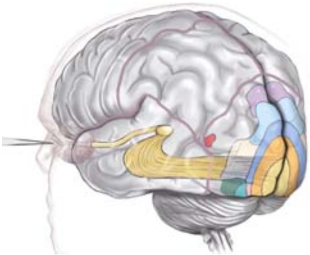
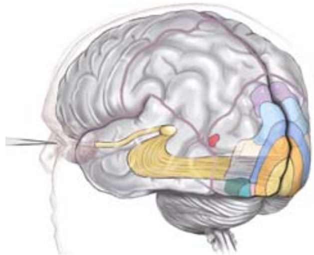
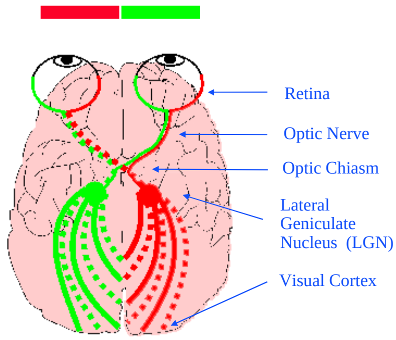
# Lecture 1

# The Human Visual System

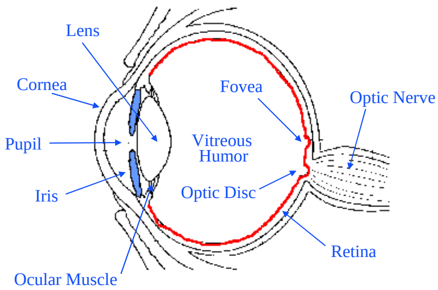


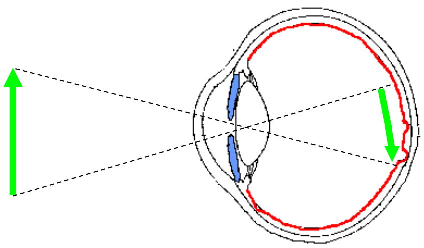
## The Human Visual System



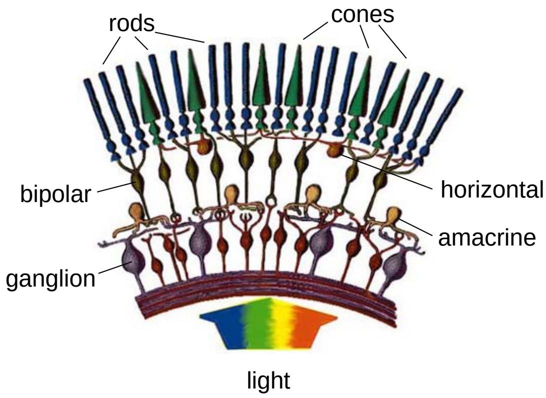



## The Human Eye

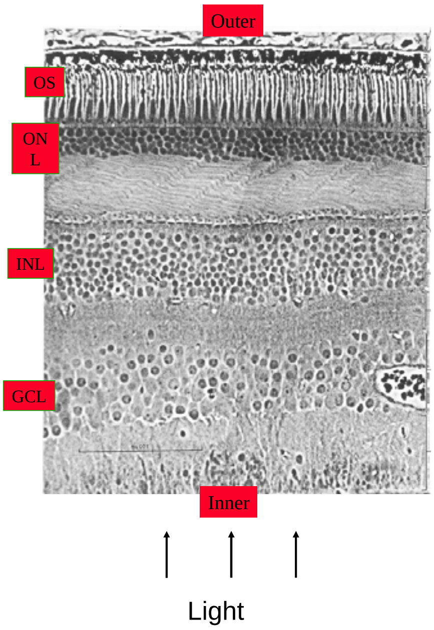


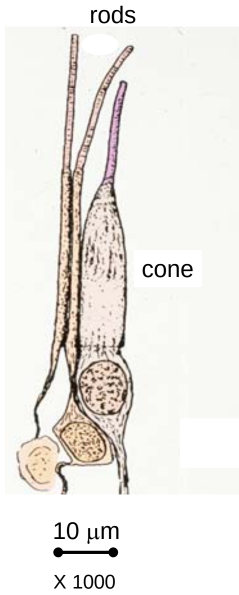
## The Human Retina



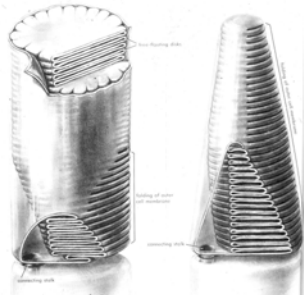
## Cross-section of Human Retina




## Retinal Photoreceptors



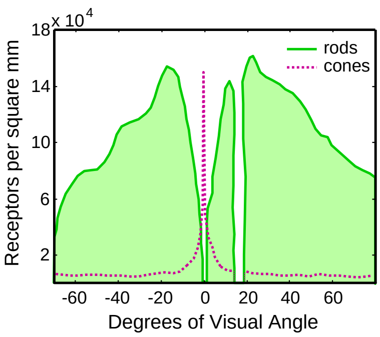

Receptor Models



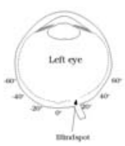
## Retinal Photoreceptors

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

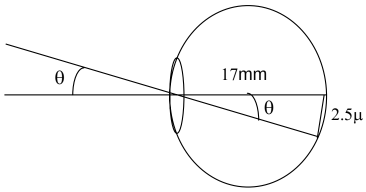
**Cones** -
- High illumination levels (Photopic vision)
- Less sensitive than rods.
- 5 million cones in each eye.
- Only cones in fovea (aprox. 50,000).
- Density decreases with distance from fovea.




Distribution of rod and cone photoreceptors




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

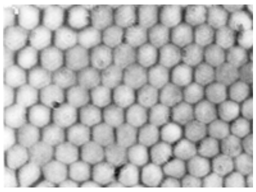



$$\tan(\theta) = \frac{2.5 \times 10^{-6}}{1.7 \times 10^{-2}} = 1.47 \times 10^{-4}$$

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

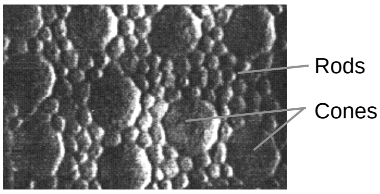
**Cones** - 2.3 μ – width
2.5 μ – inter-cone distance
0.5'– field of view

## Cone Mosaic



Cone Mosaic at Fovea

10 μm

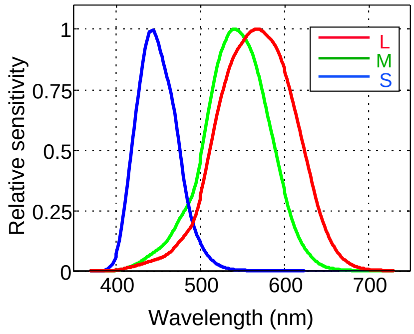



Cone Mosaic in periphery

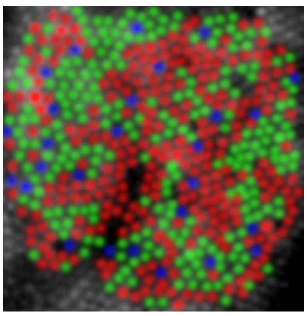
## Retinal Photoreceptors

**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



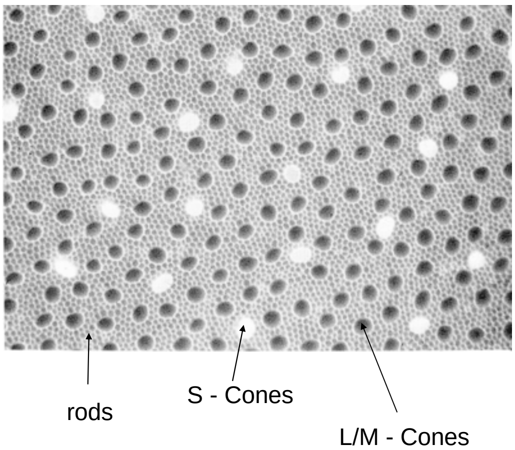

Cone Receptor Mosaic
(Roorda and Williams, 1999)



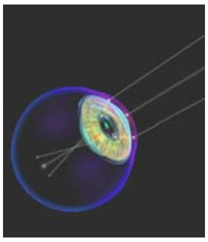
L-cones M-cones S-cones

## S cone Sampling Mosaic

Foveal Periphery

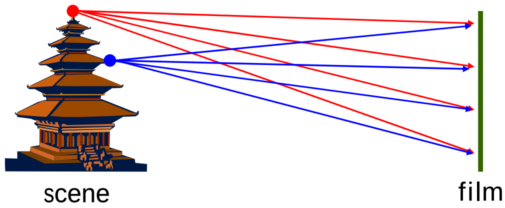


## Human Image Formation



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

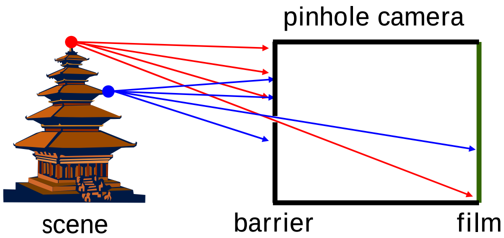
## Image Formation - Optics




Put a piece of film in front of an object.

source: Yung-Yu Chuang

## Image Formation - Optics



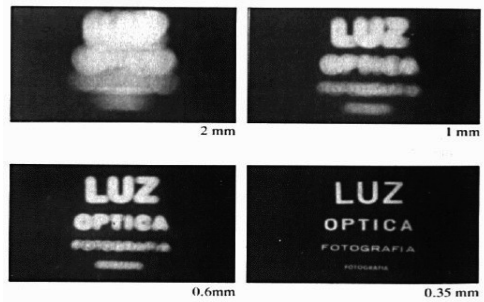

Add a barrier to block off most of the rays.

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

source: Yung-Yu Chuang

## Image Formation - Optics

### Shrinking the aperture

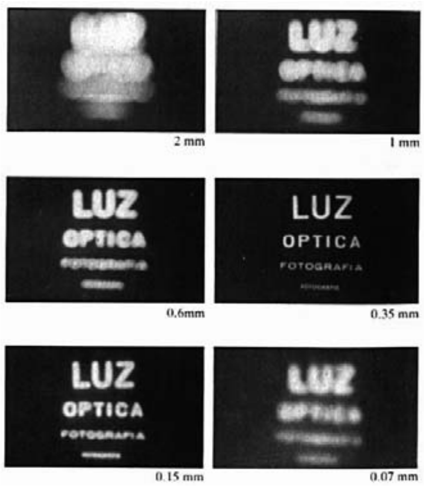



Why not create the aperture as small as
possible?

- Less light gets through
- Diffraction effect

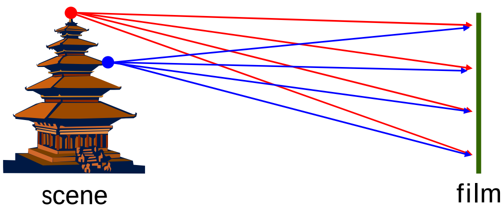
## Image Formation - Optics

### Shrinking the aperture



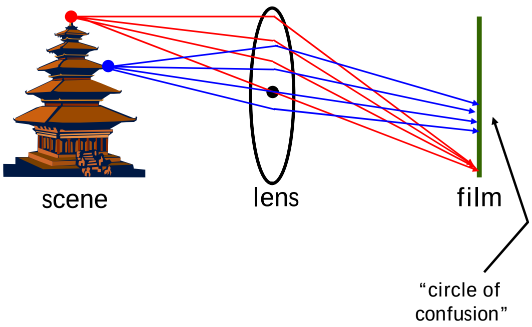

## Image Formation - Optics

### Adding a Lens

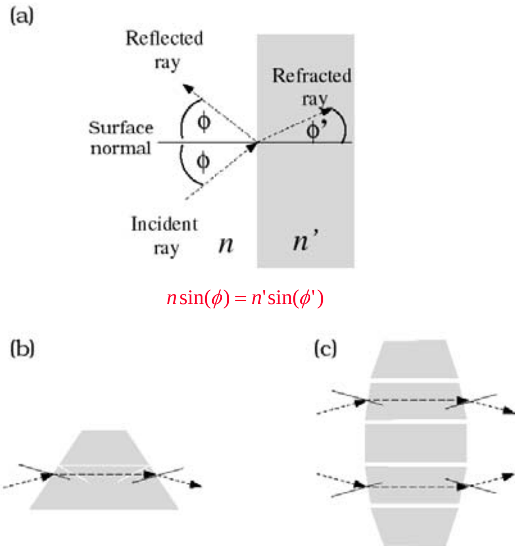



## Image Formation - Optics

### Adding a Lens

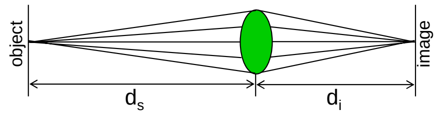



## Lens Design: Snell's Law




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

## Lensmaker's Equation

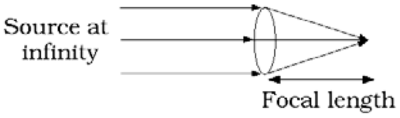



$$\frac{1}{d_s} + \frac{1}{d_i} = \frac{1}{f}$$

$d_s$ = *source dist*

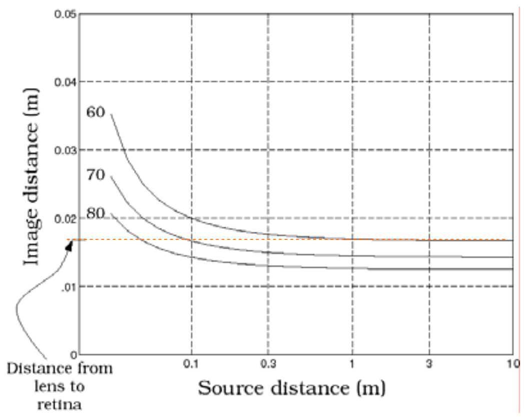
$d_i$ = *image dist*

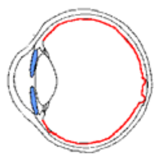
$f$ = *focal length*




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

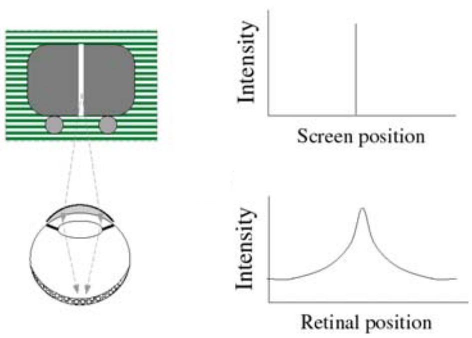
## Optical power and object distance



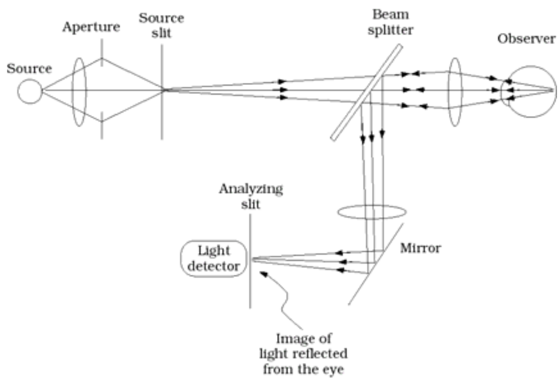
## Encoding Characteristics - Line spread

Line spread defines the optical quality of the eye




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

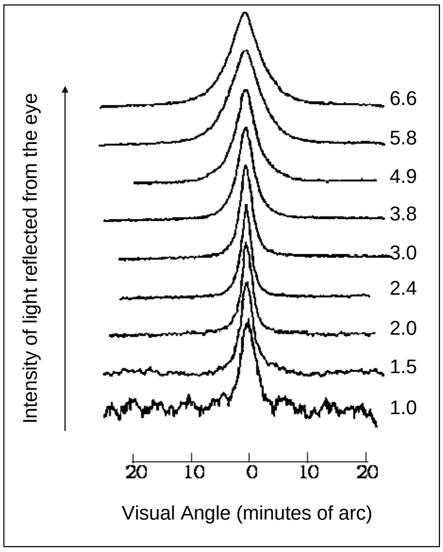
(e.g., Campbell and Gubisch)




Double Pass Method

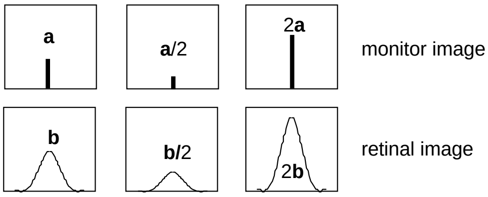
## Measurements of light reflected from the retina (Linespread) at various pupil diameters

Campell and Gubisch 1966




## Image formation satisfies :

### Homogeneity:




### Additivity:

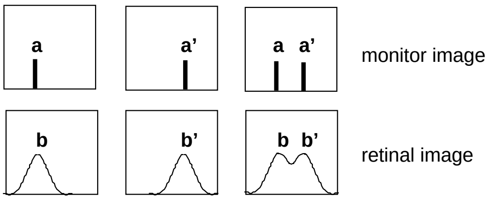



**Image formation is a linear system**

## Image Formation is a Linear System

in **a** → System f → out f(**a**) = **b**

A system is *Linear* if it satisfies superposition:

**homogeneity** f(k**a**) = kf(**a**) = k**b**

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

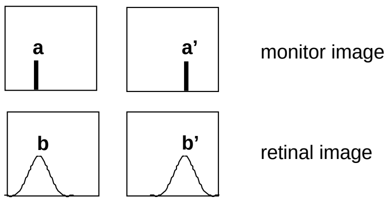
A finite dimensional linear system can be written as a matrix equation:

b = Ra

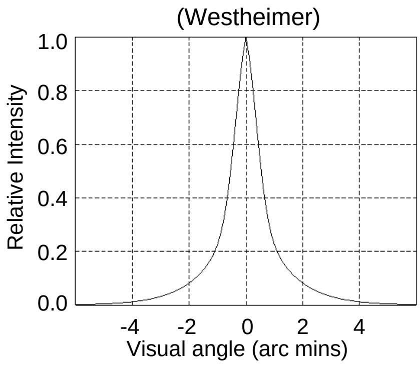
where **R** is the system matrix.

## Image formation is a *Shift Invariant* linear system

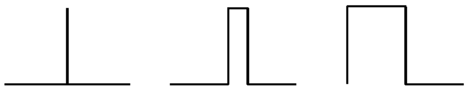
A shifted input produces a shifted output:



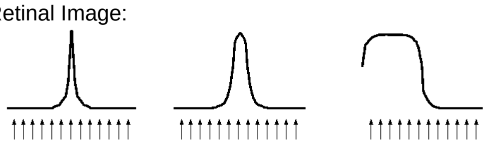
# Modeling Image Formation



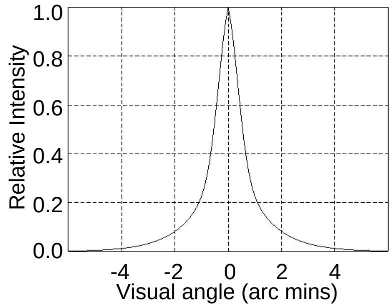

Scene:



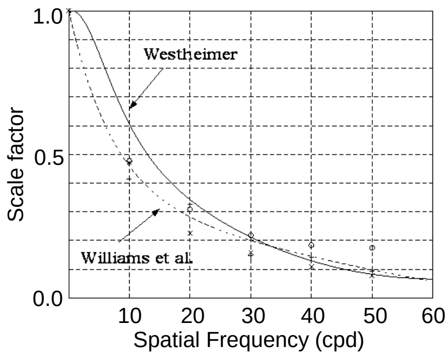
Retinal Image:



## The Human Linespread Function



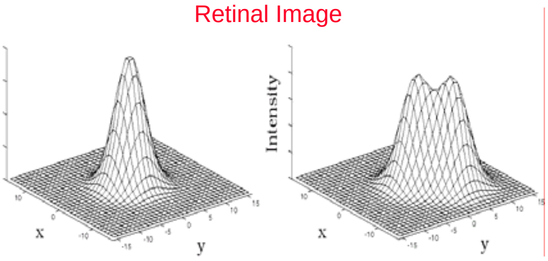

## The Human Modulation Transfer Function



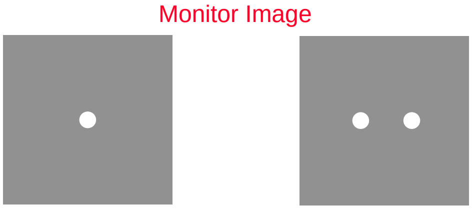

# The Pointspread Function

The pointspread function is a generalization of the linespread function.

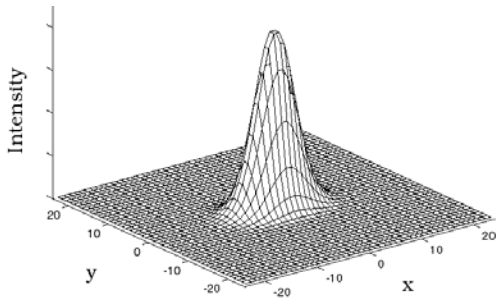
Retinal Image




Monitor Image



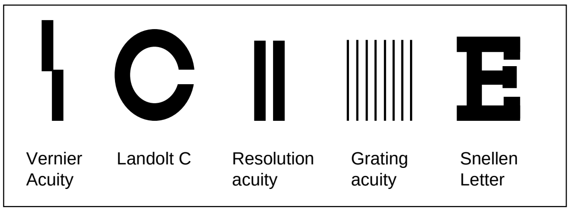
Astigmatism Measures the Assymmetry and Orientation of the Pointspread Function



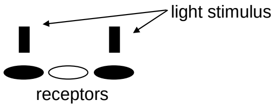
## Visual Acuity

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

Typical acuity targets:



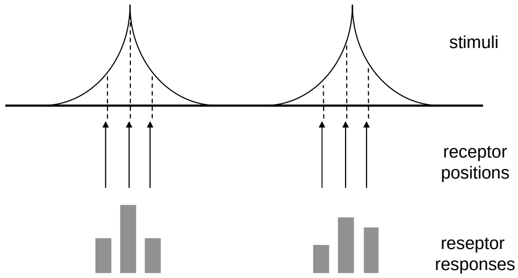

Expected acuity is size of cone or visual angle of cone.



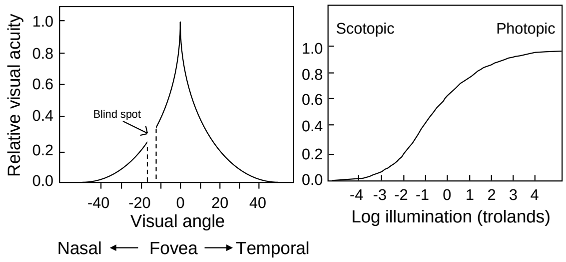

Actual acuity ≈ 5'' (arc seconds) = **Hyperacuity**

## Visual Acuity

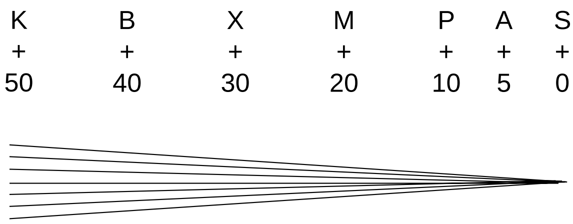
Do to linespread, movement of stimulus by less than receptor width causes change in receptor response:



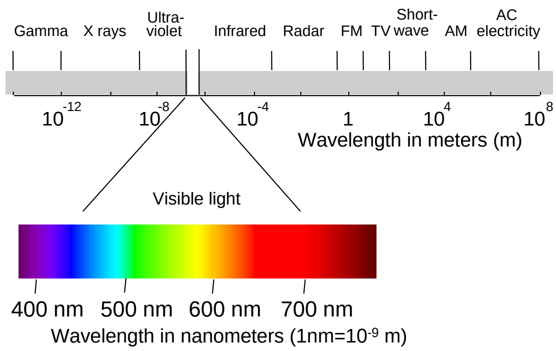

Acuity is affected by retinal position and illumination:




## Visual Acuity Test

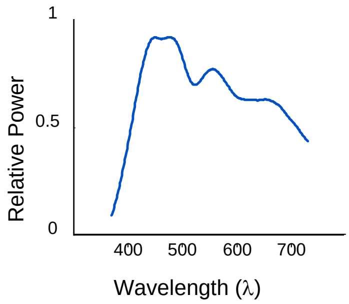



## Electromagnetic Radiation - Spectrum

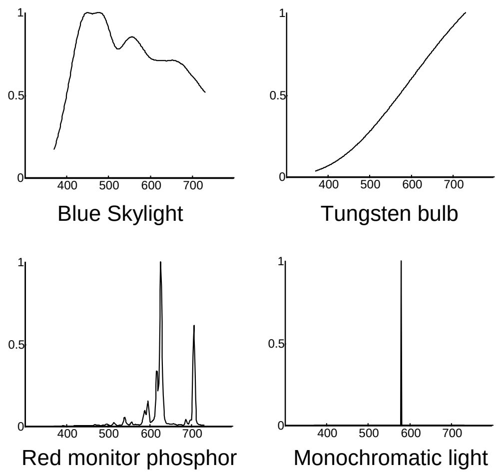


# Spectral Power Distribution

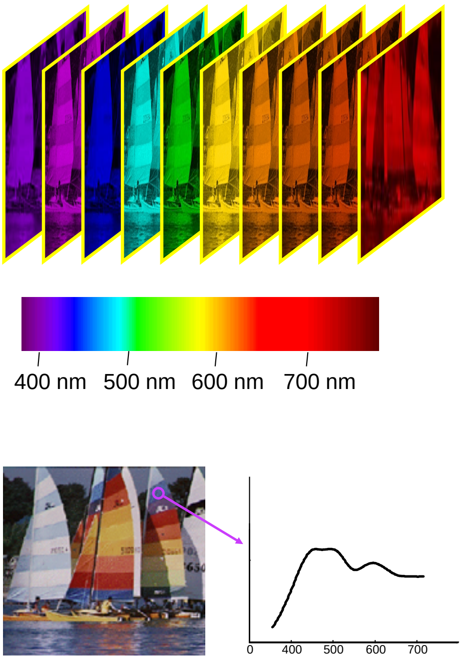
The **Spectral Power Distribution** (SPD) of a light is a function f(l) which defines the energy at each wavelength.




## Examples of Spectral power Distributions

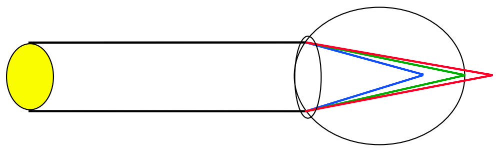


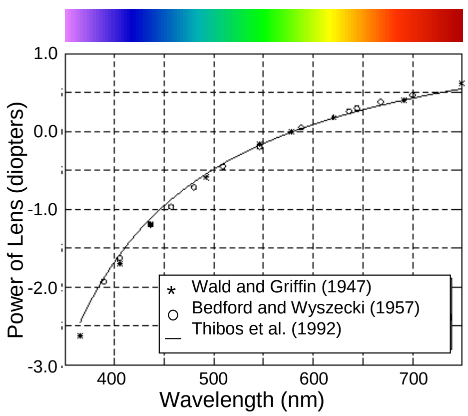

## Multispectral Images




## Chromatic Aberration

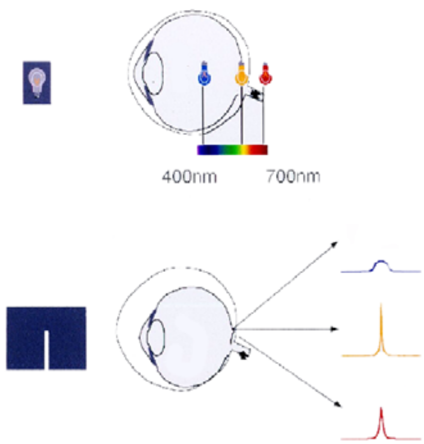
Different wavelengths bending at lens, focus at different distances.





## 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

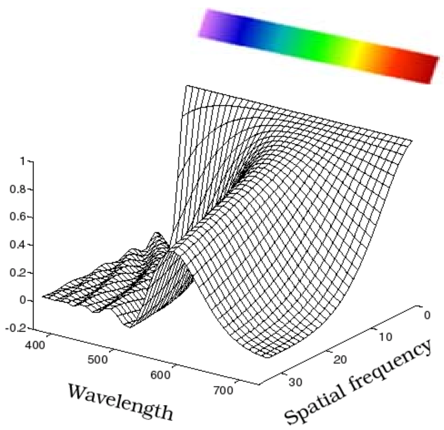
A B C D E F G

A B C D E F G

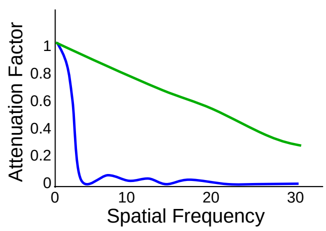
A B C D E F G

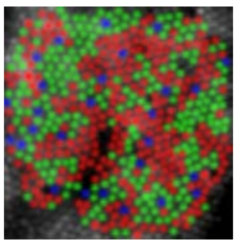
## Chromatic Modulation Transfer Function

Chromatic Aberration affects the MTF



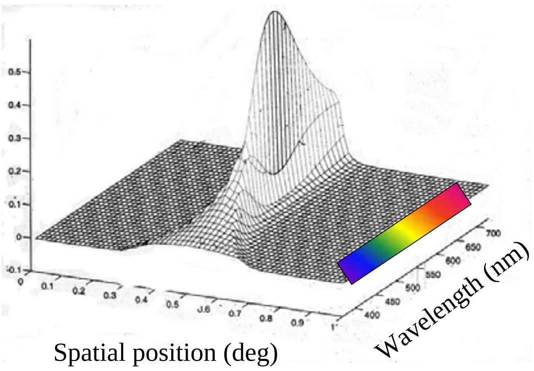

## Blue vs Green Modulation Transfer Function



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

## Chromatic Linespread Function




## Cat Eye

Some Animals Have Non-Circular Pupils