5.1 The Human Visual System

Reading

Suggested:

- Glassner, Sections 1.1–1.6
- Spencer, Shirley, Zimmerman, and Greenberg. Physically-based glare effects for digital images. SIGGRAPH 95: 325–334.
- Ferwerda, Pattanaik, Shirley, and Greenberg. A model of visual adaptation for realistic image synthesis. SIGGRAPH 96: 249–258.

Overview

1. Terms from optics
2. Structure of the eye
3. Perception of color
4. Visual phenomena

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 (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 (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 (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 (1.5).

Demonstration of visual acuity

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

Blind spot demonstration (1.8)

Eye geometry

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

Wavelength sensitivity

A sample spectrum (1.10)

Electomagnetic radiation comes in all wavelengths, from 10^{-14} to 10^{8} meters.

The eye is sensitive to EMR with wavelengths from 380 to 780 nanometers (10^{-9} meters) — called "light."

Q: What color is the light at 380nm? 780nm?

Q: Which end of the spectrum has highest energy?

Q: What is the "dimensionality" of light?

Glare effects

Flare effects (Spencer, et al., fig. 2)

Glare effects include:

- Flare:
  - Ciliary corona: Radial streaks emanating from the center of source
  - Lenticular halo: Colored, concentric rings surrounding source
- Bloom: A glow around bright objects

Causes of flare

An etched biconvex lens (Spencer, et al., fig. 5a)

Ciliary corona: Caused by semirandom density fluctuations in the lens

Lenticular halo: Caused by circular optical grating formed by radial fibers at the periphery of the lens

Q: Why are lenticular halos only seen under dark conditions?

Causes of bloom

Reduction of contrast from bloom (Spencer, et al., fig. 6)

Bloom caused by scattering from:

- cornea
- crystalline lens
- retina

Computer simulation of flare effects

Spencer, p. 333

Photopigments

Photopigment absorption (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 (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.

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?

Bleaching and regeneration of photopigments

At high light intensities, photopigments are depleted more quickly than they can be restored: called pigment bleaching.

Effect is response compression: little change in cell's response rate above certain light level.

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

Light adaptation

Light adaptation (Ferwerda, et al., fig. 8–9)

Light adaptation: Adapting from dark to light.

- Much faster for rods than cones.
- Approx 2 seconds vs. 10 minutes.

Dark adaptation

Dark adaptation (Ferwerda, et al., fig. 10)

Dark adaptation: Adapting from light to dark.

- Much slower than light adaptation.
- Requires about 35 minutes.

Computer simulation of adaptation effects

Light and dark adaptation (Ferwerda, et al., fig. 12)

Luminous efficiency

Luminous efficiency curves (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.

Contrast sensitivity

Contrast sensitivity experiment (1.17)

- Let ΔI be the just noticeable difference in intensity.
- The contrast sensitivity function is a plot of $\Delta I / I$ as a function of I.
- This fraction is nearly constant (0.02) over a large range.

Q: Why does this fact make bloom so problematic?

Q: How would you make a perceptually uniform greyscale?

Noise

Sampling on uniform vs. jittered grid (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 (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 (1.25)

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

Cause: Lateral inhibition of nearby cells.

Lateral inhibition effect (1.26)

Lightness contrast

Example of lightness contrast (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.