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 opponent

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

• 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?

Color opponency

Neural circuits in the retina
(monkey rod pathway)

Neural circuits: rod pathway

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 mosaics

Blue/yellow pathway

Cones
Bipolars
B/Y ganglion

S-cone (cross section)

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.
Surface luminance levels

- Sunlight: $10^5$ candelas/meter$^2$ (cd/m$^2$)
  - Approx. $10^9$ 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 typically range from only 0-400Hz.

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
Responses increase with contrast

low contrast

high contrast

stimulus contrast

Responses increase with contrast

low

high

stimulus contrast

Chromatic adaptation

Chromatic adaptation
Asymmetric color matching

Memory matching

Dichoptic matching

Von Kries theory of chromatic adaptation (change of gain)

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

Von Kries (1905)

Von Kries theory of chromatic adaptation (change of gain)

Adaptation scale factors

Sensor responsivity

Input SPD

\[
\begin{pmatrix}
L \\
M \\
S
\end{pmatrix} =
\begin{pmatrix}
G_L & 0 \\
0 & G_M \\
0 & 0 & G_S
\end{pmatrix}
\]

Canonical context cone absorptions

What determines the gain
Neural computation with color-opponency and adaptation

Simultaneous color contrast

Lightness constancy

Surface reflectance

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 illumination examples

Daylight

Fluorescent light

Blue sky

Disk of sun
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).

Color and pattern

S-cones have low resolution

S-cones have low resolution

Blurred Y  Blurred I  Blurred Q
Blurred Y  Blurred I  Blurred Q
Increasing spatial frequency

Monochrome MTF

Increasing contrast

Chromatic MTF

Asymmetric color matching

Asymmetric color matching results

Dichoptic color-matching: adaptation


Asymmetric color matching results

Courtesy E.J. Chichilnisky