Color Outline

Wavelength encoding (trichromacy)

Three cone types with different spectral sensitivities. Each cone outputs only a single number that depends on how many photons were absorbed. If two physically different lights evoke the same responses in the 3 cones then the two lights will look the same (metamers). Explains when two lights will look the same, not what they will look like.

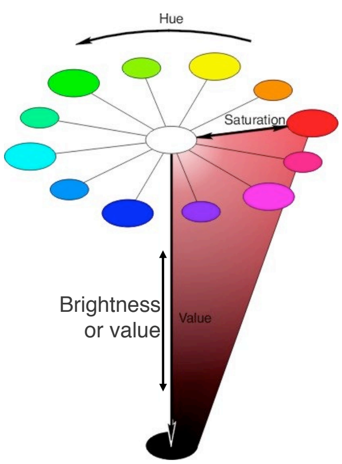
Color appearance

Color opponency: appearance depends on the differences between cone responses (R-G and B-Y).

Chromatic adaptation: color appearance also depends on context because the each cone adapts (like light and dark adaptation) to the ambient illumination.

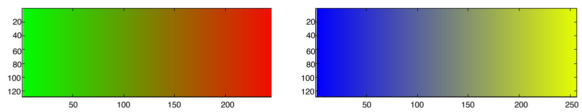
Color constancy: visual system infers surface color, despite changes in illumination.

Color appearance

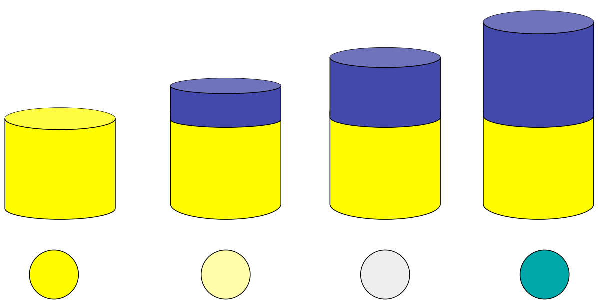


Color opponency

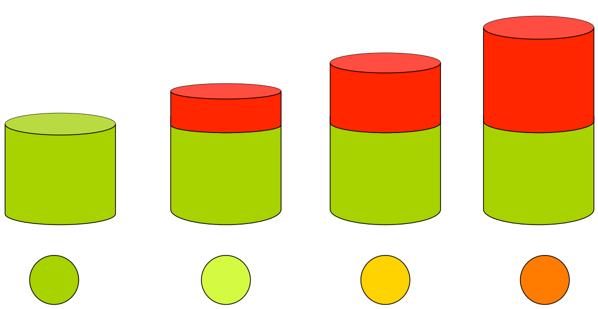
Color opponency



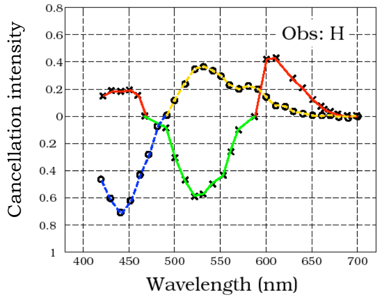
Hue cancellation experiment



Hue cancellation experiment



Hue cancellation

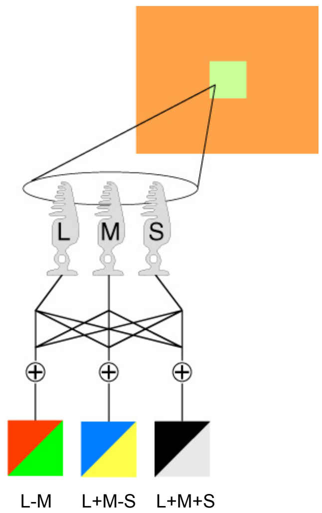


Blue curve, wavelengths that appear blue were cancelled by adding yellow light. Likewise for red and green.

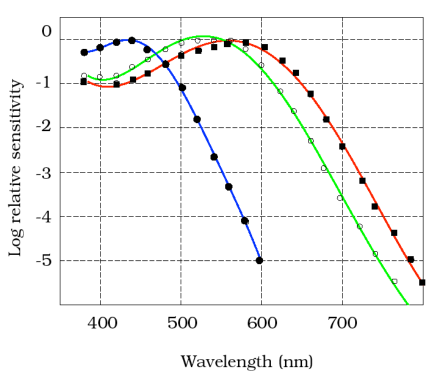
Why is the curve red below 475nm as well as above 580nm?

Hurvich & Jameson (1957)

Color opponency neural computation

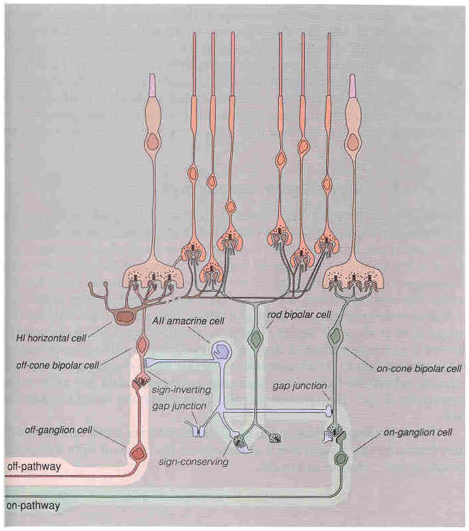


Color opponency



- Will a 650nm light look redish or greenish?
- What about a 500 nm light?
- What monochromatic light will appear neither redish nor greenish? What color will it appear to have?

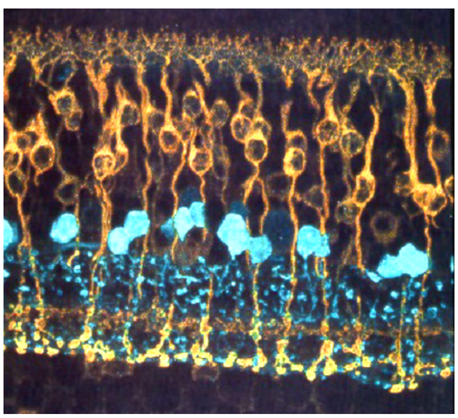
Neural circuits: rod pathway



Neural circuits in the retina (monkey rod pathway)

Rod bipolar

AII amacrines

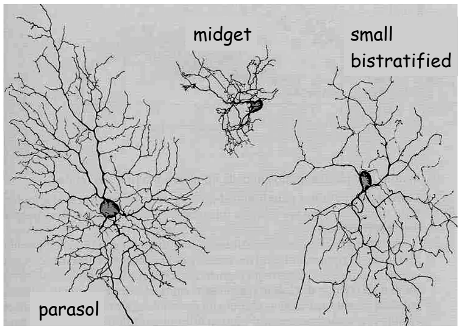


Parallel pathways (processing streams)

1. Anatomically distinct
2. Physiologically/functionally distinct
3. Complete coverage
4. Recombine

Example: rods and cones

Some retinal ganglion cell types

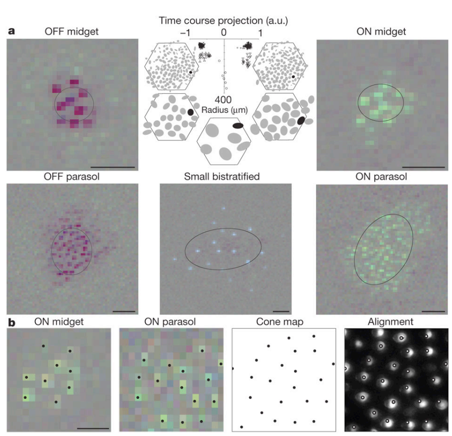


Parallel pathways: ganglion cells

Parasol ganglion cell:
1. Inputs from many photoreceptors
2. Fast/transient responses
3. Poor spatial resolution
4. Combine all cones ("color blind")

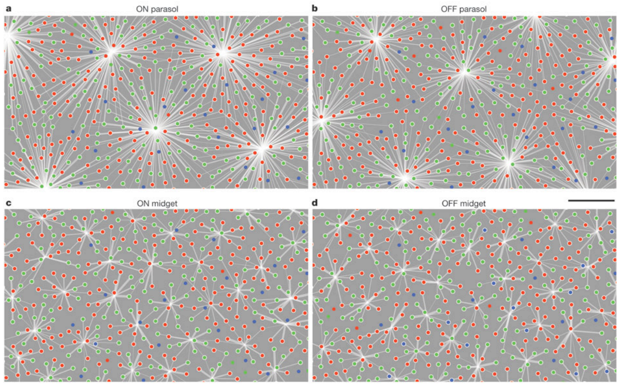
Midget ganglion cell:
1. Inputs from few (or one) photoreceptors
2. Slow/sustained responses
3. High spatial resolution

Ganglion cell receptive fields & inputs from cone lattice



Field et al., Nature (2010)

Ganglion cell mosaics



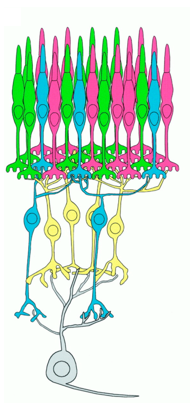
Field et al., Nature (2010)

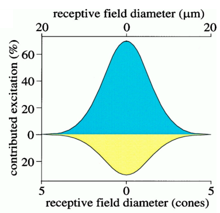
Blue/yellow pathway

Cones

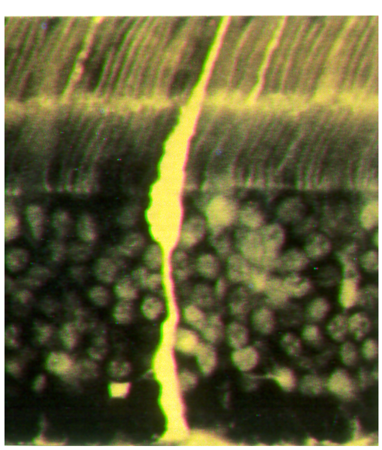
Bipolars

B/Y ganglion

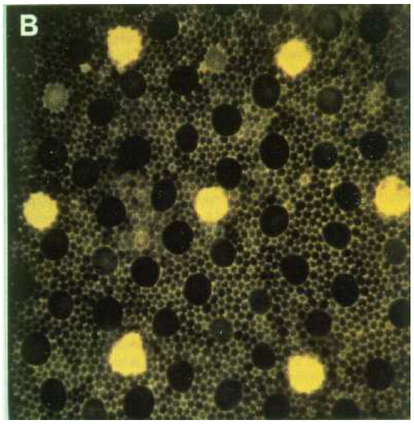




S-cone (cross section)



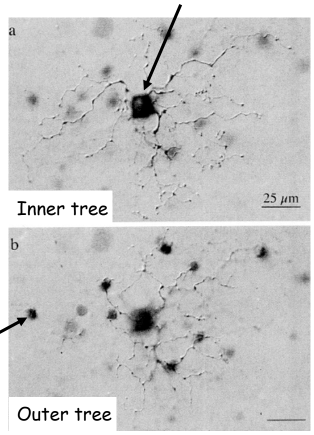
S-cone sampling mosaic



Bistratified ganglion cell

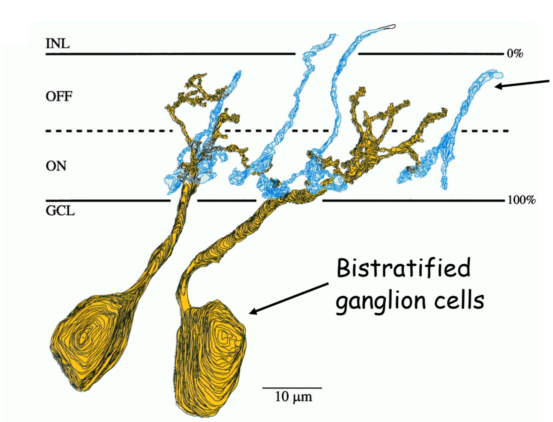
- Dendritic tree of bistratified ganglion cell branches in two separate layers of the retina.
- Inner tree avoids S cone bipolar cells.
- Outer tree has synapses with every S cone bipolar cell.

Ganglion cell



S cone bipolar cell

Blue/yellow pathway

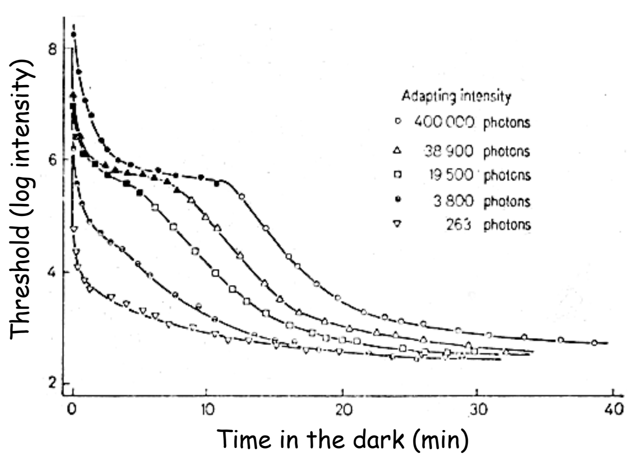


Light and dark adaptation

Surface luminance levels

- Sunlight: 10^5 candelas/meter^2 (cd/m^2)
  - Approx. 10^{22} photons/m^2/sec
  - 3%-90% of photons are reflected as luminance
  - 3% for black surfaces, 90% for white surfaces
  - Only some of the reflected photons enter the pupil of eye
- Indoor lighting, CRTs: 10^2 cd/m^2
- Moonlight: 10^{-1} cd/m^2
- Starlight: 10^{-3} cd/m^2
- The eye can adjust to changes in light level by a factor of 100,000,000!
- Yet firing rates only typically range from 0-400Hz.

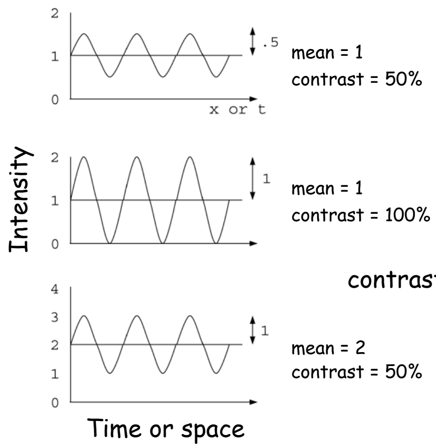
Dark adaptation



Mechanisms of light/dark adaptation

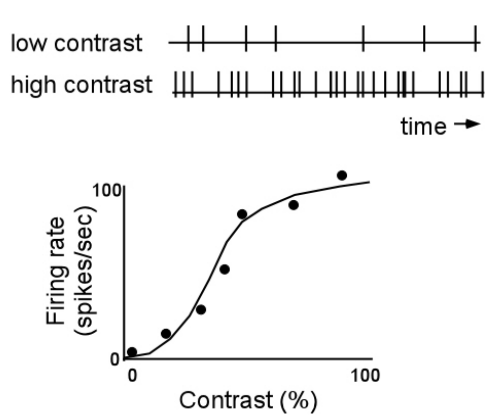
1. Pupil size
2. Switchover between rods and cones
3. Bleaching/regeneration of photopigment
4. Feedback from horizontal cells to control the responsiveness of photoreceptors

Contrast

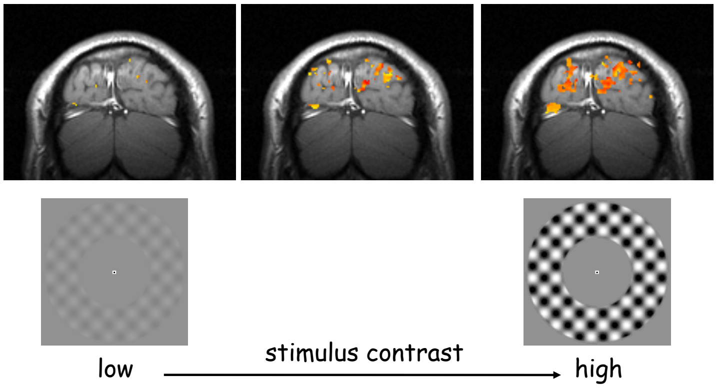


$$\text{contrast} = \frac{\text{amp of modulation}}{\text{mean}}$$

Responses increase with contrast

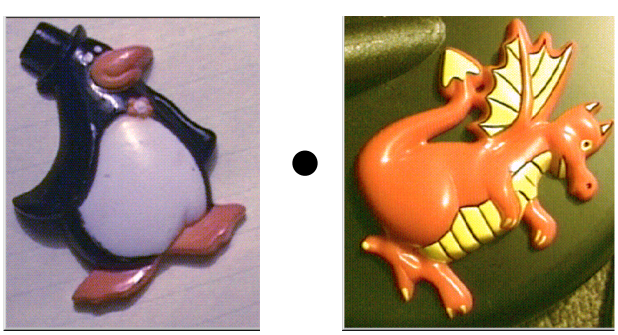


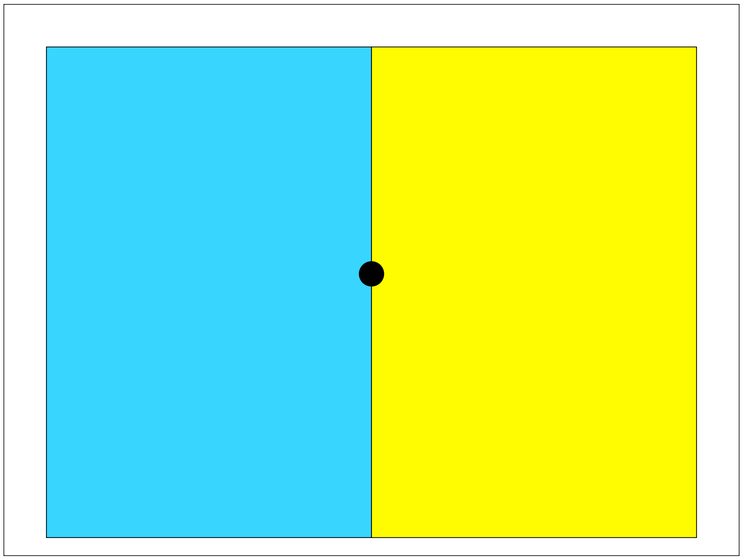
Responses increase with contrast

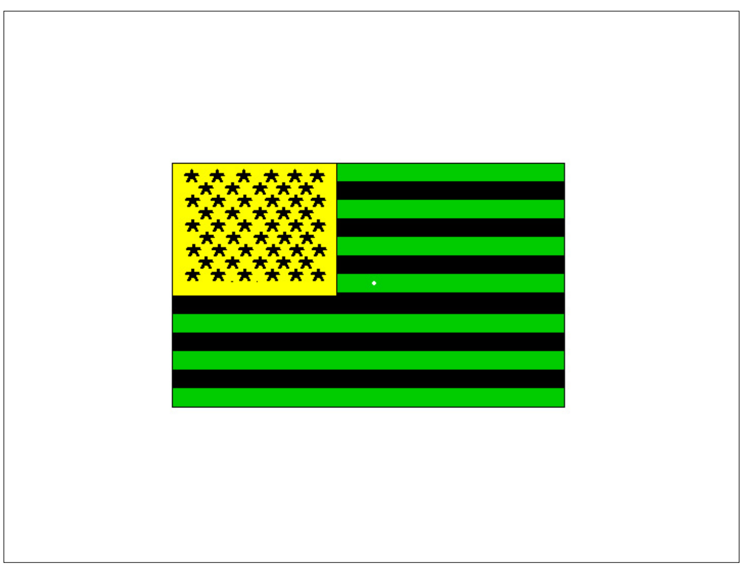


Chromatic adaptation

Chromatic adaptation

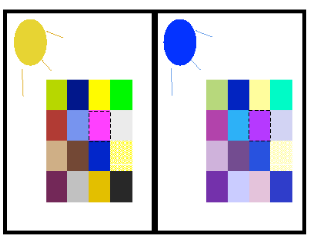




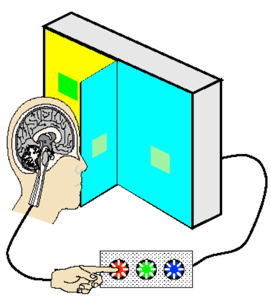


Asymmetric color matching

Memory matching



Dichoptic matching



Von Kries theory of chromatic adaptation (change of gain)

$$\begin{pmatrix} L \\ M \\ S \end{pmatrix} = \begin{pmatrix} G_L & 0 & \\ & G_M & \\ 0 & & G_S \end{pmatrix} \begin{pmatrix} L' \\ M' \\ S' \end{pmatrix}$$

Von Kries (1905)

Von Kries theory of chromatic adaptation (change of gain)

Input SPD

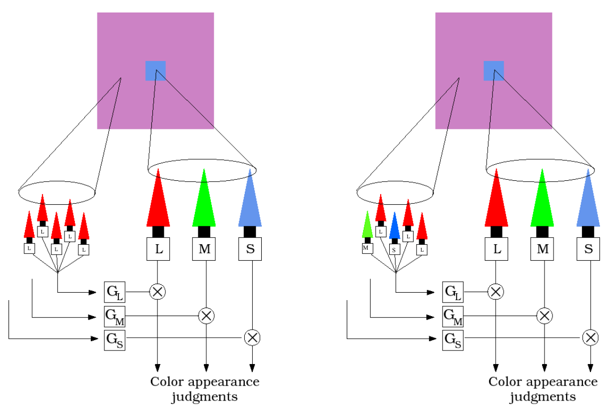
Adaptation scale factors

Photoreceptor responsivity

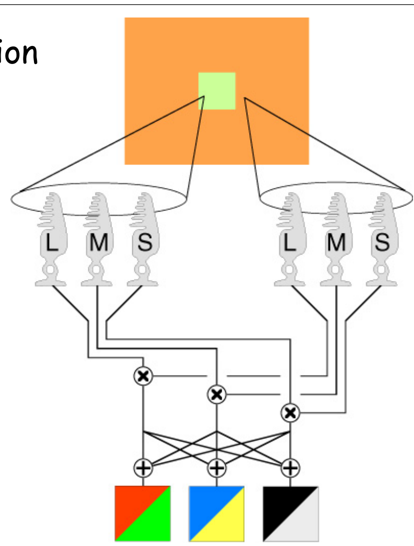
$$\begin{pmatrix} L \\ M \\ S \end{pmatrix} = \begin{pmatrix} G_L & 0 & 0 \\ 0 & G_M & 0 \\ 0 & 0 & G_S \end{pmatrix} \begin{pmatrix} \dots & L(\lambda) & \dots \\ \dots & M(\lambda) & \dots \\ \dots & S(\lambda) & \dots \end{pmatrix} \begin{pmatrix} \\ \\ \\ \end{pmatrix}$$

Canonical context cone absorptions

What determines the gain

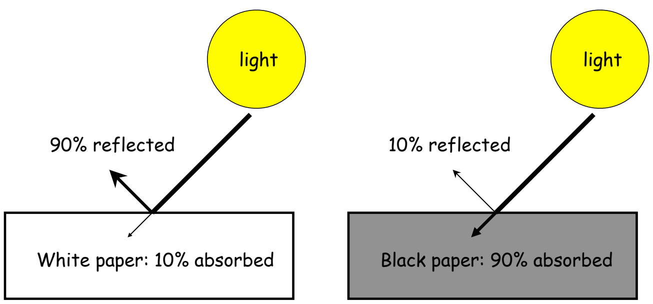


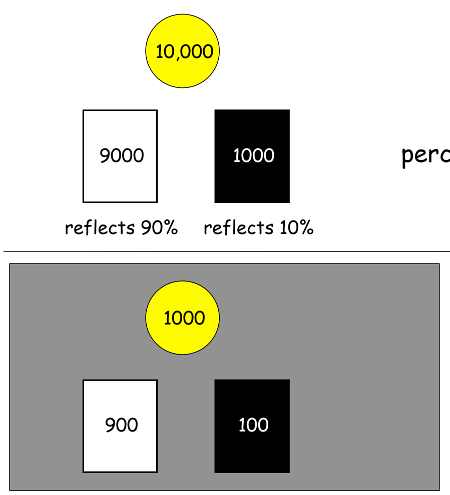
Neural computation with color-opponency and adaptation



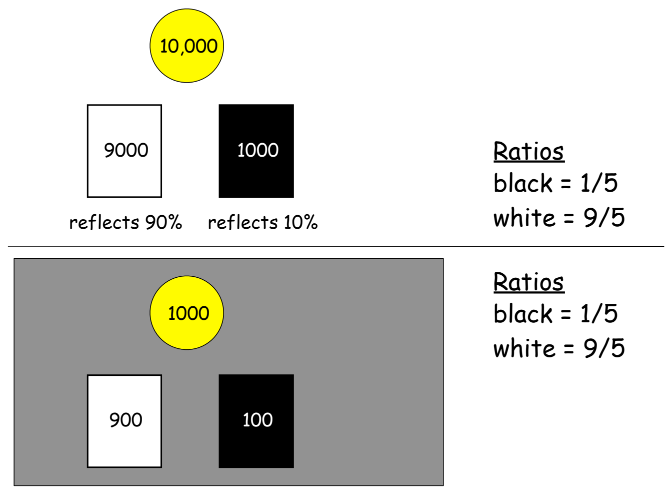
Lightness constancy

Surface reflectance





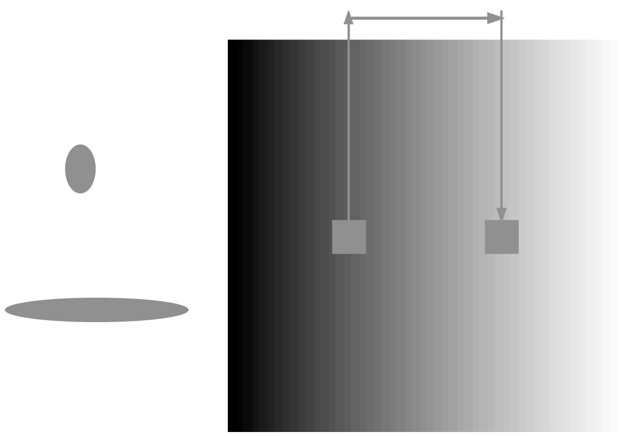
perceived brightness?



Ratios
black = 1/5
white = 9/5

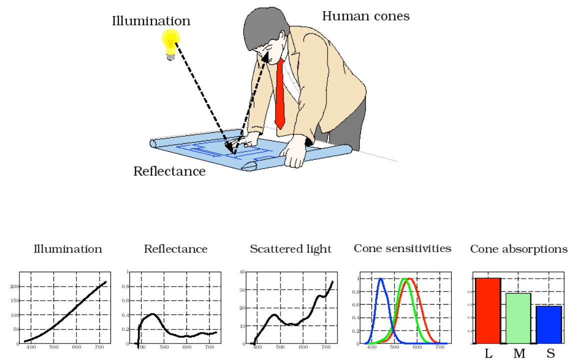
Ratios
black = 1/5
white = 9/5

Simultaneous brightness contrast

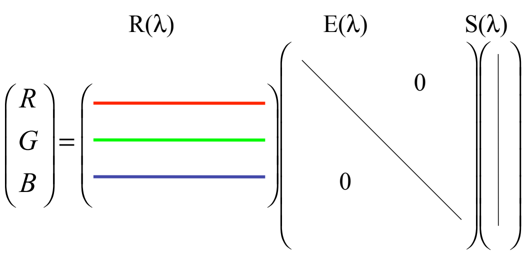


Color constancy

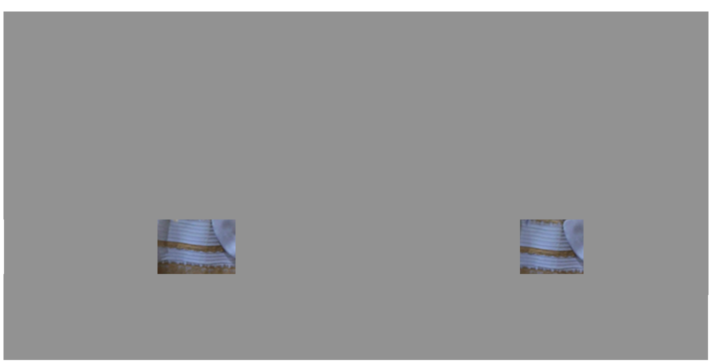
Color signaling



Surface-illuminant equations



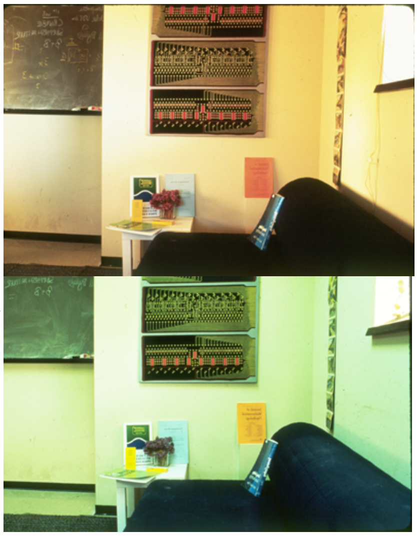
$$G = \int E(\lambda) S(\lambda) R_g(\lambda) d\lambda$$



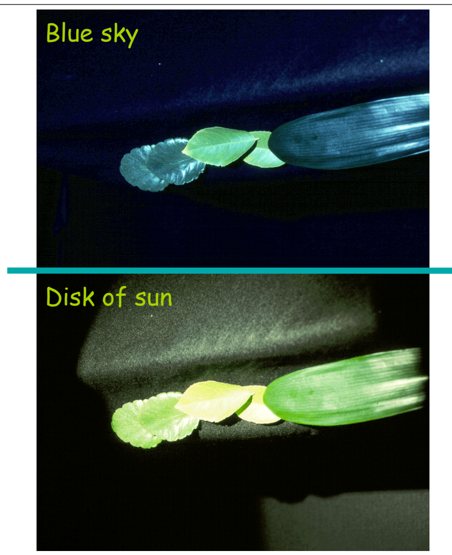
Cameras do not have color constancy

daylight

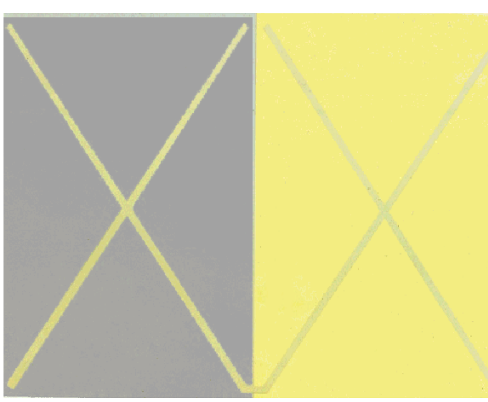
flourescent light



Daylight illumination examples



Simultaneous color contrast



Principles

- Psychophysics is part psycho and part physics.
- Theory: linear systems.
- Methodology: matching.
- Computation: linear summation, static nonlinearity, adaptation.
- Principle of univariance.
- Parallel pathways.
- Perceptual constancy (lightness, color, size, etc.), adaptation, and visual illusions (e.g., aftereffects).