8. Visual Perception and Color

Reading

Recommended:

- Hearn & Baker, Chapter 15.
- Foley *et al.*, Sections 13.2–13.3.
- Glassner, Sections 1.1–1.6.

Further reading:

- Michael Wilcox. *Blue and Yellow Don't Make Green*. North Light Books, Cincinnati, 1987.
- Gerald S. Wasserman. *Color Vision: An Historical Introduction*. John Wiley & Sons, New York, 1978.
- John E. Kaufman, ed. *IES Lighting Handbook: Reference Volume*. Illuminating Engineering Society, New York, 1981.

Overview

Color theory:

- Physics of light
- Historical development of color theory

Human visual perception:

- Terms from optics
- Structure of the eye
- Perception of color
- Visual phenomena

Color spaces:

- The CIE XYZ color system
- Other: RGB, HSV, CMY, YIQ

Theories of light

Many theories have been advanced:

- Wave theory [Hooke, Huygens, 1600's]
  Light transmitted through the "aether" in waves.
- Corpuscular theory [Newton, 1600's]
  Light propagated as minute particles, ejected intermittently in straight lines.
- Electromagnetic theory [Maxwell, 1888]
  Waves again, propagated by coupled electric and magnetic fields: $\nu = c\lambda$
- Quantum theory [Planck, Einstein, 1900]
  Particles again: $Q = h\nu$
- Unified theory [De Broglie, Heisenberg, 1913]
  Both: Waves *and* particles!

The radiant energy spectrum

The wave theory allows a nice arrangement of electromagnetic radiation (EMR) according to wavelength:

The EMR spectrum (IES, 2-1)

Note:

- All EMR travels at same speed in a given medium.
- Energy proportional to frequency.

Emission spectra

A light source can be characterized by an *emission spectrum*:

The spectrum describes the energy at each wavelength.

Q: What is the "dimensionality" of light?

Newton's experiments on color

Newton was the first to perform scientific experiments on color, in 1666.

Built a simple colorimeter:

- Hole in a shutter
- Prism to disperse white light into spectrum
- Comb-shaped aperture to manipulate spectrum
- Converging lens to recombine spectrum

Newton's experiments, cont.

Newton defined two types of light:

- Simple: Light that cannot be further dispersed by a prism (now called monochromatic).
- Compound: Light that can be dispersed.

He called the colors of simple lights primaries.

[This term has many other meanings today.]

Newton's barocentric model

Newton's barocentric model (Wasserman, 2-1)

Newton proposed a "barocentric model of color vision":

- Factored out brightness
- Identified the endpoints of the spectrum
- Placed white in the center
- Gave a qualitative model of light mixture

Q: Why did Newton choose seven divisions, or "tones"?

Subtractive mixtures

Two examples of subtractive color mixture (Wasserman, 2-2)

Newton also characterized the difference between additive and subtractive color mixtures.

Subtractive color mixtures:

- Due to selective absorption by pigments.
- Difficult to characterize in general.

Additive mixtures

Newton posed a fundamental question that took almost two centuries to answer:

Q: How many primaries does it take to produce a perfect white?

A: (Newton) Definitely more than 2; and 4 or 5 suffice.

In 1852, Helmholtz answered a generalized form of this question:

Q: How many primaries does it take to produce the *entire* spectrum?

A: (Newton) 7.

A: (Young, 1802) 3.

A: (Helmholtz) 5.

Trivariant mixtures

Illustration of trivariant color mixing (Wasserman, 2-3)

In 1856, Maxwell rescued the notion of trivariant color mixing by applying Newton's barocentric mixing more rigorously.

Q: How many primaries are required by Maxwell's model?

Q: In what sense can three primaries produce all colors?

Maxwell's imaginary primaries

A color space associated with imaginary primaries (Wasserman, 2-5)

Maxwell observed that with three "imaginary" primaries, you no longer need to use one as a desaturant.

Q: But how do you select these imaginary primaries? (*Last* 100 years devoted to answering this.)

Wright's experiments

In the late 20's, Wright found that the colors of all wavelengths could be reproduced with combinations of 3 primaries at 460, 530, and 650nm:

Relative luminances for metameric matches (Wasserman, 3-3)

Q: Why is there a double peak for the red primary?

Q: Suppose you change the set of primaries. Is there a way to avoid repeating the experiment?

Transforming primaries

Transforming primaries (Wasserman, 3-6)

A transformation of primaries can be described as a simple change of basis. . . .

Given: Color X in the ABC system:

$$X = aA + bB + cC$$

Find: Color X in the DEF system:

$$X = dD + eE + fF$$

Transforming primaries, cont.

Solution: Write A, B, C in terms of D, E, F:

Optics

To describe the eye, we'll need some terms from "optics" (the study of sight and the behaviour of light):

- Focal point – The point where parallel rays converge when passing through a lens.
- Focal length: The distance from the lens to the focal point.
- Diopter: The reciprocal of the focal length, measured in meters.
  - Example: A lens with a "power" of 10D has a focal length of _____.

Structure of the eye

Physiology of the human eye (Glassner, fig 1.1)

The most important structural elements of the eye are:

- Cornea: A clear coating over front of eye:
  - Protects eye against physical damage.
  - Provides initial focusing (40D).
- Iris: Colored annulus with radial muscles.
- Pupil: The hole whose size is controlled by the iris.

Structure of the eye, cont.

Physiology of the human eye (Glassner, fig 1.1)

- Crystalline lens: Controls the focal distance:
  - Power ranges from 10 to 30D in a child.
  - Power and range reduces with age.
- Ciliary body: The muscles that compress the sides of the lens, controlling its power.

  Q: As an object moves closer, do the ciliary muscles contract or relax to keep the object in focus?

Retina

Density of receptors on the retina (Glassner, fig 1.4)

- Retina: A layer of photosensitive cells covering 200° on the back of the eye:
  - Cones: Responsible for color perception.
  - Rods: Limited to intensity (but 10× more sensitive.
- Fovea: Small region (1 or 2°) at the center of the visual axis containing highest density of cones (and no rods).

Photomicrographs of the human retina

Photomicrographs at increasing distances from the fovea. The large cells are cones; the small ones are rods (Glassner, fig 1.5).

Demonstration of visual acuity

With one eye shut at the right distance, all of these letters should appear equally legible (Glassner, fig 1.7).

Blind spot demonstration (Glassner, fig 1.8)

Eye geometry

(a) normal, (b) myopic, and (c) hyperopic eye (Glassner, fig 1.9).

Eye geometry accounts for near- and far-sightedness:

- Emmetropic eye: Resting eye has focal point on retina.
- Myopic eye: Eye too long.
- Hyperopic eye: Eye too short.

Photopigments

Photopigment absorption (Glassner, fig 1.11)

Photopigments: The chemicals in the rods and cones that react to light. Can respond to a single photon!

- Rods contain rhodopsin, which has peak sensitivity at 500nm.
- Cones come in three varieties: S, M, L.

Principle of univariance: No information is transmitted describing the wavelength of the photon. **Q:** Why not?

Transmitting color

How color info is sent to the brain (Glassner, fig 1.37)

Color info is transmitted to the brain in three nerve bundles or channels:

1. Achromatic channel $A = M + L$
2. Red-green chromatic channel $R/G = M - L$
3. Blue-yellow chromatic channel $B/Y = S - A$

Saturation is perceived as the ratio of chromatic to achromatic response.

Metamers

Two daylight metamers that are not metamers under tungsten light (Wasserman, 3-9). The solid curve appears green both indoors and out, whereas the dashed curve looks green outdoors, but brown under yellowish incandescent light.

Many completely different emission spectra may be perceived as the same color — called *metamers*.

Q: Why would you *expect* this to happen?

Flicker

The photoreceptive cells provide a time-averaged response:

more photons → more response

Above a critical flicker frequency (CFF), flashes of light will fuse into a single image.

Q: Do all parts of the visual field have the same CFF?

Adaptation

Adaptive processes can adjust the the base activity ("bias") and scale the response ("gain").

Through adaptation, the eye can handle a large range of illumination:

Background	Luminance (cd/m^2)
Moonless overcast night	0.00003
Moonlit clear night	0.03
Twilight	3
Overcast day	300
Day with sunlit clouds	30,000

Luminous efficiency

Luminous efficiency curves (Glassner, fig 1.15)

You can plot the luminous efficiency of:

- Rods (scotopic vision)
- Cones (photopic vision)

as a function of wavelength.

The Purkinje shift refers to the change in peak wavelength perception between the two types of vision.

Noise

Sampling on uniform vs. jittered grid (Glassner, fig 9.3)

- Noise can be thought of as randomness added to the signal.
- The eye is relatively insensitive to noise.

Mach bands

Illustration of Mach bands (Glassner, fig 1.24)

- Mach bands were first discussed by Ernst Mach, an Austrian physicist.
- Appear at C^0 or C^1 intensity discontinuities.

Mach bands, cont.

Mach bands in continuous functions (Glassner, fig 1.25)

Mach bands also appear whenever there is a rapid intensity change.

Cause: Lateral inhibition of nearby cells.

Lateral inhibition effect (Glassner, fig 1.26)

Lightness contrast

Example of lightness contrast (Glassner, fig 1.27)

A related phenomenon is known as:

- Lightness contrast
- Simultaneous contrast
- Color contrast (for colors)

This phenomenon helps us maintain a consistent mental image of the world, under dramatic changes in illumination.

The XYZ system

In 1931, the CIE (Commission Internationale de l'Eclairage) adopted the XYZ system, which has the following properties:

- Every color can be made with *positive* combinations of primaries called **X**, **Y**, **Z**.
- The **X**, **Y**, **Z** primaries are imaginary.

The CIE color-matching functions

Here are the *color-matching functions* $\overline{x}, \overline{y}, \overline{z}$:

The color-matching functions (Glassner, fig 1.41)

Note: By design, the $\overline{y}$ curve is just the "luminous efficiency curve."

Computing CIE coordinates

The X, Y, Z coordinates are computed by:

$$X = \int I(\lambda)\overline{x}(\lambda)\,d\lambda$$

$$\vdots$$

From these, the chromaticity coordinates x, y, z are computed by:

$$x = \frac{X}{X+Y+Z}$$

$$\vdots$$

Note: x, y, z are all on the $X + Y + Z = 1$ plane.

The CIE chromaticity diagram

The *CIE chromaticity diagram* is the projection of the $X + Y + Z = 1$ plane onto the (X, Y) plane:

The chromaticity diagram (Glassner, fig 1.42)

Each point of the diagram gives a *chromaticity* value, which depends on:

- the "dominant wavelength" or "hue" — red, yellow, etc.;
- the "excitation purity" or "saturation" — closeness to grey.

The CIE diagram, cont.

The CIE diagram (Glassner, fig 1.42)

- *Dominant wavelengths* go around the outside of the diagram.
- *Excitation purity* is given by the ratio AC/BC, where
  - C is white light;
  - A is color being tested;
  - B is extrapolation of CA to curve — i.e., the dominant wavelength.

The CIE diagram, cont.

The CIE diagram (Glassner, fig 1.42)

- "Complementary colors"
  - Colors that can be mixed to produce white light.
  - Lie on opposite sides of C.
- "Nonspectral colors"
  - Lie on wedge that does not project to any dominant wavelength.
  - Reds, magentas, purples

Perceptual uniformity

The XYZ space is not perceptually uniform:

Areas of constant color (enlarged) (Glassner, fig 2.1)

Perceptually-uniform color spaces

Some perceptually-uniform spaces include:

- $L^*u^*v^*$
- $L^*a^*b^*$
- "Farnsworth's non-linear transformation"

The first two of these involve taking cube roots, etc.

Formulas for $L^*u^*v^*$ and $L^*a^*b^*$ in terms of XYZ are given in [Glassner].

Main point is that Euclidean distance is supposed to work better in these spaces.

Other color spaces

Other color spaces commonly used in computer graphics include:

- RGB — most natural for CRTs
- HSV — more intuitive for users
- CMY — used for hardcopy
- YIQ — used for TV broadcasting

RGB

You're already familiar with this one:

Q: Where are the greys?

HSV

A more intuitive color space.

Think of shower controls. . .

Most naturally represented by a cone:

- "Hue" — red, yellow, etc.
- "Saturation" — Distance from grey
- "Value" — Distance from black

Note: Value is not perceptually-based, so colors of the same value may have slightly different brightnesses.

CMY

A subtractive color space, used for printing.

Involves three subtractive primaries:

- Cyan — subtracts red
- Magenta — subtracts green
- Yellow — subtracts blue

Mixing two pigments subtracts their opposites from white.

Printers often use *black* ink rather than equal amounts of all three.

YIQ

Used in TV broadcasting. Exploits useful properties of the visual system:

- Uses most bandwidth for Y, the luminance
  - Exploits ability to judge relative luminance better than hue and saturation changes
  - Allows b&w TVs to just look at Y channel
- I chosen as major axis of remaining visual color space
- Q is the remaining axis
- Relative bandwidth ratios are 8:3:1

Summary

Here's what you should take home from this lecture:

1. How light is a form of EMR and how it is perceived as color.
2. The difference between subtractive and additive color mixtures.
3. The notion of trivariant color mixing, using either a desaturant or imaginary primaries.
4. How to perform a transformation of primaries.
5. The basic structures of the eye and how they work.
6. What metamers are and why they exist.
7. How perceived brightness is a function of wavelength.
8. The eye's relative sensitivity to intensity discontinuities, but insensitivity to noise.
9. The phenomena of adaptation and lightness contrast.
10. The XYZ color system, and how a color's XYZ coordinates are computed.

11. How the CIE chromaticity diagram works.
12. A qualitative sense of what the various color spaces used in computer graphics are like.