

Lecture notes 1: The human eye

The human eye is not much in use as a professional tool of astronomy. On the other hand, it is of great interest to understand how it works and by doing so we may illustrate many of the principles and problems that we will meet later in the course.

Evolution has come up with different designs for eyes, but most (if not all) can be divided into two parts¹: *a lens*, or set of lenses, for focussing light onto a *receptor* which detects light and sends information of detection on to the brain or nervous system. There are many designs and materials used for the optical set up of the lens. For example trilobites, perhaps the first animals to develop eyes some 540 million years ago during the Cambrian, used lenses made of crystal, the mineral calcite. Calcite has many interesting optical properties, amongst which is the fact that they deflect light from all angles, except one privileged axis called the *c*-axis. Each eye facet in a trilobite had its own calcite lens directed so that light would pass in only one direction to the underlying retina. While there are many designs for lenses, all light detecting cells see to be based on a single protein, or molecule, called *rhodopsin*, perhaps pointing to a common evolutionary source for all eyes extant throughout the animal kingdom².

The eye and brain work together, and the brain can correct for many of the aberrations suffered by the eye. Thus, for example, the brain compensates for the fact that the image on the retina is inverted, and for chromatic aberration.

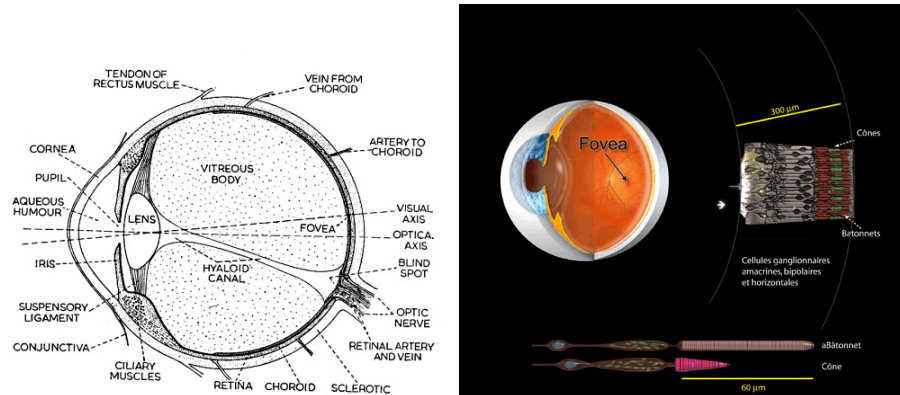


Figure 1: Cross section of the human eye (left), illustration of the eyes receptor cells; cones, used for color vision with the iodopsin layers arranged to the right, and rods with rhodopsin layers. Light enters these cells from the left before being absorbed by either iodopsin or rhodopsin.

¹Some of the information here is gathered from the highly recommended book by Nick Lane *Life Ascending, the ten great inventions of evolution*, Richard Dawkins' *Climbing Mount Improbable* also contains a chapter on the evolution of the eye.

²Note that the design of light sensitive cells is roughly divided into two groups, where all the vertebrates share a similar design and the invertebrates another.

Light is focussed on the retina, where there are two types of receptors: rods and cones. Cones for color reception, rods for black and white with higher sensitivity. For humans, rods and cones are arranged *backwards* so light must pass through the neuronal wires that send signals of light back to the brain. In contrast, octopus eyes, which otherwise are much as our own with a single lens in front and a light sensitive retina at the back, has the light sensitive parts of the retinal cells in front. This may be an accident of nature, or there may be good evolutionary reasons for the difference. Both designs are mimicked in CCD's used in astronomy, where *thinned, backlit* CCDs are used to avoid unwanted reflections from the electrodes used to drive them. The CCD in your camera or cell phone is more probably arranged in the same manner as your eye, with light having to pass through the electrodes lying on top of light sensitive doped silicon.

In the rods a pigment known as rhodopsin absorbs radiation. A protein with a weight of some 40 000 amu, arranged in layers 20 nm thick and 500 nm wide. Under influence of light a small fragment, a chromophore, will split off. The chromophore is a vitamin A derivative called retinal (or retinaldehyde) with a molecular weight of 286 amu. The portion left behind is a colorless protein called opsin. The moment of visual excitation occurs during this break off process as the cell's electrical potential increases (for invertebrates on the other hand excitation occurs because the electrical charge across the membrane is removed). This change in potential can then propagate along nerve cells to the brain. The rhodopsin molecule is then (slowly) regenerated.

The response of cones is similar, but in this case the pigment is known as iodopsin which also contains the retinaldehyde group. Cone cells come in three varieties with different spectral sensitivities (see figure 2).

In bright light much of the rhodopsin is broken up into opsin and retinaldehyde, and the rod sensitivity is much reduced so that vision is primarily provided by the cones, even though their light sensitivity is only of order 1% of the rods. The three varieties of cones combine to give color vision. At low light levels only rods are triggered by the ambient radiation and vision is then in black and white.

Upon entering the dark from a brightly lit region rhodopsin will build up over a period of roughly 30 min, thus dark-adaptation takes this long and is based on rod cells. Somewhere between 1–10 photons are necessary to trigger an individual rod. However, several rods must be triggered in order to result in a pulse being sent to the brain, as many rods can be connected to a single nerve fibre. The total number of rods is of order 10^8 , of cones 6×10^6 , these must share some 10^6 nerve fibres. Thus there are roughly 100 visual receptors per nerve fibre, note that there can be many cross connections between groups of receptors. Cones are concentrated towards the fovea centralis, which is the region of most acute vision, while rods are most plentiful towards the periphery of the field of view. Weak objects are thus most easily visible with averted vision, *ie* when it is not looked at directly. In sum with all these effects the eye is usable over a range of illuminations differing by a factor $10^9 - 10^{10}$. Note that in regions of high contrast the brighter region is often seen as too large,

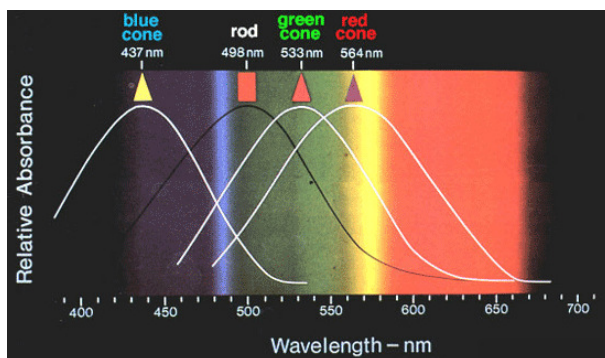


Figure 2: Absorption curves for the various types of cones, which combined give color vision, and for rhodopsin. Note that the peak sensitivity for rods (at 500 nm) and cones (at 555 nm) are at different wavelengths: this causes the sensitivity of the eye to shift towards blue at low light levels when the rods dominate.

this is a phenomena known as *irradiation*. It arises from stimulated responses of unexcited receptors due to their cross connection with excited receptors. Eye fatigue occurs when staring fixedly at a source for an extended period due to depletion of the sensitive pigment.

The Rayleigh limit of the eye, roughly given by λ/D where λ is the wavelength of the observed light and D is the size of the observing aperture, is of order 20 arcsec when the iris has its maximum diameter of 5–7 mm. However, for two separate images to be distinguished, they must be separated by at least one unexcited receptor cell, so even on the fovea centralis resolution is limited in practice to between 1 arcmin and 2 arcmin. This is much better than elsewhere on the retina, since the fovea centralis is populated by small, tightly packed, singly connected cones. The average resolution of the eye lies between 5 arcmin and 10 arcmin for point sources. Linear sources such as an illuminated grating can be resolved down to 1 arcmin. The effect of granularity of the retina is countered by rapid oscillations of the eye through a few 10 arcsec with a frequency of a few Hz, so that several receptors are involved in the detection when averaged over time.

The response of the eye to changes in illumination is logarithmic; if two sources A and B are observed to differ by a given amount, and a third source C is seen to lie midway between them, then the energy from C will differ from A by the same factor as it differs from B . The faintest stars visible at a good site (magnitude 6^m) corresponds to a detection of approximately 3×10^{-15} W. Sensitivity will vary between individuals and decreases with age, the retina of a 60 year old person will receive some 30% of the light seen by a person of 30-years.

The system used by astronomers to measure the brightness of stars is a very old one, and is based on the sensitivity of the eye. Hipparchos' catalogue of

stars divided the stars into six classes from the brightest, of the first rank or magnitude, to the dimmest of the sixth magnitude. The present day system is based on this after the work of Norman Pogson put the magnitude scale on a firm basis in 1856. Pogson suggested a logarithmic scale that approximately agreed with earlier measurements: the difference between stars of magnitude m_1 and m_2 are given by

$$m_1 - m_2 = -2.5 \log \left(\frac{E_1}{E_2} \right)$$

where E_1 and E_2 are the energies per unit area at the surface of Earth for the two stars.

Exercises

1. What is the size, in kilometers, of the smallest crater that can be distinguished on the Moon with the naked eye (as seen from Earth)?
2. Vega has a magnitude of roughly 0.0, Polaris a magnitude of 2.0. Estimate the magnitudes of the stars in Orions belt as well as Betelgeuse, Rigel, and Bellatrix. What is the magnitude of the weakest star you can find in the sky?
3. Mizar and Alcor in Ursa Majoris are separated by some $11'$. Can you separate them and see both stars? Estimate their magnitudes as well. Mizar is itself a double star the components of which can be separated with a small telescope. Interestingly, all three stars are *spectroscopic binaries* as well, bringing the star total star count up to 6. The distance to these stars is some 83 ly while the distance between Mizar and Alcor is approximately 1 ly. All six stars are gravitationally bound and are members of the Ursa Major moving group.