EECS 431
Human Perception and Electronic Media
Lecture 2

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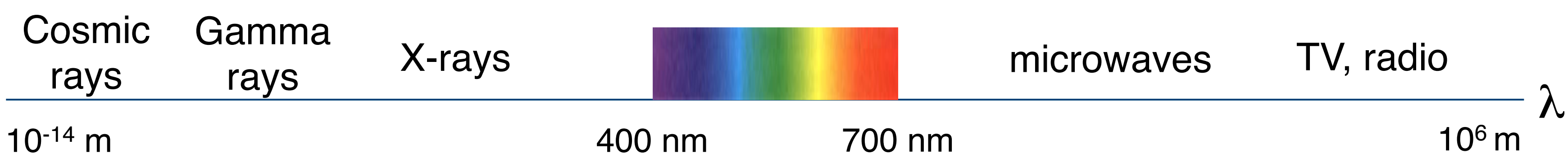
Visible Light

- Physical description: electromagnetic radiation
- Radiometric quantities
  - Radiant energy, propagated in the form of EM waves or streams of particles (photons)
  - Spectrum
- Webster's definition of light
  - something that makes vision possible; sensation aroused by stimulation of visual receptors (visible light)
- Photometric quantities
  - Radiant energy evaluated with respect to its ability to stimulate the sense of light in a human observer

Wyszecki & Stiles, "Color Science: Concepts and Methods, Quantitative Data and Formulae"

Visible Light

- EM spectrum



- Radiometric quantities
  - Irradiance (loosely “intensity”)
    + Objective, independent of observer
    + Can be measured with a radiometer
- Photometric quantities
  - Brightness: visual sensation, subjective
  - Luminance: objective, related to brightness
    + Takes into account human perception
    + Can be measured with a photometer

Radiometric Quantities

- Radiant energy
  - Propagated in the form of EM waves or streams of particles (photons) – joules (J)
- Radiant flux or power P_e
  - Radiant energy emitted, transferred, or received through a surface per unit time – watts (W)
- Irradiance $E_e = dP_e/dA$
  - Radiant power per unit area, at a point of a surface – W/cm^2
- Radiant Intensity $I_e = dP_e/d\omega$
  - Radiant power emitted by (point) source per unit of solid angle (in a given direction) – W/sr (watts/steradian)
- Radiance $L_e = DP_e/(dA \cdot \cos\varepsilon \cdot d\omega)$
  - Radiant intensity per unit area (in a given direction at a point) – W/cm^2sr

Radiometric Quantities

- Irradiance per wavelength $E_{e,\lambda}$
  - Radiant flux/power per unit area per wavelength
  - Energy per (area • time • wavelength)
  - Joules/(m^3sec) = watts/m^3
  - Energy distribution of wave passing through a plane
  - $E_{e,\lambda}$ (x,y,t)
  - Speed of EM wave, $c = \lambda \cdot f$
  - Speed, wavelength depend on material
  - Assume propagation in a vacuum
  - Index or refraction $\eta = c/c_m$ (speed in vacuum / speed in material)

CIE Luminous Efficiency Curves

- Provide connection between photometric and radiometric units
- Let $c(\lambda) = E_{e,\lambda}(x_0, y_0, t_0)$
- If $\lambda_1 \neq \lambda_2$ and $c(\lambda_1) = c(\lambda_2)$, human perception of brightness may not be the same.
- If $c(\lambda_1)$ and $c'(\lambda_2)$ appear equally bright, then the ratio $c(\lambda_1)/c'(\lambda_2)$ is the relative luminous efficiency of λ_1 to λ_2 and is independent of the amplitude $c(\lambda_1)$.
  - Define: $v(\lambda) = c(\lambda_0)/c(\lambda)$, with $\lambda_0 = 555$ nm (green light)
- $v(\lambda)$ depends on the observer in general.
- 1929: C.I.E. (Int. Commission on Illumination) standard observer
- 1948: Luminance defined by C.I.E.

CIE Luminous Efficiency Curves

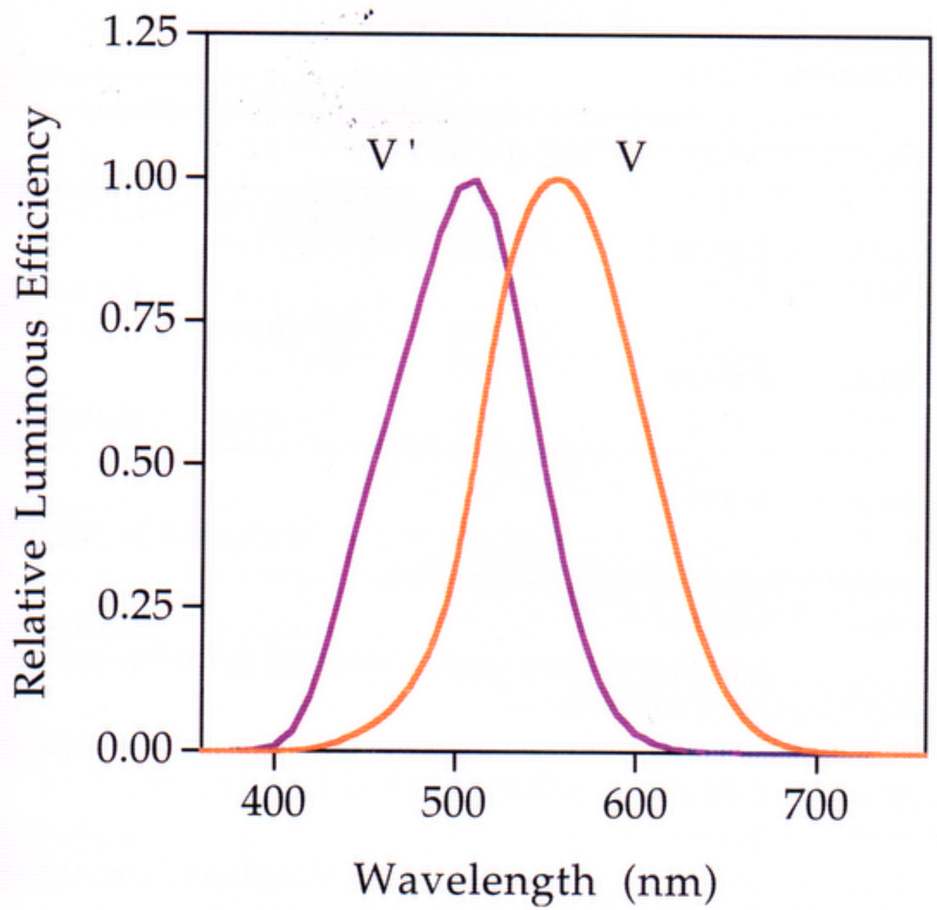


Figure 3-6. CIE scotopic, $V'(\lambda)$, and photopic, $V(\lambda)$, luminous efficiency functions.

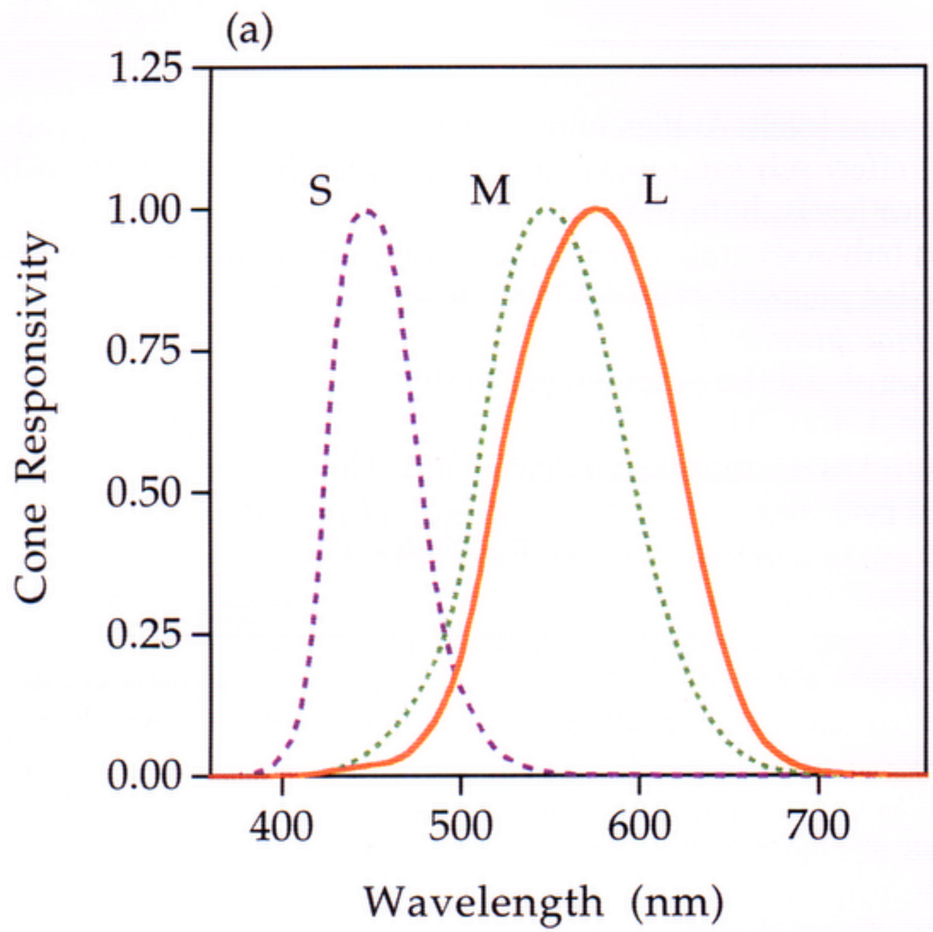
Photometric Quantities

- Luminous efficiency (photopic, scotopic)
  - Ratio of radiant flux at λ_m=555 nm to that at λ, when the two fluxes produce the same luminous sensations
- Luminous flux or power, P_v – lumen (lm)
  - $P_v = K_m \int_\lambda P_{e,\lambda}\, v(\lambda)\, d\lambda$, Km = 683 lumen/watt
- Illuminance, $E_v = dP_v/dA$ – lm/m^2
  - $E_v = K_m \int_\lambda E_{e,\lambda}\, v(\lambda)\, d\lambda$
- Luminous intensity, I_v – candela (cd) = lm/sr
  - $I_v = K_m \int_\lambda I_{e,\lambda}\, v(\lambda)\, d\lambda$
- Luminance, L_v – $cd/m^2 = lm/m^2sr$
  - $L_v = K_m \int_\lambda L_{e,\lambda}\, v(\lambda)\, d\lambda$

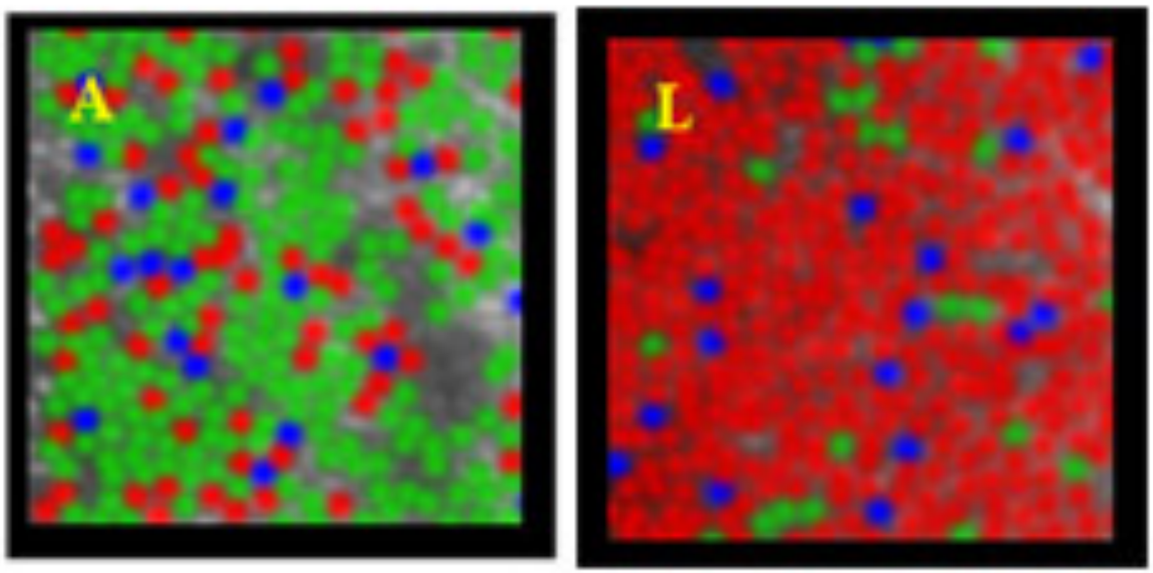
Photometric Quantities

- 1 lumen (lm) defined as: 1/60 of luminous flux emitted per cm^2 by thorium oxide at 2042 K (melting platinum)
- Other units
  - footcandle = lumen/ft^2
  - phot = lumen/cm^2
  - candelas/m^2
- Note: In video, "luma" is the weighted sum of nonlinear (gamma-corrected) R',G',B' components

Spectral Response of Cones



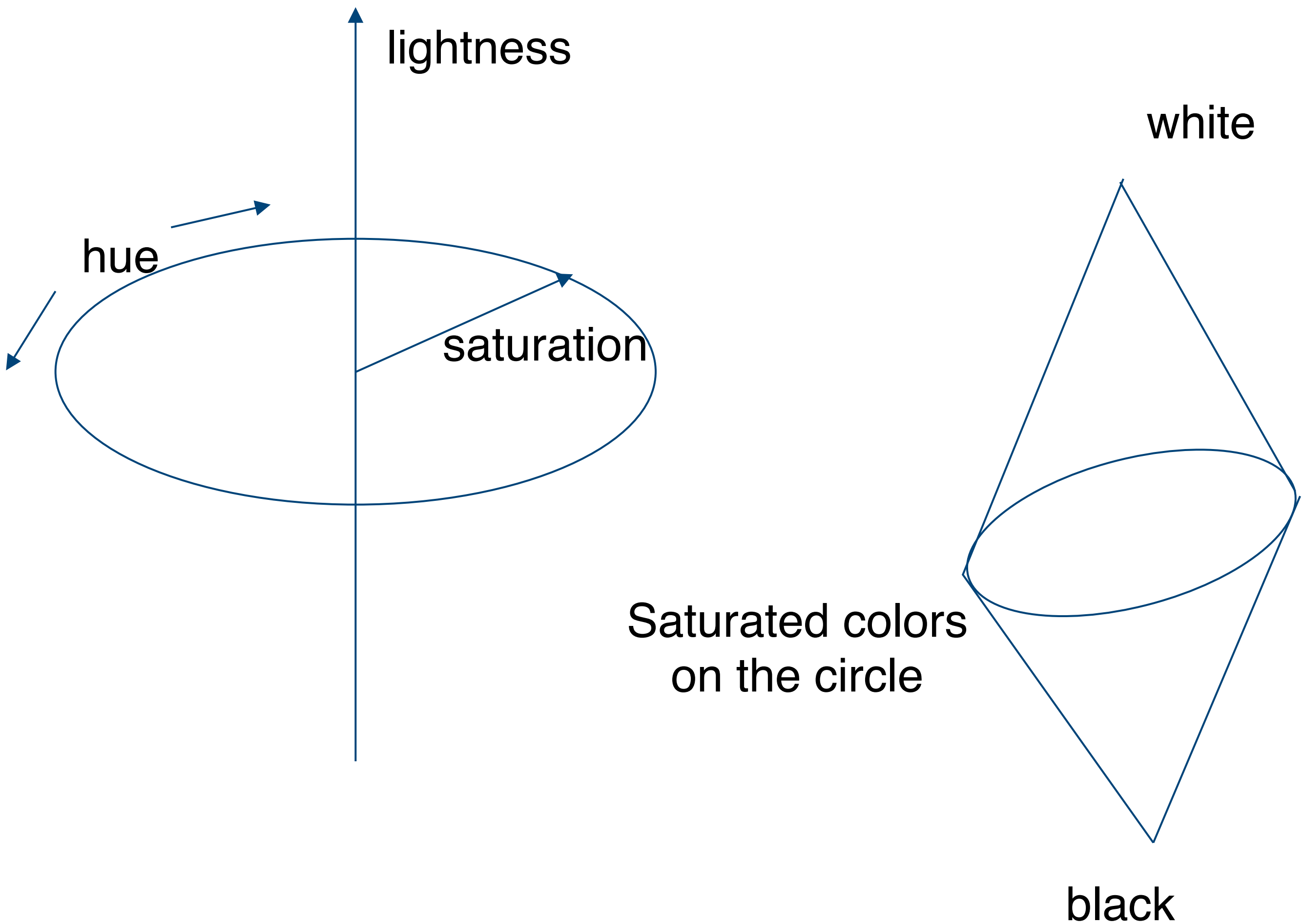
Cone Distribution



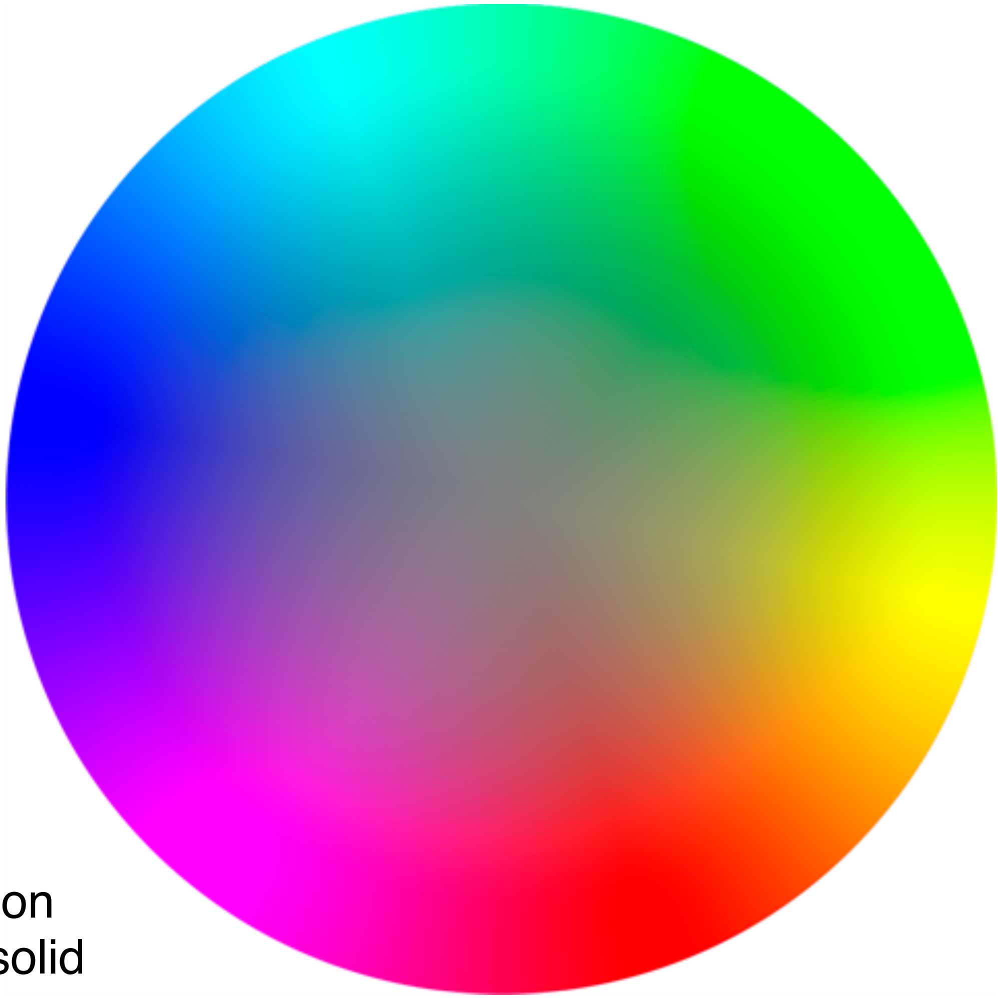
Color Perception

- Three types of sensors
  - Short (blue), Medium (green), Long (red)
- Different spectral distributions
  - Monochromatic light (impulse)
  - Polychromatic light
  - Sunlight (roughly equal energy at all wavelenths)
  - White light
- Color spaces
  - Munsell book of color: subjectively equal steps in hue, saturation (chroma), and lightness (value)

Color Solid or Spindle



Color Circle



Oblique section
through color solid

Theories of Color Vision

- (Young-Helmholtz) Trichromatic Theory
  - 1777 George Palmer
  - 1802 Sir Thomas Young
  - 1855 Maxwell
  - 1867/1925 Helmholtz
- Opponents Process Theory
  - 1878/1964 Ewald Hering
  - Color blindness: color experiences lost in pairs (red and green, blue and yellow, not red and blue or green and yellow)
  - Primary colors: red, green, blue, but also yellow
  - Absence of color mixtures: red and green, blue and yellow
  - Polar opposites from color afterimages
- Dual Process Theory

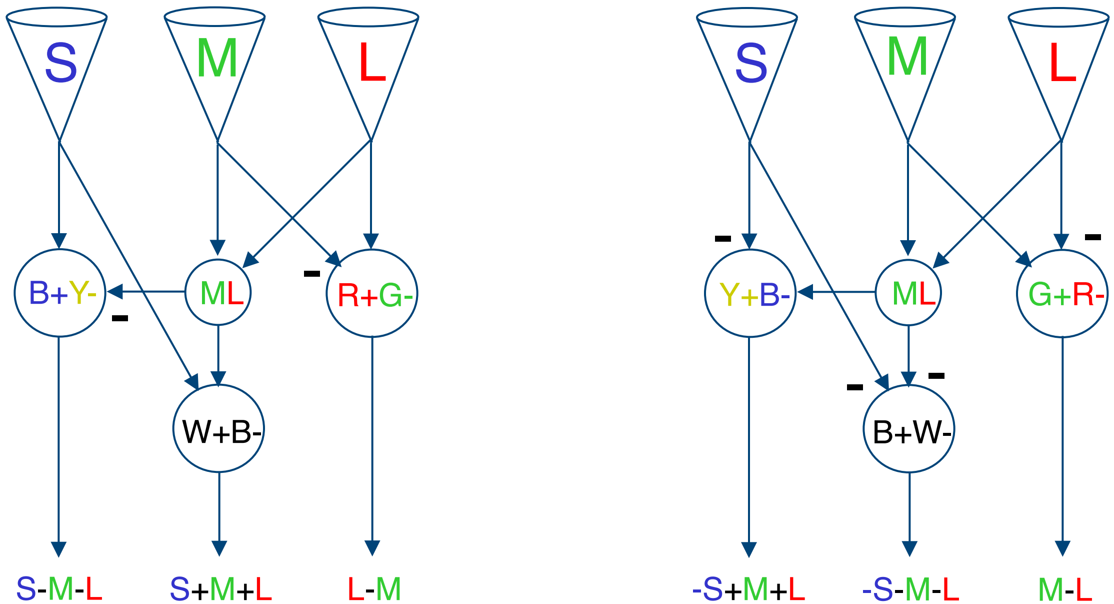
Theories of Color Vision

- (Young-Helmholtz) Trichromatic Theory
  - S, M, L sensors
- Opponent Process Theory
  - Four chromatic primaries
  - Structured into pairs or polar opposites
    - Red vs. green, yellow vs. blue, and white vs. black
- Dual Process Theory
  - Both correct at different stages of visual processing
    - 1905 von Kries
    - 1920s Mueller and Schroedinger
    - 1957 Hurvich and Jameson (quantitative)
  - Both stages occur in the retina
    - Supported by (later!) physiological evidence

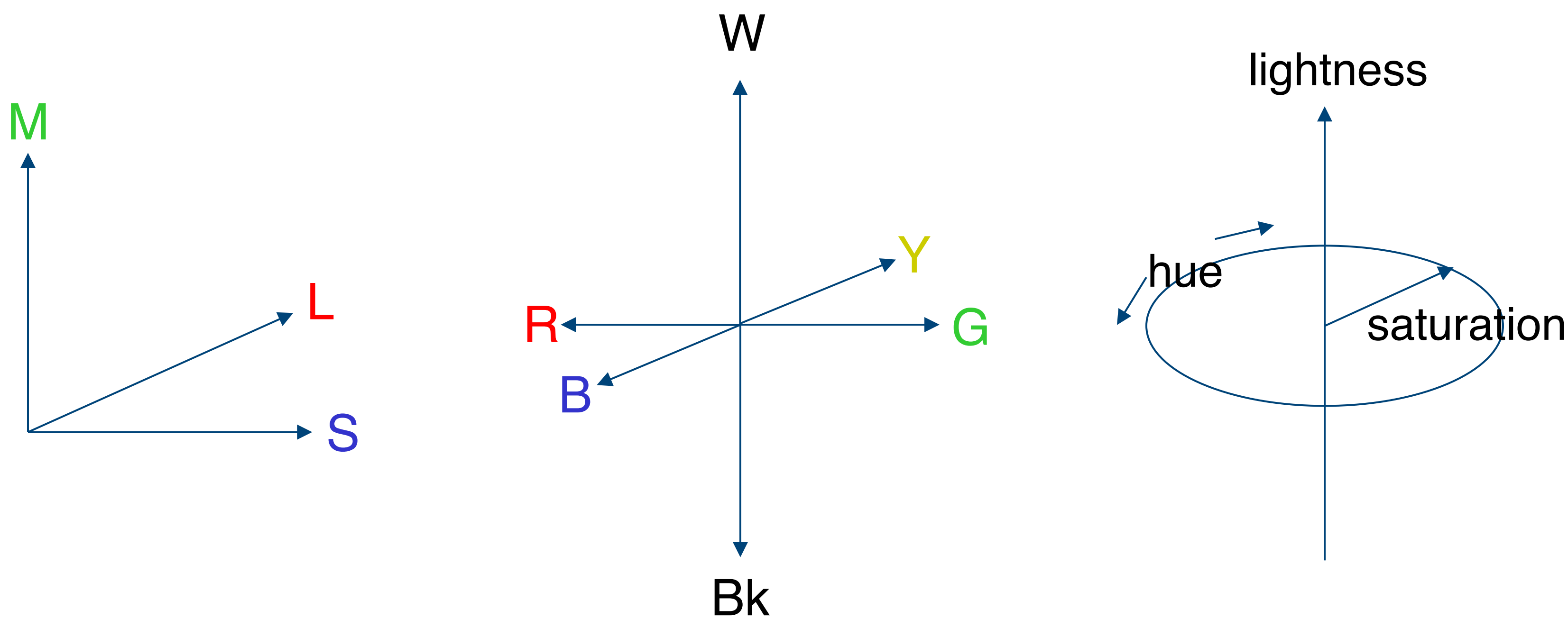
Dual Process Theory

- Color opponent cells
  - S-M-L
  - S+M+L
  - L-M
- Different representations
  - Trichromatic (S,M,L)
  - Opponent color
  - HSV representation
  - Different representations provide information that is useful for different purposes

Neural Circuits for Dual Process Theory

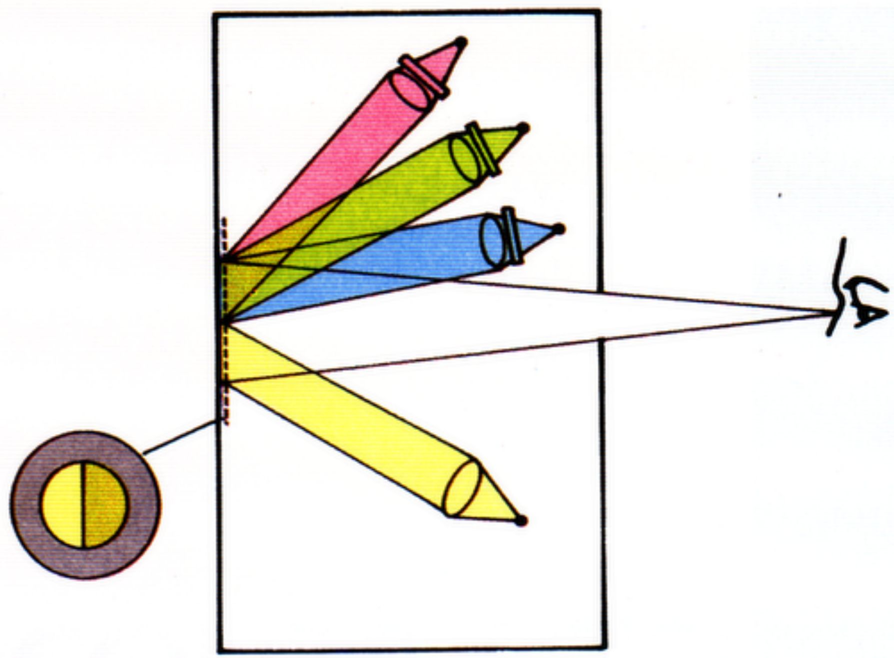


Color Representations



trichromatic opponent process HSV

Color-Matching Experiments



Color-matching experiment. An observer views a small circular field that is split into two halves. The test color illuminates one half of the circle, while the other half is illuminated by superposed red, green and blue lights, called primaries. The observer adjusts the intensities of the three primaries until the two halves of the circle match.

RGB Color Matching Functions

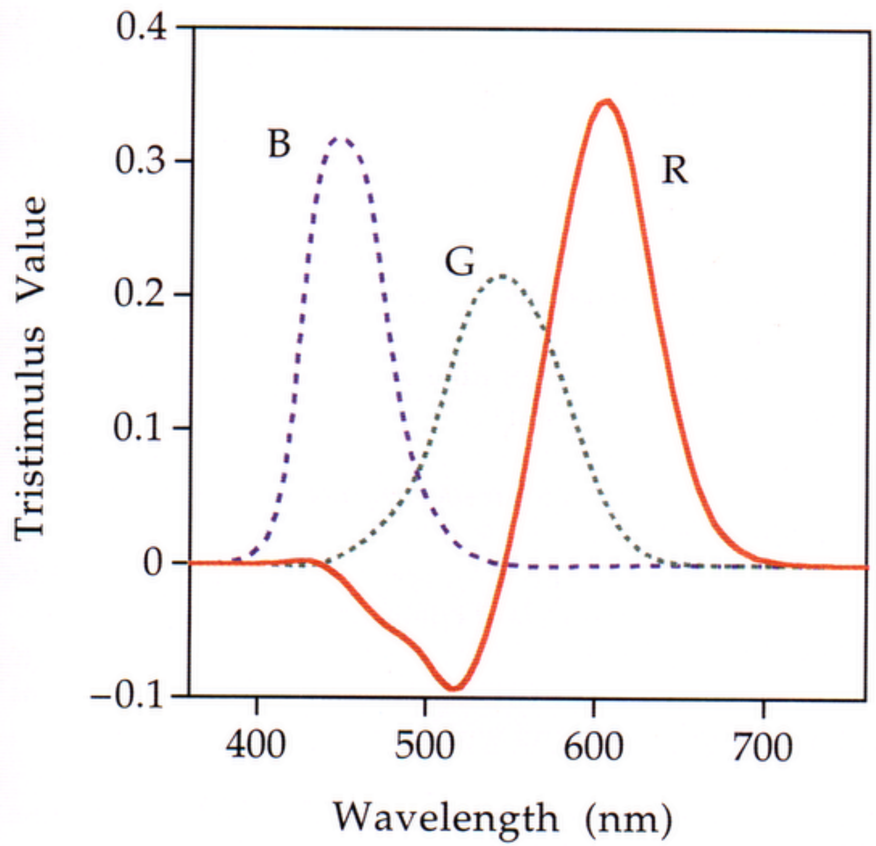


Figure 3-7. Spectral tristimulus values for the CIE *RGB* system of colorimetry with monochromatic primaries at 435.8 nm, 546.1 nm, and 700.0 nm.

Amounts of primaries needed to match the monochromatic test primary of the wavelength shown on the horizontal axis

Primaries chosen:

Blue: 436 nm

Green: 546 nm

Red: 700 nm

CIE 1931 Standard Observer

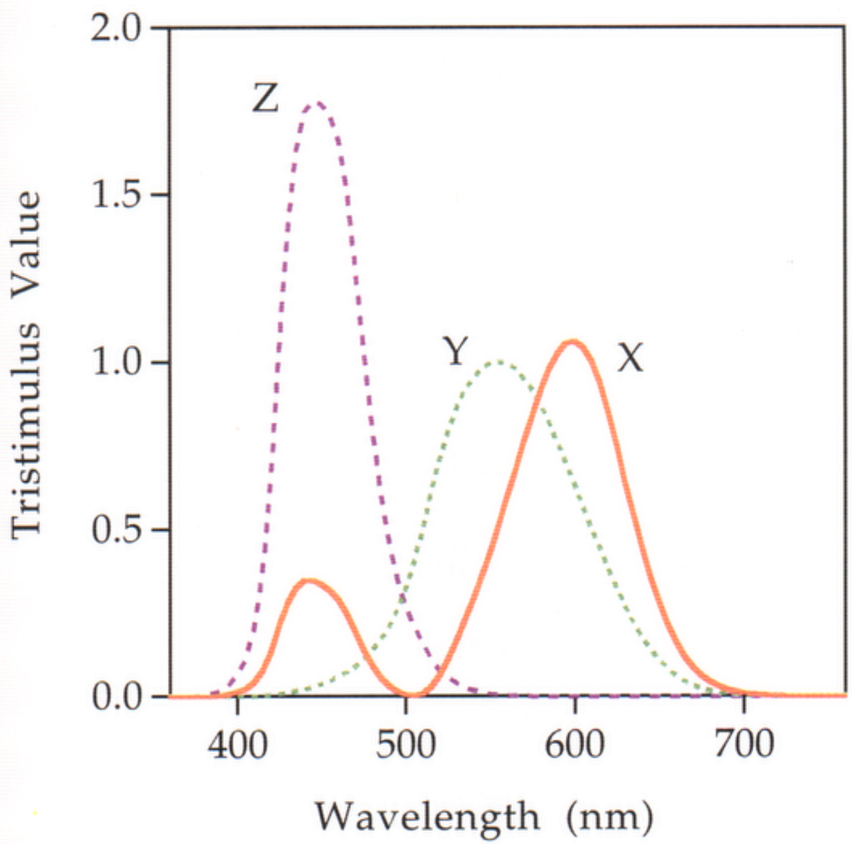
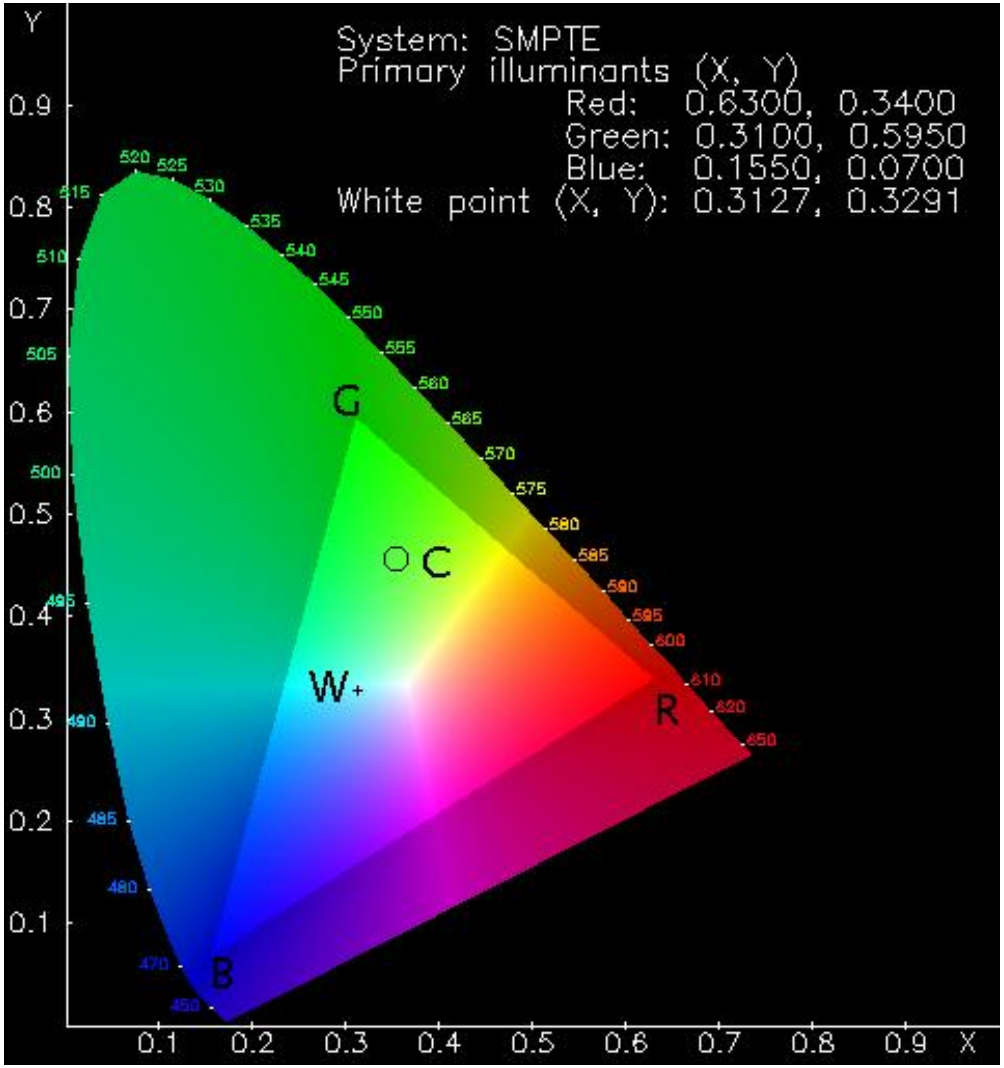


Figure 3-8. Spectral tristimulus values of the CIE 1931 standard colorimetric observer.

Perceptual Models



CIE Illuminants

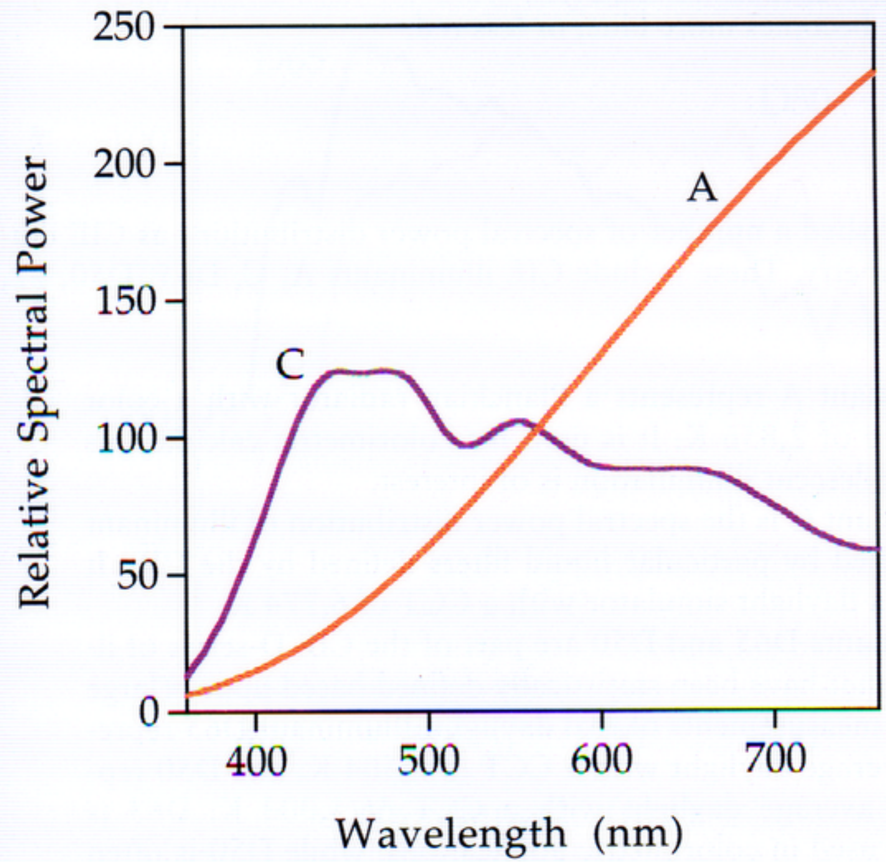


Figure 3-2. Relative spectral power distributions of CIE illuminants A and C.

A: 2856 K

(incandescent)

C: A modified by liquid filters

(daylight 6774 K)

CIE Illuminants

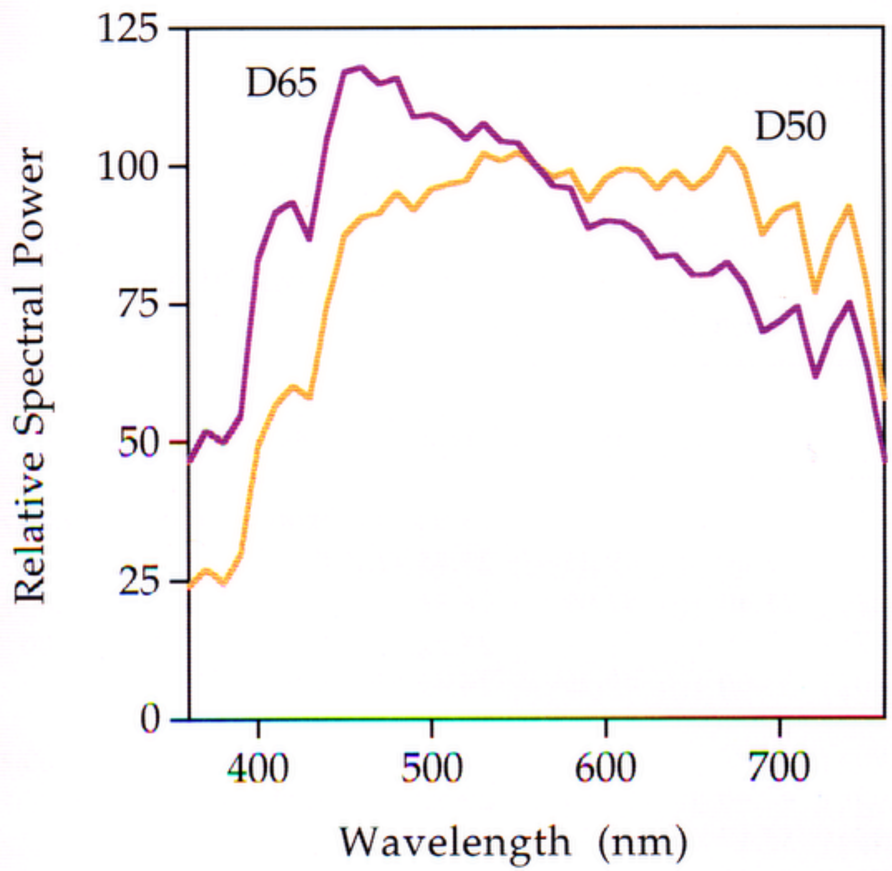
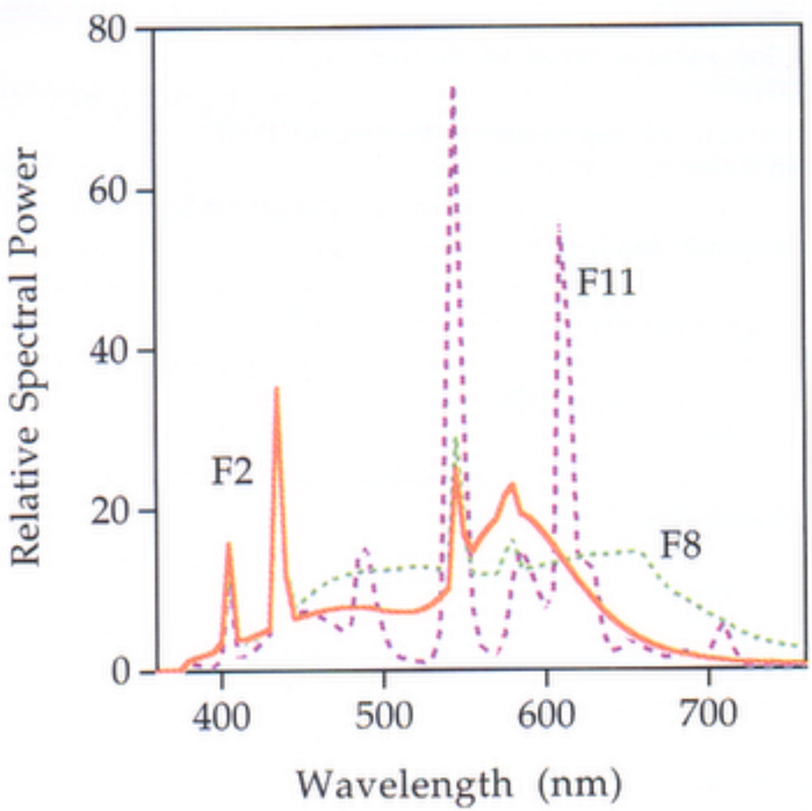


Figure 3-3. Relative spectral power distributions of CIE illuminants D50 and D65.

D65: Average daylight 6504 K (colorimetric)

D50: Average daylight 5003 K (graphic arts)

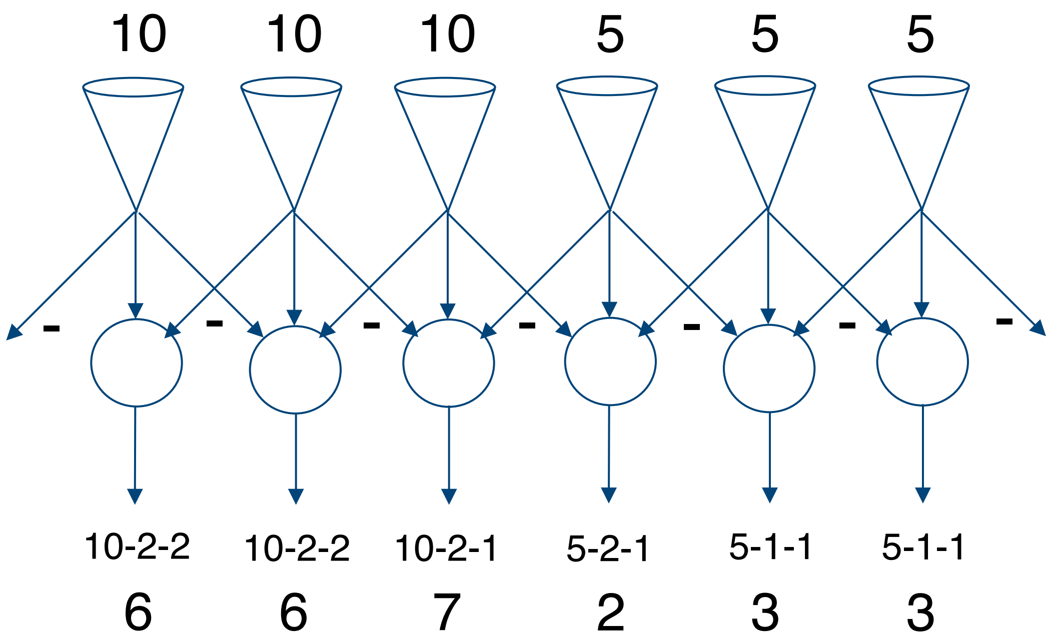
CIE Illuminants

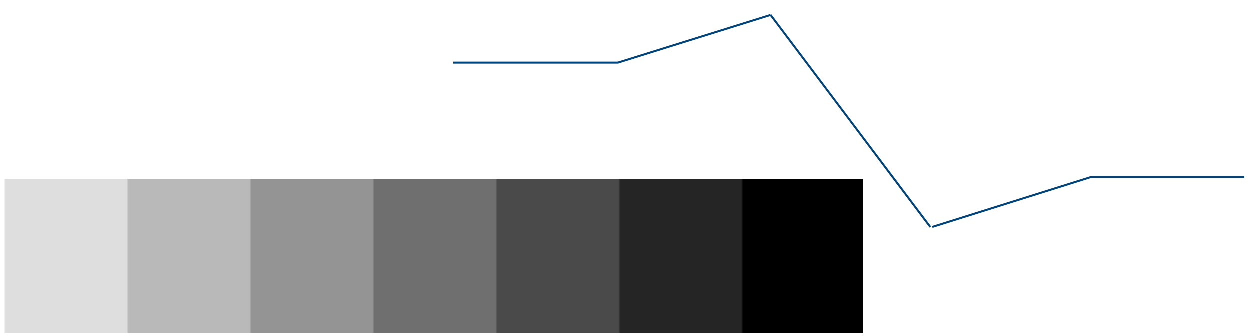


- F: Fluorescent sources
- F2: Cool white (4230 K)
- F8: Fluorescent D50 simulator (5000K)
- F11: Tri-band fluorescent source (4000 K)

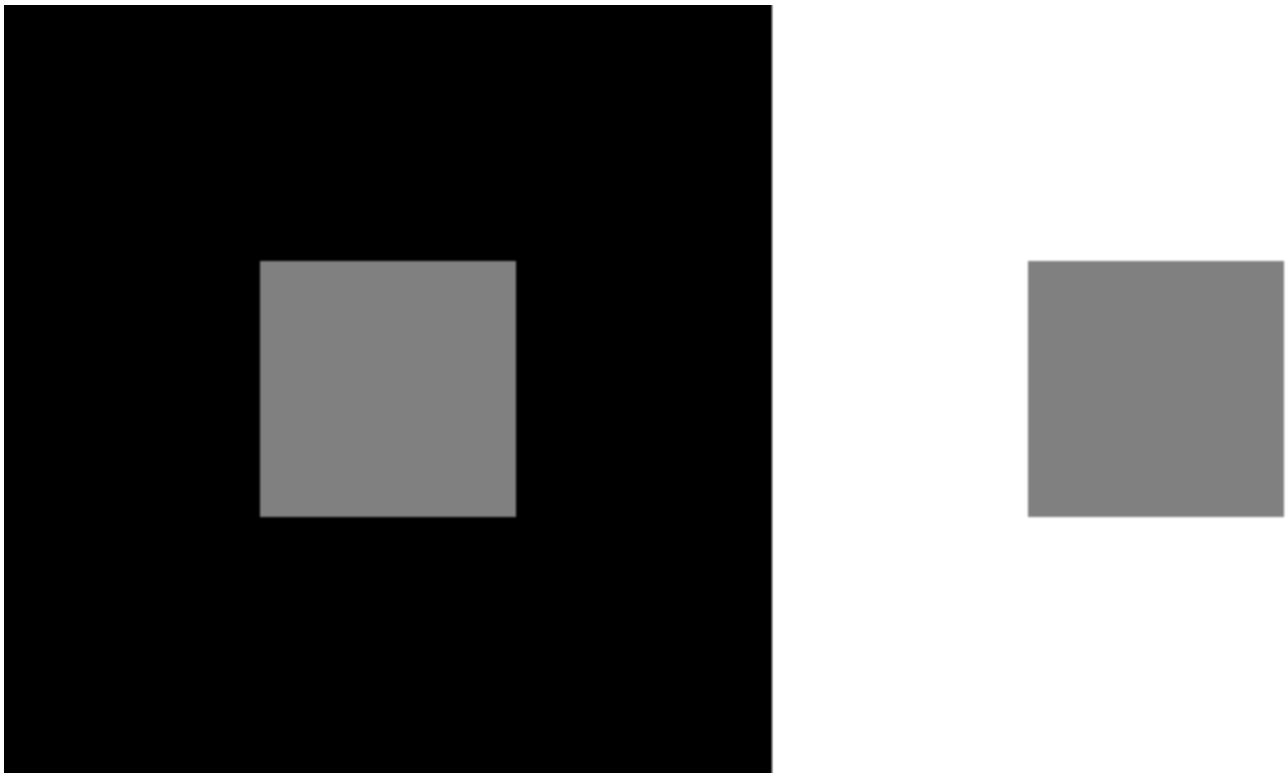
- E: Equal-energy

Lateral Inhibition





Lateral Inhibition



Lateral Inhibition

Lateral Inhibition

10	5	5	10	10	0	0	5	5	0
	5-2-1	5-1-2	10-1-2	10-2-0	0-2-0	0-0-1	5-0-1	5-1-0	
	2	2	7	8	-2	-1	4	4	

Color Constancy

- Reflectance spectrum
  - Percentage of incident light reflected at each wavelenth
  - Primarily determines "color" of a surface
  - Invariant: Does not change with lighting or viewing conditions
- Luminance spectrum
  - Determined by both reflectance and illumination
  - $L_\lambda = I_\lambda \ R_\lambda$
  - "White" sunlight (flat spectrum) provides "true color"

Color Constancy

- Ability to perceive reflectance properties of surfaces despite changes in illuminations and viewing conditions
  - Apparent invariance in the color appearance of objects as the illumination changes
  - In everyday life, we are accustomed to thinking of most colors as not changing at all
- Lightness constancy
- Chromatic color constancy

Adaptational Theories

- HVS adapts to overall change in illumination
  - Takes place in the retina
  - Requires relatively long time
  - Cannot account for all the phenomena of lightness constancy
  - Constancy can occur within a single visual scene
- Unconscious inference (Helmholtz)
  - Prior experience: take illumination into account
- Relational theories (Hering)
  - Directly from image
  - Relative luminance (contrast) between neighboring regions
    + Luminance ratios
    + Retinex (Land and McCann, Mondrians)

Chromatic Adaptation

- "White world" approach to estimating the scene illuminant
  - Assume the whitest point in the image comes from a surface that reflects light equally in all directions
  - First transform to linear color space!
  - Median filter
  - Find best representatives of white **w** and black **b**
    - Find lightest and darkest pixels
  - **C' (x,y) = [C(x,y)-b]/[w-b]** (each color component)

Color Constancy (?)