Introduction to Scientific Visualization

Color Perception

January 23, 2018
Outline

• Preamble: human vision
• Physiological basis of color perception
• Color vision models
• Color spaces
Functions of Human Vision

• Shape/size
• Depth
• Motion
• Recognition
Properties of Vision

• Accurate relative to other senses
  • Location, size, and identification at a distance
Perceived Sizes Are
Perceived Sizes Are
Ponzo Illusion
Ponzo Illusion
Properties of Vision

• **Accurate relative to other senses**
  - Location, size, and identification at a distance

• **Limitations**
  - *Veridical* perception is limited
  - Absolute judgments are often poor
  - Lack of quantification

• **Good at**
  - Relative judgments
    - *Time and space*
  - Identification
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Light

- **Visible range:** 390-700nm
- **Luminance has a large dynamic range:**
  - 0.00003 -- Moonless overcast night sky
  - 30 -- Sky on overcast day
  - 3000 -- Sky on clear day
  - 16,000 -- Snowy ground in full sunlight
- **Colors result from spectral curves**
  - dominant wavelength, hue
  - brightness, lightness
Spectral Curve (of incoming radiation)
Physiology: Eye

- retina
- fovea
- optic nerve
- lens
- cornea
- pupil
- light
- vitreous humor
- ciliary muscles
- aqueous humor

Visual Axis
Perspective Projection and Image Formation

Image plane/retina  Lens  Scene
Physiology: Photoreceptors

- **Discrete sensors that measure energy**
  - Adaptation

- **Rods** ~ 120 million
  - active at low light levels (scotopic vision)
  - only one wavelength-sensitivity function

- **Cones** ~ 6-7 million
  - active at normal light levels (photopic)
  - three types: sensitivity functions with different peaks
Cone Sensitivity Functions

Glassner ‘95, p. 16.
Cone Sensitivity Functions

[Graph showing normalized absorbance across different wavelengths for violet, blue, cyan, green, yellow, and red, with peaks at 420, 498, 534, and 564 nm, and a rod labeled "Rod" at the bottom of the graph.]
Rod Sensitivity Function

Osterberg, 1935
Rod Sensitivity Functions
Retinotopic Mapping

mapping from retina to visual cortex
LGN: lateral geniculate nucleus
Physiology: Ganglia

- Transform incoming SML into opponent color
  - G - R
  - Y - B (Y = R+G)
  - W (W ≅ R+G)

- Characteristics
  - concentric receptive fields
Physiology: Brain

- Lateral geniculate nuclei (LGN)
  - 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
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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*: match of an apparent color with a different spectral distribution (3D basis)
• **Color blindness** (different types)
Trichromatic Theory

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
Note: Additive vs. Subtractive Colors

Additive

Subtractive
Note: Additive vs. Subtractive Colors

Additive coloring:
Colors are produced by combining (adding) electromagnetic radiations of different wavelength / frequency.

Example: computer screen
Note: Additive vs. Subtractive Colors

**Subtractive coloring:** Colors are obtained by combining things that absorb different portions of the visual spectrum when they reflect/scatter the incoming light. Subtractive coloring defines the “color” of objects.

**Example:** pigments of paint
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 color perception
• Can determine color in
Opponent Color Theory

• Humans encode colors by differences
• E.g R-G, and B-Y Differences
• Color blin
Perceptual Distortions

• Color-deficiency

• Interactions between color components
  • brightness/hue (Bezold-Brucke phenomenon)
  • saturation/brightness (Helmholtz-Kohlrausch effect)

• Simultaneous contrast
  • brightness
  • hue

• Small field achrominance

• Effects of color on perceived size
Bezold-Brücke Phenomenon

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

• Hurvich ‘81, pg. 73.
Helmholtz-Kohlraush
Simultaneous Contrast
Simultaneous Contrast
Simultaneous Contrast
Chromatic Adaptation
Chromatic Adaptation
Chromatic Adaptation

sky blue-ish gray!

(63, 75, 104)
Color-size Illusion

• Cleveland and McGill ‘83.
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Color Spaces

- Perceptually based
  - Device independent, perceptually uniform
    \(\text{CIELUV, CIELAB, Munsell}\)

- Device-derived
  - Convenient for describing display device levels
    \(\text{RGB, CMY}\)

- Intuitive (transformations)
  - Based on familiar color description terms
    \(\text{HSV, HSB, HLS}\)
The Space of Human Color

Gamut

CIE 1931 XYZ

xy plot

\[ x = \frac{X}{X + Y + Z} \]
\[ y = \frac{Y}{X + Y + Z} \]
\[ z = \frac{Z}{X + Y + Z} = 1 - x - y \]
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 are both required to get all wavelengths
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

Approximate Color regions on CIE Chromaticity Diagram

- Green
- Yellow-green
- Orange
- Red
- Purple
- Blue
- Greenish-blue
- Bluish-green
- Bluish-purple
- White
- Pink
- Red-purple
- Orange
- Yellowish-orange
- Greenish-yellow
- Yellow
R-G-B Color Space

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

sRGB uses ITU-R BT.709 primaries
Red  Green  Blue  White
x  0.64  0.30  0.15  0.3127
y  0.33  0.60  0.06  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
HSV/HSL
HSI/HSV

• Value/Luminance – total amount of energy
• Saturation – degree to which color is one wavelength
• Hue – dominant wavelength
RGB to HSV

\[ V = M = \max(R, G, B); \]
\[ m = \min(R, G, B); \]
\[ S = (M - m)/M; \]
\[ \text{if} \ (R==M) \ h = (G-B)/(M-m); \]
\[ \text{if} \ (G==M) \ h = 2 + (B-R)/(M-m); \]
\[ \text{if} \ (B==M) \ h = 4 + (R-G)/(M-m); \]
\[ \text{if} \ (h<0) \ H = h/6 + 1; \]
\[ \text{if} \ (h>0) \ H = h/6; \]