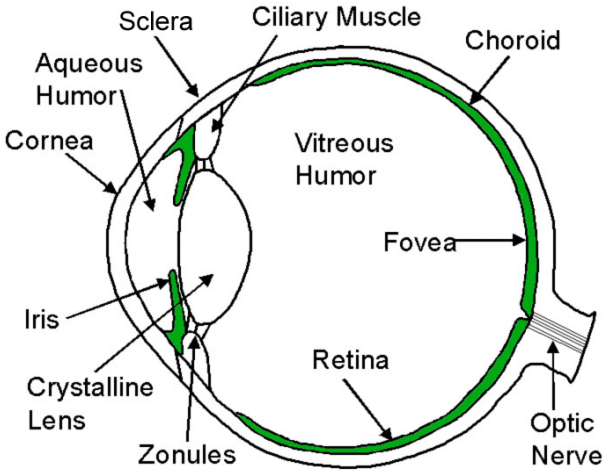


Eyeball



Top View of Right Eye

Cornea – Transparent membrane on the front of the eye. It contributes roughly two-thirds of the total power of the eye.

Aqueous Humor – Waterlike fluid in the anterior chamber between the cornea and the crystalline lens.

Iris – Pigmented diaphragm that is the eye’s aperture stop.

Crystalline Lens – Gradient-refractive-index lens that changes shape to focus on near and distant objects. It contributes the remaining one-third power of the eye.

Vitreous Humor – Jellylike fluid in the posterior chamber between the crystalline lens and the retina.

Retina – Photosensitive surface of the interior of the eyeball that converts light to neural signals.

Fovea – The central, high-resolution portion of the retina.

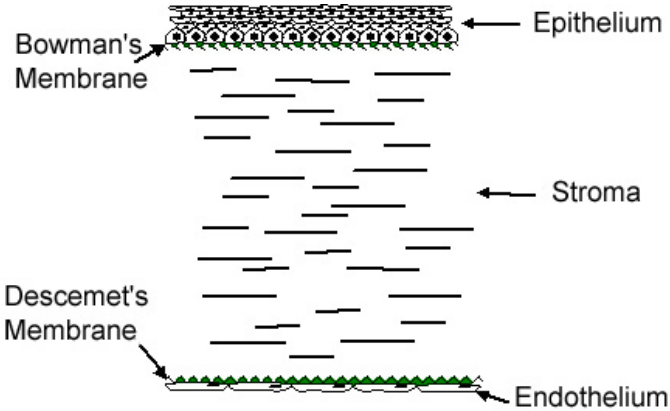
Optic Disk – The “blind spot” where nerve fibers and blood vessels enter the eyeball.

Optic Nerve – The bundle of nerve fibers that carry the information from the retina to the brain.

Sclera – The “white” of the eye, which acts as a protective outer coating to the eyeball.

Choroid – An internal opaque membrane that absorbs stray light and provides structural support of the retina

Cornea



Cross-Section of Cornea Showing Five Distinct Layers

Epithelium – Thin surface layer of cells 50–100 μm thick on the front of the cornea that blocks foreign bodies from entering the cornea and absorbs oxygen and nutrients for the underlying layers. These cells regenerate quickly if they are damaged by trauma or surgery.

Bowman's Membrane – Collagen boundary roughly 12 μm thick that divides the epithelium and the underlying stroma.

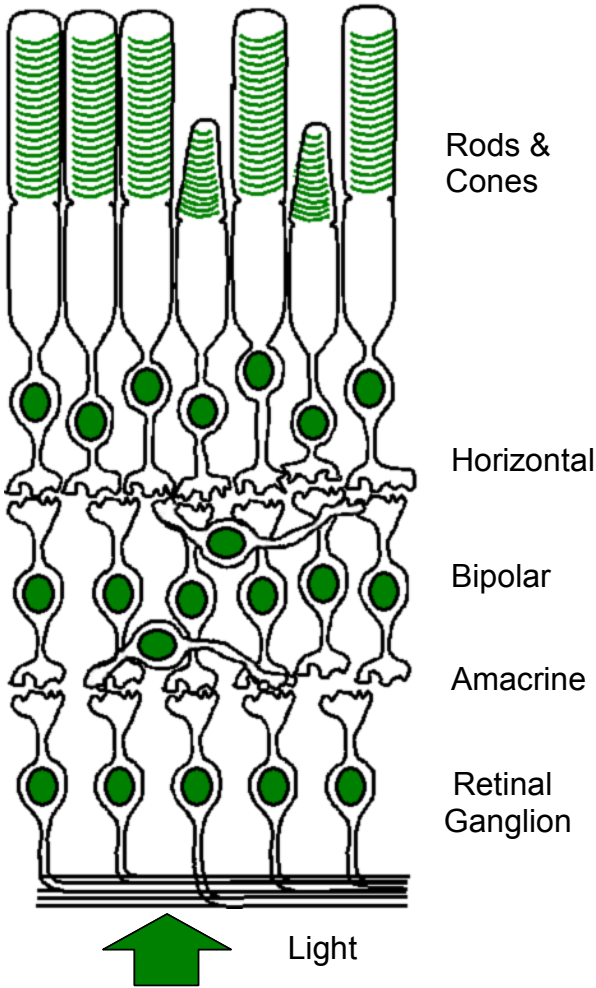
Stroma – Internal material of the cornea composed mainly of cross-linked collagen bands. The ordering of these bands is somewhat regular to promote transparency. The thickness of the stroma is about 500 μm . The collagen fibers are somewhat regularly organized, introducing corneal birefringence

Descemet's Membrane – Collagen boundary roughly 4 to 10 μm thick that separates the endothelium and the stroma.

Endothelium – Thin surface layer of cells 5 μm thick on the back of the cornea that regulates corneal nutrition and removes excess water from the cornea to maintain its clarity. Unlike the epithelial cells, these cells do not regenerate.

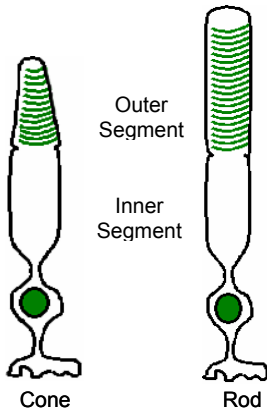
The cornea does not have a direct blood supply, so it must exchange its nutrients and waste products through its front and back surfaces. Damage or interference with these transfer mechanisms can lead to corneal edema (swelling) and opacities.

Retina



Light passes through multiple cell layers to reach the **photoreceptors**. Once absorbed, a signal is transmitted from the receptor through the **bipolar cells** to the **retinal ganglion cells**. From there, the signal propagates up into the brain for further processing. **Amacrine** and **horizontal cells** allow cells in a localized neighborhood to communicate with one another.

Photoreceptors



Two types of photoreceptors reside in the retina: **cones** and **rods**. The cones are responsible for daytime vision, while the rods respond under dark conditions. The cones come in three varieties: L, M, and S types (for long, middle, and short wavelength). Each cone type responds to a different portion of the visible spectrum, allowing for color vision. Rods have a spectral sensitivity that differs from the cones. Photoreceptors are specialized cells for detecting

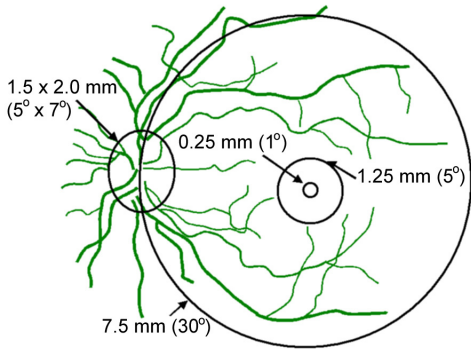
light. They are composed of the **outer nuclear layer** that contains the cell nuclei, the **inner segment** that houses the cell machinery, and the **outer segment** that contains photosensitive pigment. The outer segment of a rod has discrete disks saturated with rhodopsin molecules, while the outer segment of a cone contains similar photosensitive molecules in a series of folds. The outer segment absorbs photons, which initiates an electrochemical transmission through the cells and retinal nerve fibers, up into the brain.

Cones	Rods
Color Vision	Monochromatic
No sensitivity in the dark	High sensitivity in the dark
Respond in bright light	Bleached in bright light
Slow temporal response	Fast temporal response
Mostly in fovea	Mostly in periphery
Some in peripheral retina	None in fovea
High visual acuity	Low visual acuity
In fovea, one neuron per cone	Many rods per single neuron

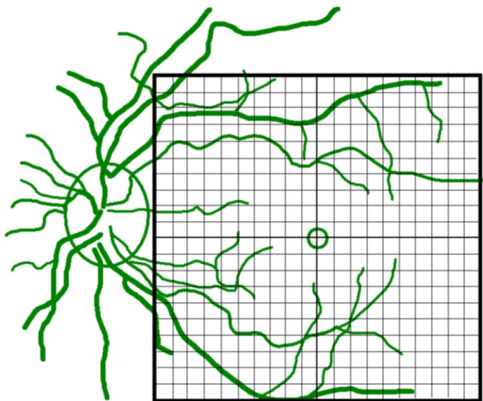
Cone diameter is roughly $2.5 \mu\text{m}$ in the fovea and rapidly increases outside fovea to $10 \mu\text{m}$ in periphery. Rod diameter is roughly $3 \mu\text{m}$ at a field angle of 18° and increases in size to $5.5 \mu\text{m}$ in periphery. The central $200 \mu\text{m}$ of the retina is free of rods. The total number of cones in the retina is 6.4 million. There are roughly 125 million rods in the retina.

Retinal Landmarks

Looking into the eye, blood vessels are visible on the retinal surface. The blood vessels appear to emanate from an oval region known as the **optic nerve head**. The optic nerve head is located on the nasal side of the eye. It has a physical size of about 1.5×2.0 mm and subtends $5^\circ \times 7^\circ$ from the rear nodal point. The blood vessels curve around an avascular region known as the **fovea centralis**, which is about 1.25 mm in diameter. The center of the fovea centralis is the **foveola**, which is only 0.25 mm in diameter. The figure below shows a view of the left eye with the dimension and angular subtense of each of these landmarks.



The **Amsler grid** is a device used to rapidly assess early problems in macular function. It is composed of a grid of 20 by 20 squares, each 5 mm on a side. The grid is held at reading distance and subtends roughly 20° of visual angle. The projection of the grid onto the retina appears below.



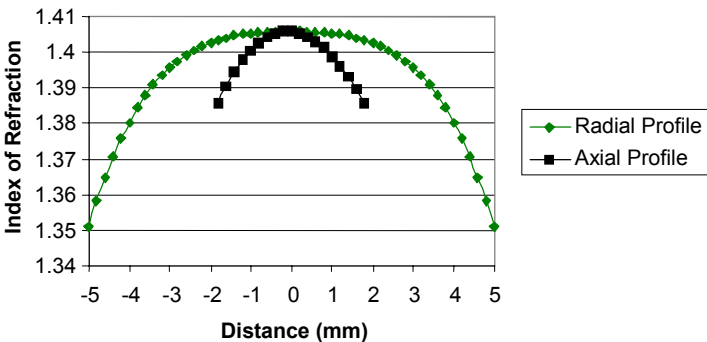
Properties of Ocular Components

Mean and Range

Anterior corneal radius: 7.80 mm (Range 7.00–8.65 mm)
Posterior corneal radius: 6.50 mm (Range 6.20–6.60 mm)
Anterior chamber depth: 3.68 mm (Range 2.80–4.60 mm)
Crystalline lens power: 20.35 D (Range 15.00–27.00 D)
Crystalline lens thickness: 4.00 mm
Anterior lens radius: 10.20 mm (Range 8.80–11.90 mm)
Posterior lens radius: 6.00 mm
Axial length: 24.00 mm (Range 20.00–29.50 mm)
Ocular power: 59.63 D (Range 54.00–65.00 D)

Material	Index	Abbe Number
Cornea	1.3771	57.1
Aqueous Humor	1.3374	61.3
Crystalline Lens	1.36 to 1.41	47.7
Vitreous Humor	1.336	61.1

The **crystalline lens** has a gradient index structure, such that its index of refraction varies both axially and radially. This distribution is not well documented *in vivo*, so good measures of the values across large populations do not currently exist. The **lens paradox** arises from a steepening of the lens surfaces with age, suggesting an increase in lens power, while the overall ocular power tends to reduce with age. The effective index of refraction of the crystalline lens must reduce with age, to account for the lens paradox.



Accommodation

Accommodation is the mechanism that adjusts the power of the eye to allow near objects to be in focus on the retina. This power change is accomplished by modifying the shape of the crystalline lens. The **capsule** is an elastic membrane that encases the crystalline lens. The capsule and lens are supported by a series of fibrils called the **zonules of Zinn**. The zonules are attached to the **ciliary muscle**. The **Helmholtz Theory of Accommodation** states that when the ciliary muscle is relaxed, the tension on the zonules is high, resulting in tension on the capsule and the equator of the lens. The tension flattens the surface curvatures (i.e., reduction in lens power). When the ciliary muscle constricts, the tension on the zonules is reduced and the crystalline lens curvatures steepen, thus increasing the power of the lens. In addition to the curvatures of the lens steepening during accommodation, the thickness of the lens increases and the lens shifts towards the cornea. The radius of the anterior lens decreases by about 0.4 mm per diopter of accommodation, while the posterior radius decreases at 0.2 mm per diopter of accommodation.

The shape, size, and position of the crystalline lens are highly dependent upon age. For an unaccommodated eye, Koretz *et al.* found age dependencies for the anterior chamber depth (ACD), the lens thickness, and the anterior and posterior lens radius of curvature (ROC). There is a large standard deviation among individuals for all values presented.

$$\text{ACD} = -0.0215 \text{ Age} + 4.274$$

$$\text{Thickness} = 0.0194 \text{ Age} + 3.088$$

$$\text{Anterior ROC} = -0.0759 \text{ Age} + 13.949$$

$$\text{Posterior ROC} = 0.0106 \text{ Age} - 6.436$$

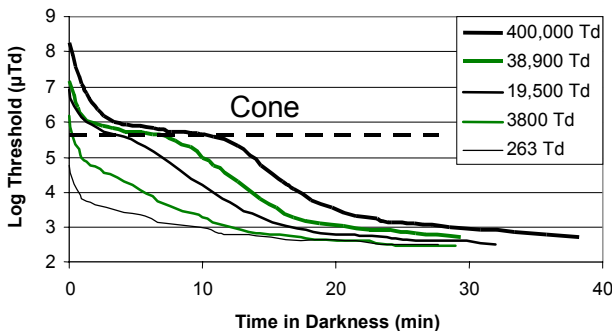
The distance from the corneal vertex to the posterior lens surface appears to remain constant with age, suggesting that the lens moves toward the cornea as it thickens.

Pupil Size and Dark Adaptation

The pupil varies in size with illumination level. Individual variation is large, so mathematical fits to pupil size can vary by ± 2 mm for a given luminance level. In the general population, the average pupil size is given by $D = 4.9 - 3 \tanh[0.4(\log L + 1)]$, where D is the pupil diameter in mm and L is the luminance in cd/m^2 . The pupil size also varies with age. The pupils exhibit a **consensual light reflex**, in which stimulation of one eye causes an equal pupillary response in the other eye. The pupils also tend to constrict roughly 15% moving from a distant to near object. This effect is known as the **near reflex**. In response to illumination, the pupil shrinks in less than a second. In darkness, the pupil takes several seconds to dilate, while the retina takes minutes to dark adapt.

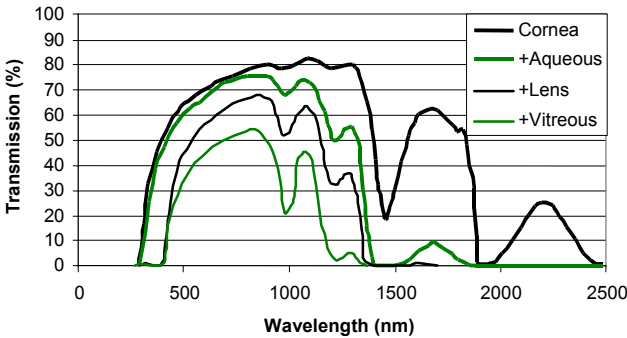
Luminance (cd/m^2)	D (mm)
0.684	8.046–0.043 (Age)
334	4.070–0.015 (Age)

Dark adaptation: If the eye views a bright light source for an extended period, the photopigments in the rods and cones will become bleached or depleted. Regeneration of the pigments takes time, once the source has been removed. Cone photopigment regenerates more quickly than rod pigment, with the time course being 6–10 minutes for cones and 30 minutes for rods. Below is a plot of the threshold retinal illuminance in trolands (Td) required to detect a small violet spot. The eye views fields of different illuminance levels prior to immersion in the dark. Above the cone threshold, the spot appears colored. Below the threshold, it is achromatic.

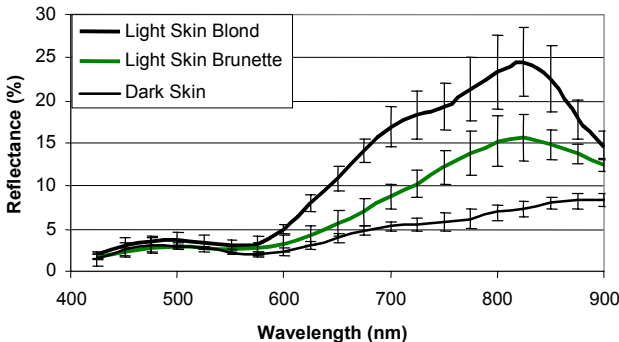


Transmission and Reflectance

Ocular transmission: The eye transmits wavelengths from roughly 400 nm to 1400 nm. The cornea and aqueous humor are responsible for absorbing infrared radiation beyond 1400 nm. The crystalline lens absorbs ultraviolet radiation (UV) below 400 nm. Below is a plot of the cumulative transmission of the eye. As the eye ages, the crystalline lens tends to yellow, which affects the transmission of blue wavelengths. Intraocular lens (IOL) implantation following cataract surgery increases transmission in the ultraviolet and blue end of the spectrum. Most IOLs contain UV absorbing chromophores to reduce the risk of retinal damage.



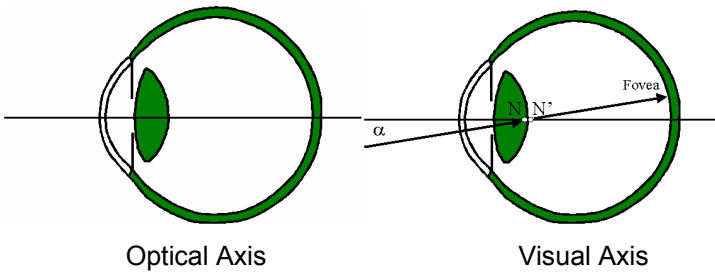
Retinal reflectance: Of the light that makes it to the retina, a portion of it is reflected out of the eye. This reflectance varies with wavelength and skin pigmentation.



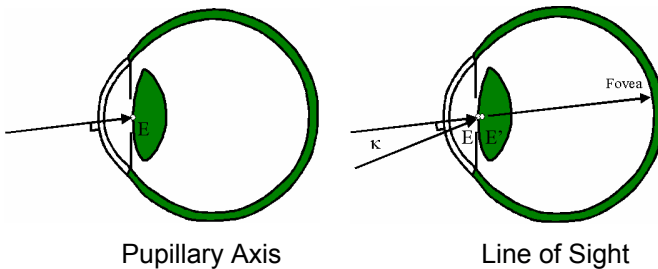
Axes of the Eye

Since the eye is not rotationally symmetric (i.e. the centers of curvature of each surface do not lie on a common axis), several axes can be defined which all collapse to the optical axis in rotationally symmetric systems. A line passing through the centers of curvature of the optical surfaces in a least squares sense is taken as the **optical axis** of the eye. In general, this axis is ill-defined due to the complex shapes of the various ocular surfaces.

The **visual axis** connects the fixation point to the front nodal and the rear nodal to the fovea. Usually denoted by angle α measured from optical axis. Typically $4^\circ \leq \alpha \leq 8^\circ$.



The **pupillary axis** strikes the cornea at right angles and passes through the center of the entrance pupil. The **line of sight** (LOS) connects the fixation point to the center of the entrance pupil, and the center of the exit pupil to the fovea. The LOS is equivalent to the chief ray from the fixation point. The LOS, with angle κ from pupillary axis, typically has $\kappa \leq \alpha$.



The fovea is usually displaced temporally and is slightly inferior to the intersection of the optical axis and the retina.
