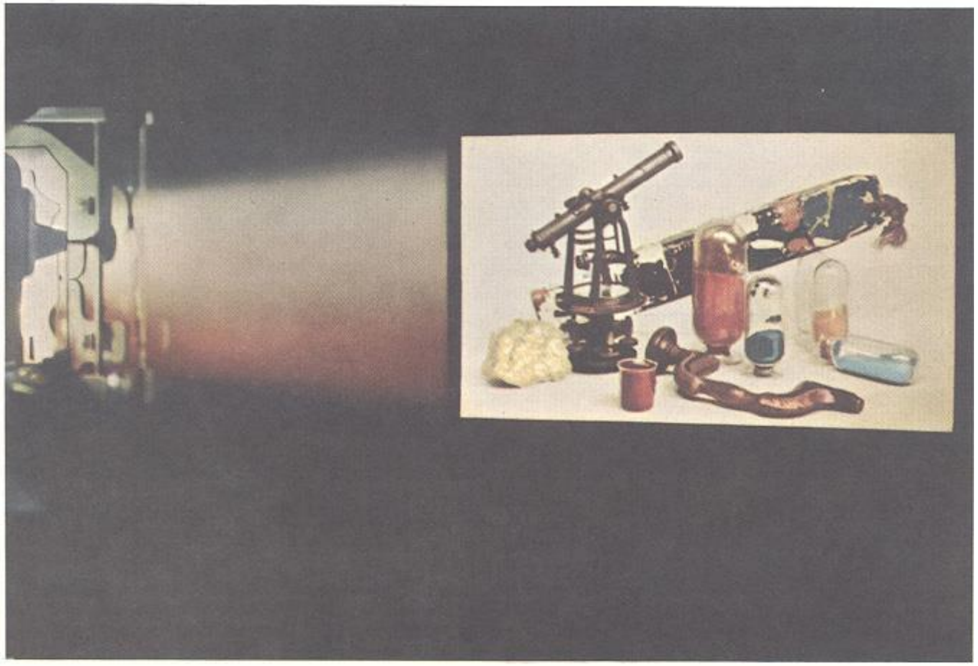
Experiments in Color Vision

Edwin Land
Scientific American (May 1959)

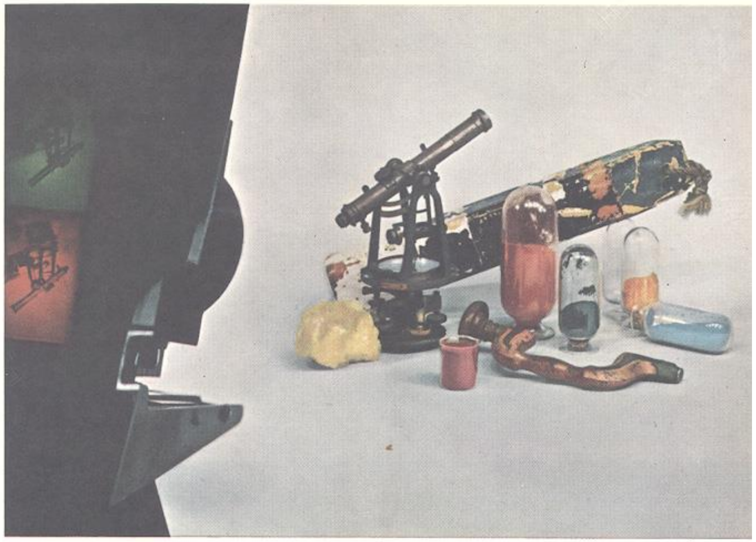


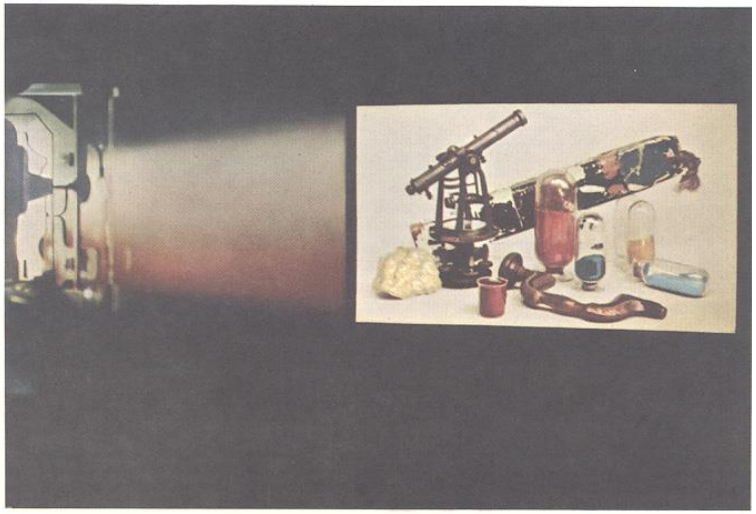
LONG AND SHORT RECORDS are provided by transparencies of these black-and-white photographs made through a red filter (*top*) and a green filter (*bottom*). In projection the long record (*top*) is illuminated by the longer of two wavelengths or bands of wavelengths, and the short record is illuminated by the shorter wavelength or band of wavelengths.



535 ↑ ↑ 589

579 ↑ ↑ 599





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Opponent Process Theory

(Leo Hurvich & Dorothea Jameson)

Information from Red, Green and Blue Cones is organized into <u>three discrete channels</u> before ascending to the visual cortex:

Two pairs of **OPPONENT COLOR channels** code for HUE

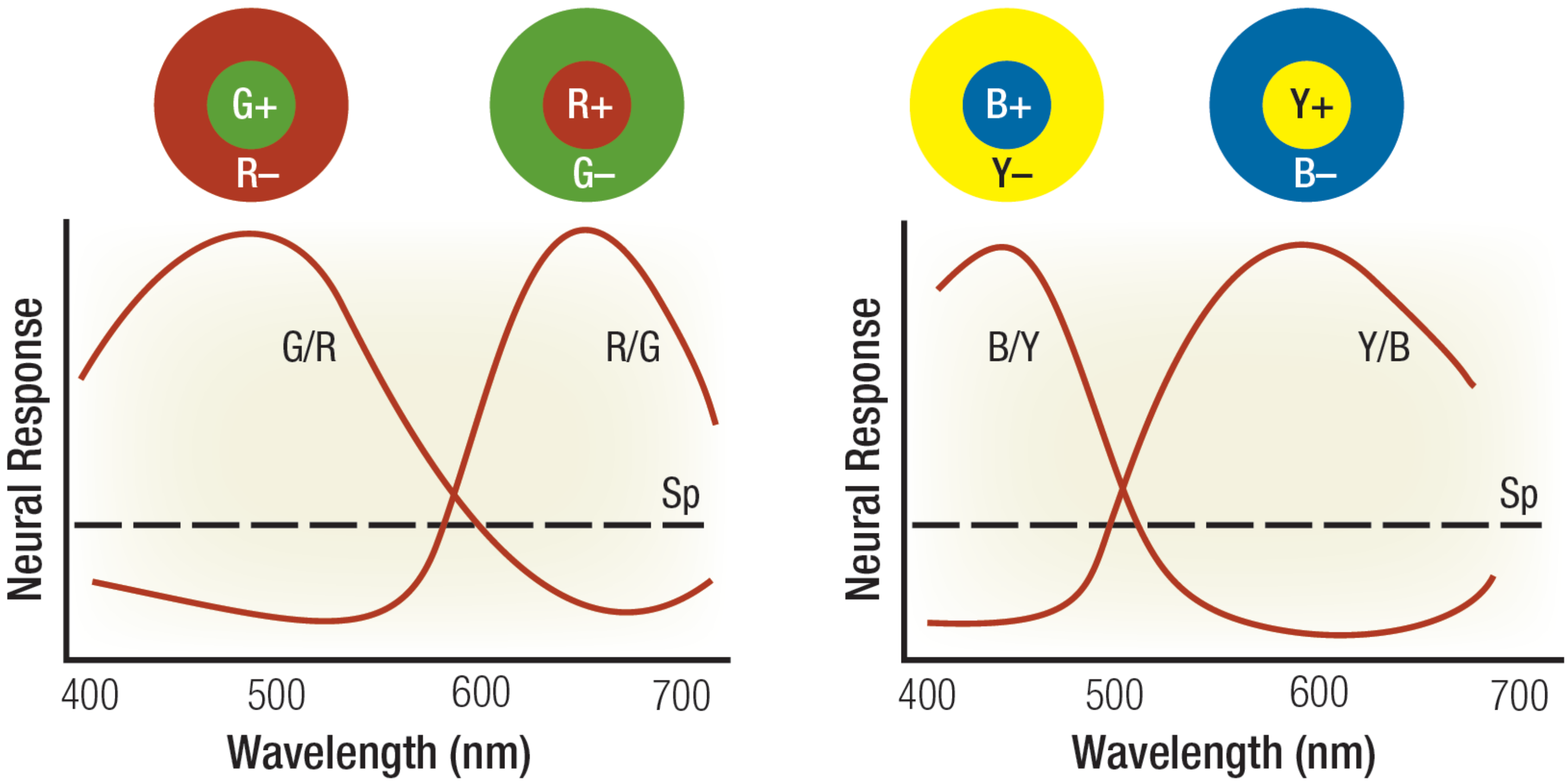
Red vs. Green channel	L ←→ M cones
Blue vs. Yellow channel	S ←→ L+M cones

One **ACHROMATIC channel** codes for BRIGHTNESS

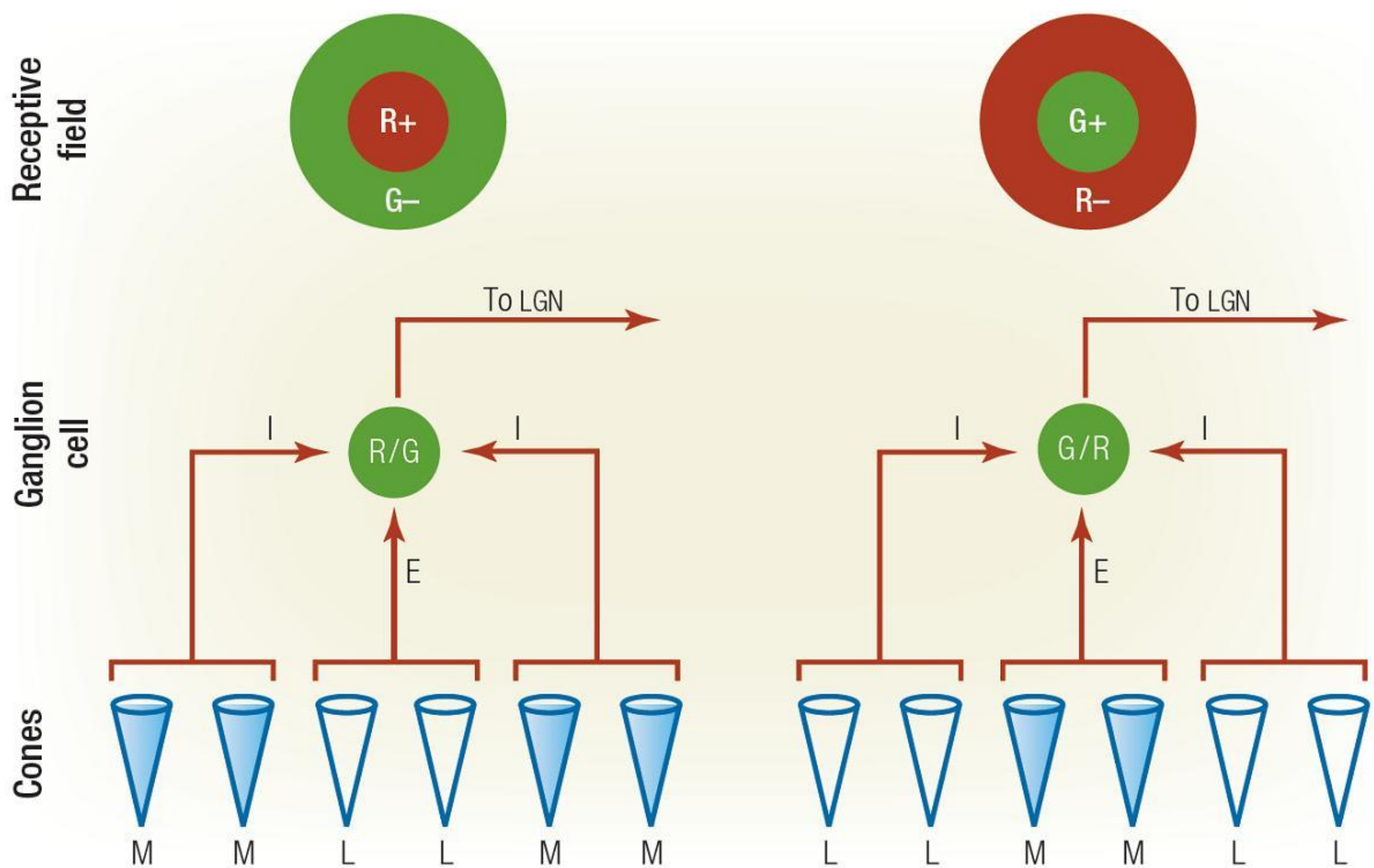
Black vs. White	L+M in center-surround antagonism

DeValois & DeValois (1975)

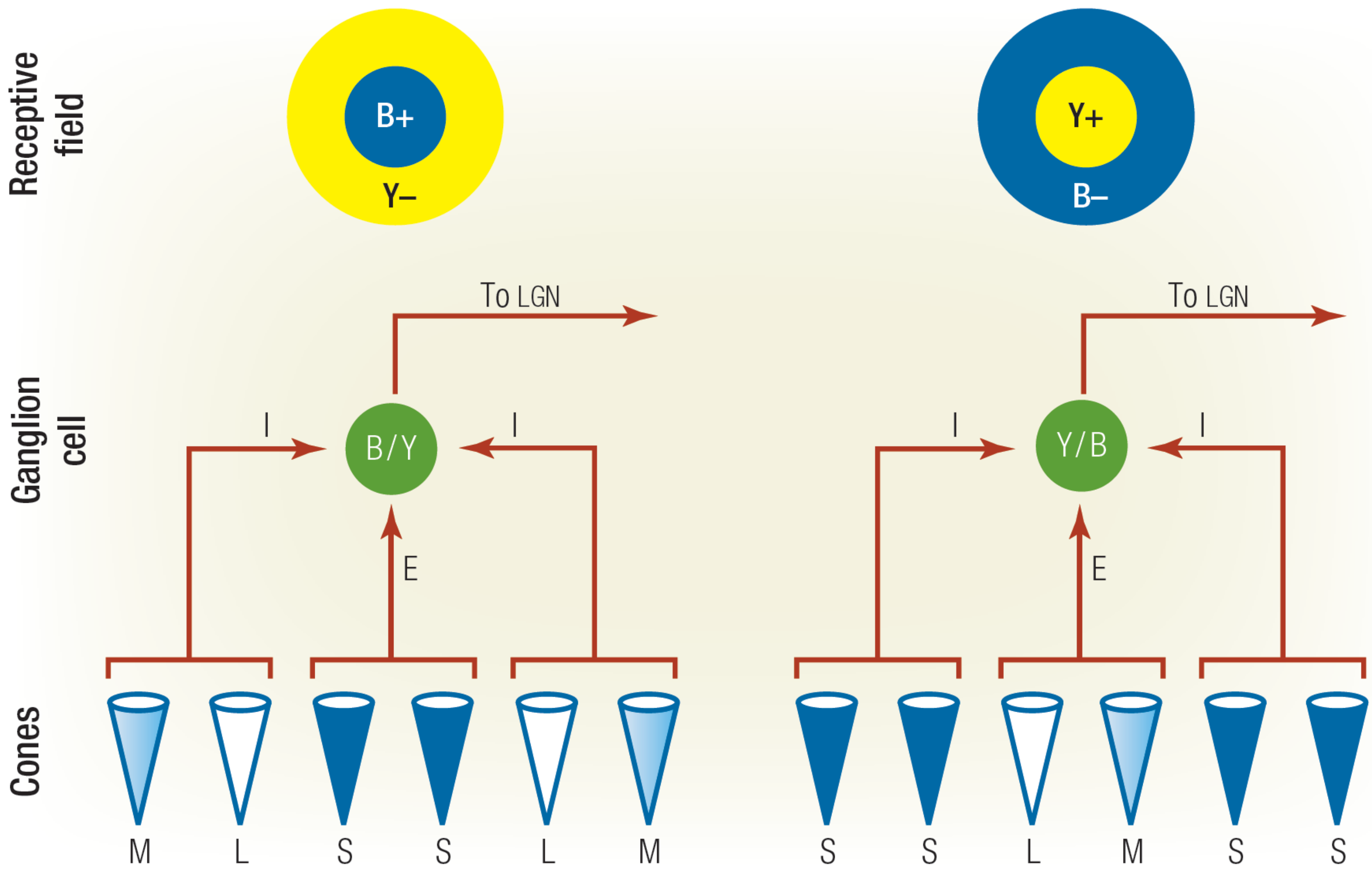
Color-Opponent Cells in the LGN



Red-Green Ganglion Cell

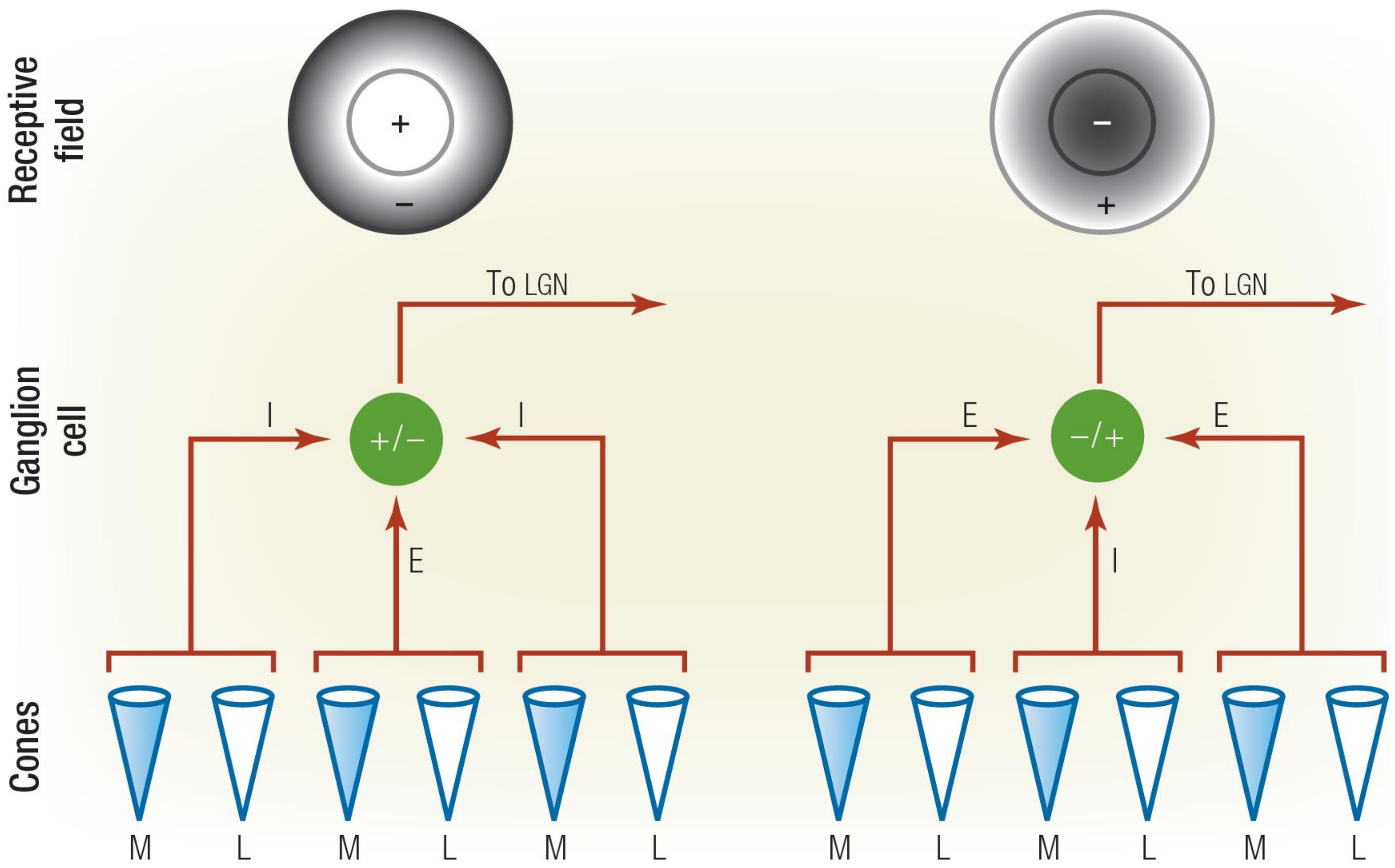


Blue-Yellow Ganglion Cell

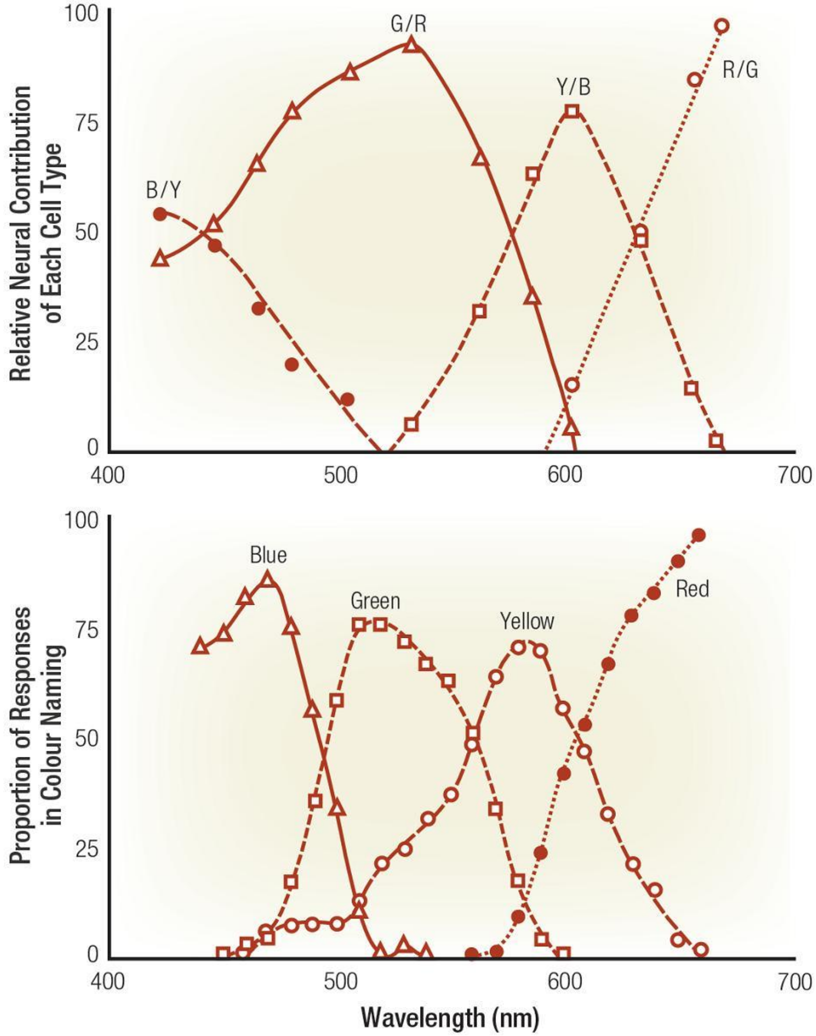


Achromatic Ganglion Cell

(Notice that Blue Light is “Discounted”)



Psychophysical vs. Physiological Results



DeValois & DeValois (1975) Monkey LGN data

Boynton & Gordon's (1965) Color Naming Results

Present brief-flash of mono-chromatic light; Identify appearance using four color categories: RED, YELLOW, GREEN or BLUE

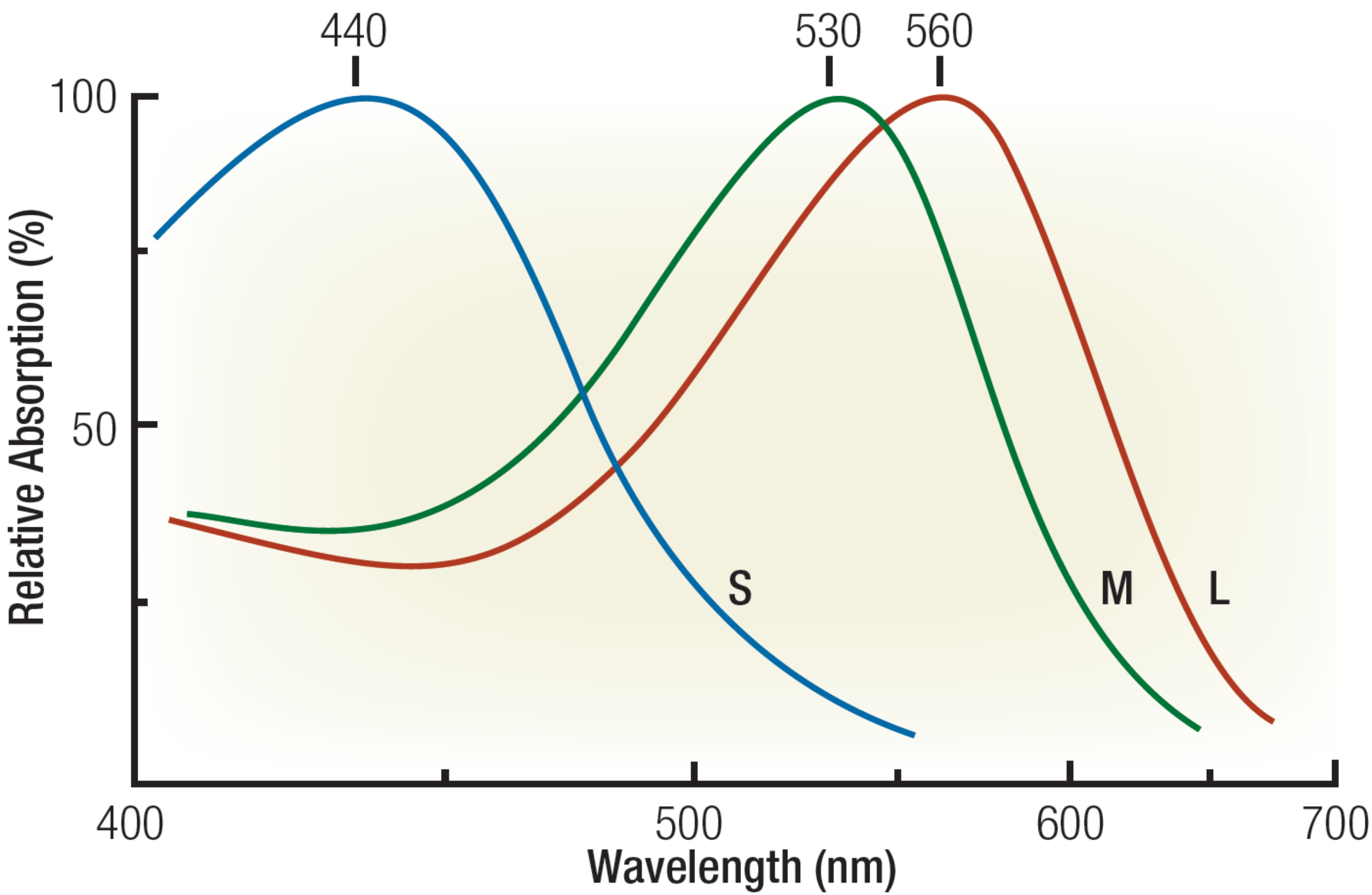
Dichromatic Color “Blindness”

Only TWO cone types available
3D color-space reduced to 2D color-space
(i.e., diminished color discrimination capability)

Prevalence

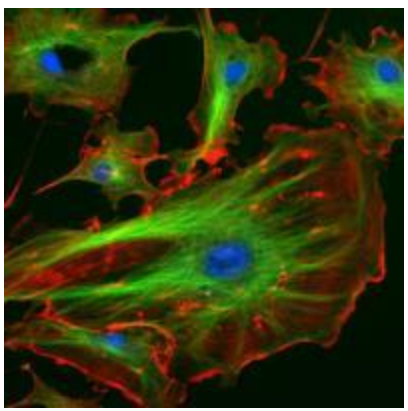
		Males	Females
Protanopia	Missing L-cones	2%	0.02%
Deuteranopia	Missing M-cones	6%	0.4%
Tritanopia	Missing S-cones	0.01%	0.01%

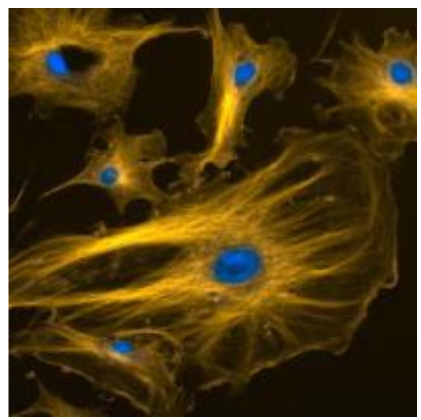
Human Cone Spectra



Daltonization

Computational algorithms can be used to optimize the color palettes of images in order to minimize the occurrence of metamerisms.





Trichromat

Red/Green Dichromat

Source: www.vischeck.com/daltonize