Lectures on Medical Biophysics

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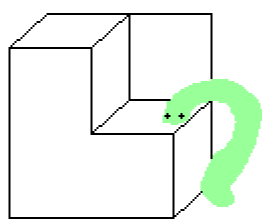
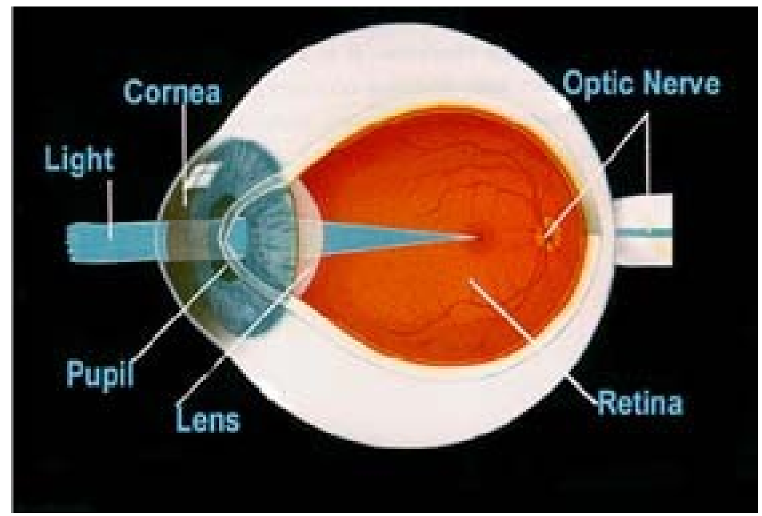




Biophysics of visual perception

Lecture outline

- Basic properties of light
- Anatomy of eye
- Optical properties of eye
- Retina – biological detector of light
- Colour vision

Basic properties of light

Visible electromagnetic radiation:

λ = 380 – 760 nm

shorter wavelength – **Ultraviolet light (UV)**

longer wavelength – **Infrared light (IR)**

Visible light – (VIS)

Medium in which the light propagates is called **optical medium.**

In homogeneous media, light propagates in straight lines perpendicular to wave fronts, this lines are called **light rays.**

Speed (velocity) **of light** (in vacuum)

$$c = 299\,792\,458\ \mathrm{m\cdot s^{-1}}\ \text{approx.} = 300\,000\,000\ \mathrm{m\cdot s^{-1}}$$

Light (VIS) sources

- **Natural**
- **Man – made (artificial)**

- **Natural: The sun**

Sun light is what drives life. It’s hard to imagine our world and life without it.

- **Man – made: light bulbs, fluorescent tubes, laser…**

Polychromatic and Monochromatic Light, Coherence

- **Polychromatic or white light**

  consists of light of a variety of wavelengths.
- **Monochromatic light**

  consists of light of a single wavelength

According to phase character light can be

- **Coherent - ** Coherent light are light waves "in phase“ one another, i.e. they have the same phase in the same distance from the source. Light produced by lasers is coherent light.
- **Incoherent -** Incoherent light are light waves that are not "in phase“ one another.

  Light from light bulbs or the sun is incoherent light.

Reflection and refraction of light

Reflection - Law of reflection: The angle of reflection α' equals to the angle of incidence α. The ray reflected travels in the plane of incidence.

Refraction: When light passes from one medium into another, the beam changes direction at the boundary between the two media. This property of optical media is characterised by **index of refraction**

$$n = c/v \text{ [dimensionless]}$$

n – index of refraction of respective medium
c – speed of light in vacuum
v – speed of light in the respective medium
index of refraction of vacuum is 1

Reflection and refraction of light

Snell's law (Law of refraction)

$$\frac{\sin\alpha}{\sin\beta} = \frac{n_2}{n_1} = \frac{v_1}{v_2}$$

α – angle of incidence (in medium 1)
β – angle of refraction (in medium 2)
(Angles are measured away from the normal!)
n_1, n_2 – indices of refraction
v_1, v_2, – speed of light in respective media
n is large: large optical density
n is small: small optical density
$n_1 > n_2$ – light refraction away the normal occurs
$n_1 < n_2$ – light refraction toward the normal occurs

Lens–maker's equation

$$\frac{1}{f} = \left(\frac{n_2}{n_1} - 1\right) \cdot \left(\frac{1}{r_1} + \frac{1}{r_2}\right)$$

f - focal distance (length) [m]

n_2 - index of refraction of the lens

n_1 - index of refraction of the medium

r_1, r_2 - radii of curvature of the lens

Common principles of optical imaging

Real image (can be projected): convergence of rays

Virtual image (cannot be projected): divergence of ray

Principal axis – optical axis of centred system of optical boundaries

Principal focus is a point where rays parallel to the principal axis intersect after refraction by the len[illegible]r reflection by the curved mirror - front (object) focus and back (image) focus

Focal distance (length) *f* [m] is the distance of focus from the centre of the lens or the mirror

The **radii of curvature** are positive (negative) when the respective lens or mirror surfaces are convex (concave).

Dioptric power (strength of the lens): reciprocal value of focal length

$\phi = D = S = 1/f$ **[m^{-1} = dpt = D (dioptre)]**

Converging lenses: *f* and ϕ are positive

Diverging lenses: *f* and ϕ are negative

Lens equation

- The rays parallel to the principal axis are refracted into the back focus (in converging lens), or so that they seem to be emitted from the front focus (in diverging lens). The direction of rays passing through the centre of the lens remains uninfluenced. Lens equation (equation of image, imaging equation):

$$\frac{1}{f} = \frac{1}{a} + \frac{1}{b}$$

***a* – object distance [m]**

***b* – image distance [m]**

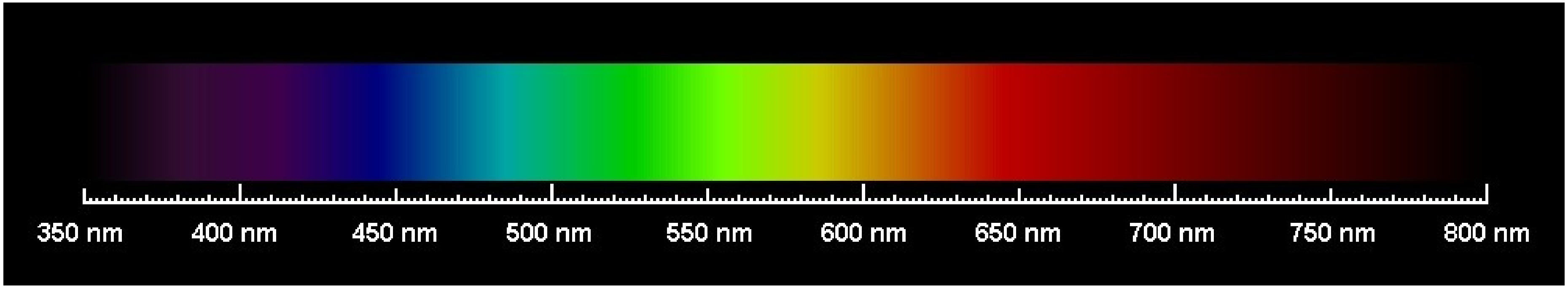
Sign convention:

a is positive in front of the lens, negative behind the lens;

b is negative in front of the lens (the image is virtual), positive behind the lens (the image is real)

Visible spectrum

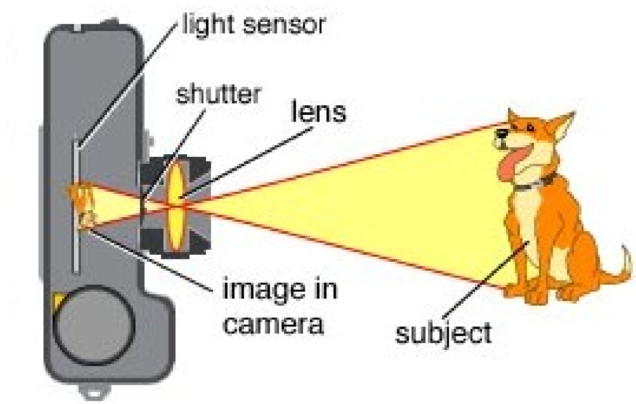
The human eye can detect light from about 380 nm (violet) to about 760 nm (red). Our visual system perceives this range of light wavelength as a smoothly varying rainbow of colours. We call this range **visible spectrum**. The following illustration shows approximately how it is experienced.



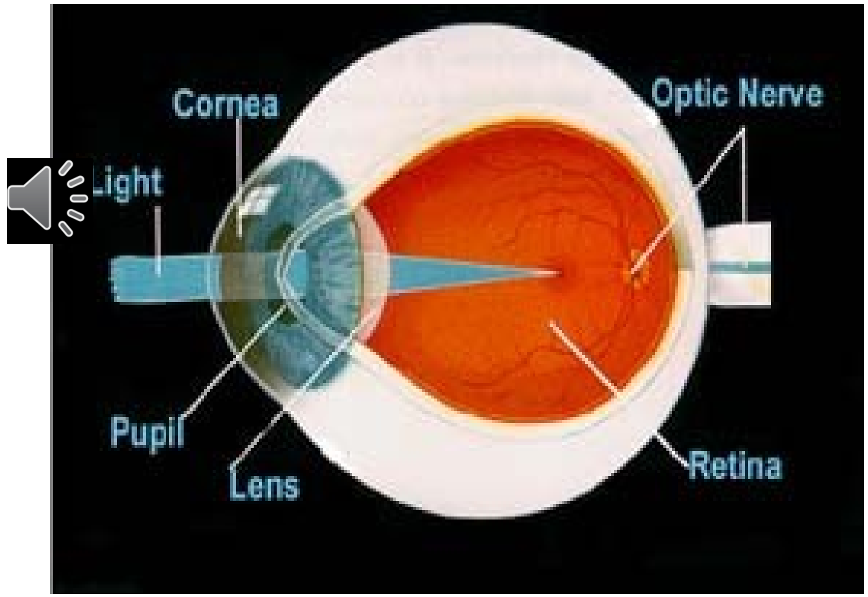
Anatomy of eye

How Does The Human Eye Work?

The individual components of the eye work in a manner similar to a camera. Each part plays a vital role in providing clear vision.



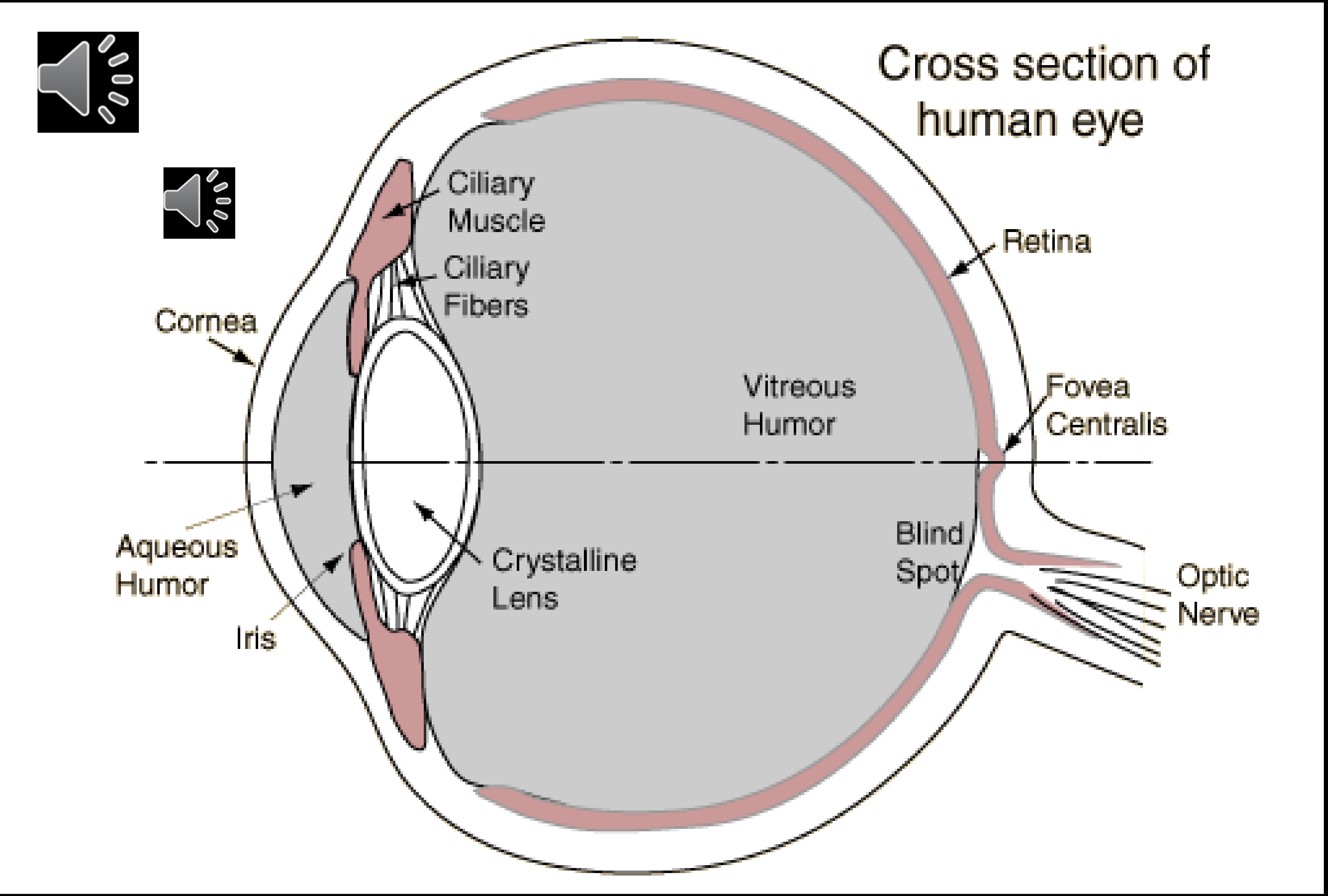
The Digital Camera



The Human Eye

Visual analyser consists of three parts:

- **Eye –** the best investigated part from the biophysical point of view
- **Optic tracts –** channel which consists of nervous cells, through this channel the information registered and processed by the eye are given to the cerebrum
- **Visual centre** – the area of the cerebral cortex where is outwards picture perceived


Cross section of
human eye
Ciliary
Muscle
Ciliary
Fibers
Retina
Cornea
Vitreous
Humor
Fovea
Centralis
Aqueous
Humor
Crystalline
Lens
Blind
Spot
Optic
Nerve
Iris

Anatomy of the eyeball

The tough, outermost layer of the eye is called the **sclera**. It maintains the shape of the eye.

The front about sixth of this layer is clear and is called the **cornea**. All light must first pass through the cornea when it enters the eye. Attached to the sclera are the six muscles that move the eye, called the **extraocular muscles**.

The **chorioid** (or uveal tract) is the second layer of the eye. It contains the blood vessels that supply blood to structures of the eye. The front part of the chorioid contains two structures:

The **ciliary body** - the ciliary body is a muscular area that is attached to the lens. It contracts and relaxes to control the curvature of the lens for focusing.

Anatomy of the eyeball

The **iris** - the iris is the coloured part of the eye. The colour of the iris is determined by the colour of the connective tissue and pigment cells. Less pigment makes the eyes blue; more pigment makes the eyes brown. The iris is an adjustable diaphragm around an opening called the **pupil**.

Inside the eyeball there are two fluid-filled sections separated by the lens. The larger, back section contains a clear, gel-like material called **vitreous humour**

The smaller, front section contains a clear, watery material called **aqueous humour**

The aqueous humour is divided into two sections called the anterior chamber (in front of the iris) and the posterior chamber (behind the iris). The aqueous humour is produced in the ciliary body

Anatomy of the eyeball

The iris has two muscles:

The *m. dilator pupillae* makes the iris smaller and therefore the pupil larger, allowing more light into the eye;

the *m. sphincter pupillae* makes the iris larger and the pupil smaller, allowing less light into the eye.

Pupil size can change from 2 millimetres to 8 millimetres.

This means that by changing the size of the pupil, the eye can change the amount of light that enters it by 30 times.

Anatomy of the eyeball

The transparent ***crystalline lens*** of the eye is located immediately behind the *iris*. It is a clear, bi-convex structure about 10 mm in diameter. The lens is kept in flattened state by tension of fibres of suspensory ligament. The lens changes shape because it is attached to muscles in the ciliary body, which act against the tension of ligament. When this **ciliary muscle** is

- **relaxed**, its diameter increases and the **lens is flattened**.
- **contracted**, its diameter is reduced, and the **lens becomes more spherical** (which is its natural state).

These changes enable the eye to adjust its focus between far objects and near objects.

The crystalline lens is composed of 4 layers, from the surface to the center: capsule, subcapsular epithelium, cortex, nucleus

Intraocular pressure

(production versus drainage of aqueous humour - dynamic balance)

2.66 kPa (20 mmHg) 0.3 kPa

Changes greater than 0.3 kPa are pathological

Optical properties of eye

Gullstrand model

The eye is approximated as an centred optical system with ability of automatic focussing, however, this model does not consider certain differences in curvature of the front and back surface of cornea as well as the diferences of refraction indices of the core and periphery of the crystalline lens.

Gullstrand´s model of the eye – basic parameters

Allvar Gullstrand
1852 – 1930
Nobel Award – 1911
Swedish ophthalmologist

❖ **Refraction Index:**

cornea................................ 1.376
aqueous humour............... 1.336
lens... ....1.413
vitreous humour……………. 1.336

❖ **Dioptric power:**

cornea .... 42.7 D
lens – inside eye................ 21.7 D
eye (whole)........................ 60.5 D

❖ **Radius of curvature:**

cornea .... 7.8 mm
lens – outer wall........ .... 10.0 mm
lens – inner wall..................... -6.0 mm

❖ **Focus location:**

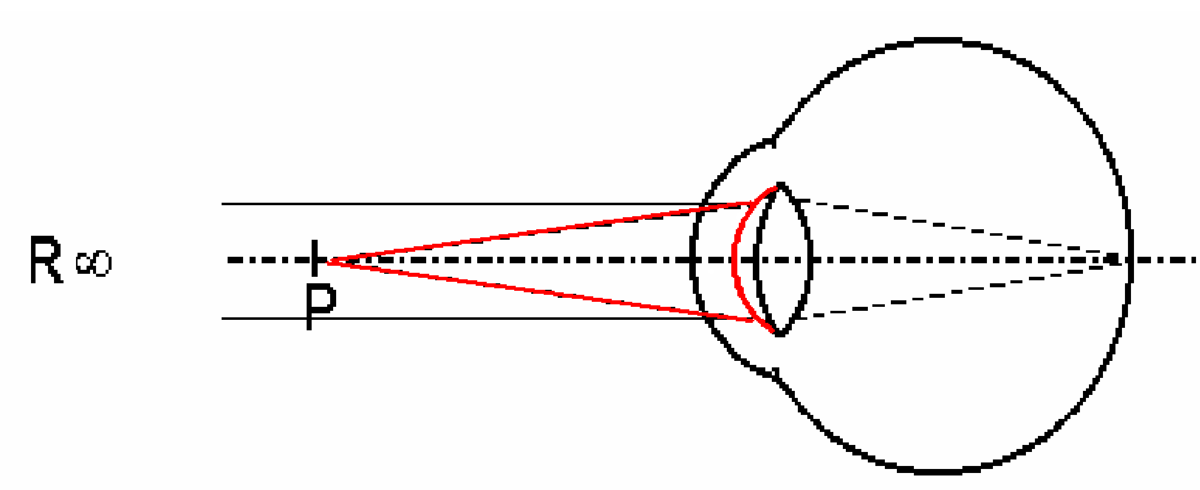
(measured from top of the cornea):
front (object) focus.................... -14.99 mm
back (image) focus .... 23.90 mm
retinae location.......................... 23.90 mm

Accommodation

Accommodation is eye lens ability to change its dioptric power in dependence on distance of the observed object.

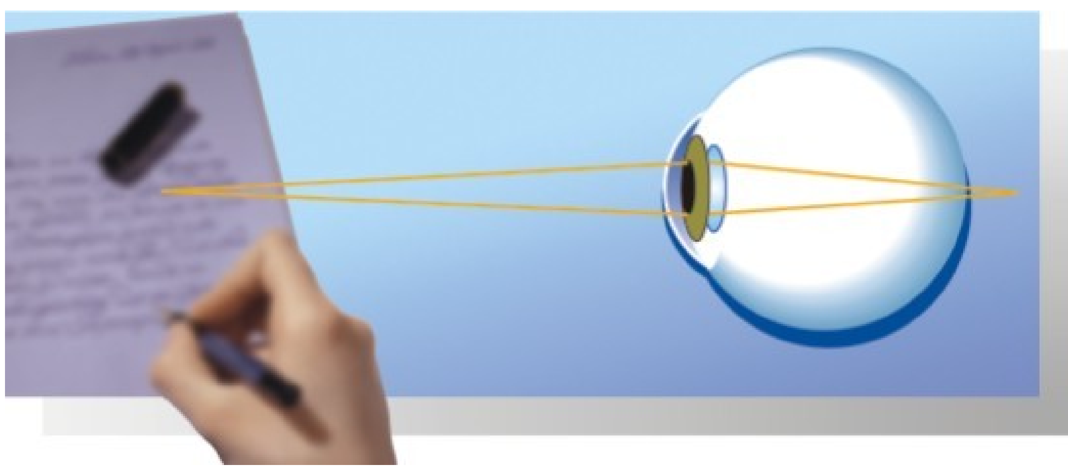
Accommodation – allowed by increasing curvature of outer lens wall (J.E.Purkyně)

- **Far point** - *punctum remotum* (R) - farthest point of distinct vision without accommodation.
- **Near point** - *punctum proximum* (P) - nearest point of distinct vision with maximum accommodation.
- The **amplitude of accommodation** is defined as the difference of reciprocal values of the distances of the near a and far point, expressed in dioptres. In an emmetropic eye the reciprocal value equals to zero ($1/\infty = 0$), thus the amplitude of accommodation is given by the reciprocal value of the near point distance.

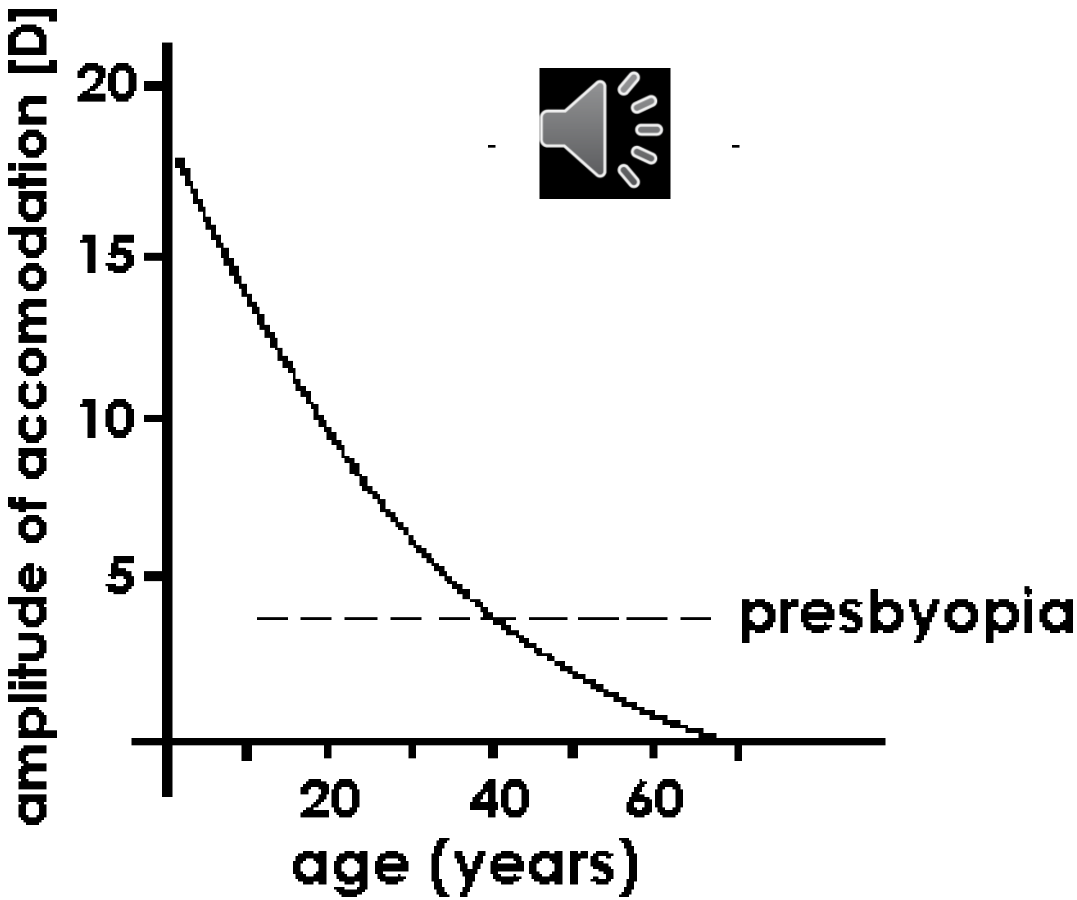


Presbyopia (“after 40” vision) Old–age sight

After age 40, and most noticeably after age 45, the human eye is affected by ***presbyopia***, which results in greater difficulty maintaining a clear focus at a near distance with an eye which sees clearly at a far away distance. This is due to a lessening of flexibility of the crystalline lens, as well as to a weakening of the ciliary muscles which control lens focusing, both attributable to the aging process.



Decrement of accommodation ability in dependence on age



Retina – biological detector of the light

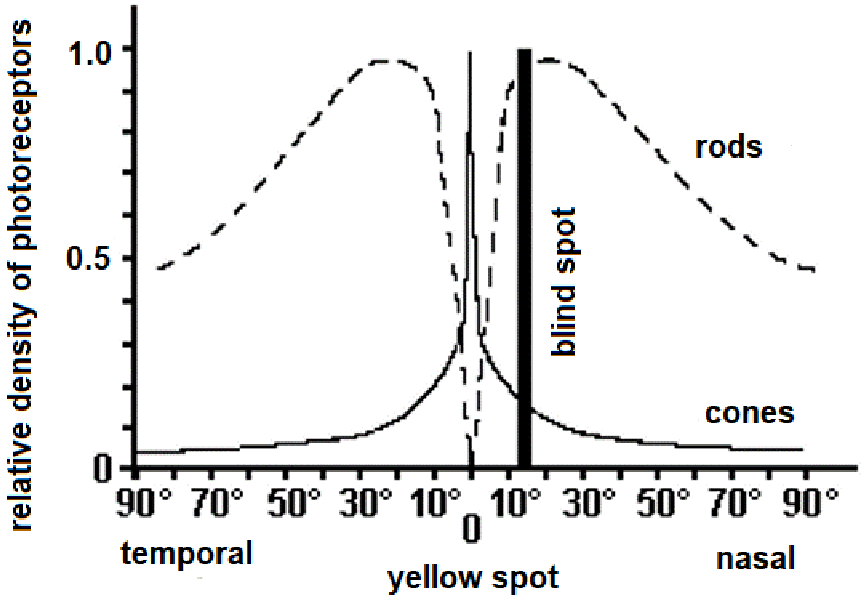
Retina - the light-sensing part of the eye.

It contains **rod cells**, responsible for vision in low light, and **cone cells**, responsible for colour vision and detail. When light contacts these two types of cells, a series of complex chemical reactions occurs. The light-activated rhodopsin creates electrical impulses in the optic nerve. Generally, the outer segment of rods are long and thin, whereas the outer segment of cones are more cone-shaped.

In the back of the eye, in the centre of the retina, is the **macula lutea (yellow spot).** In the centre of the macula is an area called the **fovea centralis.** This area contains only cones and is responsible for seeing fine detail clearly.

Blind spot

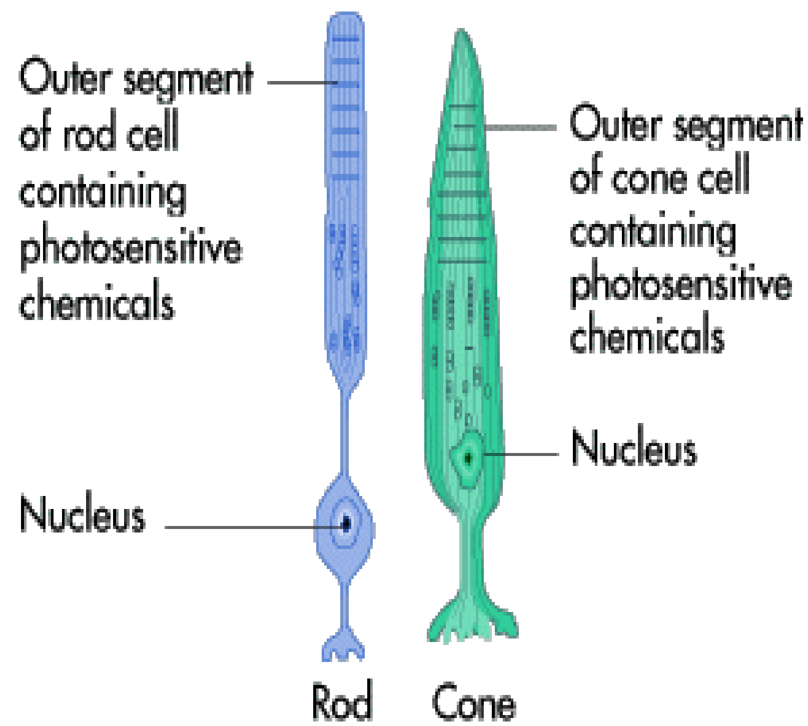
Density of cones decreases from the yellow spot to the periphery of retina. The rods have maximum density in a circle around the yellow spot (20^o from this spot, the angle is measured from the back vertex of the lens). The nerve fibres transmitting the stimulation of photoreceptors converge to a place positioned nasally from the yellow spot. This place with no photoreceptors is called **blind spot.**



Rods and cones

The outer segment of a rod or a cone contains the photosensitive chemicals. In rods, this chemical is called **rhodopsin.** In cones, these chemicals are called **colour pigments**.

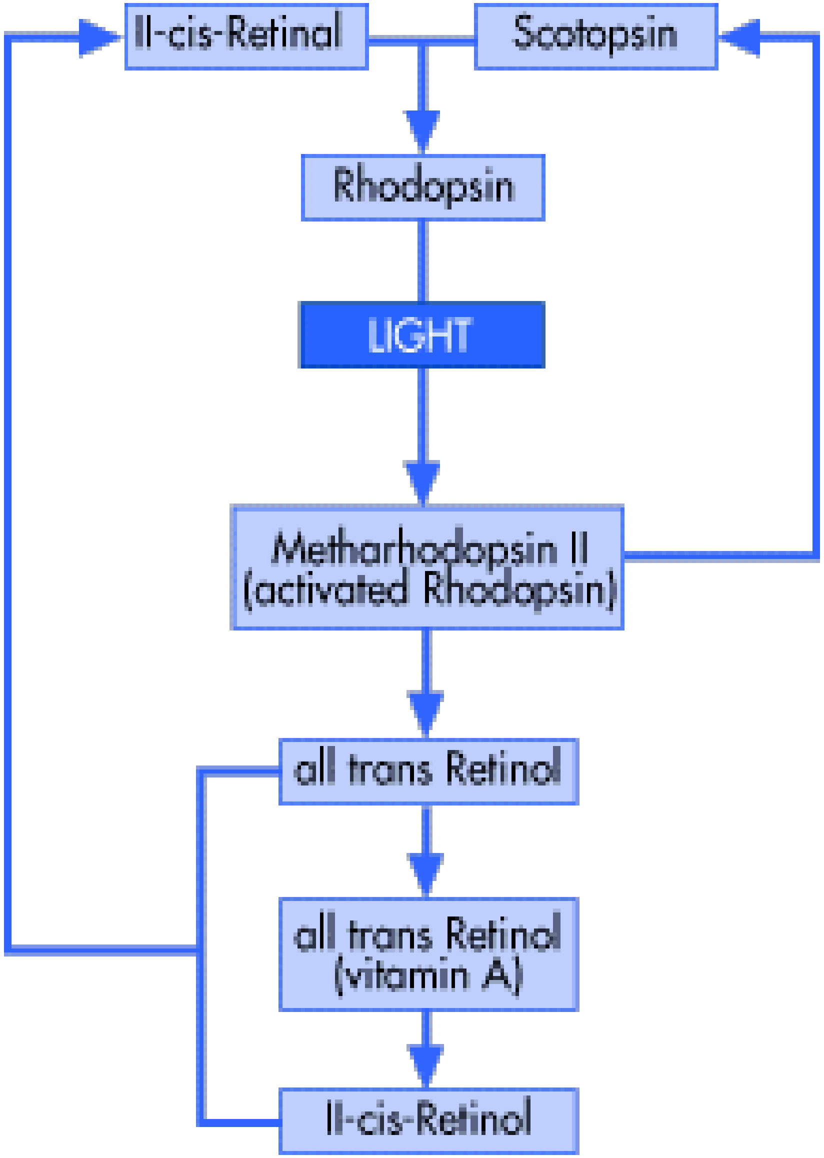
The retina contains 100 million rods and 7 million cones.

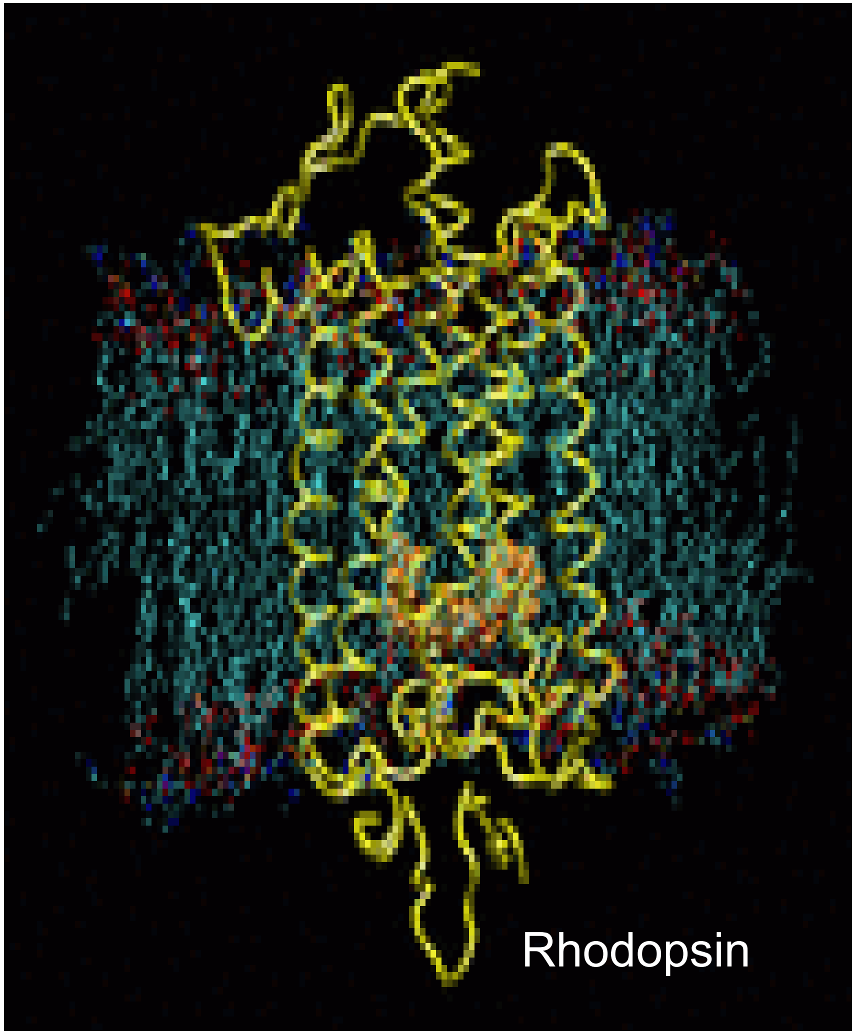


Rhodopsin

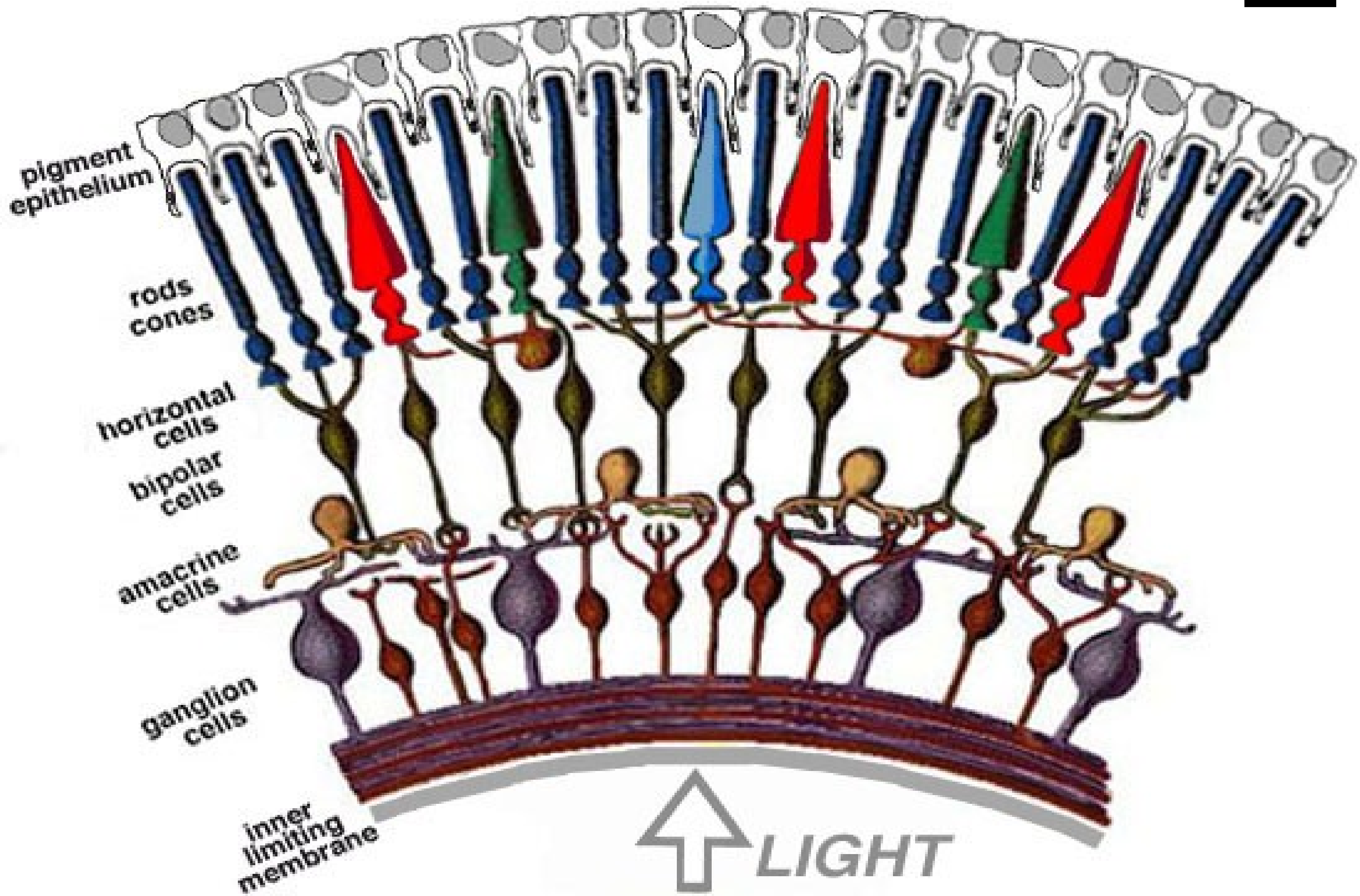
When light comes in contact with the photosensitive chemical **rhodopsin** (also called **visual purple**) a photochemical reaction occurs. Rhodopsin is a complex of a protein called **scot(opsin)** and **11-cis-retinal** - the latter is derived from **vitamin A** ($\Rightarrow$ lack of vitamin A causes vision problems). Rhodopsin decomposes when it is exposed to light because light causes a physical change in the 11-cis-retinal, changing it to **all-trans retinal**. This first reaction takes only a few *trillionths of a second* (10^{-18}). The 11-cis-retinal is an angulated molecule, while all-trans retinal is a straight molecule. This makes the chemical unstable. Rhodopsin breaks down into several intermediate compounds, but eventually (in less than a second) forms **metarhodopsin II** (activated rhodopsin). This chemical causes electrical impulses that are transmitted to the **brain** and interpreted as **light**. Here is a diagram of the chemical reaction we just discussed:

Biochemistry of rhodopsin:



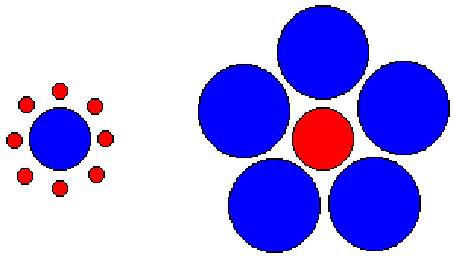


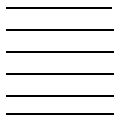
Structure of retina

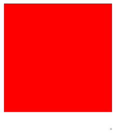


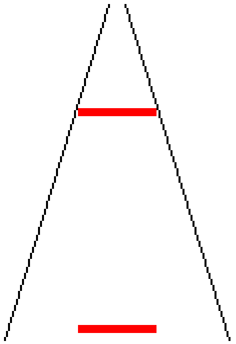
Optical illusions

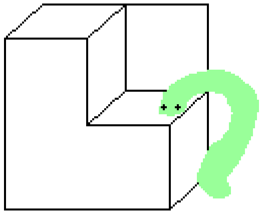
indicating the role of visual cortex in processing of visual information





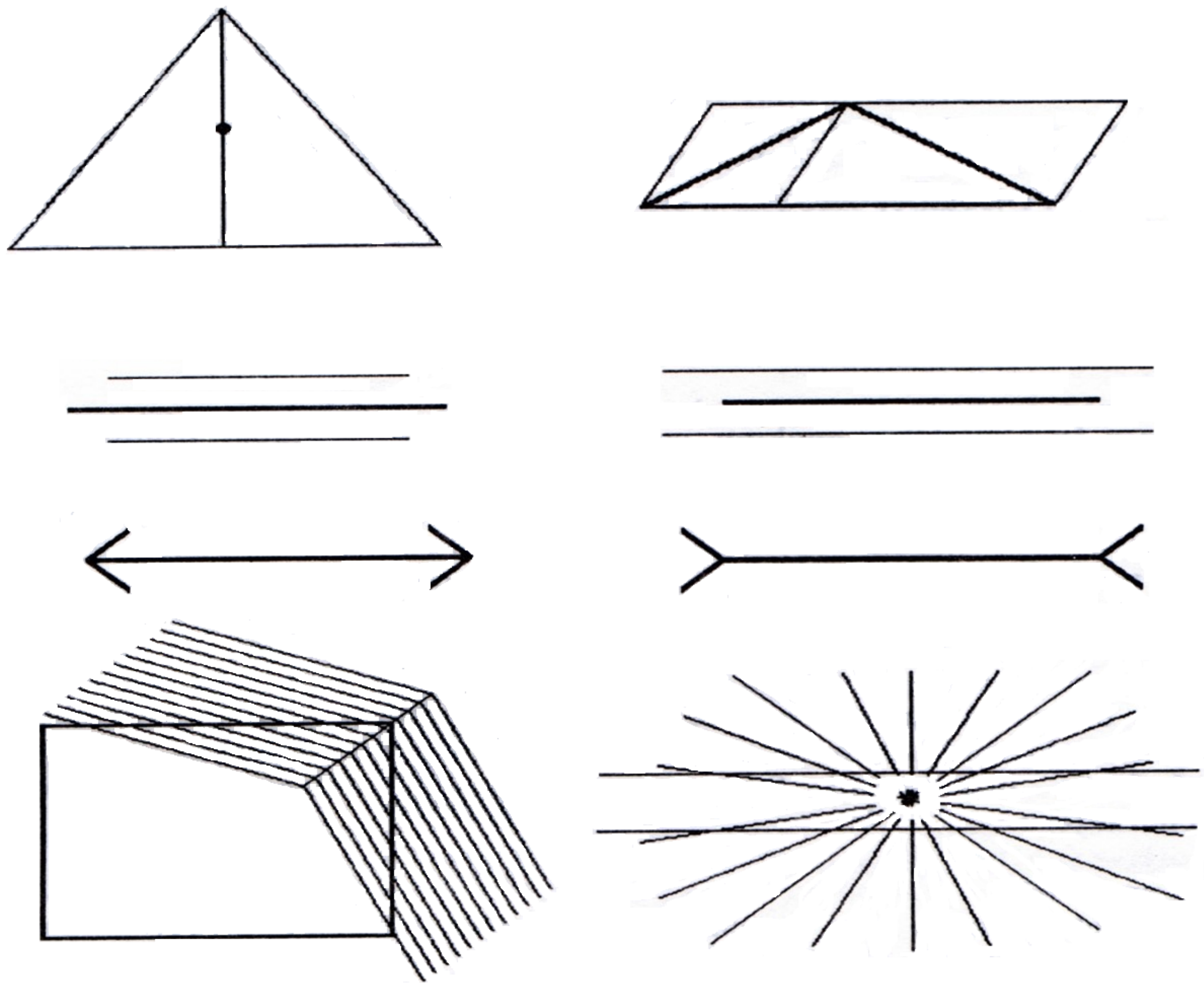






Optical illusions

indicating the role of visual cortex in processing of visual information



Electrical phenomena in retina

The electrical activity of retina is closely connected with photochemical reactions taking place in photoreceptors after illumination.

- **Early receptor potential**
- **Late receptor potential**

Electroretinography (ERG), recorded by means of two differential electrodes, measured voltage ranges from 100 to 400 μV

Colour vision

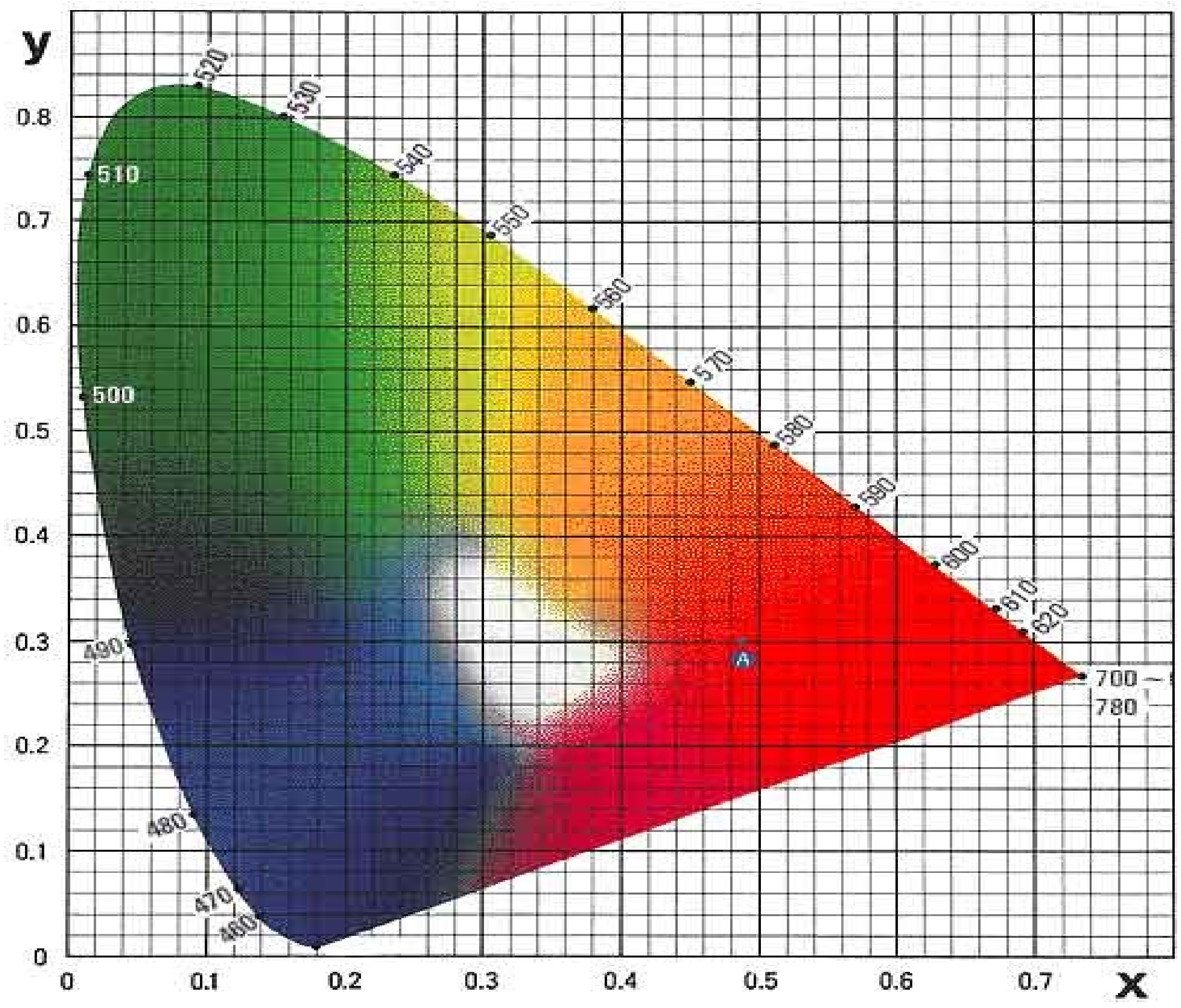
Colour Vision

The colour-responsive chemicals in the cones are called **cone pigments** and are very similar to the chemicals in the rods. The retinal portion of the chemical is the same, however the scotopsin is replaced with photopsins. Therefore, the colour-responsive pigments are made of retinal and photopsins. There are three kinds of colour-sensitive pigments:

- **Red-sensitive pigment**
- **Green-sensitive pigment**
- **Blue-sensitive pigment**

Each cone cell has one of these pigments so that it is sensitive to that colour. The human eye can sense almost any gradation of colour when red, green and blue are mixed (originally Young-Helmholtz trichromatic theory).

Colour Vision



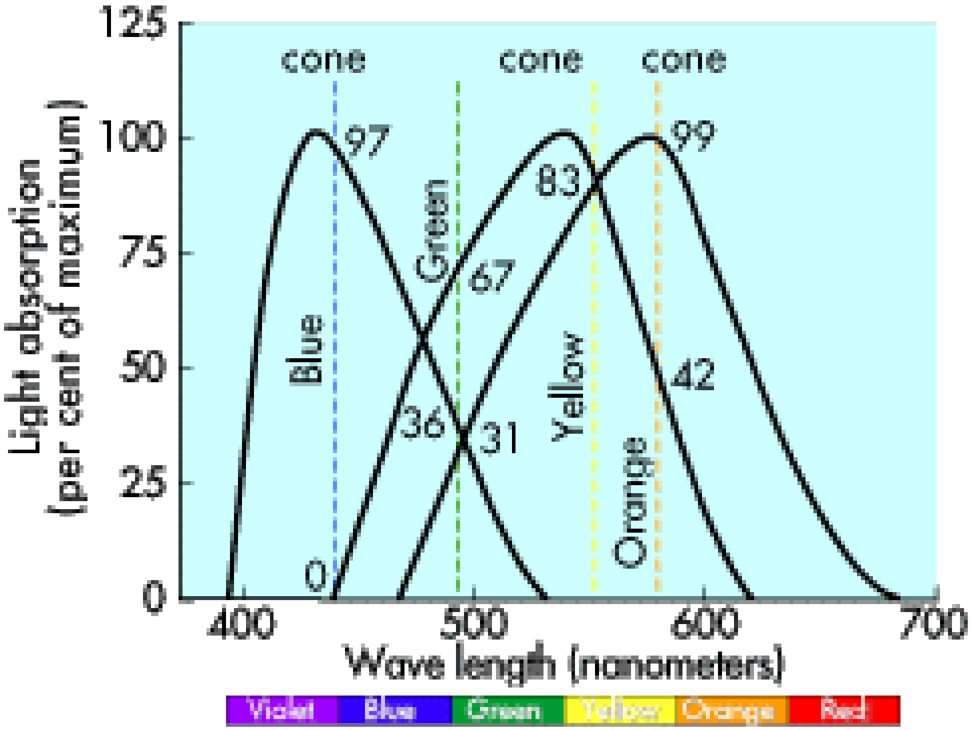
x– red 650 nm,

y– green 530 nm

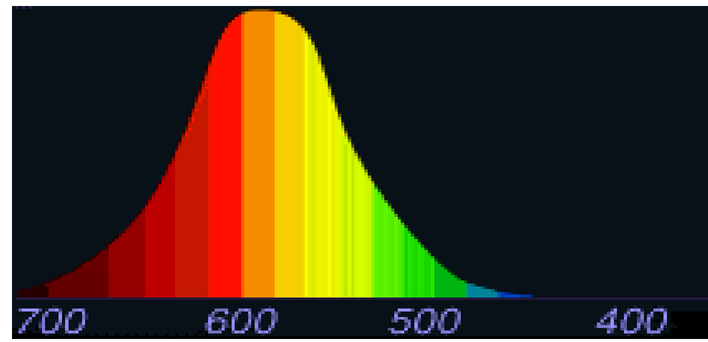
z – blue 460 nm

x + y + z = 1

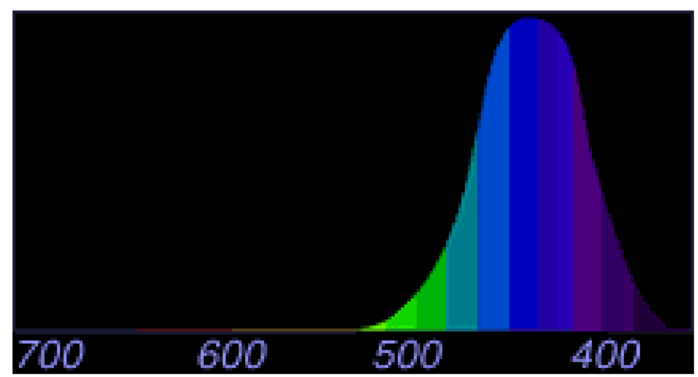
Colour Vision – spectral sensitivity



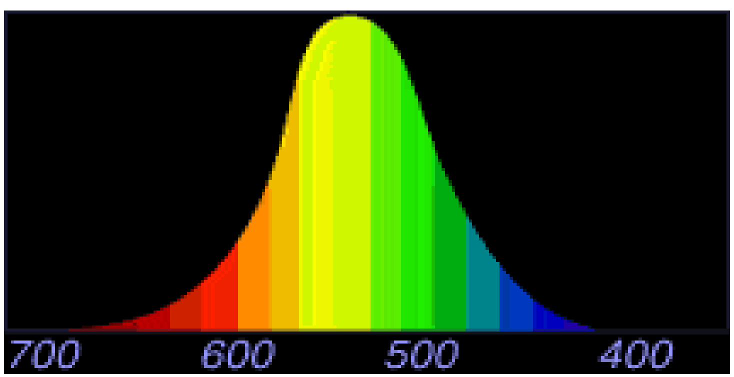
"Red-sensitive" or "L" cones



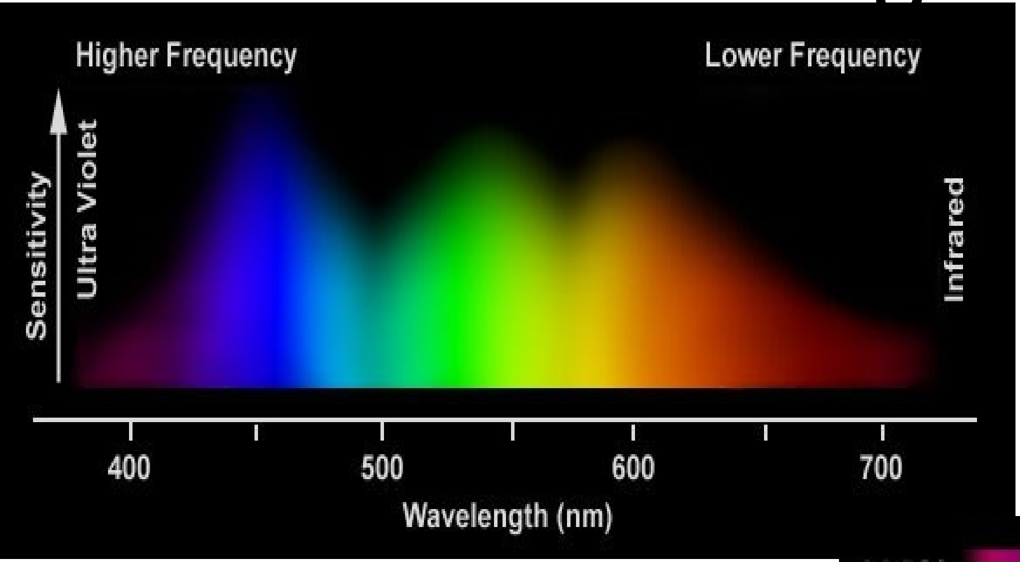
"Blue-sensitive" or "S" cones



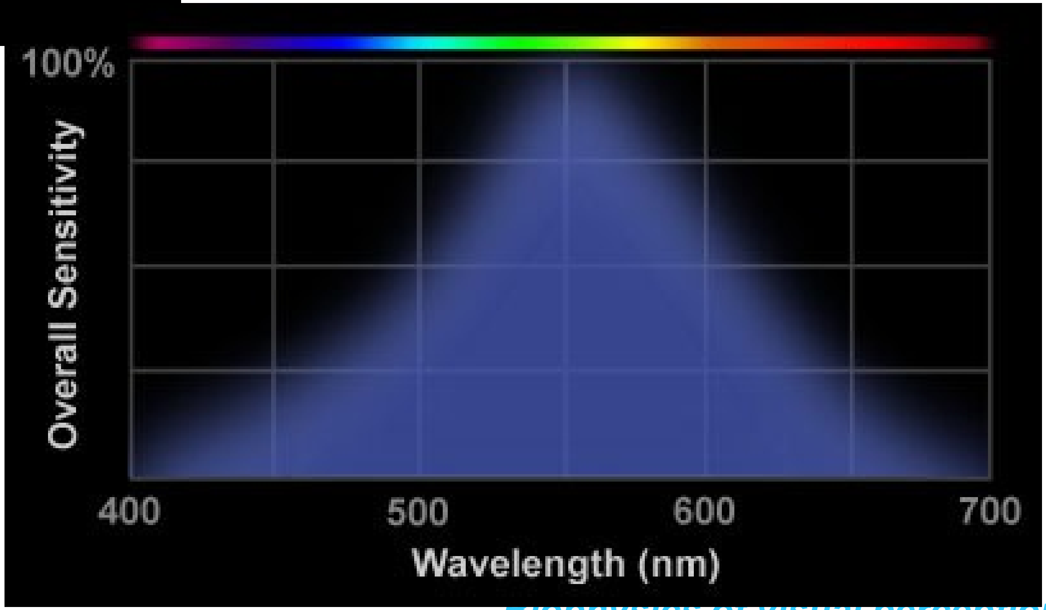
"Green-sensitive" or "M" cones



Wavelength Sensitivity



cones „summary“



Colour Vision

- **PHOTOPIC VISION**

  normal vision in daylight; vision with sufficient illumination that the cones are active and hue is perceived

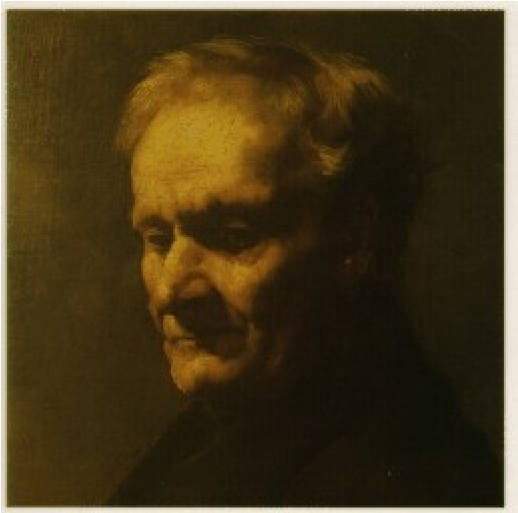
  Maximum at 555 nm, brightness over 100 $cd \cdot m^{-2}$

- **SCOTOPIC VISION**

  the ability to see in reduced illumination (as in moonlight)

  Maximum at 507 nm

- **Purkinje effect** (The tendency of the peak sensitivity of the human eye to shift toward the blue end of the spectrum at low illumination levels.)



J. E. Purkyně

Colour Vision

Trichromates - have normal colour vision

Monochromates - have only one cone colour sensing system

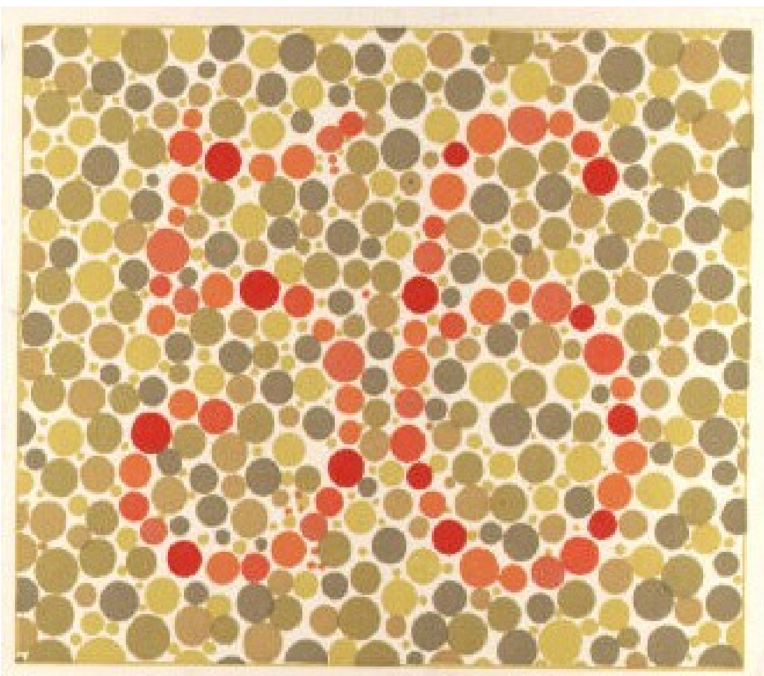
Dichromates:

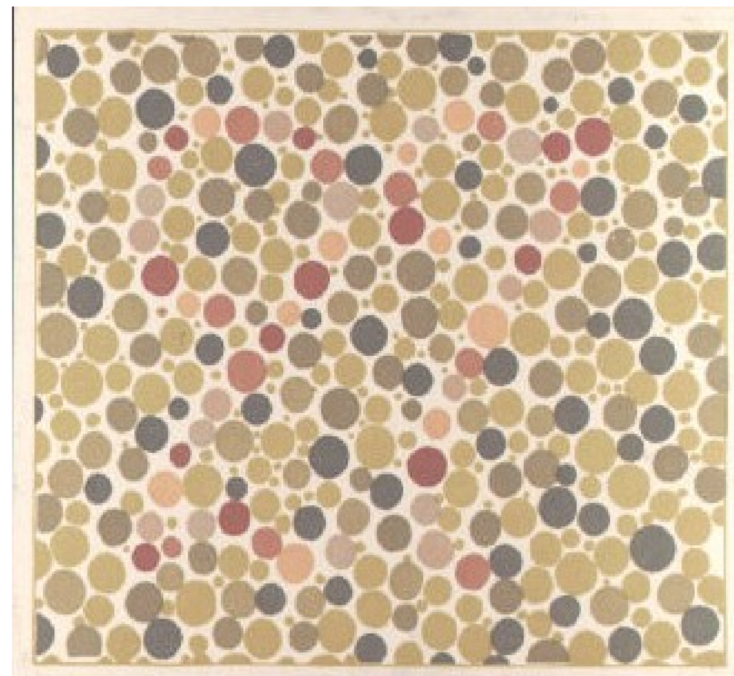
protanopia (difficult distinguishing between blue/green and red/green) – „ red blindness “

deuteranopia (difficult distinguishing between red/purple and green/purple) – „ green blindness “

tritanopia (difficult distinguishing between yellow/green and blue/green) – „ blue blindness “

Investigation of colour vision pseudoisochromatic tables





Limits of vision

- **visual acuity:** given by angle of 1min. of arc (tested by Snellen's charts)
- **sensitivity (intensity) limit:** 2 – 3 photons in several ms
- **frequency:** 5 - 60 Hz depending on brightness
- **wavelength limit about:** 380 – 760 nm
- **limit of stereoscopic vision:** stereoscopic parallax difference smaller than 20 seconds of arc

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