Physiological Optics and the Photoreceptor Mosaic

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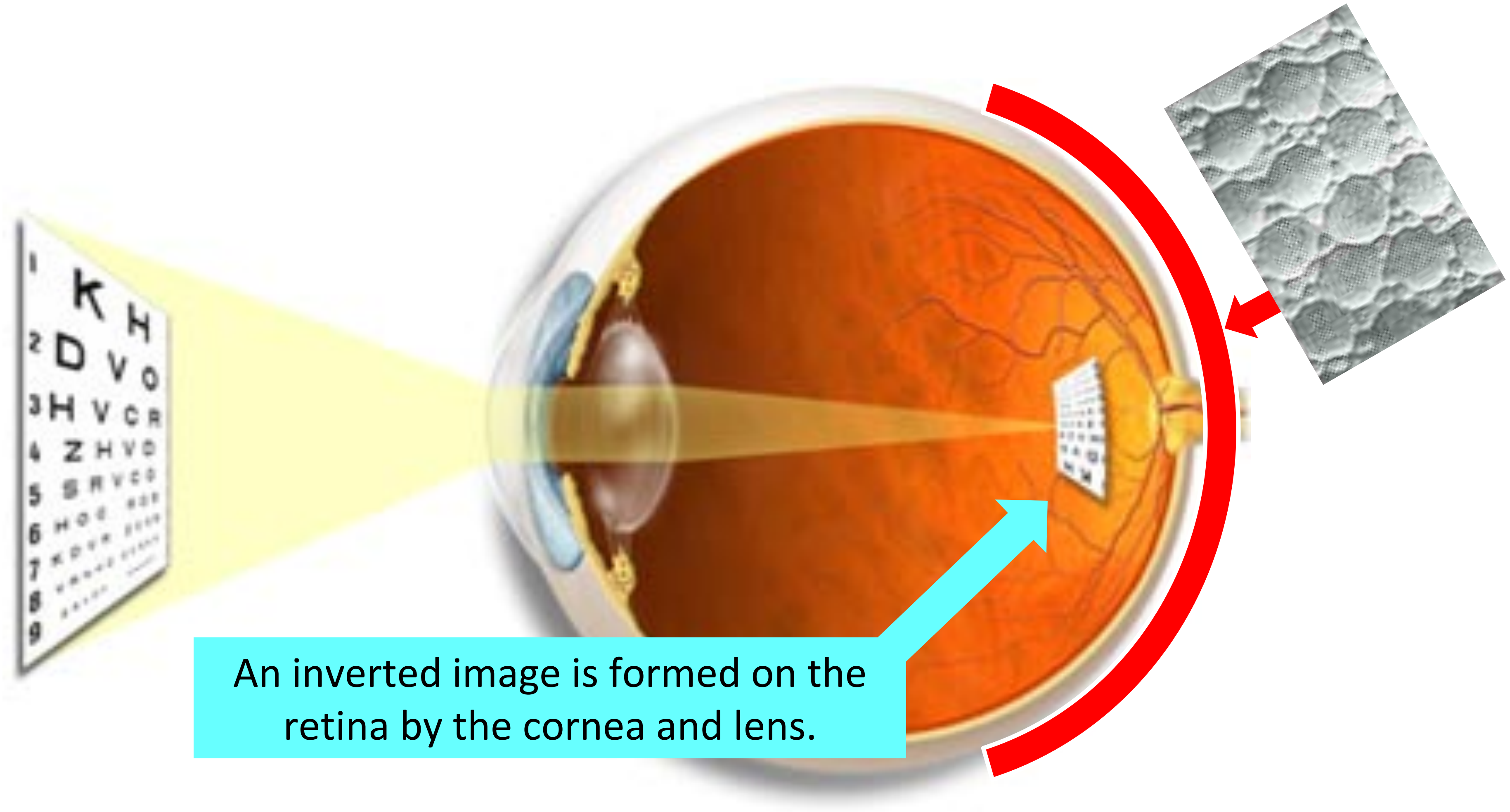
14 January 2020

NEUR 0017 Visual Neuroscience

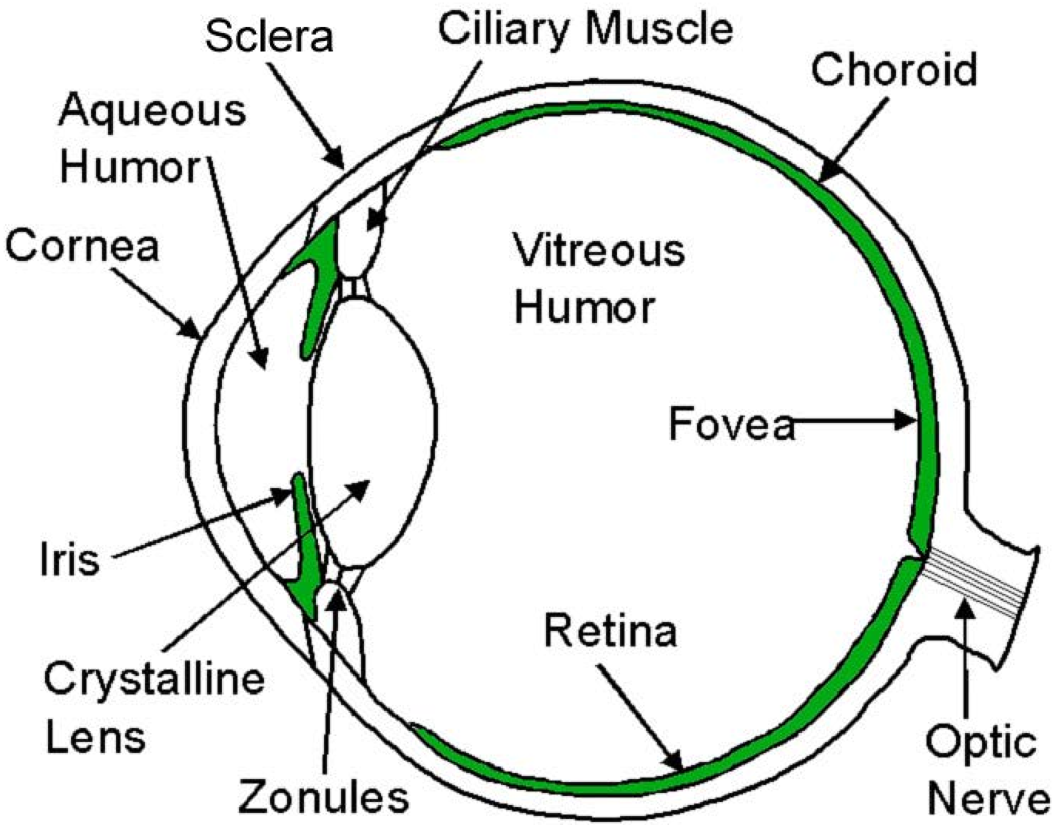
Outline

- The eye
- Visual optics
- Image quality
- Measuring image quality
- What limits visual performance?
- Refractive errors
- Sampling
- Why visual acuity should be limited by the optics and sampling
- Adaptive optics
- Chromatic aberrations

The retina is carpeted with light-sensitive rods and cones



An inverted image is formed on the retina by the cornea and lens.



Cornea – Clear membrane on the front of the eye.
Crystalline Lens – Lens that can change shape to alter focus.
Retina – Photosensitive inner lining of eye
Fovea – central region of retina with sharpest vision.
Optic Nerve – bundle of nerve fibers that carry information to the brain.

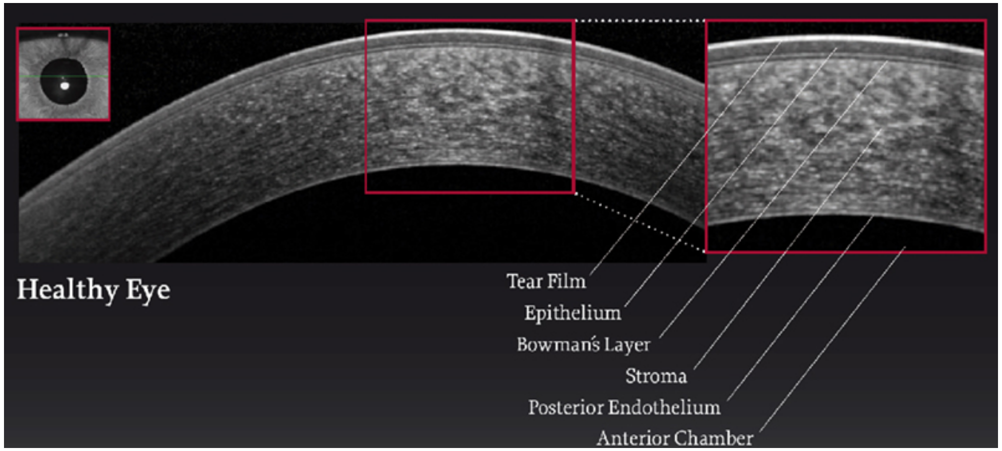
Jim Schwiegerling

Eye Dissection and Part of the Eye

Visual optics

Cornea

Crystalline Lens



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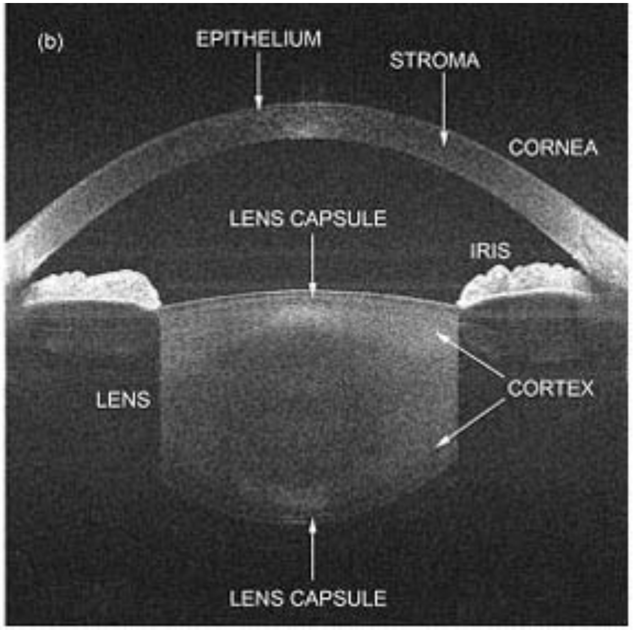
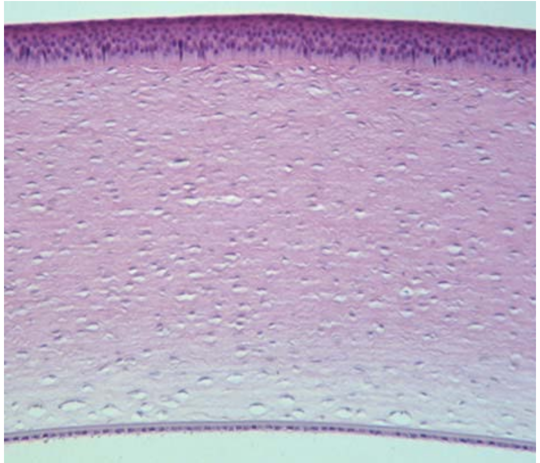
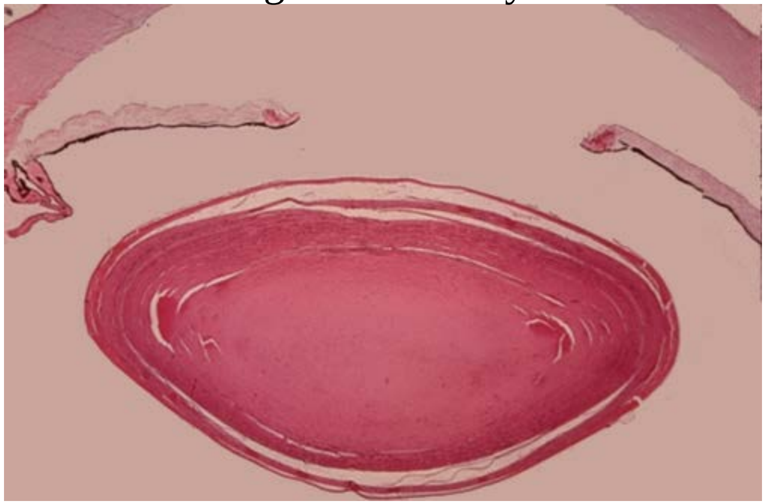


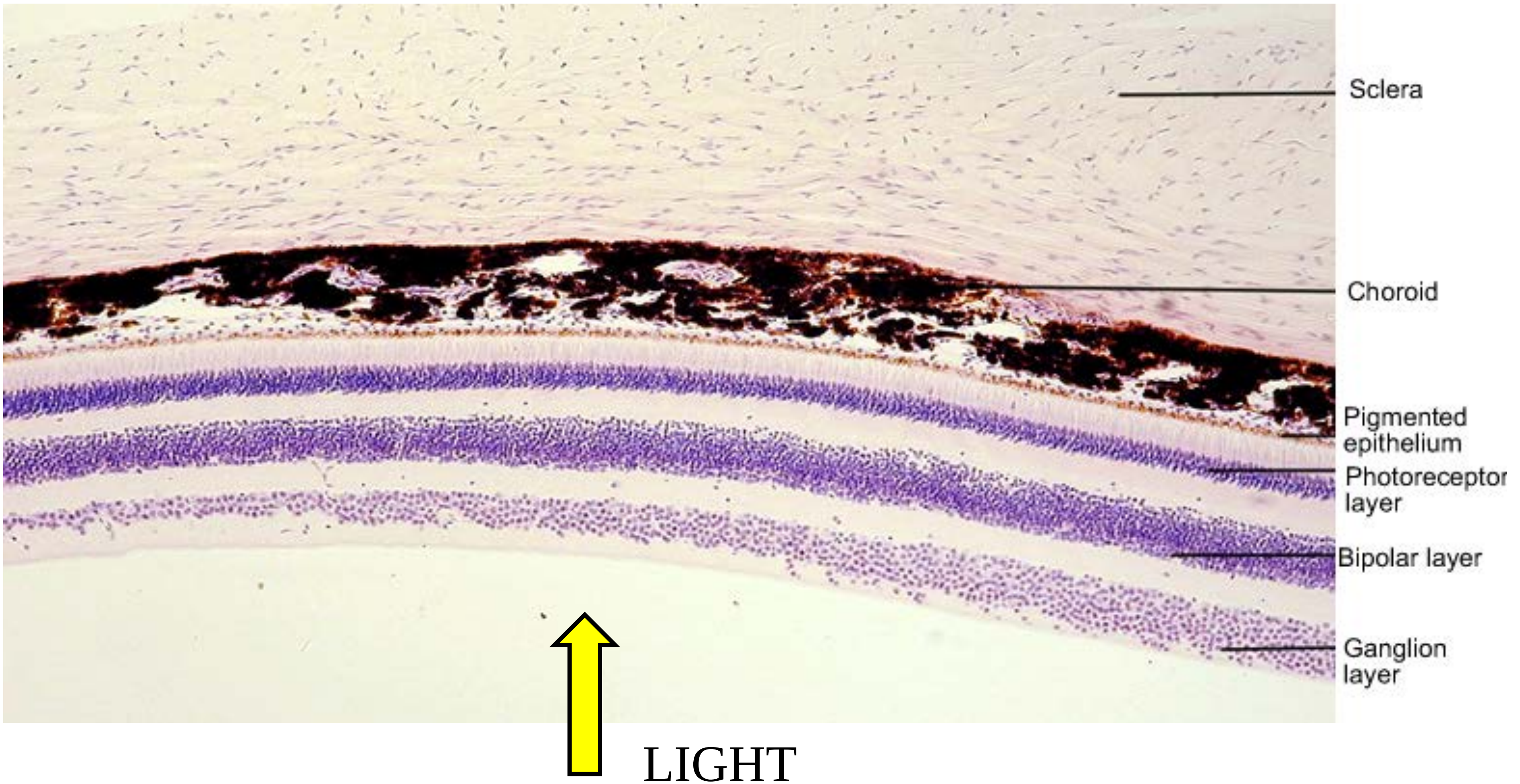
Leitgeb Laboratory





Borrowed from Jim Schwiegerling

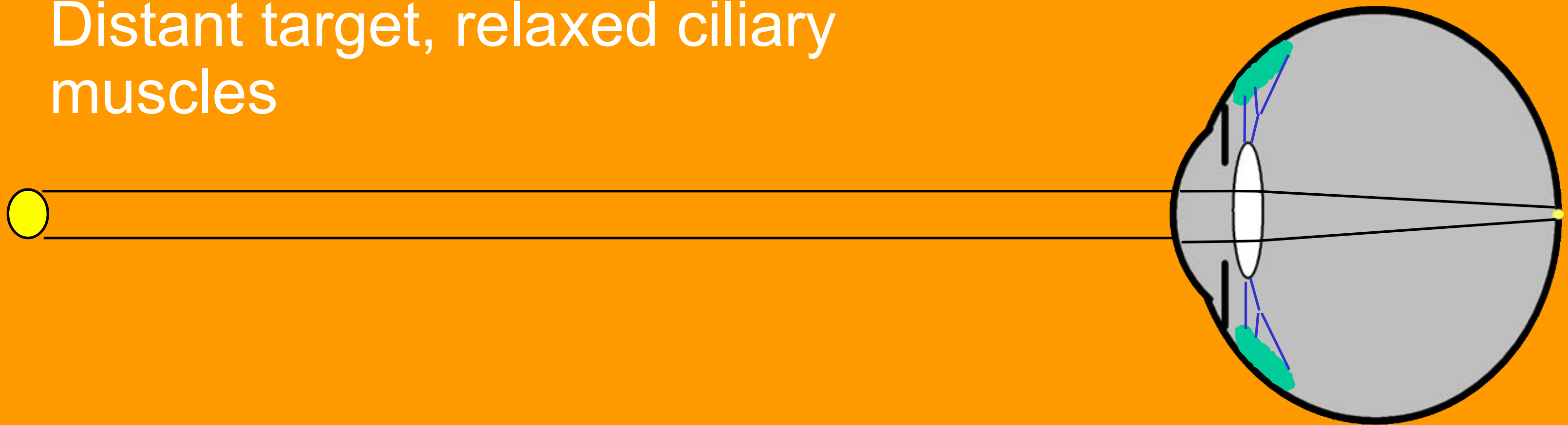
Retinal cross-section



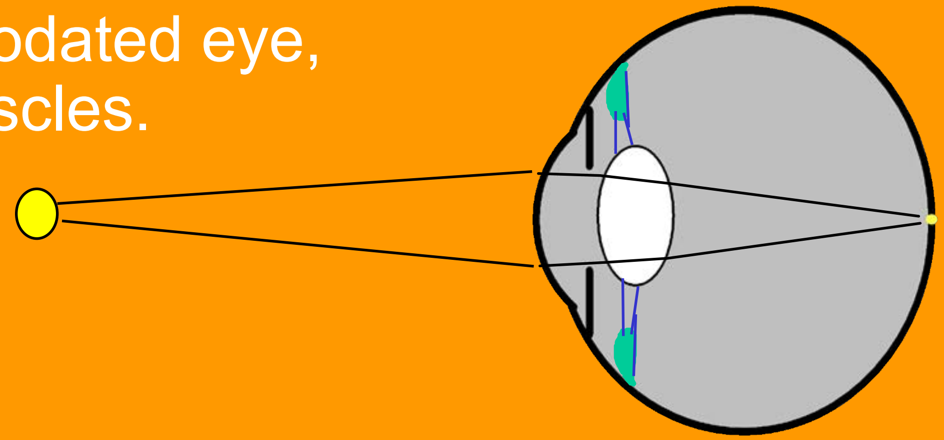
Retina 200 ×

Accommodation to Target Distance

Distant target, relaxed ciliary muscles

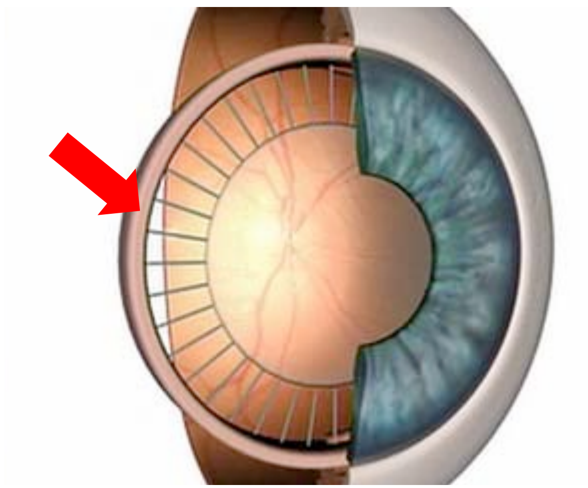


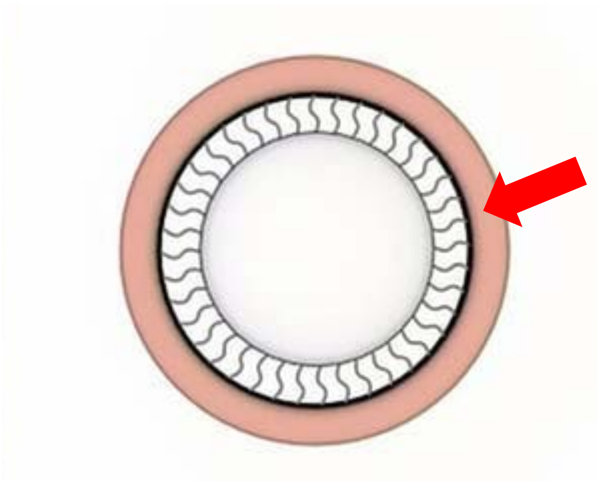
Near target, accommodated eye, constricted ciliary muscles.



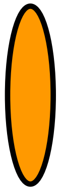
Larry Thibos

Accommodation

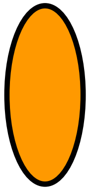




Relaxed ciliary muscle pulls zonules taut an flattens crystalline lens.

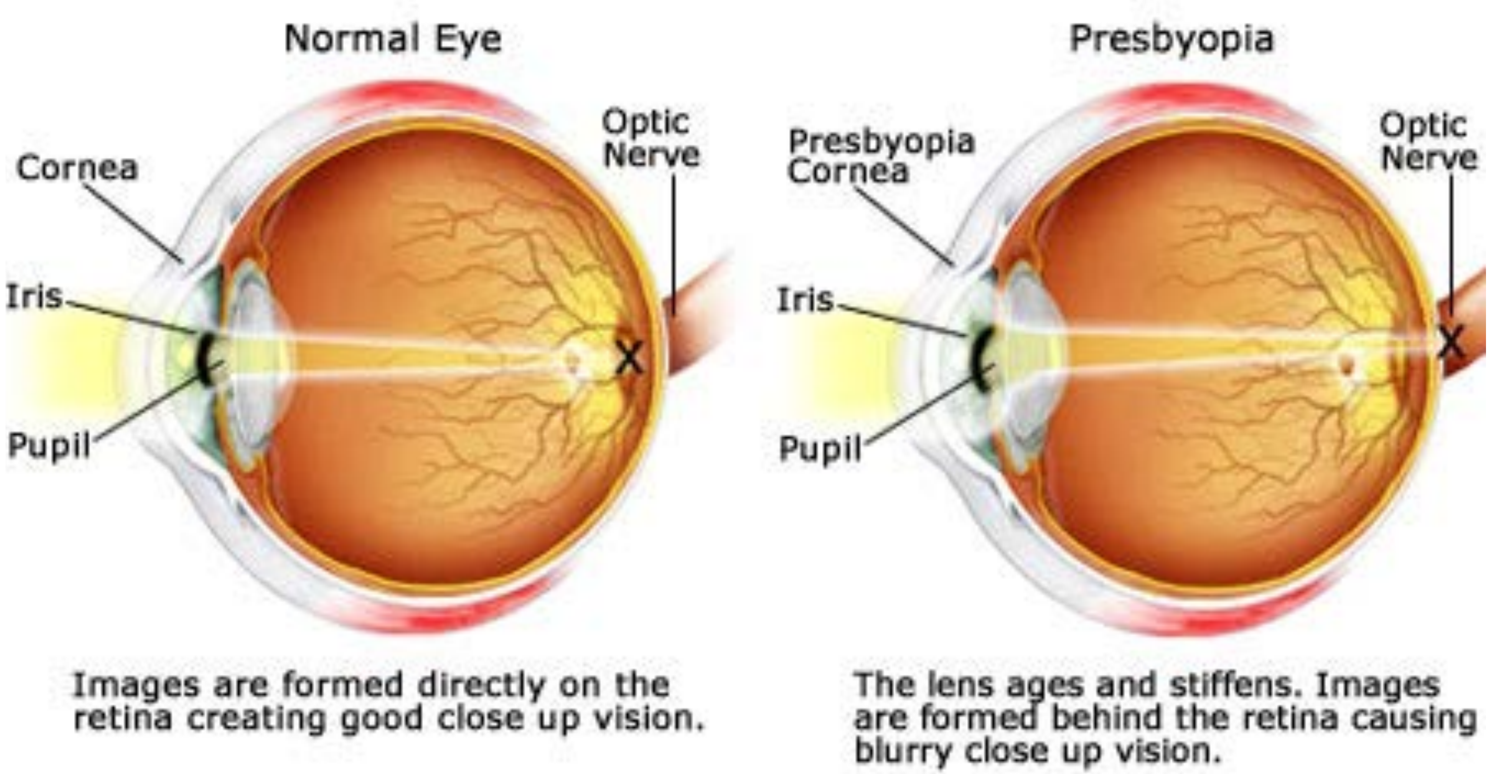


Constricted ciliary muscle releases tension on zonules and crystalline lens bulges.

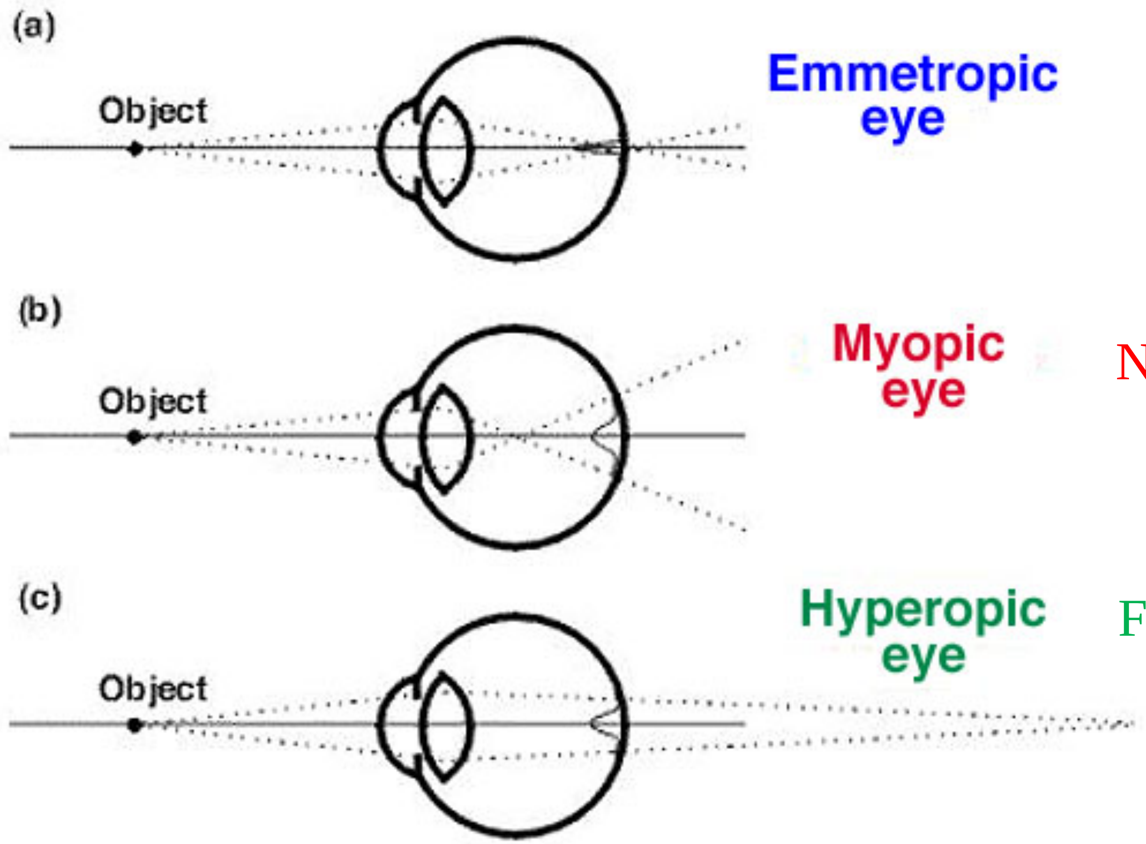


Jim Schwiegerling

Presbyopia (age related far-sightedness)



PSFs for different refractive errors



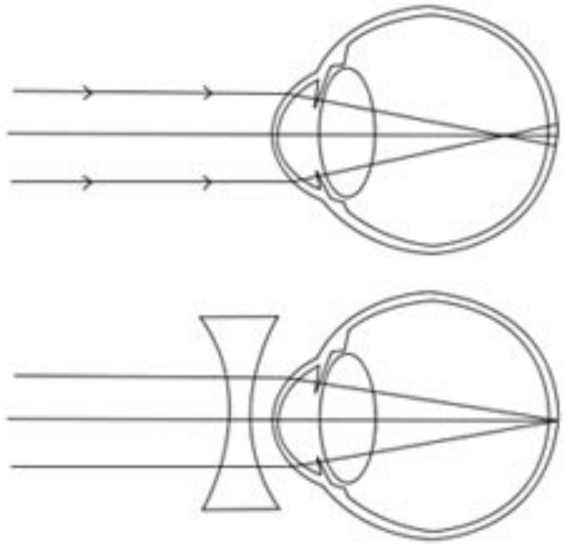
Nearsighted

Farsighted

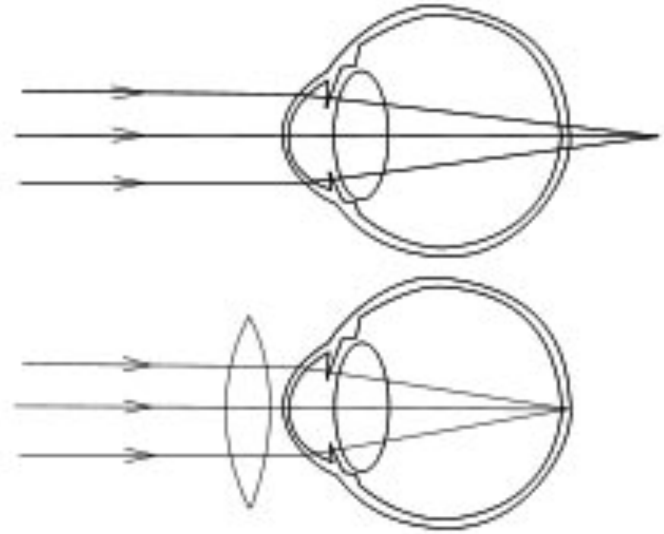
From Webvision, Michael Kalloniatis

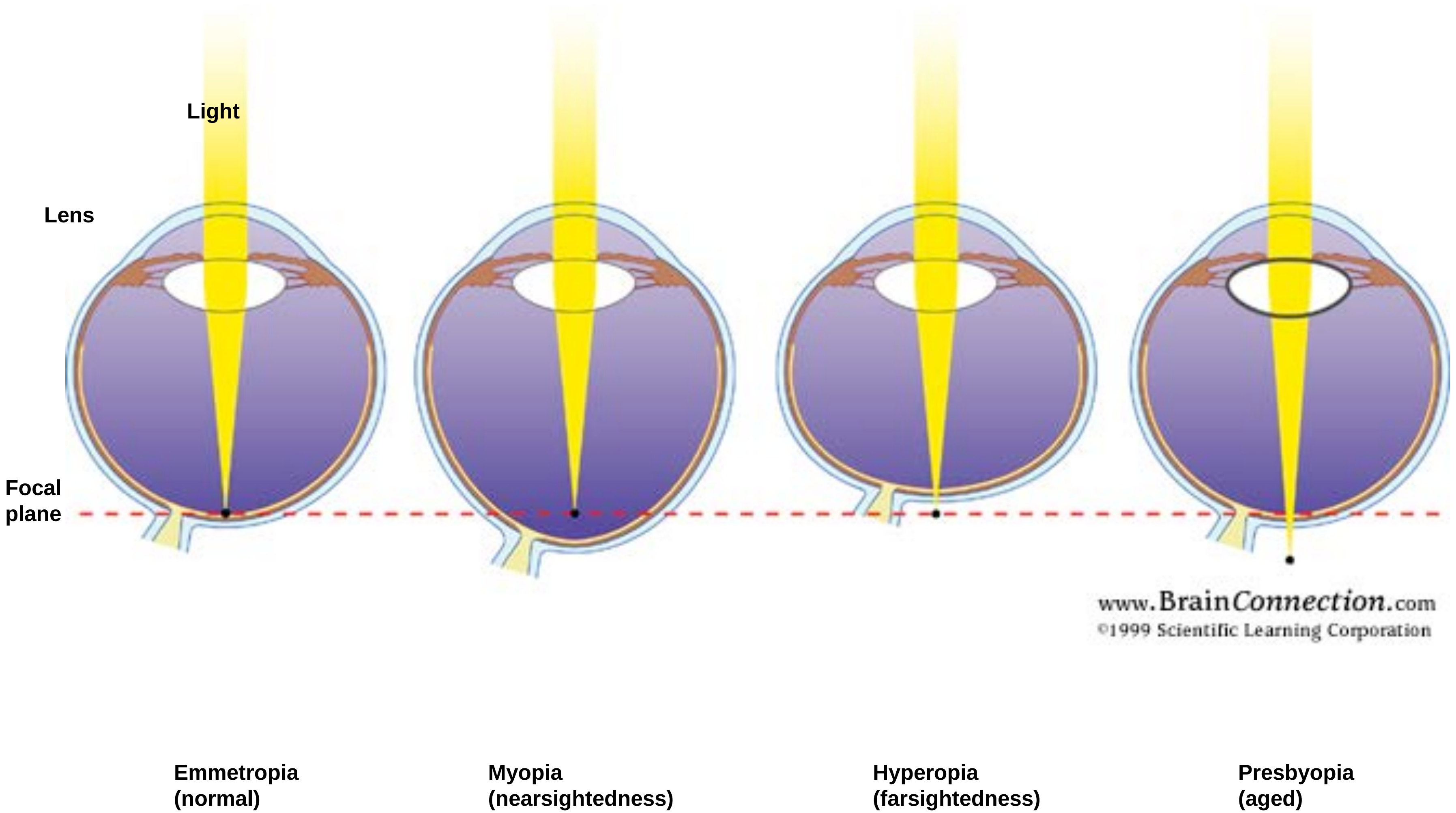
Corrective lenses

Myopia



Hyperopia




Light
Lens
Focal
plane
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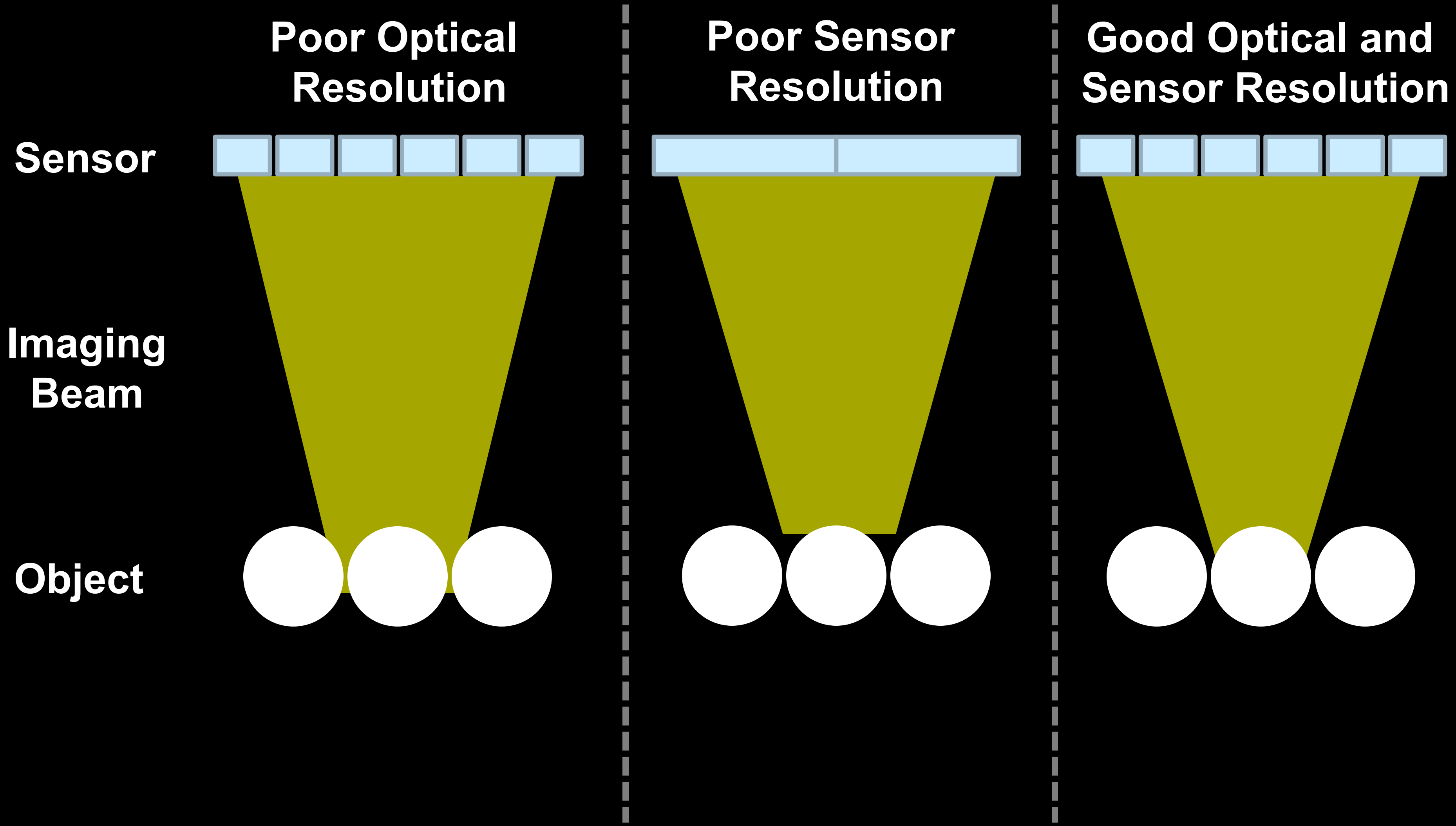
Emmetropia
(normal)
Myopia
(nearsightedness)
Hyperopia
(farsightedness)
Presbyopia
(aged)

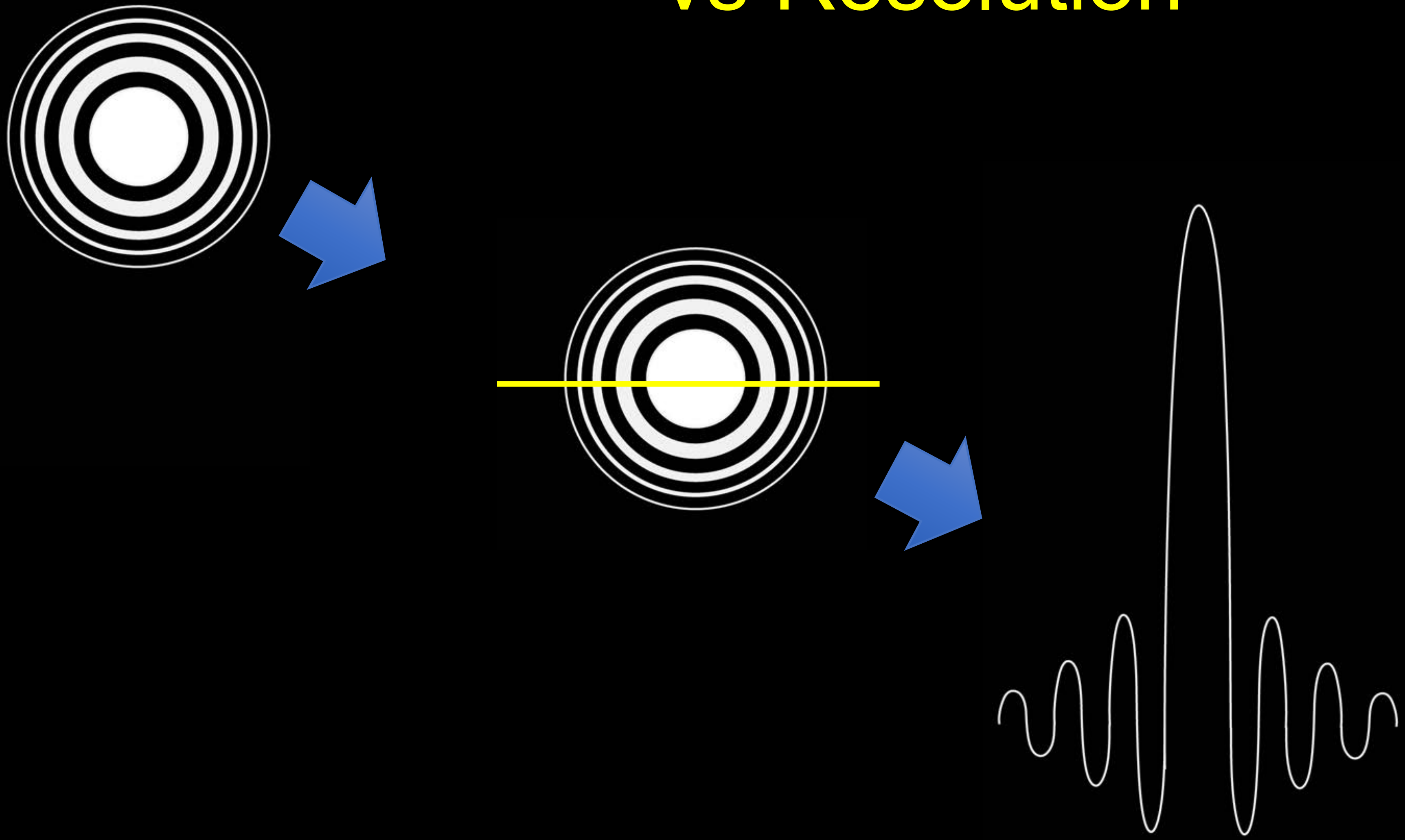
Retinal Sampling and Resolution

Imaging Resolution



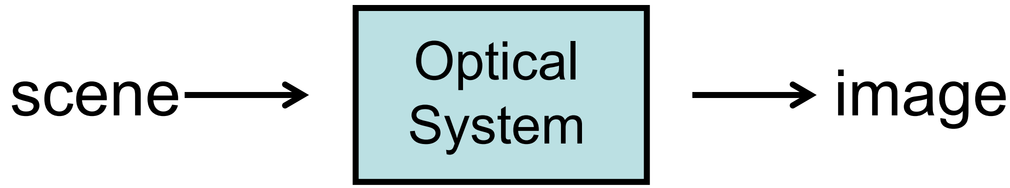
The Point Spread Function (PSF) characterizes the optical performance of the eye.

Point Spread Function Shape vs Resolution

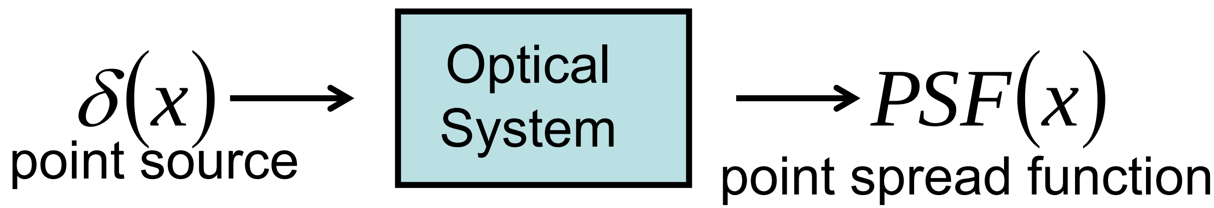


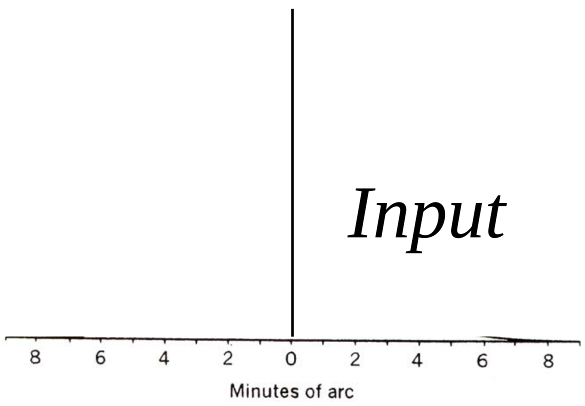
Point Spread Function

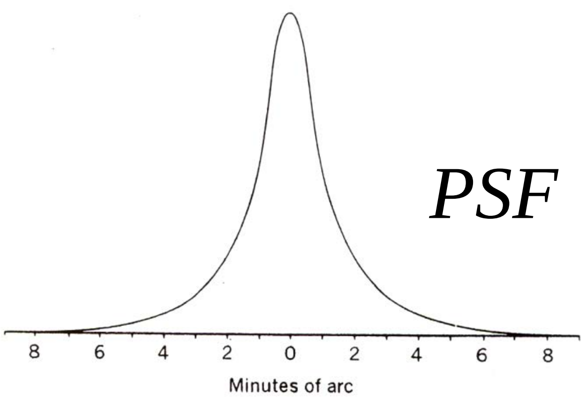
Optical systems are rarely ideal.



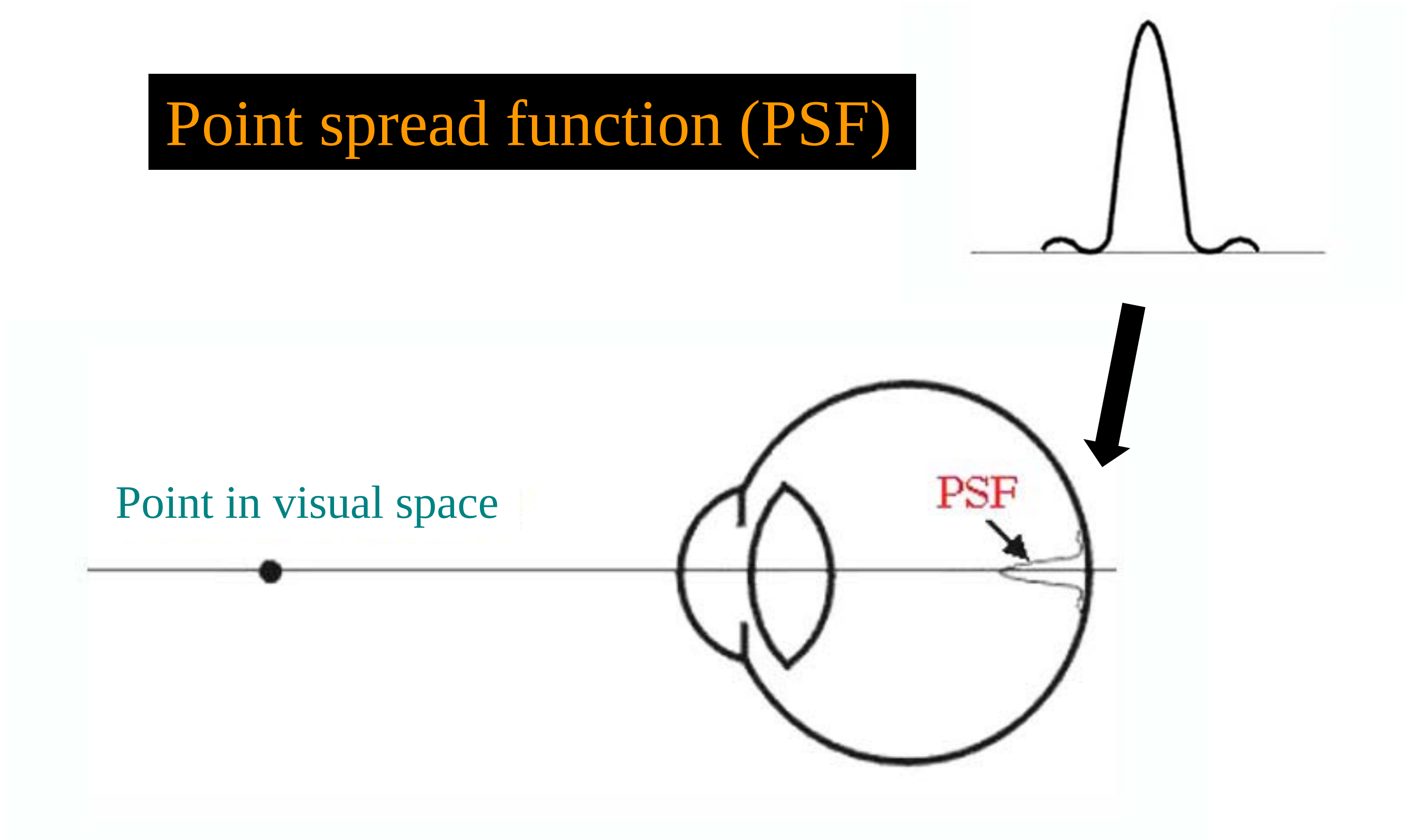
Point spread function of Human Eyes







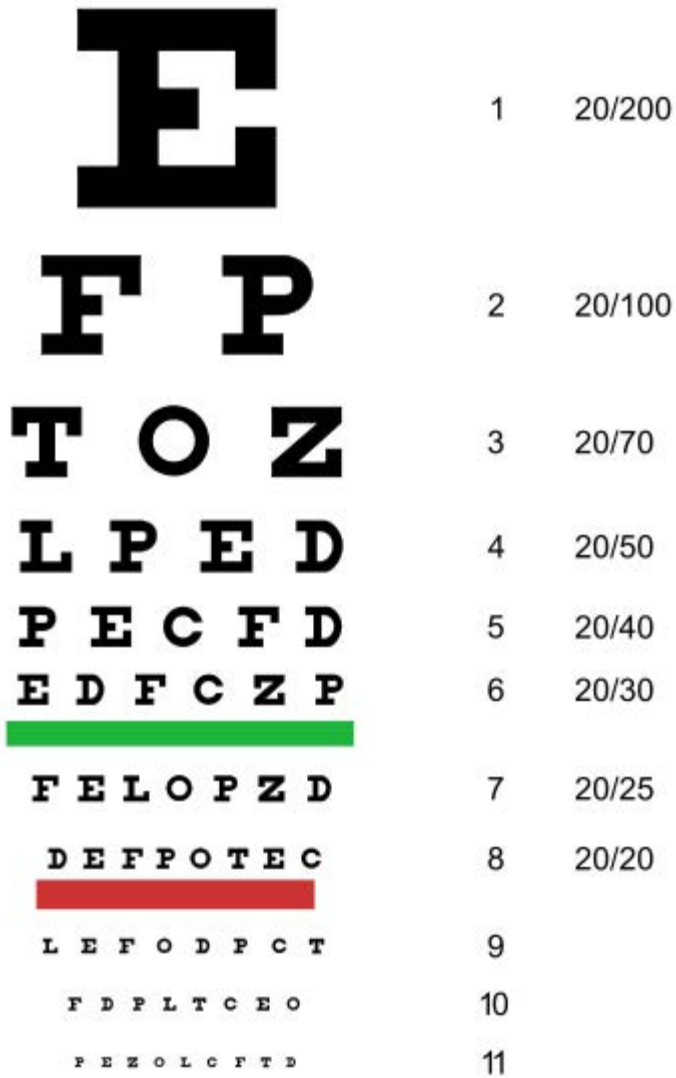
Point spread function (PSF)



From Webvision, Michael Kalloniatis

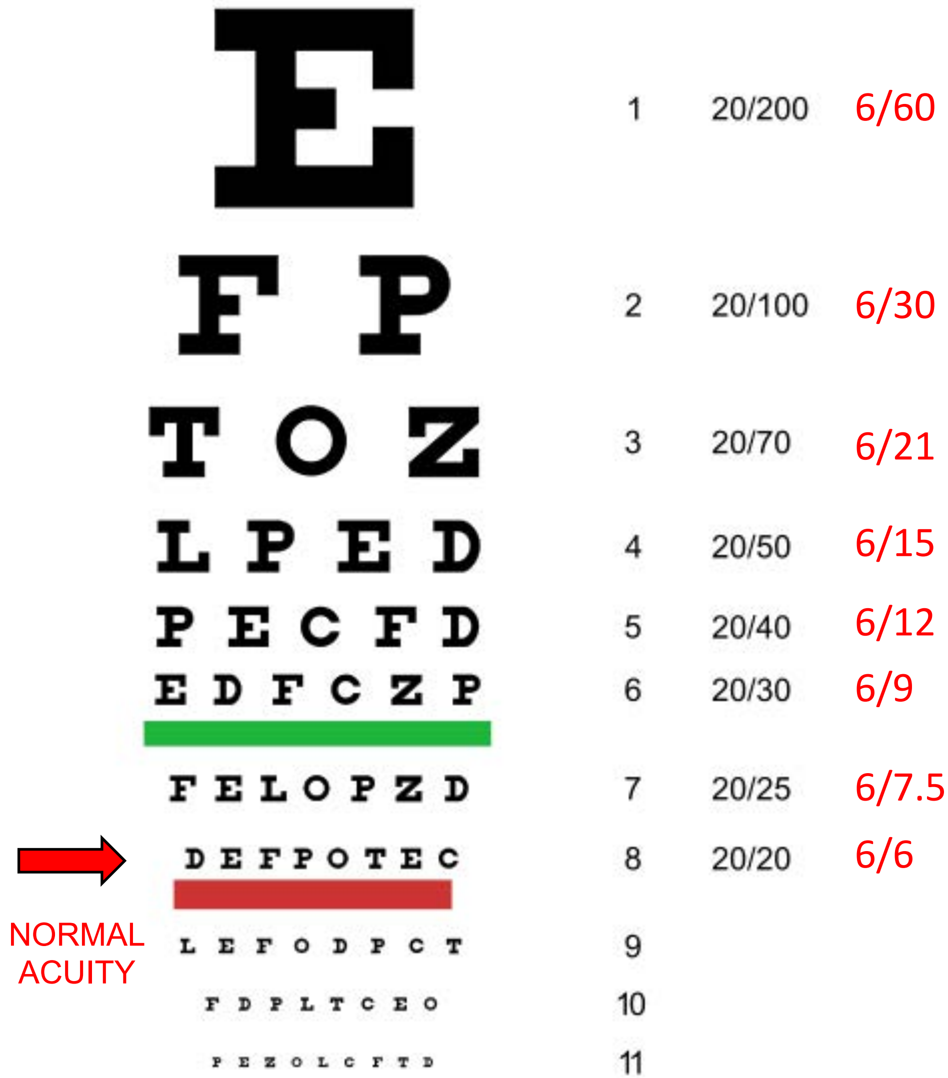
Measuring Image Quality Psychophysically

1. Visual acuity measures
   - Review methods for measurement in the clinic/trial setting
   - What do these measures represent
2. Spatial contrast sensitivity measures
   - Review methods for measurement in the clinic/trial setting
   - How does this represent our vision



6/60
6/30
6/21
6/15
6/12
6/9
6/7.5
6/6

Smallest resolvable black and white target. Many different types of tests are available , but the letter chart introduced by Snellen in 1862 is the most common.



Snellen defined “standard vision” as the ability to recognize one of his optotypes when it subtended 5 minutes of arc. Thus, the optotype can only be recognized if the person viewing it can discriminate a spatial pattern separated by a visual angle of 1 minute of arc.

A Snellen chart is placed at a standard distance, twenty feet in the US (6 metres in Europe). At this distance, the symbols on the line representing "normal" acuity subtend an angle of five minutes of arc, and the thickness of the lines and of the spaces between the lines subtends one minute of arc. This line, designated 20/20, is the smallest line that a person with normal acuity can read at a distance of twenty feet.

The letters on the 20/40 line are twice as large. A person with normal acuity could be expected to read these letters at a distance of forty feet. This line is designated by the ratio 20/40. If this is the smallest line a person can read, the person's acuity is "20/40."

Visual Acuity: four standard methods

Letter acuity (Snellen)

Can the subject correctly identify the letter or the letter orientation?

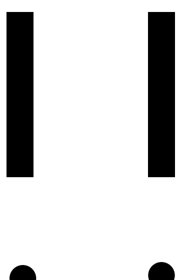
Grating acuity

Orientation resolution acuity

Detection acuity

2-line resolution

2-point resolution



Can the subject see two lines or points rather than one?

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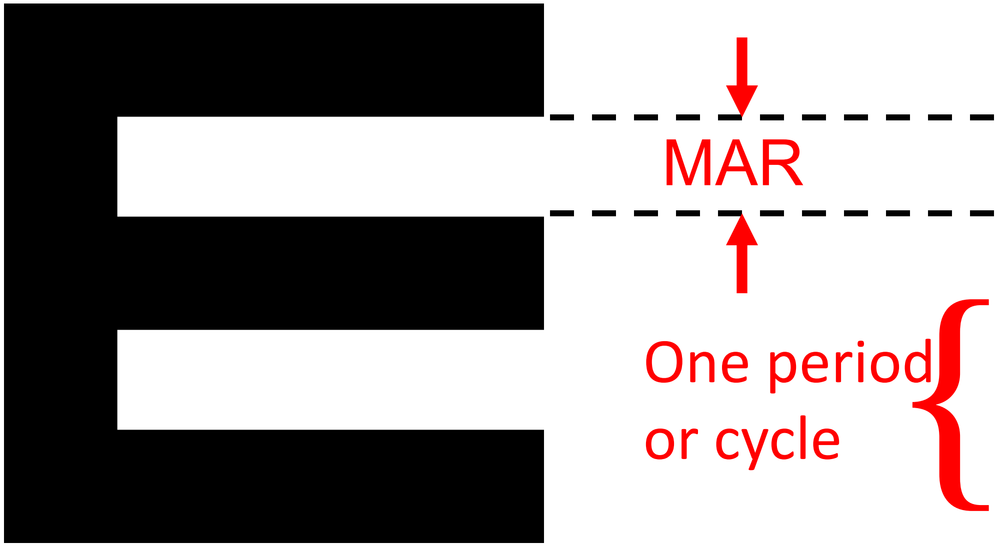
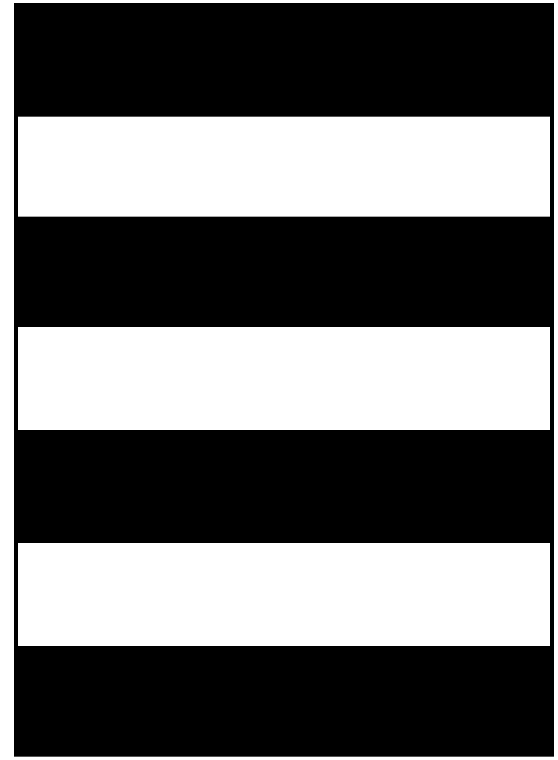
MAR = Minimum Angle of Resolution





MAR is the smallest gap between letter strokes or grating bars that can be detected/resolved.

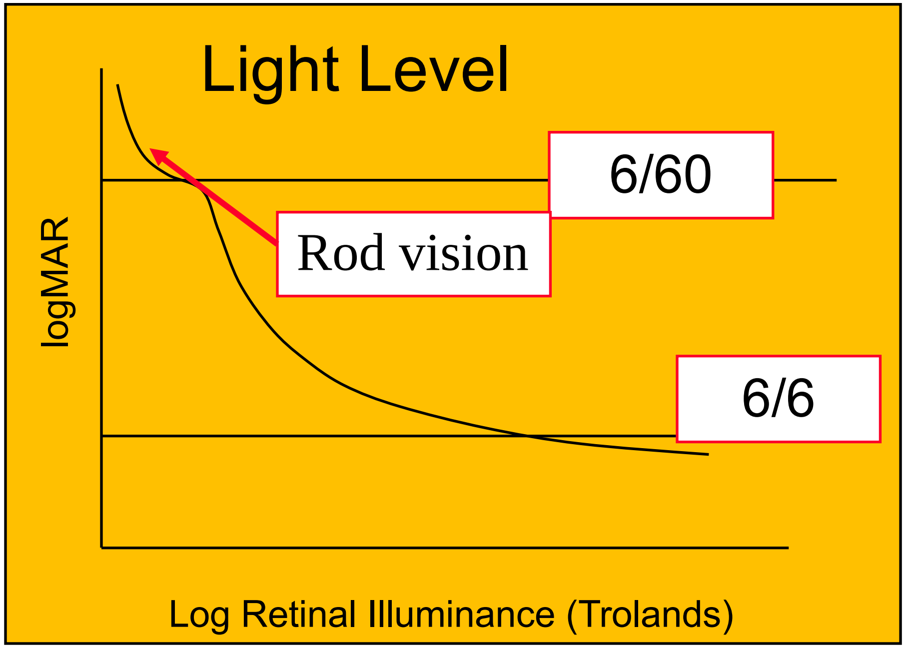
6/6 (20/20) letter: bar/stroke width = 1 arc minute, letter height = 5 min Grating period = 2 arc minute (1/30 degree) when bar = 1 min, and grating SF = 1/period = 30 c/deg,

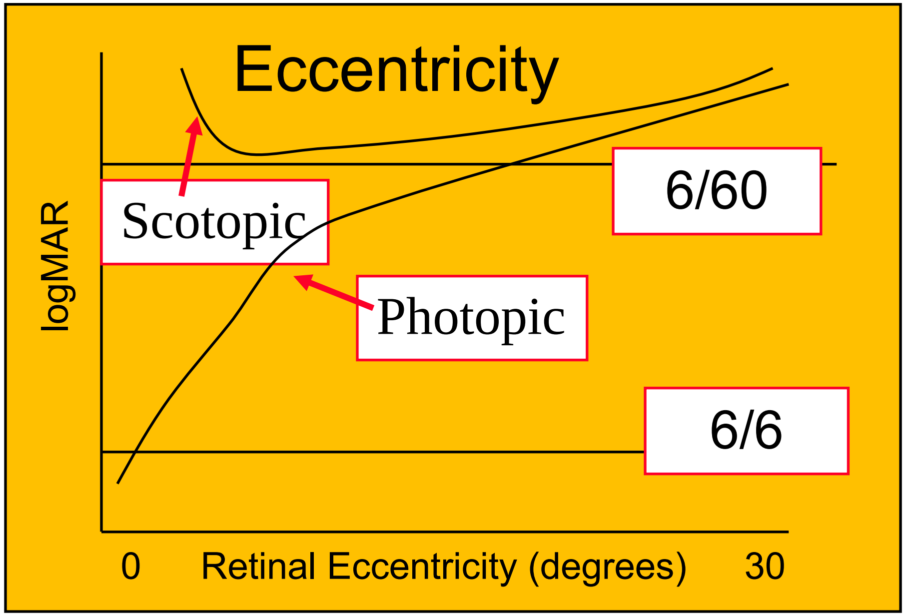
Comparison of seven different visual acuity measures

Snellen	Metric Snellen	MAR in arc minutes	Log MAR	Decimal	Grating VA c/deg
20/10	6/3	0.5	-0.3	2.0	60
20/15	6/4.5	0.75	-.12	1.33	40
20/20	6/6	1	0.0	1.0	30
20/25	6/7.5	1.25	0.1	0.8	24
20/30	6/9	1.5	0.18	0.7	21
20/40	6/12	2	0.3	0.5	15
20/50	6/15	2.5	0.4	0.4	12
20/70	6/21	3.5	0.54	0.3	9
20/100	6/30	5	0.7	0.2	6
20/200	6/60	10	1.0	0.1	3

NORMAL ACUITY

Arthur Bradley





Vision is not always 6/6!

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Measuring Image Quality Psychophysically

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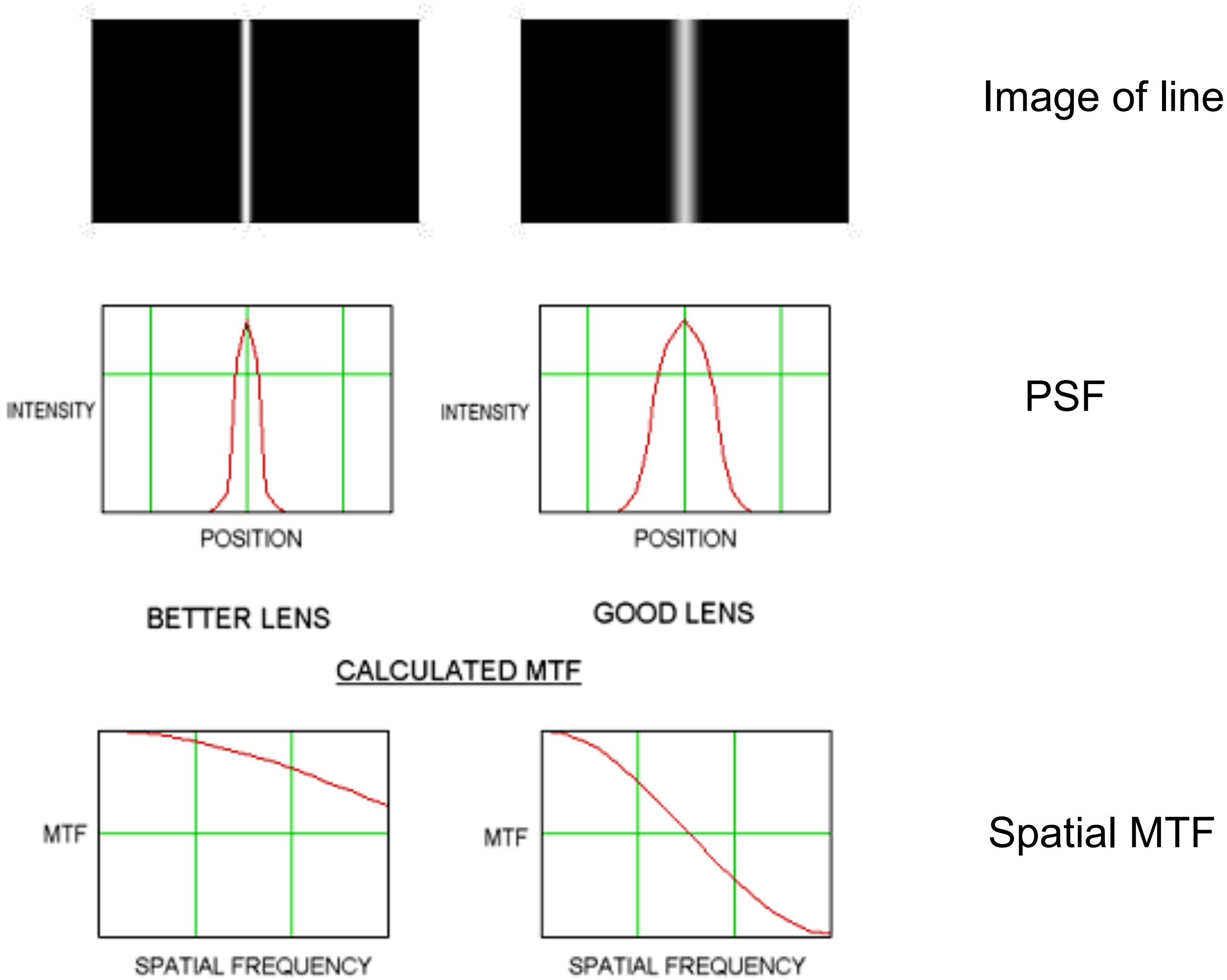
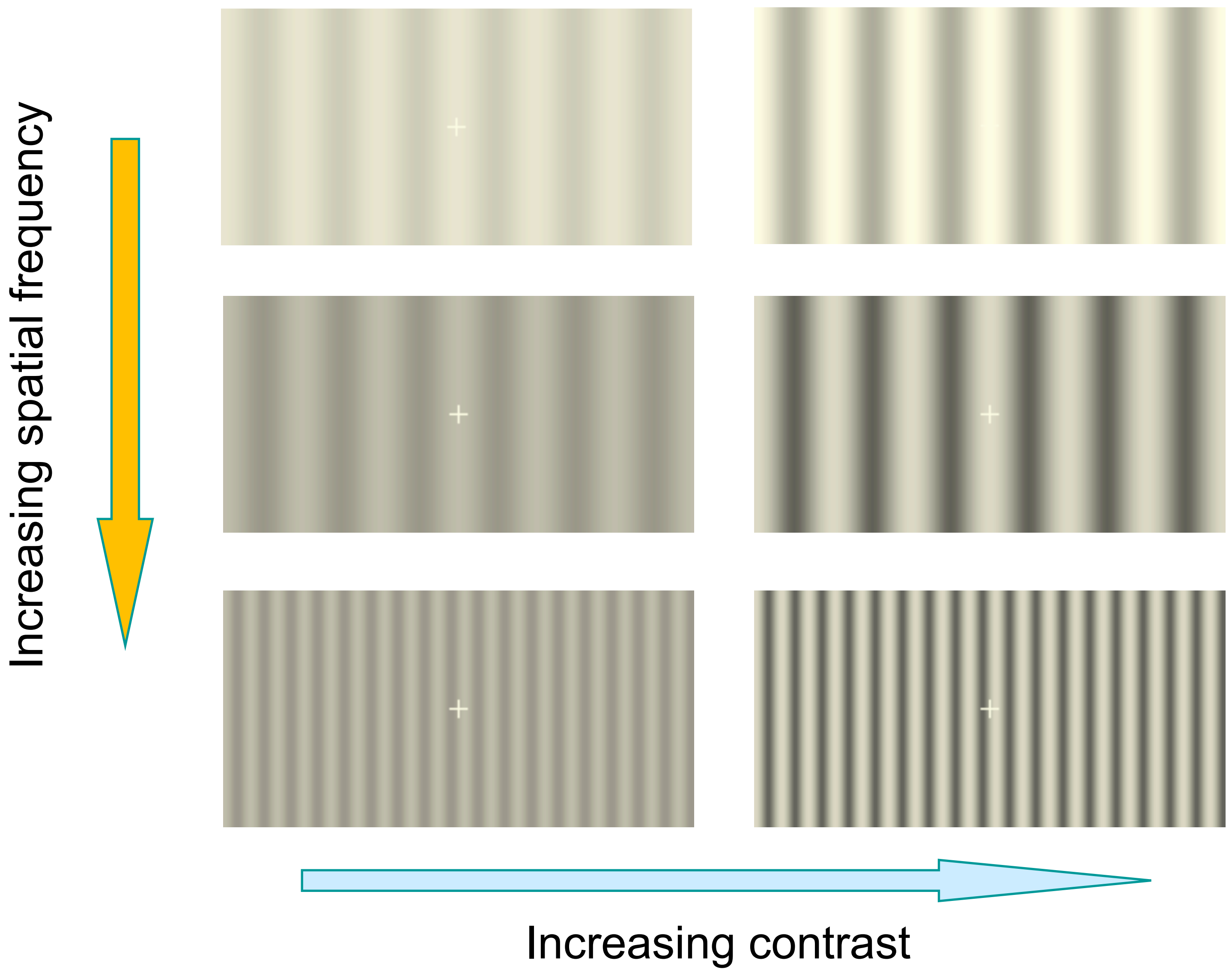


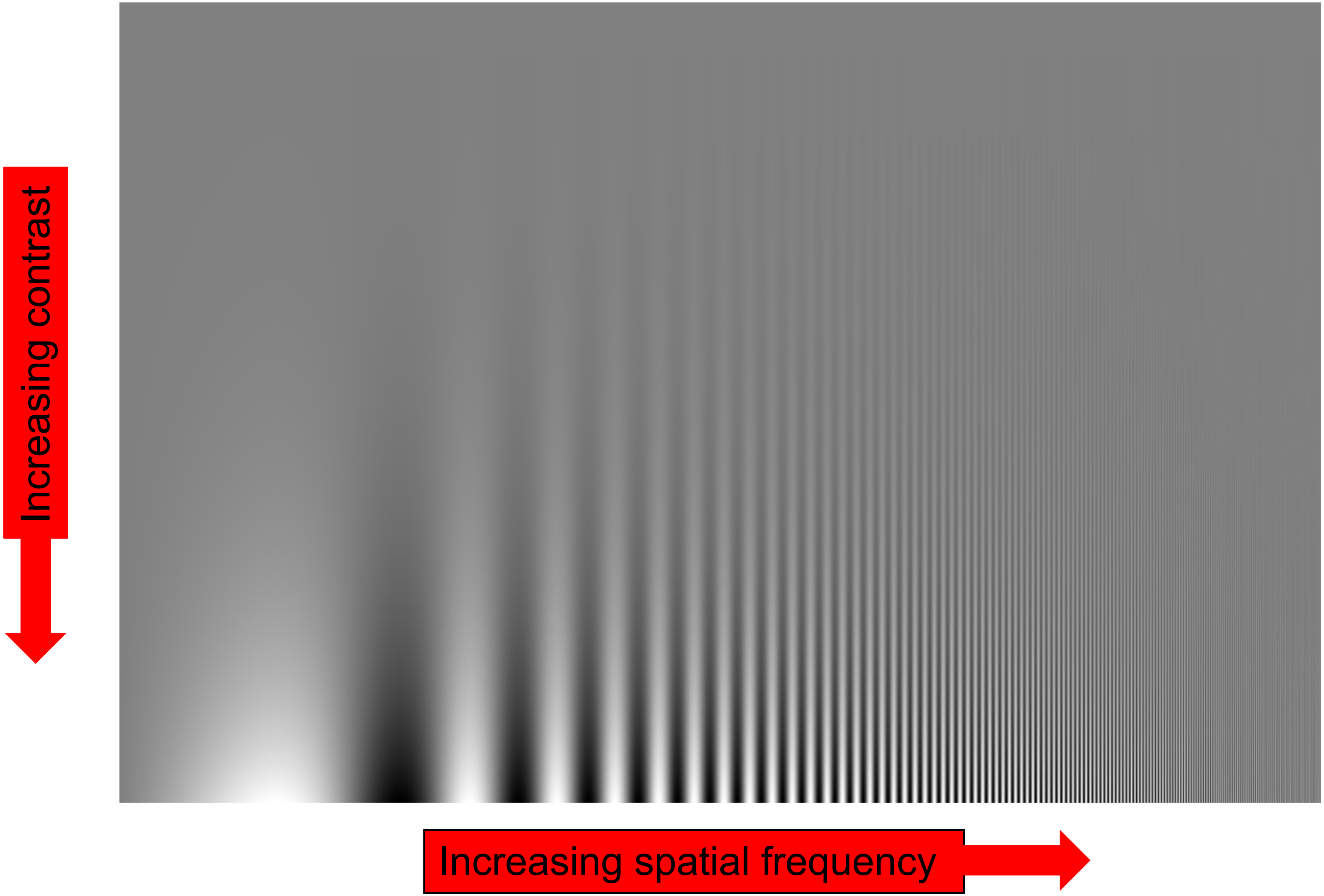
What would the results for a perfect lens look like?

Spatial Frequency Gratings



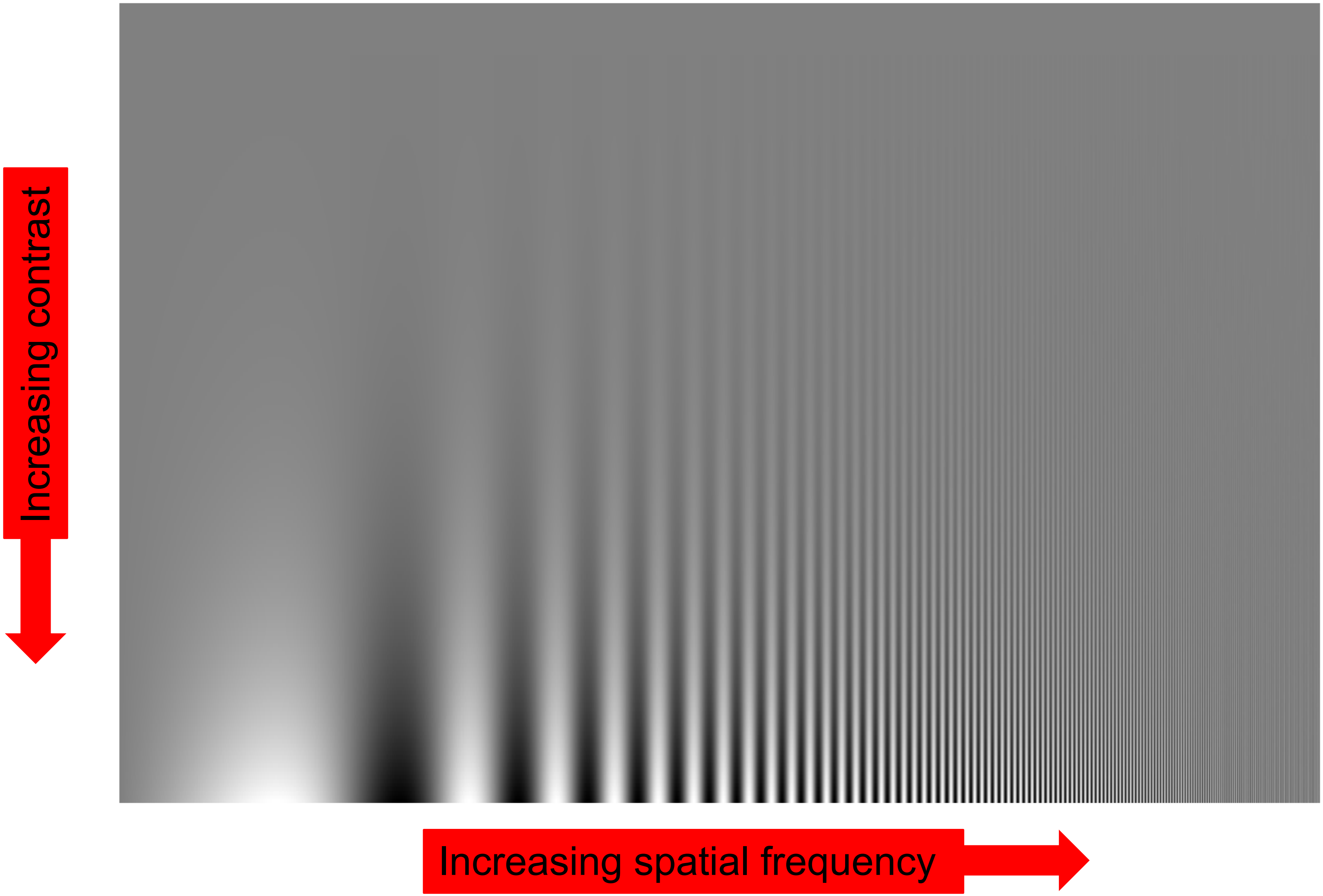
Spatial MTF

Spatial frequency in this image increases in the horizontal direction and modulation depth decreases in the vertical direction.



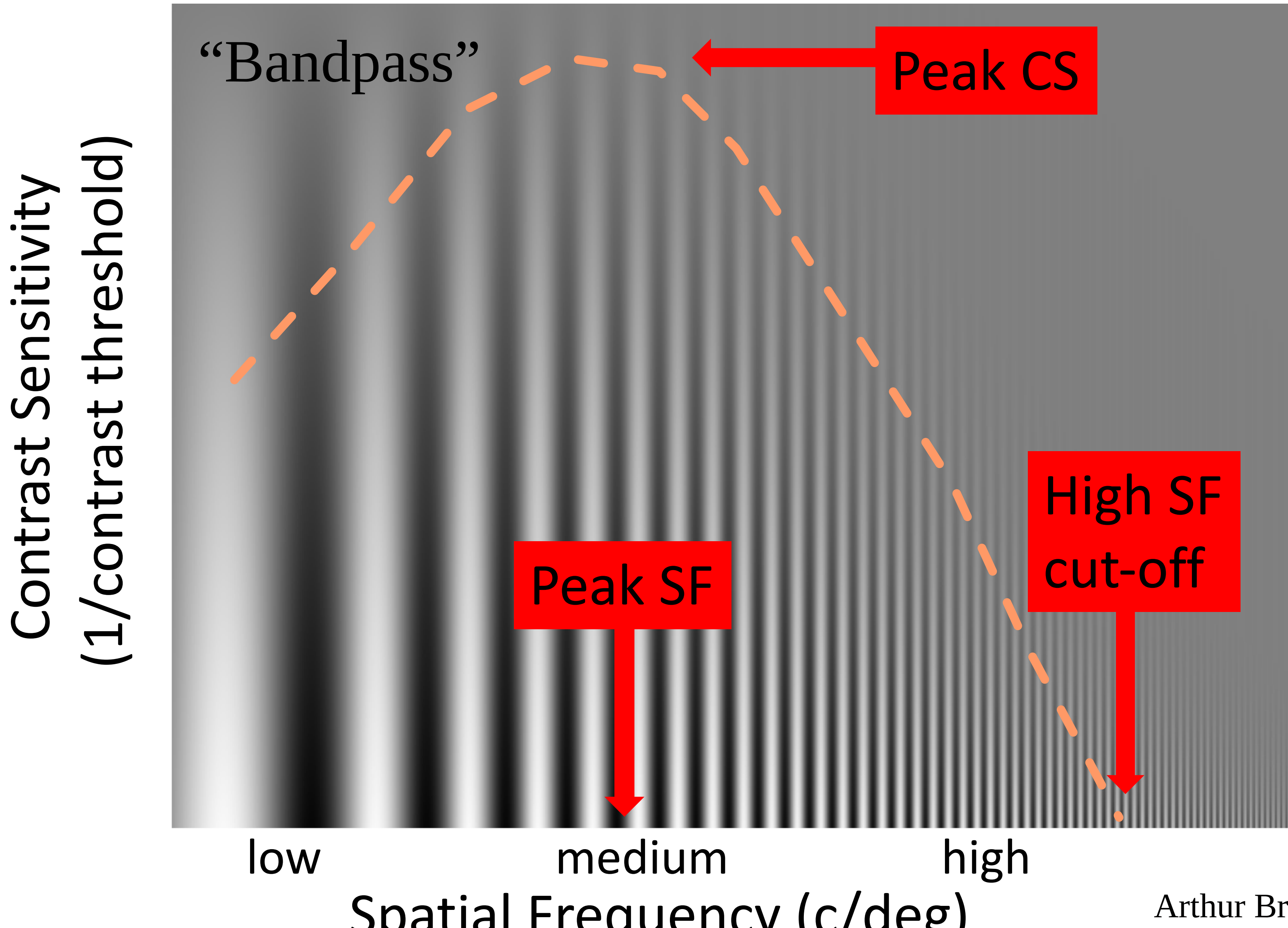
Spatial MTF

The apparent border between visible and invisible modulation corresponds to your own visual modulation transfer function.



2. Grating Contrast Sensitivity

Contrast Sensitivity Function (CSF)



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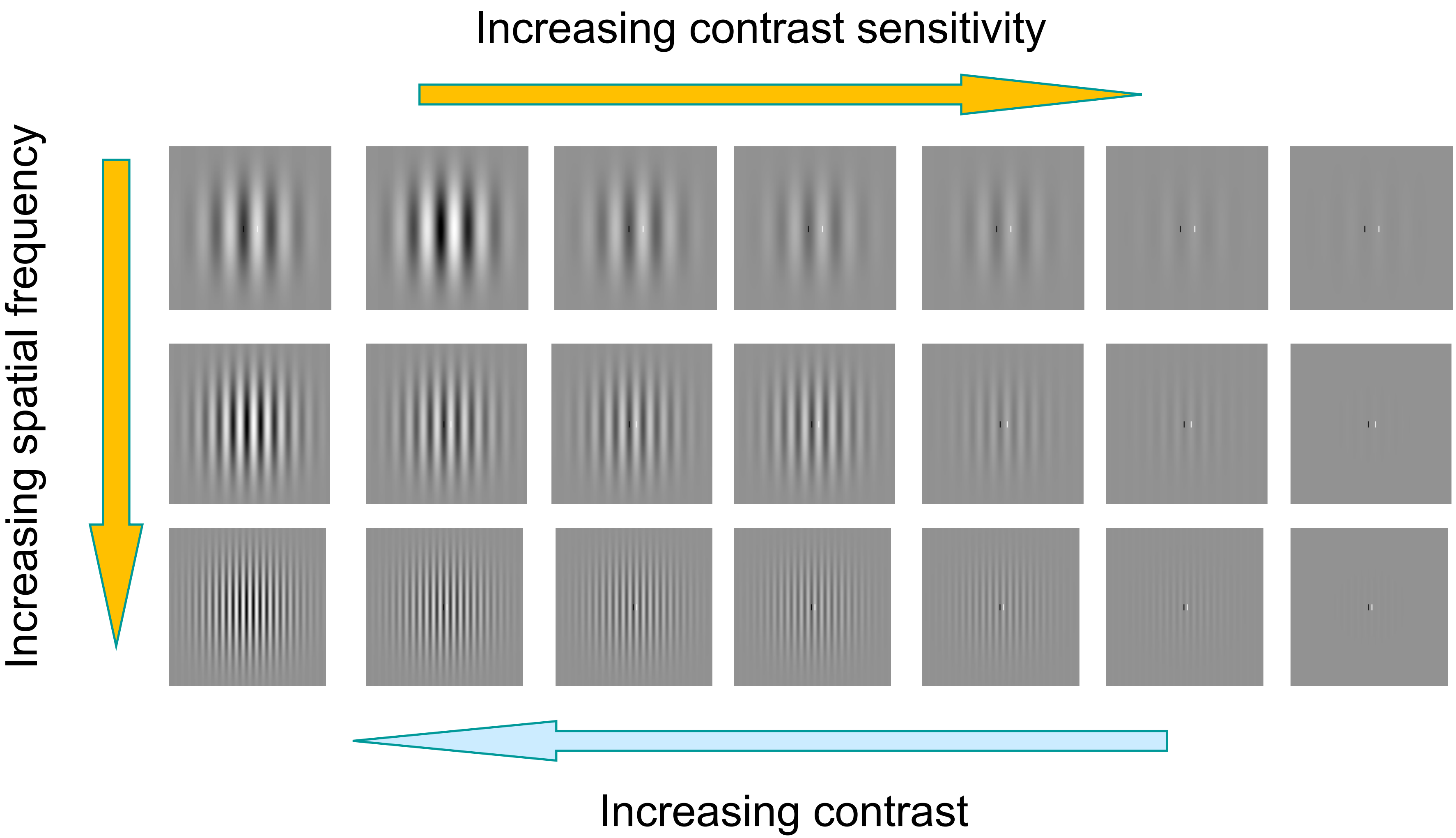
Example of grating contrast sensitivity test using printed grating



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Spatial CSFs

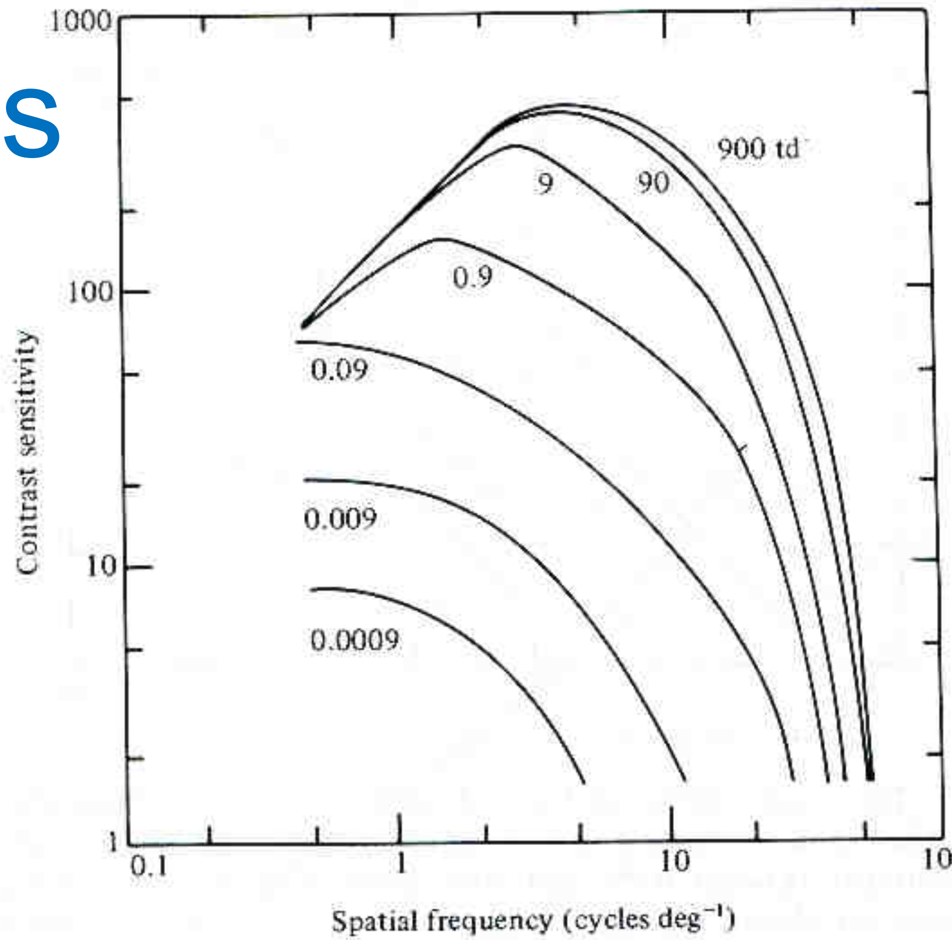
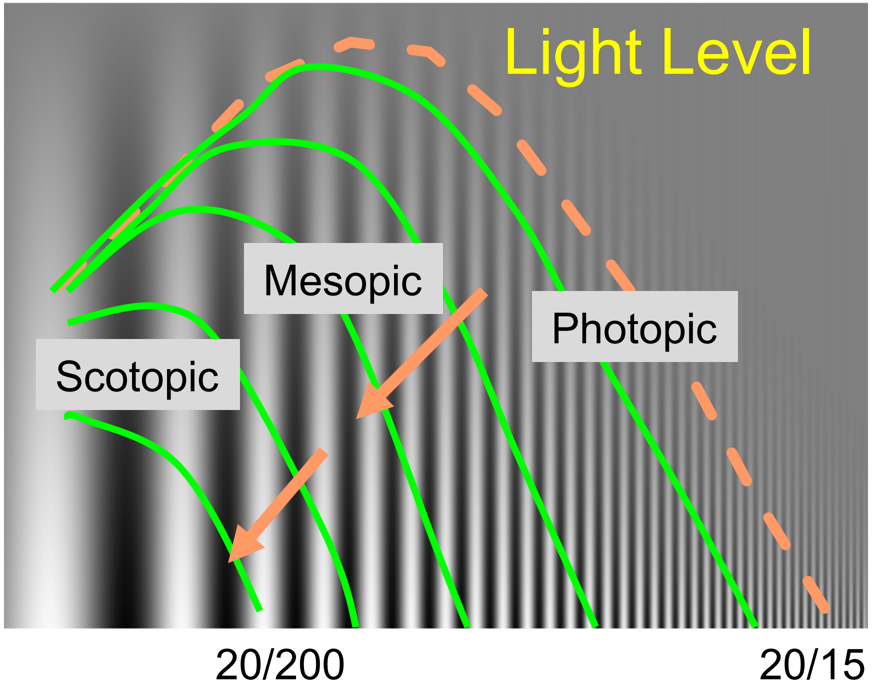
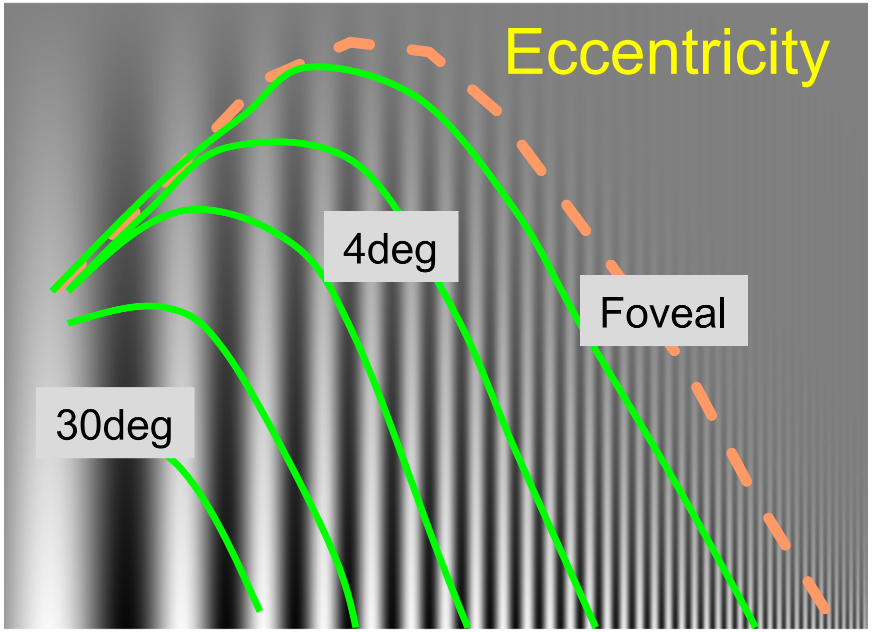


Fig. 8.4. Spatial contrast sensitivity curves at seven different retinal illuminance levels between 0.0009 and 900 trolands. The subject viewed the gratings through a 2 mm diameter artificial pupil. The wavelength of the light was 525 nm. Notice the loss of sensitivity for medium and high frequencies as the retinal illumination is decreased. (Adapted from Van Nes & Bouman, 1967.)

Contrast sensitivity varies!





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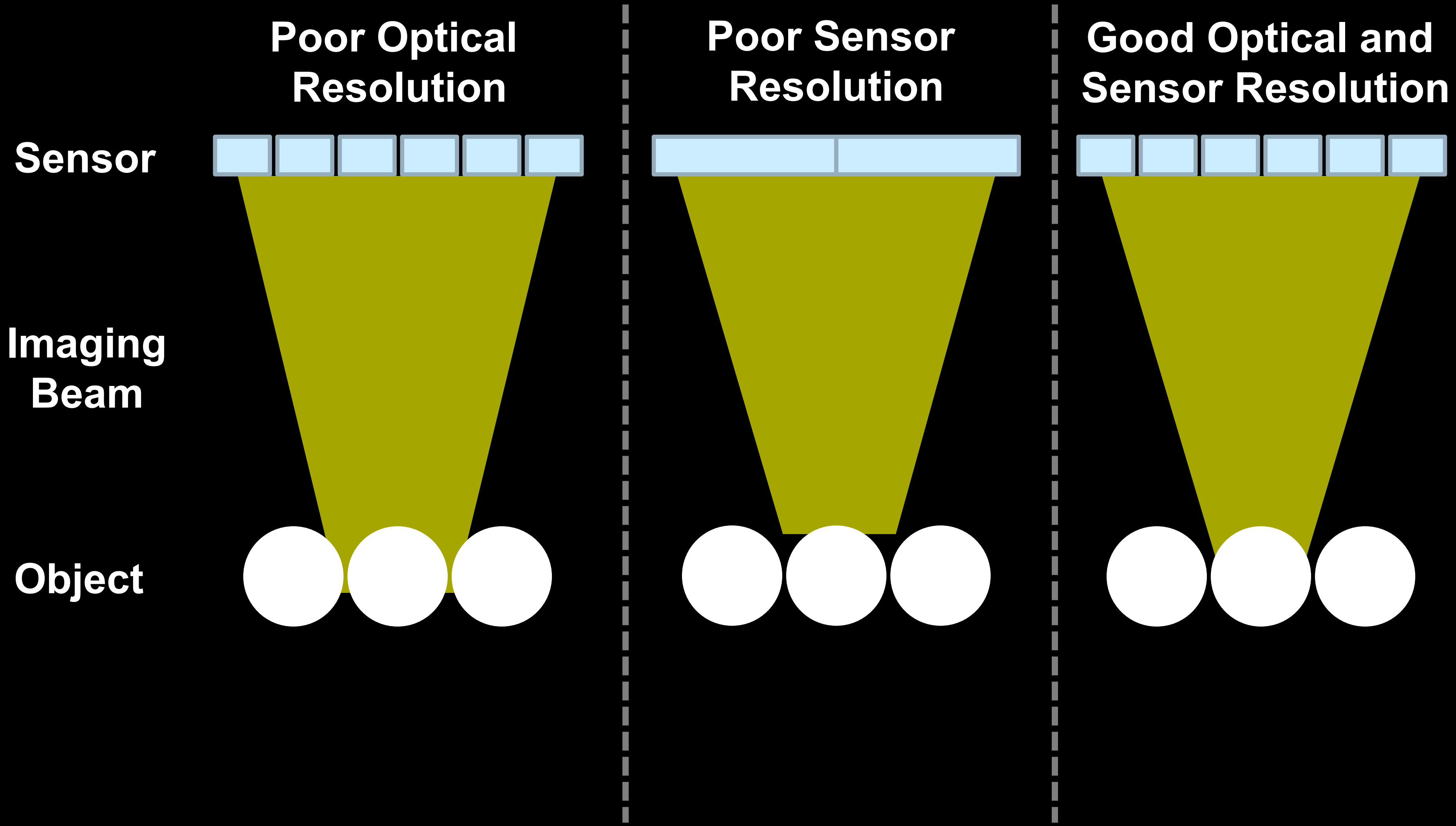
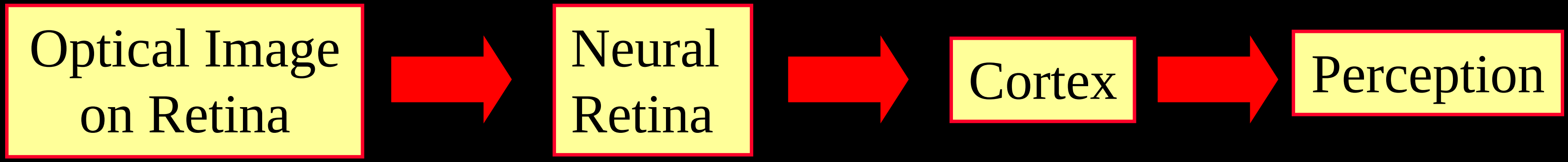
What limits visual performance?

Imaging Resolution



Stages



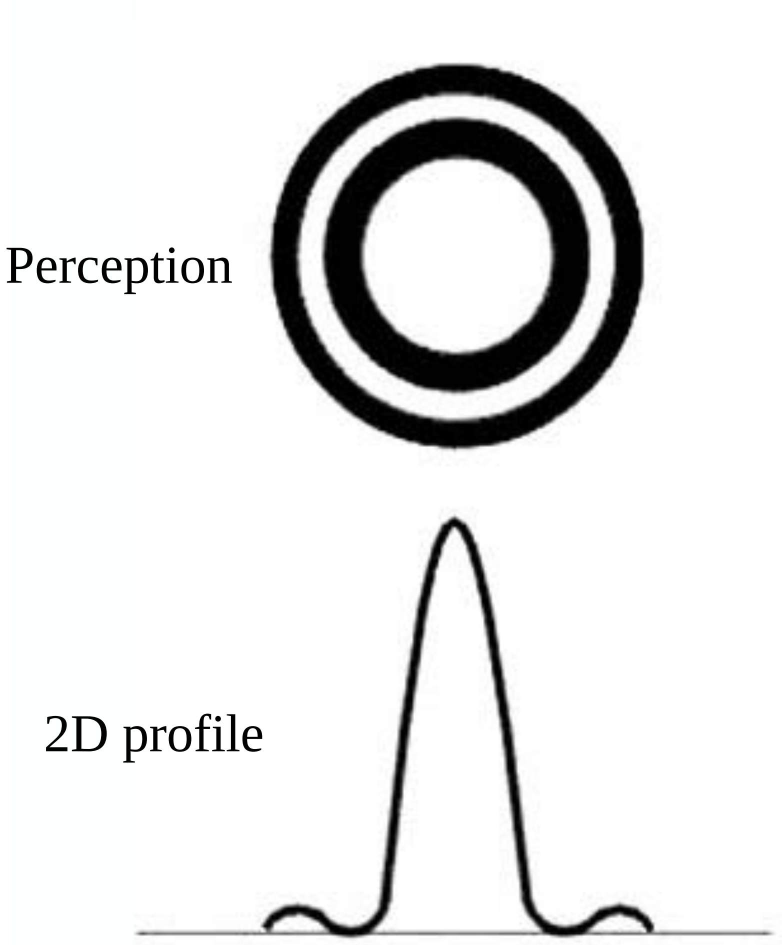
Stages

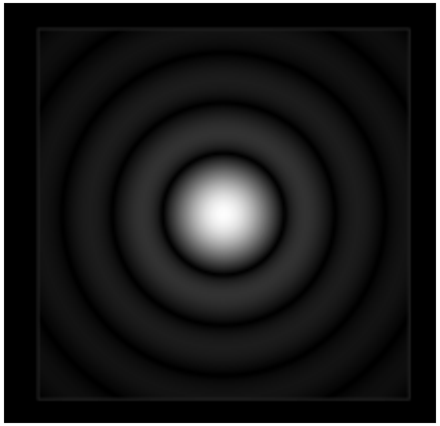
Optical Image on Retina →

Consider optical limits first

Airy disc (PSF)

For a diffraction-limited image an Airy disk pattern is formed on the retina from a point source due to the diffraction at the pupil.





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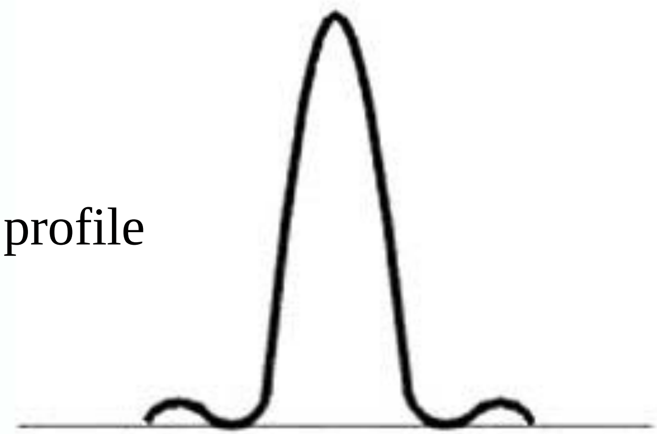
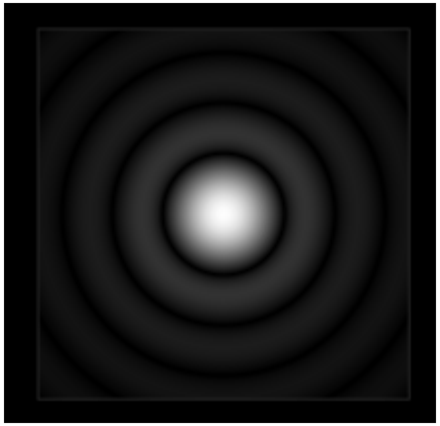
Airy disc (PSF)

How does this affect spatial resolution?

Perception

2D profile





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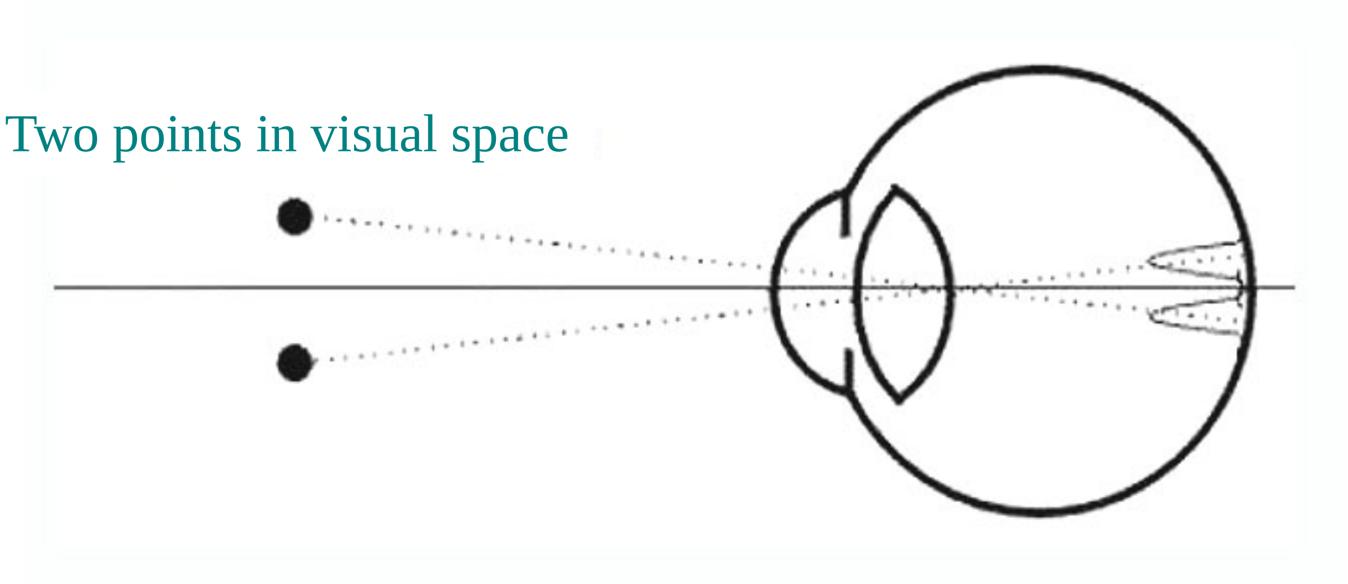
Overlapping point spread functions (PSF)



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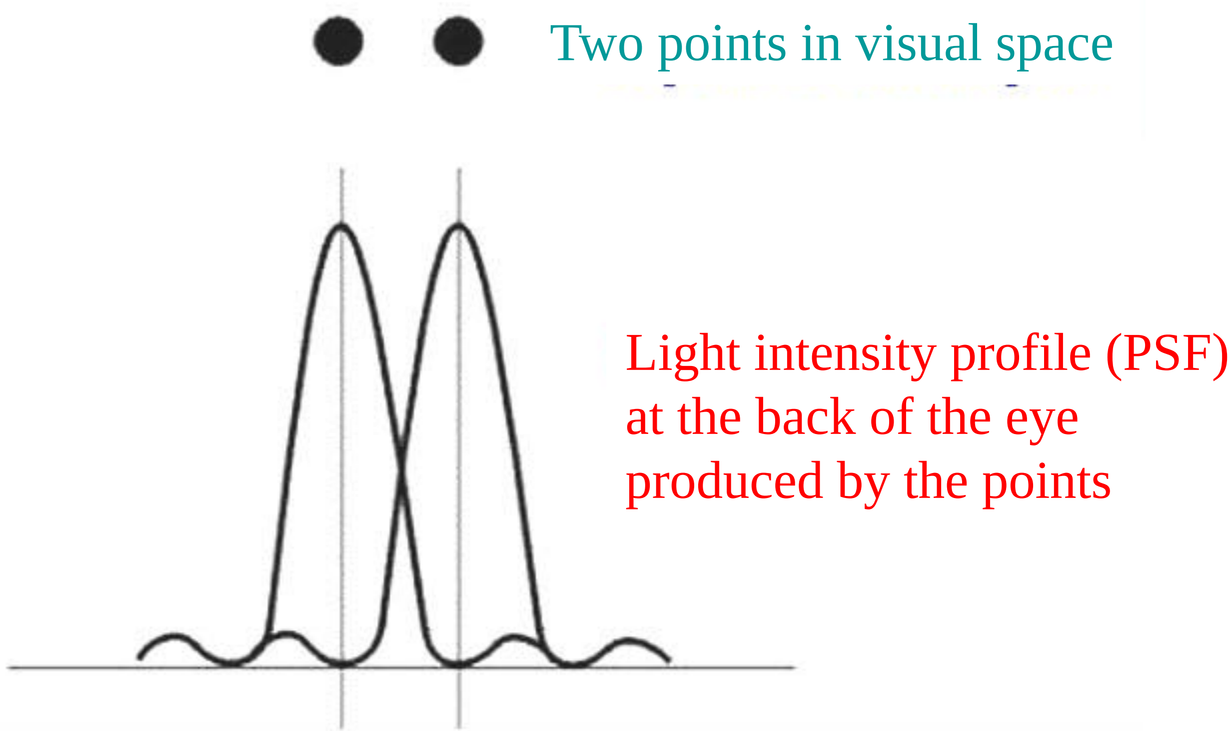
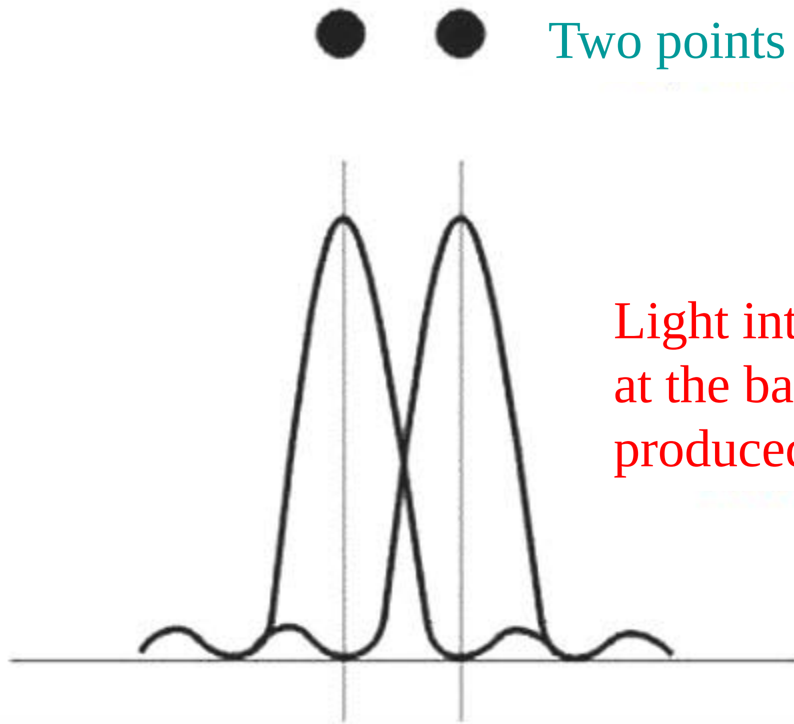


The **Rayleigh criterion** for resolving two point sources of equal brightness is when the peak of one diffraction pattern lies upon the first minimum of the other. This yields a theoretical maximum angular resolution referred to as *diffraction-limited resolution* given by:

$$\Delta\theta = 1.22\frac{\lambda}{D}$$

where $\Delta\theta$ is in radians, D is the diameter of the aperture (i.e. the pupil in this case) in the same units as the wavelength λ of the light.

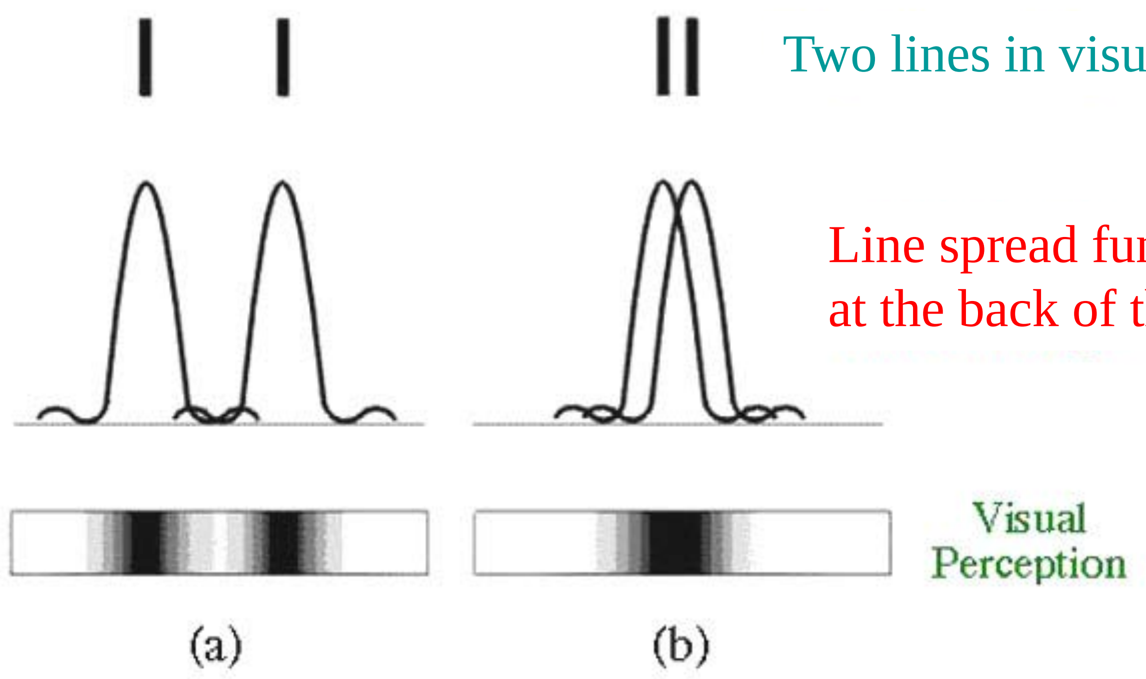
Two points in visual space



Light intensity profile (PSF) at the back of the eye produced by the points

$$\Delta\theta = 1.22\frac{\lambda}{D}$$

So, for a 550 nm light and a 3 mm diameter pupil, $\Delta\theta$ = 0.77 min of arc.



The two lines (a) can be perceptually resolved, but the two lines (b) cannot and are perceived as a single line.

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Comparison of seven different visual acuity measures

Snellen	Metric Snellen	MAR in arc minutes	LogMAR	Decimal	Grating VA c/deg	Jaeger Near VA
20/10	6/3	0.5	-0.3	2.0	60	NA
20/15	6/4.5	0.75	-.12	1.33	40	NA
20/20	6/6	1	0.0	1.0	30	J1+
20/25	6/7.5	1.25	0.1	0.8	24	J1
20/30	6/9	1.5	0.18	0.7	21	J2
20/40	6/12	2	0.3	0.5	15	J3
20/50	6/15	2.5	0.4	0.4	12	J5
20/70	6/21	3.5	0.54	0.3	9	J7
20/100	6/30	5	0.7	0.2	6	J10
20/200	6/60	10	1.0	0.1	3	J16

DIFFRACTION LIMIT

Arthur Bradley

Effect of Aperture: Pupil size

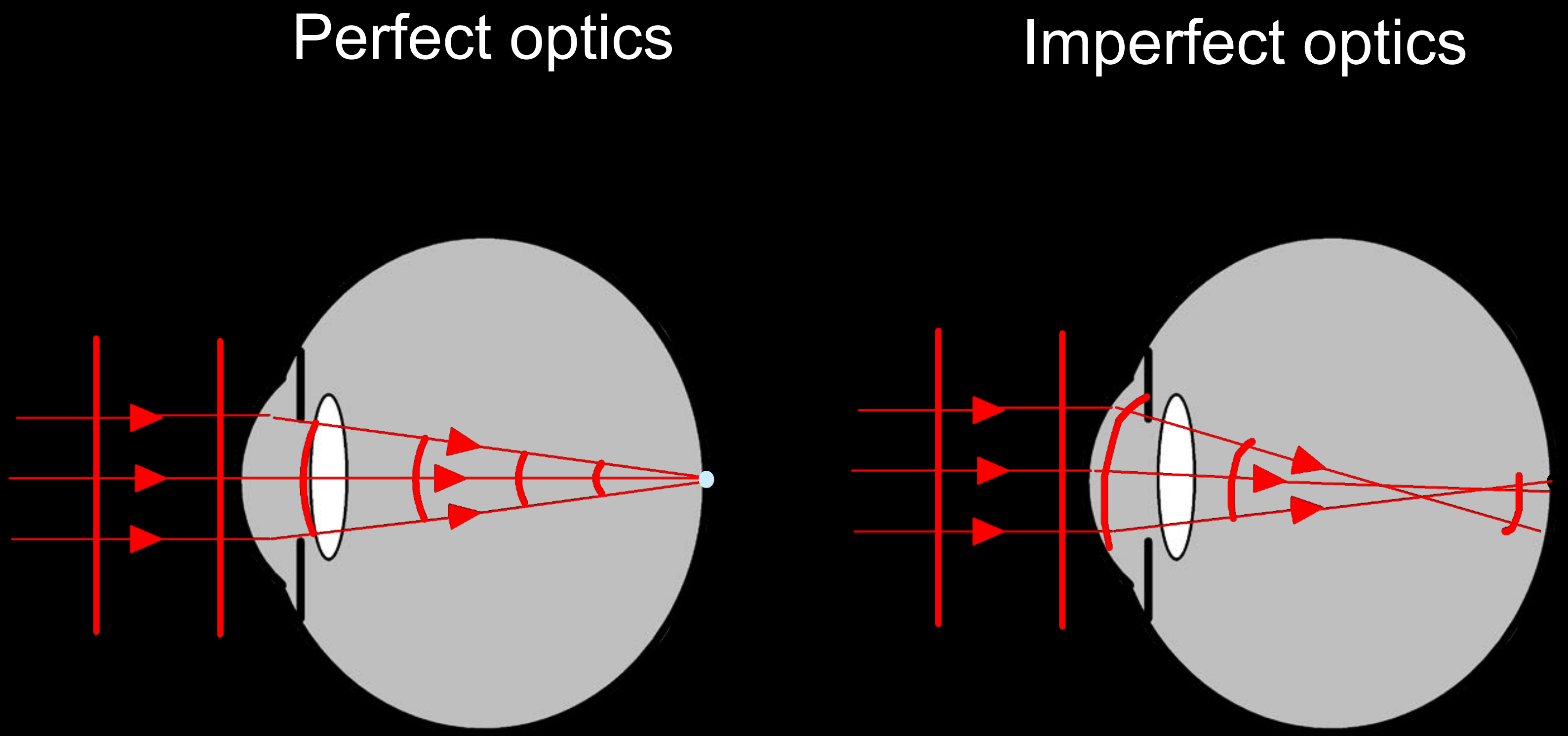
The size of the pupil is an important factor affecting visual acuity.

A large pupil allows more light to reach the retina and reduces diffraction but resolution is reduced because the optical aberrations are greater (a greater area of the lens and cornea are used and they are imperfect).

A small pupil reduces optical aberrations but resolution is then diffraction limited.

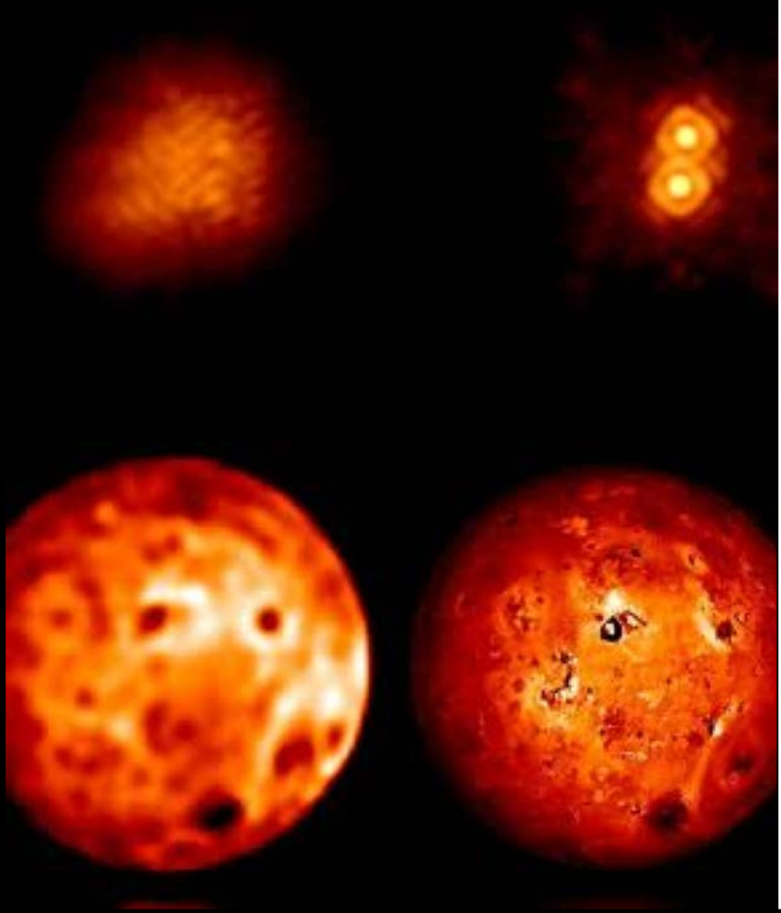
A mid-size pupil of about 3 mm to 5 mm represents a compromise between the diffraction and aberration limits

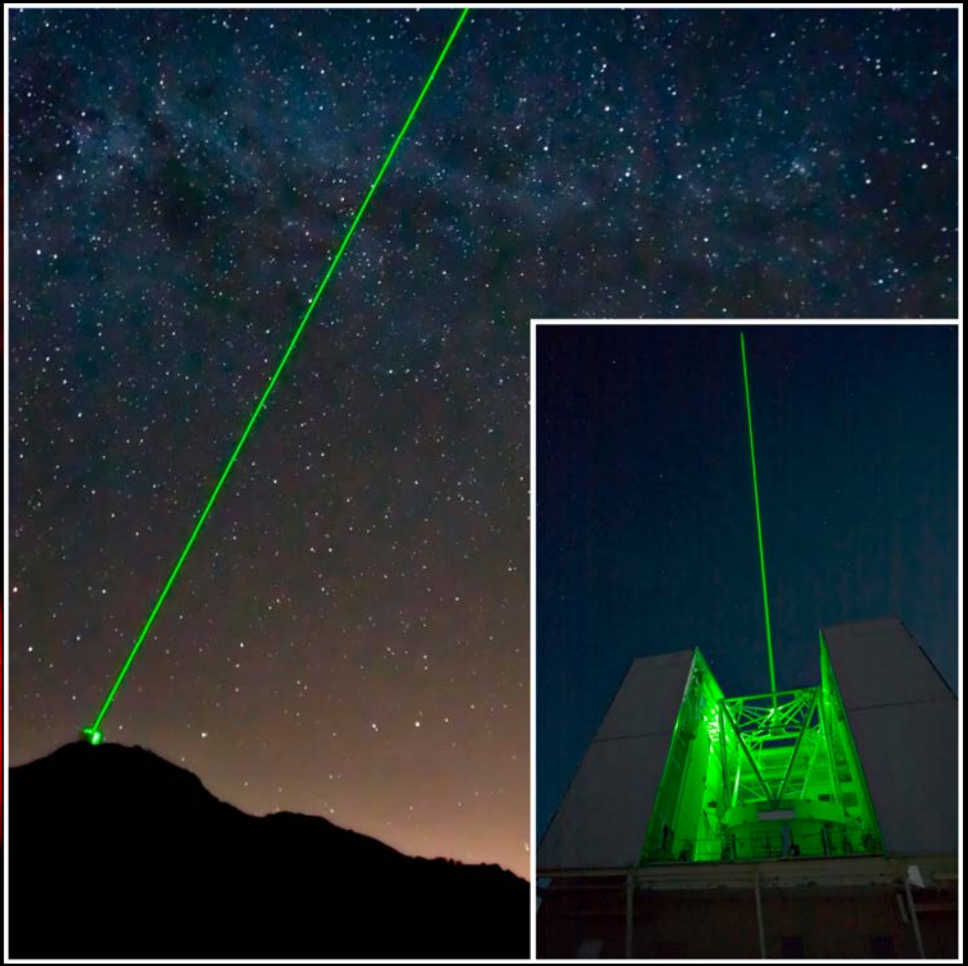
Aberrations of the Eye



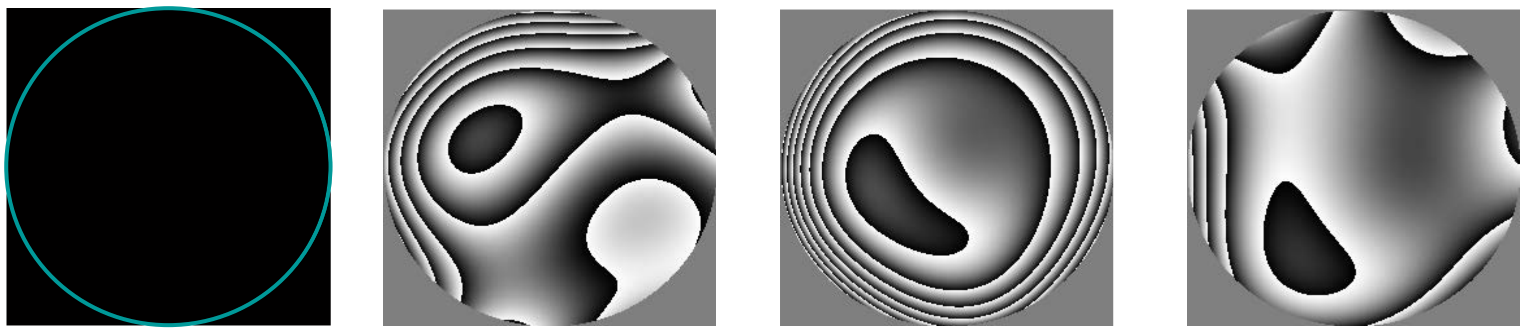
Larry Thibos

Removing Atmospheric Blur….
Adaptive Optical Systems



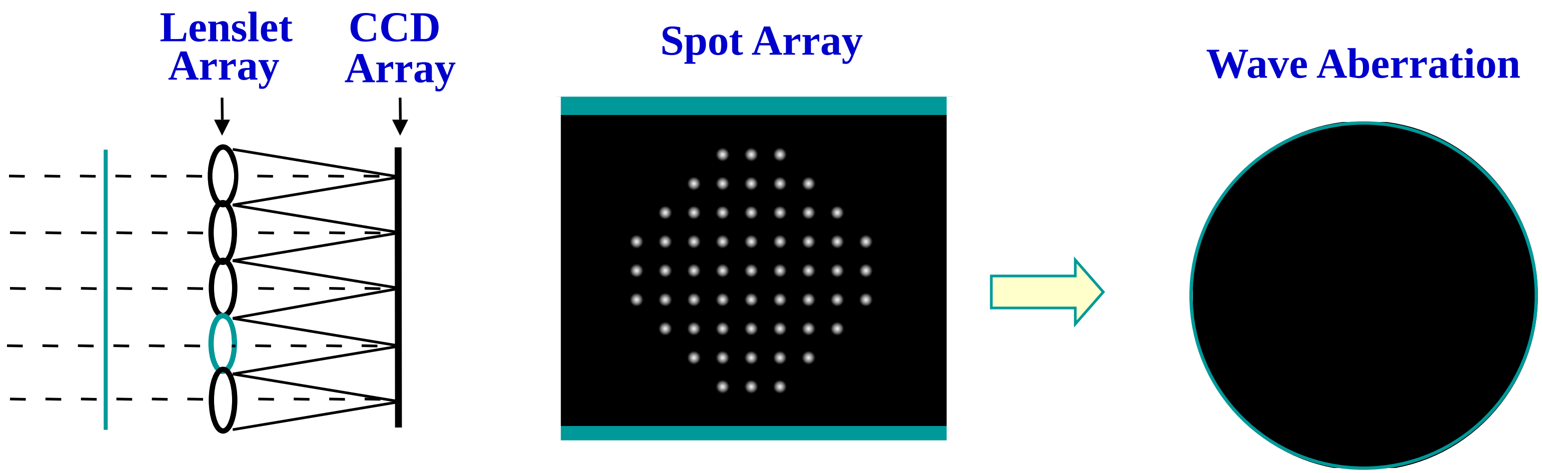


The Human Eye is Highly Aberrated

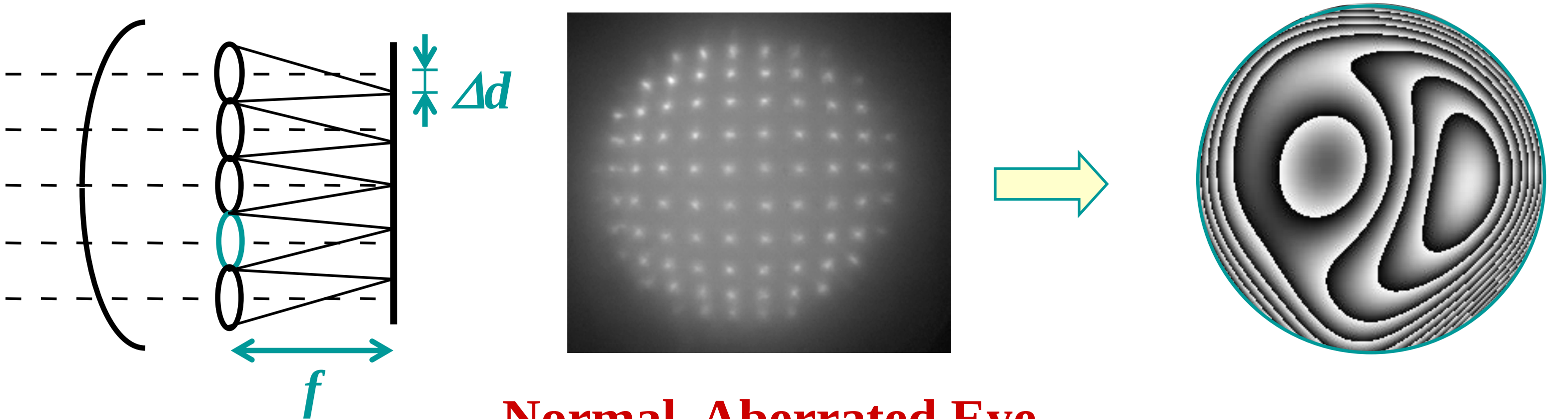


Courtesy: Jason Porter

The Human Eye is Highly Aberrated



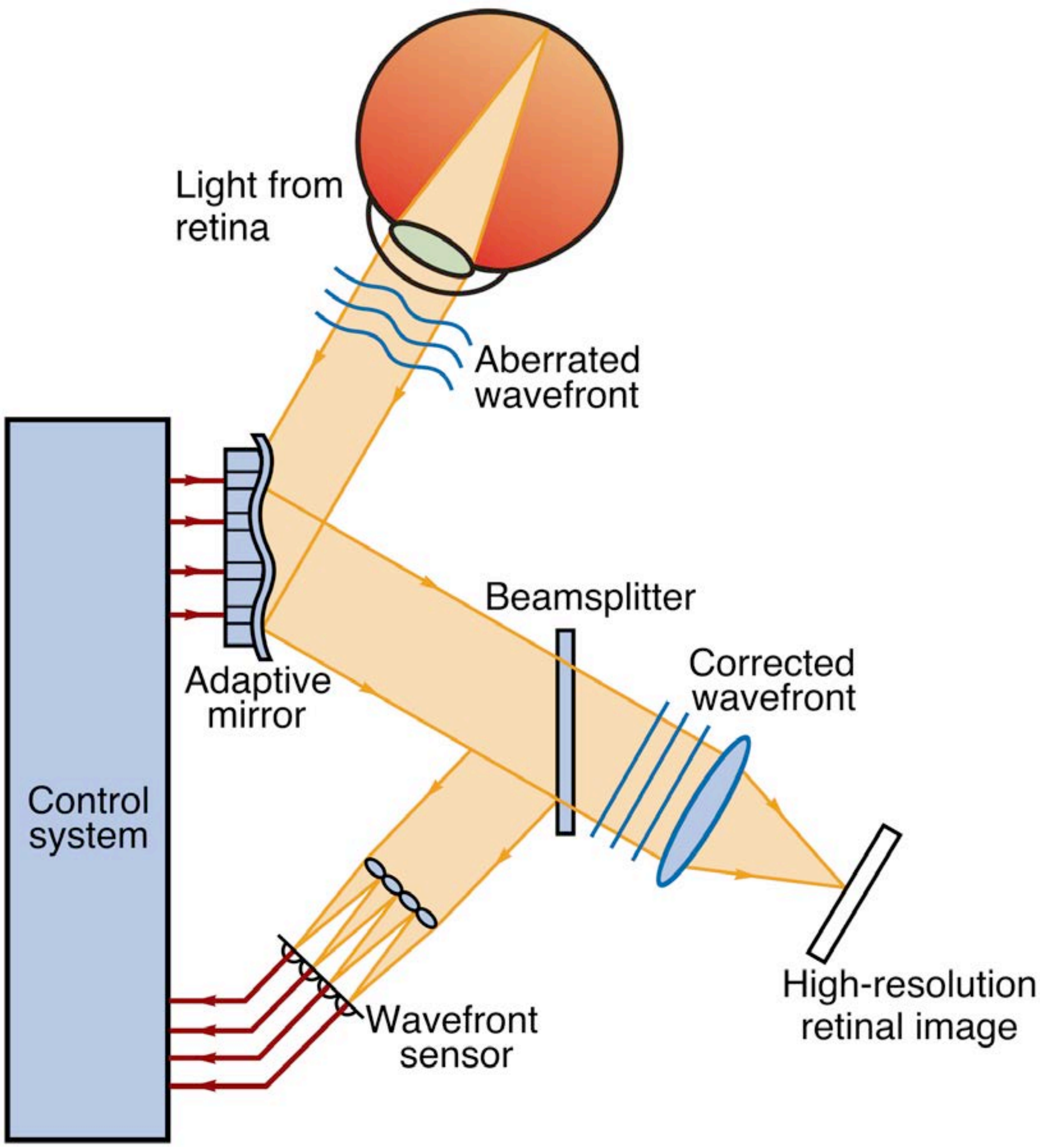
Ideal, Diffraction-Limited Eye

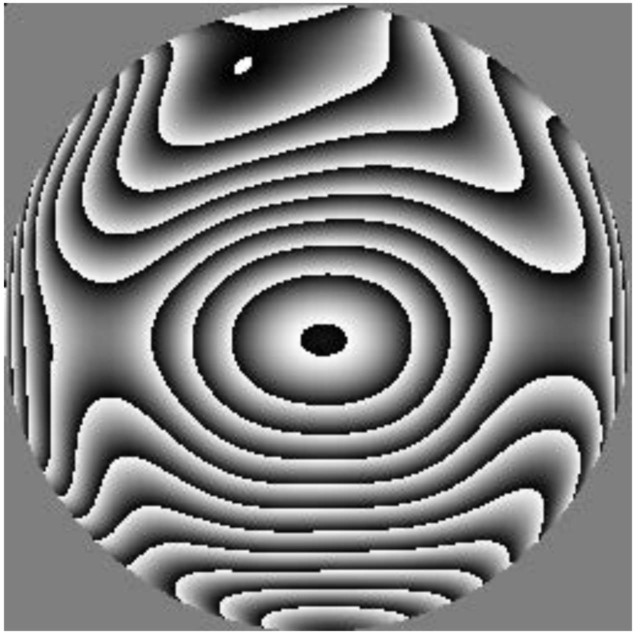


Normal, Aberrated Eye

$$\frac{\partial W(x,y)}{\partial x} = \frac{\Delta d_x}{f}$$

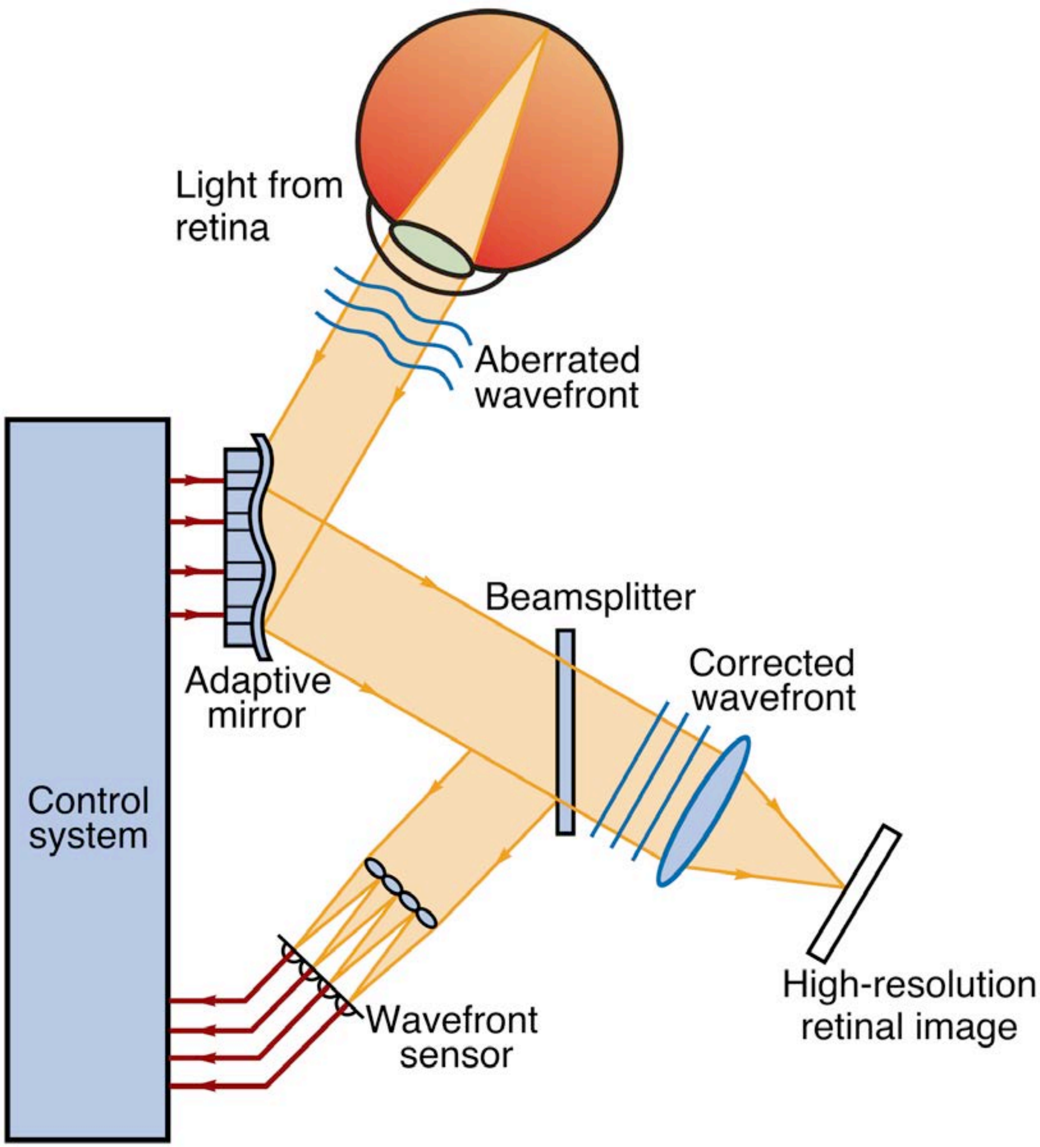
Principle of Adaptive Optics Retinal Imaging



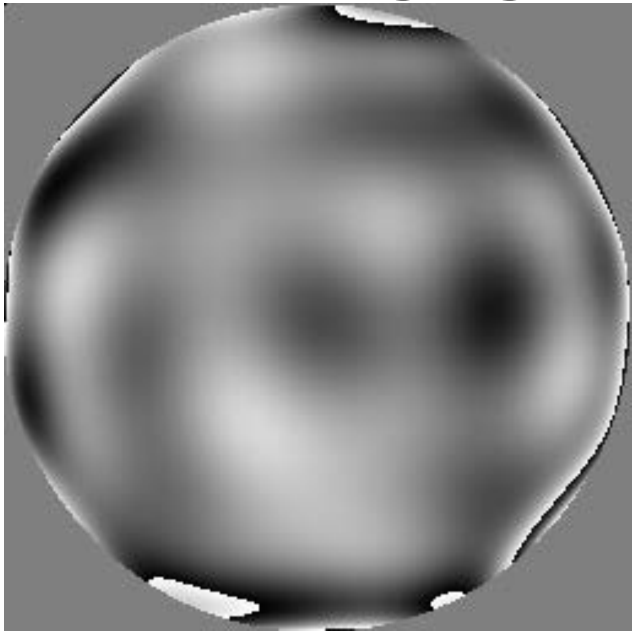


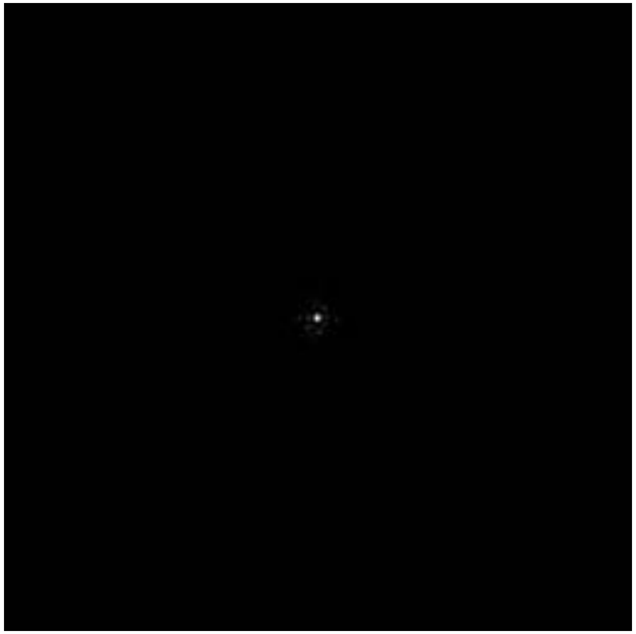
J. Carroll, D. Gray, A. Roorda, D. R. Williams (2005)

Principle of Adaptive Optics Retinal Imaging



J. Carroll, D. Gray, A. Roorda, D. R. Williams (2005)

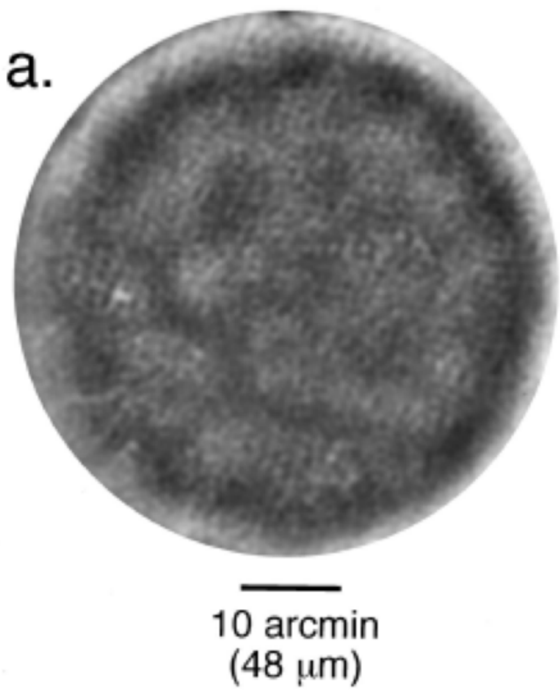


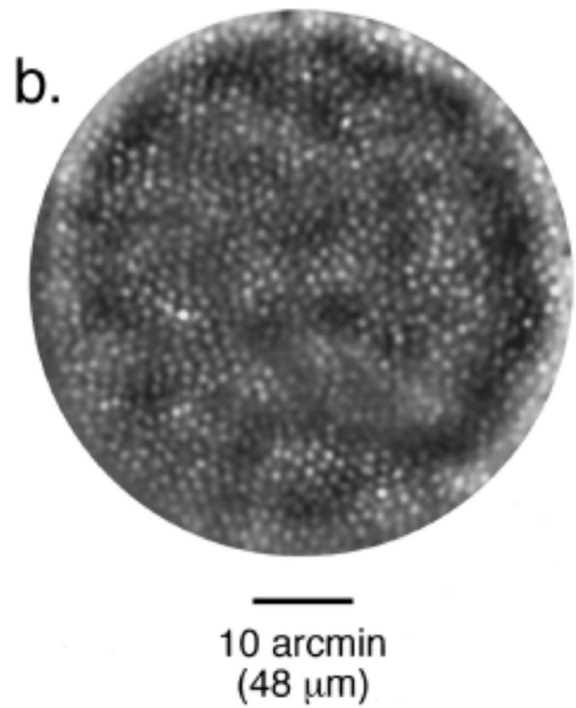


Supernormal vision and high-resolution retinal imaging through adaptive optics

Junzhong Liang, David R. Williams, and Donald T. Miller*

Center for Visual Science, University of Rochester, Rochester, New York 14627



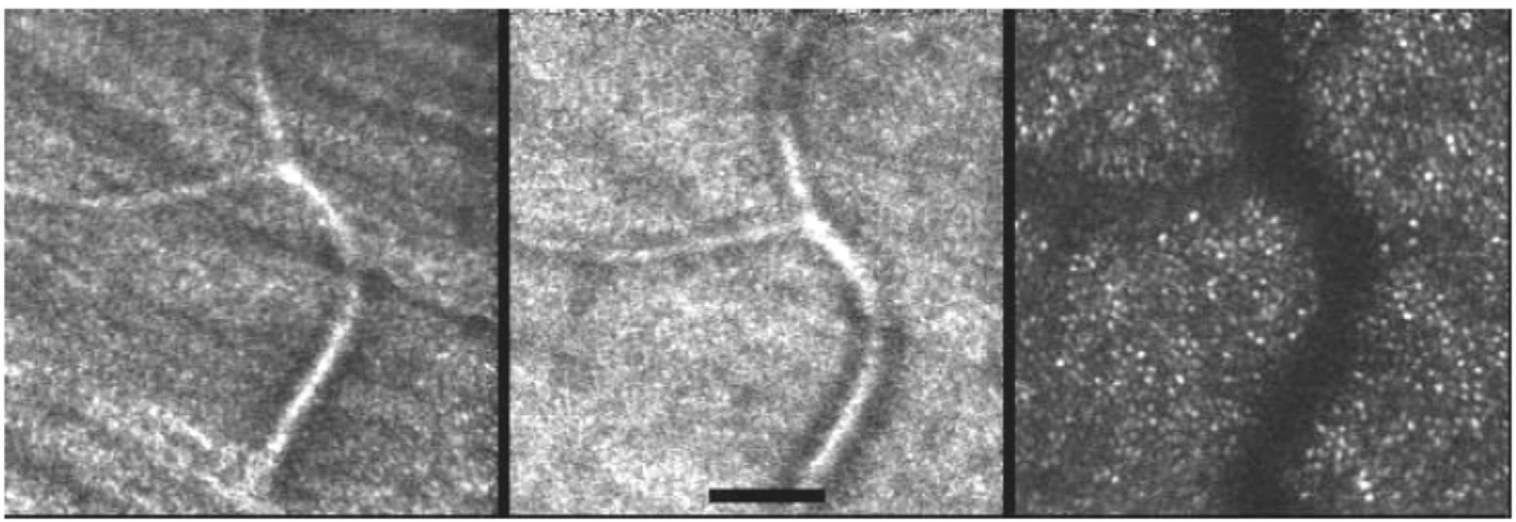


Adaptive optics scanning laser ophthalmoscopy

Austin Roorda, Fernando Romero-Borja, William J. Donnelly III, Hope Queener
College of Optometry, University of Houston, Houston Texas 77204-2020
aroorda@uh.edu

Thomas J. Hebert
Department of Computer and Electrical Engineering, University of Houston, Houston, TX 77204-4007

Melanie C.W. Campbell
School of Optometry, University of Waterloo, Waterloo, Ontario, Canada N2L 3G1

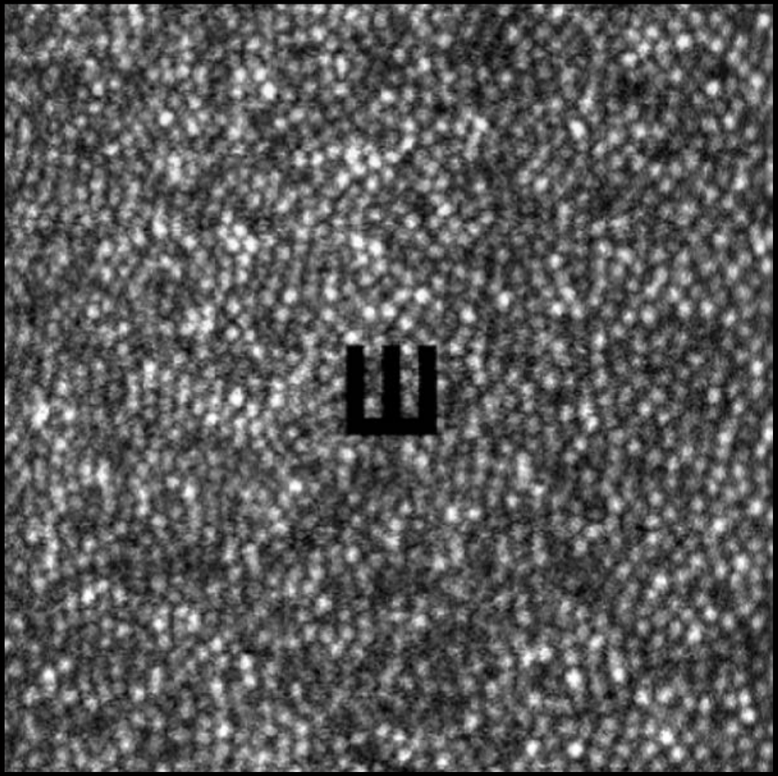


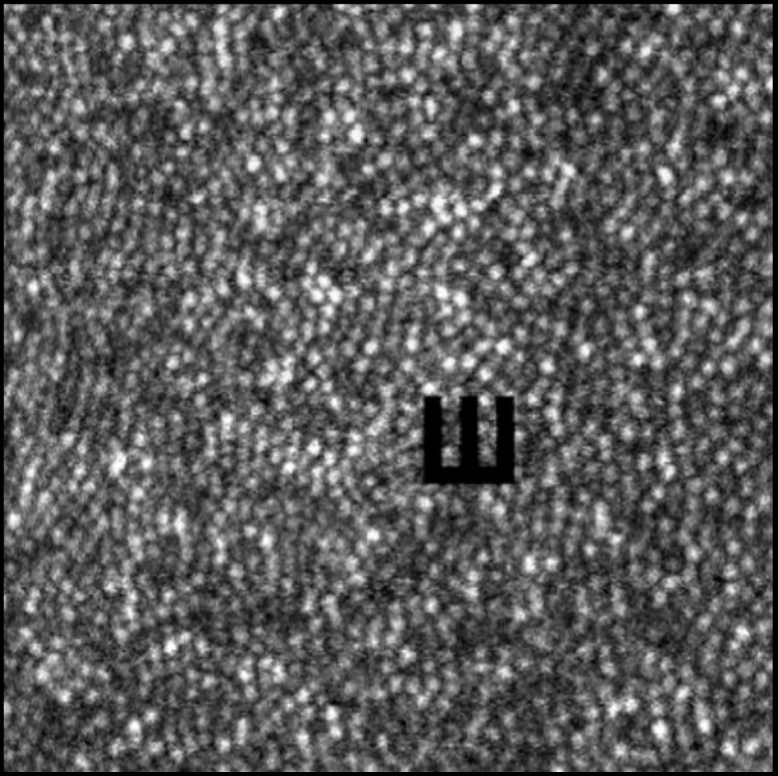
BRIEF COMMUNICATIONS

The relationship between visual resolution and cone spacing in the human fovea

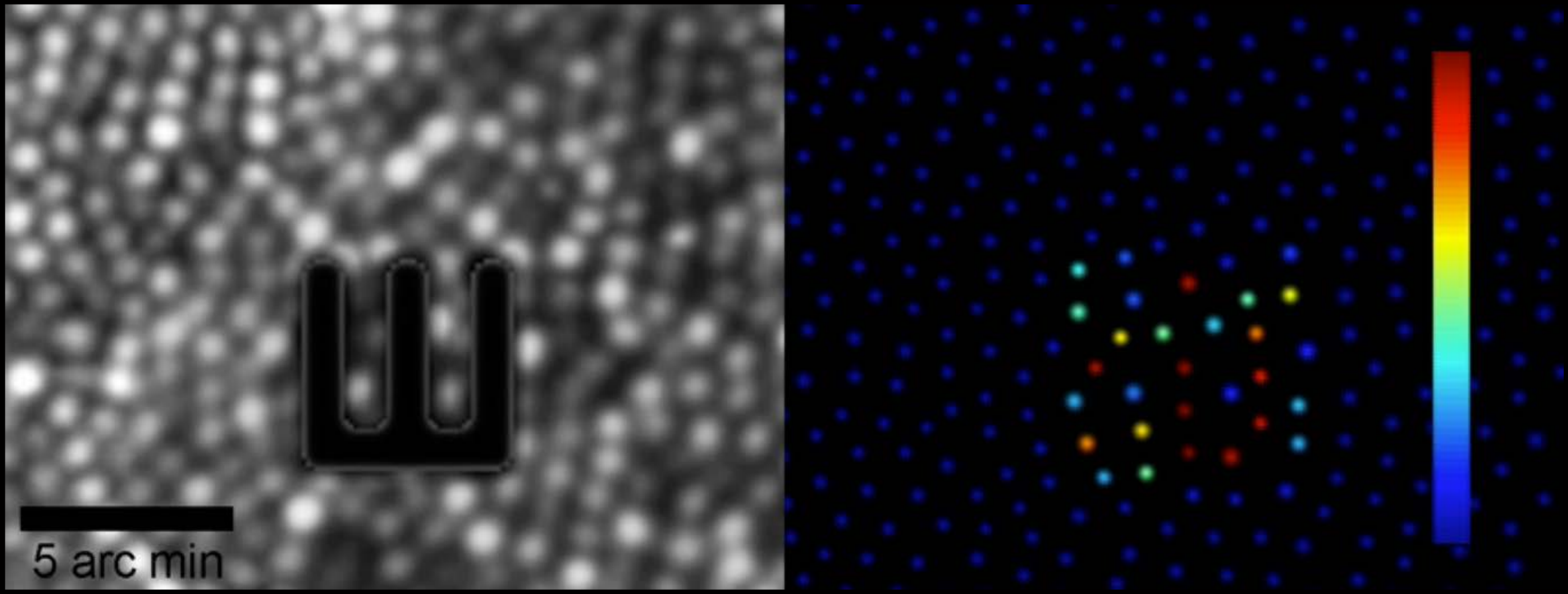
Ethan A Rossi[1] & Austin Roorda[1,2]

Visual resolution decreases rapidly outside of the foveal center. The anatomical and physiological basis for this reduction is unclear. We used simultaneous adaptive optics imaging and psychophysical testing to measure cone spacing and resolution across the fovea, and found that resolution was limited by cone spacing only at the foveal center. Immediately outside of the center, resolution was worse than cone spacing predicted and better matched the sampling limit of midget retinal ganglion cells.

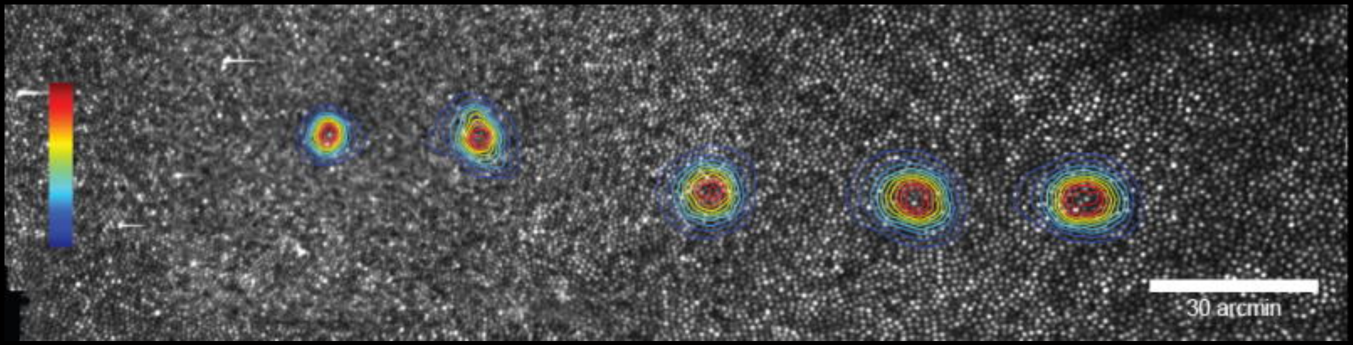




Cone Inputs and Visual Sensation

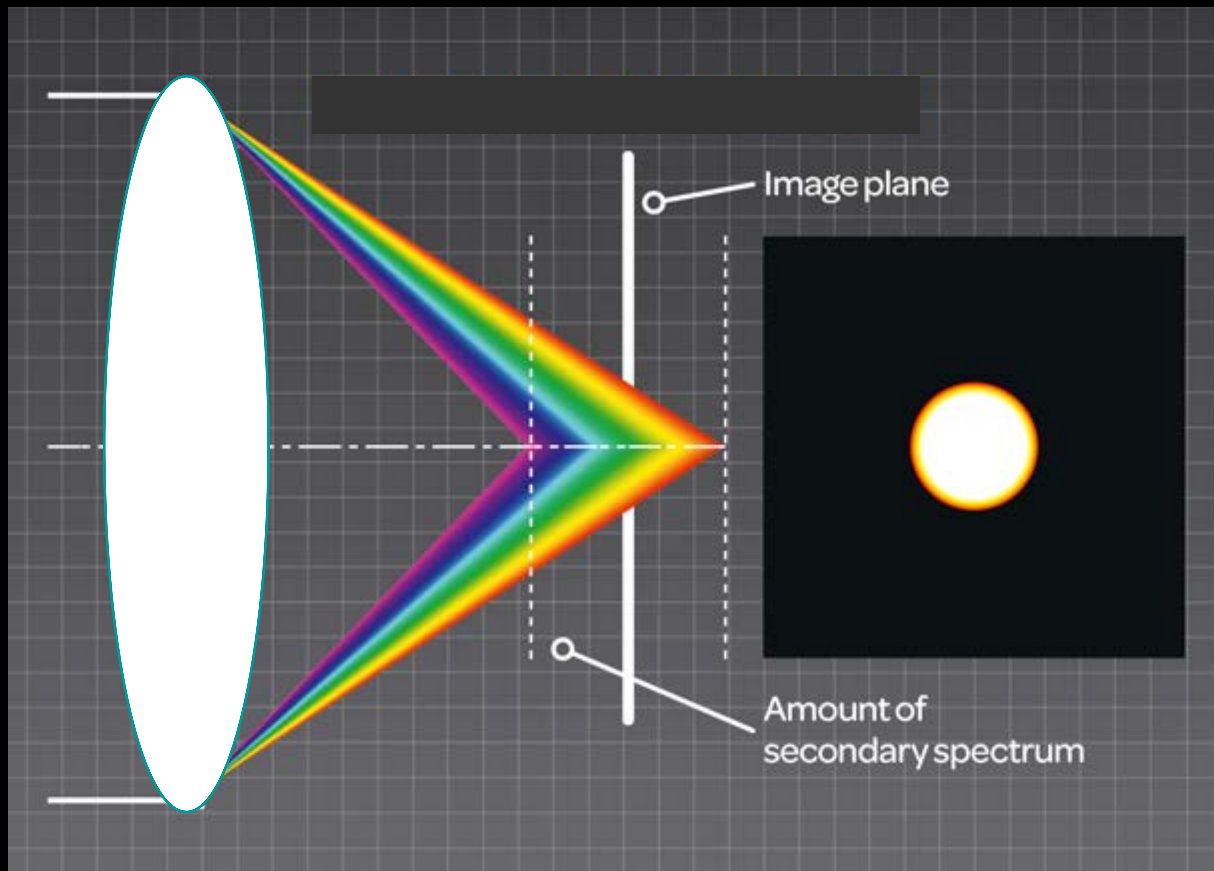


Cone Stimulation Map



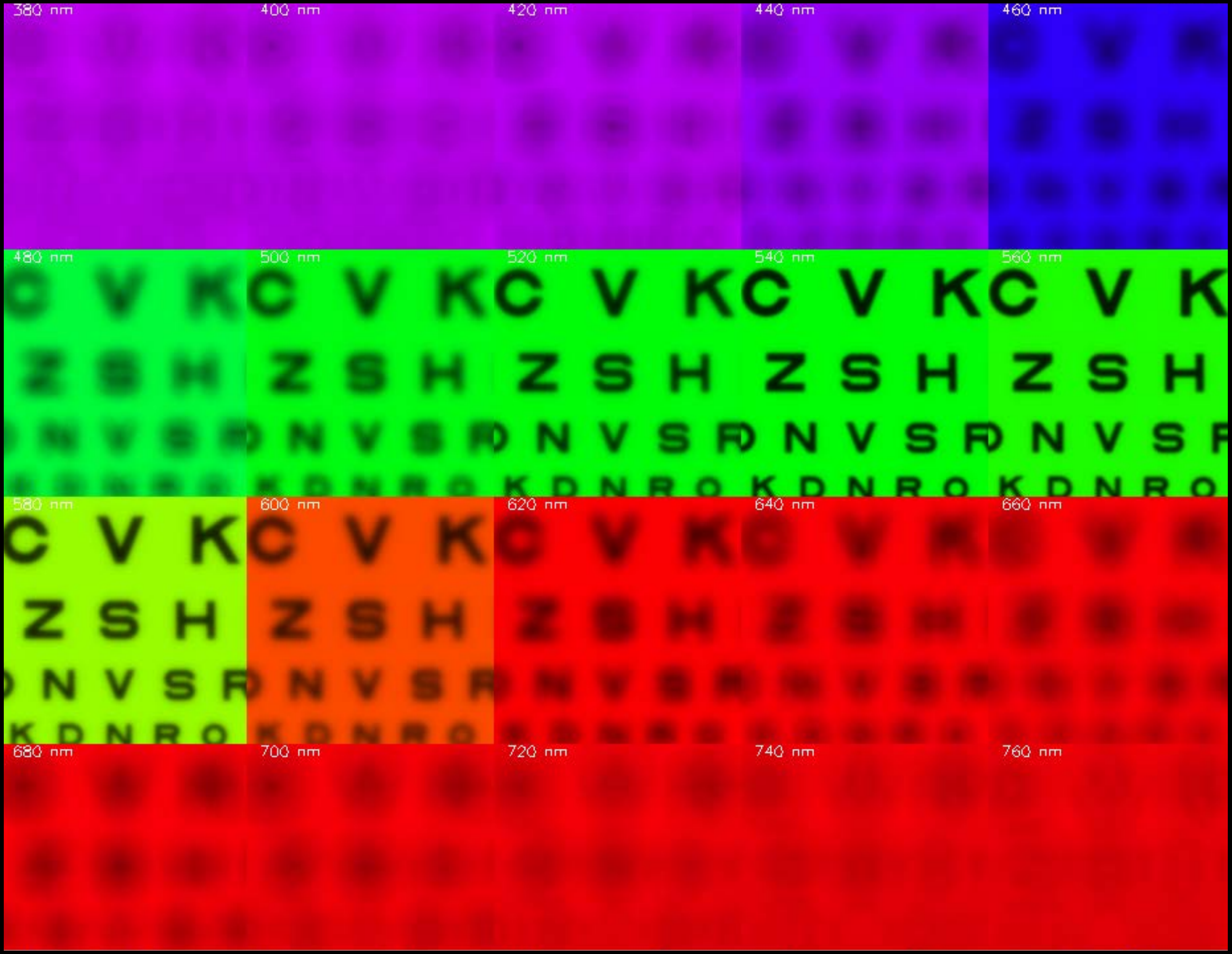
Chromatic aberrations

Chromatic aberration



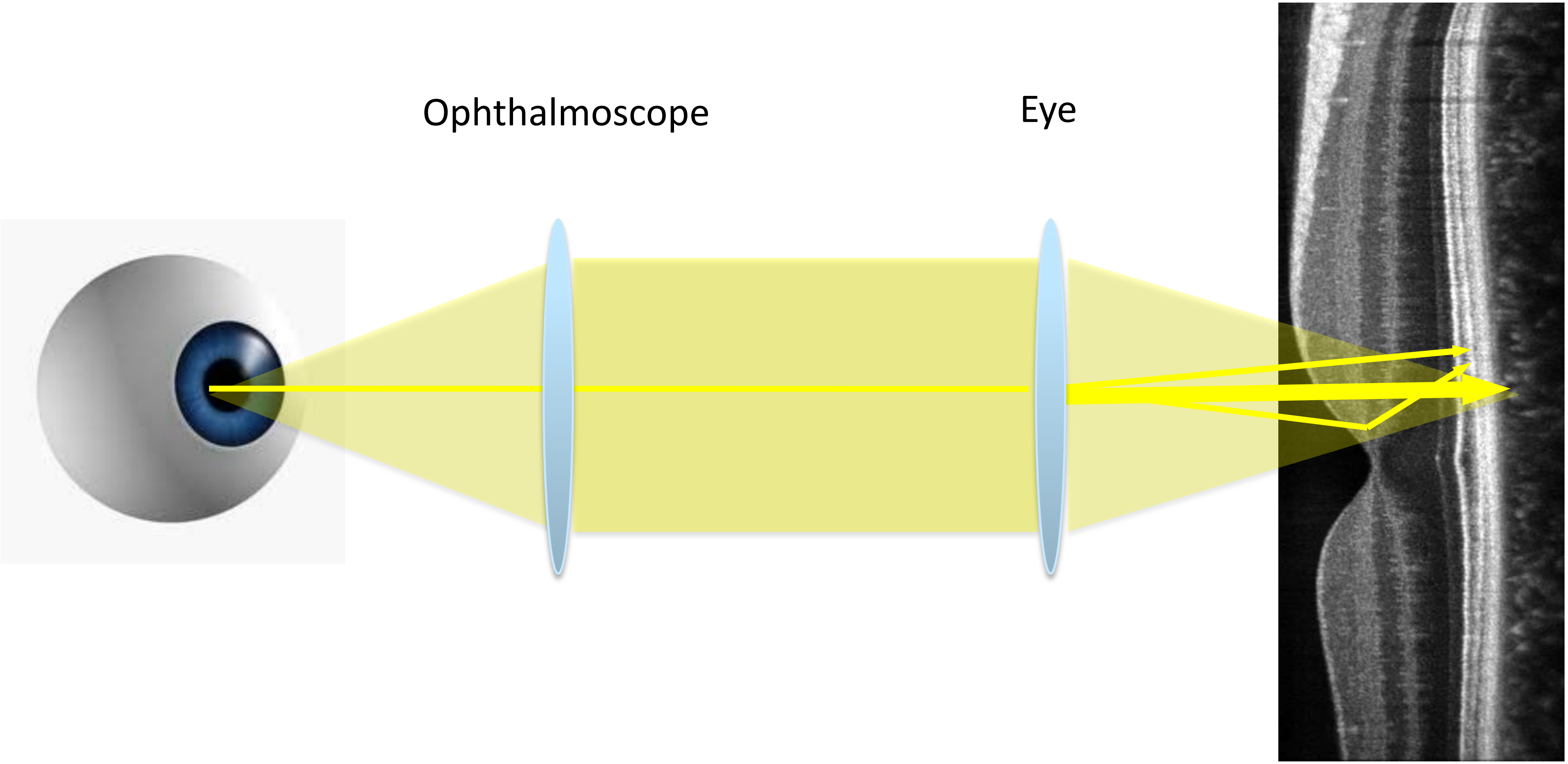
Base picture: Digital camera world

Effect of chromatic blur on eye chart

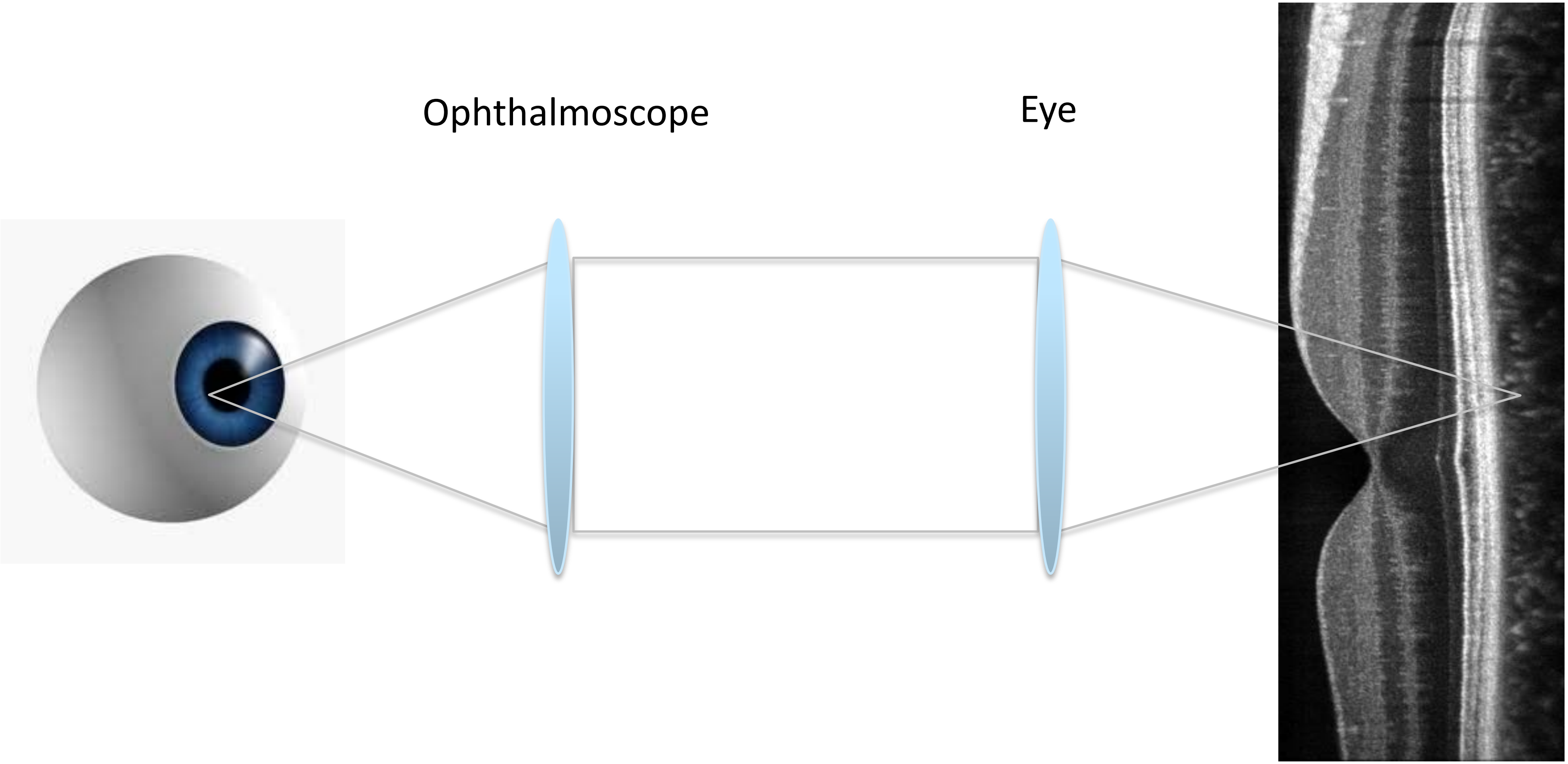


Jim Schwiegerling

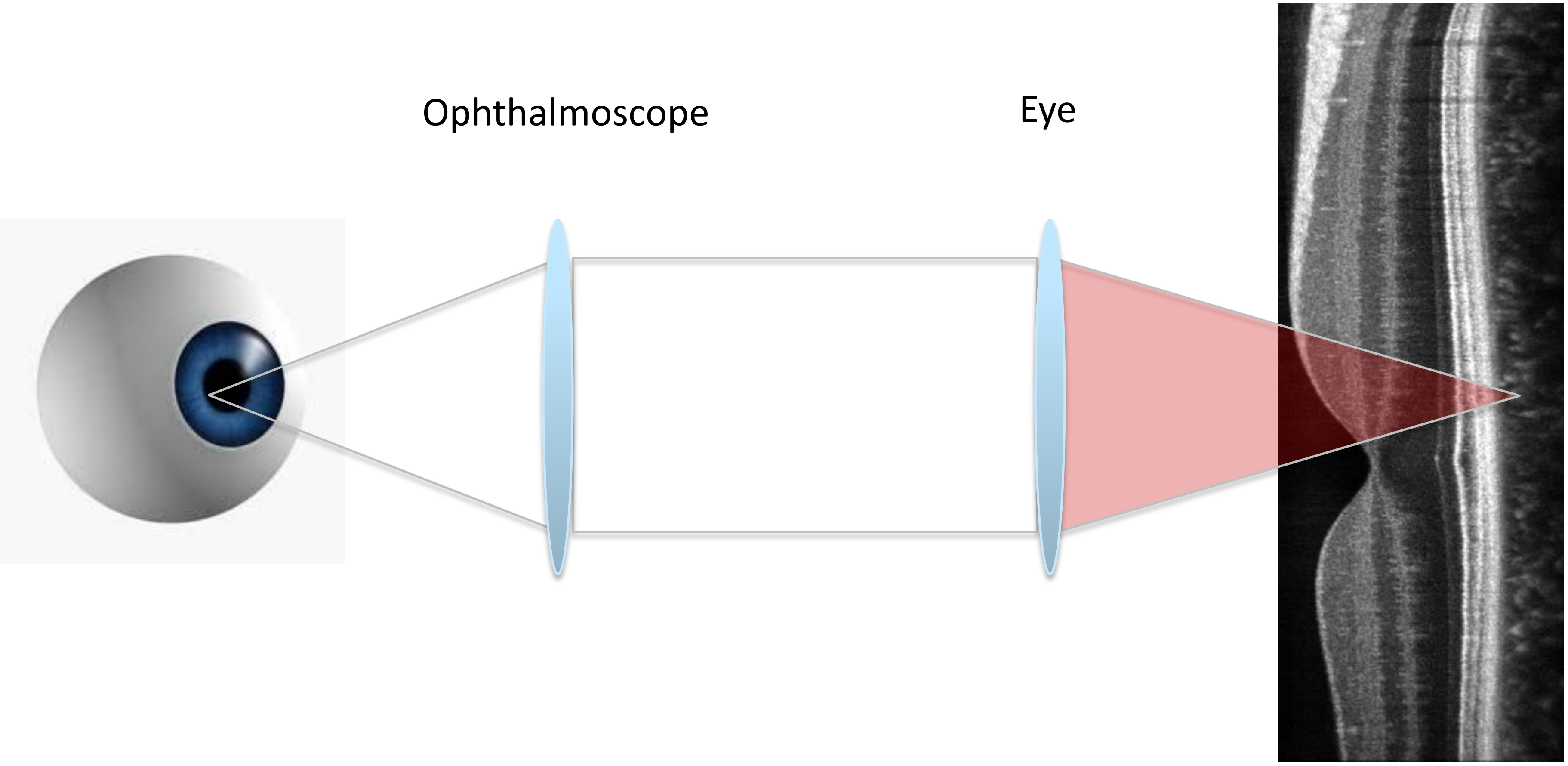
Ray Tracing: Light to Image



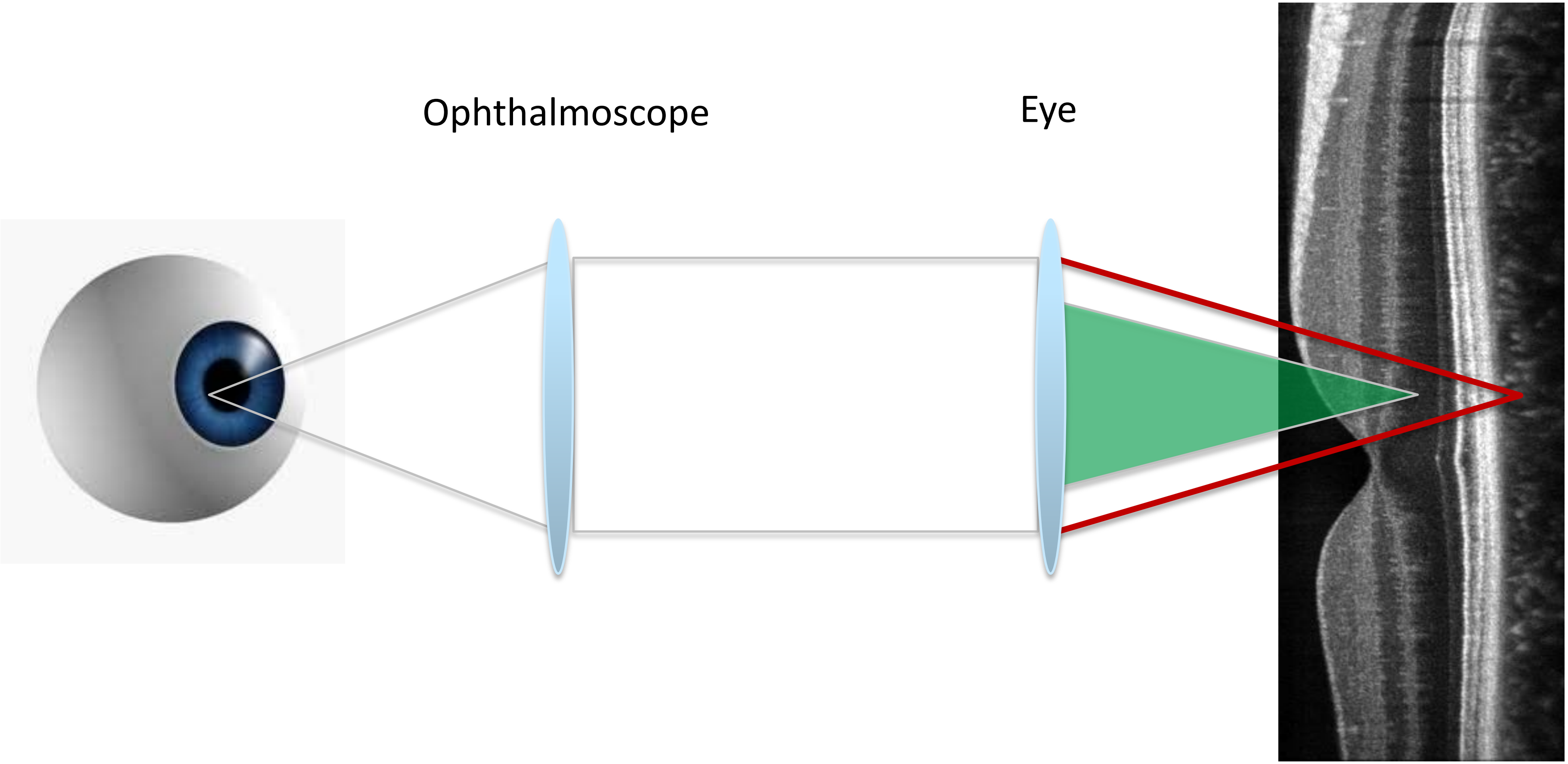
Ray Tracing: Light to Image



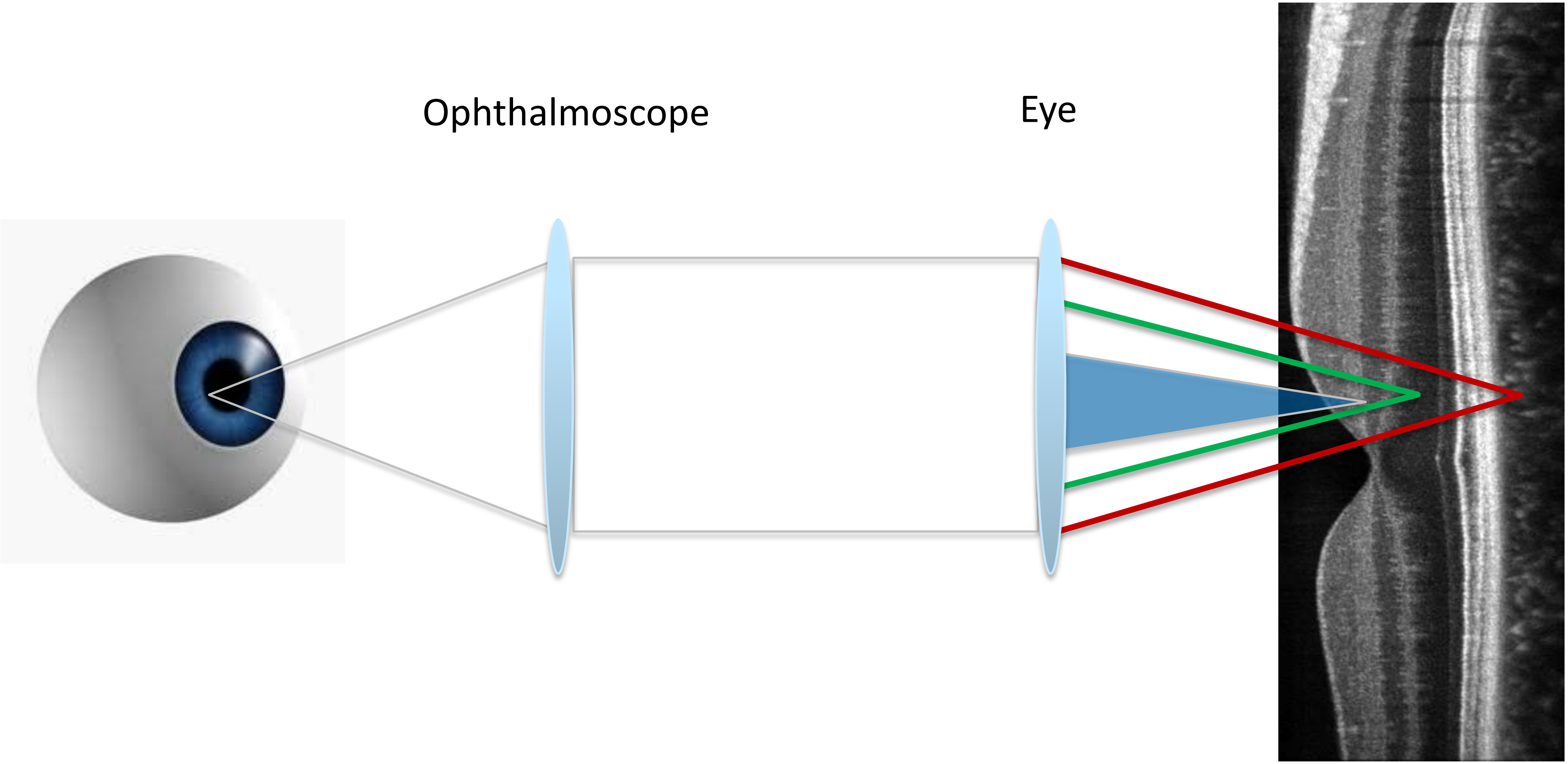
Ray Tracing: Light to Image



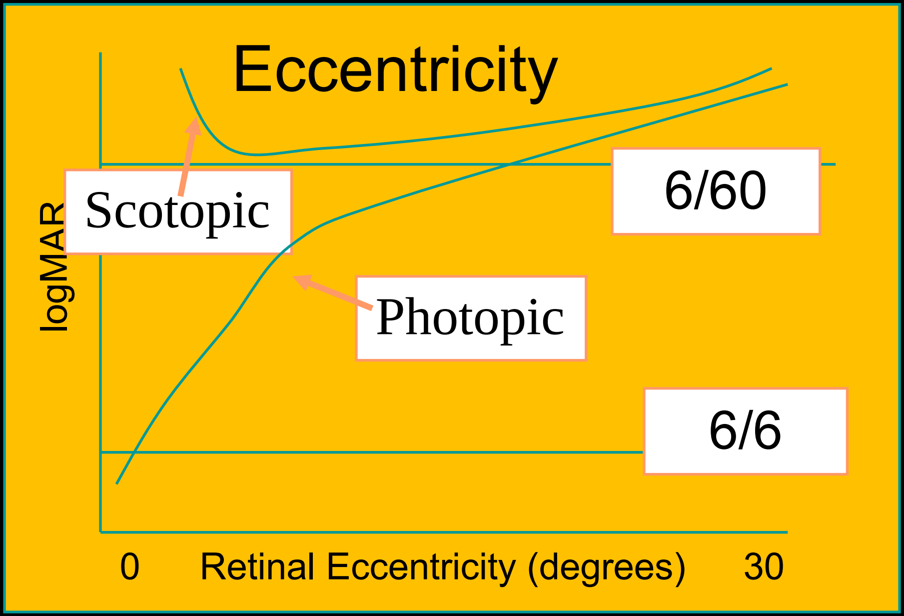
Ray Tracing: Light to Image

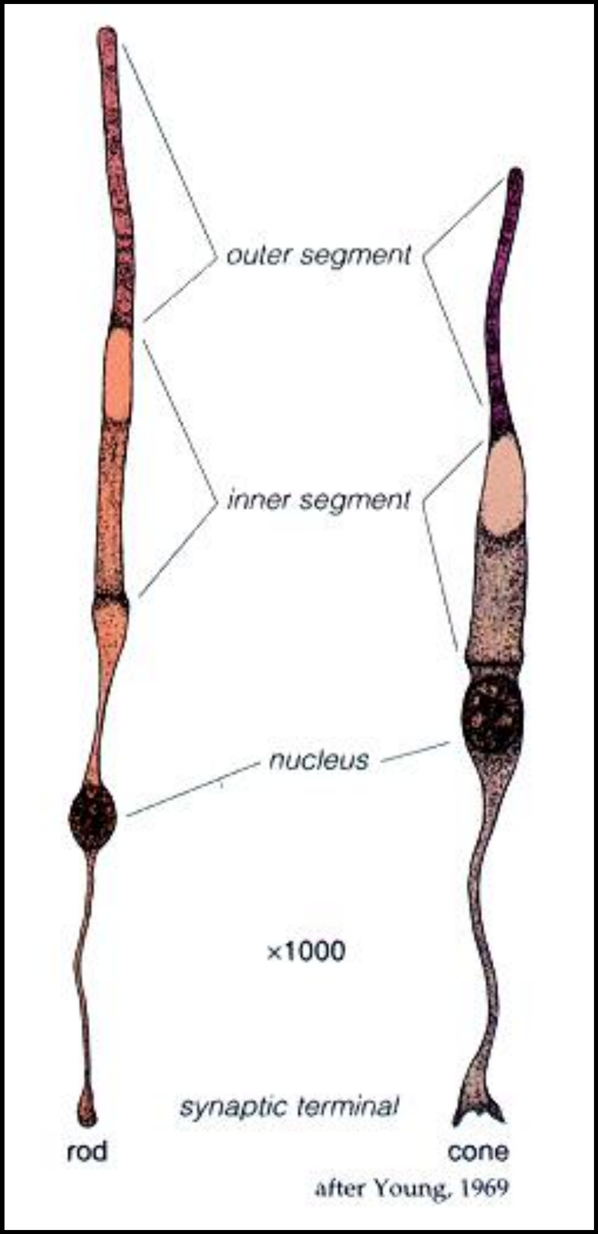


Ray Tracing: Light to Image



Changes with eccentricity


Eccentricity
logMAR
Scotopic
6/60
Photopic
6/6
0
Retinal Eccentricity (degrees)
30



Human photoreceptors

- **Rods**
  - Achromatic night vision
  - 1 type

Rod

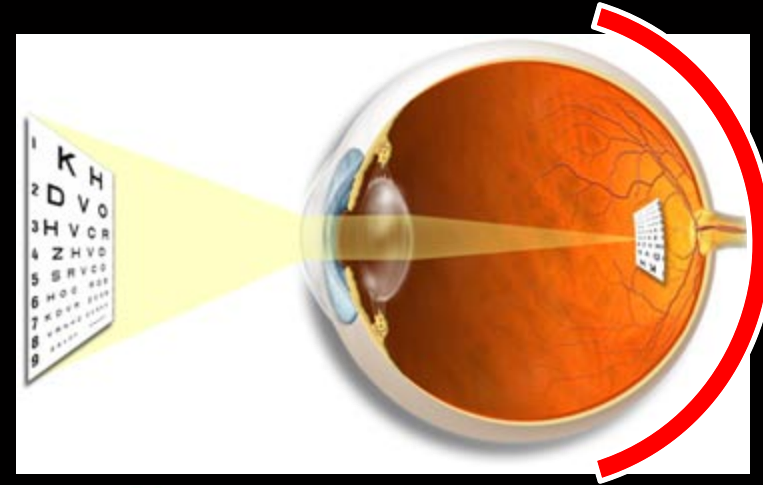
- **Cones**
  - Daytime, achromatic *and* chromatic vision
  - 3 types

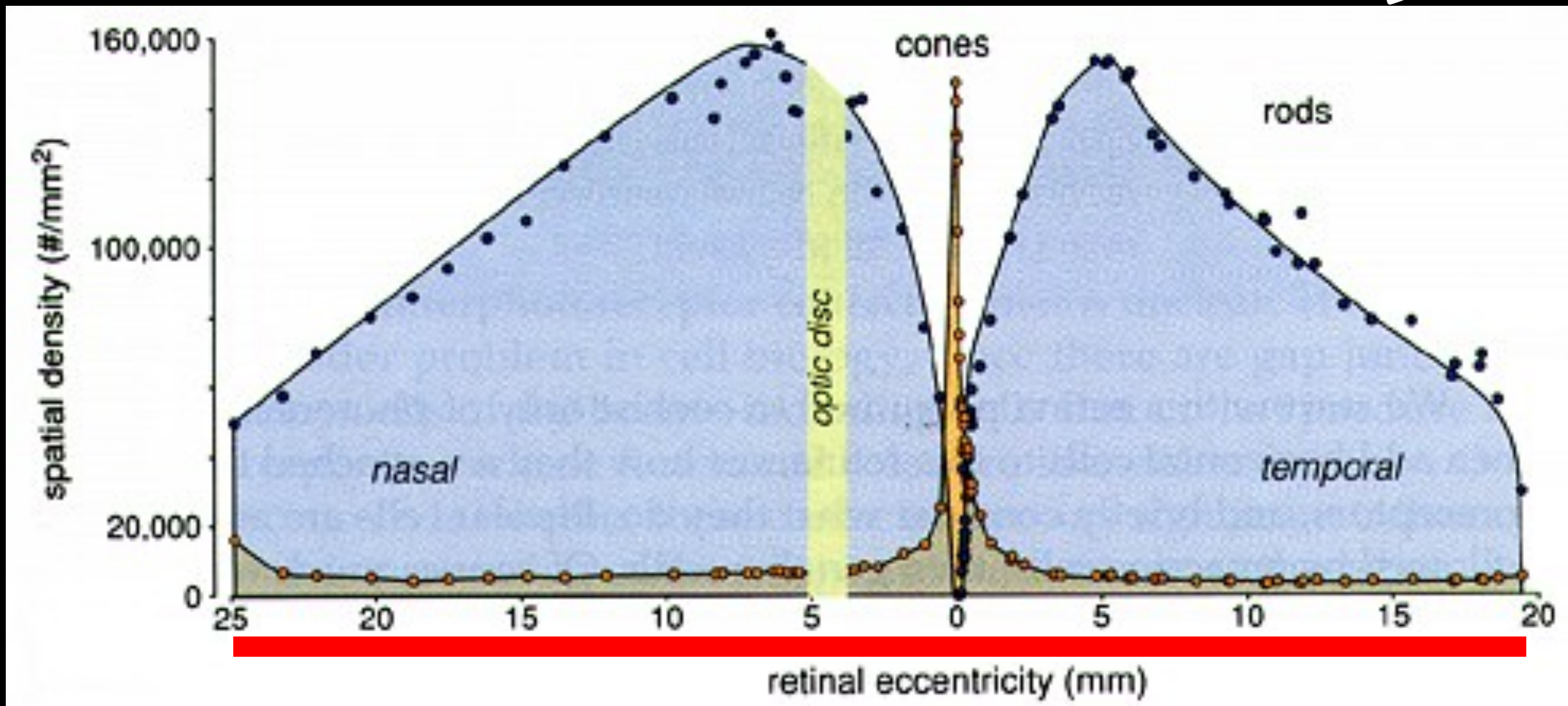
Long-wavelength-sensitive (L) or "red" cone

Middle-wavelength-sensitive (M) or "green" cone

Short-wavelength-sensitive (S) or "blue" cone

Rod and cone distribution

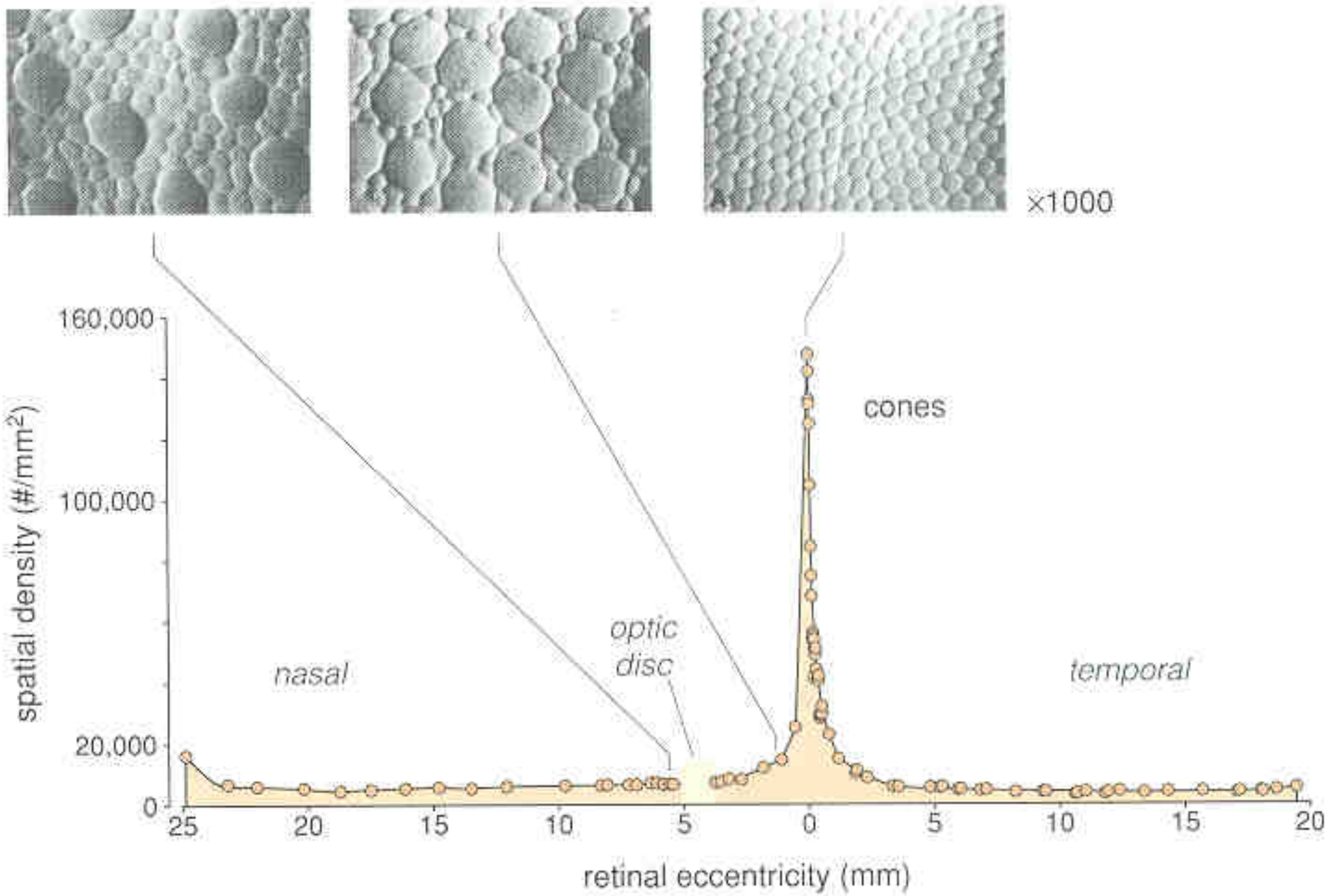




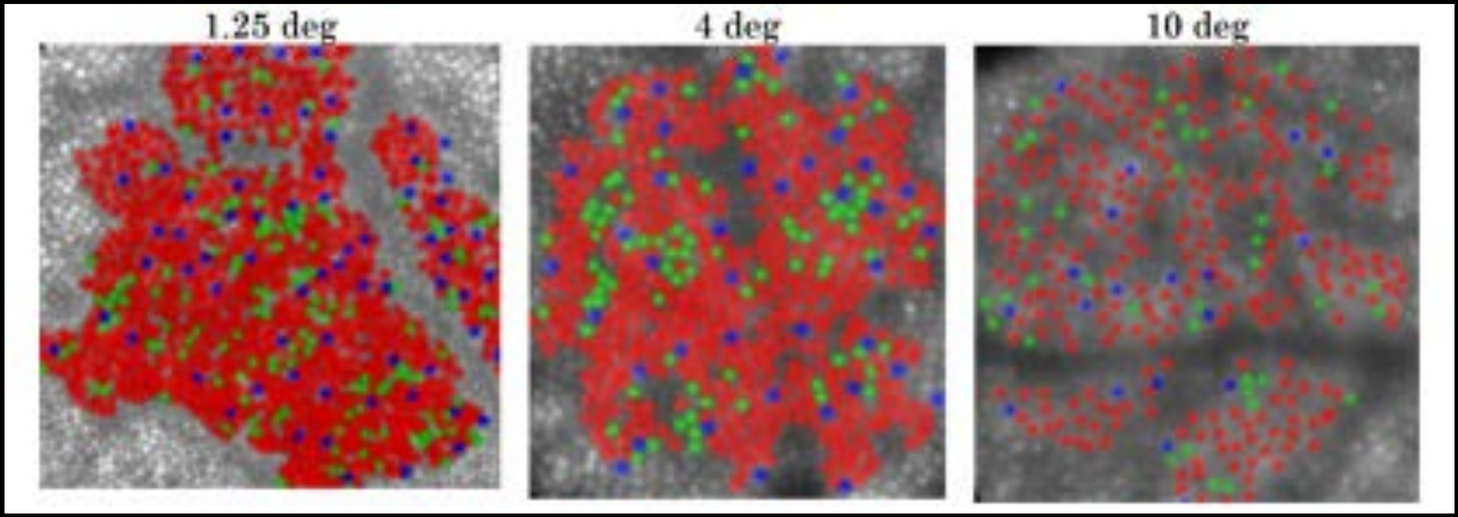
3 mm of eccentricity is

after Østerberg, 1935; as modified by Rodieck, 1988

Cone distribution and photoreceptor mosaics



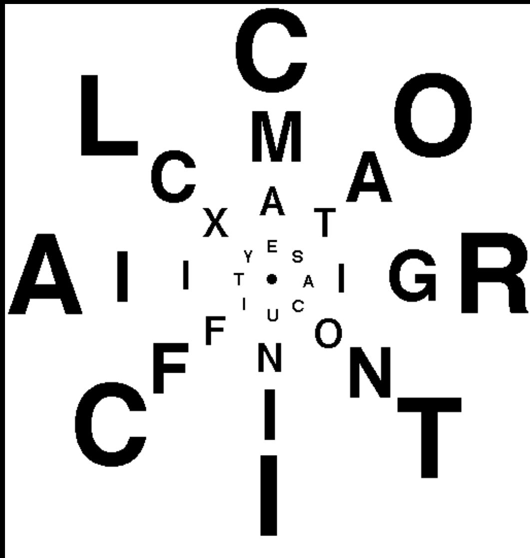
after Østerberg, 1935; as modified by Rodieck 1988;
micrographs from Curcio et al., 1990


1.25 deg
4 deg
10 deg

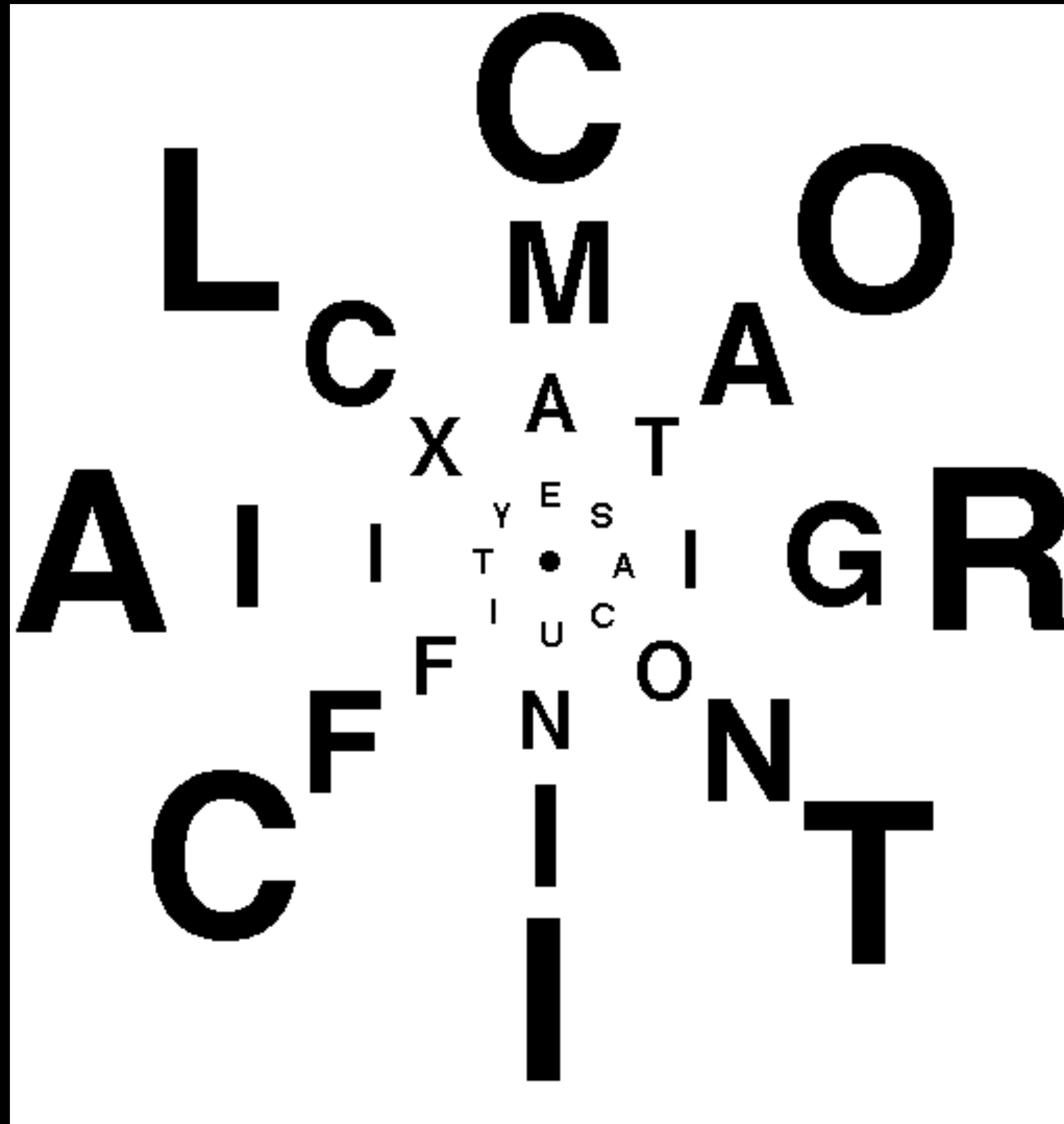
The human visual system is a foveating system

Simulation of what we see when we fixate with cone vision.

Credit: Stuart Anstis, UCSD



Visual acuity gets much poorer with eccentricity



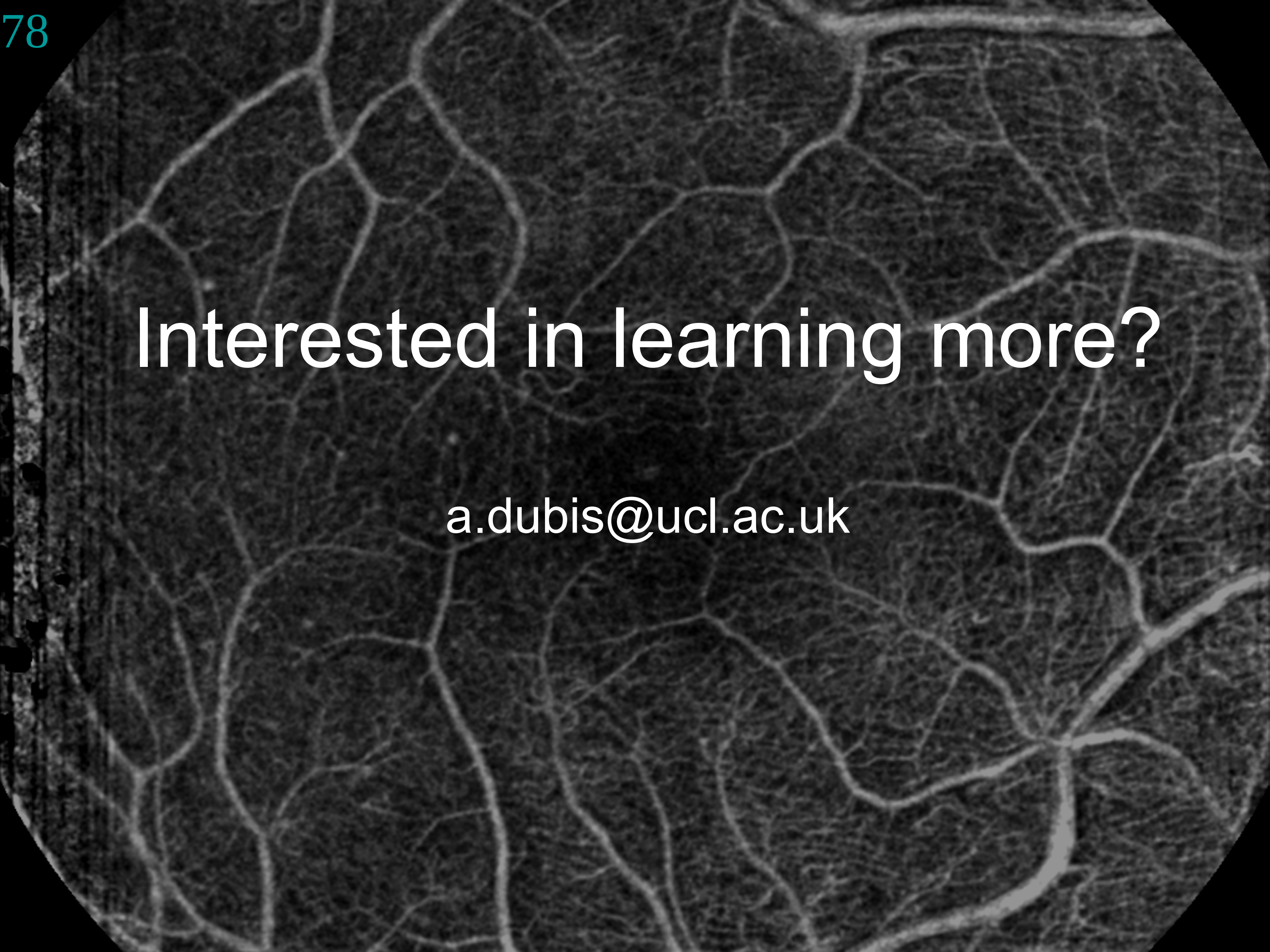
Credit: Stuart Anstis, UCSD

Conclusions

- Light can function as both a particle and a wave, these are important properties to understand how light interacts with the environment to permit vision

- Light passes through the cornea, where refractive index changes cause aberrated focusing

- Fixation is dependent on a cone rich foveal region that provides high acuity and colour vision, outside this region is rod rich, very light sensitive but lacks acuity or colour discrimination



Interested in learning more?

a.dubis@ucl.ac.uk