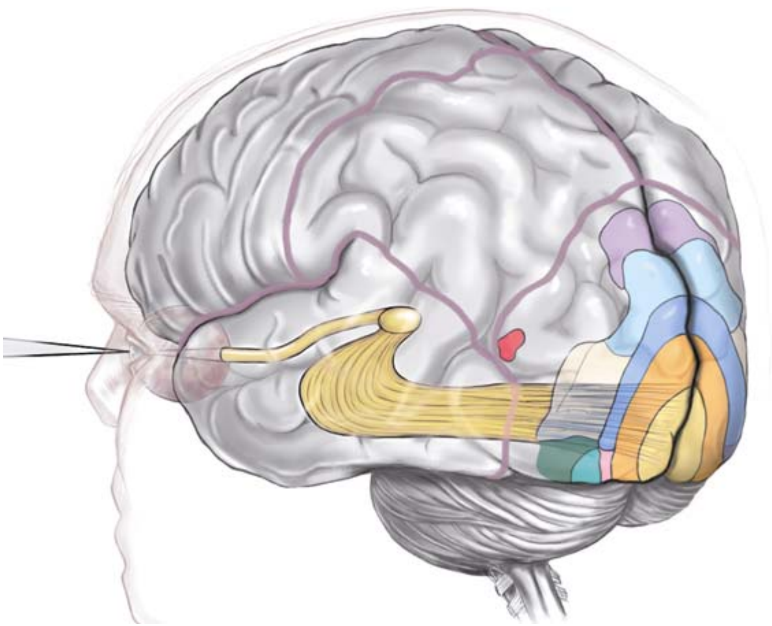
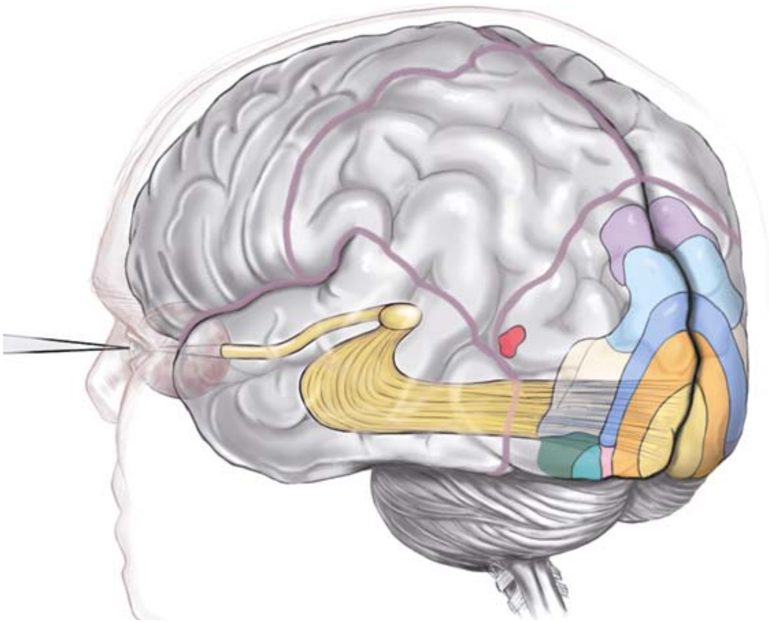
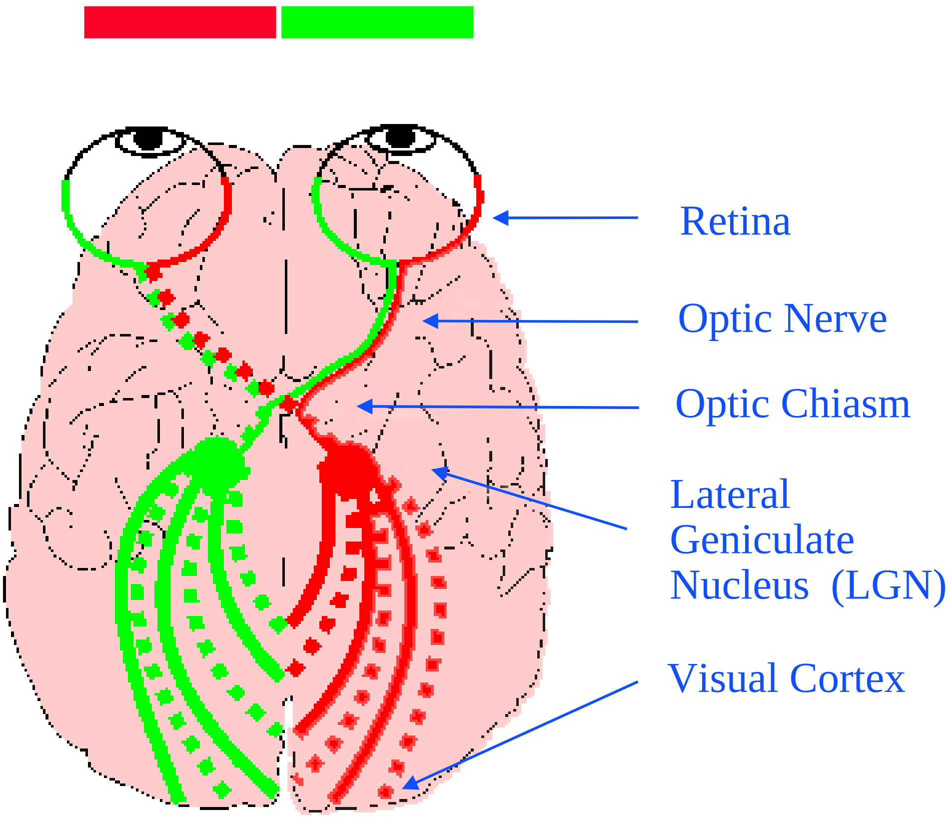
Lecture 1

The Human Visual System

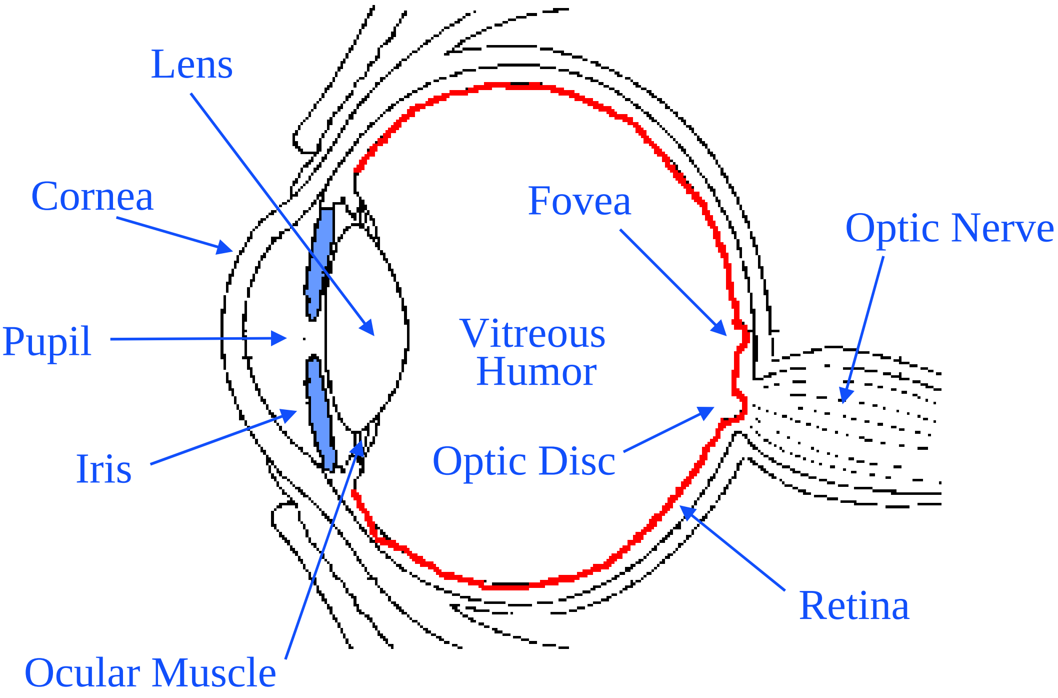


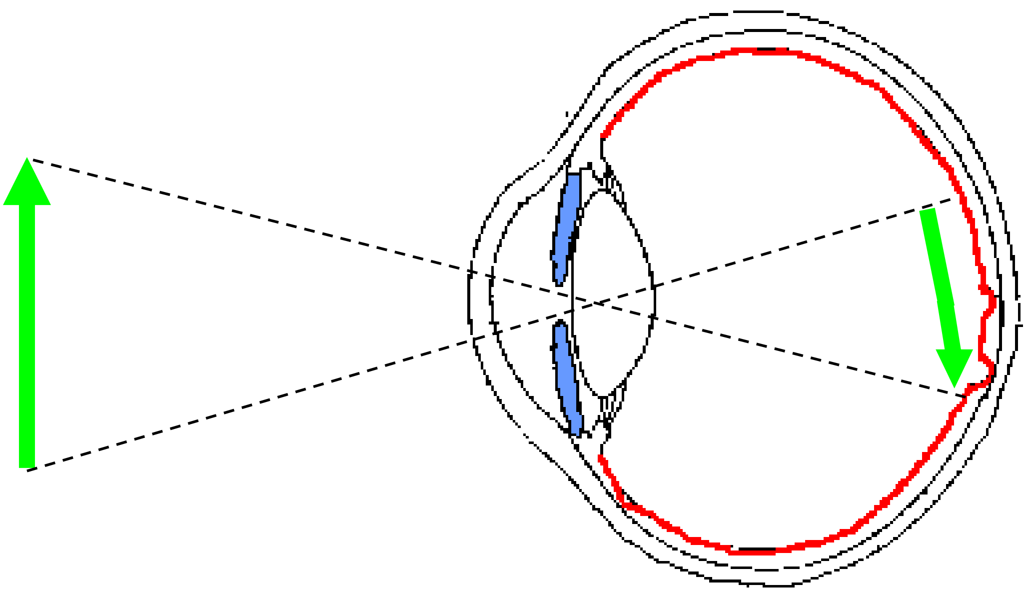
The Human Visual System



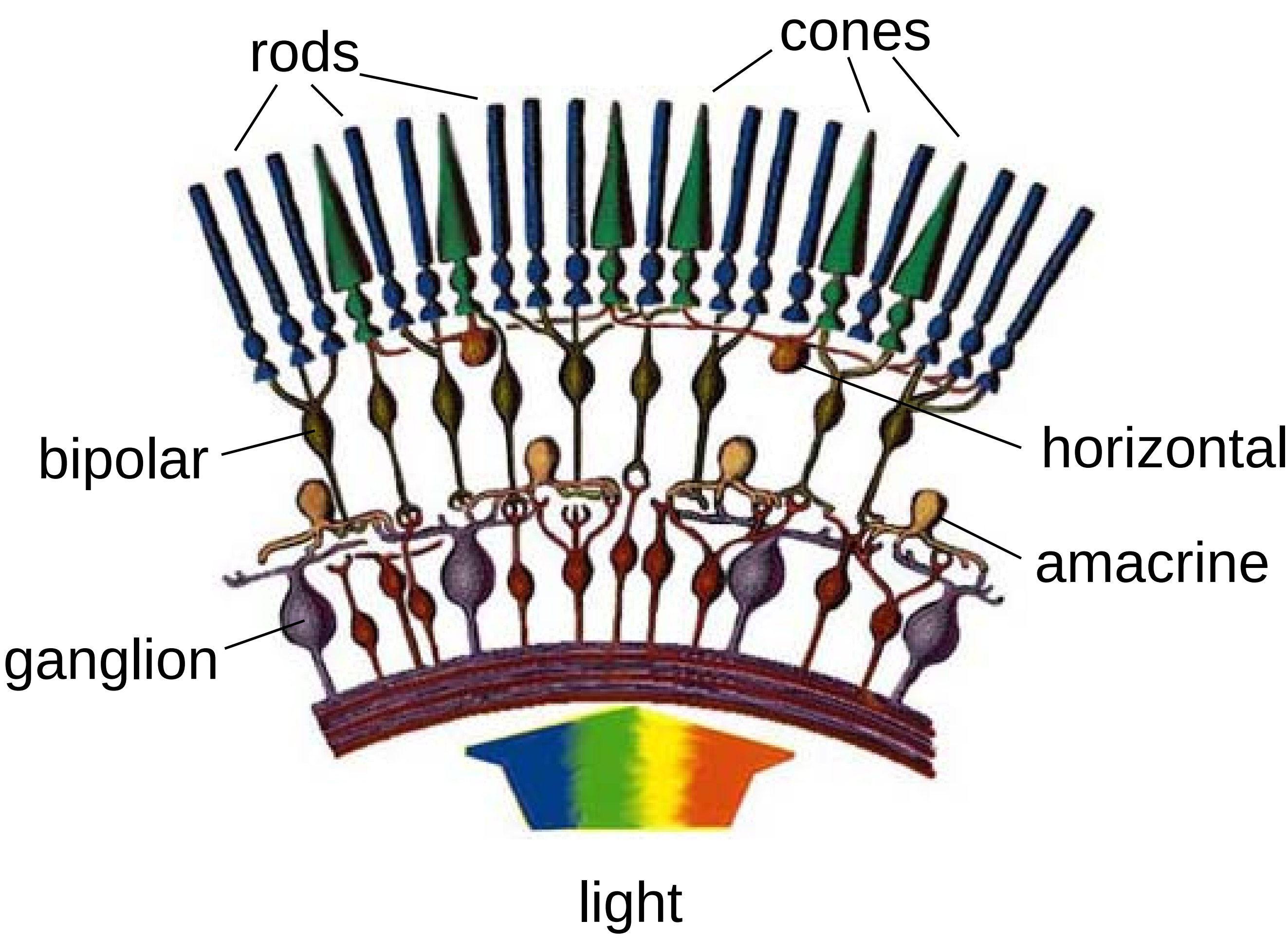


The Human Eye

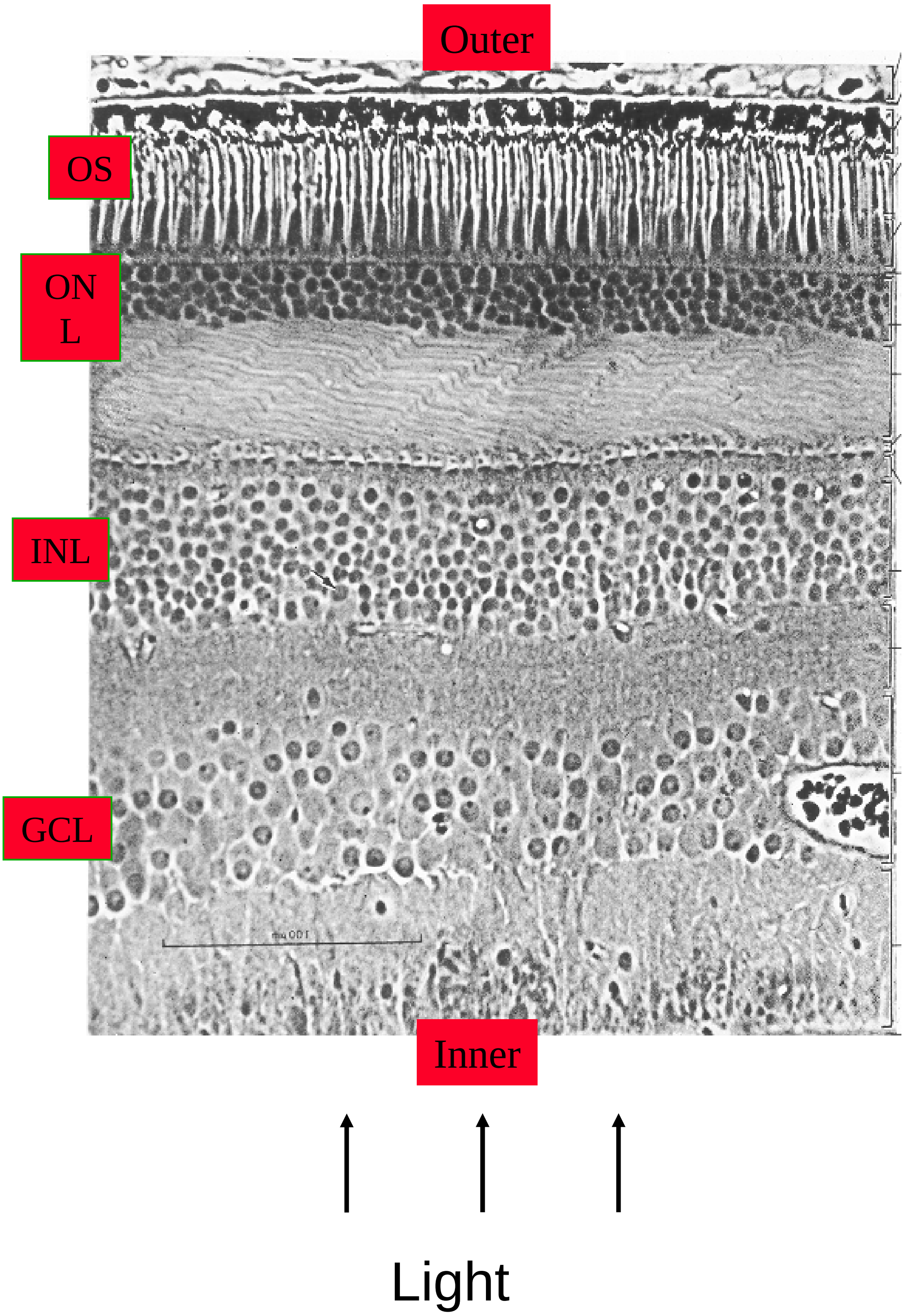




The Human Retina

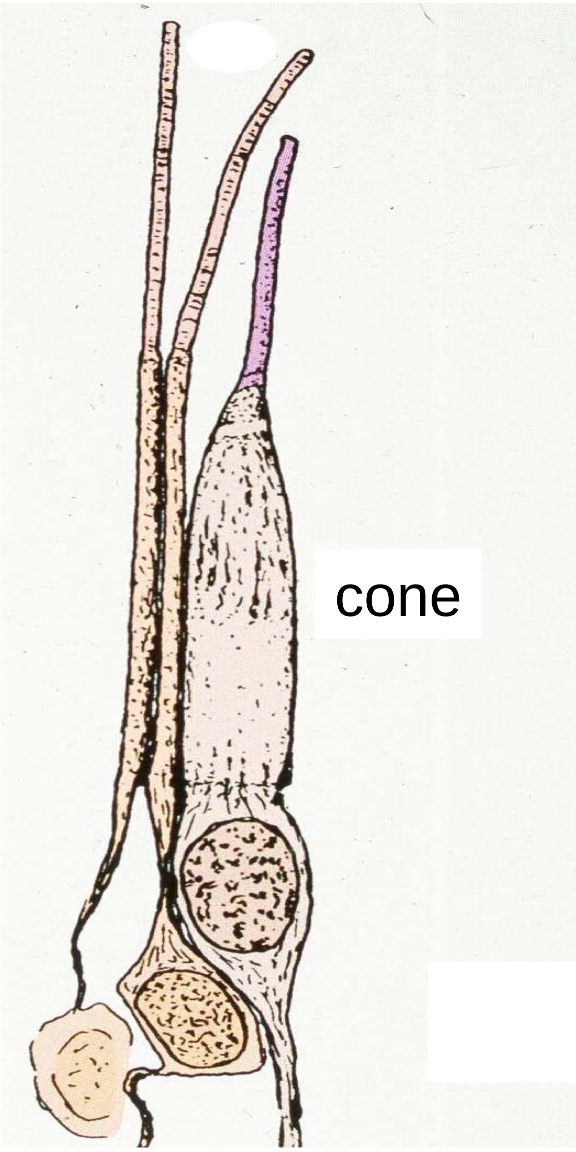


Cross-section of Human Retina

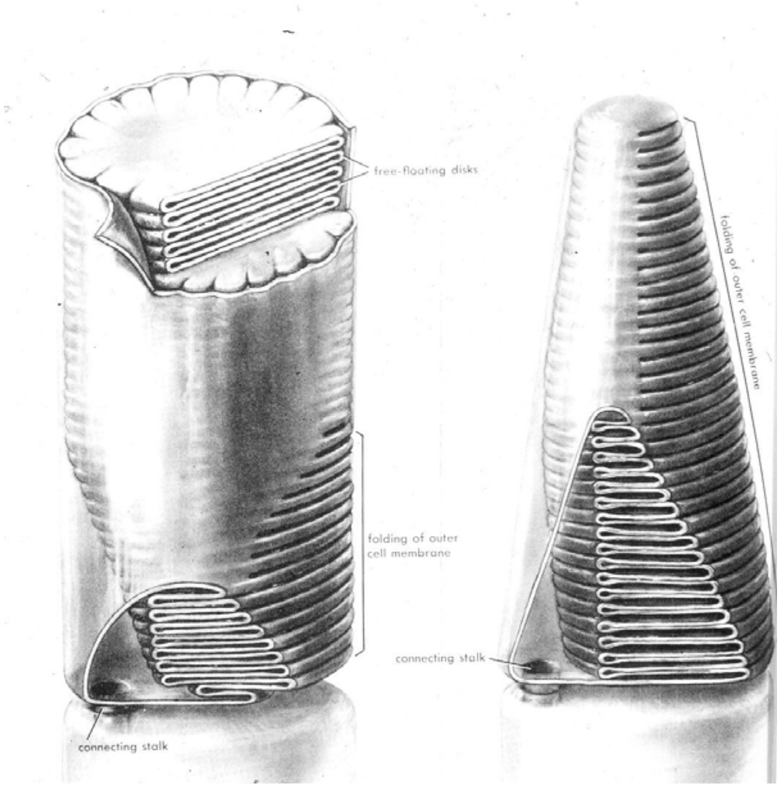


Retinal Photoreceptors

rods



Receptor Models



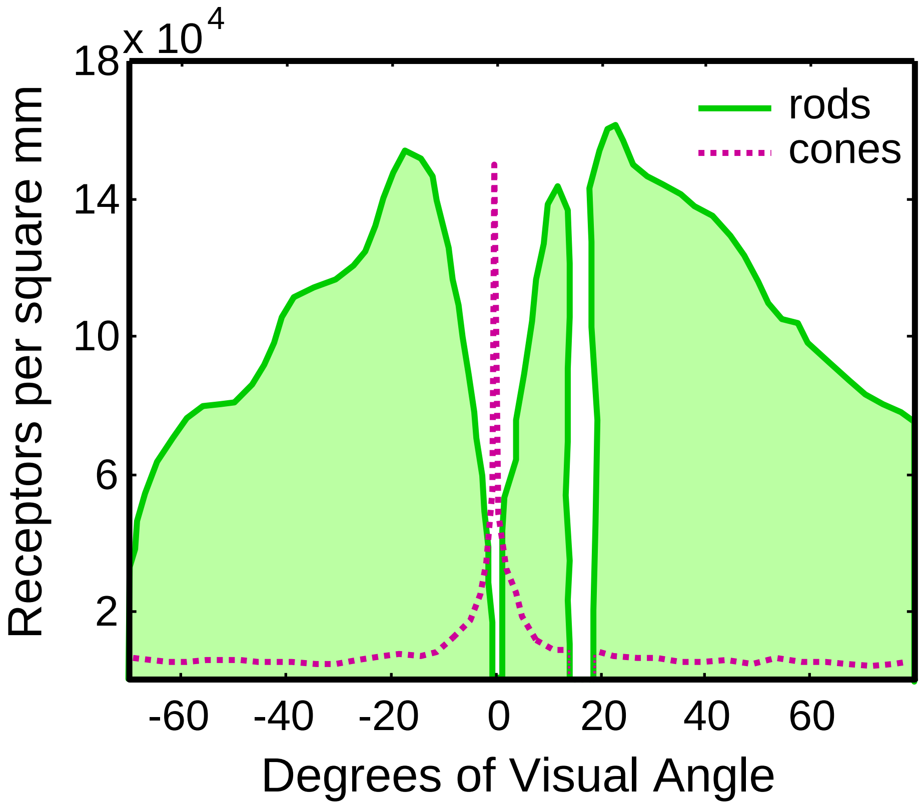
10 μm

X 1000

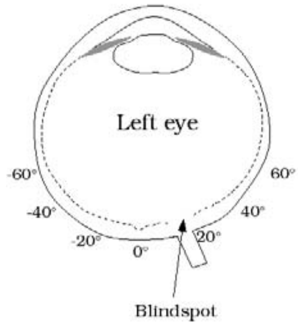
Retinal Photoreceptors

Rods -
- Low illumination levels (Scotopic vision).
- Highly sensitive (respond to a single photon).
- 100 million rods in each eye.
- No rods in fovea.

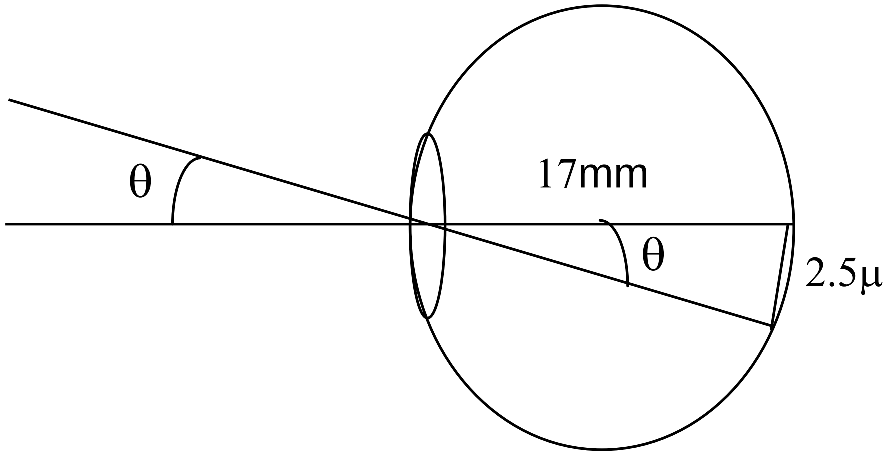
Cones -
- High illumination levels (Photopic vision)
- Less sensitive than rods.
- 5 million cones in each eye.
- Only cones in fovea (aprox. 50,000).
- Density decreases with distance from fovea.



Distribution of rod and cone photoreceptors



Calculating the viewing angle of a single cone in the fovea:

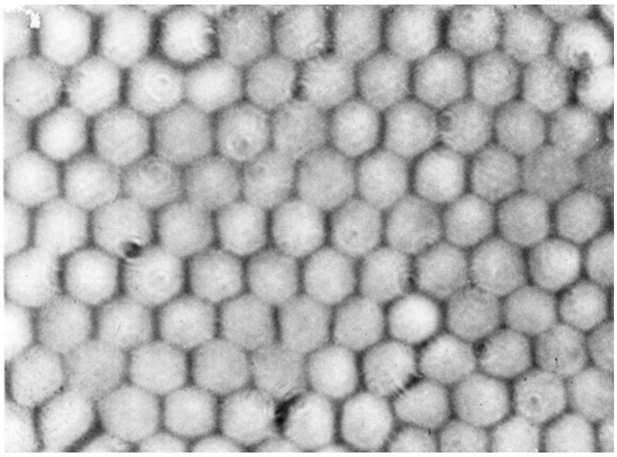


$$\tan(\theta) = \frac{2.5 \times 10^{-6}}{1.7 \times 10^{-2}} = 1.47 \times 10^{-4}$$

$$\theta = 0.0084 \text{ deg} \cong 0.5' \text{ (arcmin)}$$

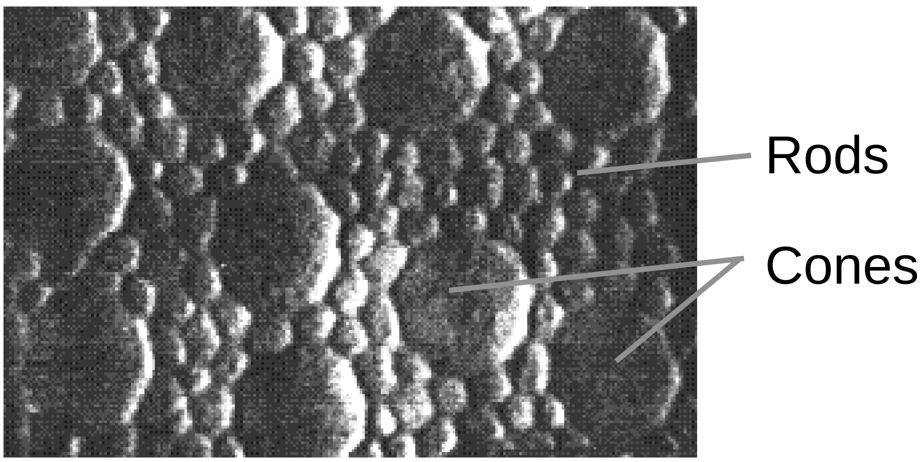
Cones - 2.3 μ – width
2.5 μ – inter-cone distance
0.5'– field of view

Cone Mosaic



Cone Mosaic at Fovea

10 μm

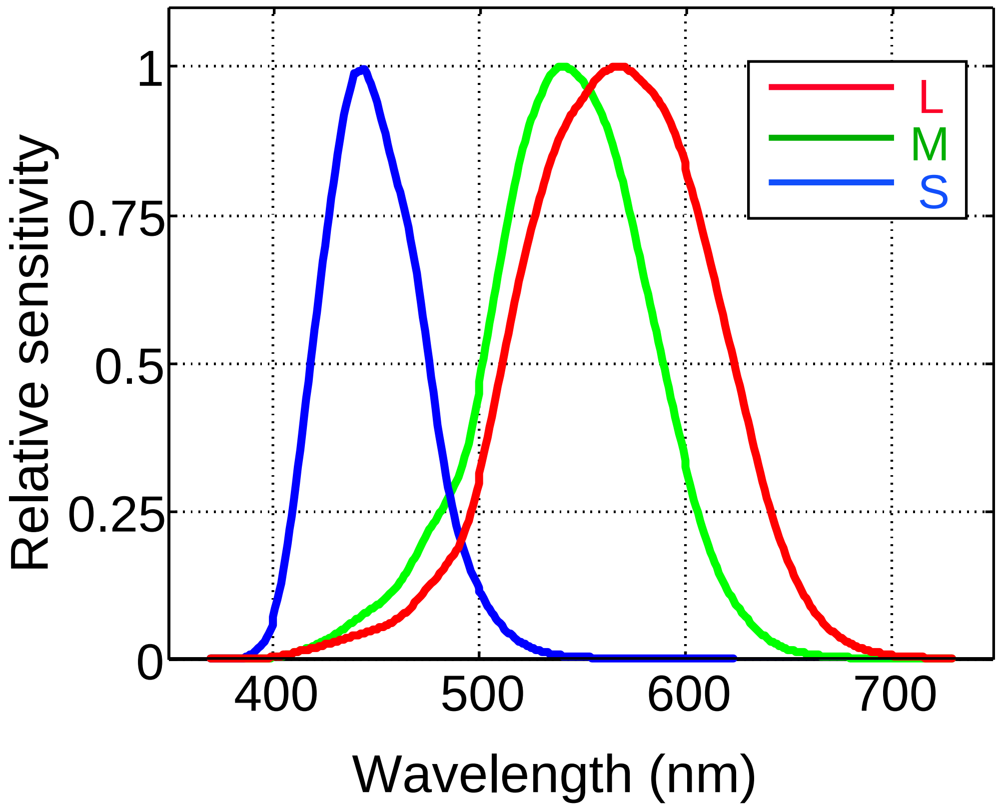


Cone Mosaic in periphery

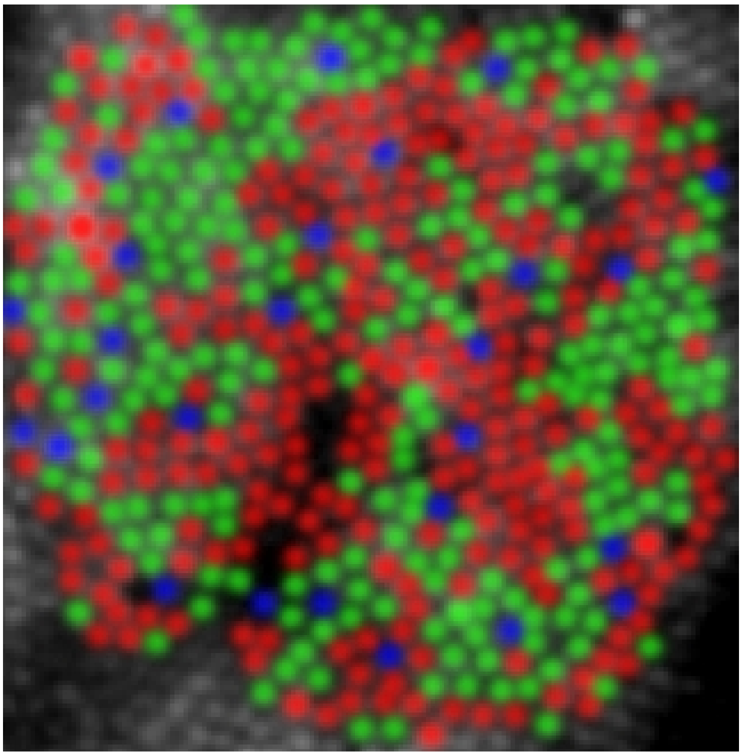
Retinal Photoreceptors

Cones -
- High illumination levels (Photopic vision)
- Less sensitive than rods.
- 5 million cones in each eye.
- Only cones in fovea (aprox. 50,000).
- Density decreases with distance from fovea.
- 3 cone types differing in their spectral sensitivity: L , M, and S cones.

Cone Spectral Sensitivity



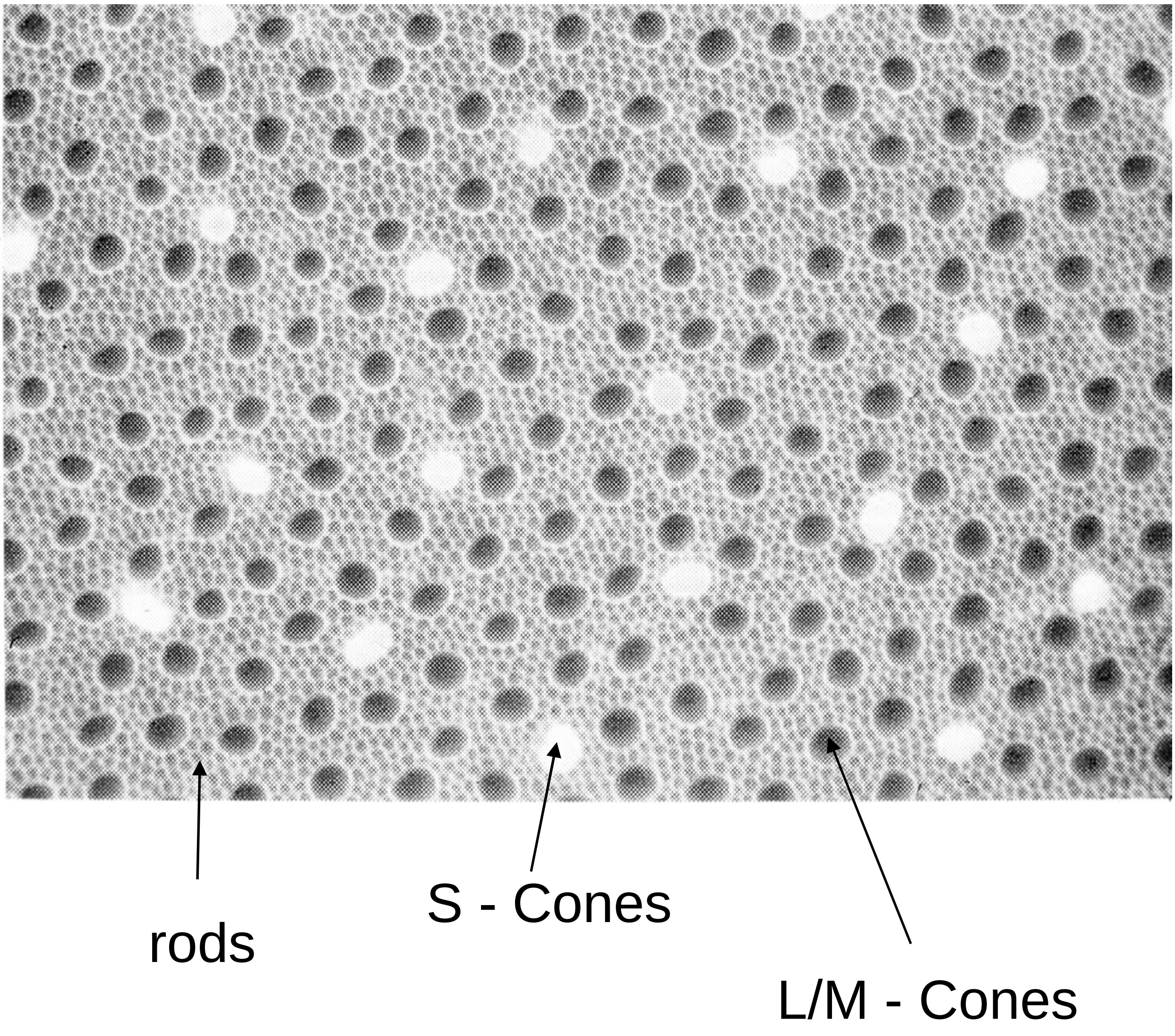
Cone Receptor Mosaic
(Roorda and Williams, 1999)



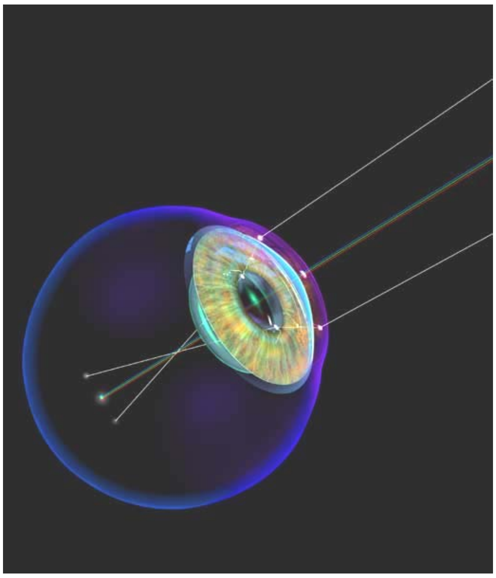
L-cones M-cones S-cones

S cone Sampling Mosaic

Foveal Periphery

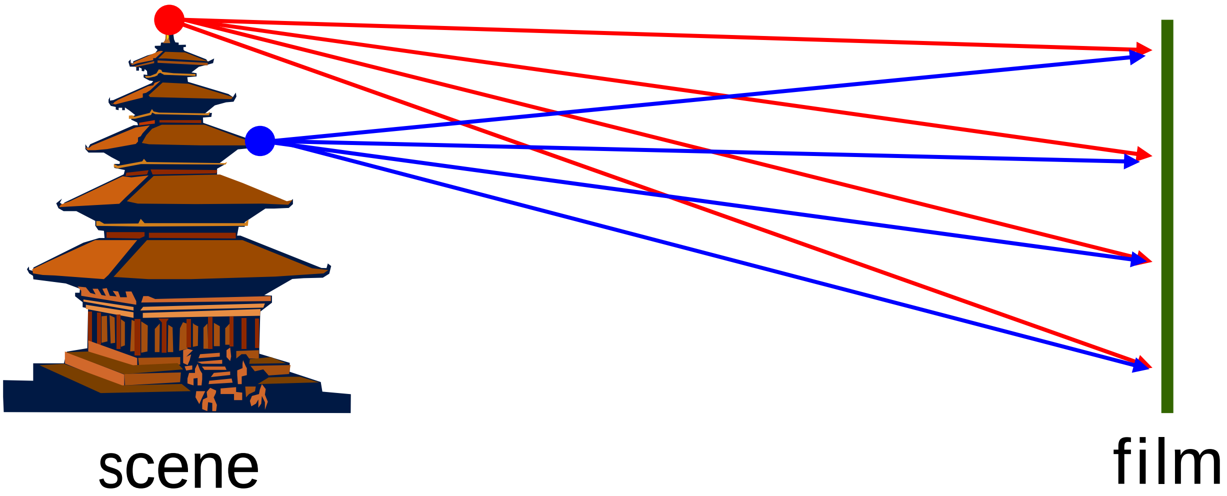


Human Image Formation



What is the quality of the optics
of the human eye?

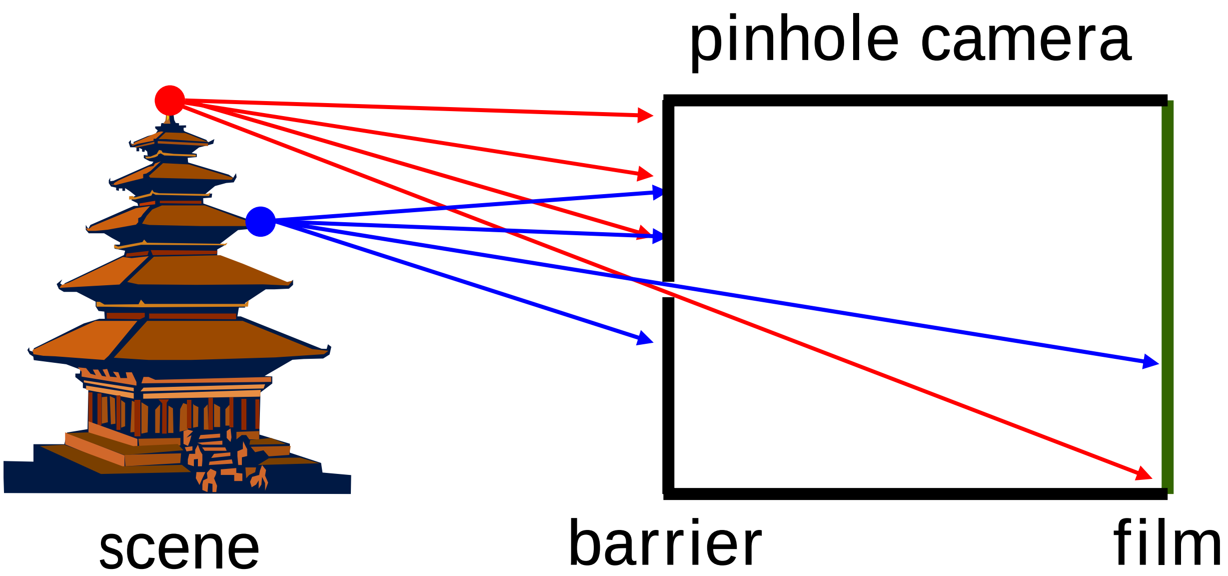
Image Formation - Optics



Put a piece of film in front of an object.

source: Yung-Yu Chuang

Image Formation - Optics



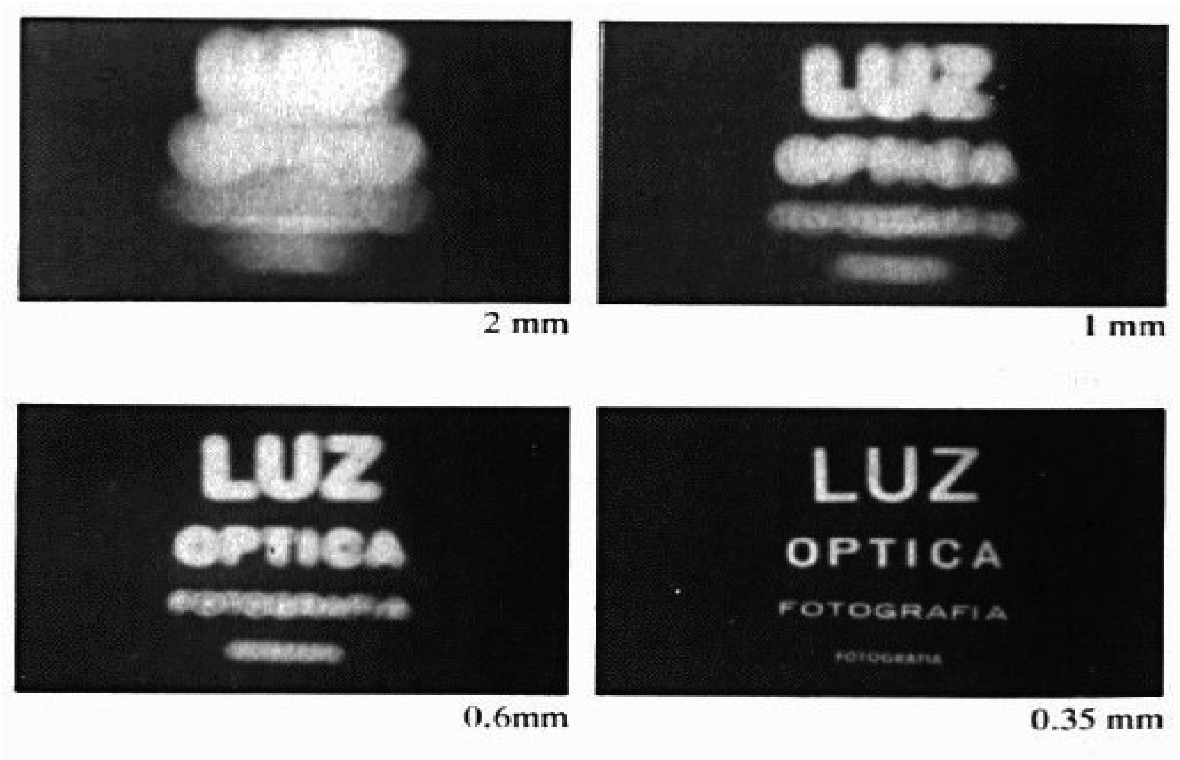
Add a barrier to block off most of the rays.

- It reduces blurring
- The pinhole is known as the aperture
- The image is inverted

source: Yung-Yu Chuang

Image Formation - Optics

Shrinking the aperture



Why not create the aperture as small as possible?

- Less light gets through
- Diffraction effect

Image Formation - Optics

Shrinking the aperture

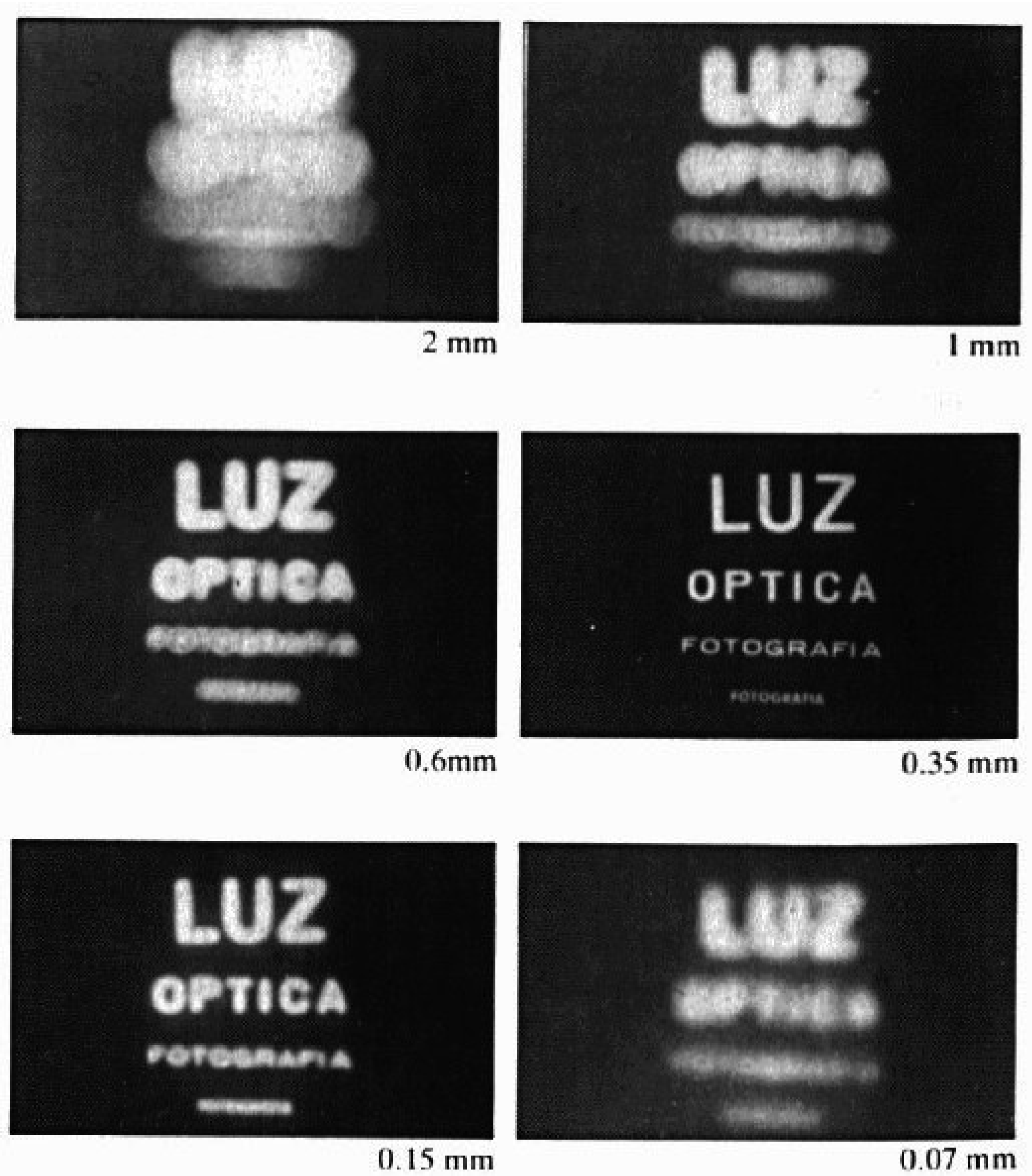


Image Formation - Optics

Adding a Lens

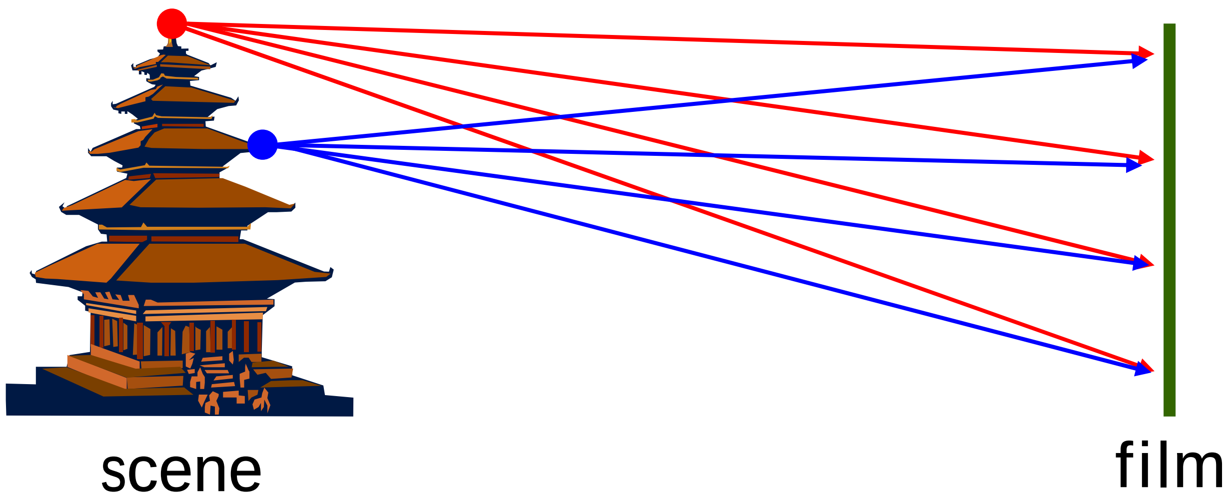
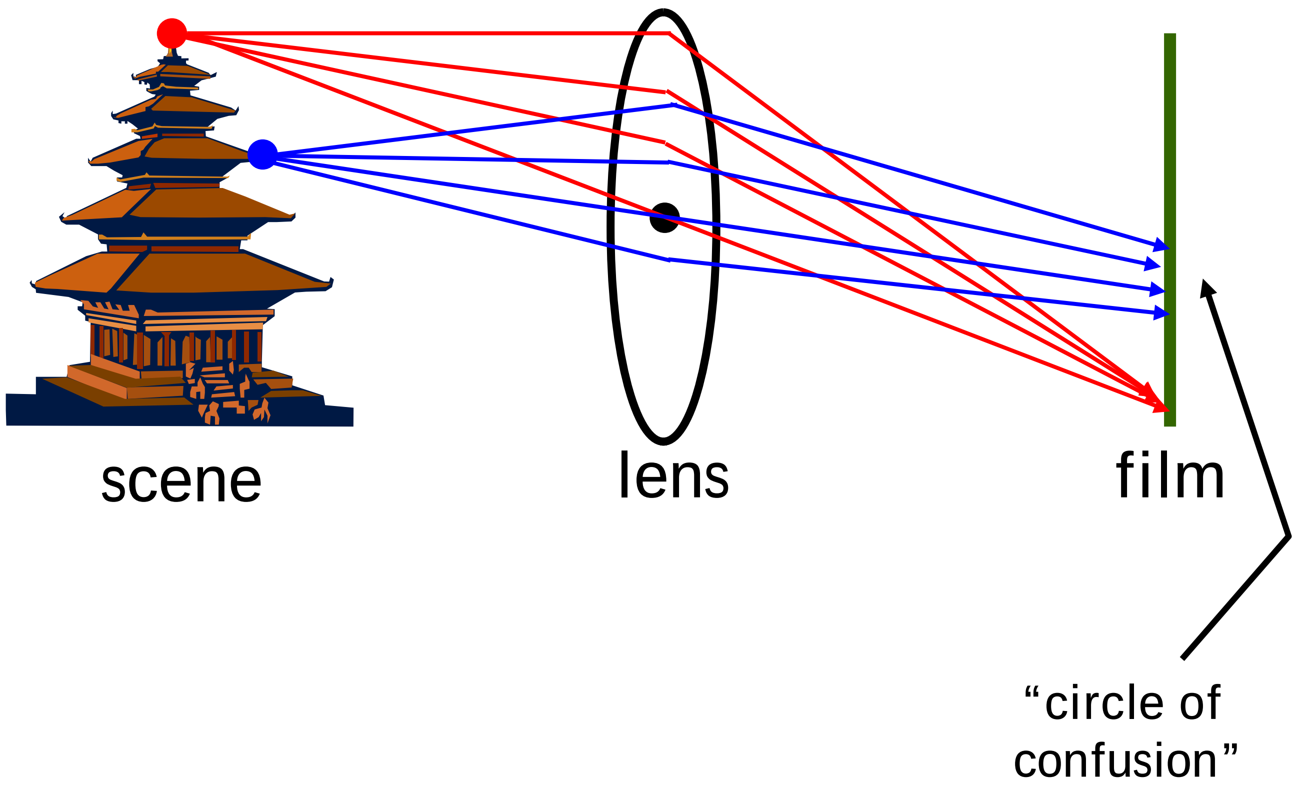


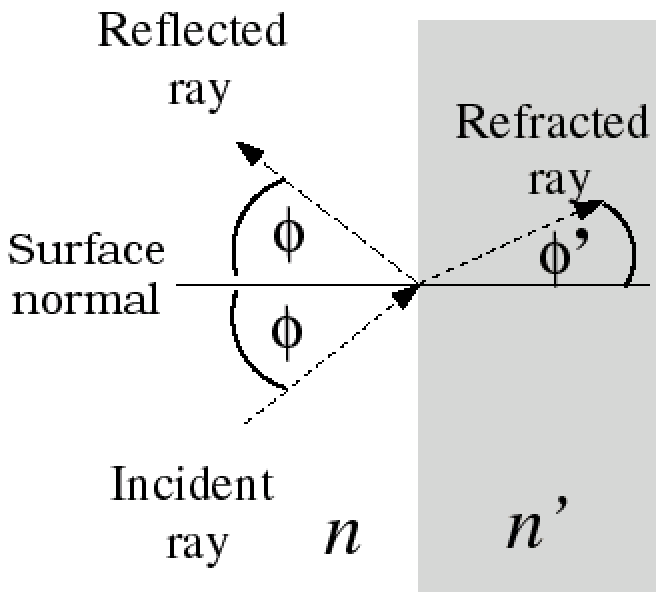
Image Formation - Optics

Adding a Lens



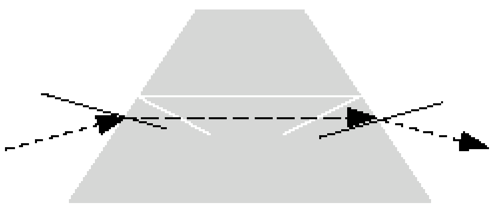
Lens Design: Snell's Law

(a)

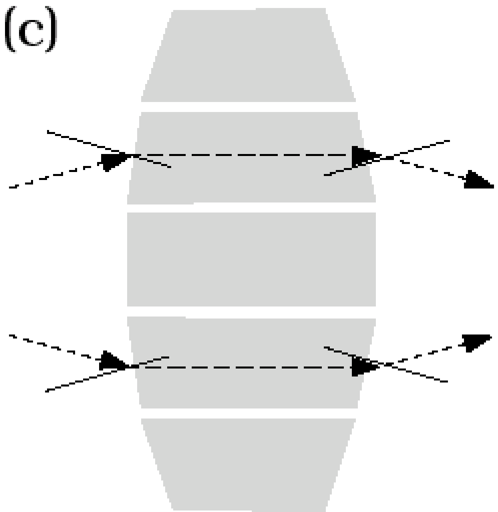


$$n \sin(\phi) = n' \sin(\phi')$$

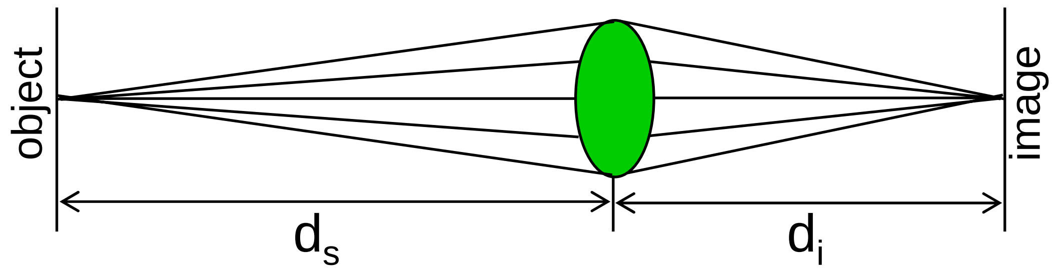
(b)



(c)



Lensmaker's Equation

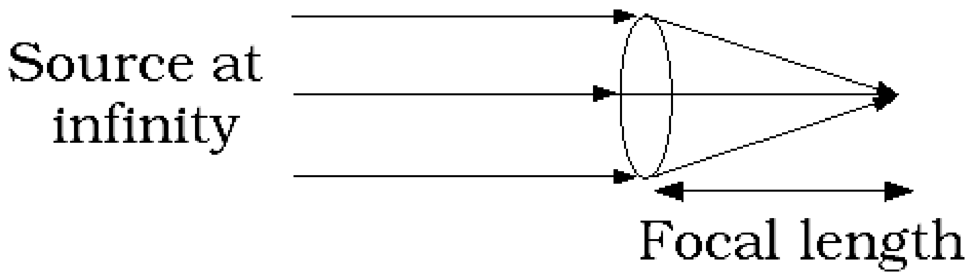


$$\frac{1}{d_s} + \frac{1}{d_i} = \frac{1}{f}$$

d_s = *source dist*

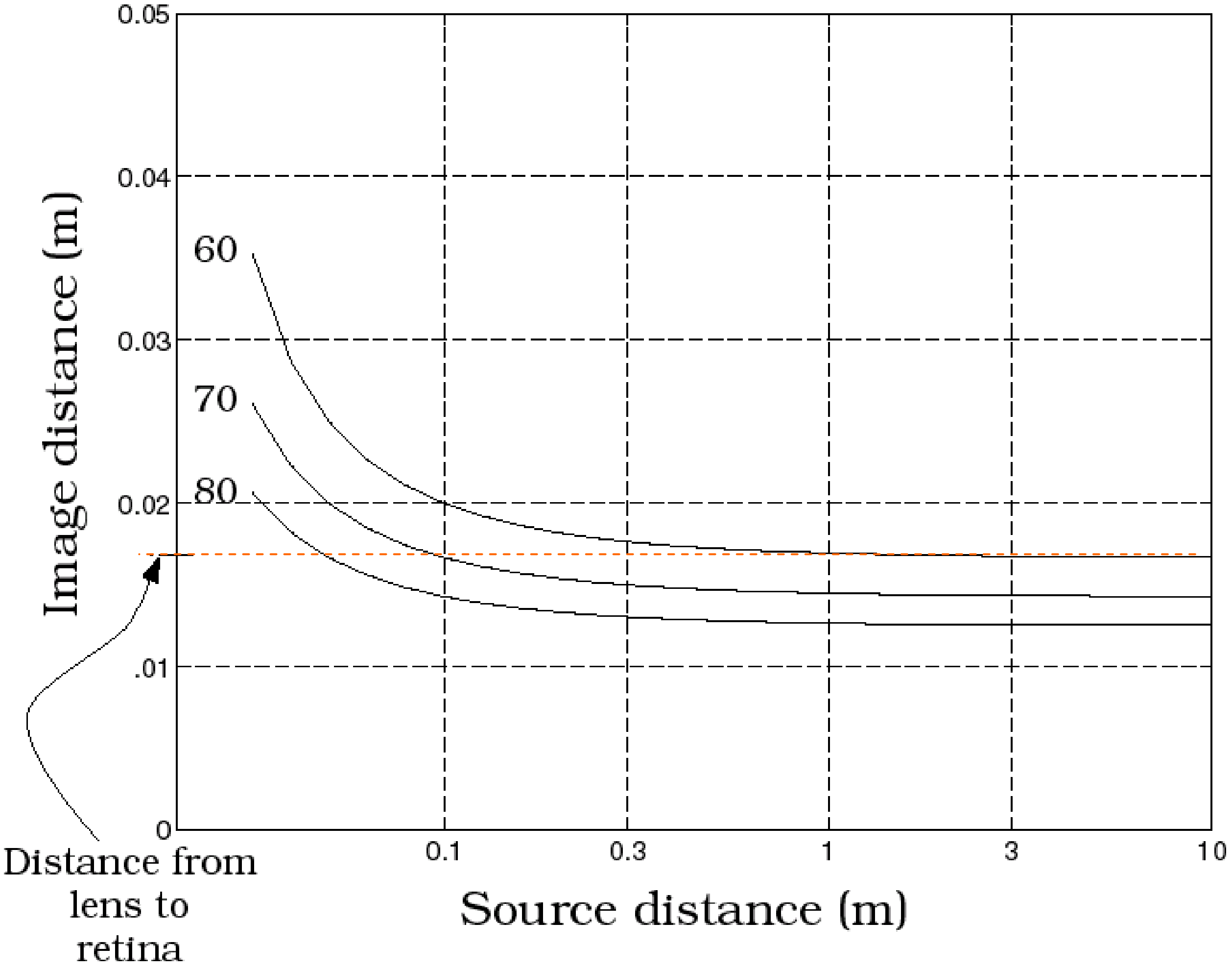
d_i = *image dist*

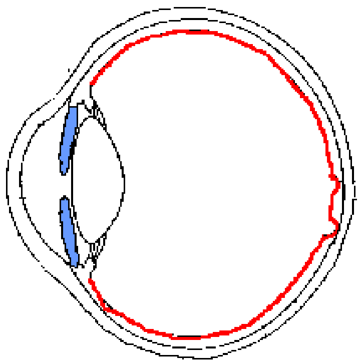
f = *focal length*



$$\text{Lens power (diopters)} = \frac{1}{\text{Focal length (m)}}$$

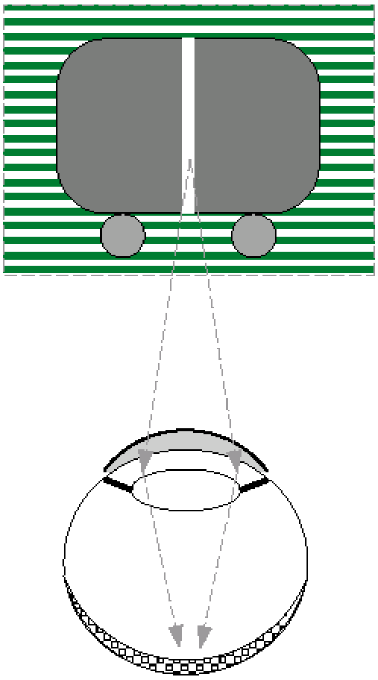
Optical power and object distance

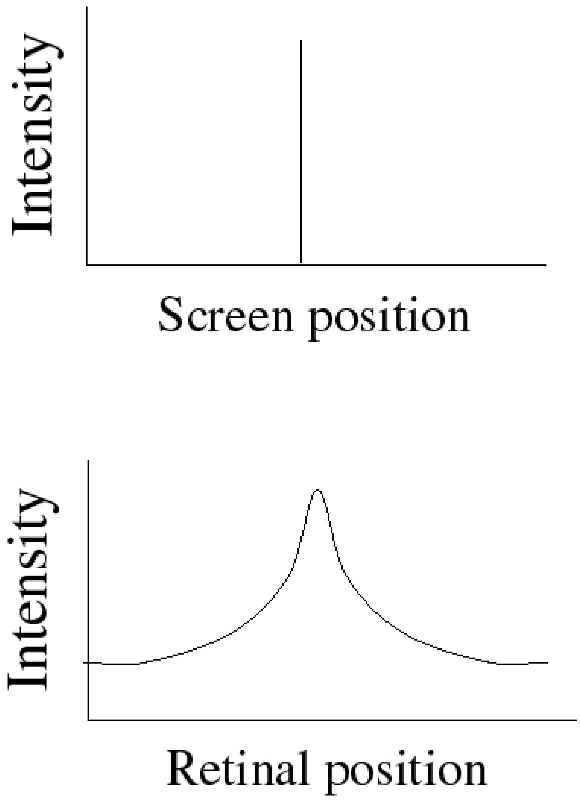




Encoding Characteristics - Line spread

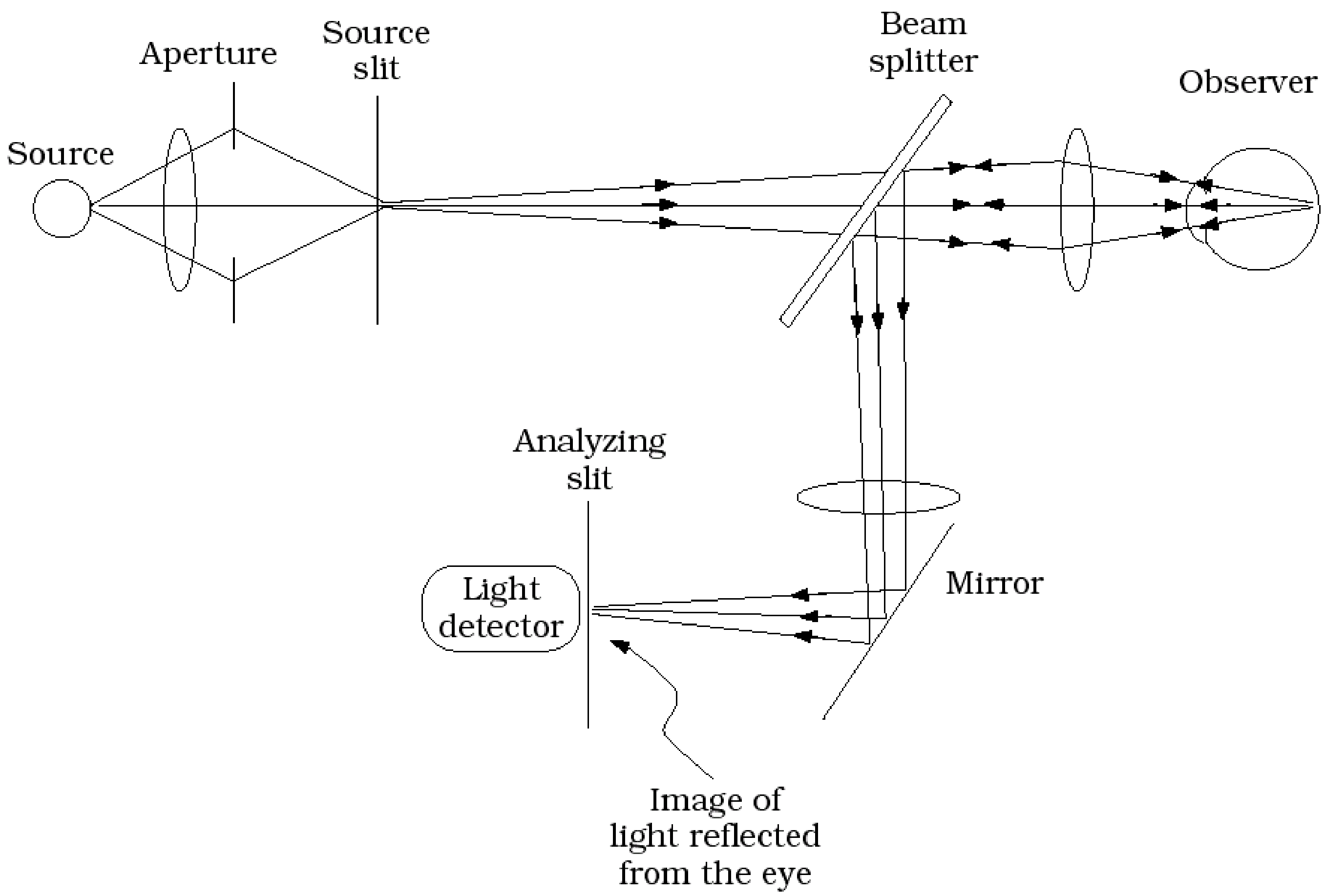
Line spread defines the optical quality of the eye





Light Scattered From From The Retina Is Used To Estimate Optical Quality

(e.g., Campbell and Gubisch)



Double Pass Method

Measurements of light reflected from the retina (Linespread) at various pupil diameters

Campell and Gubisch 1966

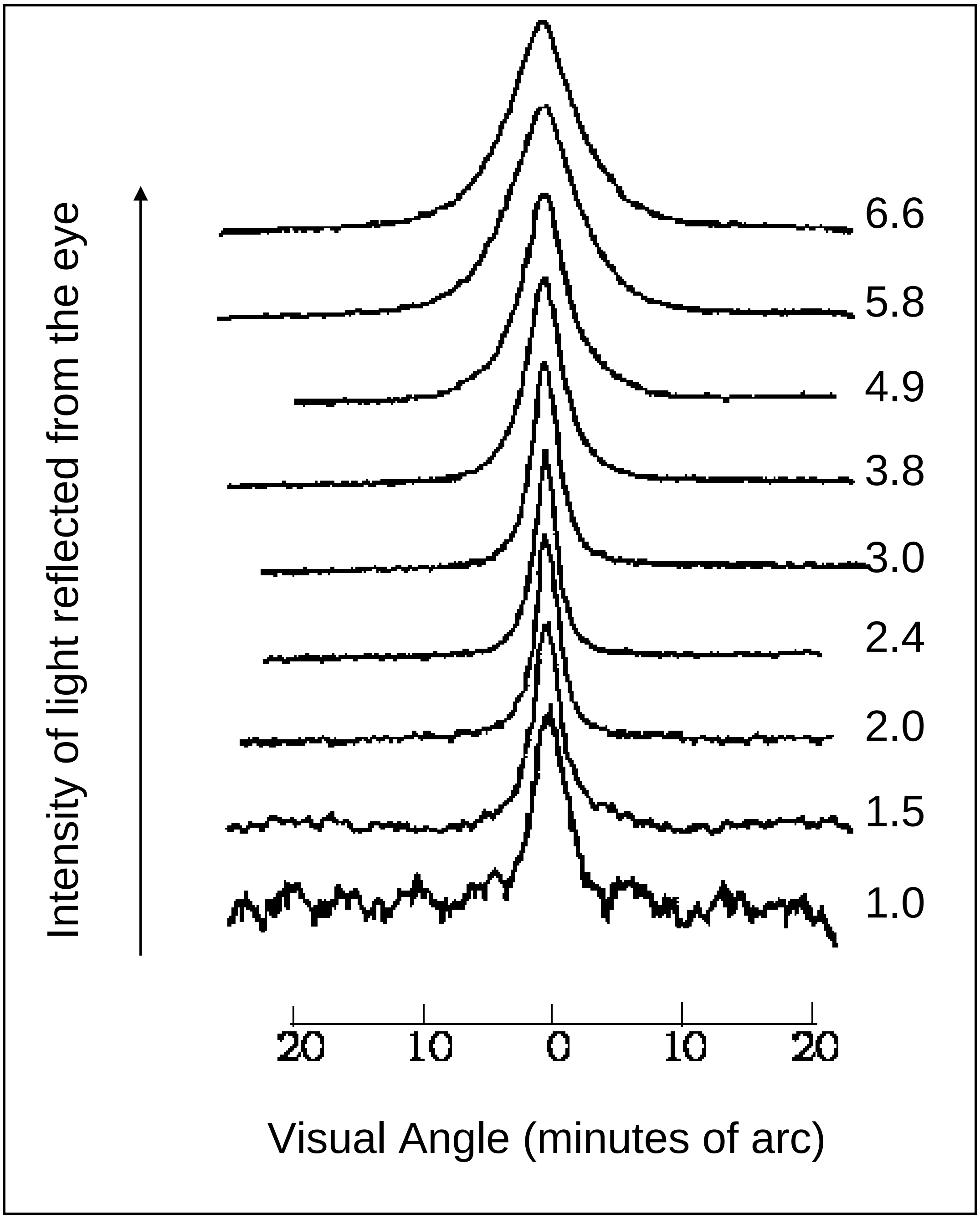
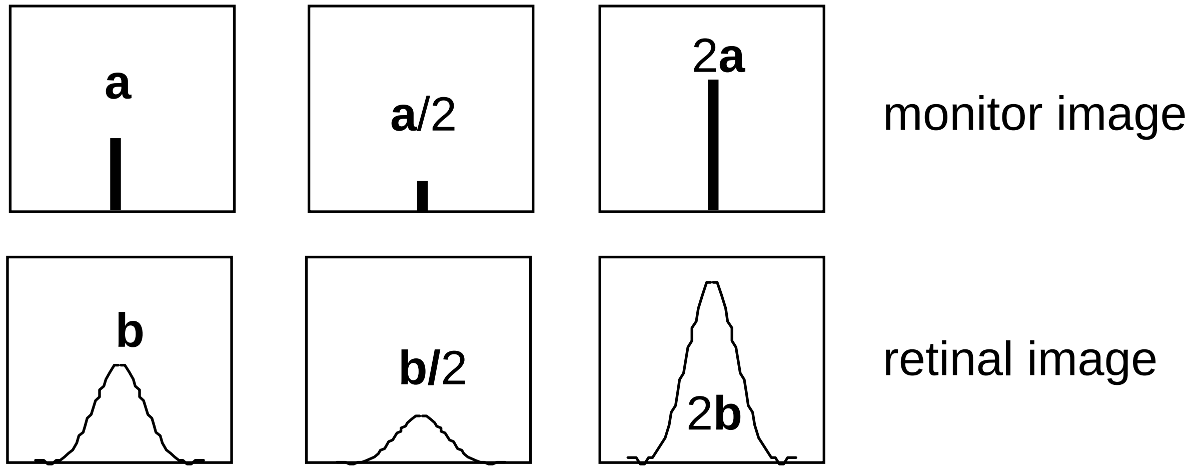


Image formation satisfies :

Homogeneity:



Additivity:

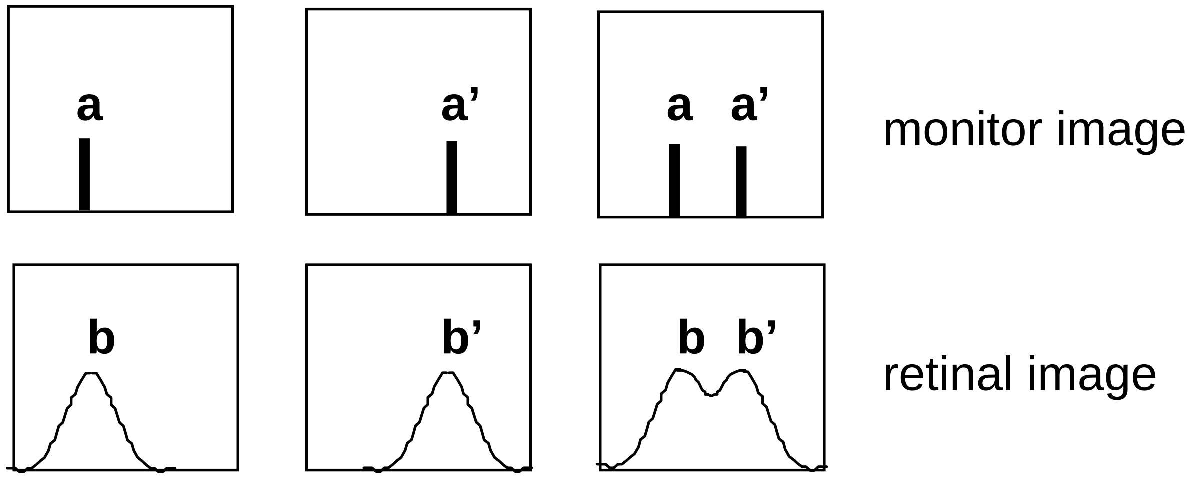
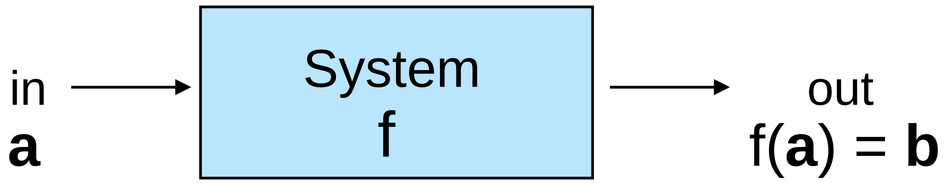


Image formation is a linear system

Image Formation is a Linear System



A system is *Linear* if it satisfies superposition:

homogeneity $f(k\mathbf{a}) = kf(\mathbf{a}) = k\mathbf{b}$

additivity $f(\mathbf{a}_1+\mathbf{a}_2) = f(\mathbf{a}_1) + f(\mathbf{a}_2) = \mathbf{b}_1 + \mathbf{b}_2$

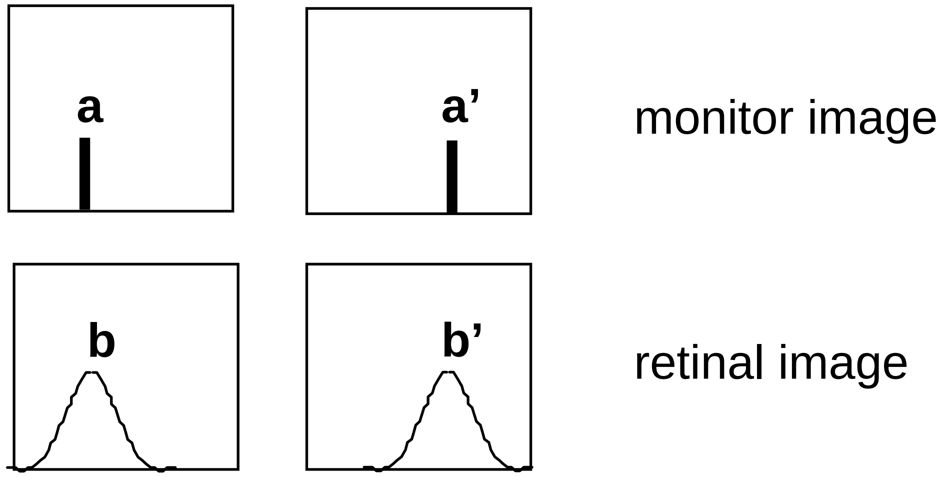
A finite dimensional linear system can be written as a matrix equation:

$$b = Ra$$

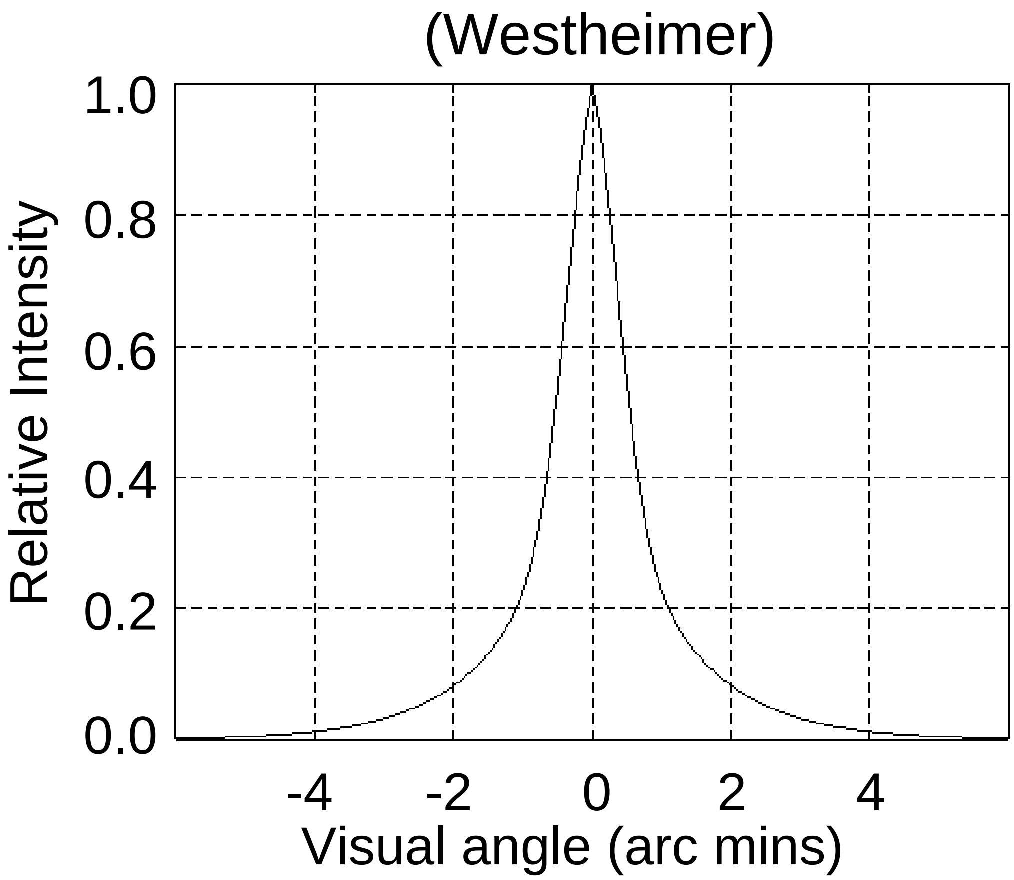
where **R** is the system matrix.

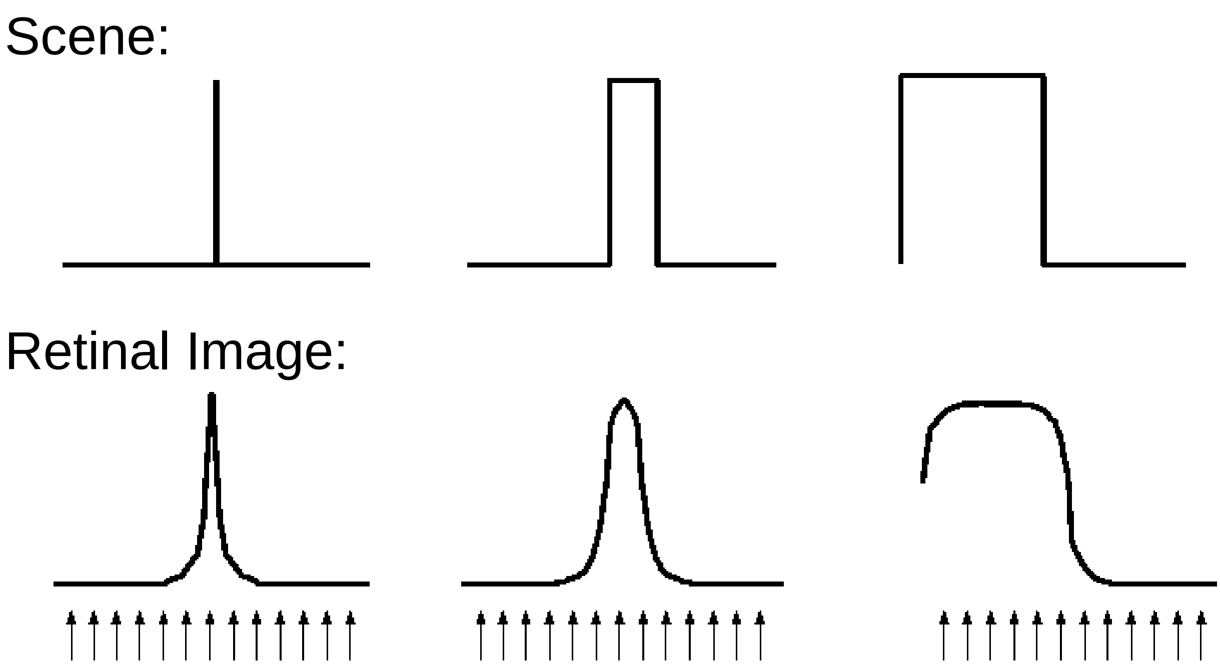
Image formation is a *Shift Invariant* linear system

A shifted input produces a shifted output:

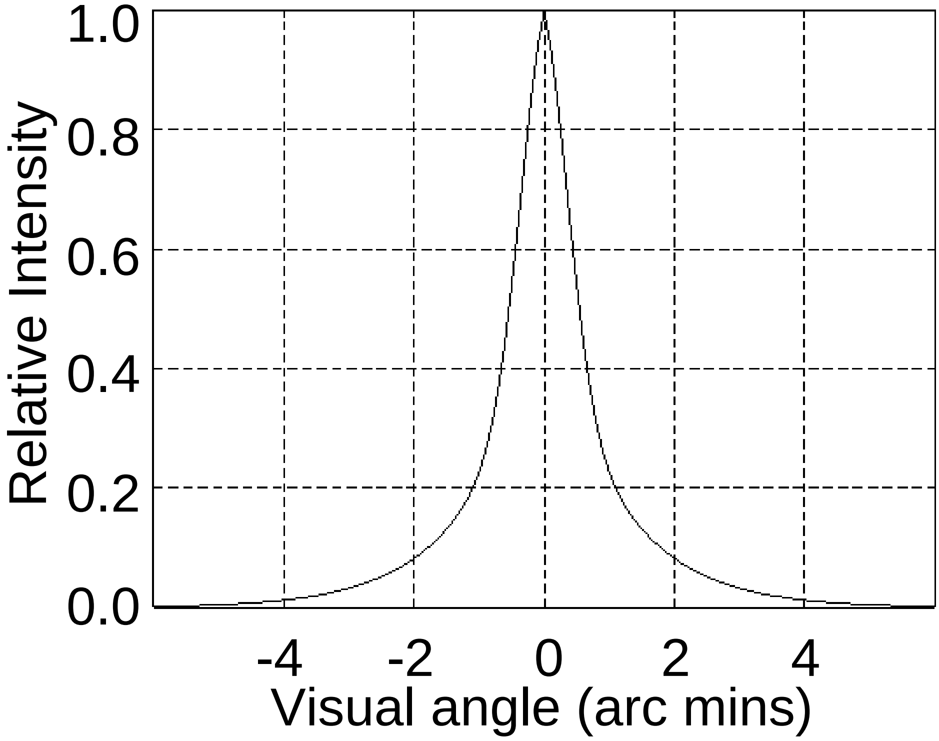


Modeling Image Formation

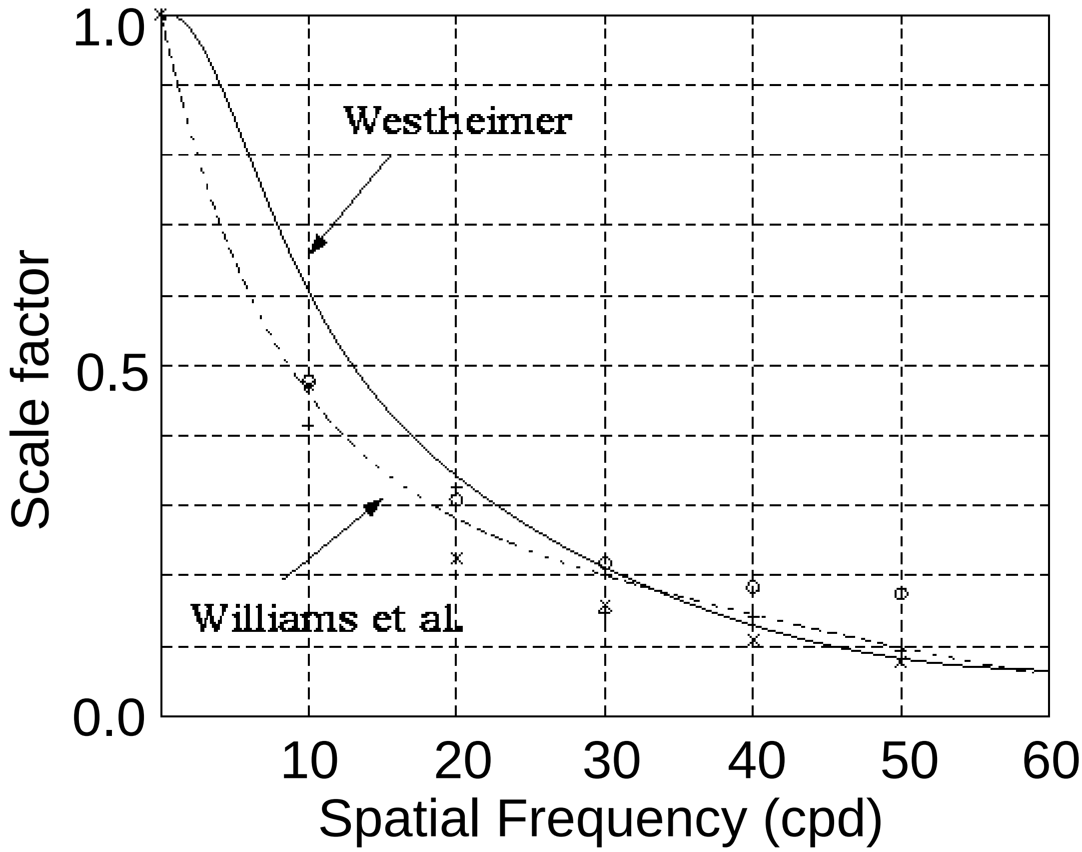




The Human Linespread Function



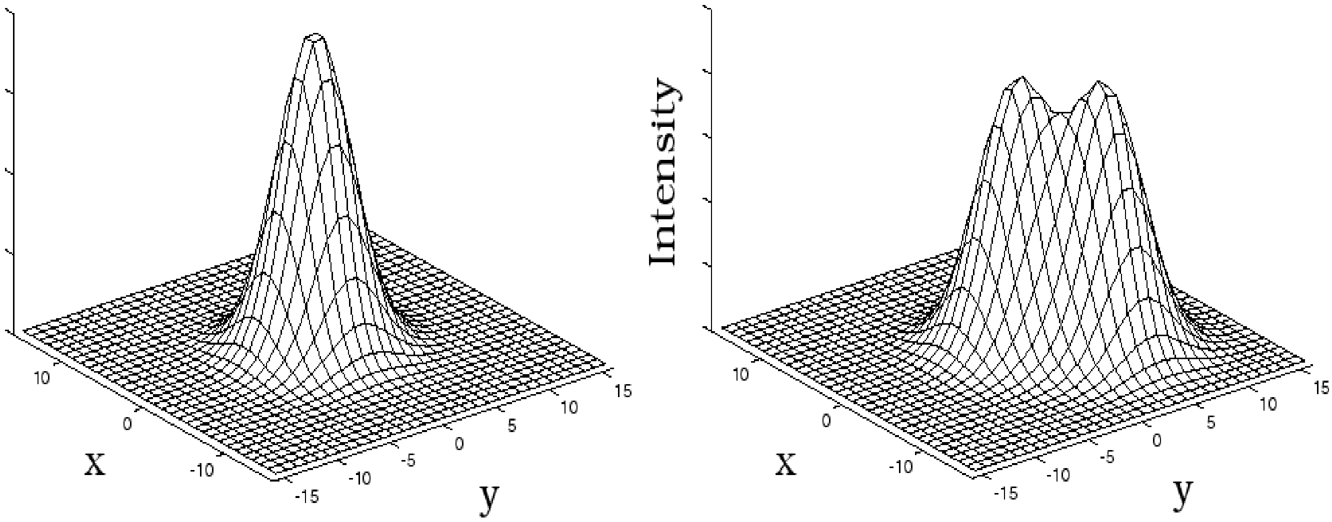
The Human Modulation Transfer Function



The Pointspread Function

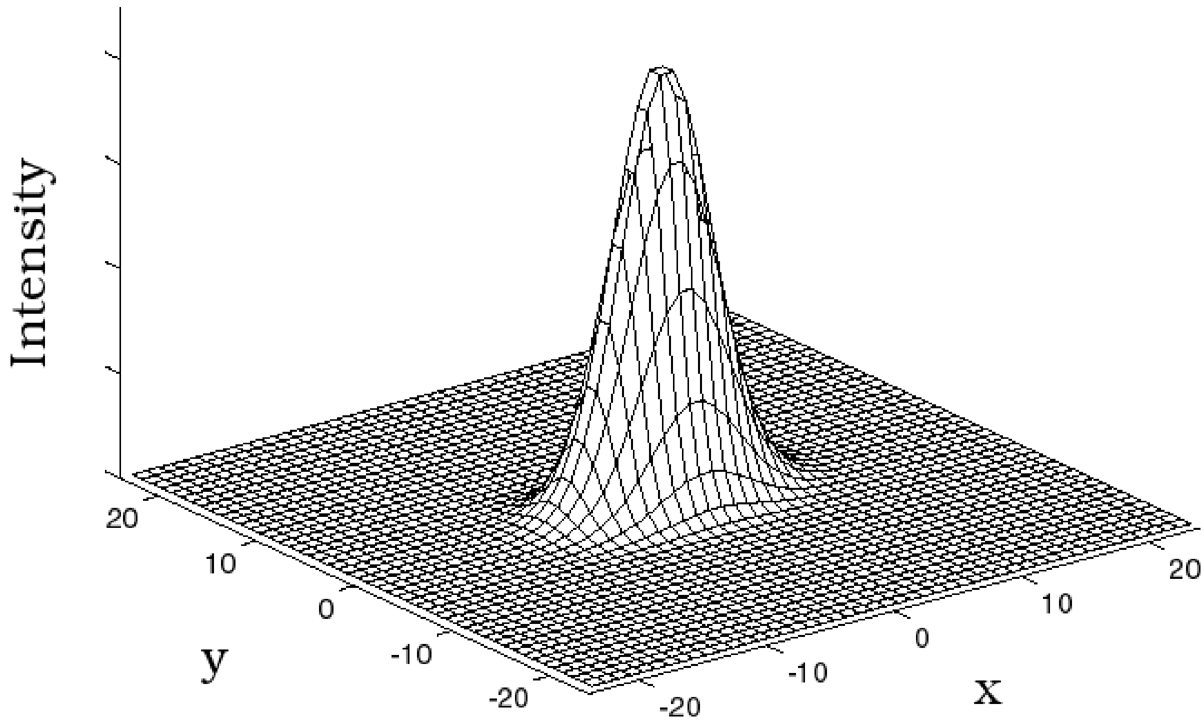
The pointspread function is a generalization of the linespread function.

Retinal Image



Monitor Image

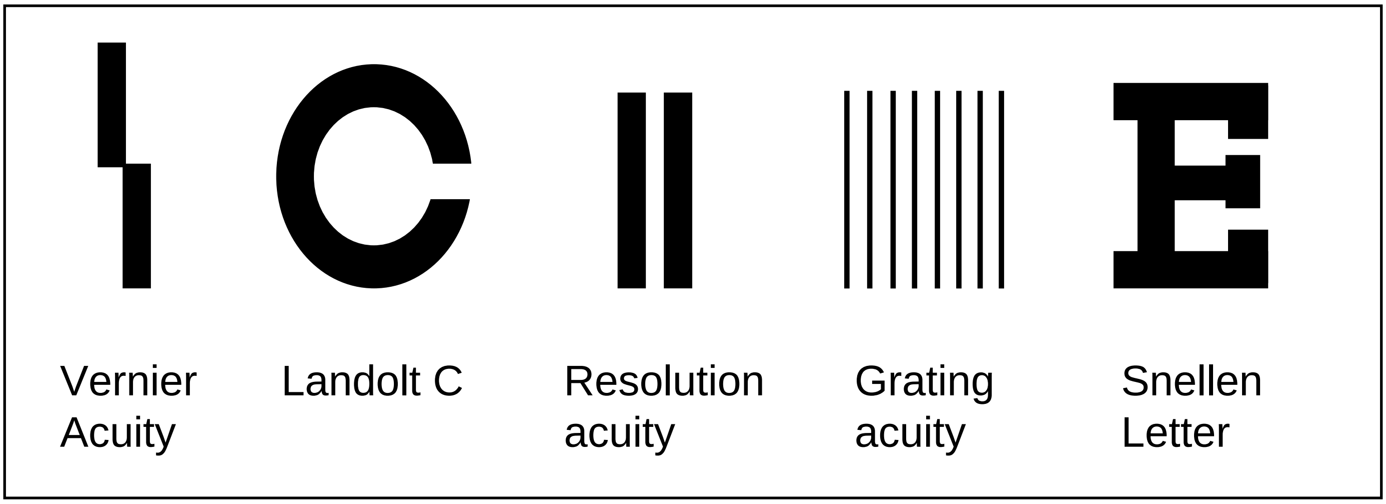
Astigmatism Measures the Assymmetry and Orientation of the Pointspread Function



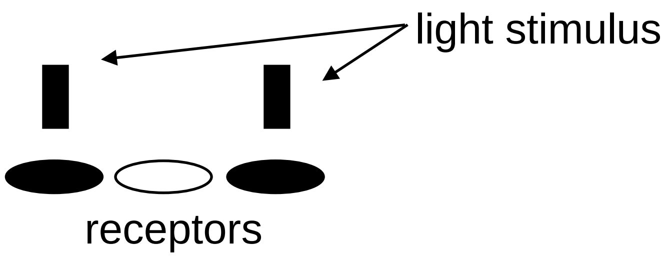
Visual Acuity

Cones at fovea are 2.5μ apart corresponding to 0.5' (arc min).

Typical acuity targets:



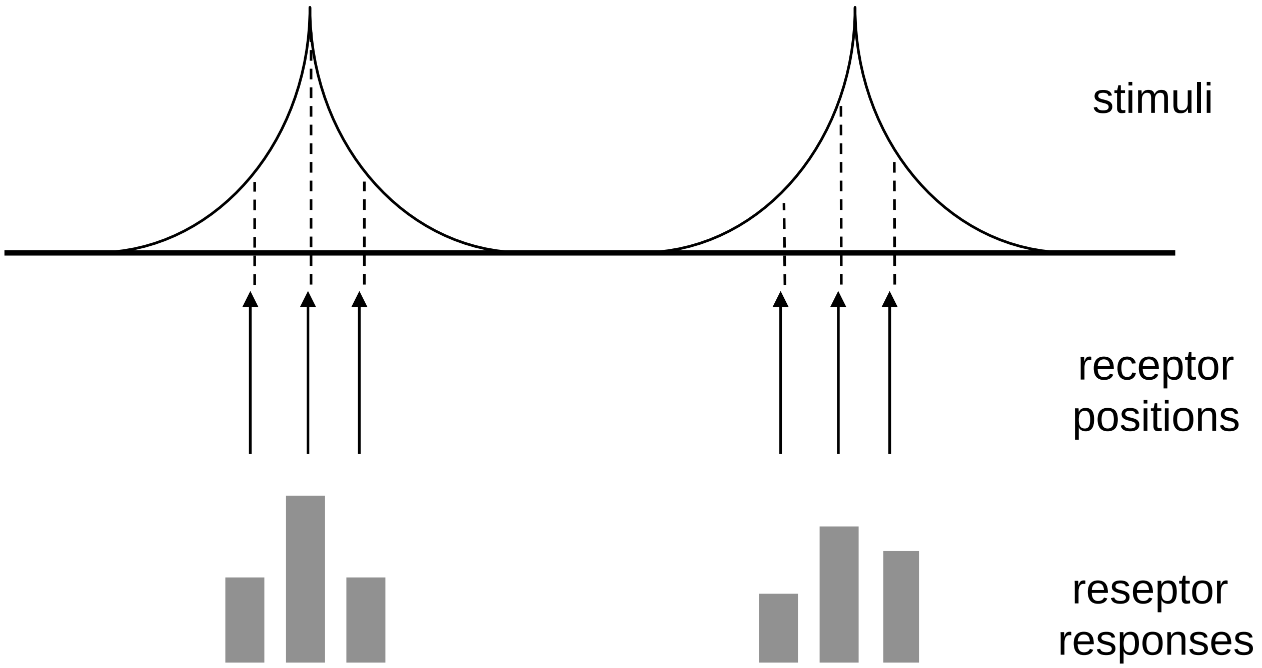
Expected acuity is size of cone or visual angle of cone.



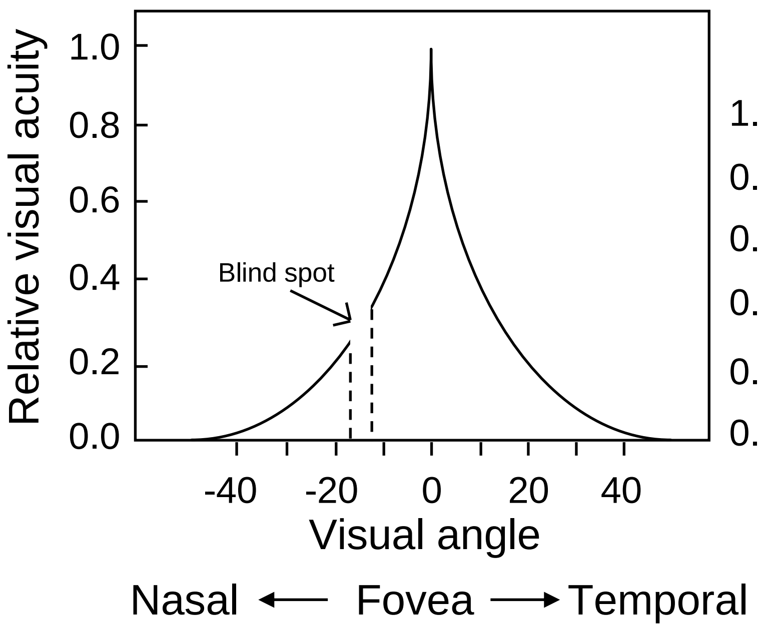
Actual acuity $\approx$ 5'' (arc seconds) = **Hyperacuity**

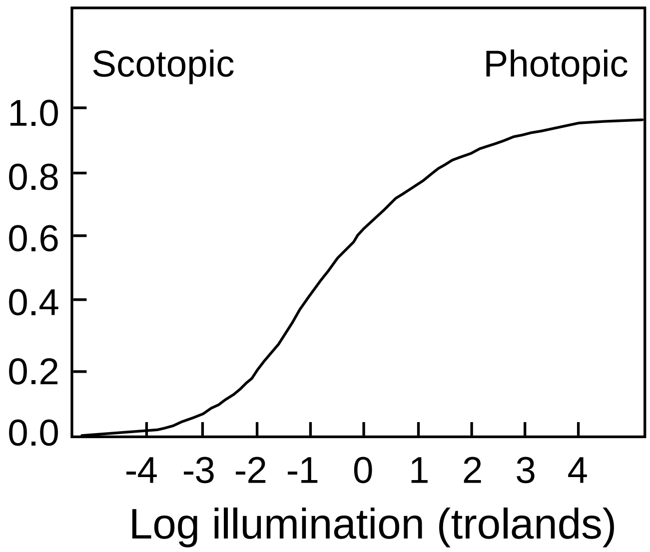
Visual Acuity

Do to linespread, movement of stimulus by less than receptor width causes change in receptor response:



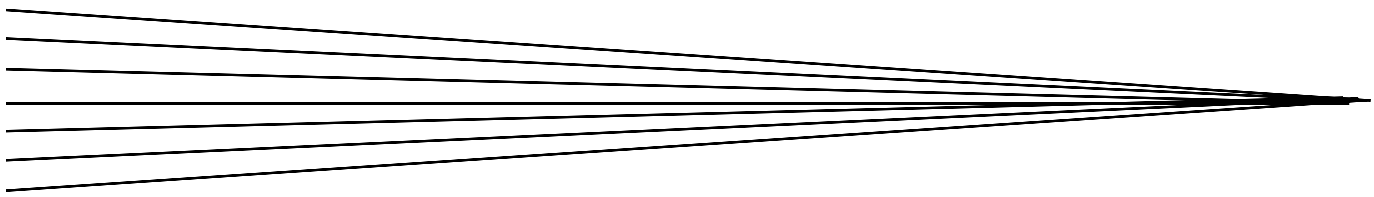
Acuity is affected by retinal position and illumination:



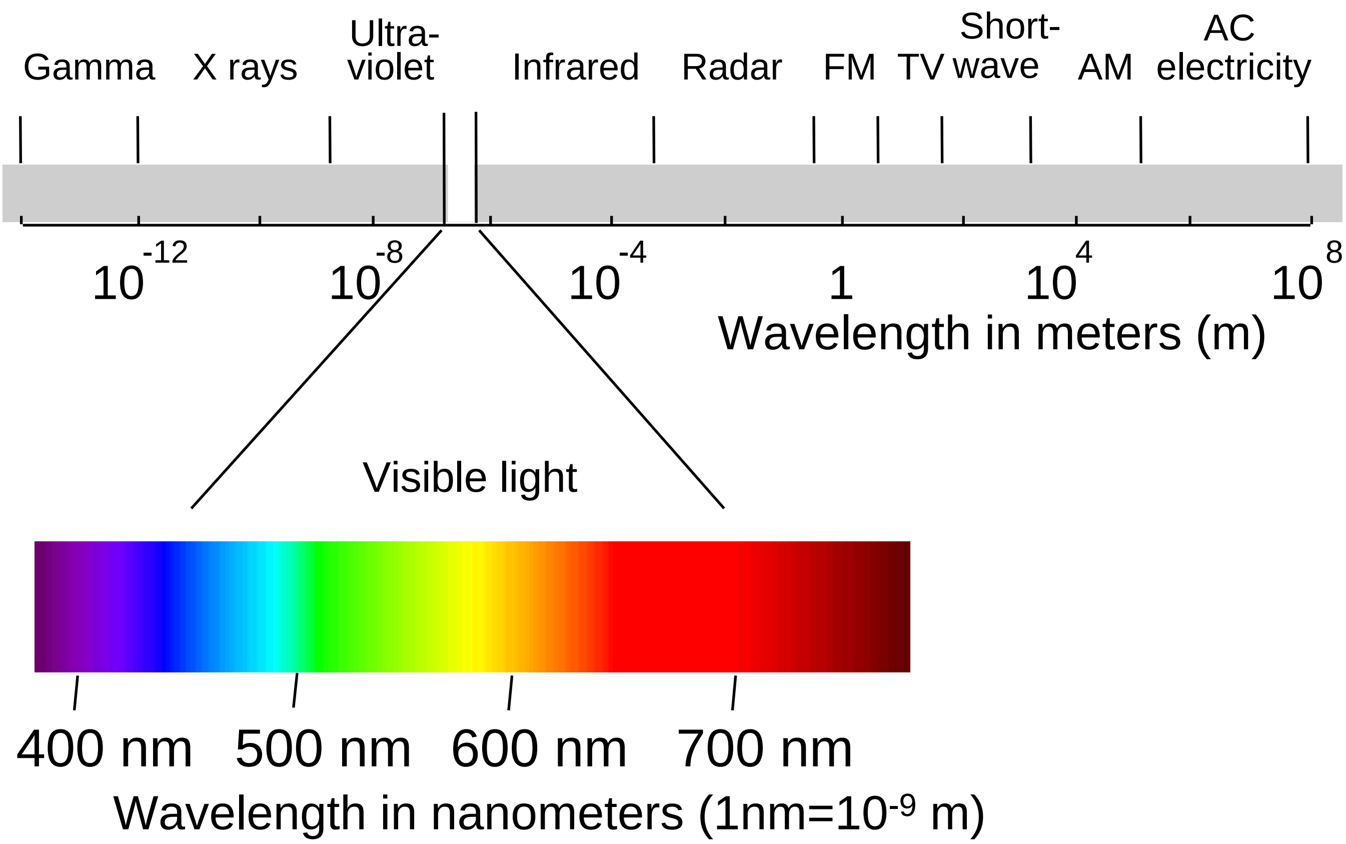


Visual Acuity Test

K	B	X	M	P	A	S
+	+	+	+	+	+	+
50	40	30	20	10	5	0

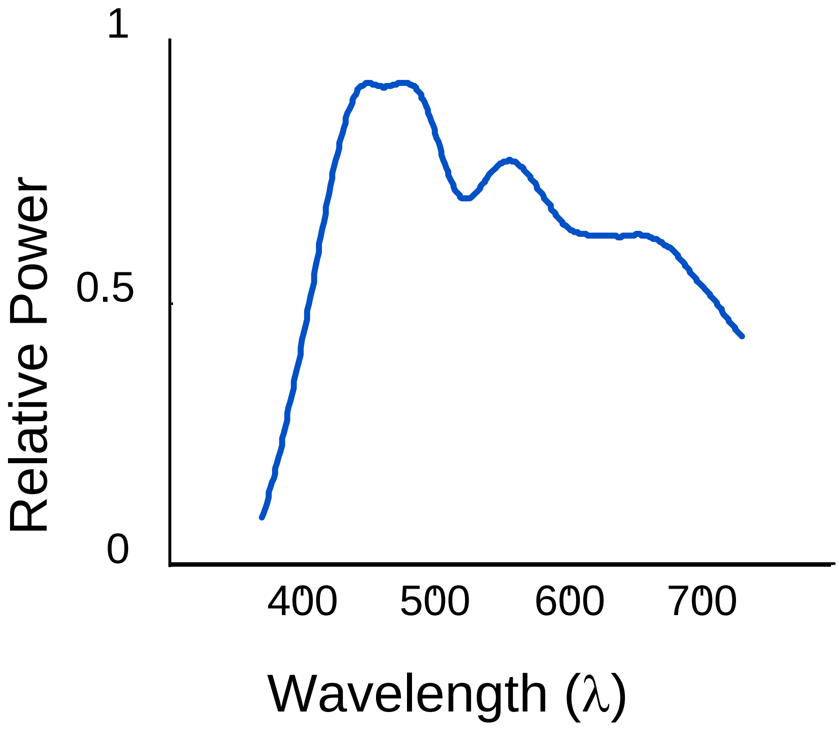


Electromagnetic Radiation - Spectrum

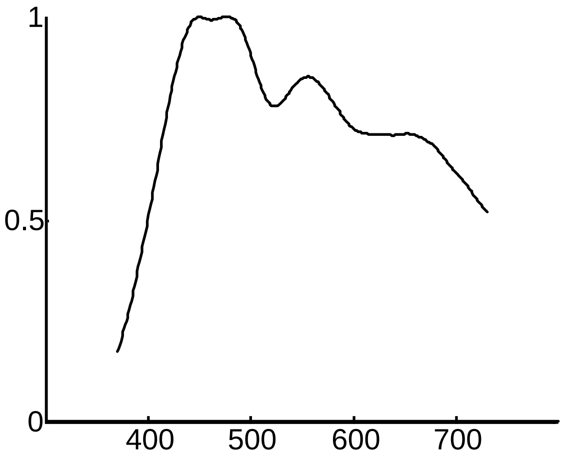


Spectral Power Distribution

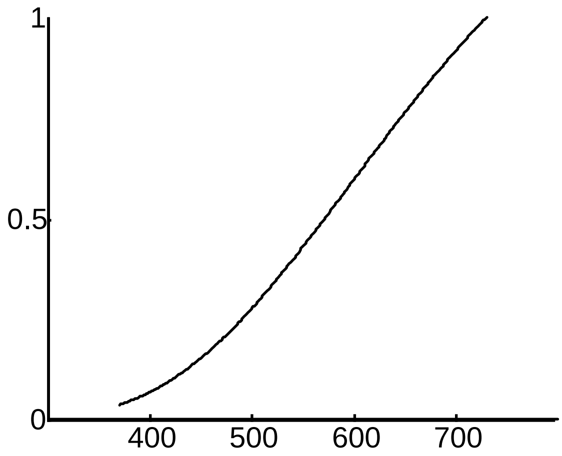
The **Spectral Power Distribution** (SPD) of a light is a function f(l) which defines the energy at each wavelength.



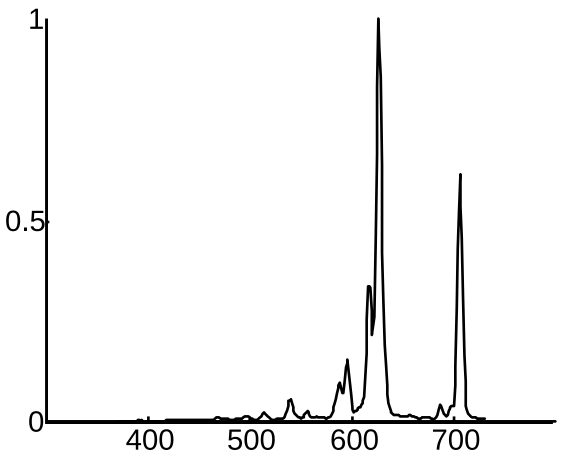
Examples of Spectral power Distributions



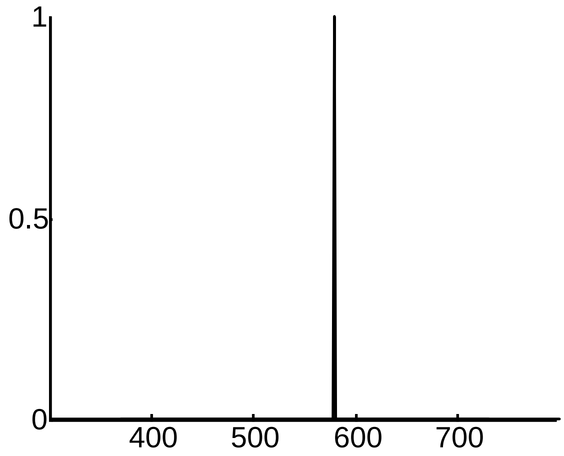
Blue Skylight



Tungsten bulb

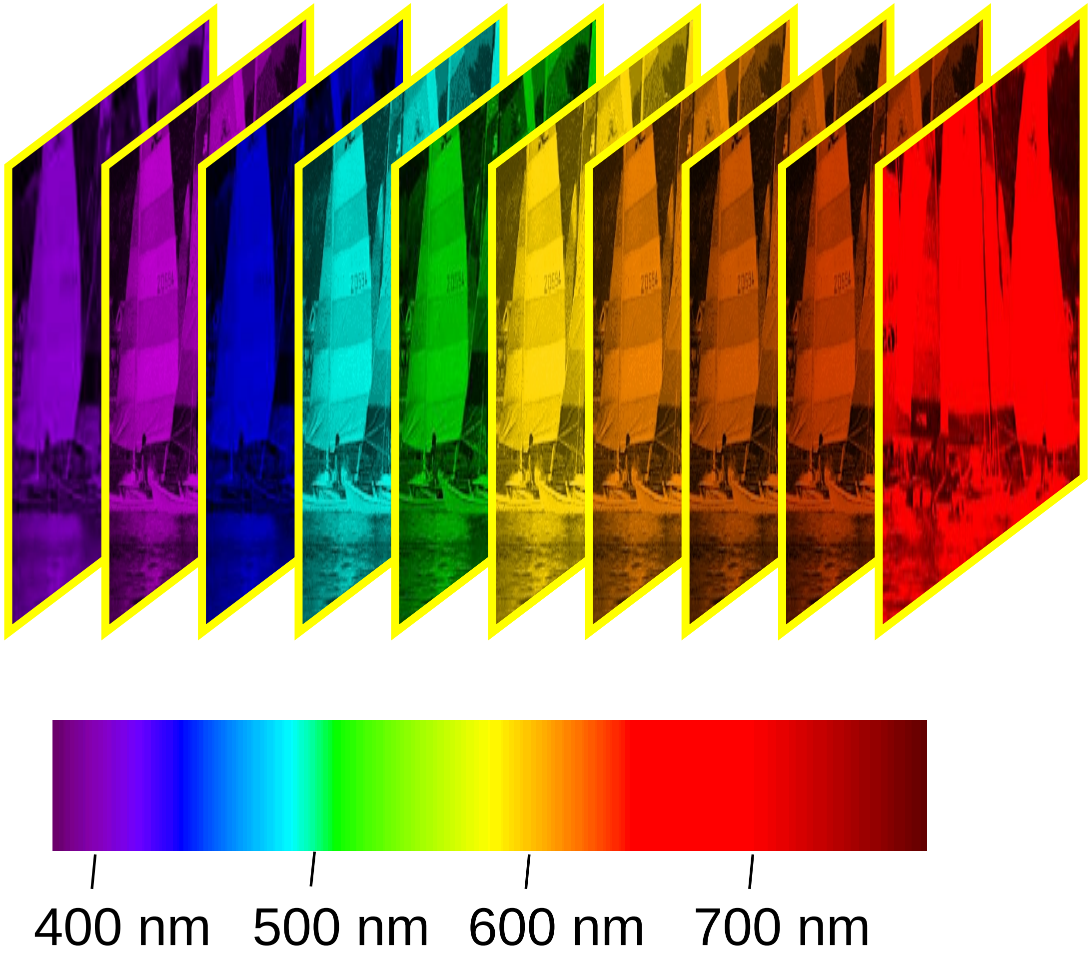


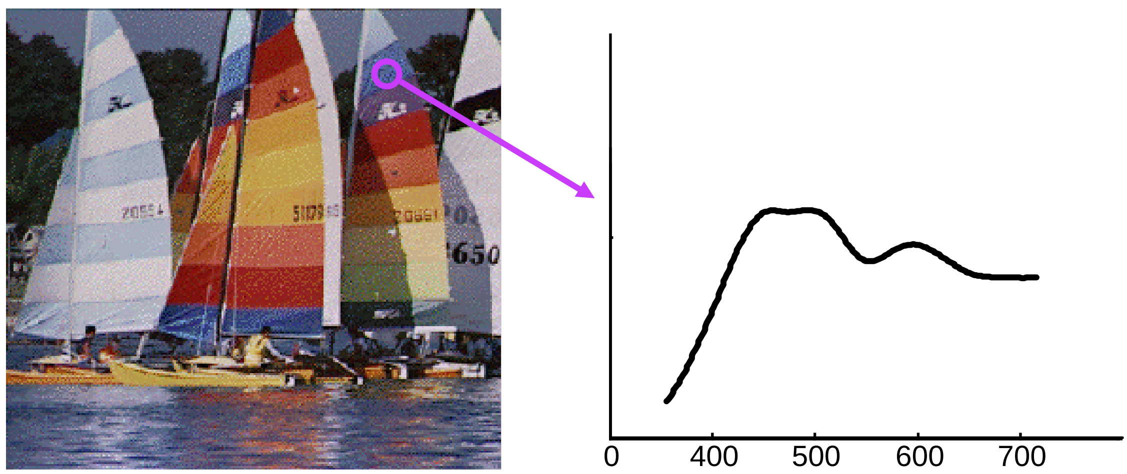
Red monitor phosphor



Monochromatic light

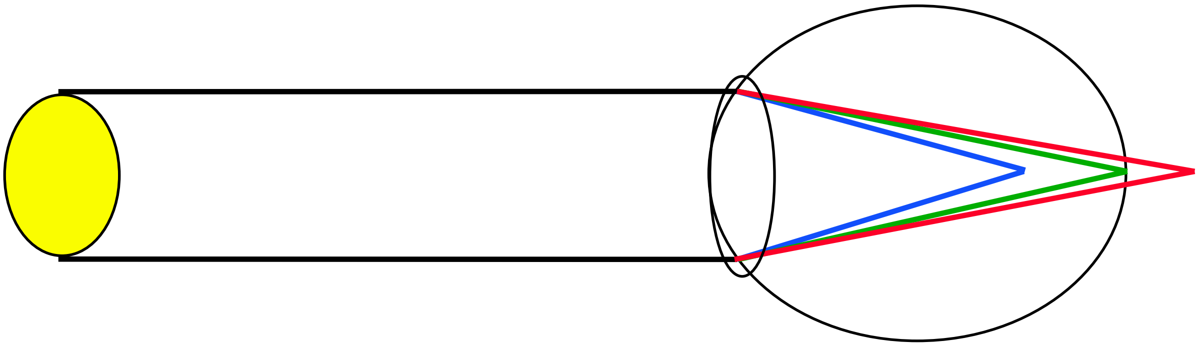
Multispectral Images

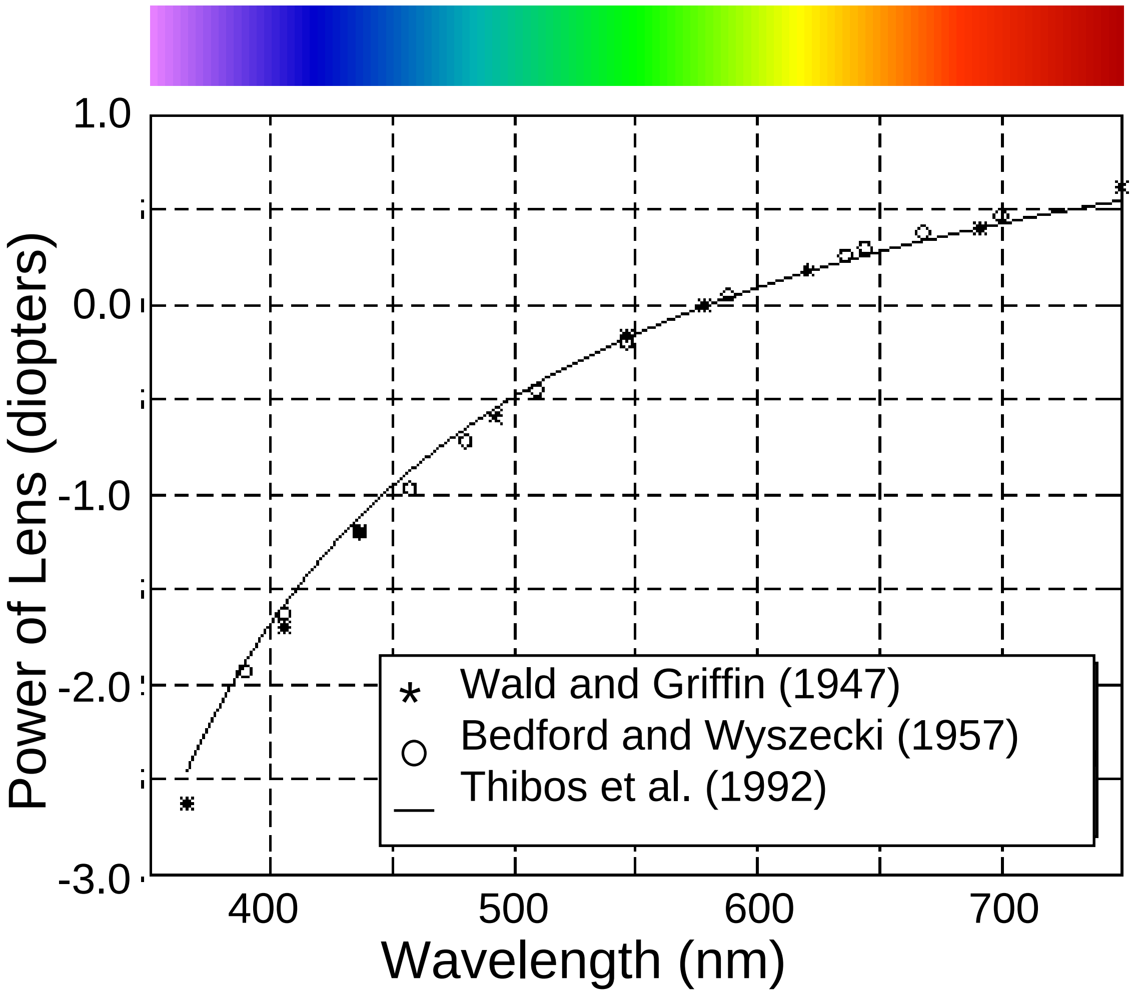




Chromatic Aberration

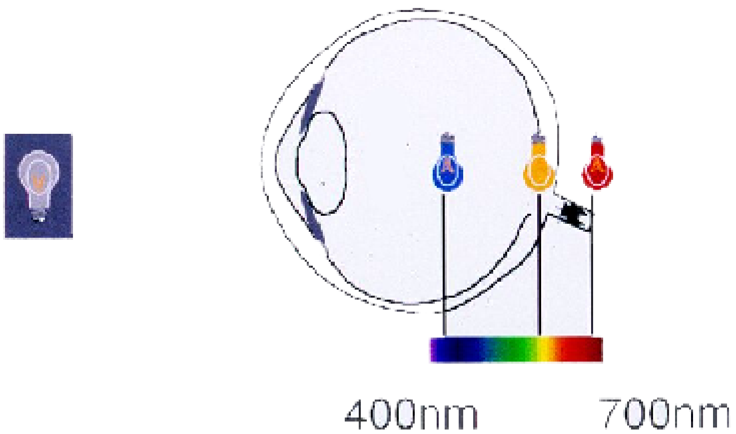
Different wavelengths bending at lens, focus at different distances.

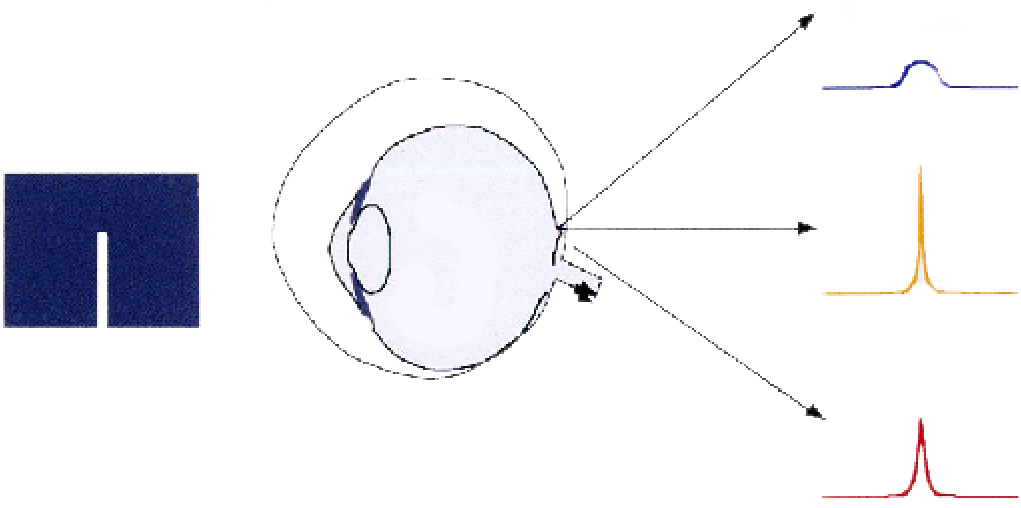




Chromatic Aberration

Chromatic Aberration Measures Differences in Optical Focus Across Wavelength





A B C D E F G

A B C D E F G

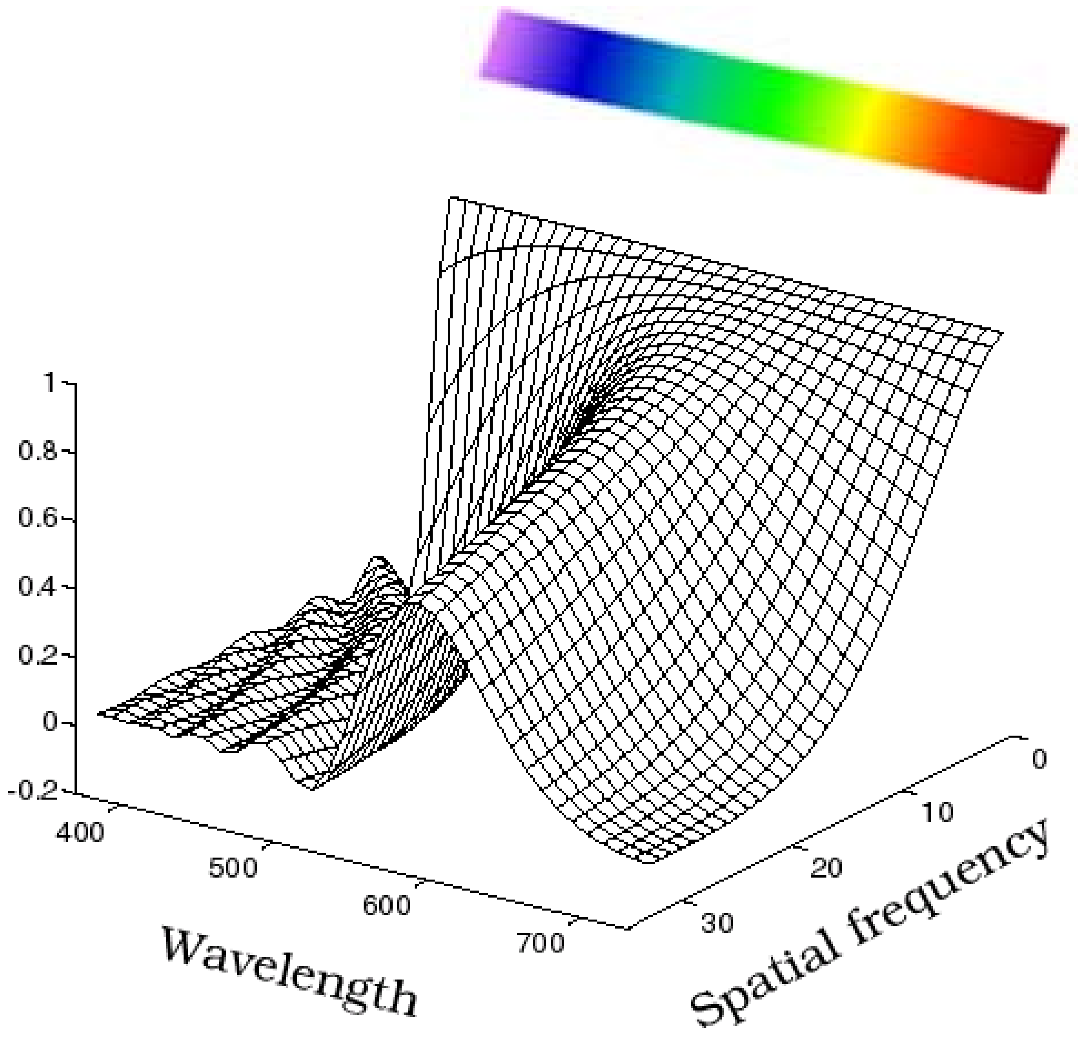
A B C D E F G

A B C D E F G

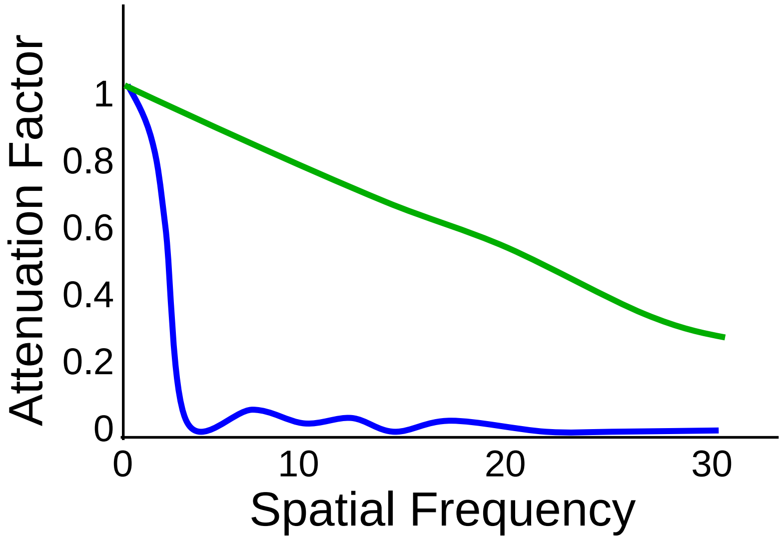
A B C D E F G

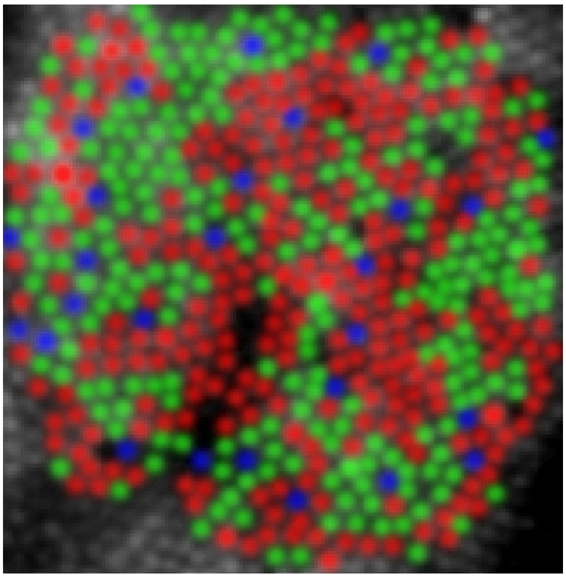
Chromatic
Modulation Transfer Function

Chromatic Aberration affects the MTF



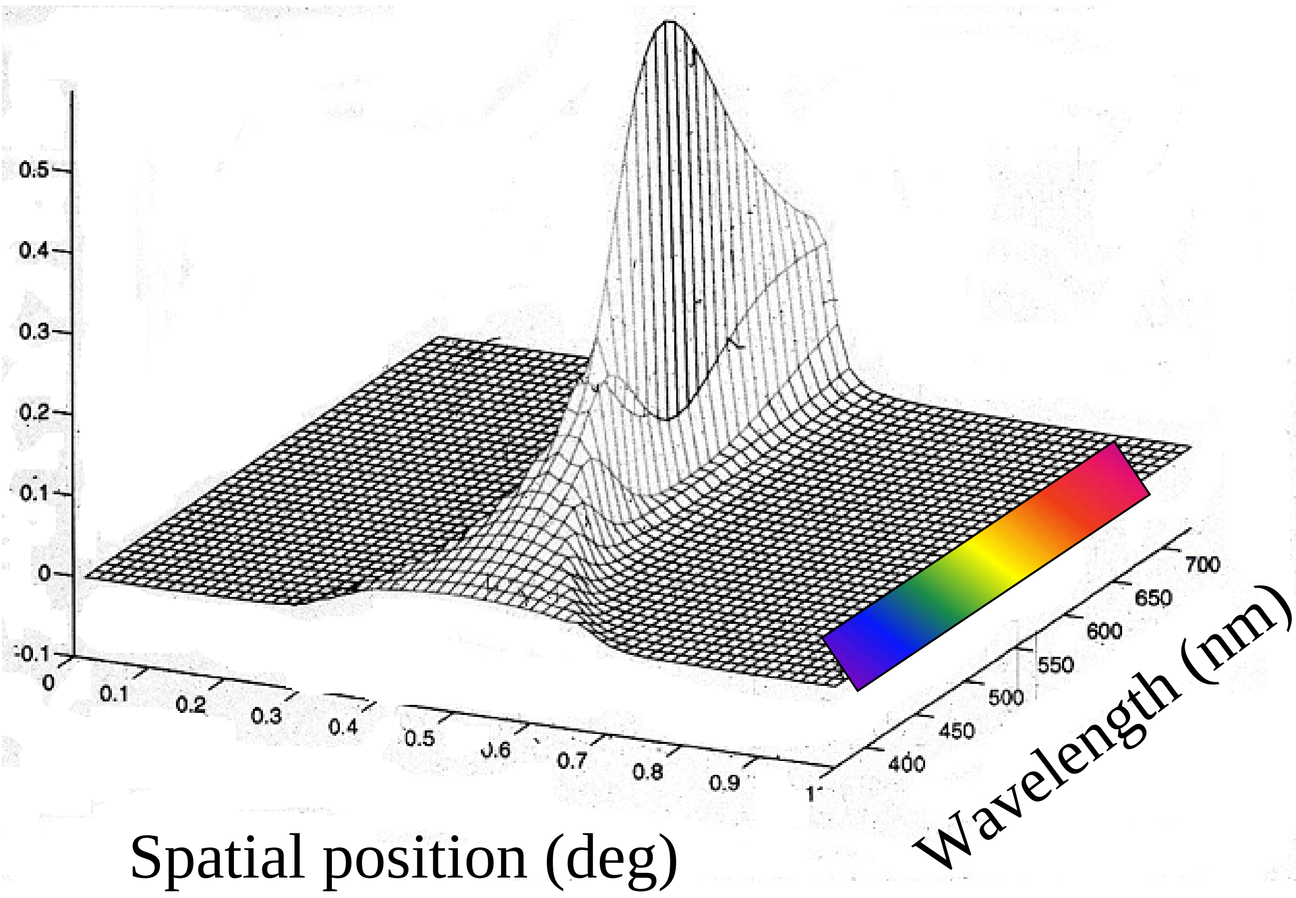
Blue vs Green
Modulation Transfer Function





Sampling rate of Blue vs Green is in accord with Nyquist Theorem

Chromatic
Linespread Function



Cat Eye

Some Animals Have Non-Circular Pupils