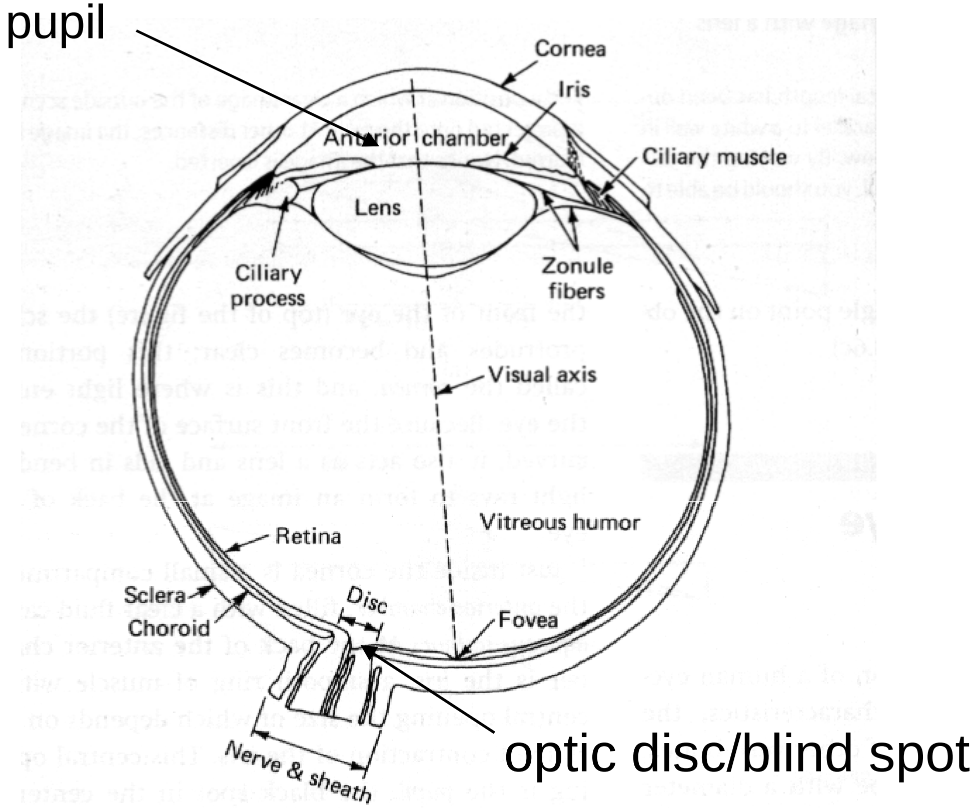
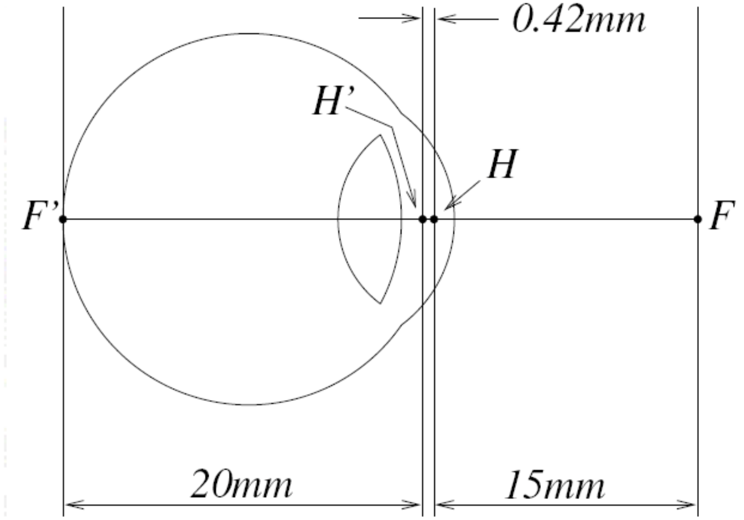
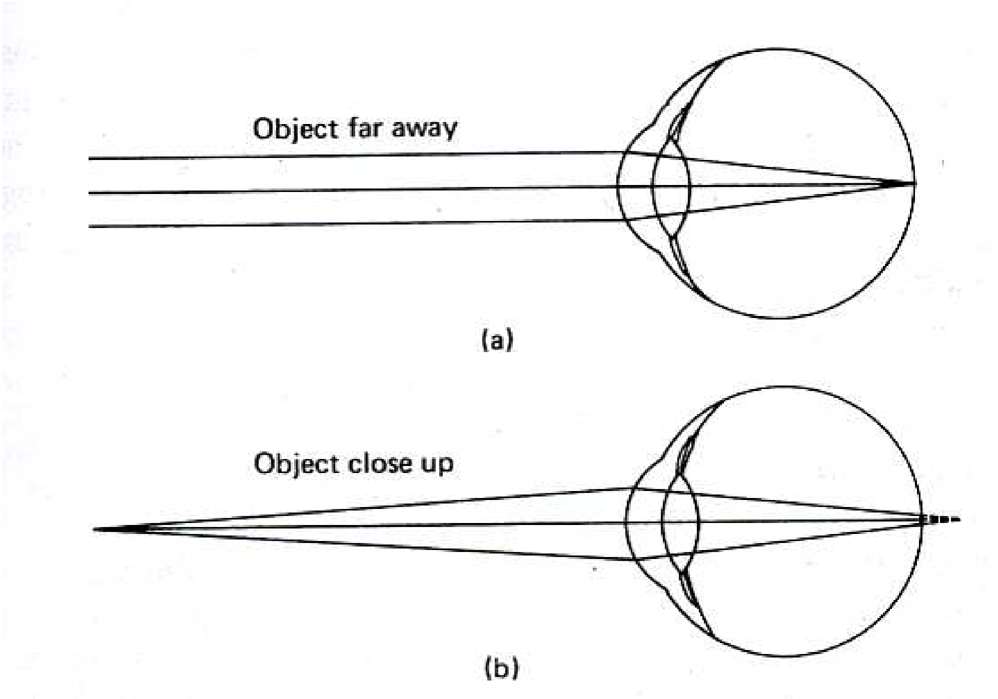
The Eye



- Functionally similar to a camera of 160^{o}(width)x135^{o}(height)



- Cornea and crystalline lens focus the image of the visual world onto the retina



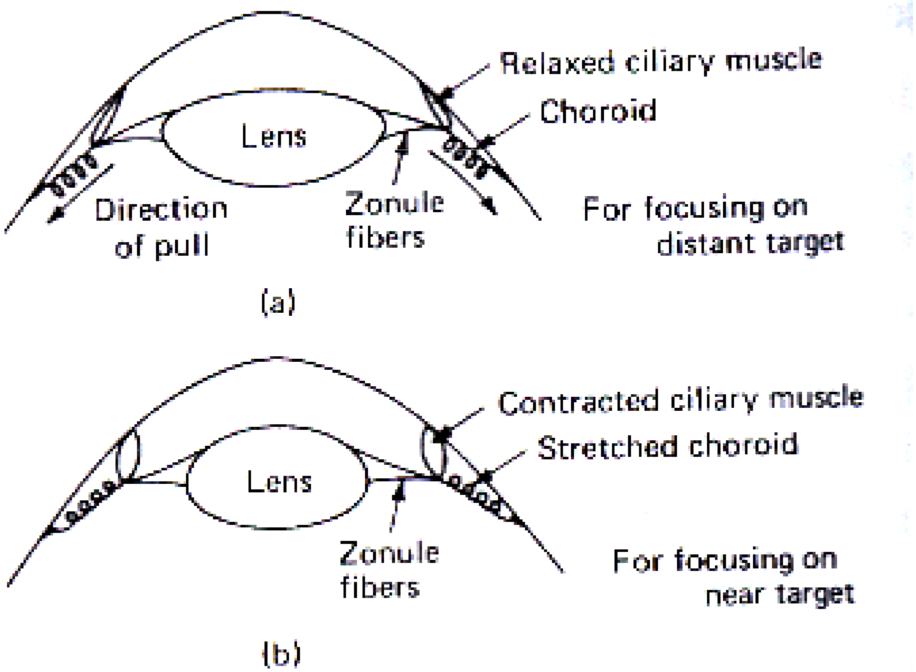
$$\frac{1}{d'} \simeq \frac{1}{f}$$

$$\frac{1}{d}\nearrow + \frac{1}{d'}\swarrow = \frac{1}{f}$$

if *f* is constant

Accommodation

- The lens however is capable of changing its refractive power to focus on objects at different distances from the eye (*accommodation*)
- The ciliary muscles flatten/curve the lens to increase/reduce its focal length
- Focal length varies between 15-17 mm



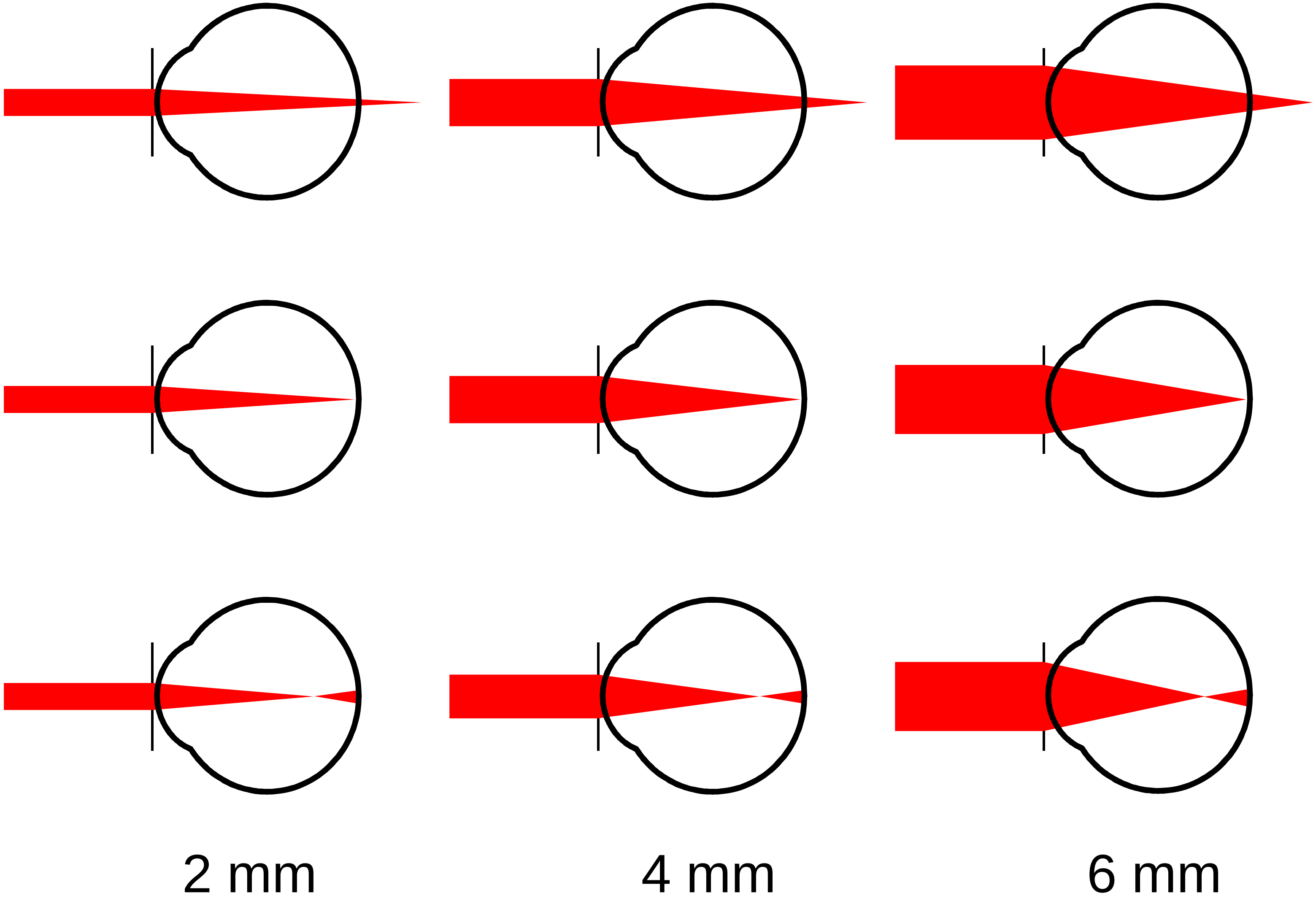
$$\frac{1}{d}+\frac{1}{d'}=\frac{1}{f}$$ max focal length

$$\cancelto{}{\frac{1}{d}}+\frac{1}{d'}=\cancelto{}{\frac{1}{f}}$$ …to min focal length

Control of pupil size

- The pupil is the aperture of the iris
- It is controlled by the status of two antagonist muscles (sphincter and dilator)
- Pupil size varies from 1 to 8 mm in response to illumination changes
- It restricts or increase the amount of light entering the eye; however this effect is minimal if compared to the dynamic range of the eye
- Other effects:
  - allows only the most accurate part of the lens to be employed (the central area)
  - increase the *depth of field* (at small apertures the eye becomes more similar to a pin-hole camera)

Optics of the eye: Depth of Focus



(slide from A. Roorda University of Houston)

Optics of the eye: Depth of Focus

Focused
behind
retina

In focus

Focused
in front
of retina

2 mm

4 mm

6 mm

(slide from A. Roorda University of Houston)

- The optics of the eye reduce the intensity of the light that reaches the retina and blur the image
- The quality of this image depends on diffraction at the pupil, aberrations in the cornea and lens, light scatter in the optical media, and the optical properties of the retina itself
- The retinal image of a single point of light (for example a distant star), corresponds to the impulse response or point spread function (PSF) of the eye's optics
- The PSF provides a complete description of image quality at that retinal location for a given wavelength of light. Indeed, if the PSF is known at a retinal location, one can calculate the retinal image for any object imaged in monochromatic light at that location

Packer, O., Williams, D.R Light, the retinal image, and photoreceptors. (The Science of Color, 2003 Elsevier Ltd*), 2nd Edition, Chapter 2.*

The real eye

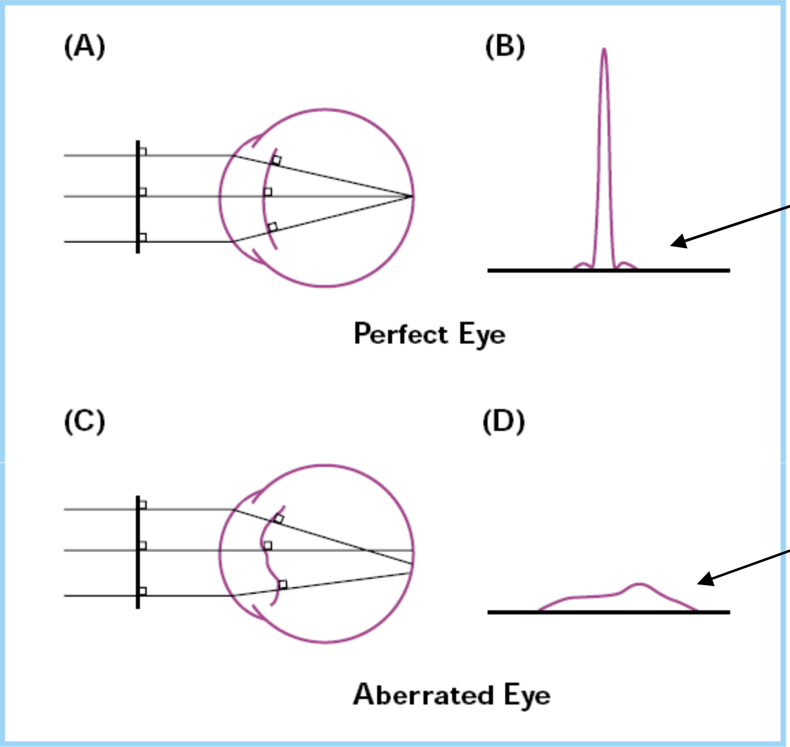
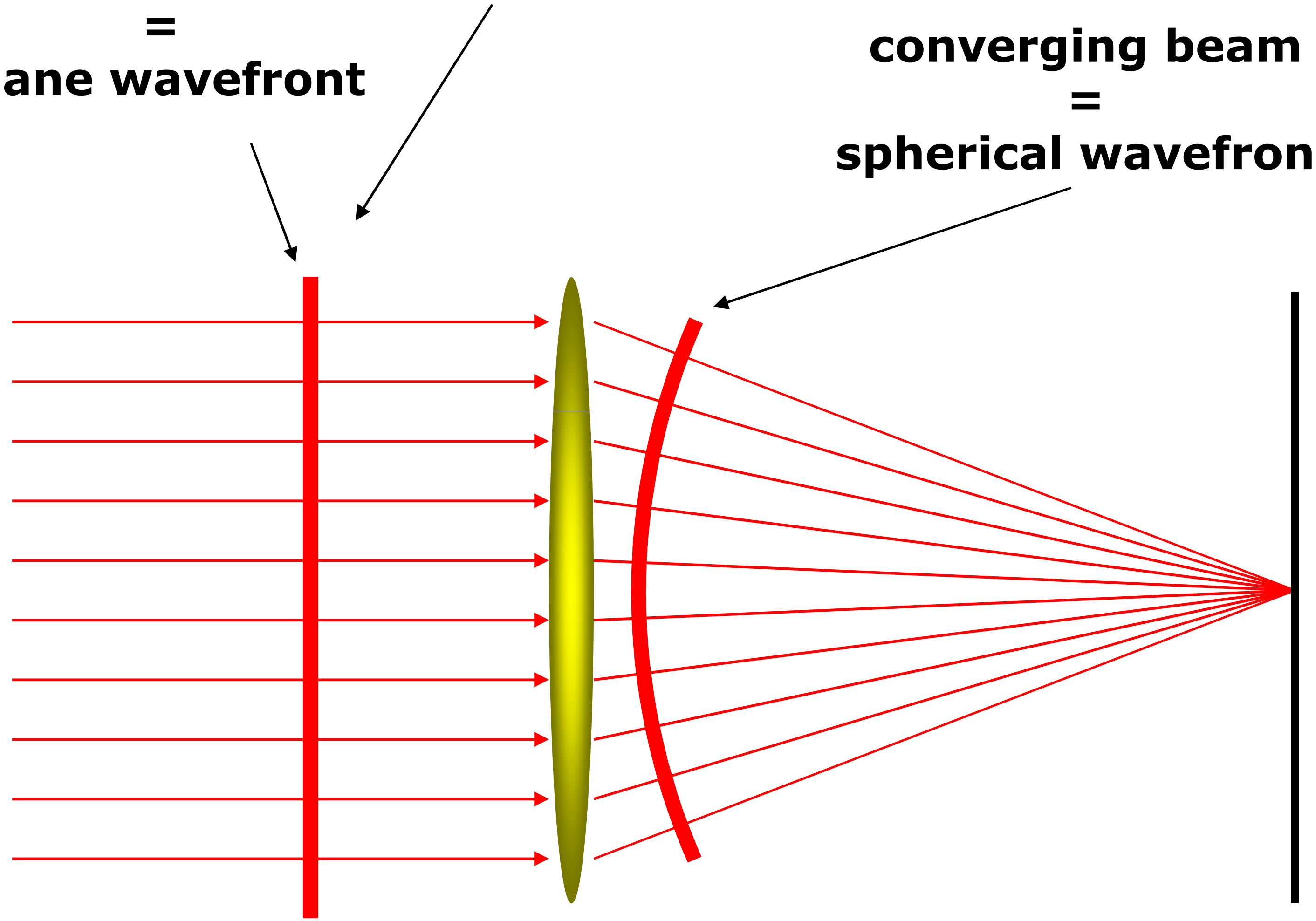


Image of a distant “star”, optical performance in the “perfect eye” is limited only by diffraction, the spreading of the light occurring at the pupil (greater for small pupil size and longer wavelengths)

Image of a distant “star”, optical performance is affected by imperfection in the optics (worse with larger pupil diameter)

other imperfections arise from:

- chromatic aberrations
- scatter by the cornea, lens and retina

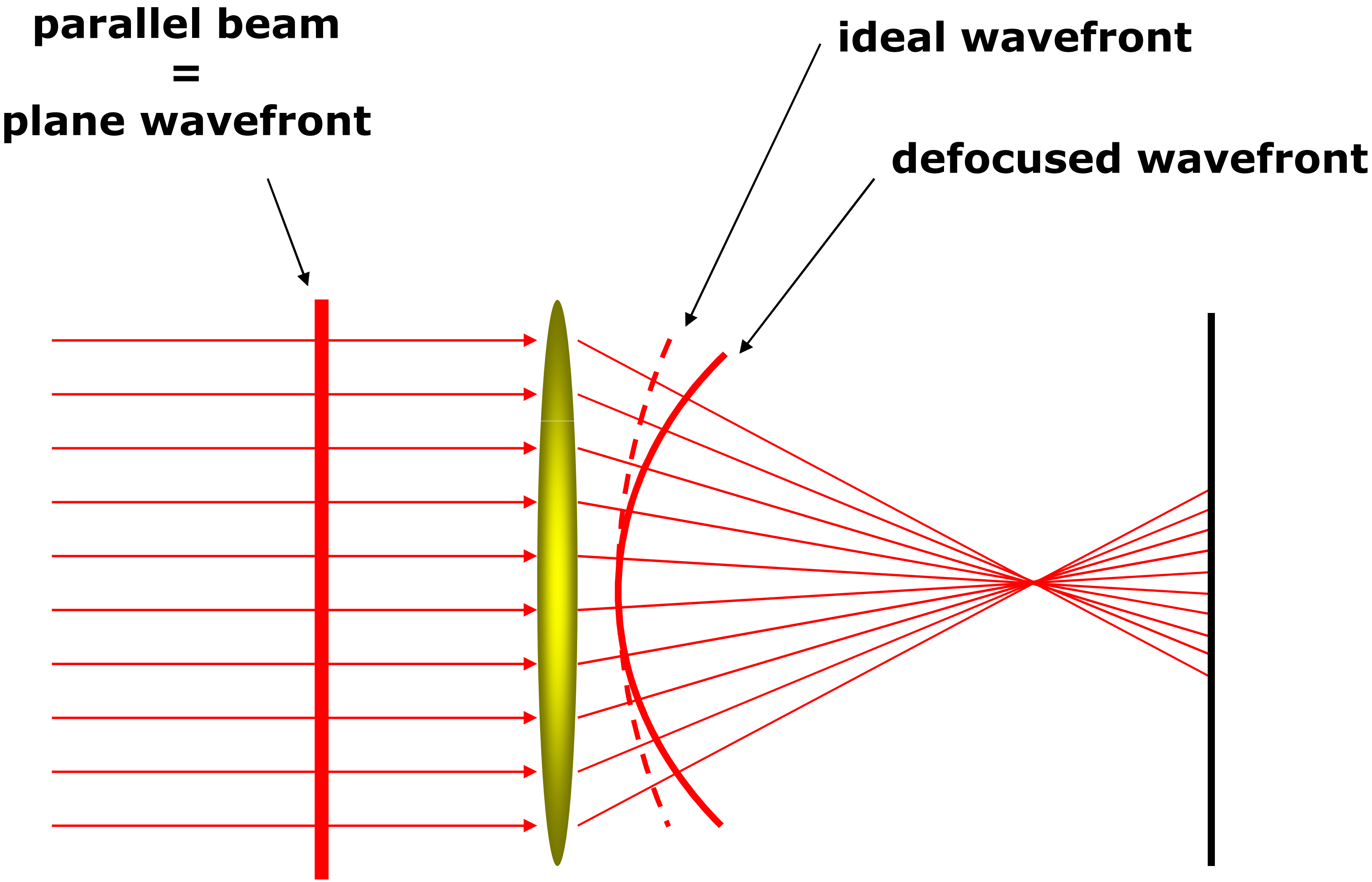


nearest points that have the same phase

parallel beam
=
plane wavefront

converging beam
=
spherical wavefront

(slide from A. Roorda University of Houston)



parallel beam
=
plane wavefront

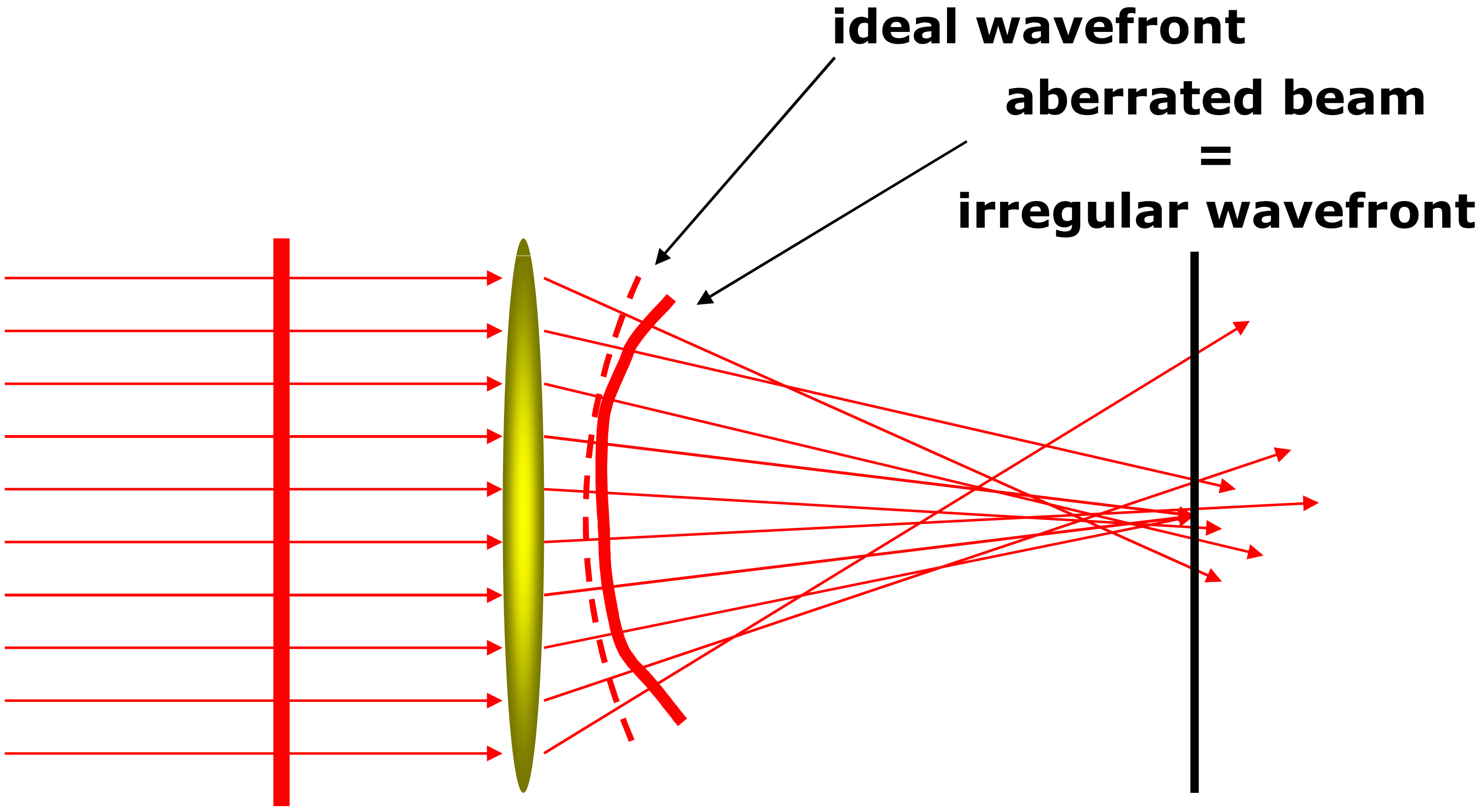
ideal wavefront

defocused wavefront

(slide from A. Roorda University of Houston)

- Each of the parallel light rays arriving from the star can be thought of as indicating the direction in which the wave front is travelling. If, starting at some position on the optical axis, we connected the nearest points on each wave that had the same phase, the resulting surface, called a wave front, would be a plane
- The optics of a perfect eye transform this planar wave front from the star into a spherical wave front. The spherical wave front, in turn, collapses upon itself to form a crisp point of light on the retina. To form the spherical wave front, the perfect eye delays light travelling through the center of the pupil relative to that travelling through the edge so that each takes exactly the same time to reach the retinal location where the image is formed

- In the aberrated eye the wave front is not delayed by the proper amounts as it passes through the optics and the actual wave front inside the eye departs from the ideal spherical wave front
- The malformed wave front fails to collapse to a crisp point at the retina
- The errors in the delays could arise from several sources, such as a misshapen cornea or lens



ideal wavefront

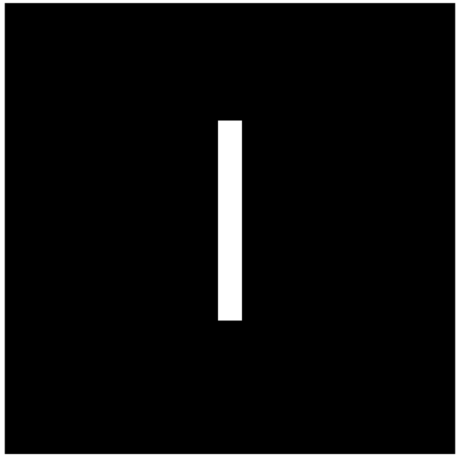
aberrated beam
=
irregular wavefront

(adapted from A. Roorda University of Houston)

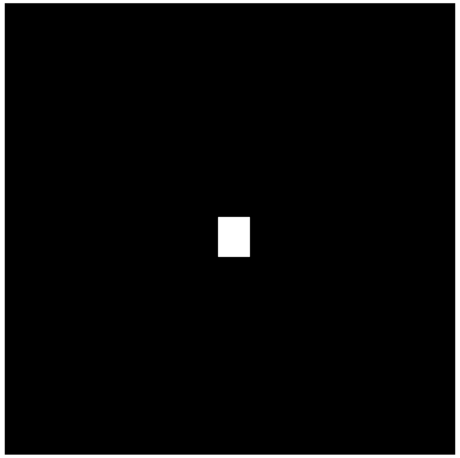
Diffraction

- Even in an eye with perfect optics, the light from the star is not imaged as a single point. Rather the image is a bright central point surrounded by dimmer rings.
- This occurs because light spreads or **diffracts** whenever it passes through a circular aperture such as the pupil.
- Diffraction occurs when a wave encounters an obstacle (e.g. an opening).The light spreads and produces interferences patterns consisting in alternating patterns of light and dark regions.
- Its effects are most pronounced for waves where the wavelength is on the order of the size of the diffracting objects

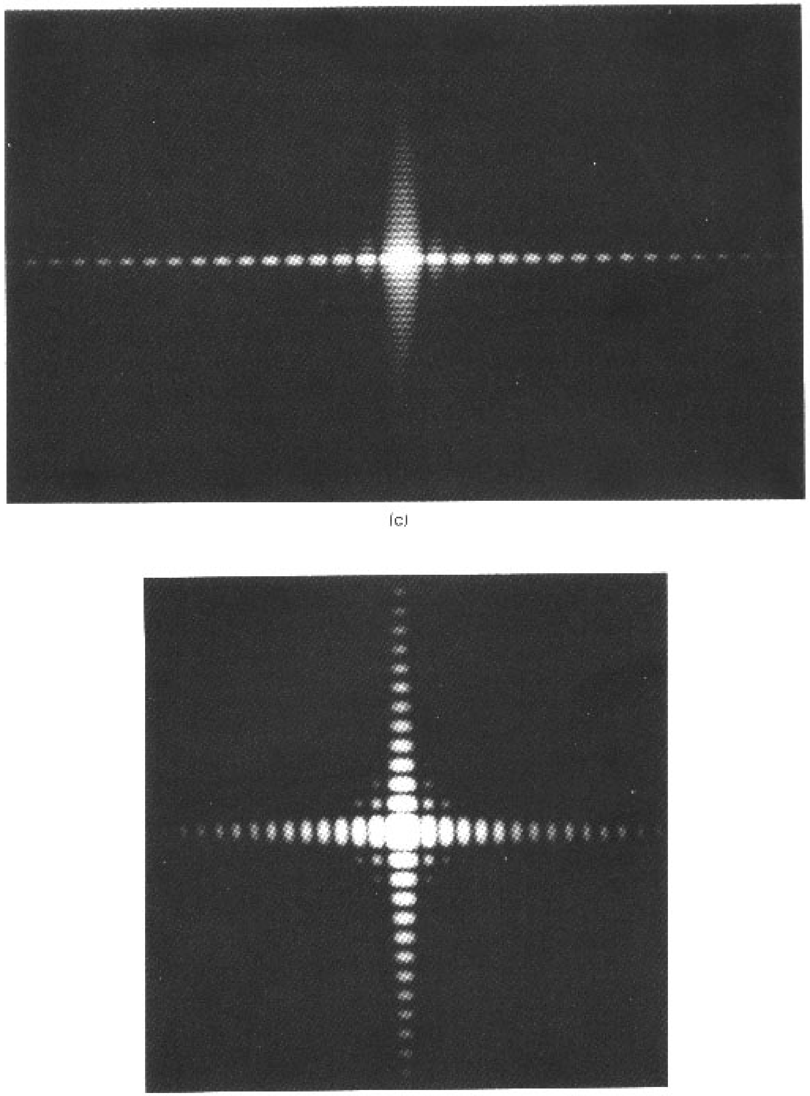
rectangular aperture



square aperture



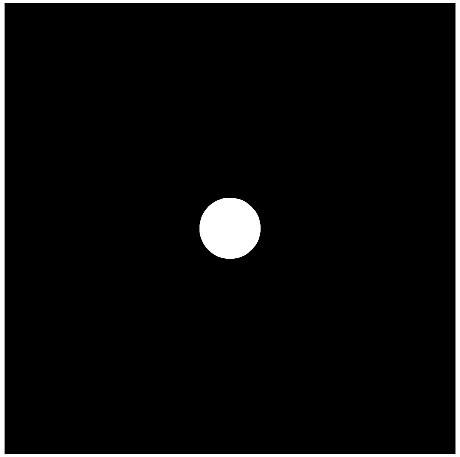
Sec. 19-3 Rectangular and Circular Apertures 393

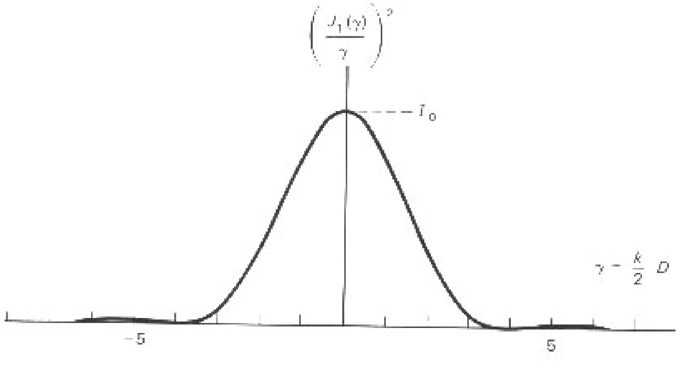

(c)

(d)

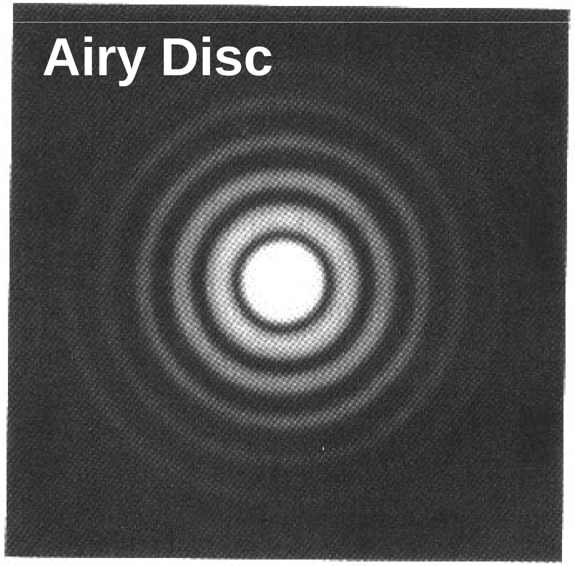
Figure 19-5 (Continued)

circular aperture

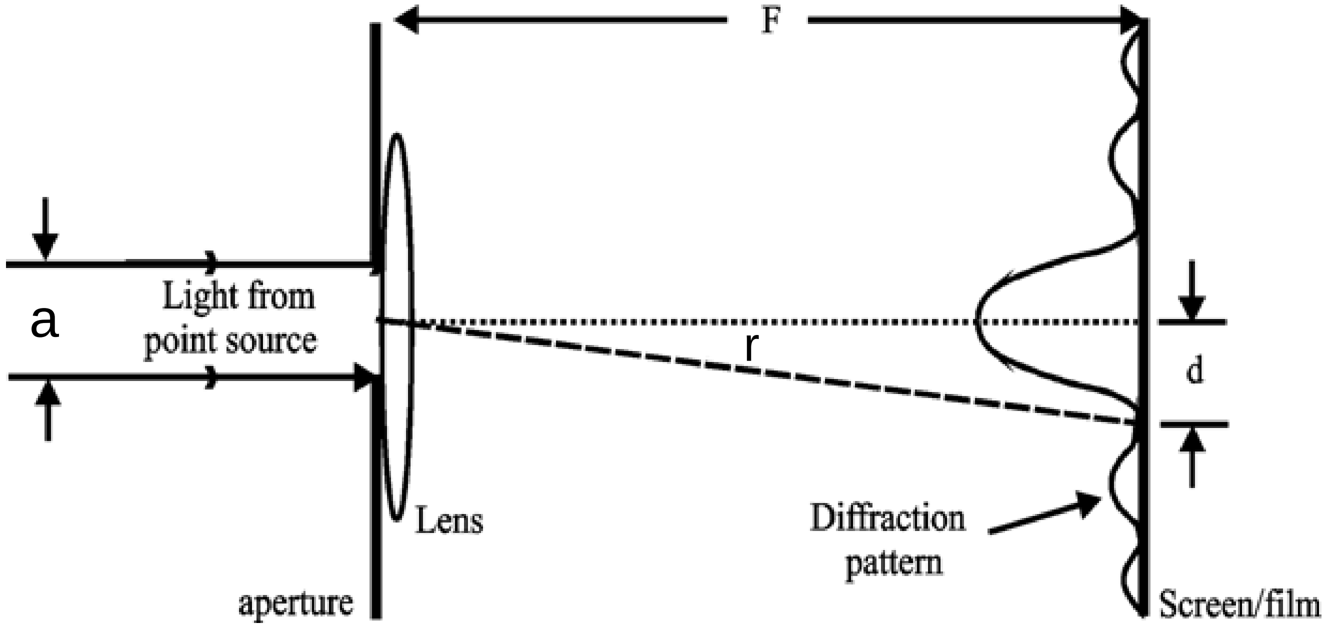




(a)



(b)



$$I(r) = \left[\frac{2J_1(\pi r)}{\pi r} \right]^2$$

where: *J* is the first order Bessel function

$$r_0 = 1.22 \frac{\lambda}{a}$$

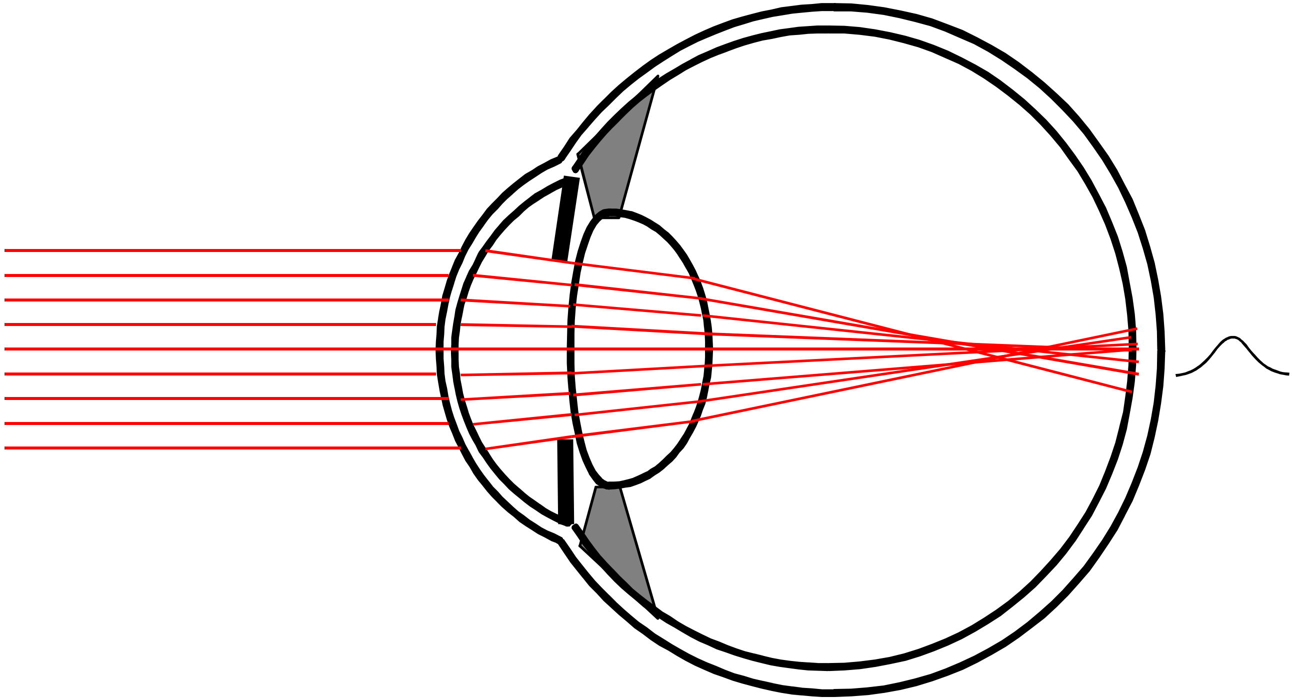
wavelength

diameter of the
aperture

radius of the PSF, in radians, from the peak to the
first point at which the intensity is zero

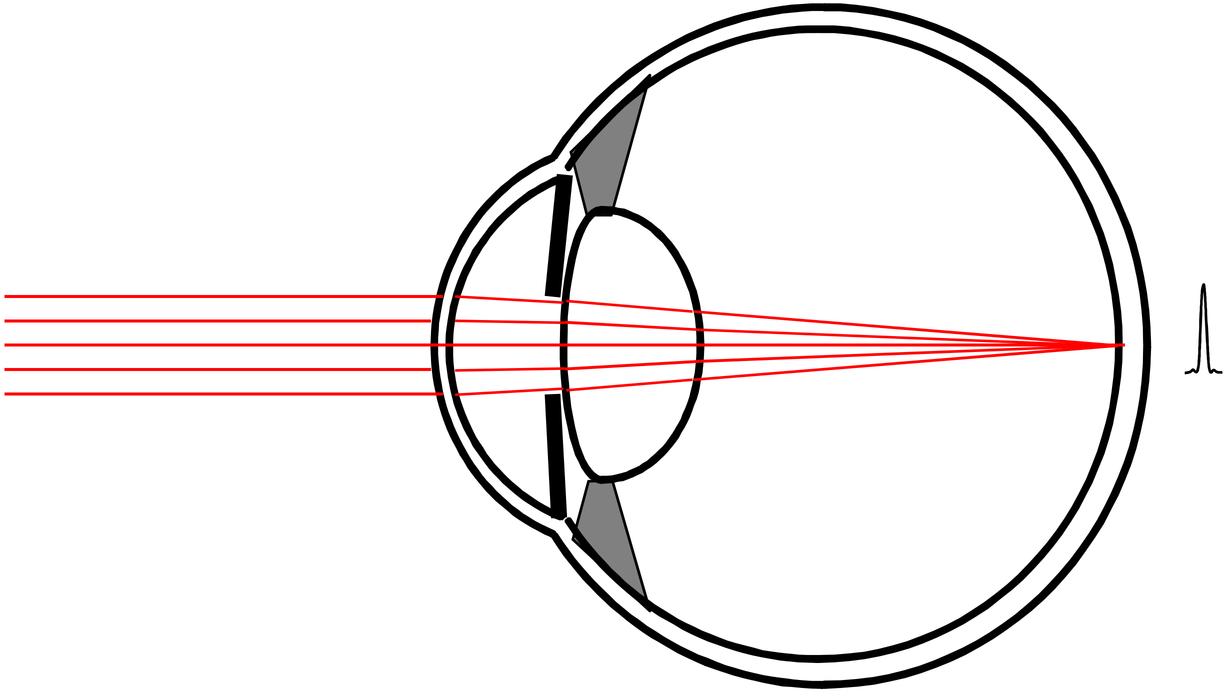
Larger pupil

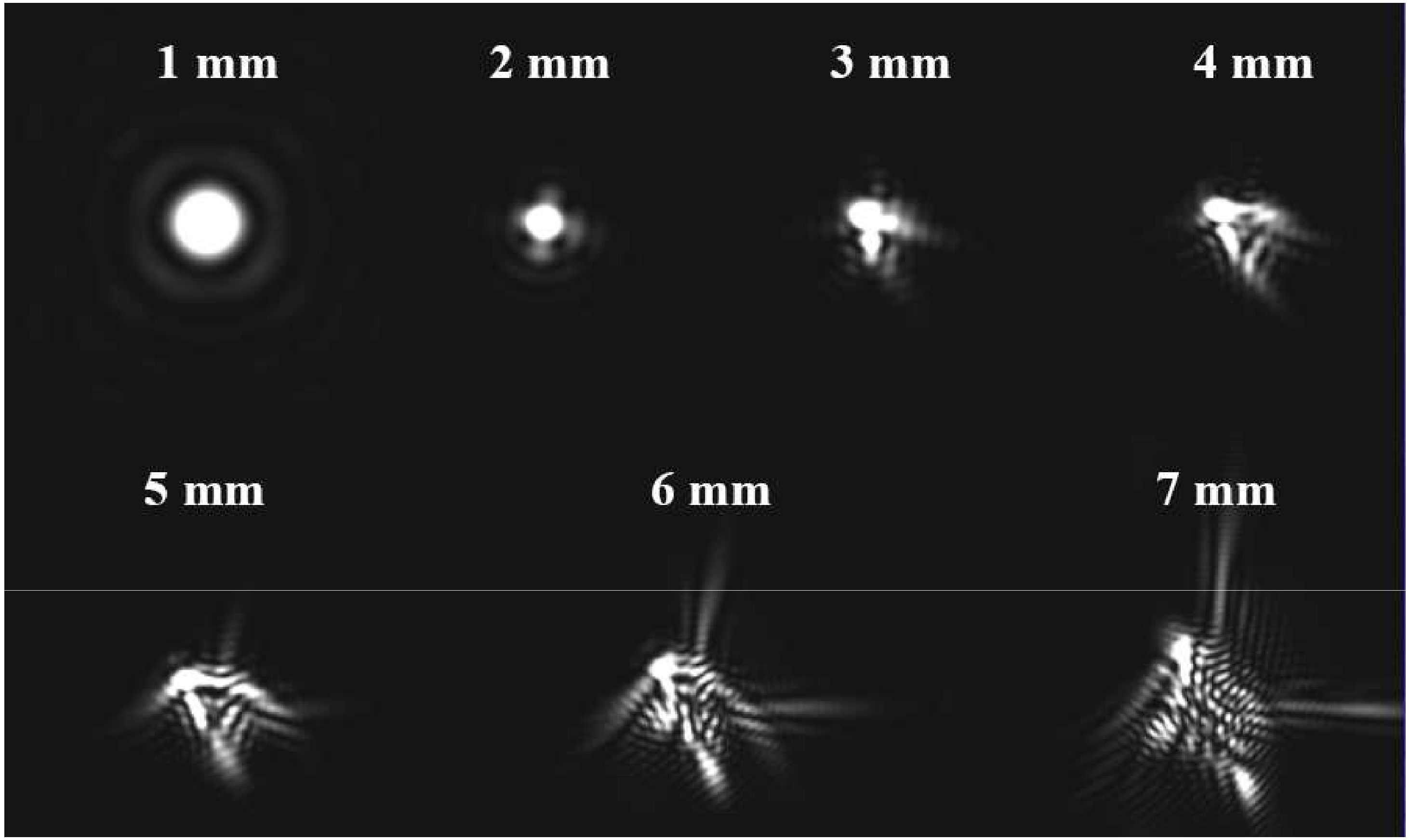
- Aberrations generally affect the light rays that enter the edge of the pupil more strongly than they affect rays entering the center of the pupil



Small Pupil

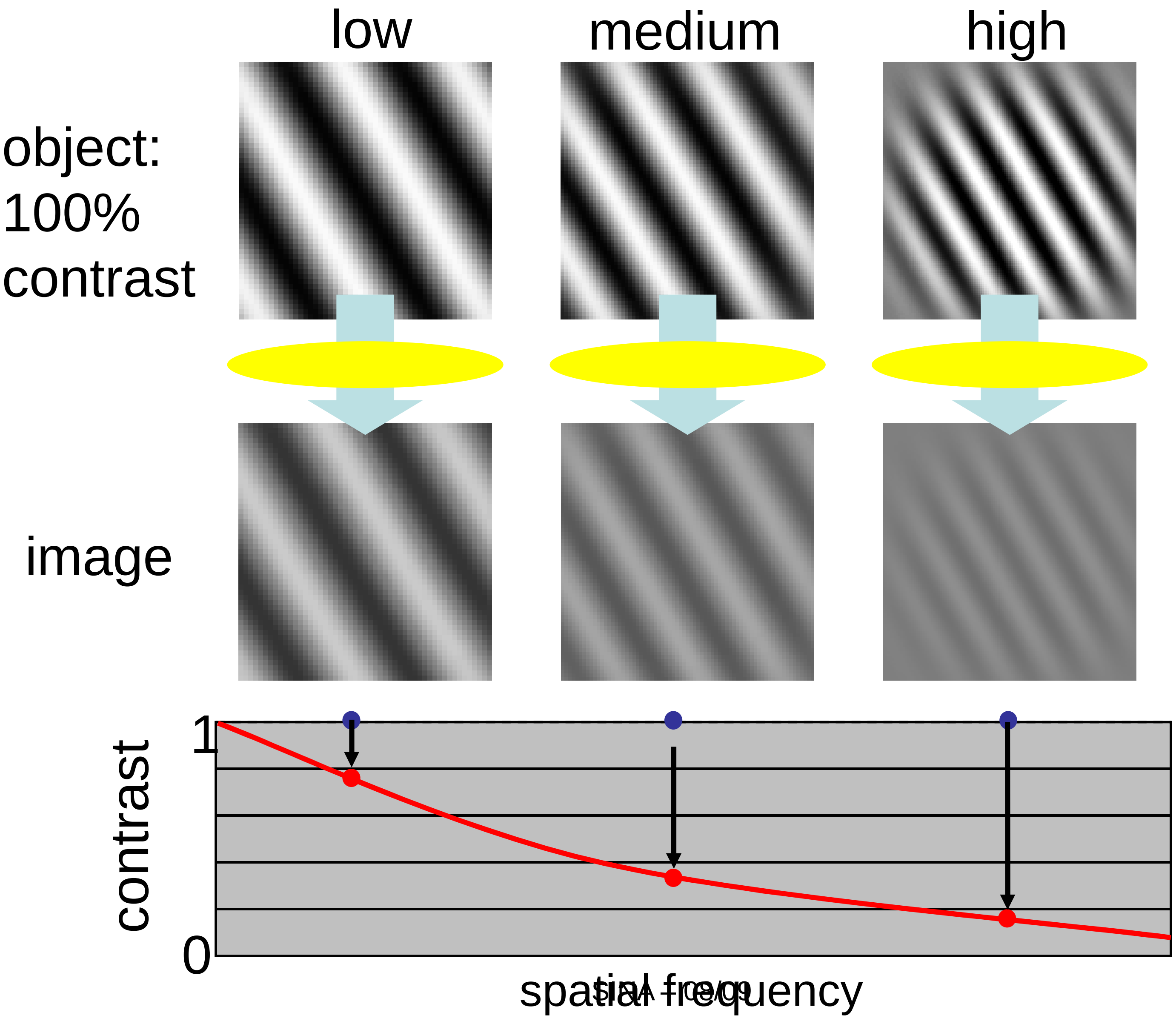
- At small pupil sizes aberrations are insignificant and diffraction dominates





Dependence of the Point Spread Function on pupil size in a typical eye. Small apertures are dominated by diffraction, optical aberrations cause blur for larger pupils.

Modulation Transfer Function (MTF)



Spatial Frequency

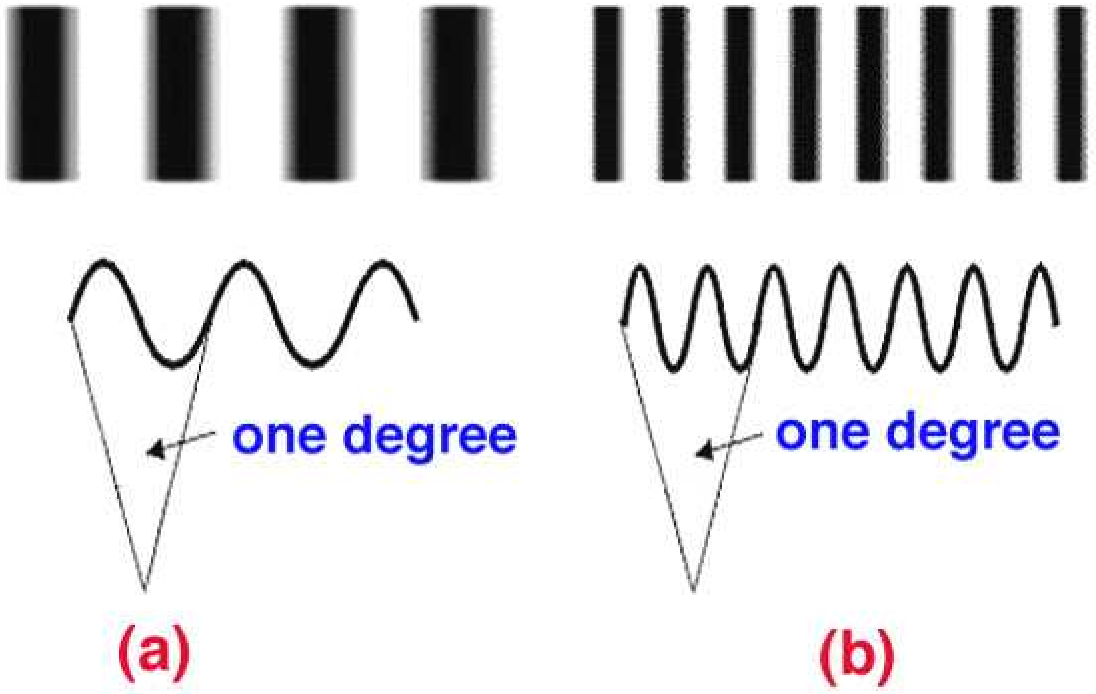


Figure 22. Spatial frequency is a measure of the number of cycles subtended at the eye per degree. (a) One cycle per degree. (b) Two cycles per degree.

- Measure the optical quality of the eye

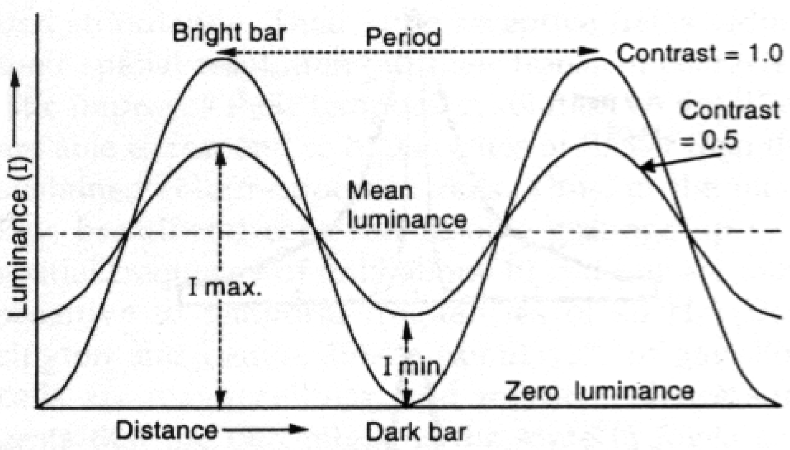


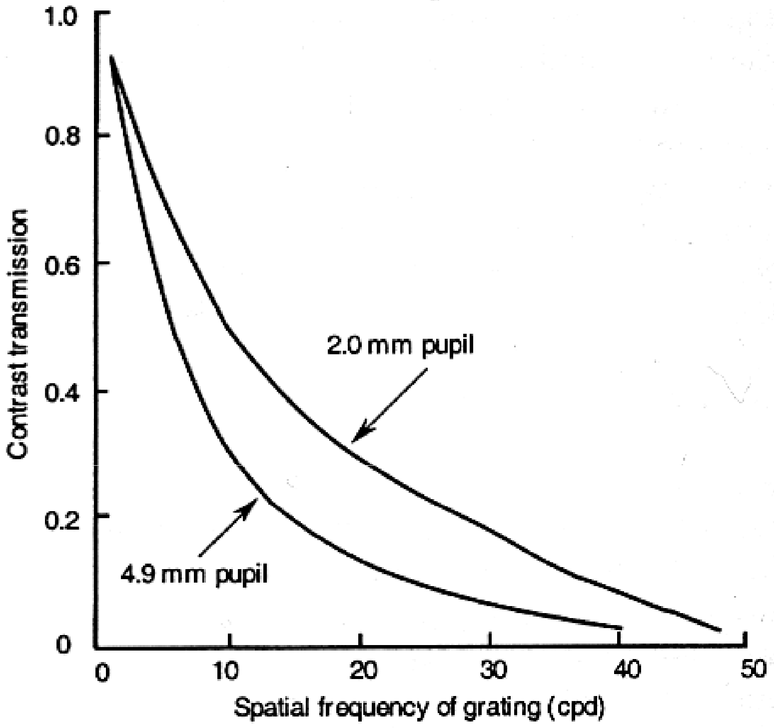
Figure 5.7. Characteristics of a sine-wave grating. Spatial frequency is the number of luminance modulations per degree of visual angle—the reciprocal of the period. Two levels of contrast are illustrated.

$$\text{Mean luminance} = \frac{I_{max} + I_{min}}{2}$$

$$\text{Luminance modulation} = I_{max} - I_{min}$$

$$\text{Michelson contrast} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

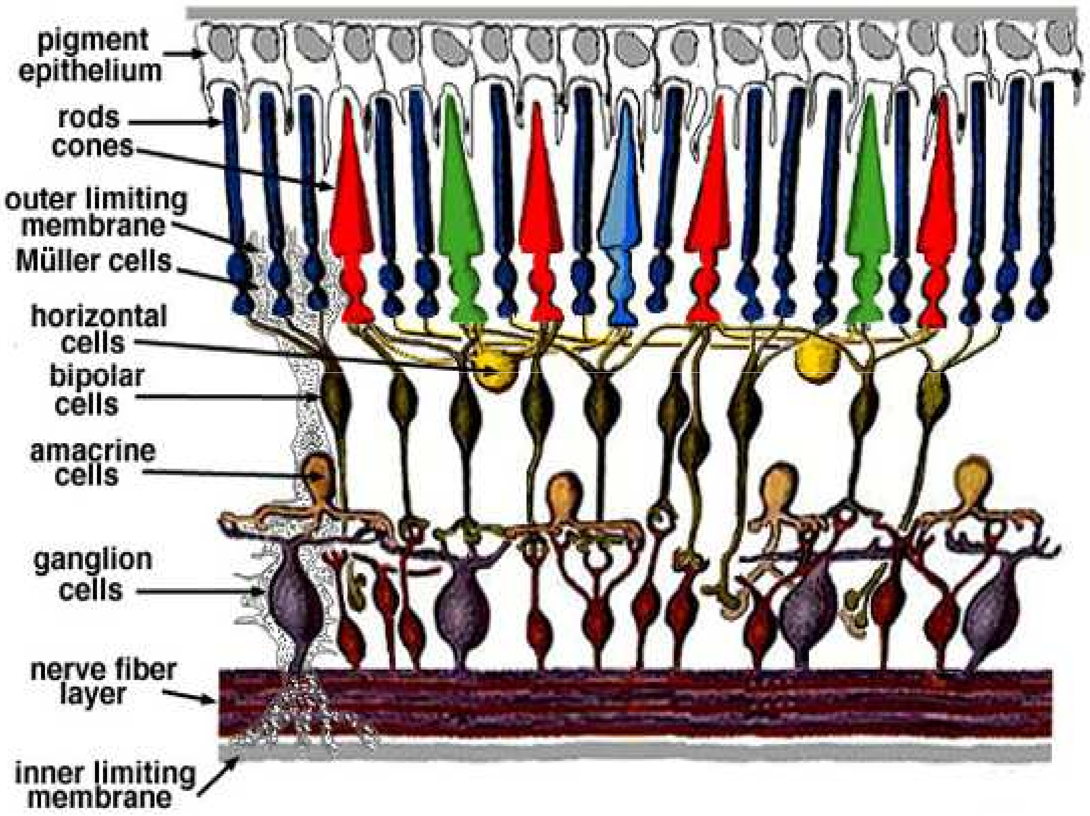
normalizes the variation of the stimulus with respect to the average intensity (Weber Law)



(a) Transfer functions for two pupil sizes. The curves were obtained by measuring the light reflected from the image of a grating on the fovea of a human eye. The functions result from loss of contrast due to diffraction and other optical aberrations.

The Retina

provides epithelium to the photoreceptors
absorbs light, avoids scatter



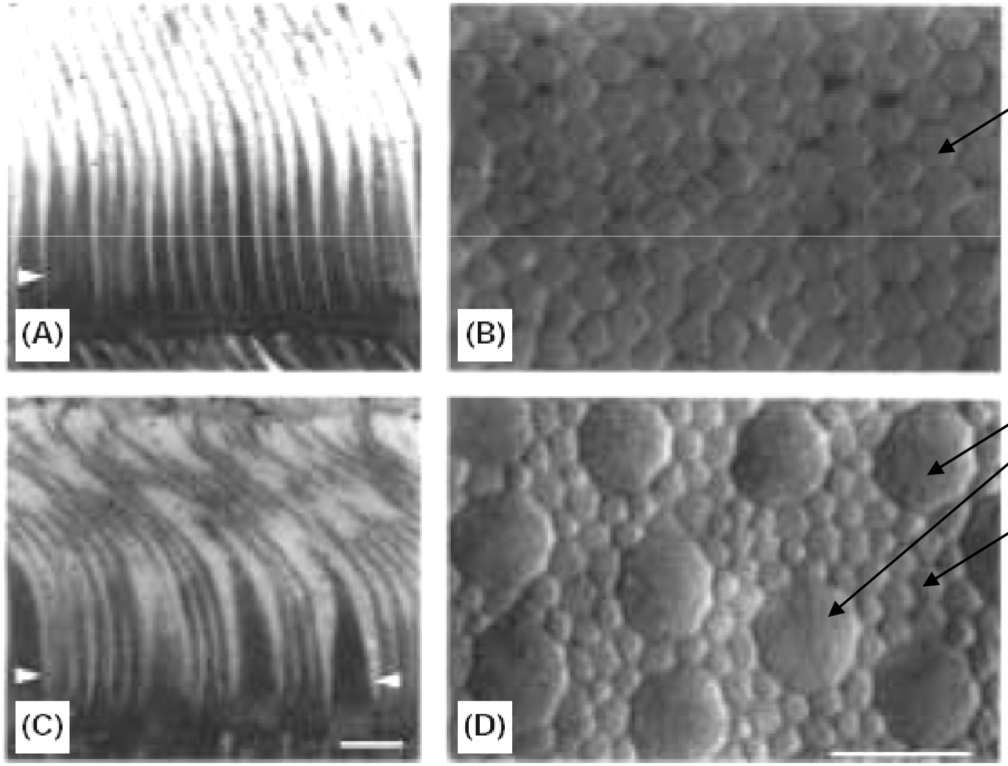
limited loss of light (roughly .2 mm)

light

horizontal cells: first stage of processing in the retina, connect distant areas
bipolar cells: interconnects two points, link between outer and inner layers (amacrine and ganglion cells)
amacrine cells: horizontal elements of the inner layer
ganglion cells: communicate directly with the brain, sole output of the retina, through the optic nerve

Photoreceptors

- Photoreceptors transduce the light into neural signals
- Two types of receptors: cones and rods



cones in the fovea

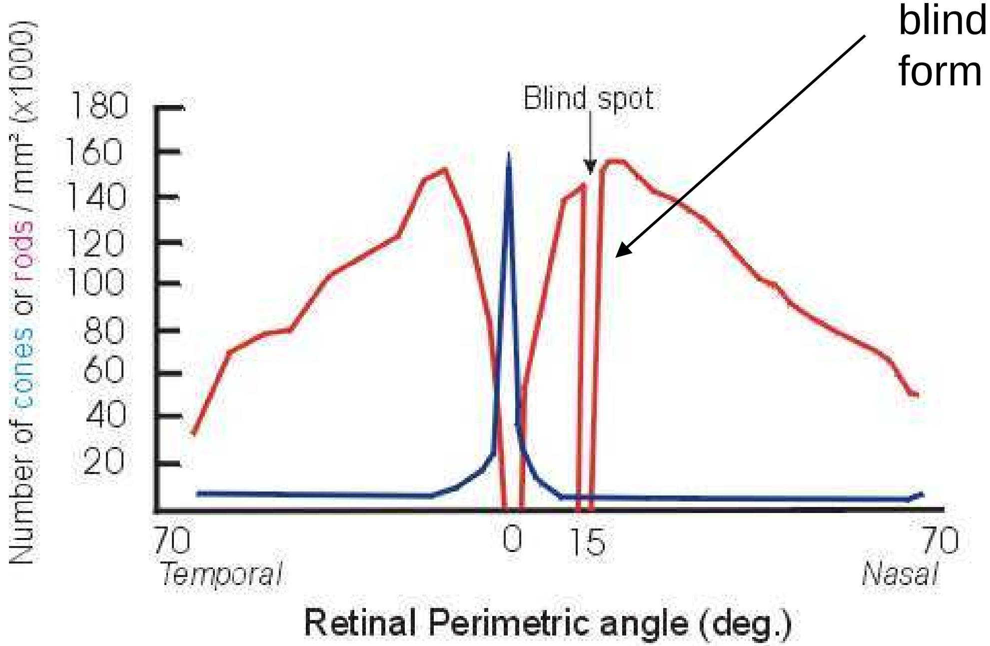
cones (mid-periphery)

rods (mid-periphery)

10um

Cones and Rods

- ~100×10^6 rods, ~5×10^6 cones, unevenly distributed
- Cones have highest concentration at the fovea ($1.6 \times 10^5/mm^2$)
- No rods in the fovea, maximum concentration at roughly 15 degrees
- Rods are very sensitive to light, but poor spatial resolution (many rods converge to the same receptive field)
- Cones on the contrary, are less sensitive to light but have very high spatial resolution

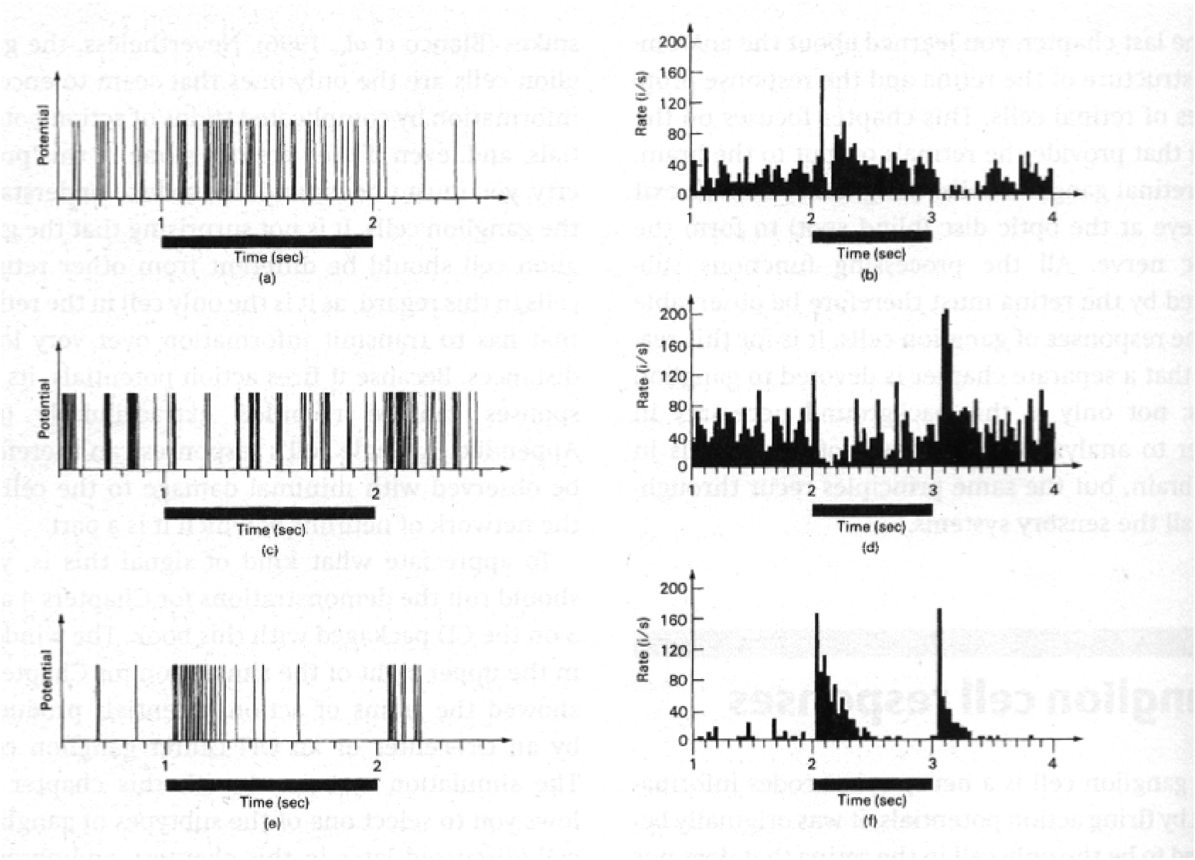


blind spot, where the ganglion cell axons form the optic nerve and exit the retina

Adapted after Østerberg, 1935

Ganglion Cells Responses

- Receptive Field: area of the retina “under control of a” cell
- Roughly circular
- The size of the Receptive Fields vary:
  - min in the fovea (a single cone maps onto more ganglion cells)
  - increase with eccentricity (in the periphery more cones map to a single ganglion cell)
- Sensitive to contrast (on-center/off-center)



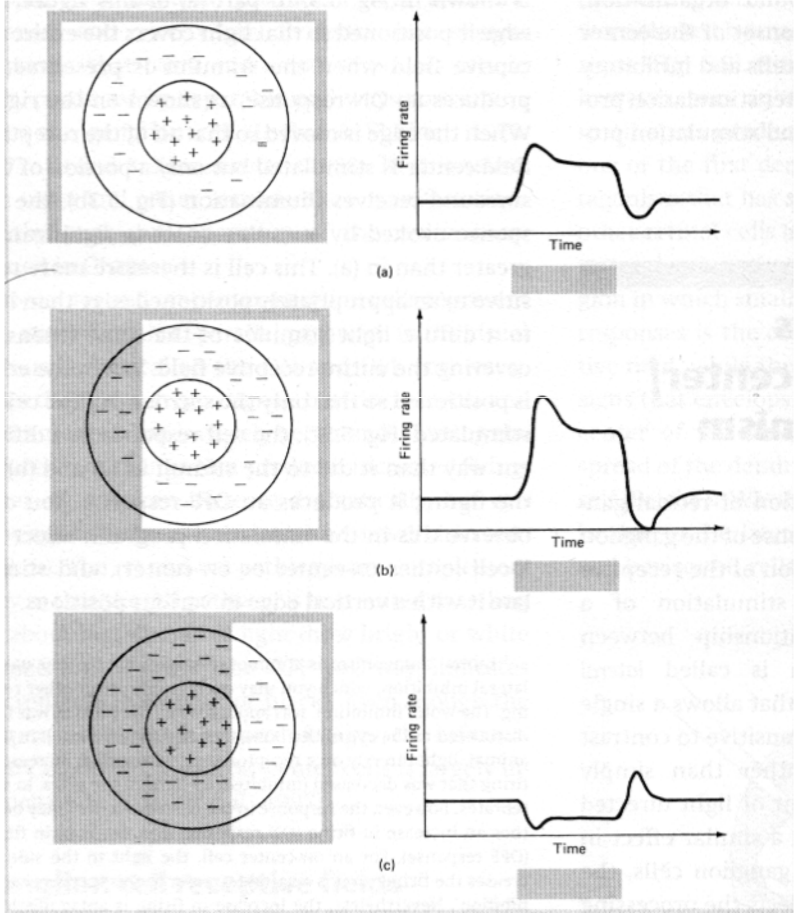
ON-cell

OFF-cell

ON-OFF cell

Responses of ganglion cells to small spots of light. Duration of the stimulus is marked by the dark bar below each response. Left: spike trains. Right: peristimulus time histograms (PSTHs) (computer-generated plots)

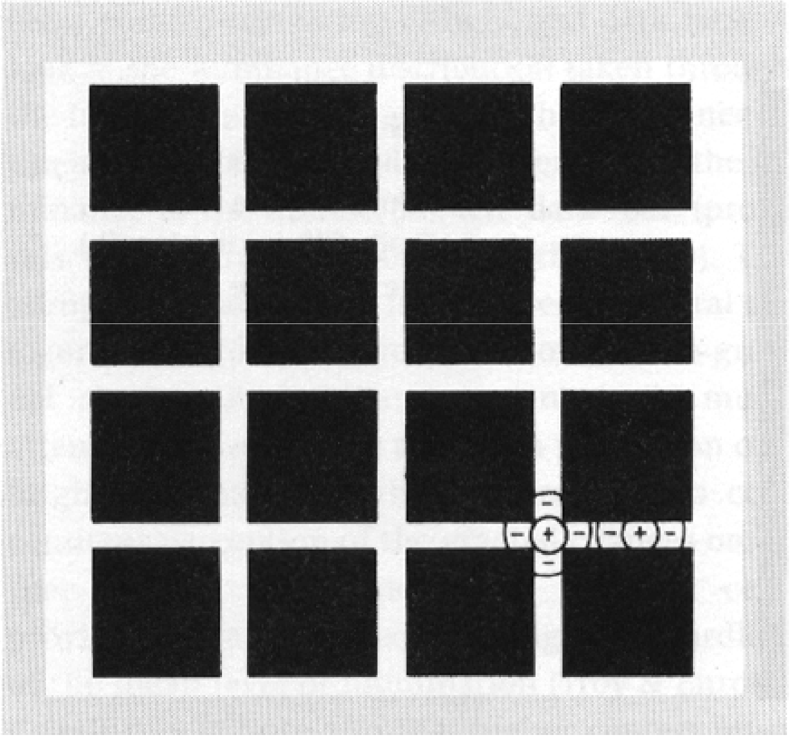
Lateral antagonism



Ganglion cells are sensitive to contrast rather than to the total illumination within the field

Responses of a hypothetical **on-center** cell to an edge of light positioned at different places

Hermann grid: effect of lateral inhibition and variable size of receptive fields



Other classifications

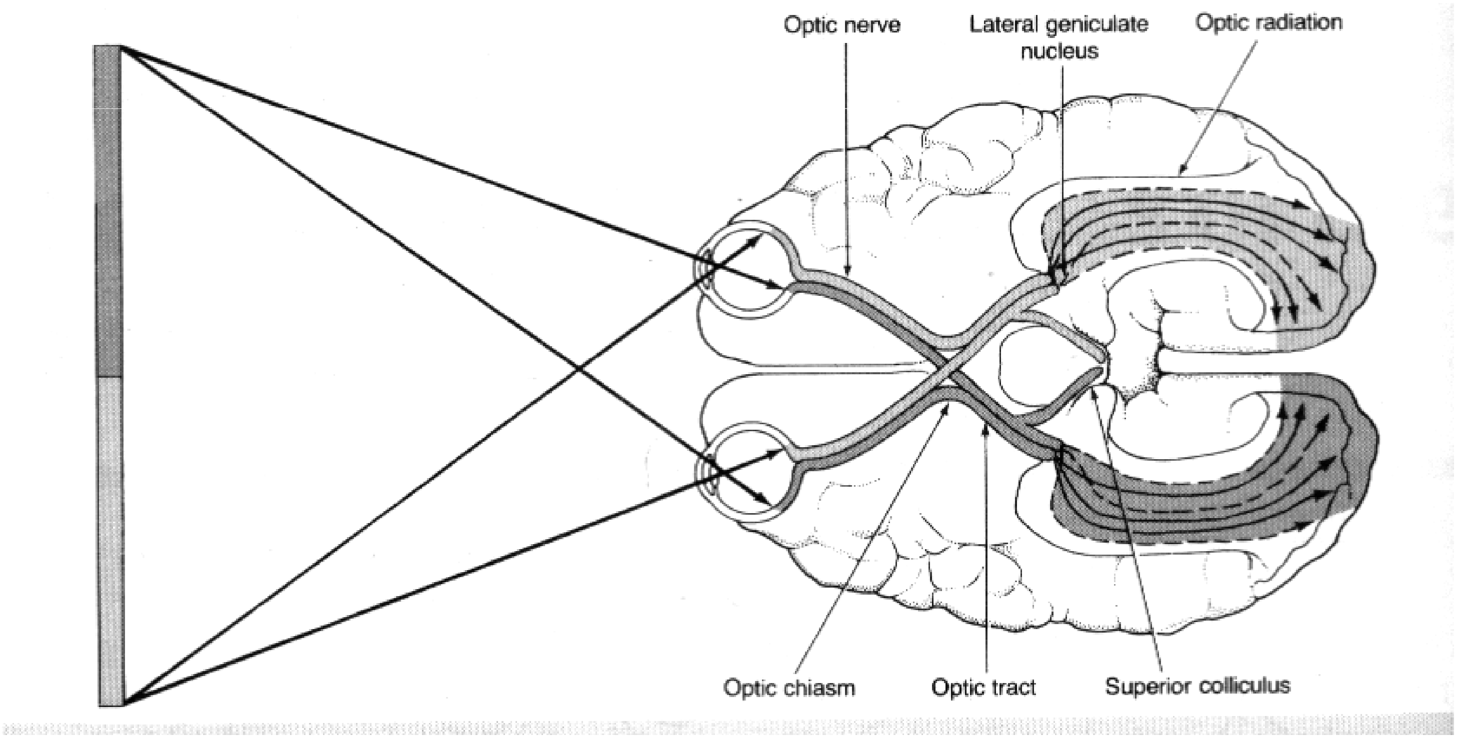
In the cat, X, Y,W depending on the size of the receptive fields, their location on the retina, the area in the brain where they map, temporal response

In primates:

- P (parvo) cells: color opponent, smaller in size, sensitive to details
- M (magno) cells: achromatic, larger receptive fields, quick response to stimulus onset/offset, more specialized for detecting motion and lower luminance

The Visual Pathway

- Axons of retinal ganglion (optic nerves) intersect in the *optic chiasm*
- Optic nerves branch in two *optic tracts*:
  - – some of the fibers continue to the contralateral hemisphere,
  - – the rest do not cross but stay in the same half of the brain (ipsilateral hemisphere)
- Fibers coming from the nasal retina go to the contralateral brain, whereas fibers from the temporal retina stay in the *ipsilateral* hemisphere



- The left portion of the brain “sees” the right portion of the world
- The right portion of the brain “sees” the left portion of the world
- However, the same point in visual space projects to the same part of the brain – two half retinas are combined in the optic chiasm

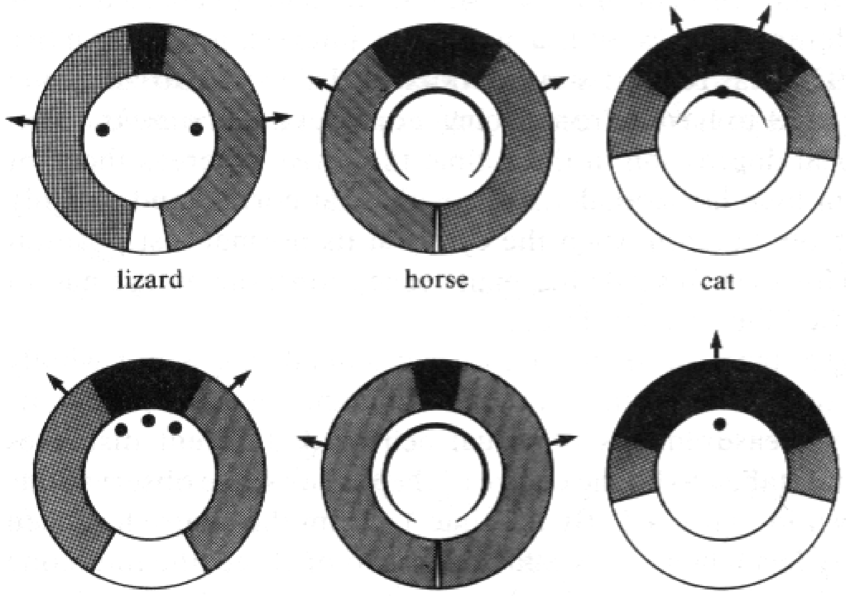


Figure 1.4 Maximum horizontal monocular (shaded areas) and binocular (black areas) fields, directions of optical axes (arrows), and location of the *area centralis* (inside ring) in different species (data from Walls, 1942; Hughes, 1977; Martinoya et al, 1981; Martin, 1984).

- This applies only to animals that have their eyes in front of their heads (humans and many predators) → large overlap, help in *depth perception* to locate their “food”
- For *hunted animals* on the other hand it is more important to have a large field of view, so virtually all nerve fibers cross to the contralateral side of the brain

Lateral Geniculate Nucleus

- In primates 90% of axons in each optic tract project to the LGN (the other 10% goes to other areas, like the superior colliculus)
  - *Principal cells (relay* cells), leave the LGN to the cortex in the *optic radiation*
  - *Interneurons,* whose axons remain within the LGN (processing)

Projections from ganglion cells form retinotopic maps organized in layers: inputs from corresponding areas of the two eyes lie in **projection column** running perpendicular to the laminae (left, below). The retinotopic map of the visual field onto the LGN (layer 6) is shown on the right.

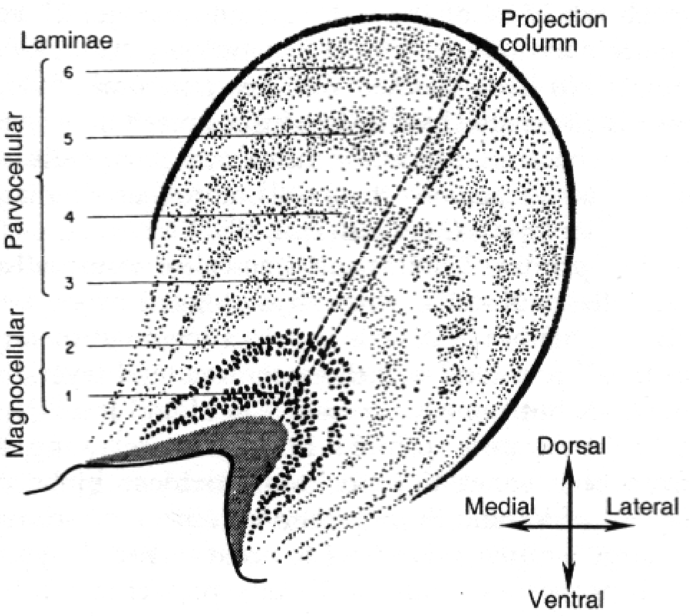


Figure 5.13. The lateral geniculate nucleus. Lamination and projection columns in a coronal section of the LGN of a monkey. A column is defined as having 90 % of the cells with a single visual direction. (From Szentágothai 1973)

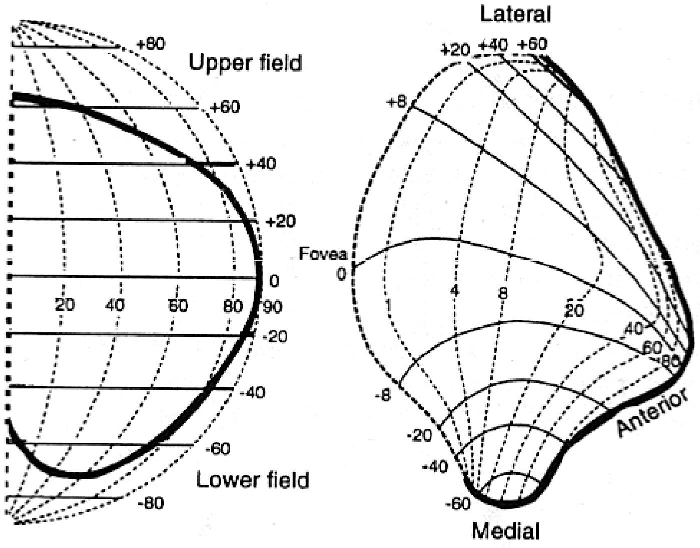
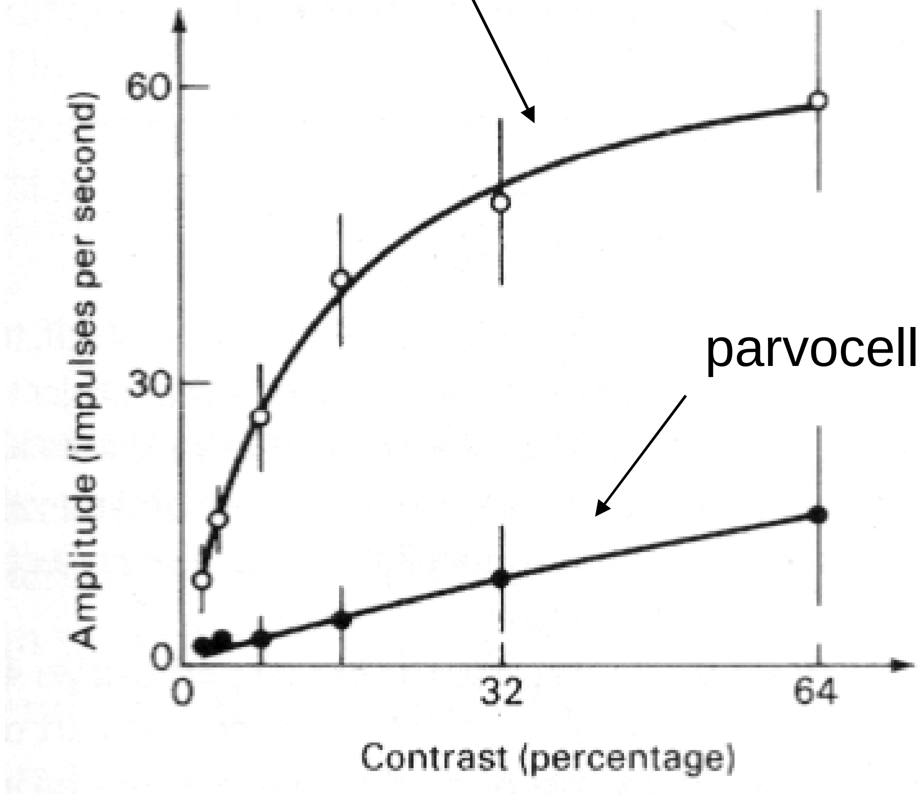


Figure 5.12. Projection of the visual field onto the LGN. Schematic view of the right hemifield of the monkey's retina and its projection onto the dorsal surface of layer 6 of the left LGN. Numbers represent degrees. The dotted lines are azimuths and the solid lines are elevations. The heavy dotted and solid lines represent the limits of the visual field. (Adapted from Malpeli and Baker 1975)

contrast sensitivity of
parvo versus magno
cells in LGN

magnocellular cells



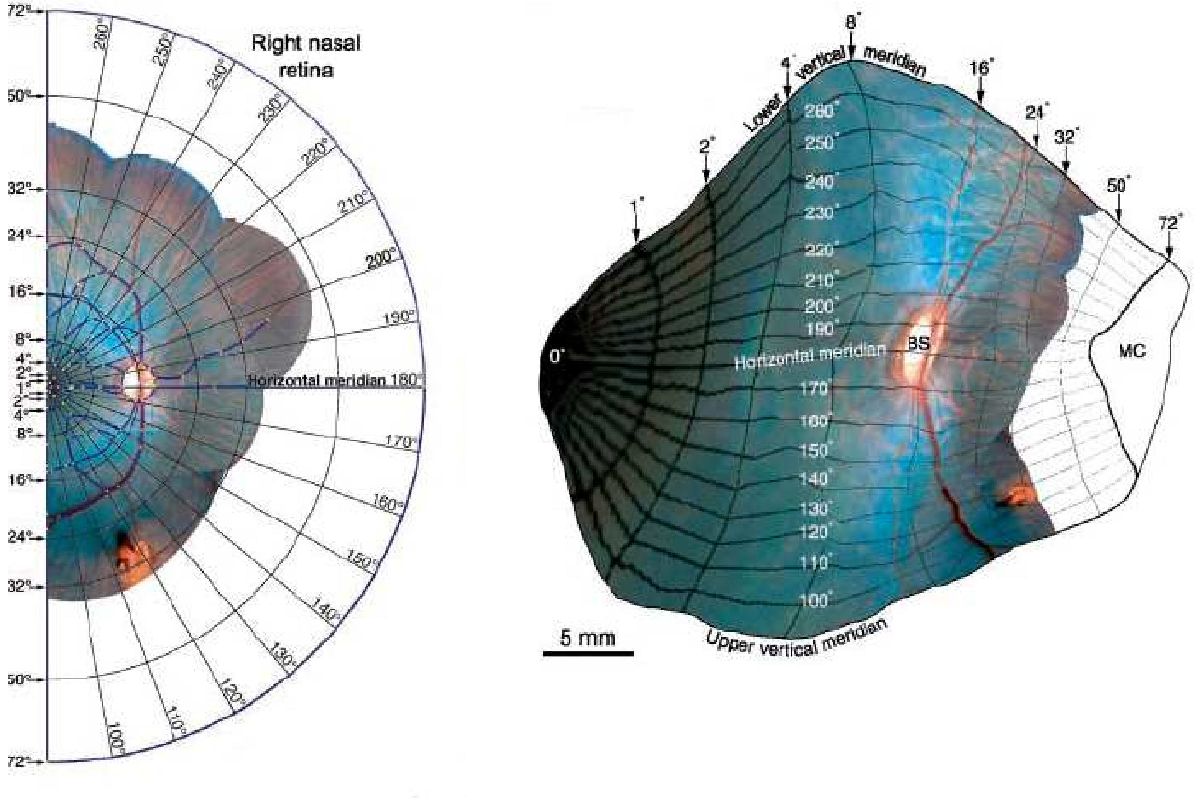
parvocellular cells

Functional role of LGN

- In general the responses of LGN cells closely resemble the responses of retinal ganglion cells (concentric center/surround receptive field mechanisms), although with some differences
- Possible role as a relay system
- Large portion of the input to the LGN come from parts of the brain other than the retina
- Activity in the LGN seems to be modulated by, saccadic eye movements and spatial attention
- Feedback loops from the visual cortex affecting properties of LGN and thus of cortical cells
- Possible modulation of visual activity from other sensory modalities

Visual Area V1

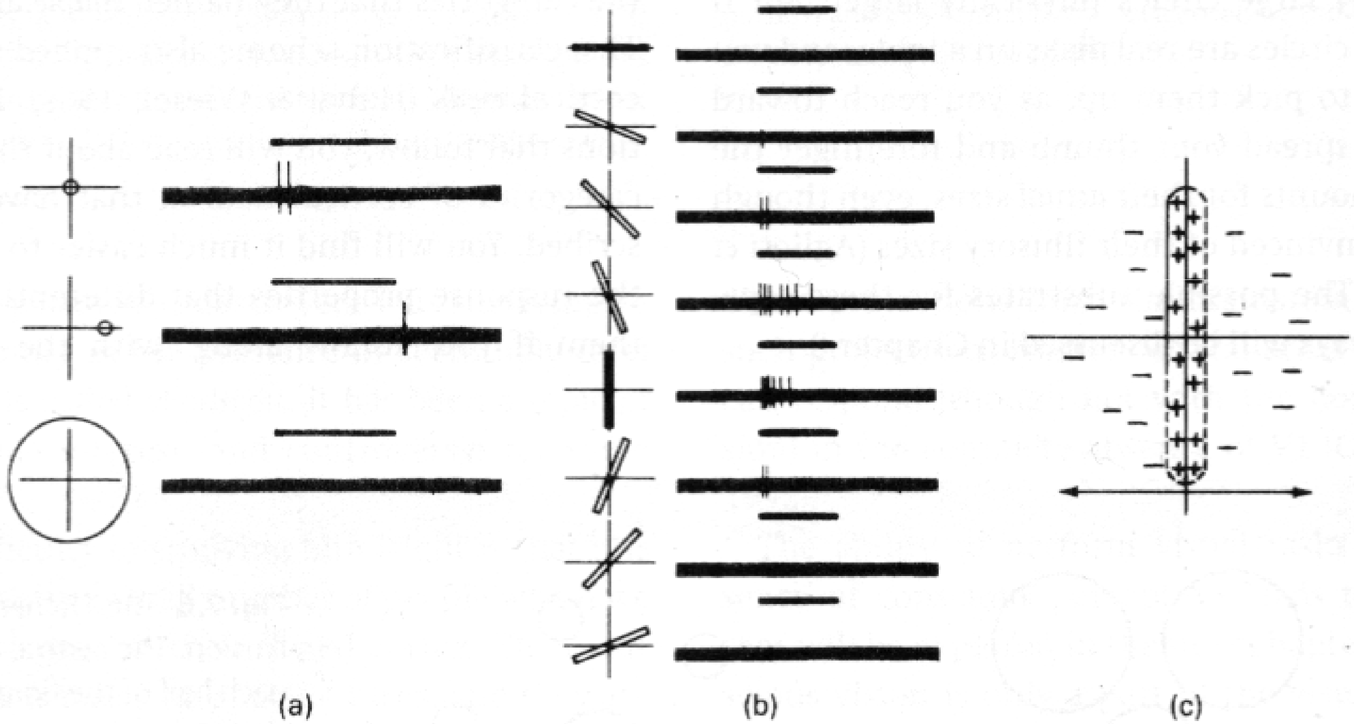
- Organized in layers: layer 4 receives input from LGN
- *retinotopic maps*: more cortical area is devoted to the foveal regions of the visual field (magnification factor)



Shadows Cast by Retinal Blood Vessels Mapped in Primary Visual Cortex, D. L. Adams and J. C. Horton, Science, October 2002.

Receptive Fields of cells in the Visual Cortex

- sensitive to orientation
- does not care about the “length” of the stimulus



a) response to a small spot of light, b) response to a bar of light in different orientation , c) Map of the receptive field

Simple cells, examples

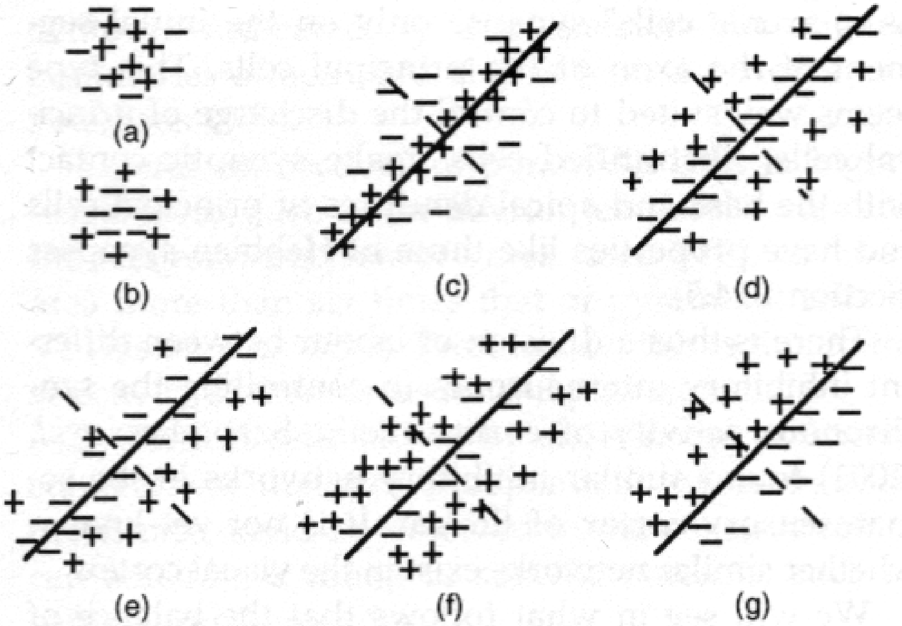


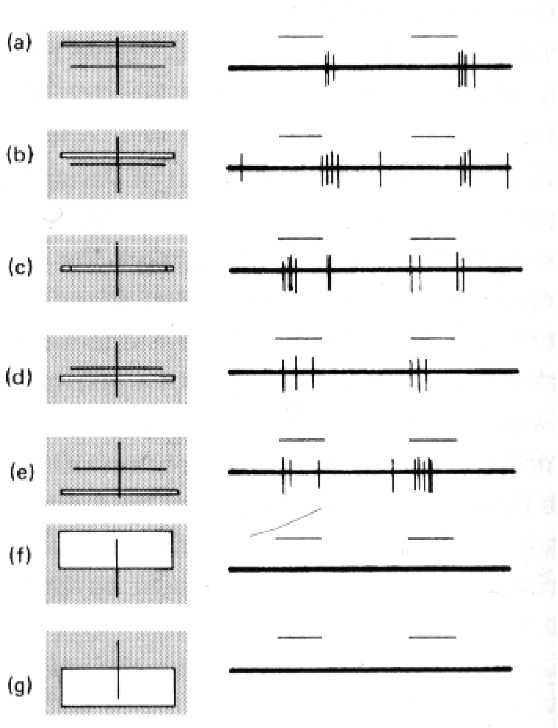
Figure 5.20. Types of receptive field.
(a) An on-centre receptive field of a ganglion cell.
(b) An off-centre receptive field of a ganglion cell.
(c)-(g) Receptive fields of simple cells in cat visual cortex. The receptive fields are shown with preferred orientations of 45°. (Adapted from Hubel and Wiesel 1962)

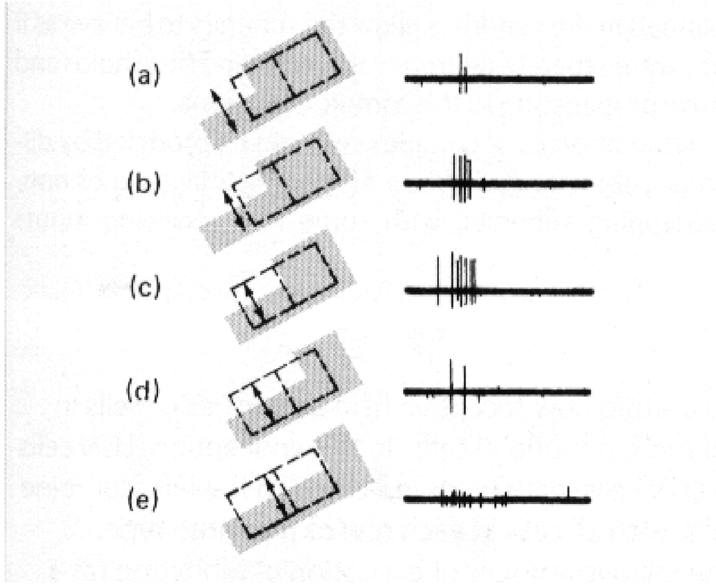
Simple cells properties:

- The response of a simple cell is a linear sum of the response to spots of light in each part of its receptive field (integration)
- No response to even illumination
- The response is independent of the direction of movement of the stimulus
- Some non-linearities:
  - saturation to contrast
  - faster response to high contrasts
  - cross-orientation inhibition: stimulus oriented at 90° with respect to a cell's preferred orientation suppresses the response to a stimulus at the preferred orientation

Not all cells are “simple”

- orientation tuning, but less restrictive to its position
- receptive fields not clearly segregated
- sensitive to direction of motion





end-stopped cells: have a preferred stimulus “length”