Color Perception

This lecture is (mostly) thanks to Penny Rheingans at the University of Maryland, Baltimore County
Characteristics of Color Perception

- Fundamental, independent visual process
  - after-images
  - Simultaneous color contrast
  - Chromatic Adaptation
- -> Relative, not absolute
- Interactions between color and other visual properties
Color Pathway

• Red, green, and blue (roughly) cones (564–580 nm, 534–545 nm, and 420–440 nm)
• Bipolar Cells and Amacrine Cells
• Retinal ganglion cells
• Parvocellular layers in the lateral geniculate nucleus (LGN)
• Areas in visual cortex
  – V1: blobs
  – V2: thick stripes
  – V4: color
Physiology: Receptors

- **Cones**
  - active at normal light levels
  - three types: sensitivity functions with different peaks

Glassner '95
Physiology: Brain

- Lateral geniculate nuclei
  - assemble data for single side of visual field
  - 2 monochromatic layers => magnocellular path
  - 4 chromatic layers => parvocellular path

- Visual cortex
  - visual area 1: blobs
  - visual area 2: thick stripes
  - visual area 4: color
Parvocellular Division

• Role in vision
  – discrimination of fine detail
  – color

• Characteristics
  – color: sensitive to wavelength variations
  – acuity: small RF centers
  – speed: relatively slow response
Models of Color Vision

• Tricolor theory
• Opponent process theory
Trichromatic Theory

• Three types of cones – each with a characteristic wavelength
• Mixture of 3 responses defines color
• Explains some psychophysical data
  – 3D color space (i.e. 3 colors match any perceived)
  – Metamers
  – Color blindness (different types)
Trichromatic Theory

http://psych.hanover.edu/JavaTest/Media/Chapter6/MedFig.TrichromatCones.html

Violet  Blue  Green  Yellow  Orange  Red

0  100

Relative Activity Level (% of total)

- Short wavelength receptors
- Medium wavelength receptors
- Long wavelength receptors
Trichromatic Theory
Shortcomings

• Color blindness
  – R-G, B-Y, All
• Yellow seems primary
• Color constancy
Color Blindness

Normal

Protan (L-cone)

Deutan (M-cone)

Tritan (S-cone)
Mondrian Color Patches

• Colors look different depending on their neighbors
• Adjacency/black lines
• Color edges are critical to color perception
• Can determine color in non-white lighting conditions
Opponent Color Theory

- Humans encode colors by differences
- E.g. R-G, and B-Y Differences
  - Color blindness

![Diagram](attachment:image.png)
Perceptual Distortions

- Color-deficiency
- Interactions between color components
  - brightness - hue (Bezold-Brücke Phenomenon)
  - saturation - brightness (Helmholtz-Kohlrausch effect)
- Simultaneous contrast
  - brightness
  - hue
- Small field achrominance
- Effects of color on perceived size
Bezold-Brücke Phenomenon
http://www.lifesci.ucsb.edu/~mrowe/Bezold-Brucke.html

- Hurvich ‘81, pg. 73.
Bezold-Brücke Phenomenon

- Hurvich ‘81, pg. 73.
Helmholtz-Kohlrausch effect
Simultaneous Contrast
Simultaneous Contrast
Simultaneous Contrast
Chromatic Adaptation
C/S Illusion

Cleveland and McGill ‘83.
Color-size Illusion

Cleveland and McGill ‘83.
**Color Spaces**

- **Perceptually based**
  - device independent, perceptually uniform
  - CIELUV, CIELAB, Munsell
- **Device-derived**
  - convenient for describing display device levels
  - RGB, CMY
- **Intuitive (transformations)**
  - based in familiar color description terms
  - HSV, HSB, HLS
spectral locus

Mixing colors

purple line
CIE Color Space

- Humans can mimic any pure light by addition (and subtraction) of 3 primaries
  - Color is a 3D space
- With R-G-B, addition and subtraction were required to get all wavelength

The color matching functions are the amounts of primaries needed to match the monochromatic test primary at the wavelength shown on the horizontal scale.
The CIE Color Space

• In nature, light adds (but does not subtract)
• Conversion to another coordinate system X-Y-Z is a convenience---they are not primary colors
• Any 3 primaries (additive) can produce only a subset of all visible colors

\[
X = \int_0^\infty I(\lambda) \bar{x}(\lambda) \, d\lambda \\
Y = \int_0^\infty I(\lambda) \bar{y}(\lambda) \, d\lambda \\
Z = \int_0^\infty I(\lambda) \bar{z}(\lambda) \, d\lambda
\]
The Chromaticity Diagram

Approximate Color regions on CIE Chromaticity Diagram
R-G-B Color Space

- Convenient colors (screen phosphors)
- Decent coverage of the human color
- Not a particularly good basis for human interaction
  - Non-intuitive
  - Non-orthogonal (perceptually)
The Chromaticity Diagram

sRGB uses ITU-R BT.709 primaries
- Red: x = 0.64, y = 0.33
- Green: x = 0.30, y = 0.60
- Blue: x = 0.15, y = 0.06
- White: x = 0.3127, y = 0.3290

AdobeRGB(98) uses Red and Blue like sRGB and Green like NTSC

CIE-RGB are the primaries for color matching tests: 700/546.1/435.8nm

Wavelengths in nm
HSL/HSV

Hue

Saturation

Lightness

Value
HSV

- $Max = \max(R, G, B)$
- $Min = \min(R, G, B)$
- $S = (\max - \min)/\max$
- If $R==Max \rightarrow h = (G-B)/(\max-\min)$
- If $G==Max \rightarrow h = 2+(B-R)/(\max-\min)$
- If $B==Max \rightarrow h = 4 + (R-G)/(\max-\min)$
- If $h<0 \rightarrow H = h/6 + 1$
- If $h>0 \rightarrow H = h/6$
HSV User Interaction
HSI

- \( S = \sqrt{\frac{(R-G)^2 + (R-B)^2 + (G-B)^2}{2}} \)
- \( I = \frac{R + G + B}{3} \)
- \( H = \frac{a - \arctan\left(\frac{R-I}{b}\right)}{2\pi} \) --- angle
  - \( a = \)
    - \( \pi/2 \) if \( G > B \)
    - \( 3\pi/2 \) if \( G < B \)
    - \( H = 1 \) if \( G = B \)
- \( a = \sqrt{3} \)
Perceptual Spaces

Distance corresponds to perception

- Hill et al. ‘97, pg. 136