PERCEIVING COLOR

ICS 280: Visual Perception

Functions of Color Vision

- Object identification
  - Evolution: Identify fruits in trees
- Perceptual organization
- Add beauty to life
Visible Light Spectrum

Color is due to...

- Selective emission/reflection of different wavelengths by surfaces in the world
- Different response to different wavelengths of the eye
Illumination – $I(\lambda)$

Reflectance – $R(\lambda)$
Color Stimuli – $C(\lambda)$

\[ I(\lambda) \times R(\lambda) = C(\lambda) \]

Different Types of Stimuli

- Monochromatic
  - Laser
- Achromatic
  - Sunlight (close to)
- Polychromatic
  - Most common
Properties of Stimulus

- **Luminance**
  - Amount of stimulus in cd/m²
  - Perceived as brightness
  - Governed by the area under the curve

- **Hue**
  - Predominant wavelength
  - Mean
Properties of Stimulus

- **Saturation**
  - Amount of Achromatic light
  - Variance from the mean

  All these three parameters are interrelated. Cannot be changed independently.

Lightness

- Relative amount of light reflected
- A black ball does remain black both outside and inside
  - Relative amount of light reflected remains same
  - Absolute amount of light reflected changes
  - Lightness remains same, brightness changes
Color Mixtures

- Subtractive –
  - Intersection of two spectrums $C_1(\lambda)$ and $C_2(\lambda)$
  - In paints

\[ C_1(\lambda) \]
\[ C_2(\lambda) \]

- Additive
  - Union of two spectrums $C_1(\lambda)$ and $C_2(\lambda)$
  - In light

\[ C_1(\lambda) \]
\[ C_2(\lambda) \]
Newton’s Additive Color Wheel

- Boundary is saturated color
  - Unsaturated colors in the interior
- Combination of two colors generate a color on the line joining them

Three colors to create a reasonable subset
- Devices
- Even Eye
- Same color can be created by a different set of primaries
Linear Transformation of Primaries

- A set of primaries is a linear transformation of another set of primaries
  - Since they define different 2D coordinates
- Board Work:
  - \( P \) can be transformed from one coordinate system to another by a linear transformation

Newton’s Additive Color Wheel

- Increasing the number of primaries
- More colors can be represented
Helmholtz/Maxwell’s Color Matching Experiment

- All colors can be produced by different amounts of three wavelengths
- Cannot match certain wavelengths
- Register as negative amount

Color Matching Functions

- Can be thought of response of sensors with peak sensitivity at the matching wavelengths
- Why do we need at least three?

Three wavelengths used for matching
Human Visual Response

- Trichromatic Theory
  - Proposed by Thomas Young
  - Eye has three kinds of receptors
  - Produce psychologically similar sensations of red, green and blue
Color Perception

- The response generated by a stimulus in the cones gives the perceived color

Metamerism

- Because of this selective response
  - Two dissimilar stimuli can generate equal strength of s, m and l
  - Phenomenon is called metamerism
  - The two stimuli are called the metamers
  - So, we experience all the metamers similarly
CIE Standard Color Matching Functions

- Negative weights do not make sense
- Humans perceive the entire range
  - But cannot be reproduced by just three primaries
- Need some color matching functions that would be able to span the entire range
  - With only positive weights
- Imaginary color matching functions
  - Can be found by linear transformations
  - Does not correspond to real colors

CIE Functions for Standard Observer

[Diagram showing the CIE color matching functions with axes for wavelength and amplitude, along with curves for x, y, and z components.]
Tristimulus Values

Integration over wavelength

\[ X = \int_{\lambda=400}^{\lambda=700} C(\lambda) x(\lambda) = \sum_{\lambda=400}^{\lambda=700} C(\lambda) x(\lambda) \]

\[ Y = \int_{\lambda=400}^{\lambda=700} C(\lambda) y(\lambda) = \sum_{\lambda=400}^{\lambda=700} C(\lambda) y(\lambda) \]

\[ Z = \int_{\lambda=400}^{\lambda=700} C(\lambda) z(\lambda) = \sum_{\lambda=400}^{\lambda=700} C(\lambda) z(\lambda) \]

XYZ forms a three dimensional space to define color

Two colors added by just adding the XYZ coordinates
Problem with the XYZ representation

- No physical feel as to how colors are arranged
- How are saturated hues arranged?
- How are unsaturated hues arranged?
- Perceptually not easy to deal with
- Experiment with color palette

Chromaticity Chart

- Relative proportions of X, Y, and Z are more important
- For example, equal proportions of each signifies an achromatic color
- Chromaticity Diagram
  \[ x = \frac{X}{X+Y+Z} \]
  \[ y = \frac{Y}{X+Y+Z} \]
Chromaticity Coordinates

- Shows all the visible colors
- Achromatic Colors are at (0.33, 0.33)
  - Why?
  - Called white point
- The saturated colors at the boundary
  - Spectral Colors

Chromaticity Chart

- Exception is purples
  - Non-spectral region in the boundary
- All colors on straight line from white point to a boundary has the same spectral hue
  - Dominant wavelength
What happens here?
- Complimentary wavelength
- When mixed generate achromatic color

Purity (Saturation)
- How far shifted towards the spectral color
- Ratio of $a/b$
- Purity $=1$ implies spectral color with maximum saturation

Relationship to $XYZ$ space
- Plane through $X+Y+Z = c$
- Colors on this straight line have same hue but different luminance $(X+Y+Z)$
How to combine colors?

- **Board Work**
  - Using just XYZ
  - Using hue, saturation and luminance
- **What happens when add two colors of same hue and saturation?**

Eye and Devices

- **Difference between the eye and the devices**
  - Eye has unique properties
  - Devices cannot reproduce that
- **Gamut**
  - Any color within the gamut can be reproduced by the device
Eye and Devices

- Gamut Matching Problem
  - Gamut Mapping
- More primaries can give wider gamut
- Why not?
  - Underconstrained system
  - No unique solution

Trichromatic Theory
Color Matching Experiments

- All colors can be produced by mixing various proportions of three wavelengths
  - 420nm, 560nm and 640nm
  - Young Helmholtz theory of color vision
- Three types of receptors excited
  - Pattern of excitation depends on the color or the wavelength of the light

Physiological Explanation

- Three different types of cone
  - Different pigment with different absorption spectra
  - Pigments have different amino acids in their opsins
    - Causes the different absorption spectra
- S, M, L
  - S and M are 44% similar, peaks 112nm apart
  - M and L are 96% similar, peaks 27nm apart
Response of Cones

- S
- M
- L

Color Deficiency

- Monochromat
- Dichromat
- Color weakness
- Cerebral achromatopsia
Reasons

- Monochromat
  - No cones
- Dichromat
  - No L, No M, and No S
- Color weakness
  - S, M and L not very sensitive
- Cerebral achromatopsia
  - Cones are fine but problem in visual cortex

Dichromatism

- Why more males?
  - Resides in X chromosome
  - Both X’s need to have the defect in women
  - Can be passed on by women with one deficient X to the male offspring