1. Visual perception

Reading

Recommended:

- Glassner, Sections 1.1–1.6. [Most figures from here]
- Wandell, Chapter 3, pp.45-50

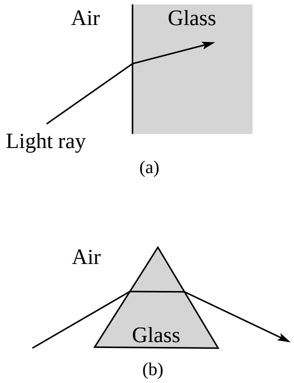
Further reading:

- 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.

Early history

- Plato (B.C. 428–347)
  - The eye is a lantern
  - Seeing is the meeting of inner and outer light
- DaVinci (1452-1519)
  - The eye is a camera obscura
- Kepler (1604)
  - Analyzed the optics of the eye
- Descartes, Scheiner (1625,1630)
  - Verified Kepler by looking through an animal's eye
- Newton (1704), Young (1802), Helmholtz (1852), Maxwell (1856)
  - Chromatic theory of light

Refraction

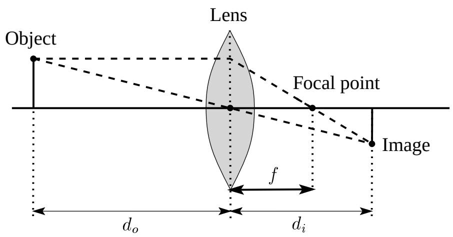


Refraction at air-glass interfaces

Think of a light "ray" as a bundle of light heading in a particular direction.

Rays will "refract" or bend when passing from one medium to another. They will bend toward the perpendicular or "normal" to the surface when going into a denser medium (e.g., from air into glass).

Optics

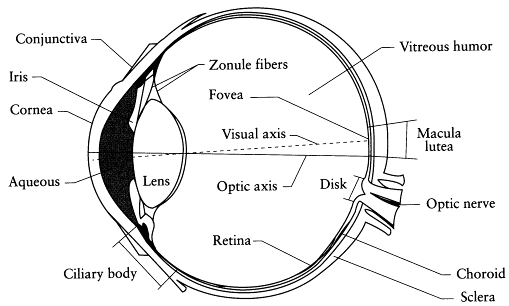


To describe the eye, we'll need some terms from optics:

- 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 ________.
- Gaussian lens formula:

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$$

Structure of the eye

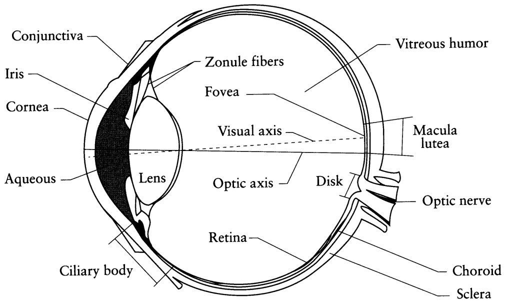


Physiology of the human eye (1.1)

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.

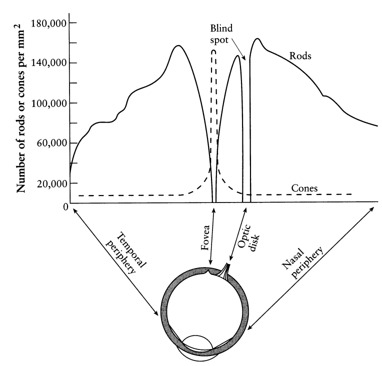


Physiology of the human eye (1.1)

- 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?

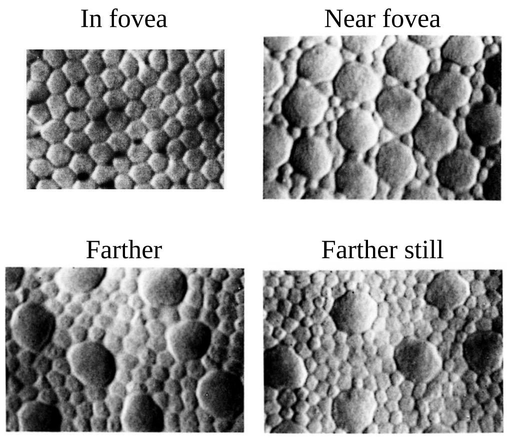
Retina



Density of receptors on the retina (1.4)

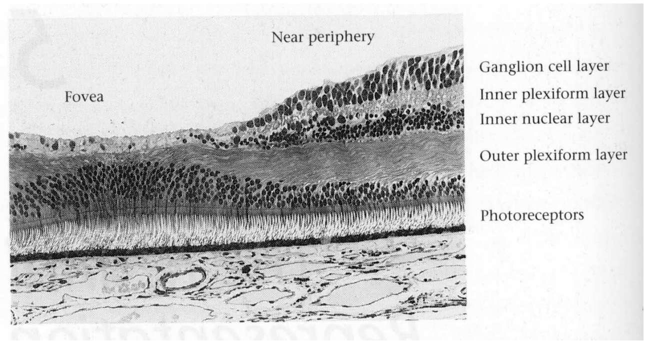
- Retina: A layer of photosensitive cells covering 200° on the back of the eye:
  - Cones: Responsible for color perception.
  - Rods: Limited to intensity (but 10× more sensitive.
- Fovea: Small region (1 or 2°) at the center of the visual axis containing highest density of cones (and no rods).

Photomicrographs of the human retina

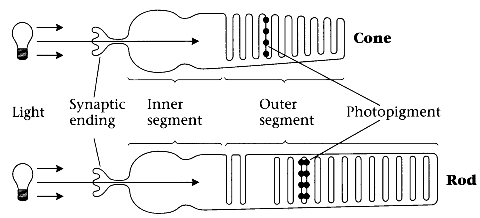


Photomicrographs at increasing distances from the fovea. The large cells are cones; the small ones are rods (1.5) and (Wandell, Fig. 3.4).

The retina and light gathering



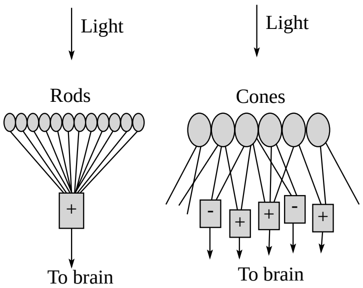
Photomicrograph of a cross section of the retina near the fovea (Wandell, 5.1).



Light gathering by rods and cones (Wandell, 3.2).

Neural processing

Even though the eye actually has a very dense coverage of both rods and cones, we have much more acuity in the fovea than in the periphery.

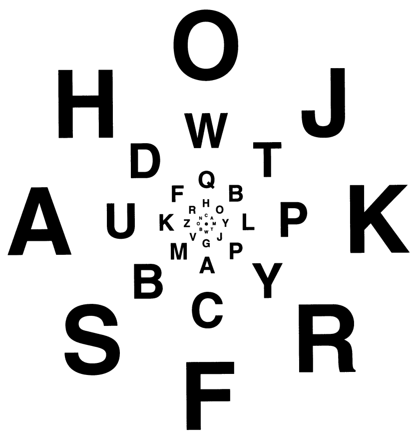


Rod and cone pathways

In the periphery, the outputs of rods are averaged together, thus lower the effective resolution. 1000 rods may converge to a single neuron.

In the fovea, the outputs of cones go to many other neurons for detailed proecssing in the brain.

Demonstration of visual acuity

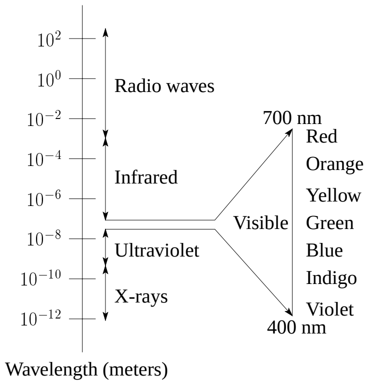


With one eye shut at the right distance, all of these letters should appear equally legible (1.7).

Blind spot demonstration (1.8)

The radiant energy spectrum

We can think of light as waves, instead of rays. Wave theory allows a nice arrangement of electromagnetic radiation (EMR) according to wavelength:



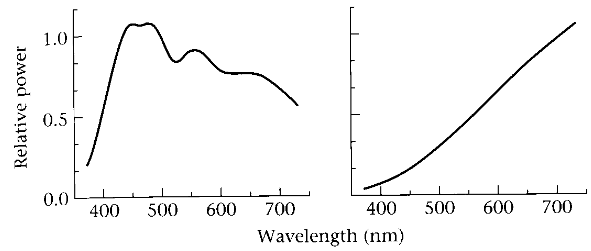
The EMR spectrum

Note:

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

Emission spectra

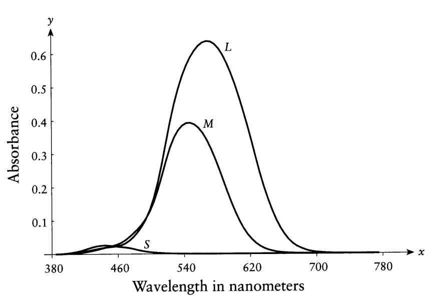
A light source can be characterized by an emission spectrum:



Emission spectra for daylight and a tungsten lightbulb (Wandell 4.4)

The spectrum describes the energy at each wavelength.

Photopigments



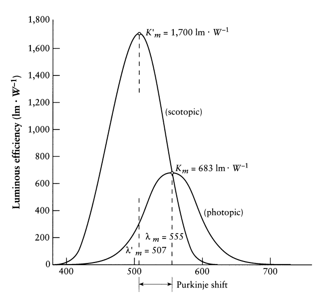
Photopigment absorption (1.11)

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?

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.

Perceptual light intensity

We perceive light intensity as we do sound: on a *relative* or *logarithmic* scale.

Example: The perceived difference between 0.20 and 0.22 is the same as between 0.80 and _________.

Ideally, to display $n+1$ equally-spaced intensity levels, the intensity levels on the monitor should be spaced as:

$$\frac{I_1}{I_0} = \frac{I_2}{I_1} = \cdots = \frac{I_n}{I_{n-1}} = r$$

Example: Suppose $I_0 = 1/8$ and $n = 3$. What are the four intensity levels to be displayed?

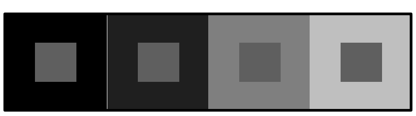
Adaptation

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

Lightness contrast



Example of lightness contrast

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.

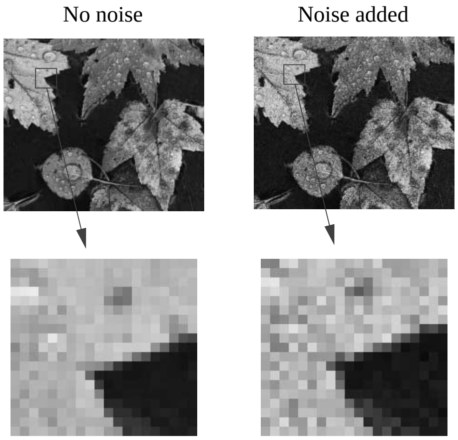
Flicker

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.

Noise



Adding noise to an image

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

Mach bands

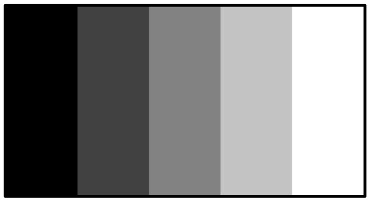


Illustration of Mach bands with instensity steps

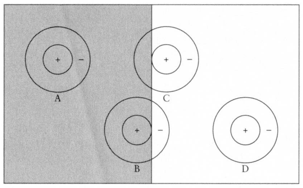
- Mach bands were first discussed by Ernst Mach, an Austrian physicist.
- Appear at C^0 or C^1 intensity discontinuities.

Mach bands, cont.

Mach bands in continuous functions

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

Cause: Lateral inhibition of nearby cells.



Lateral inhibition effect (1.26)