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?

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')

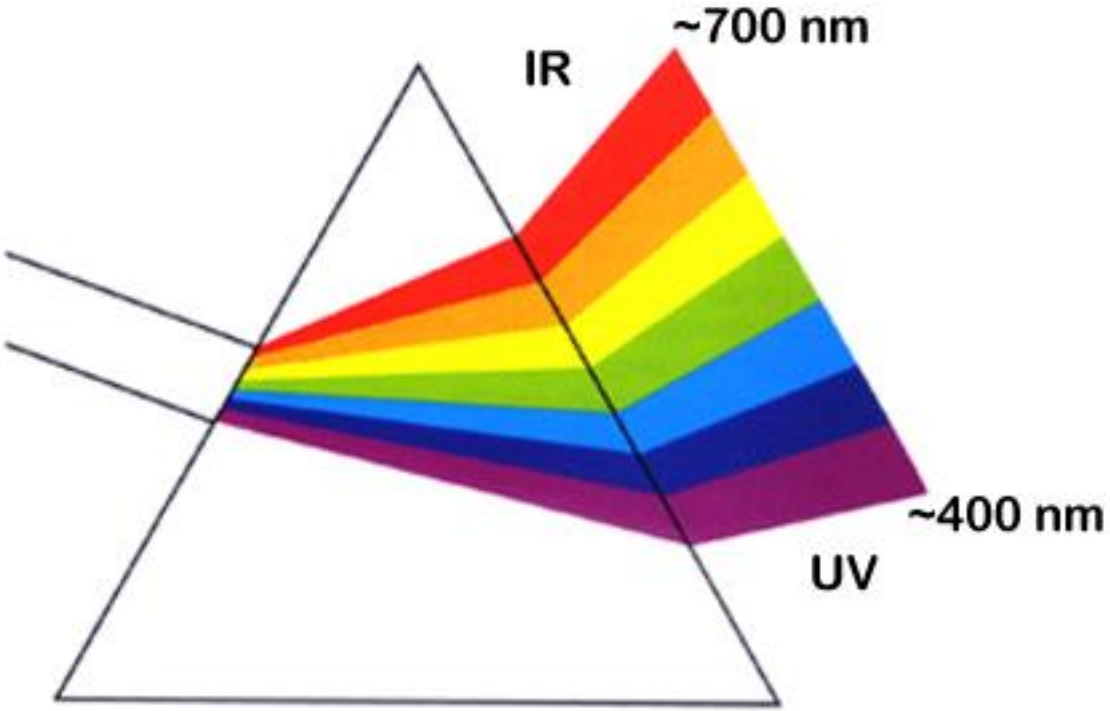
- **Saturation**
  Purity of the hue experience (i.e., relative absence of 'white' or 'gray') (reciprocal of 'added white' required for a color-match-to-sample)

Color Stimulus Triad

- **Illuminant Spectrum**
- **Surface Reflectance Spectrum**
- **Spectral Sensitivity of the Visual System**

Illuminant Emission Spectra

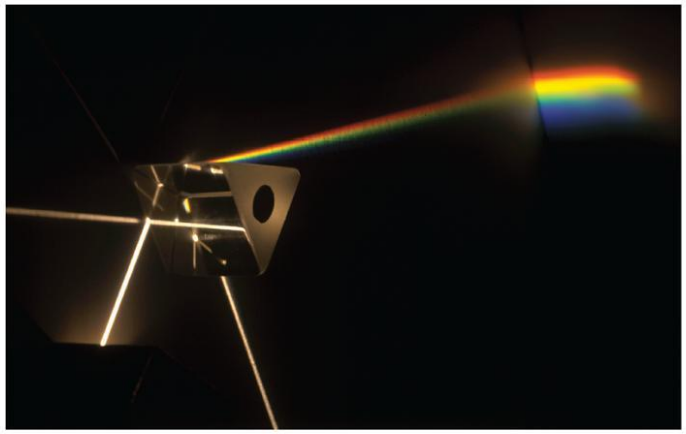
“White” Light is a mixture of many different WAVELENGTHS



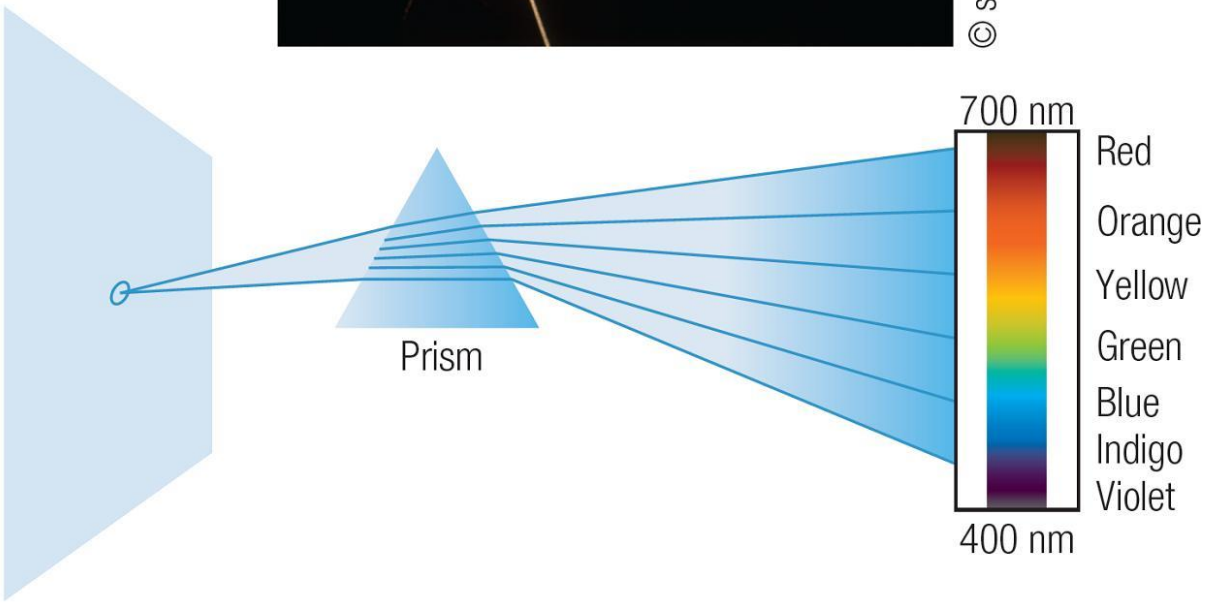
We perceive different wavelengths as different colors

Newtonian Light Spectrum

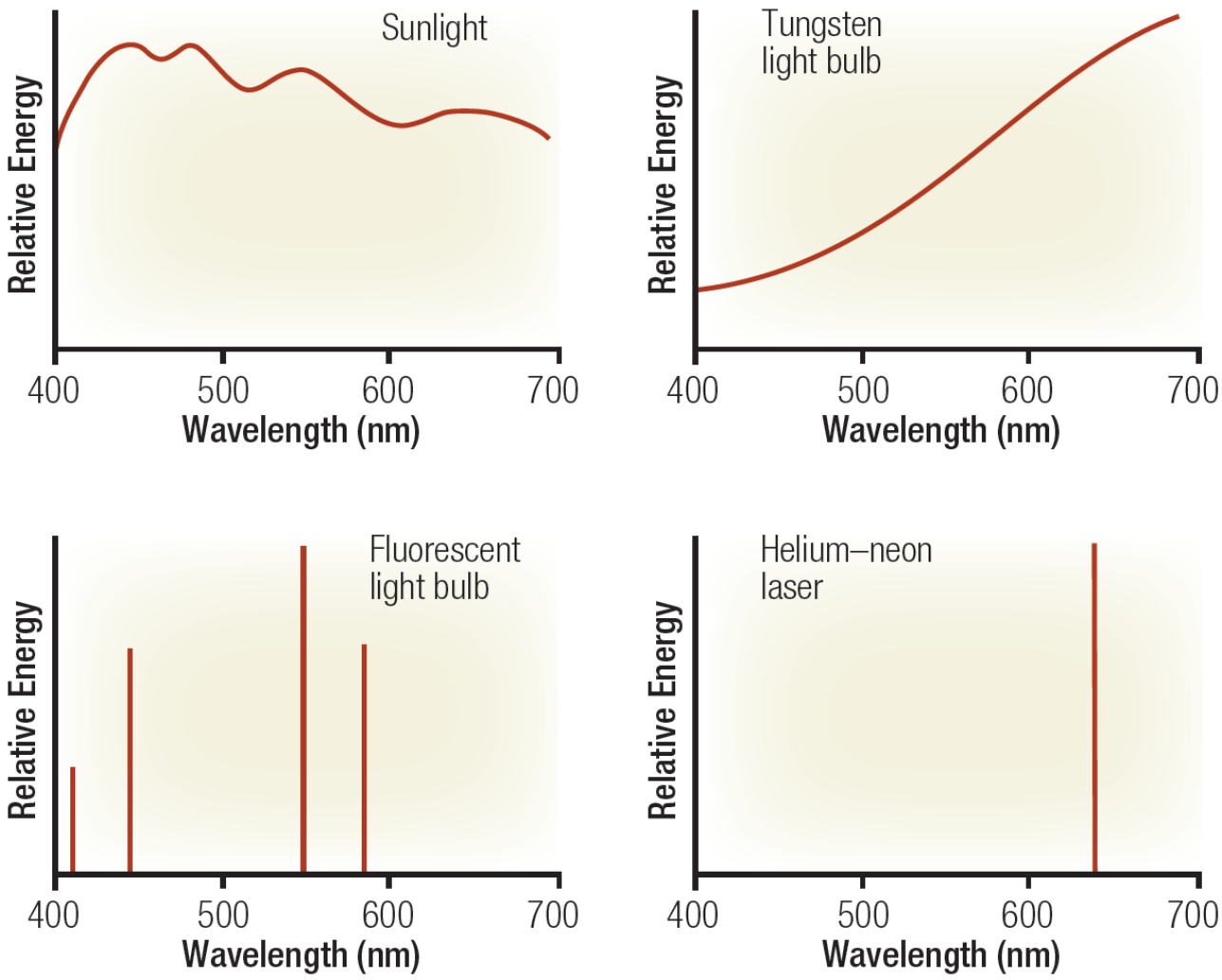
(ROY G BIV)



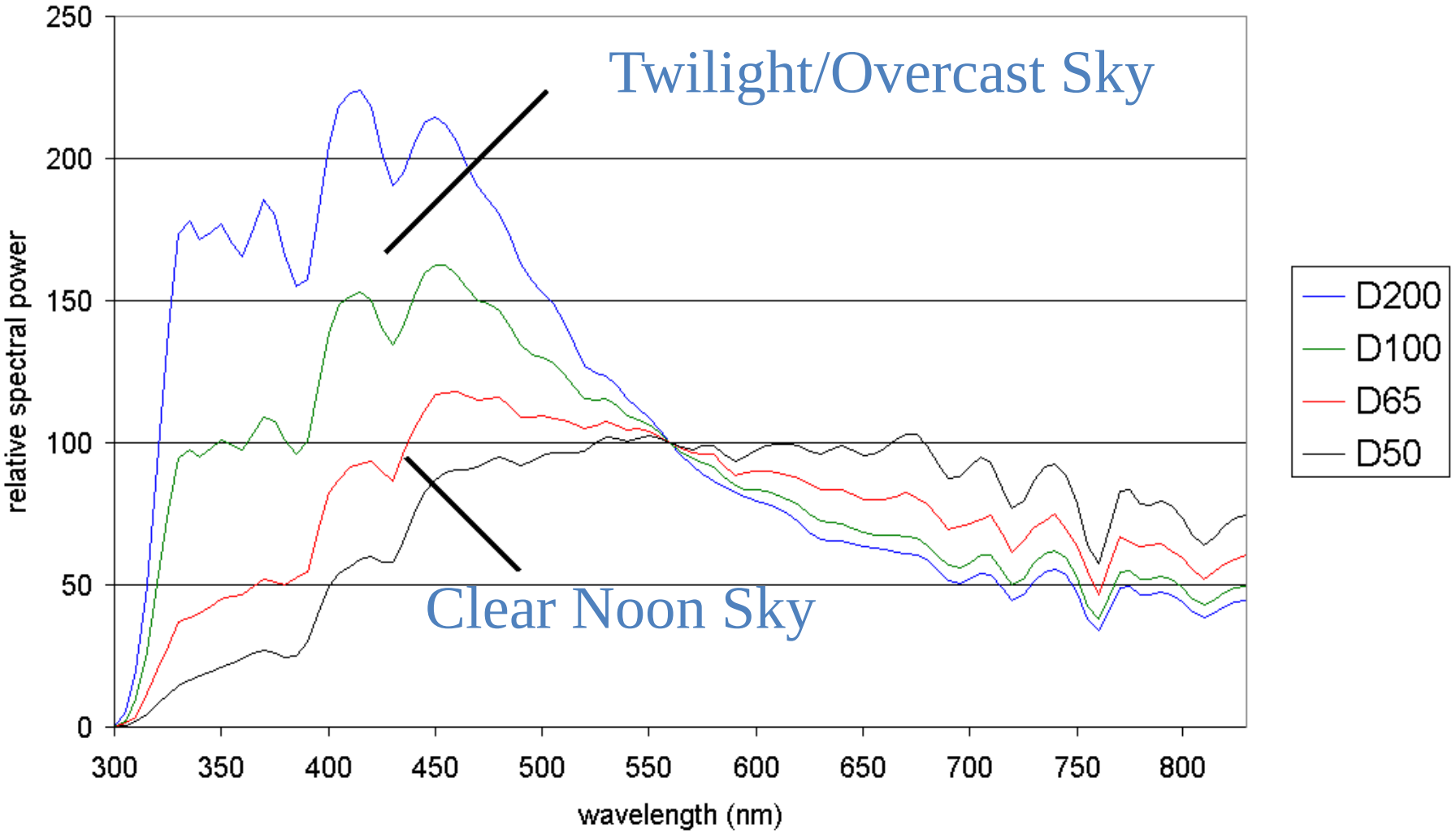
© sciencephotos/Alamy



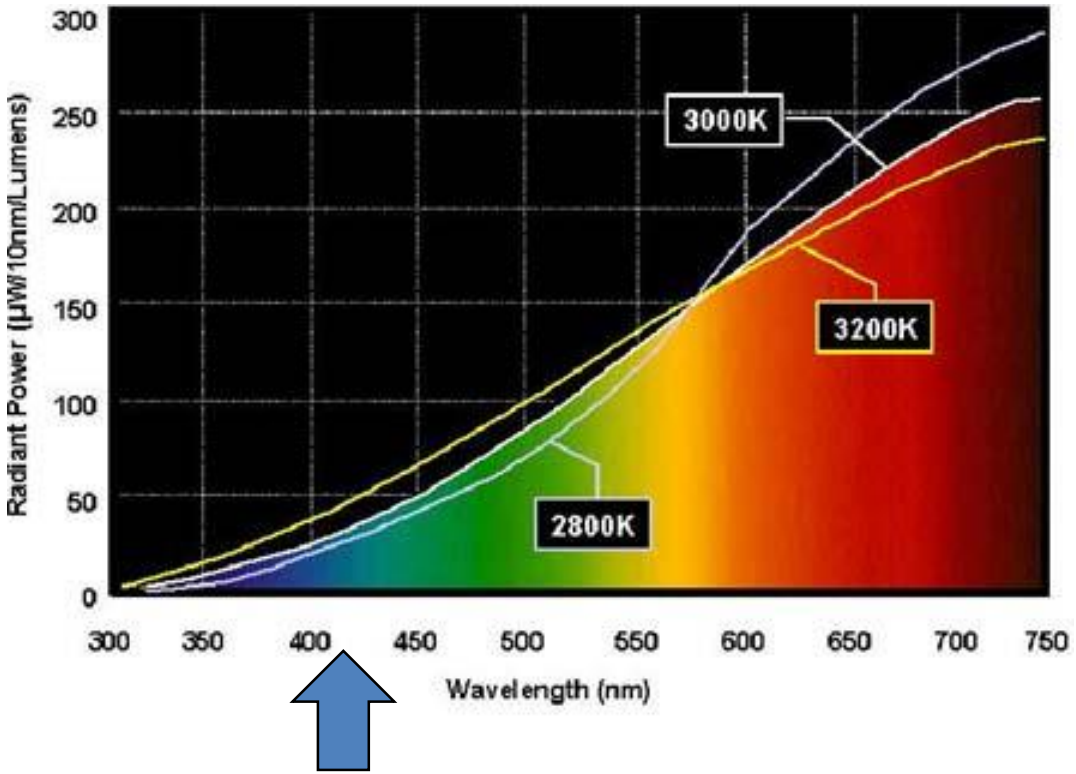
Spectra of Some Common Illuminants



Sunlight


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

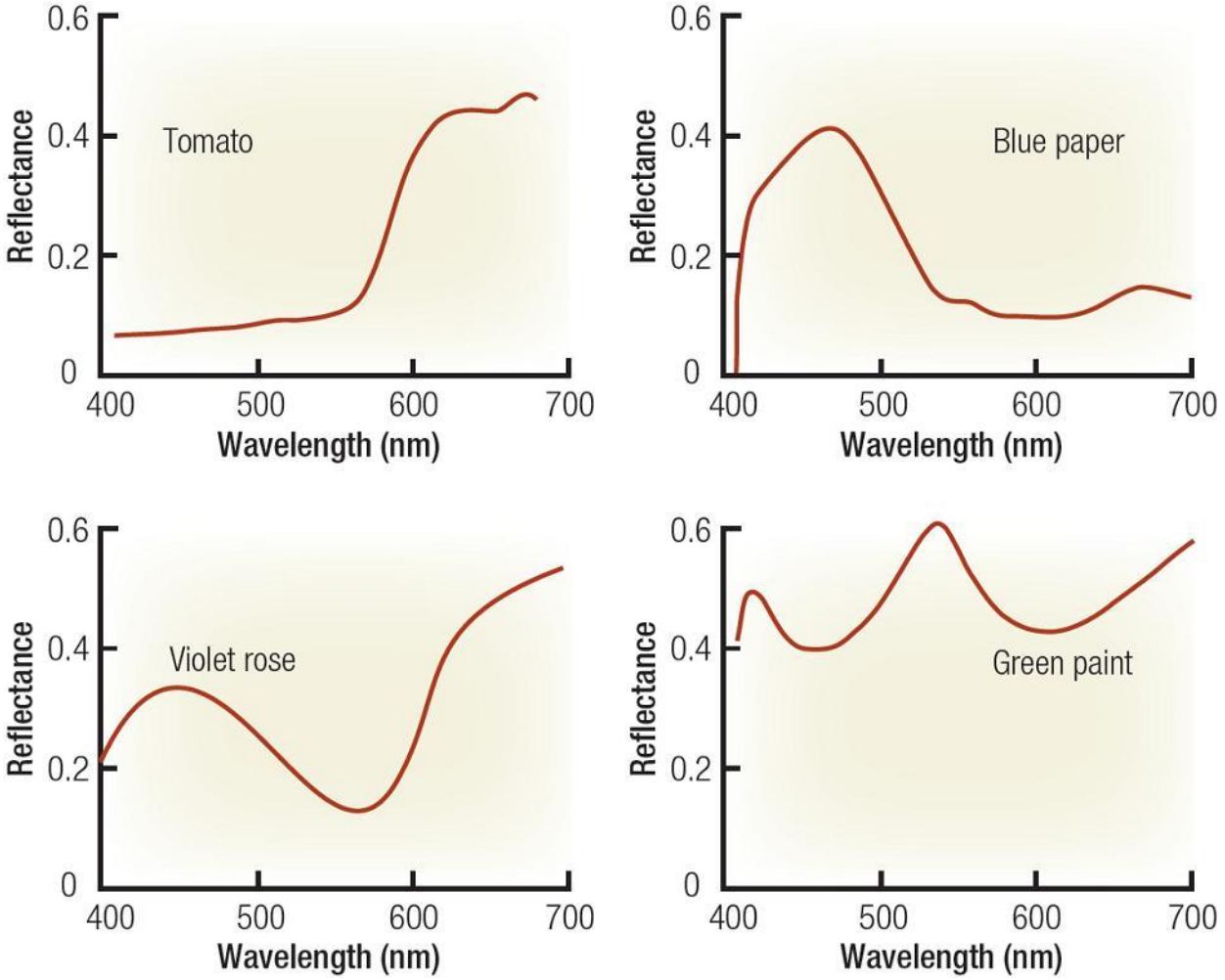
Incandescent Lamps



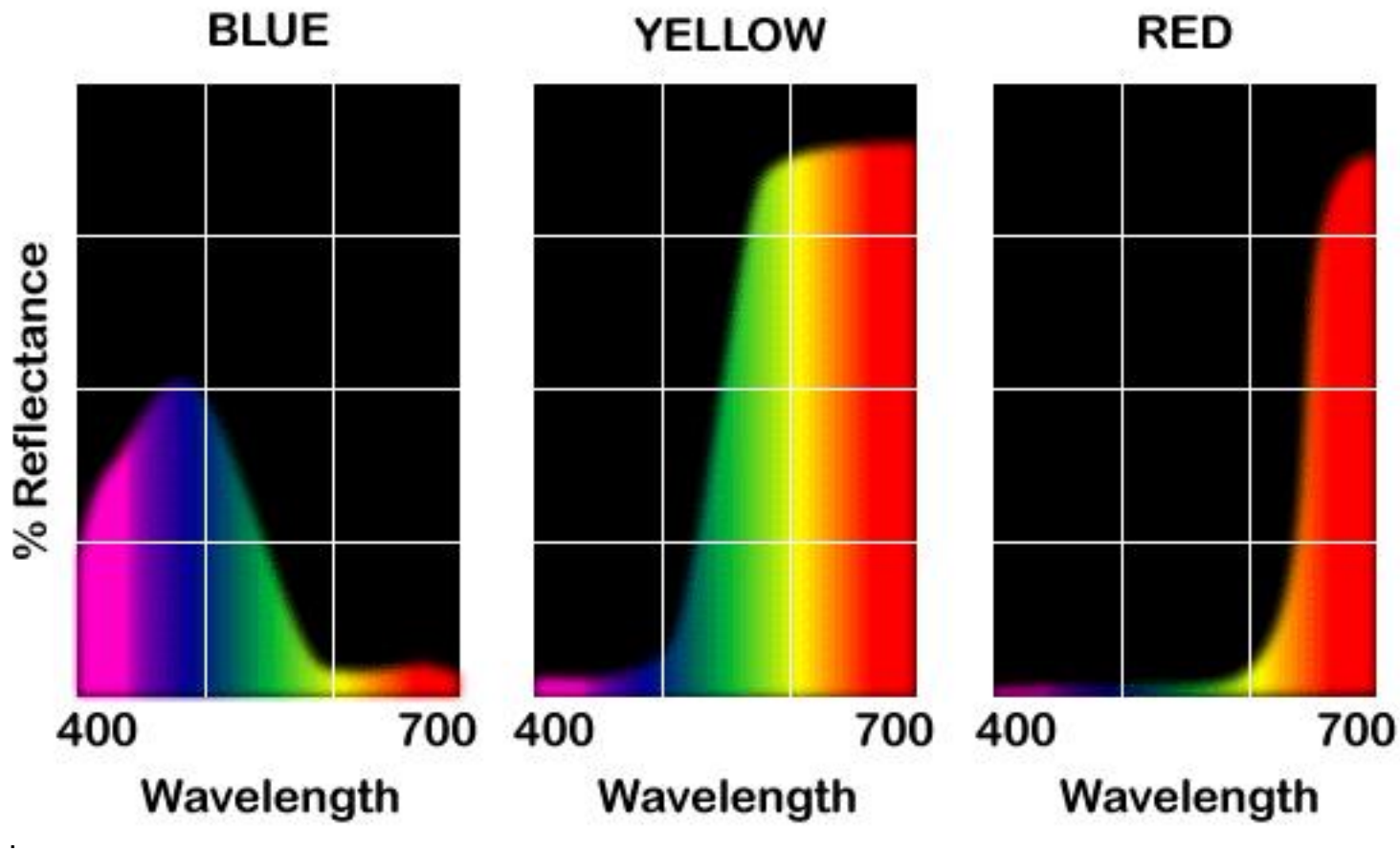
Surface Reflectance Spectra

Objects REFLECT some wavelengths but ABSORB others….

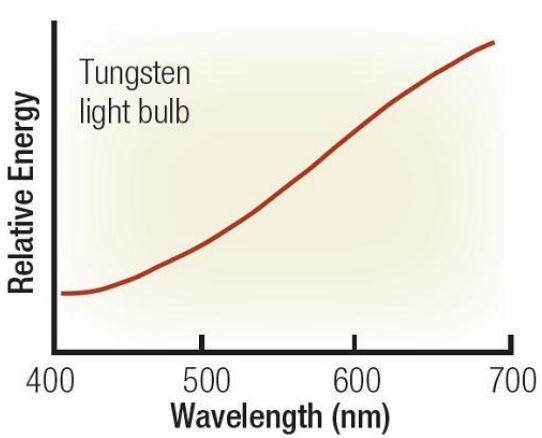
Surface Reflectance Spectra

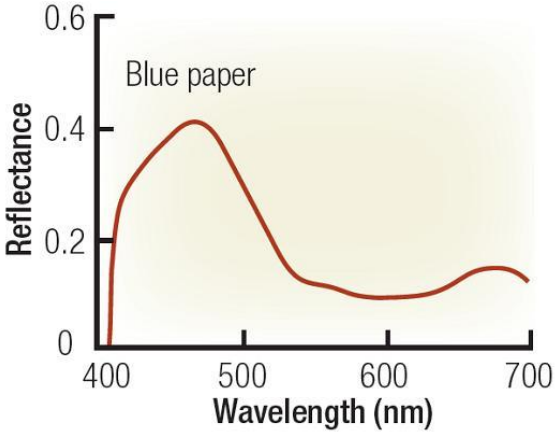


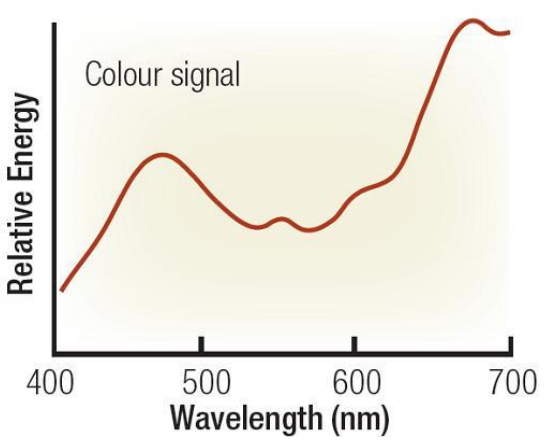
The Spectral Reflectance Profile is the basic stimulus for Color Vision



Visual Stimulus Spectrum = Illuminant x Surface Reflectance

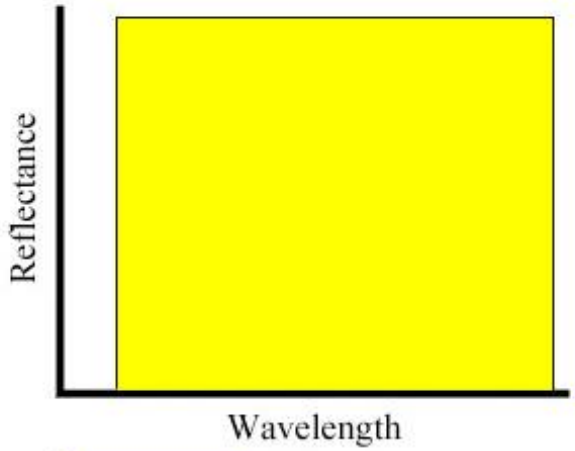




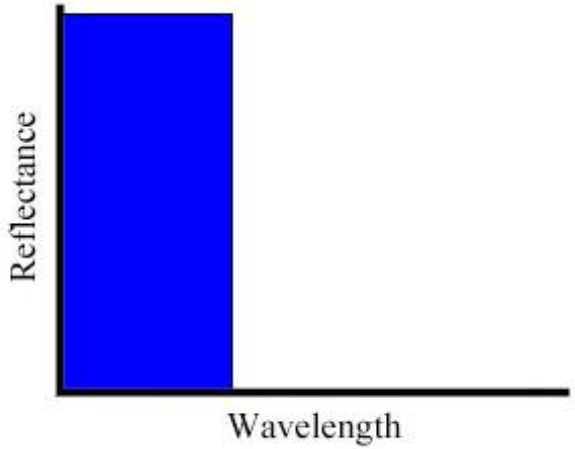


Additive vs. Subtractive Color Mixing

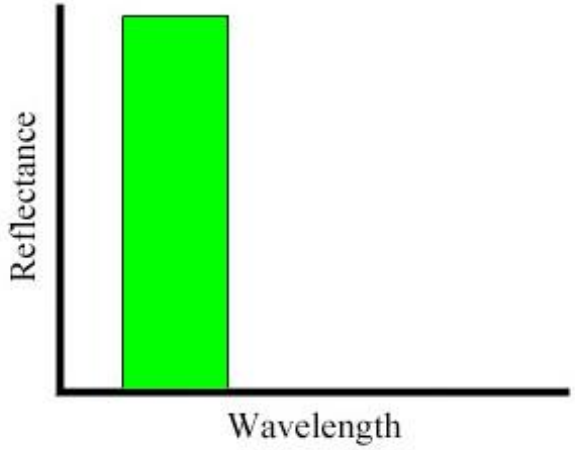
- Color Mixing Demo



Ideal “Yellow” Pigment



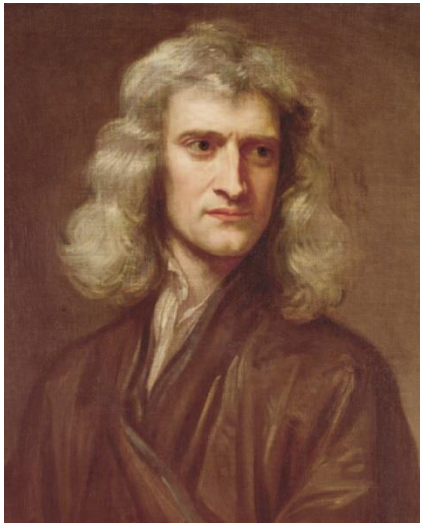
Ideal “Blue” Pigment



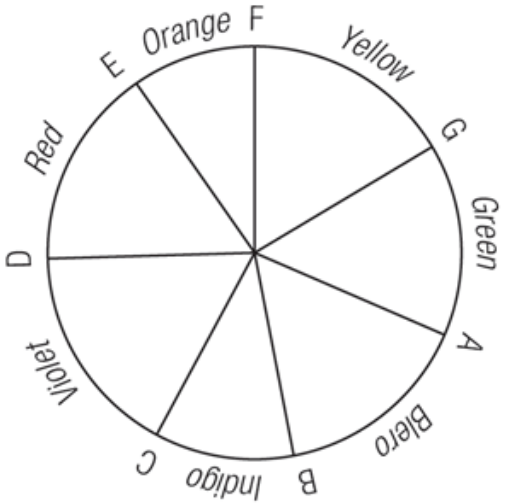
Residual “Green” Pigment resulting from mixing Yellow+Blue

Spectral Response of the Visual System

Newton's Color Experiments



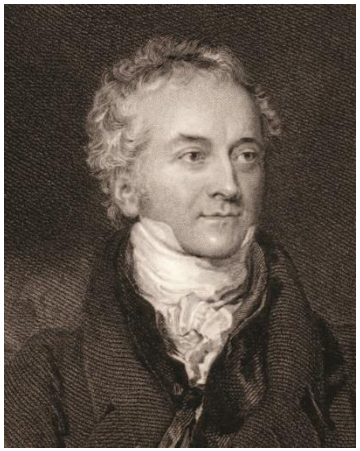
Sir Isaac Newton
(1643-1727)



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 psychological theories in the classic scientific literature

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

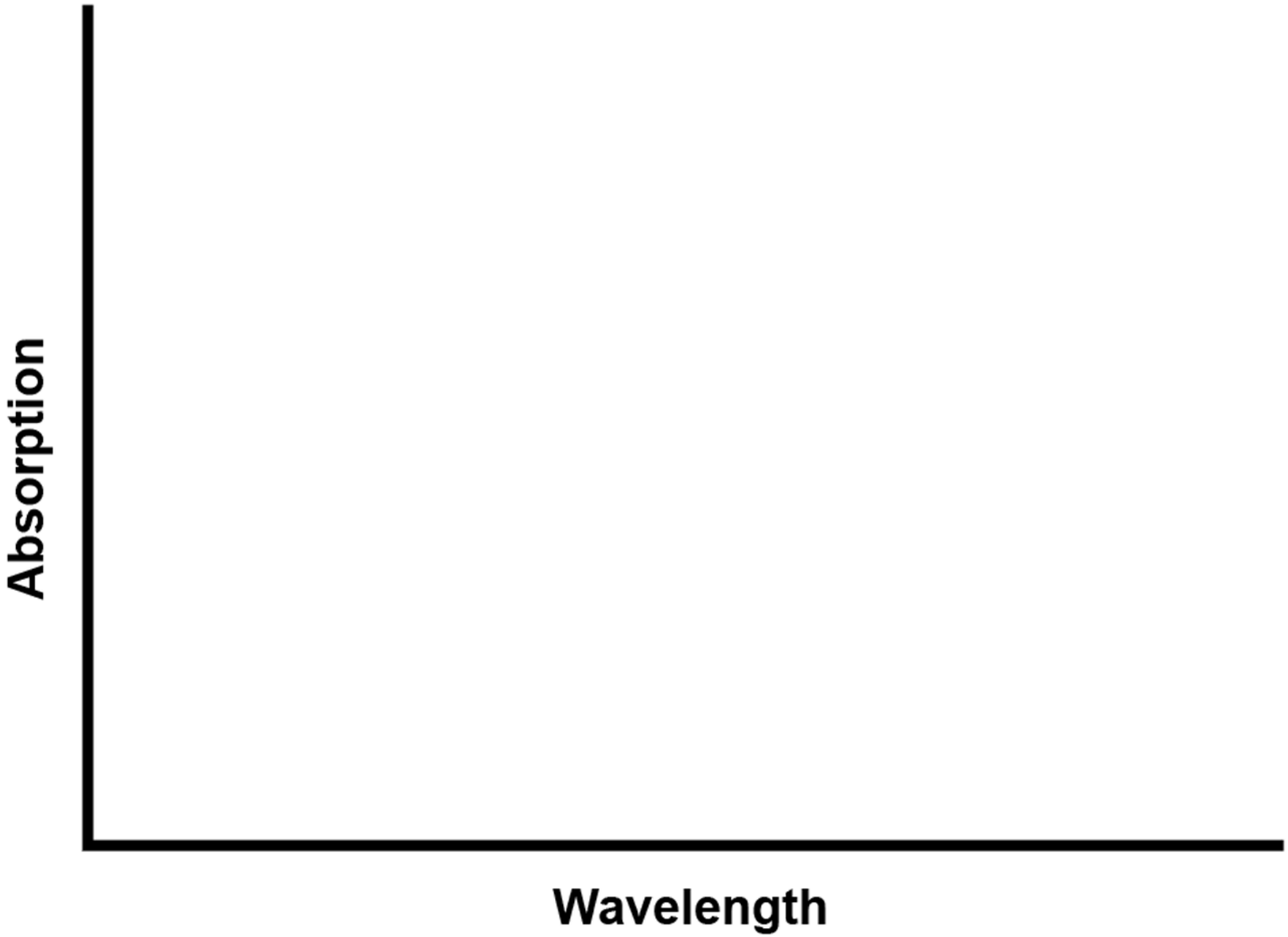
- Evidence strongly suggests that the retina must "encode" color based upon more than one type of wavelength-tuned photoreceptor
  [***Univariance Principle***]

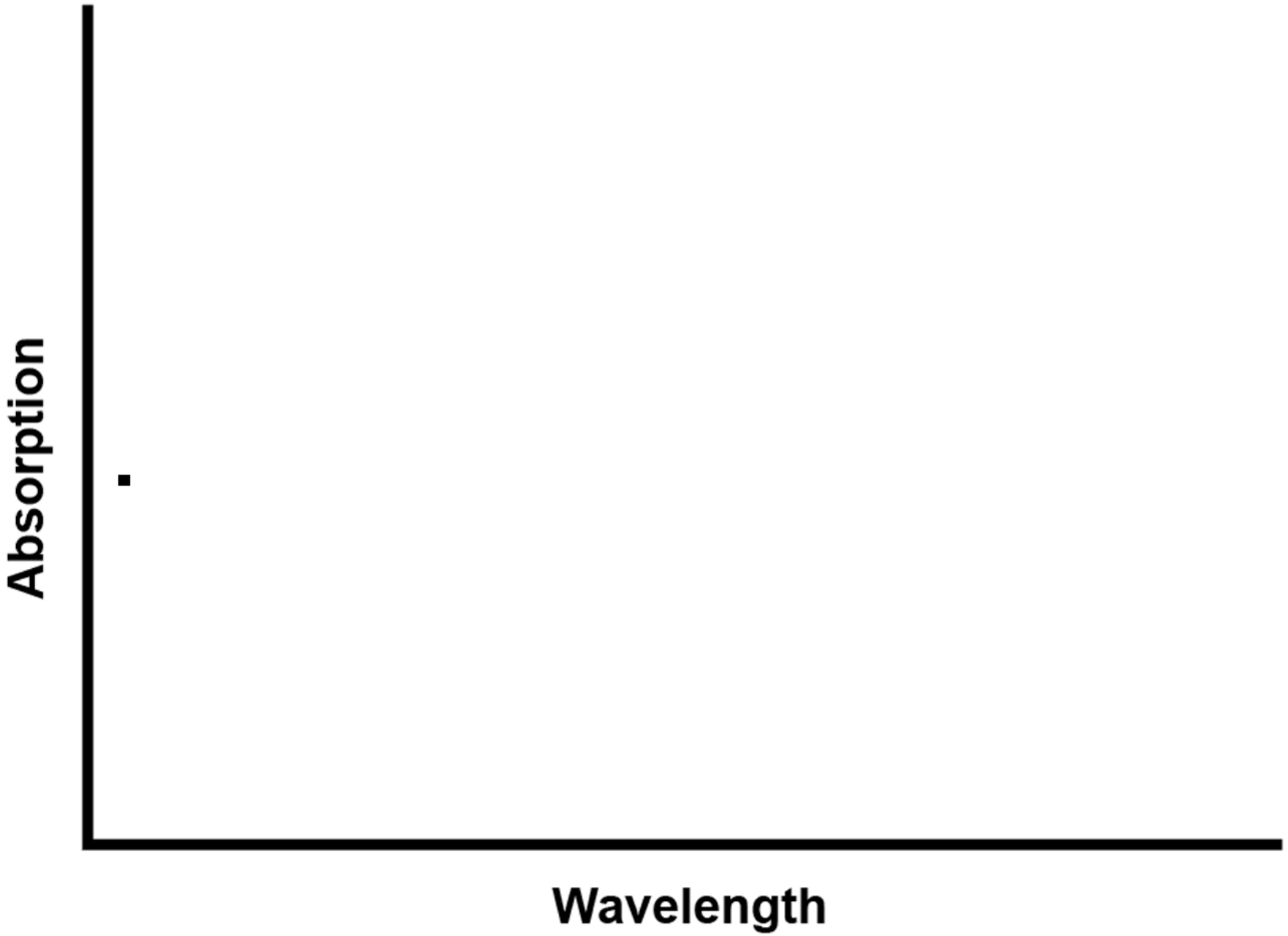
- Additive color matching experiments suggest that three wavelength sensors are required
  [aka Trichromatic Theory]

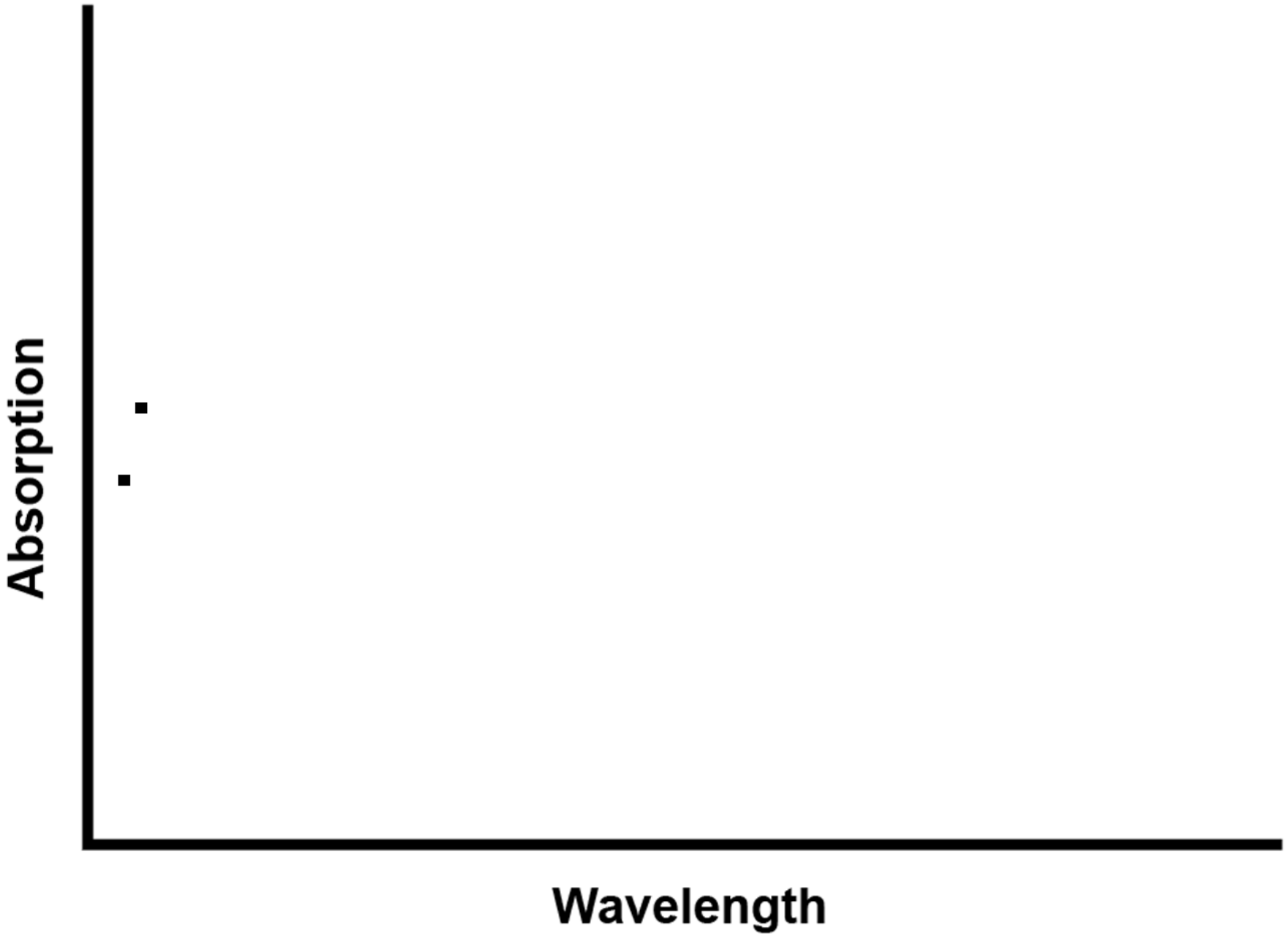
Classic Color Demonstrations Explained by Trichromatic Mechanism

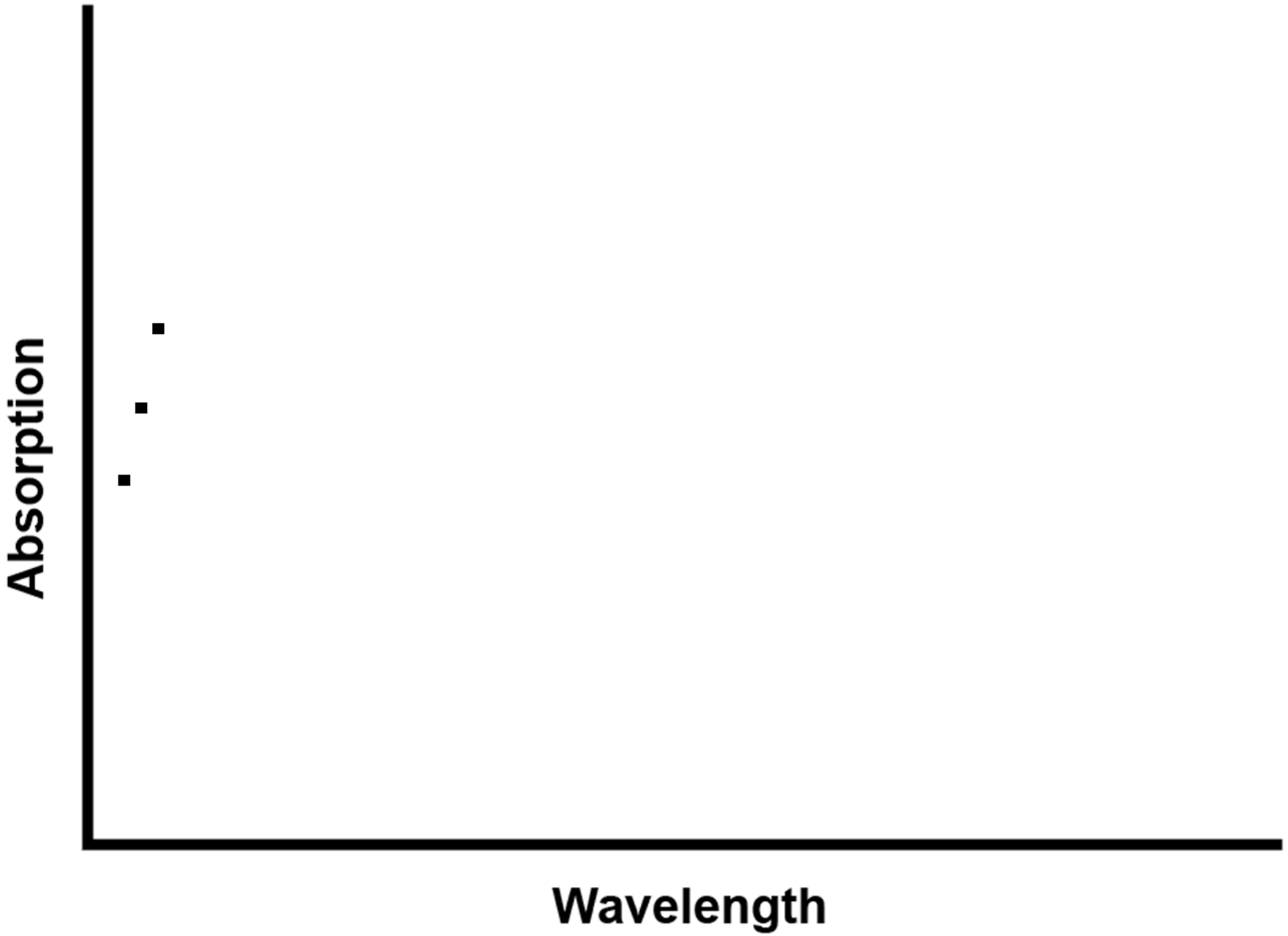
- Tristimulus Color Mixing Findings
  Maxwell Color Matching
- Fast Color Adaptation
  (Basis for **Color Constancy**)

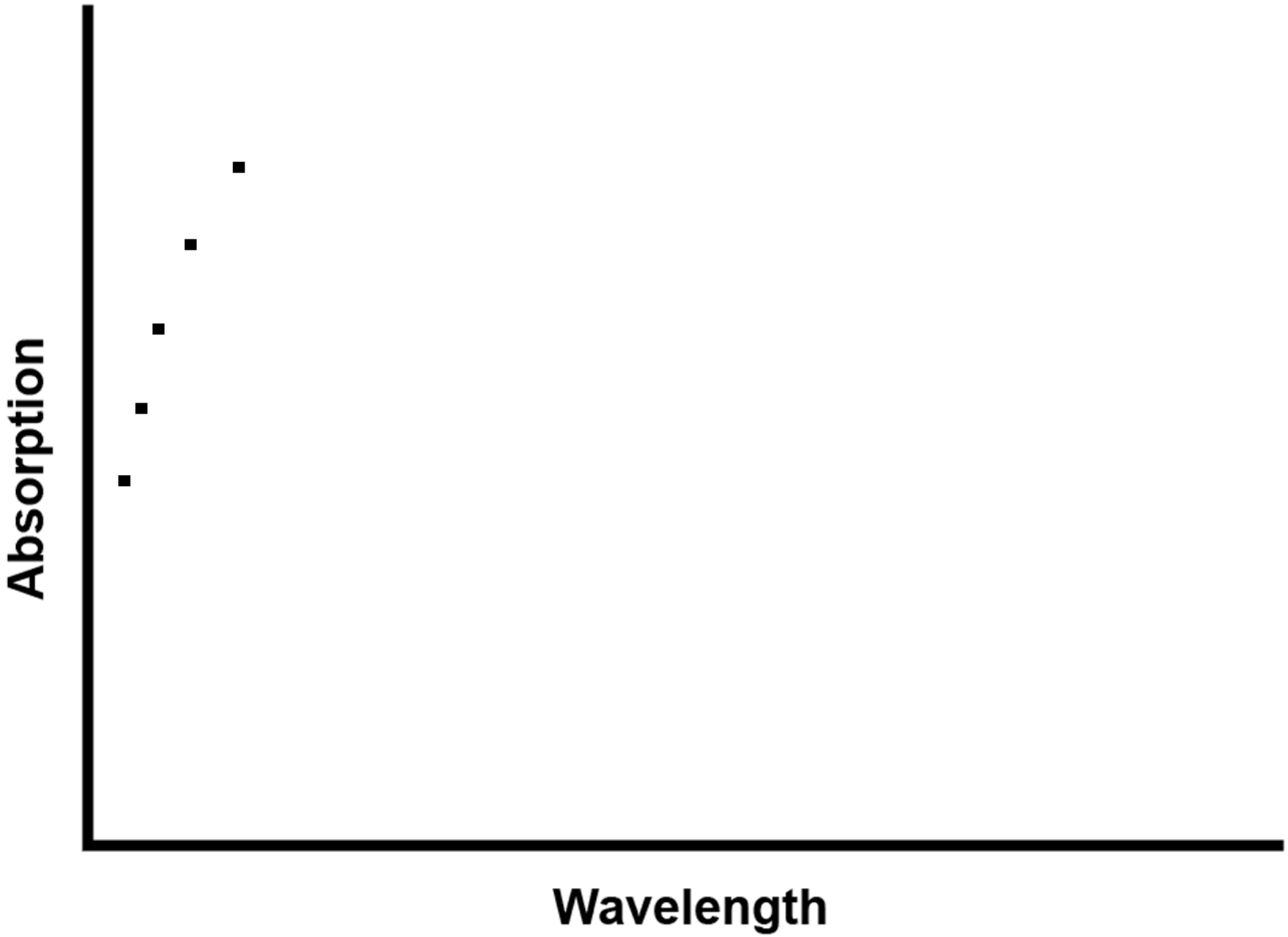
Simulated Microspectrophotometry Analysis of Human Retina

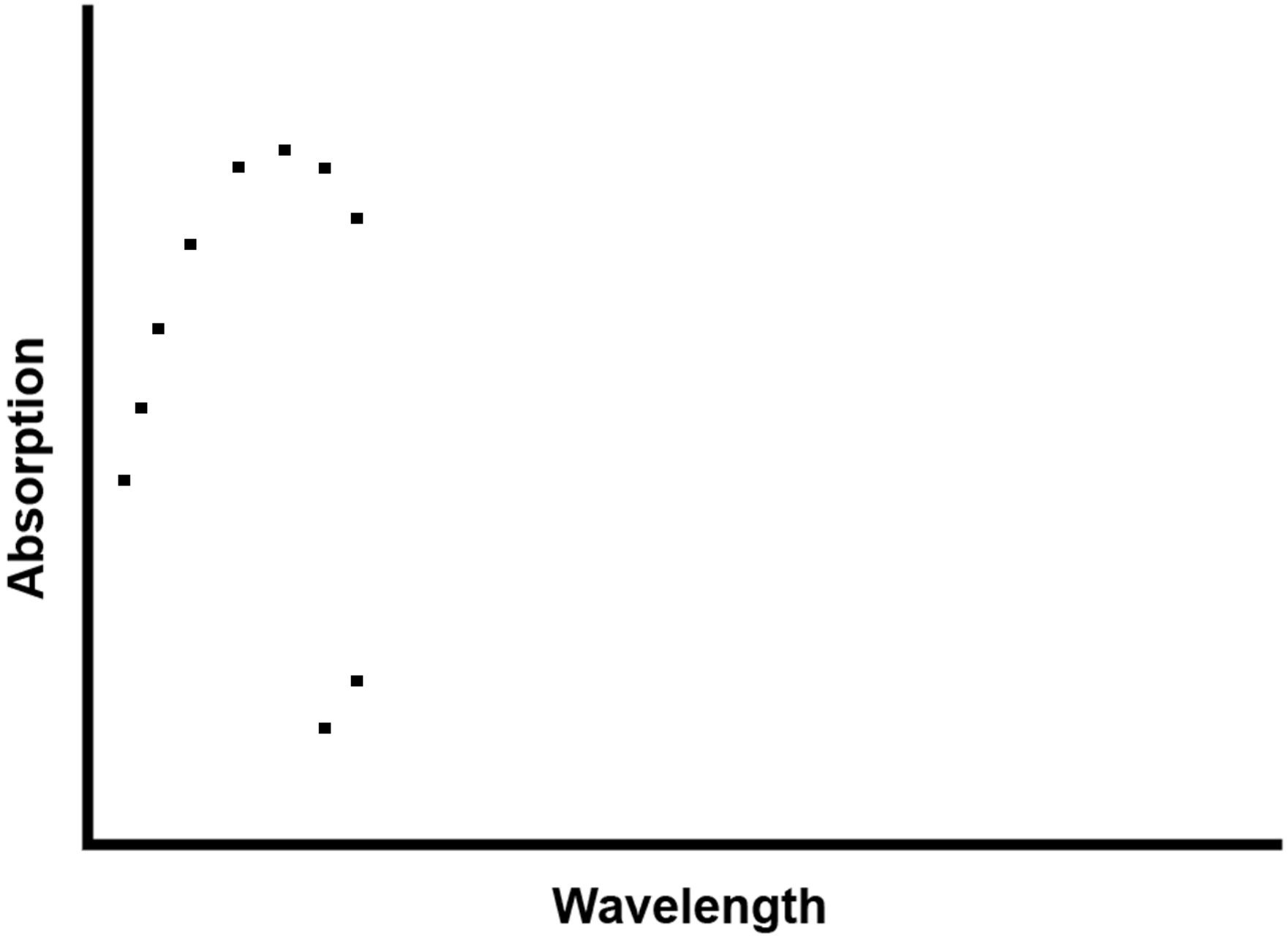

Absorption
Wavelength

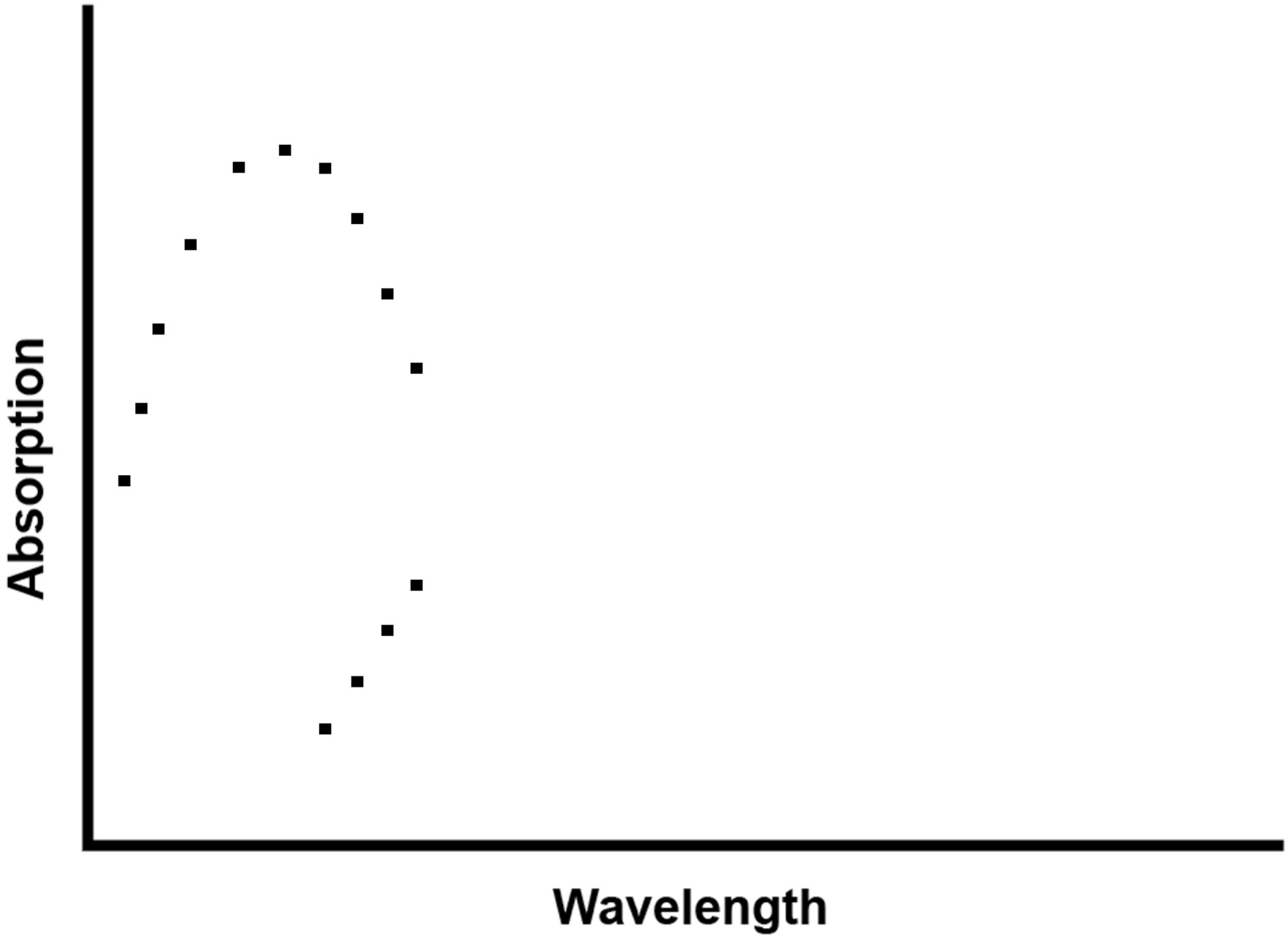

Absorption
Wavelength

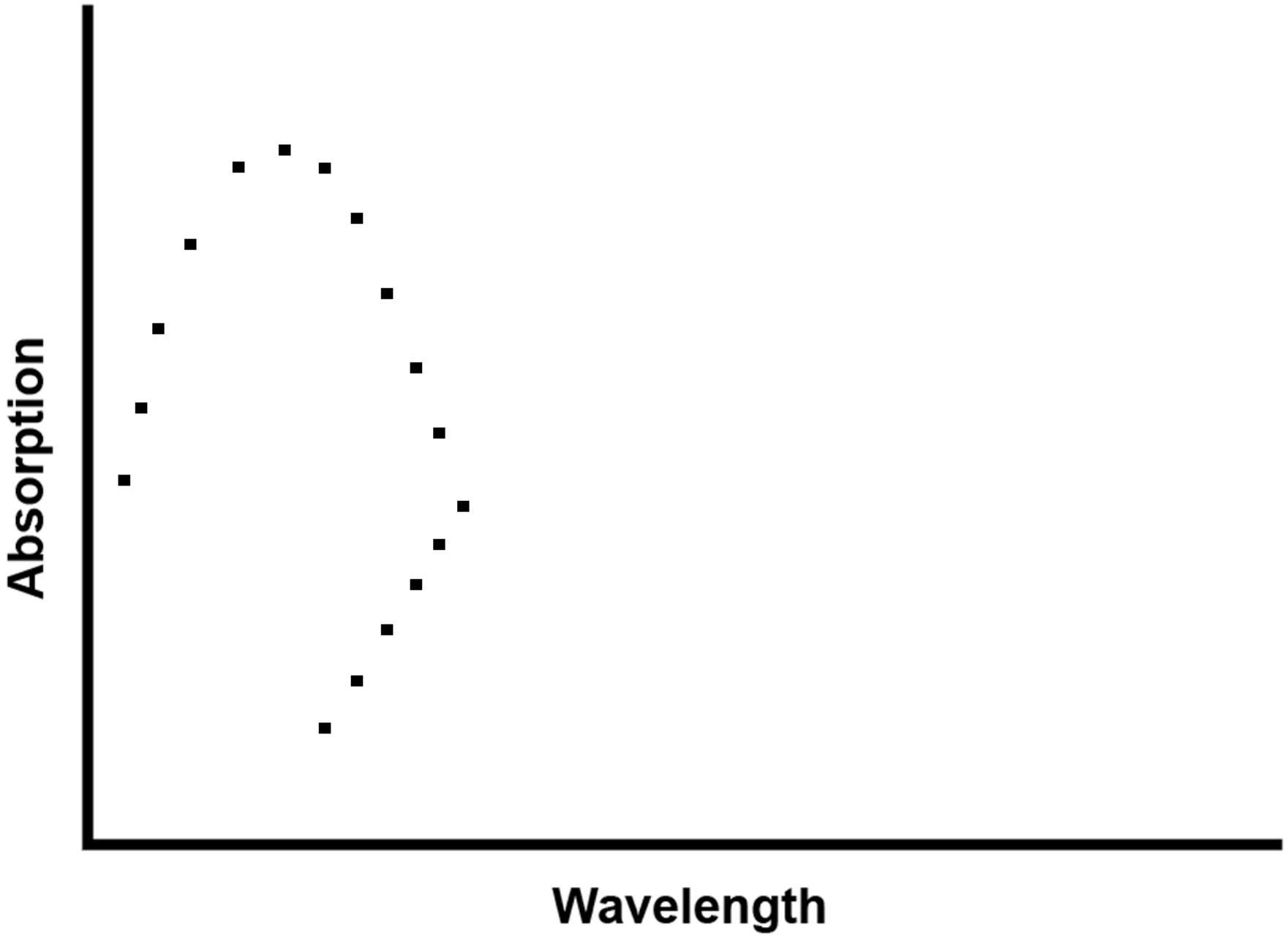

Absorption
Wavelength

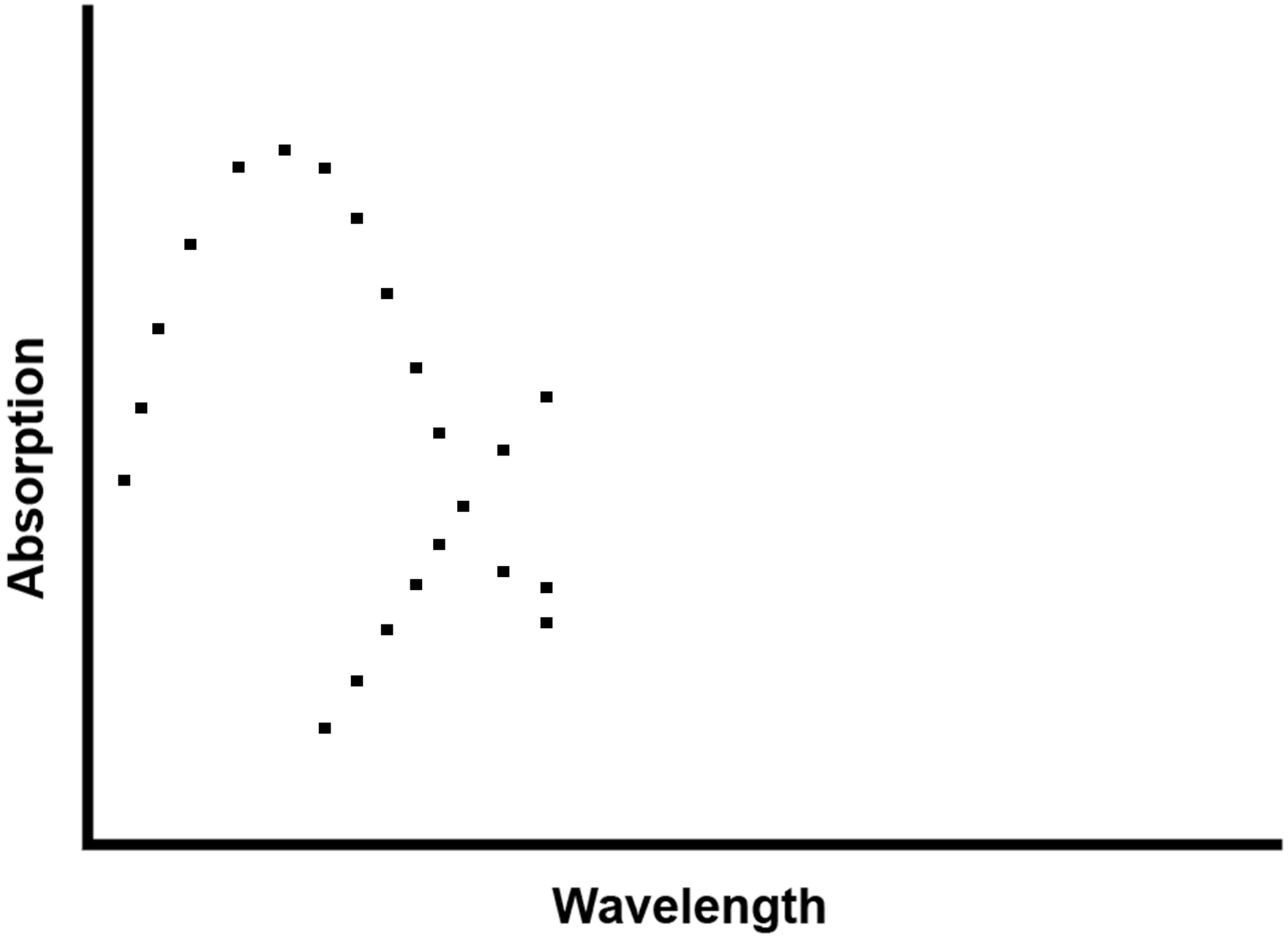

Absorption
Wavelength

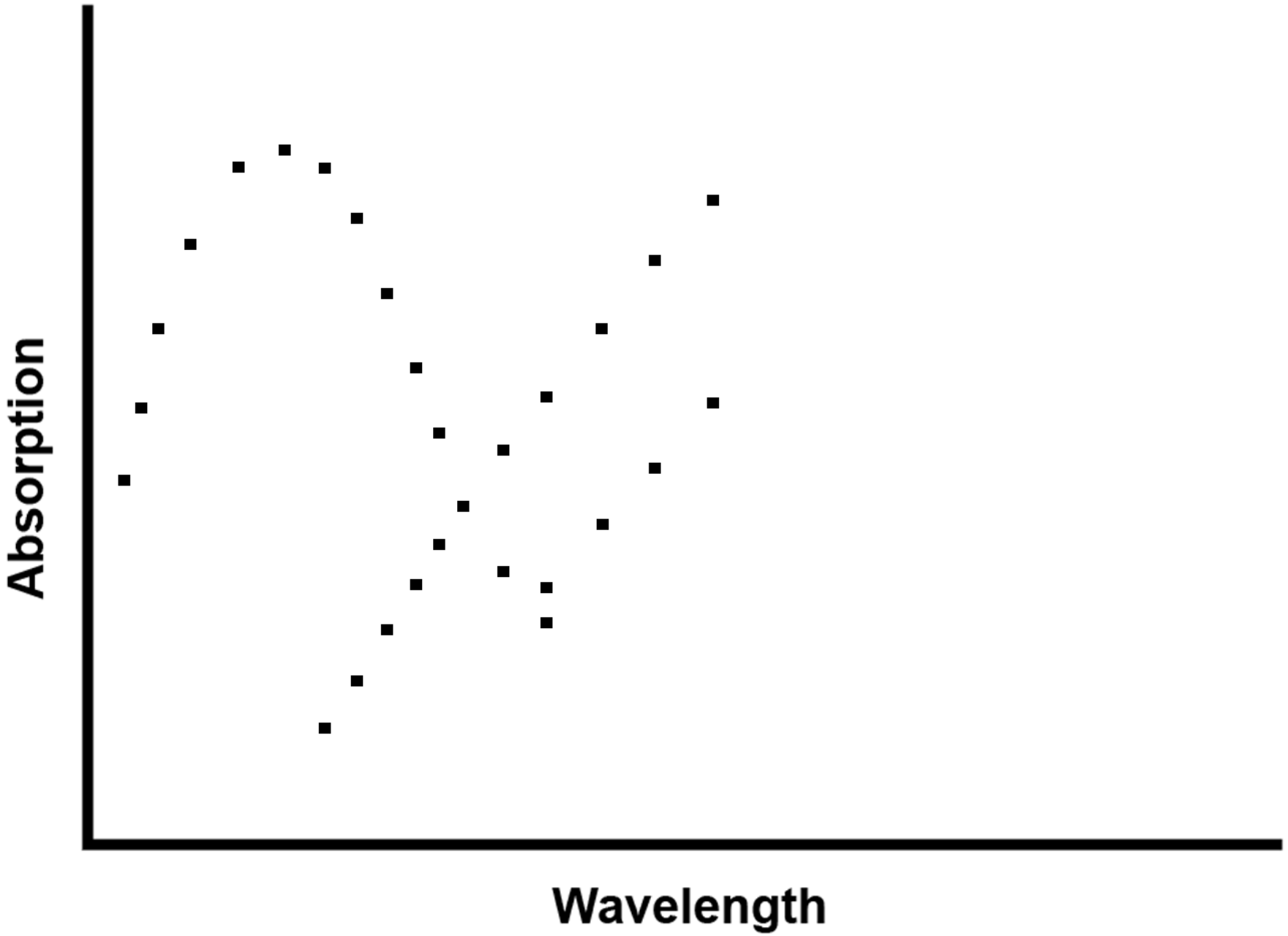

Absorption
Wavelength

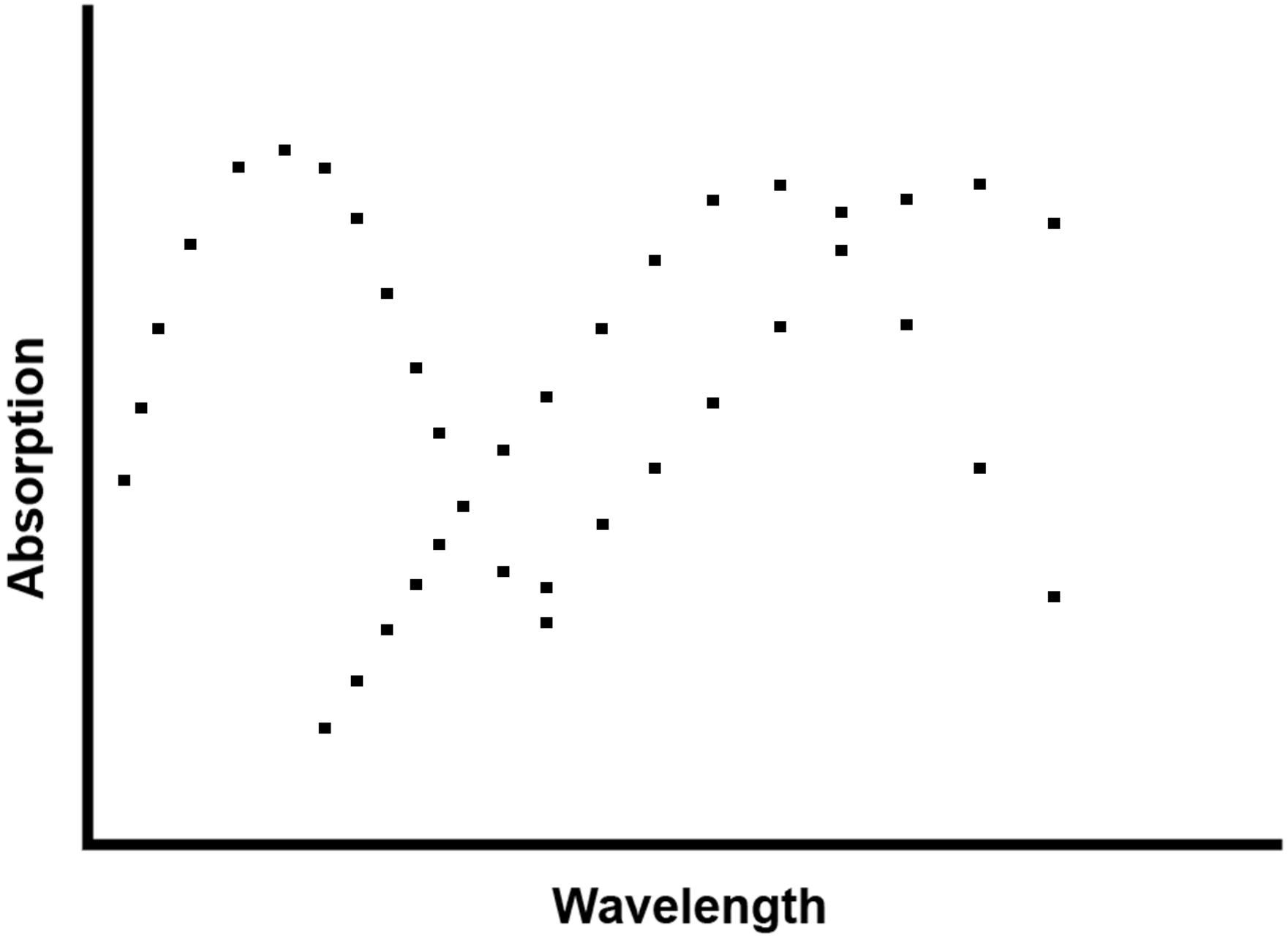

Absorption
Wavelength

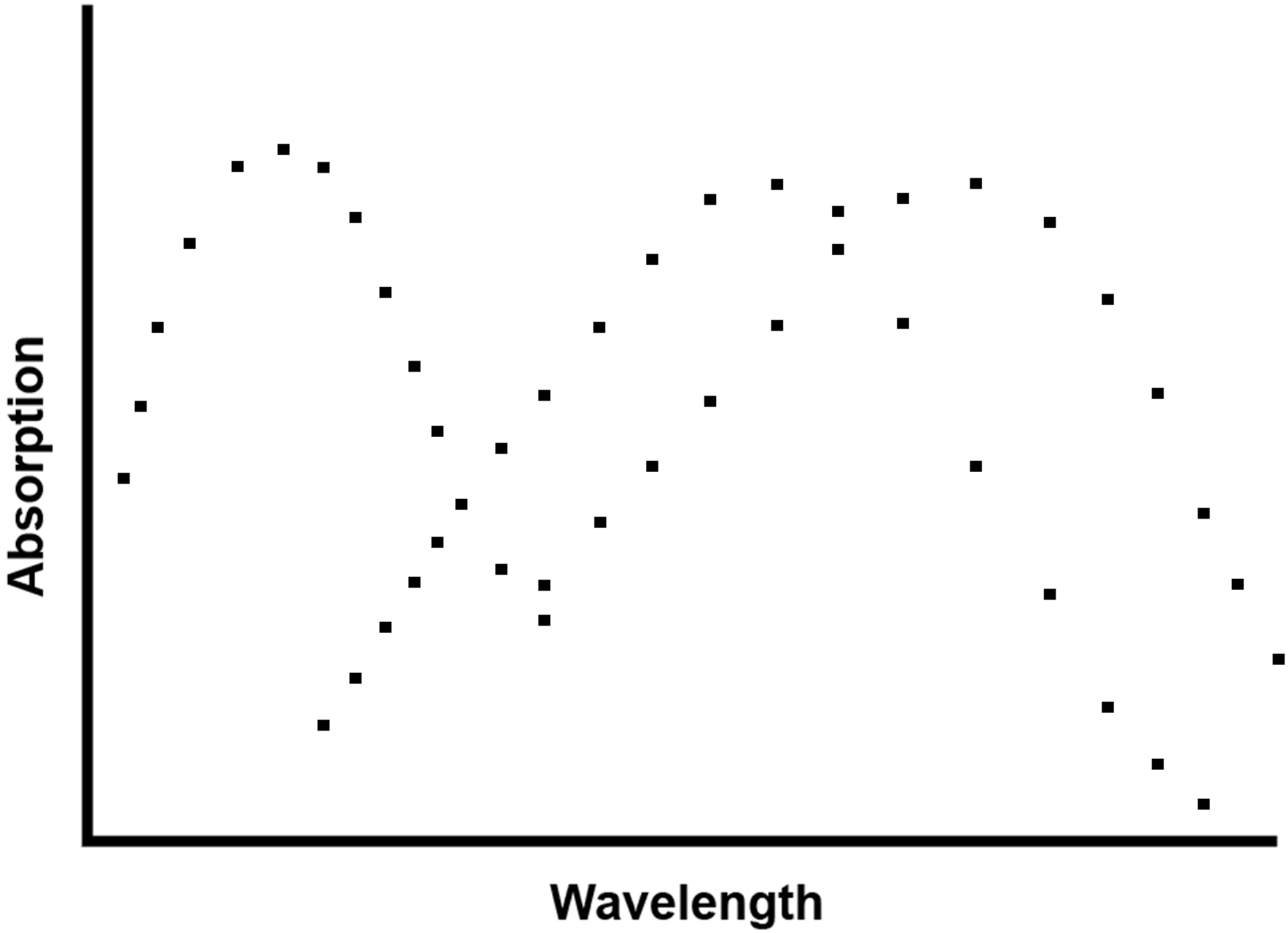

Absorption
Wavelength


Absorption
Wavelength

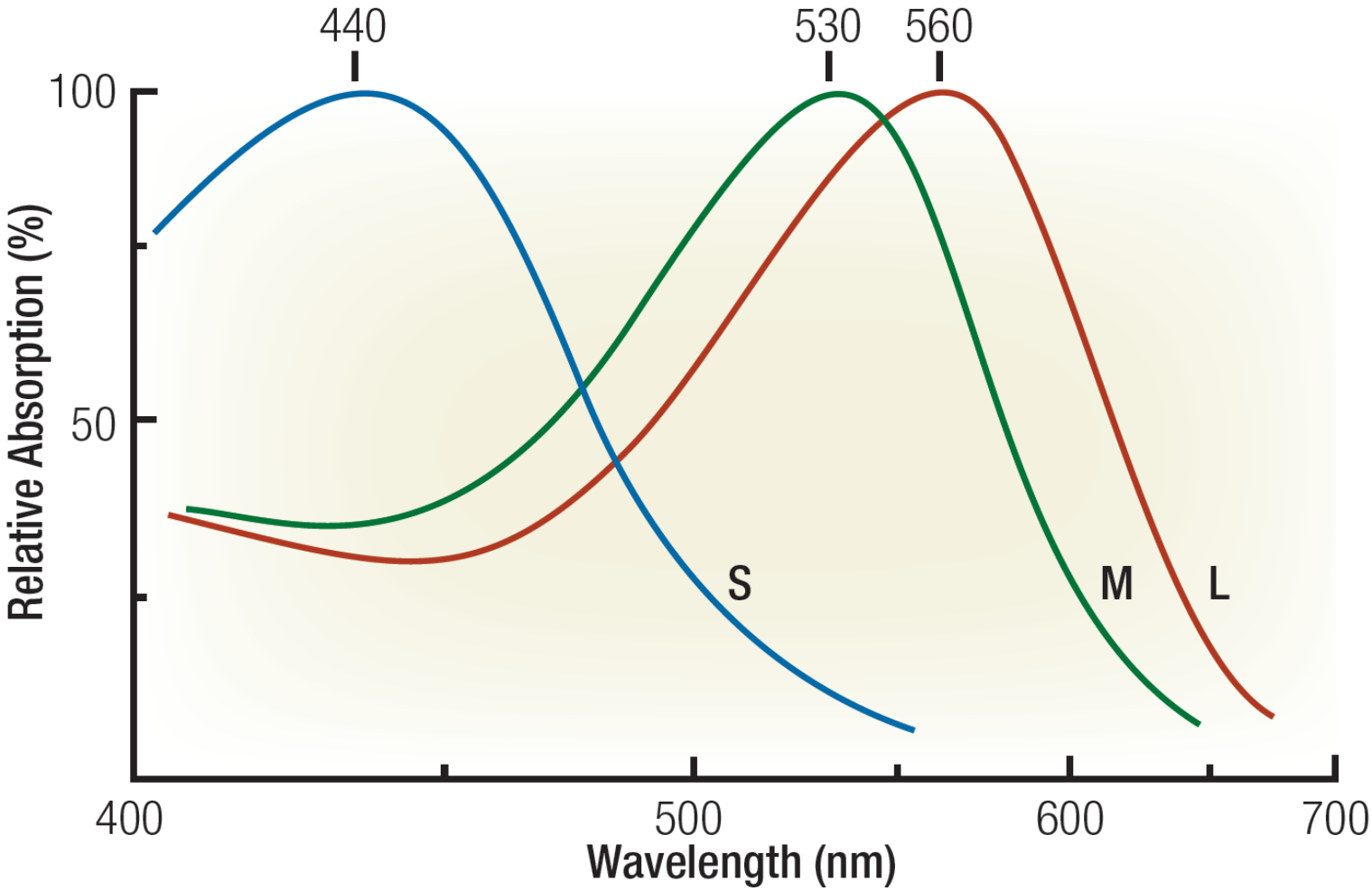

Absorption
Wavelength


Absorption
Wavelength

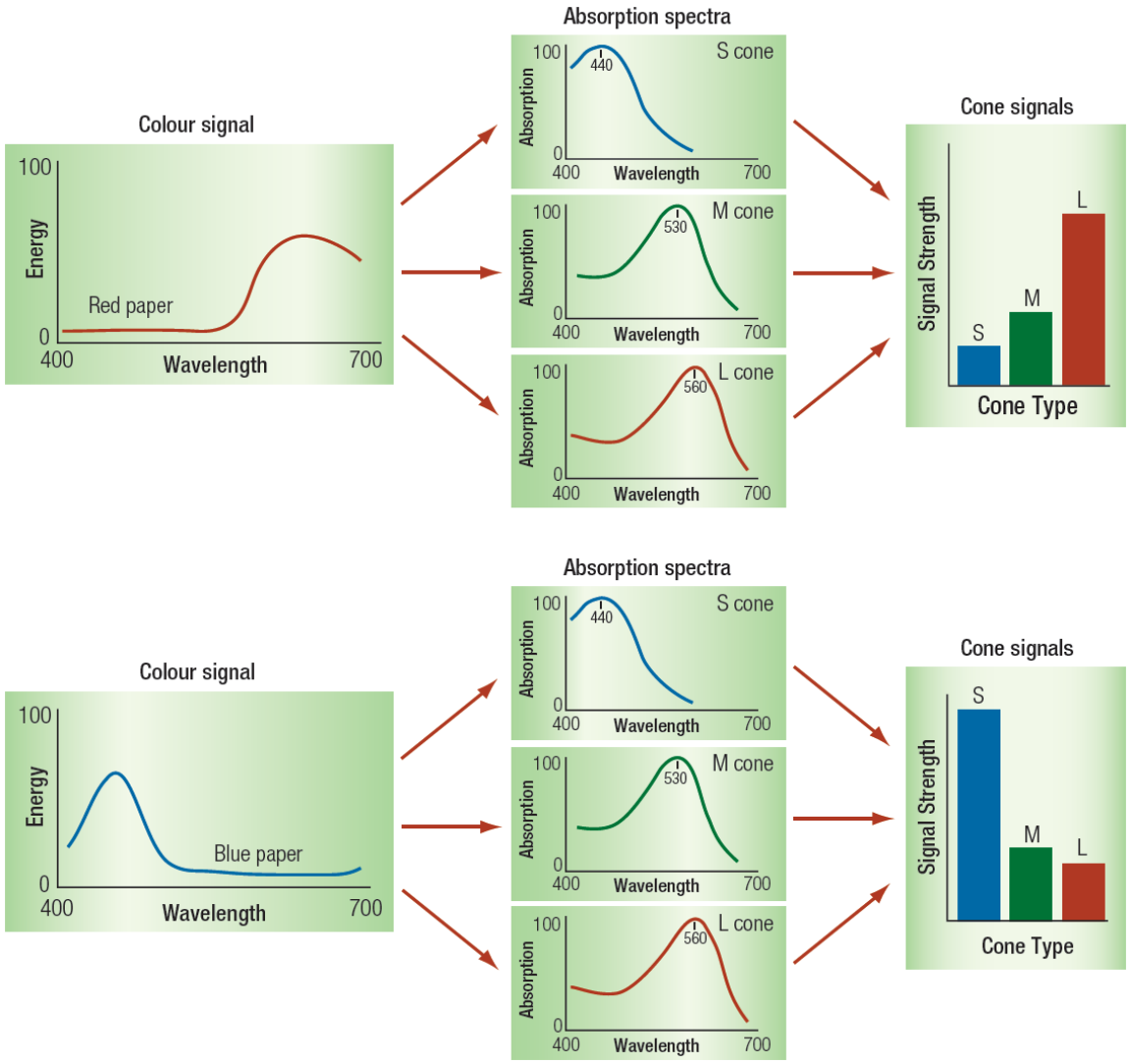

Absorption
Wavelength


Absorption
Wavelength

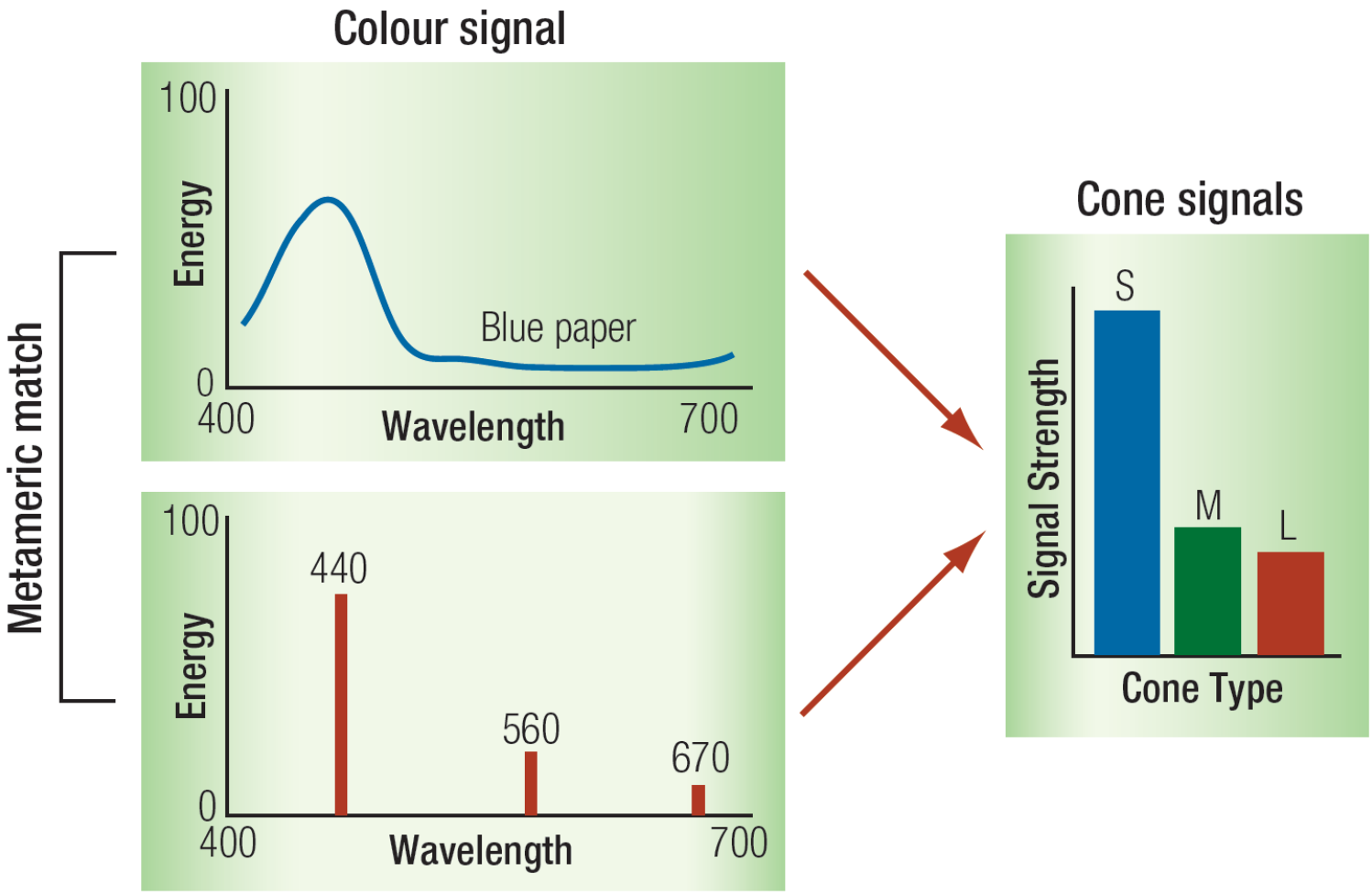
3 Cones Revealed by MSP



Trichromatic Response to Spectral Stimulus



Color Metamers



Color Specification Systems
(Hue,Saturation,Brightness)

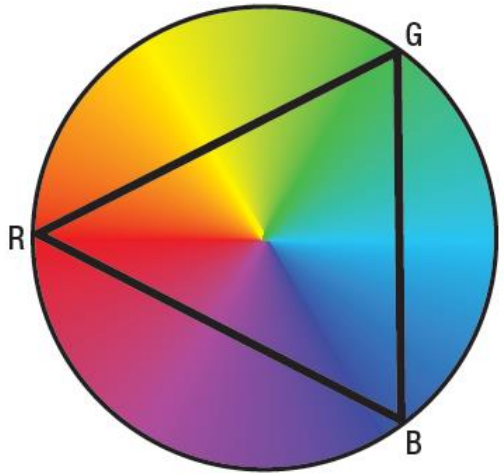
- **CIE (1931) Chromaticity**
  (x,y) captures hue x saturation

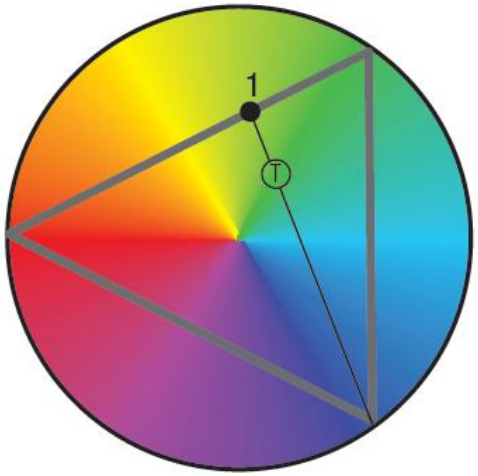
- **Munsell Color System**
  (18 Hues, 18 Chroma; 10 Values)

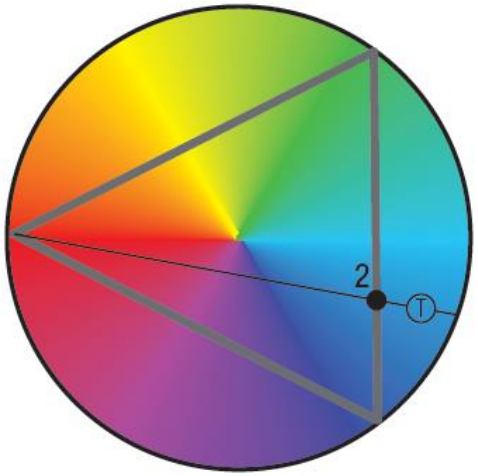
- **Pantone**
  (Proprietary Color Matching Standards)

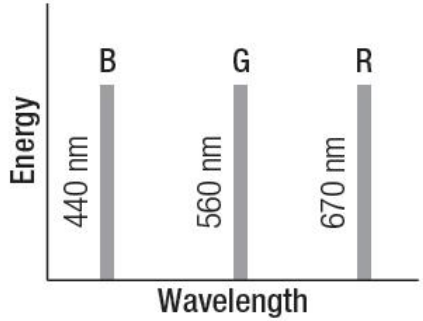
CIE Color Matching Paradigm

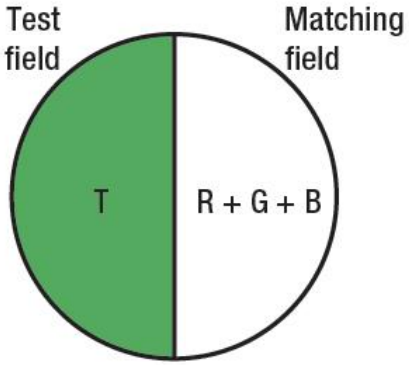
(Specifying Tristimulus Values)

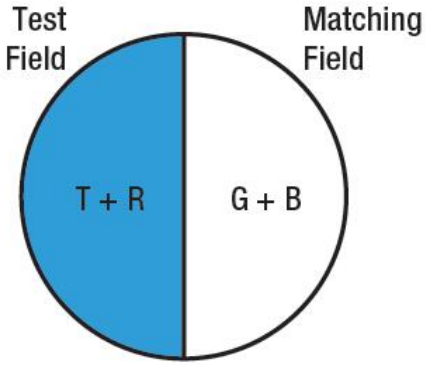


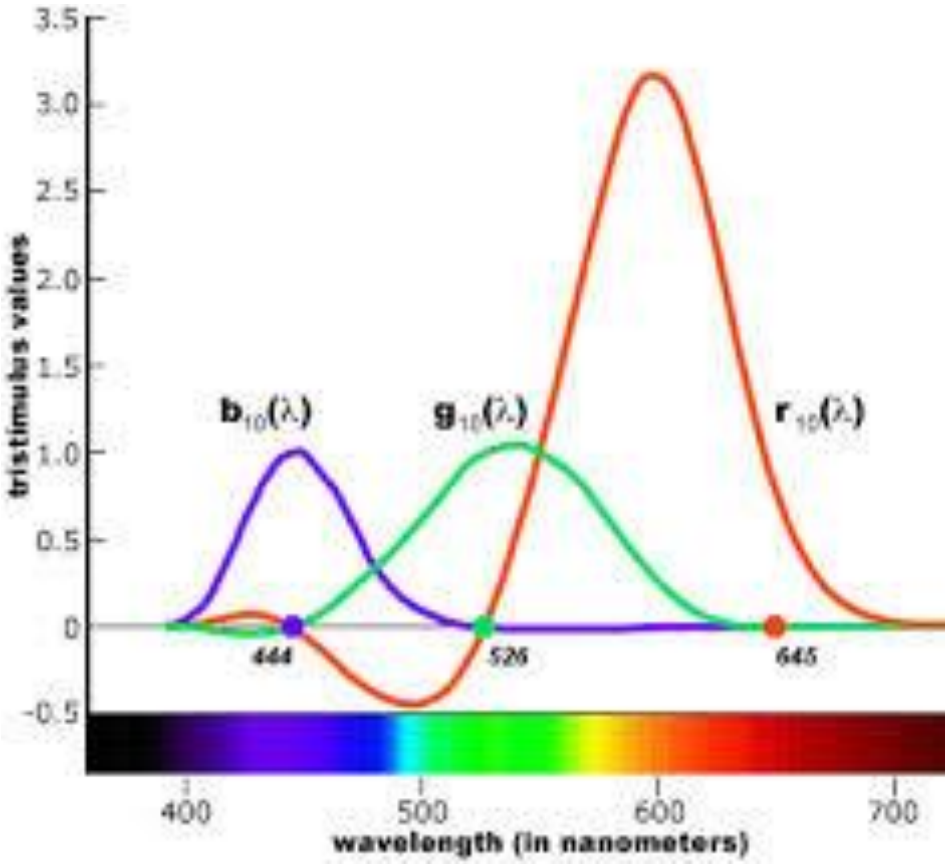




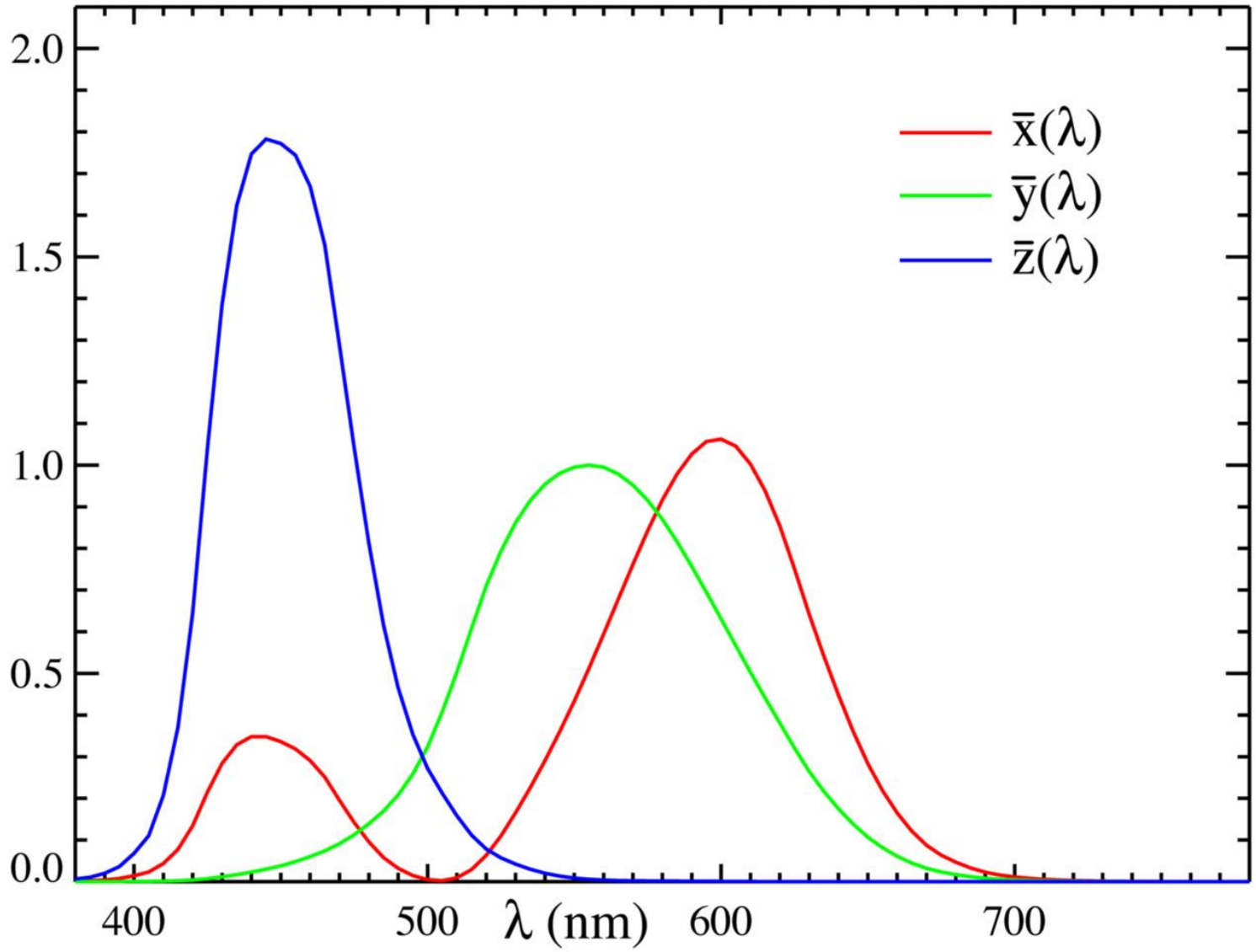








CIE Maxwellian Color Matching Functions



CIE (1931) Standardized Tristimulus Color Matching Functions

CIE (1931) Chromaticity Diagram

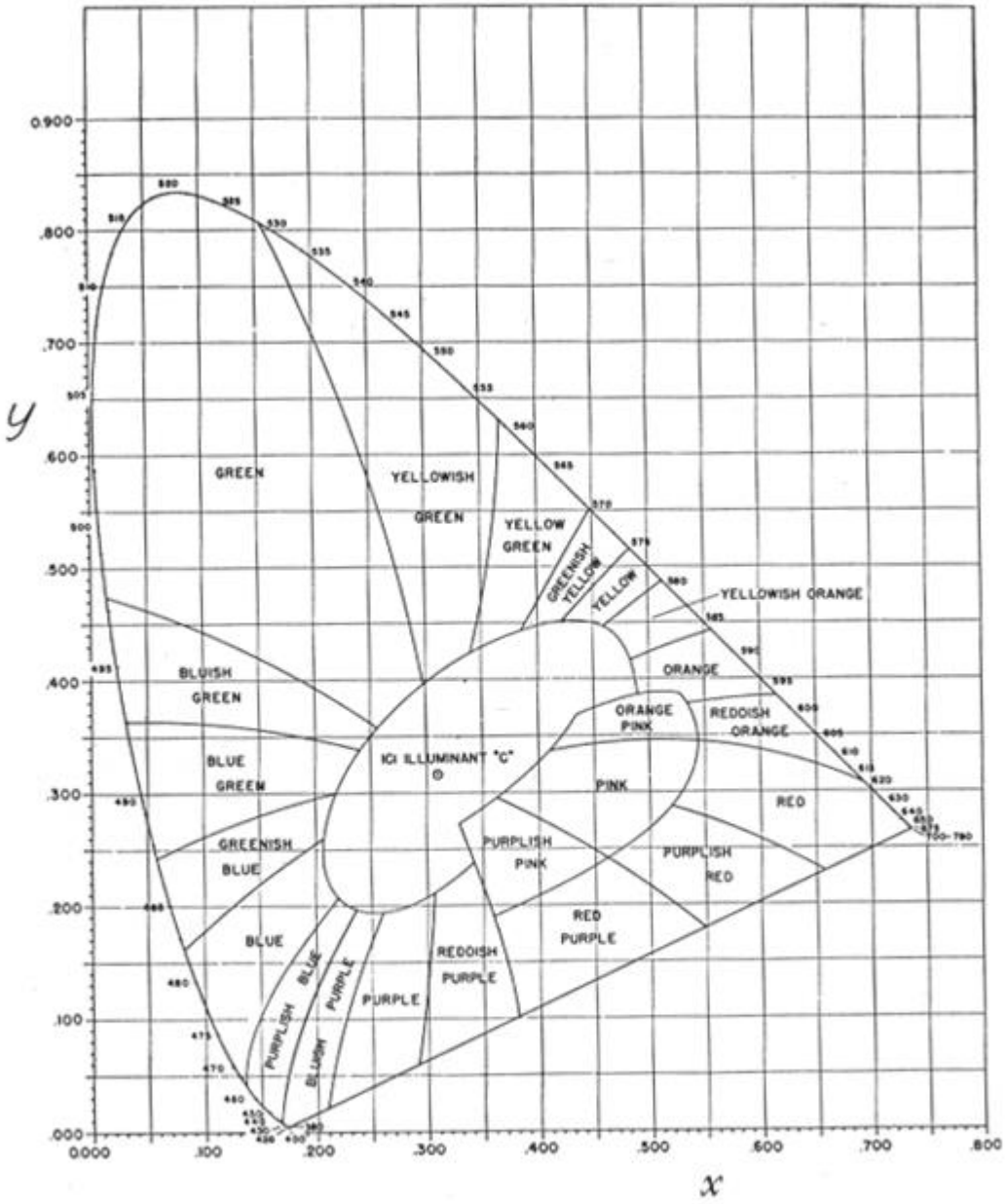


Fig. 4-6. CIE 1931 chromaticity diagram showing color designations for lights, by K. L. Kelly. (From *J. Opt. Soc.* **33**, 627, 1943).

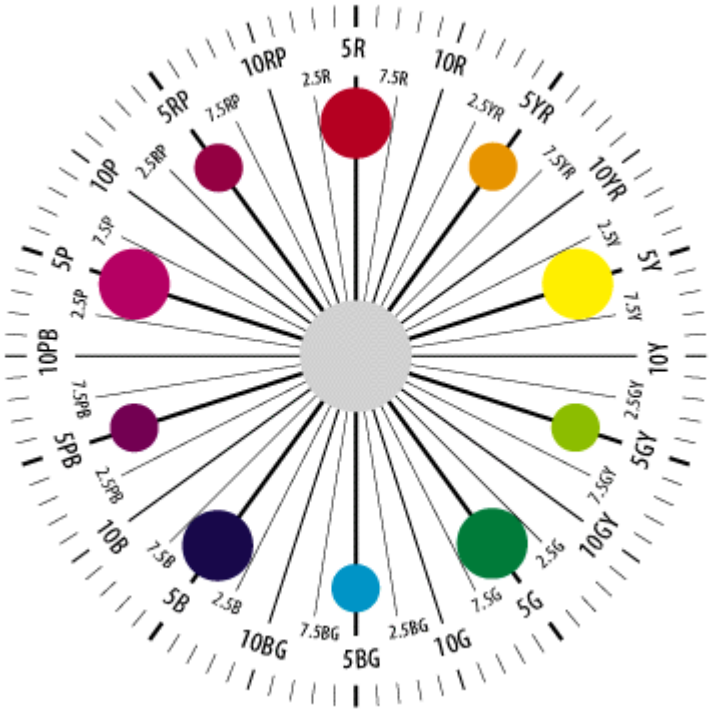
TRISTIMULUS VALUE = X,Y,Z

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

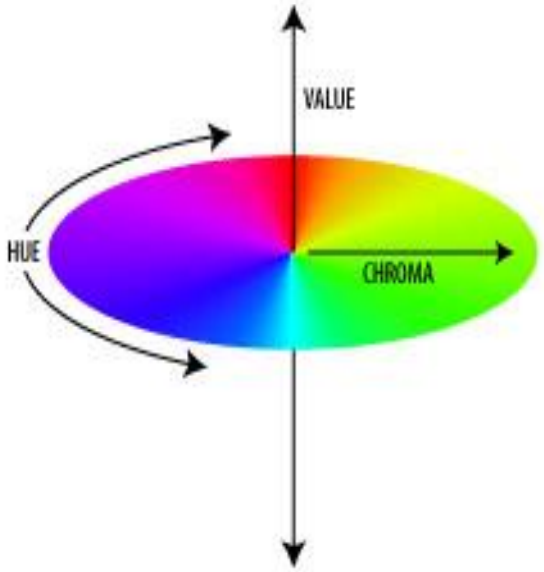
$x = X / (X+Y+Z)$
$y = Y / (X+Y+Z)$
$z = Z / (X+Y+Z)$

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

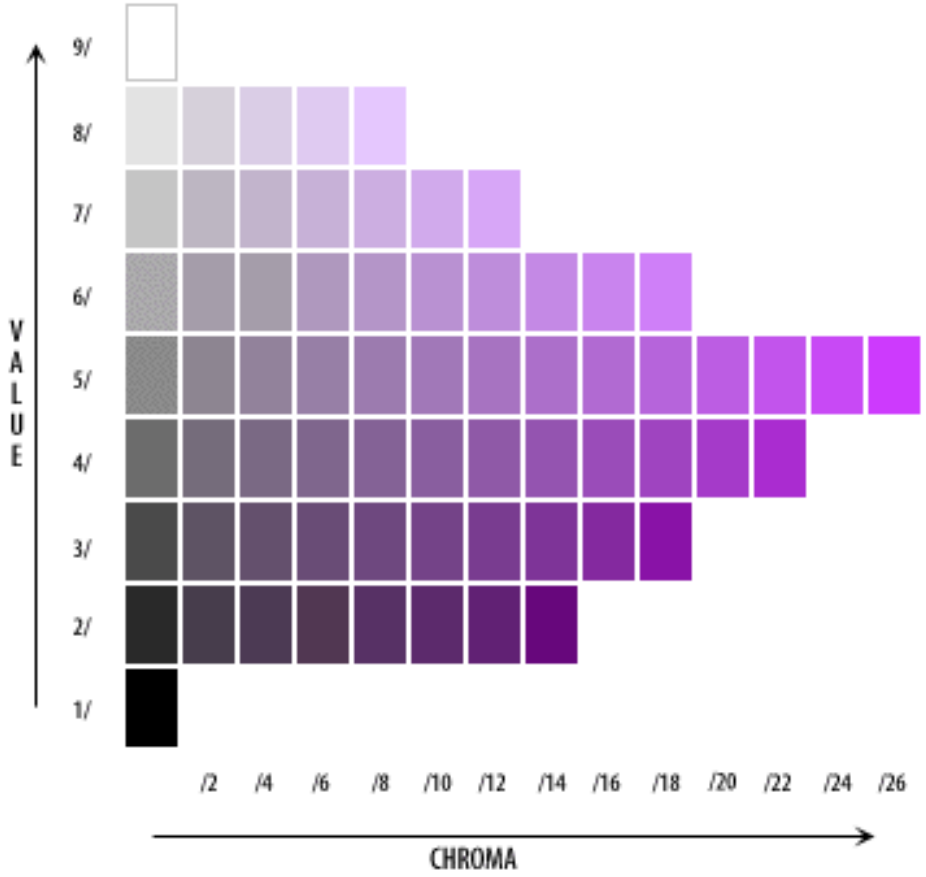
Munsell = (Hue,Value,Chroma)



Munsell Hues



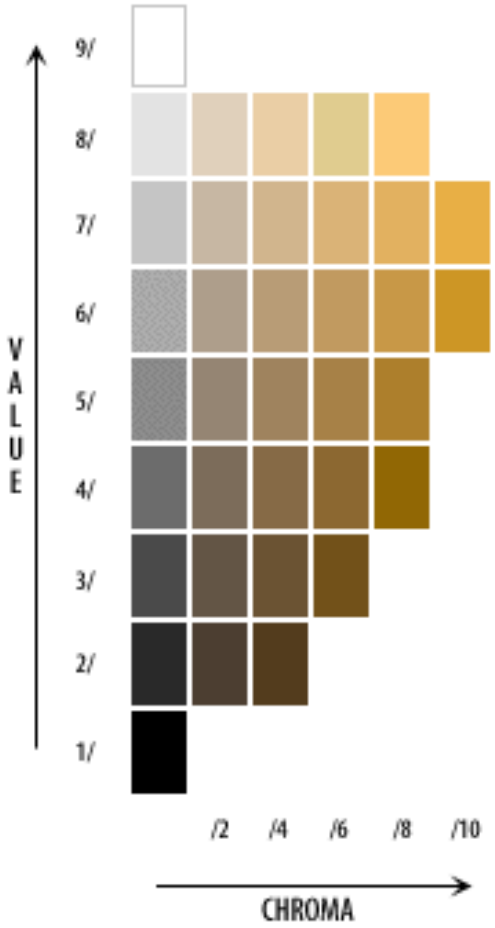
Munsell Book of Colors



Hue 5RP (Red-Purple)

(Most saturated: 5RP 5/26)

Hue — Value — Chroma



Hue 10YR (Yellow-Red)

Problems with 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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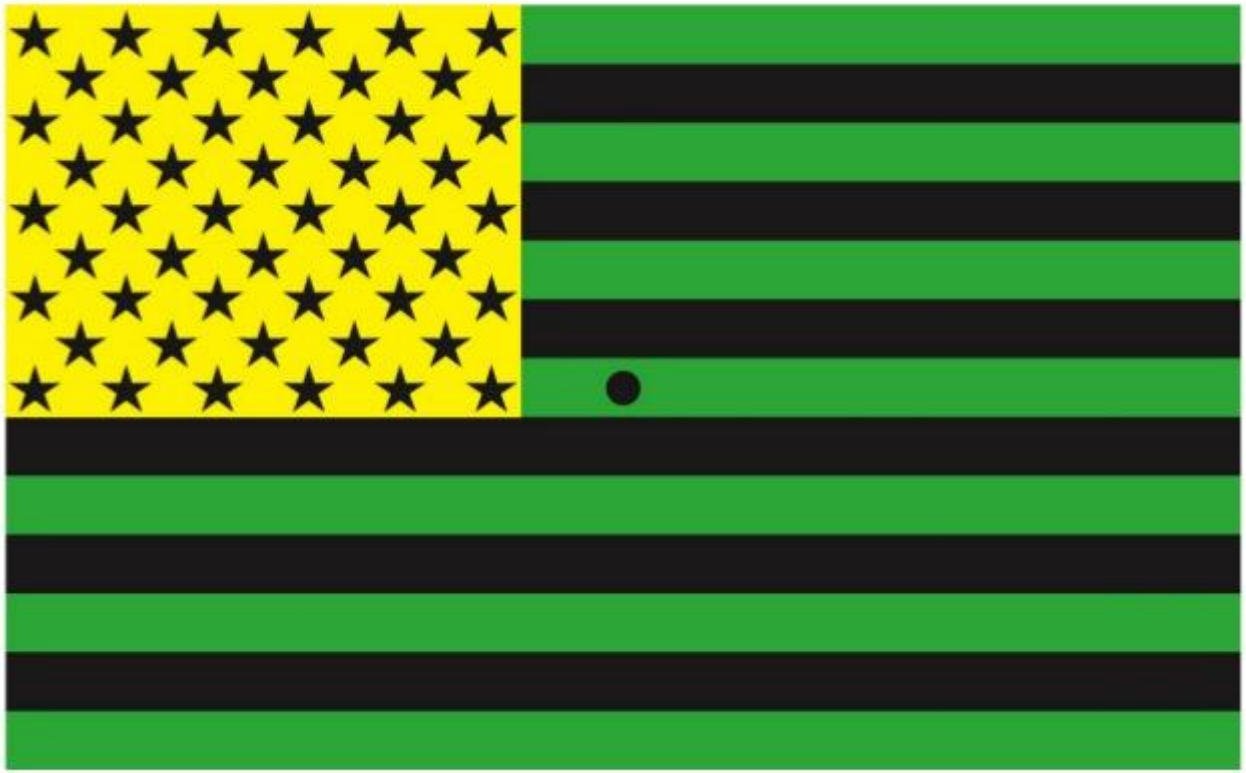
Complementary Color Afterimages

Challenge for Simple Trichromatic Theory



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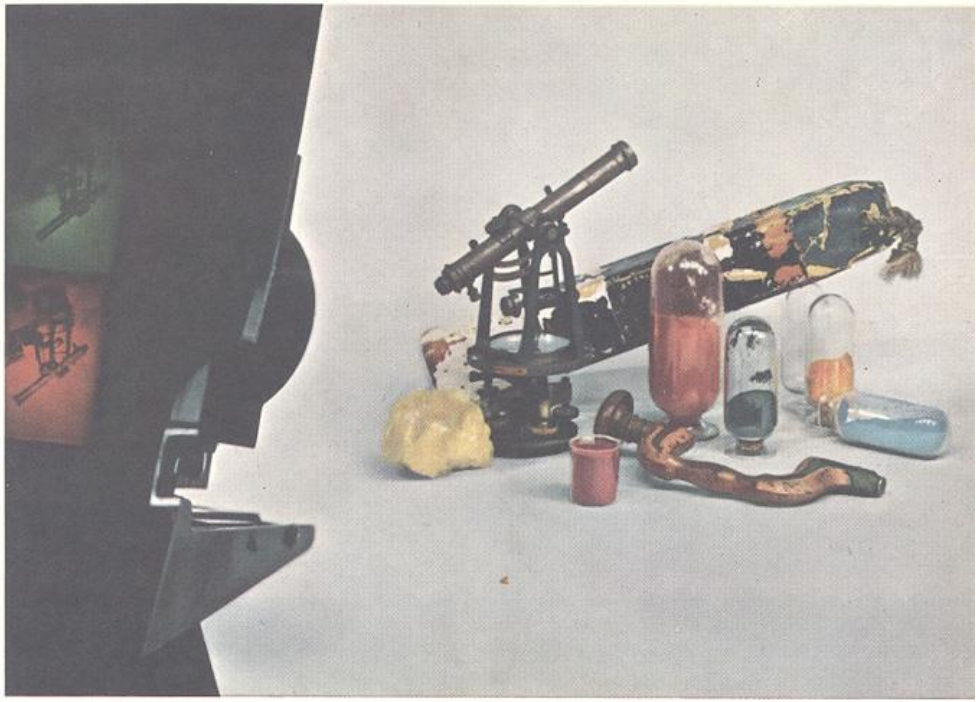
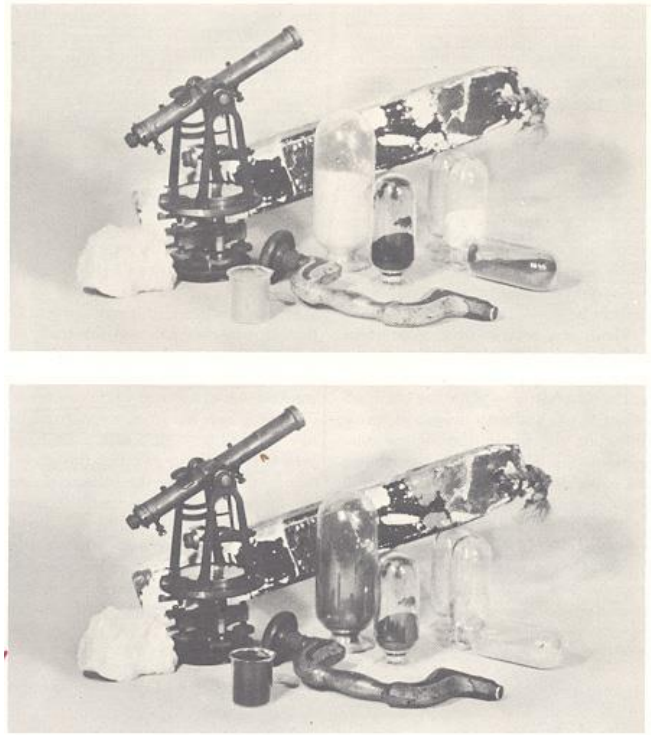
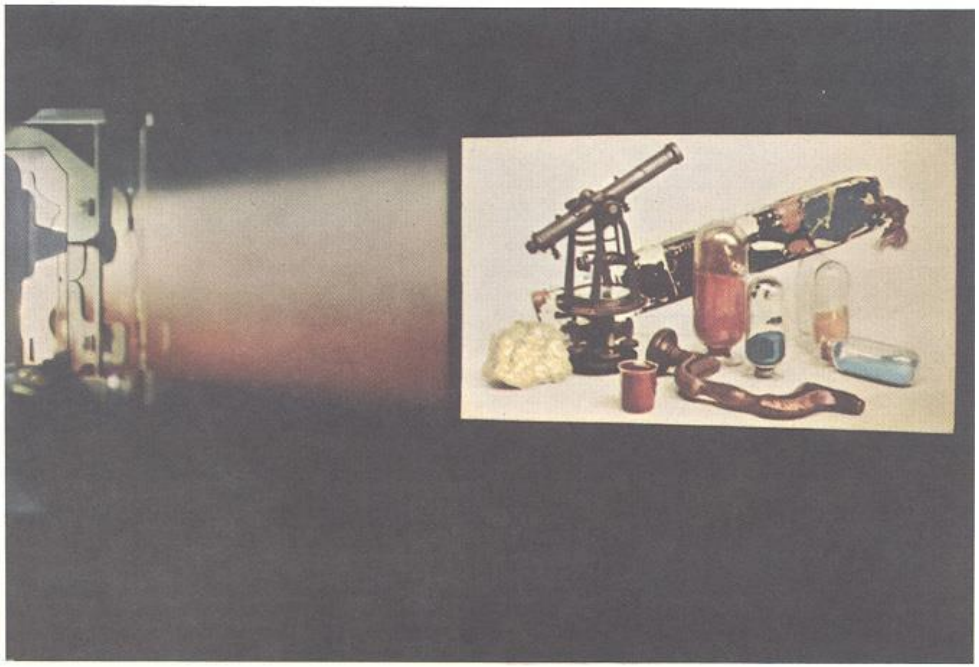
Experiments in Color Vision

Edwin Land
Scientific American (1960)



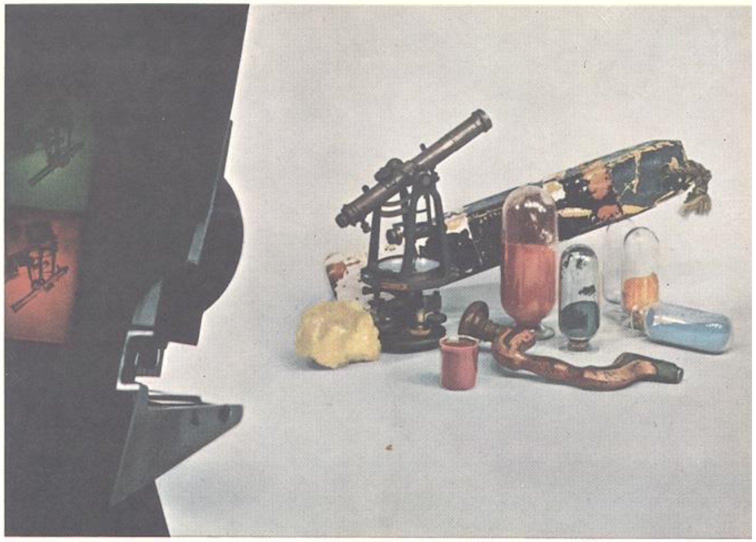


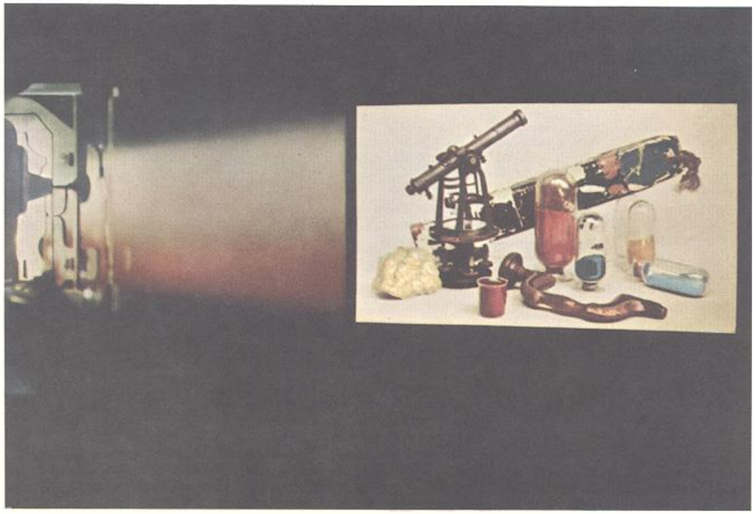
LONG AND SHORT RECORDS are provided by transparencies of these black-and-white photographs made through a red filter (*top*) and a green filter (*bottom*). In projection the long record (*top*) is illuminated by the longer of two wavelengths or bands of wavelengths, and the short record is illuminated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



535 589

579 599





Problems with 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

Opponent Process Theory

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

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

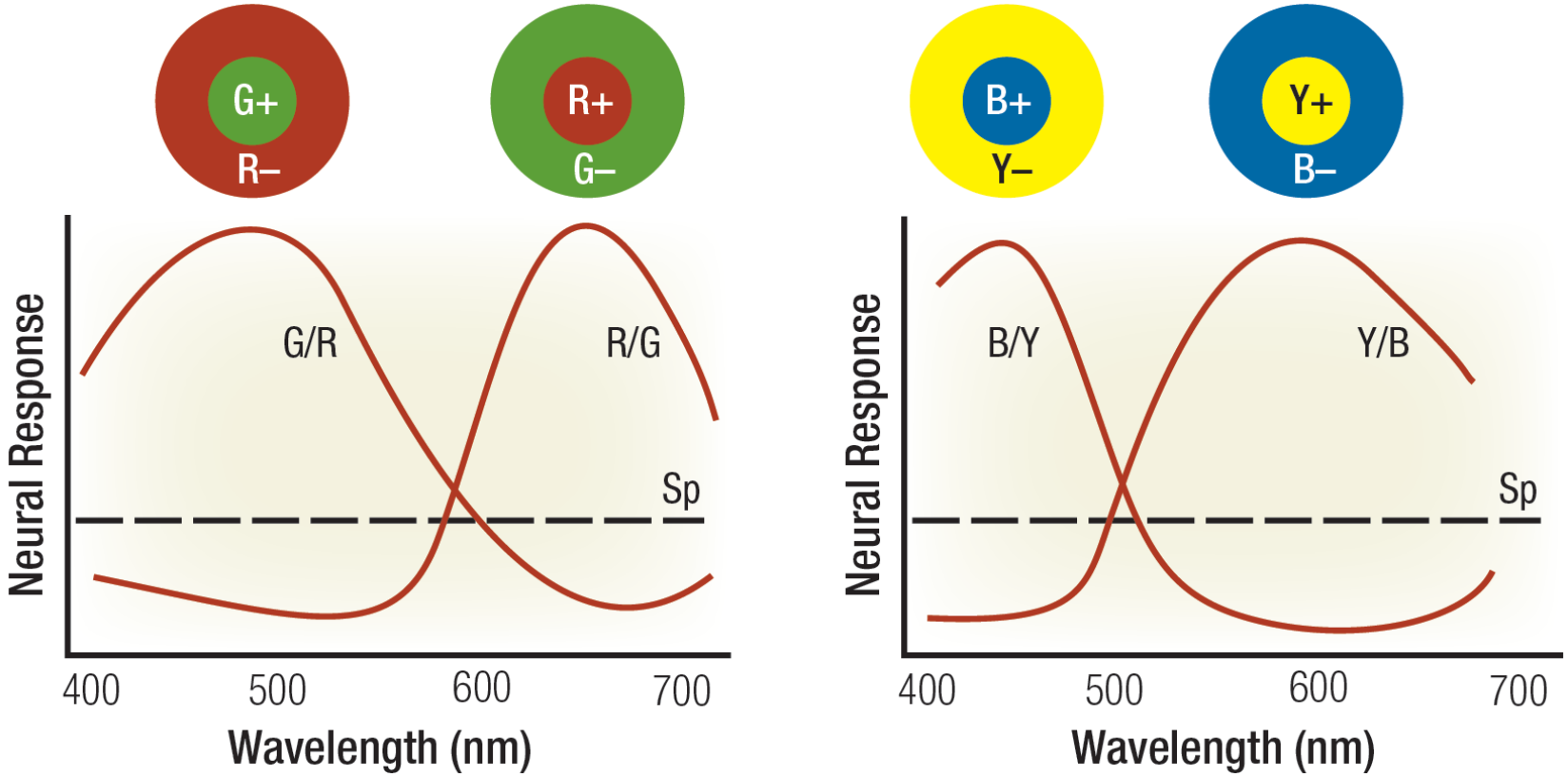
Red vs. Green channel	L ←→ M cones
Blue vs. Yellow channel	S ←→ L+M cones

One **ACHROMATIC channel** codes for BRIGHTNESS

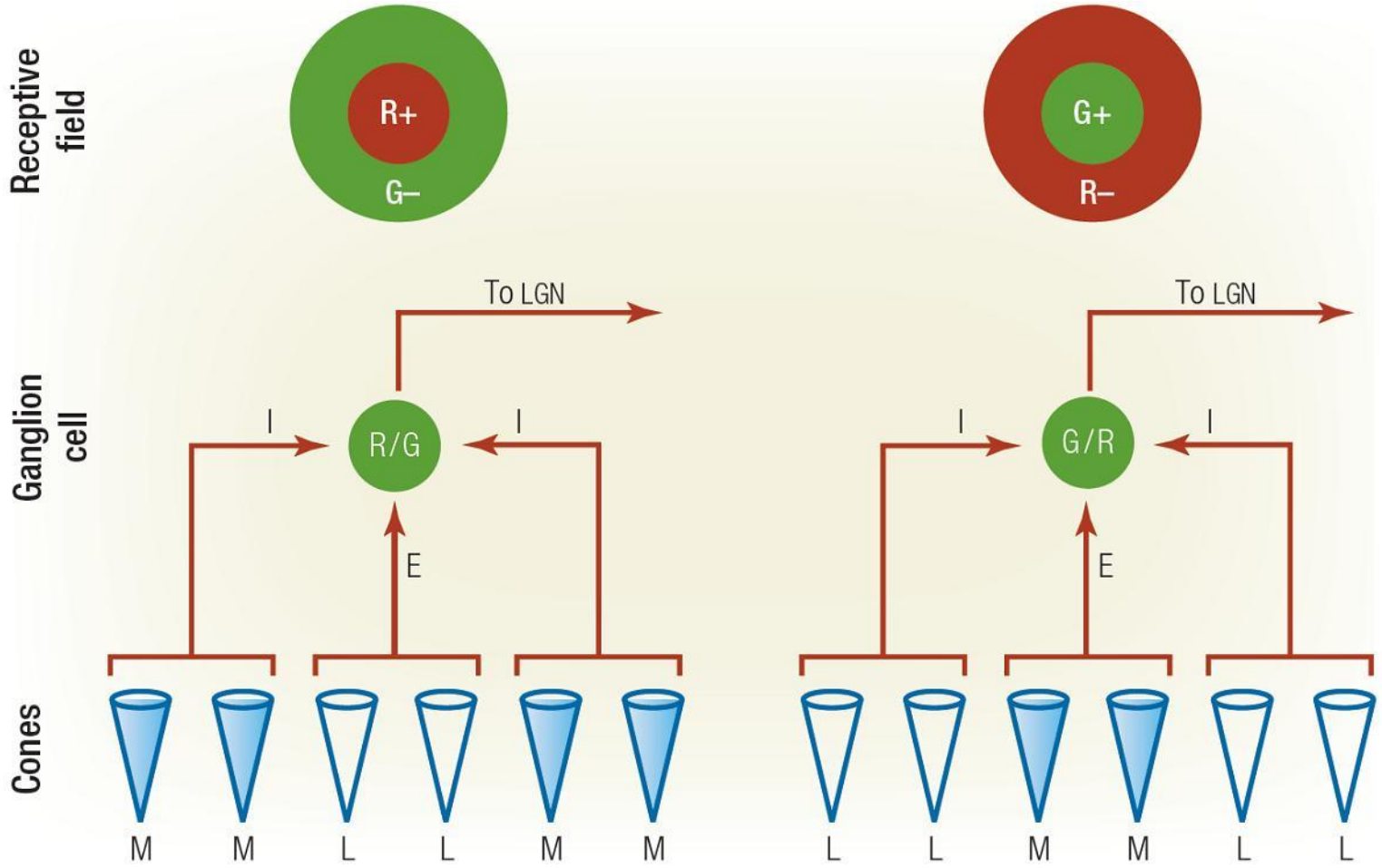
Black vs. White	L+M in center-surround antagonism

DeValois & DeValois (1975)

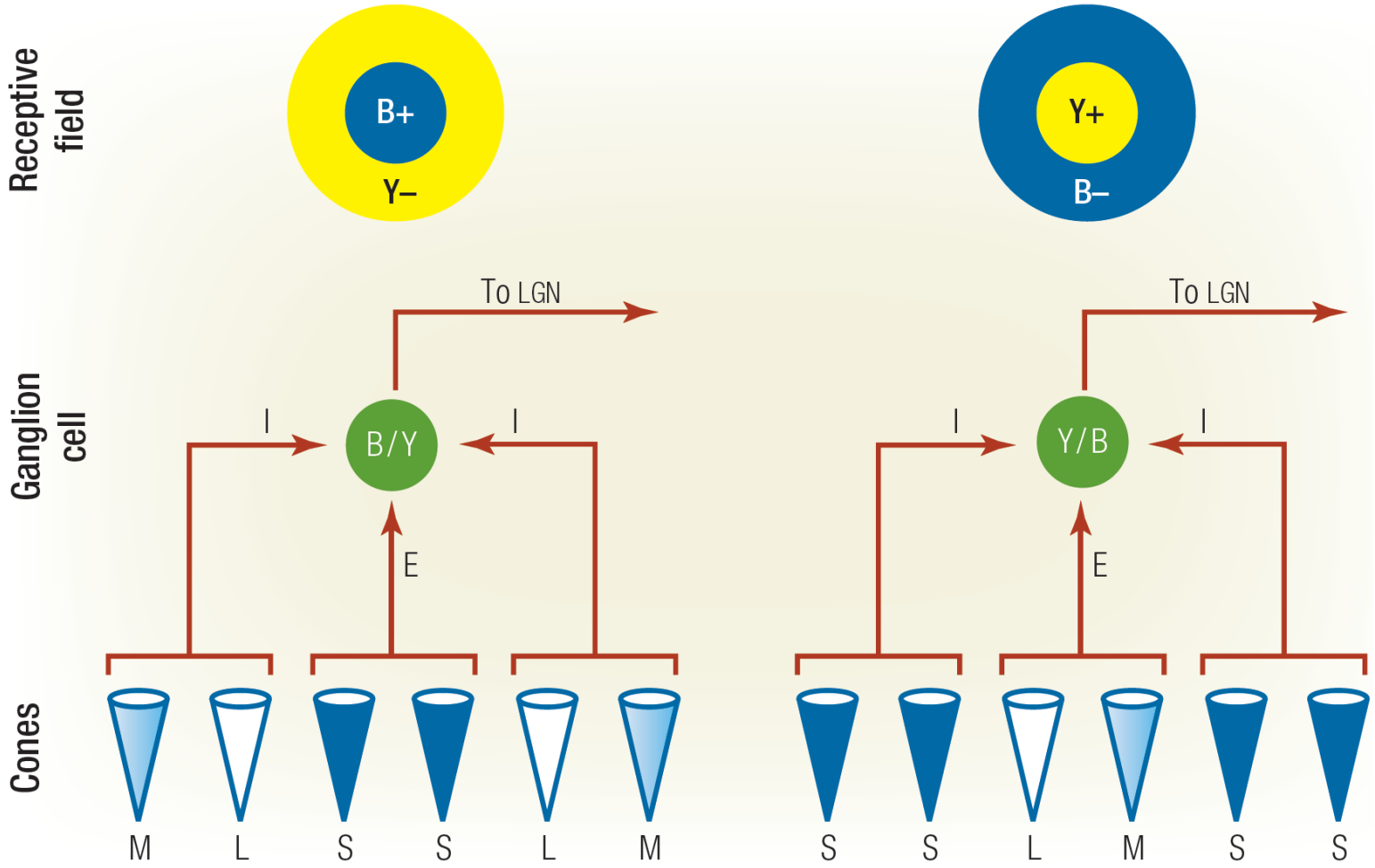
Color-Opponent Cells in the LGN



Red-Green Ganglion Cell

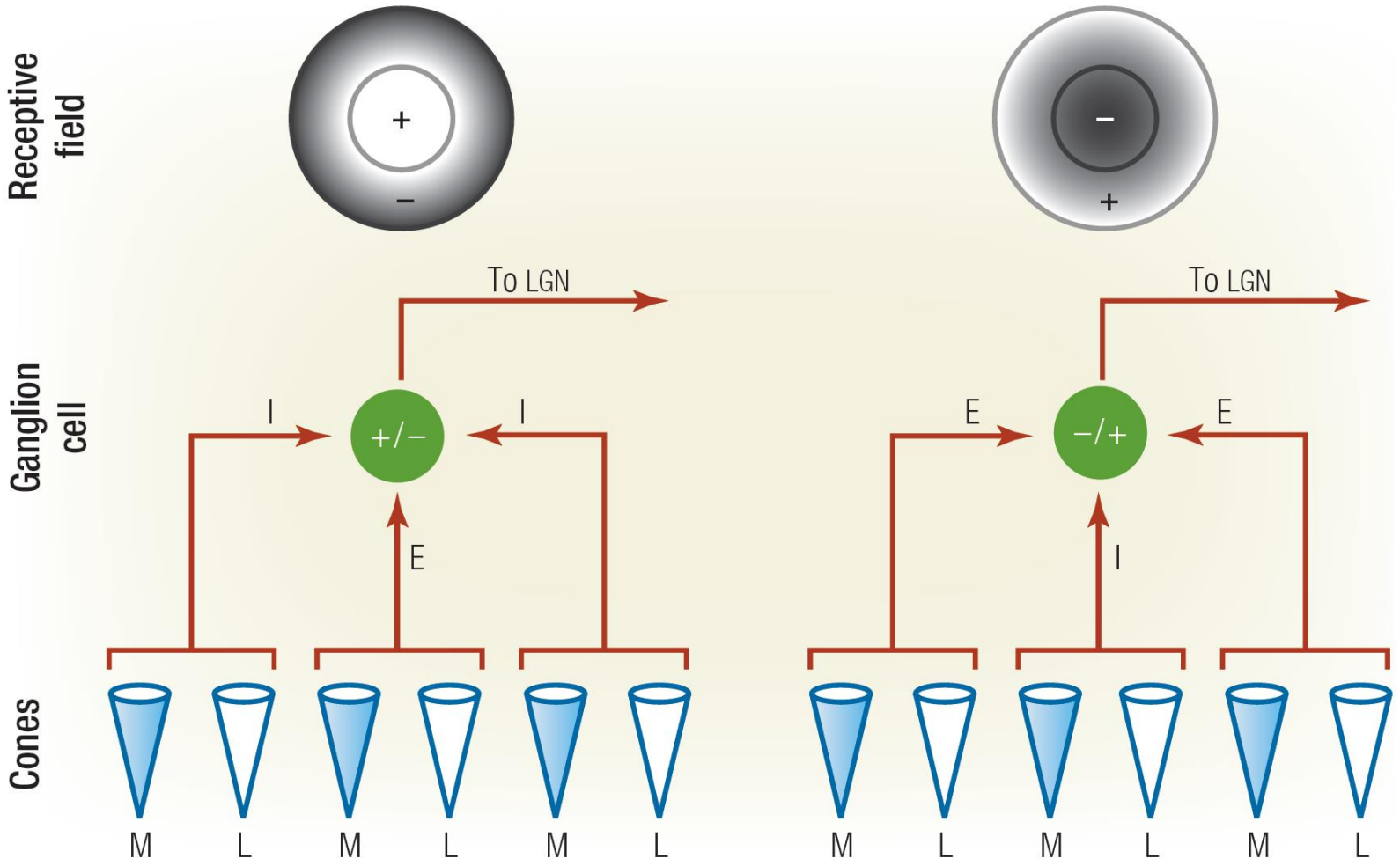


Blue-Yellow Ganglion Cell

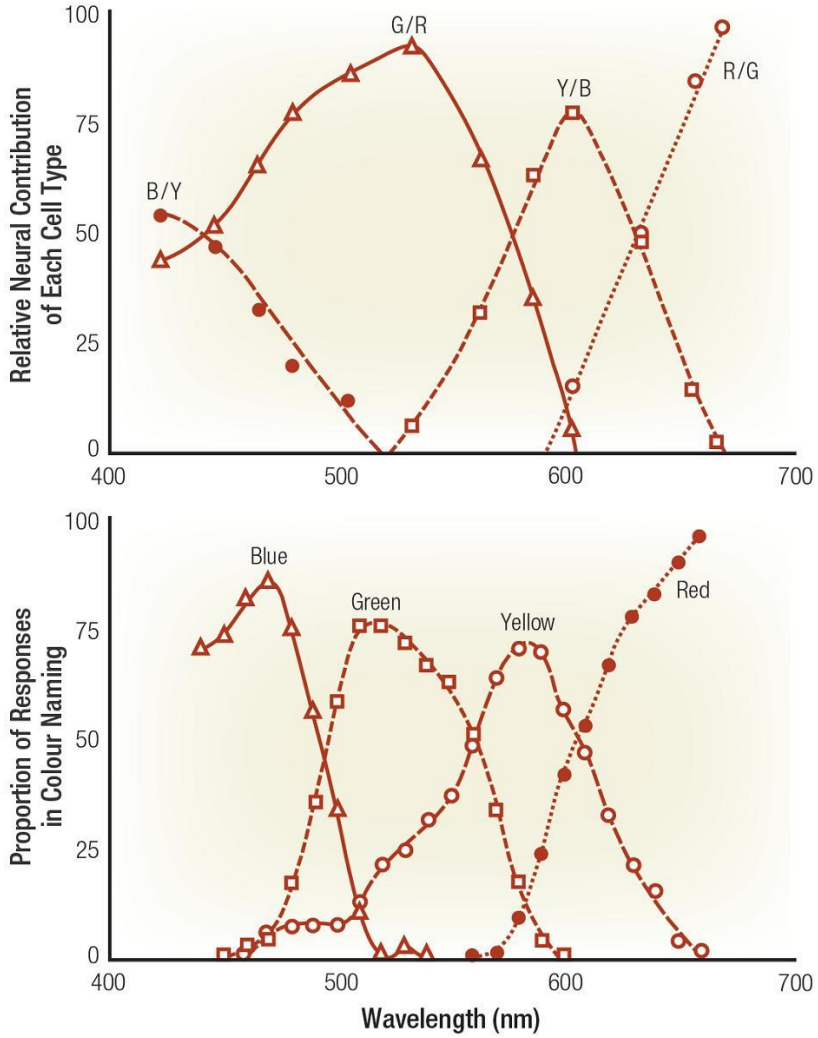


Achromatic Ganglion Cell

(Notice that Blue Light is “Discounted”)



Psychophysical vs. Physiological Results

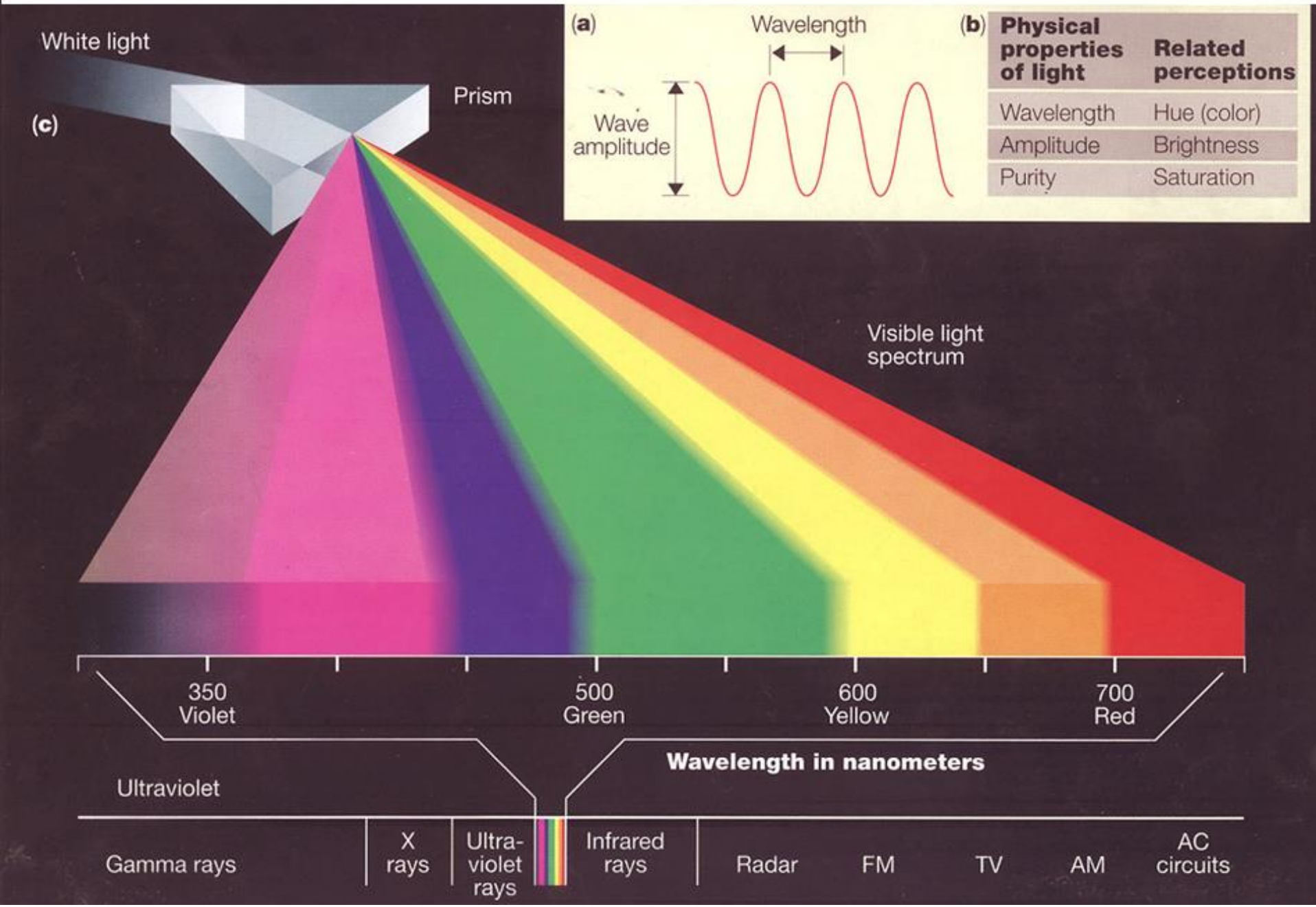


DeValois & DeValois (1975)
Monkey LGN data

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

Bornstein (1975) Infant Color Vision Study

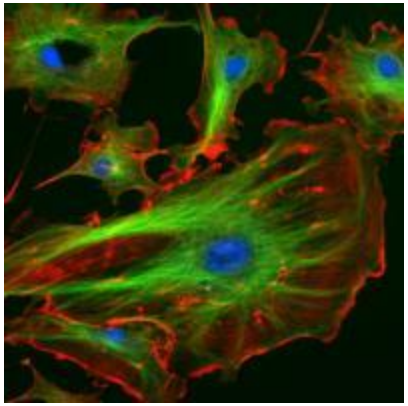


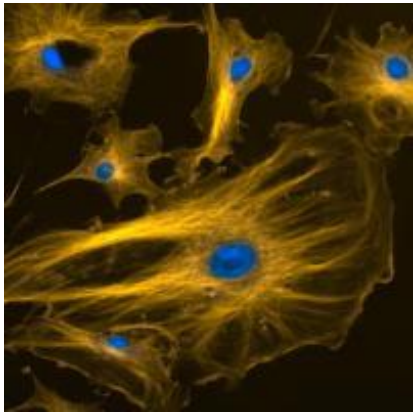
Dichromatic Color "Blindness"

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%





Trichromat

Red/Green Dichromat

Source: www.vischeck.com/daltonize