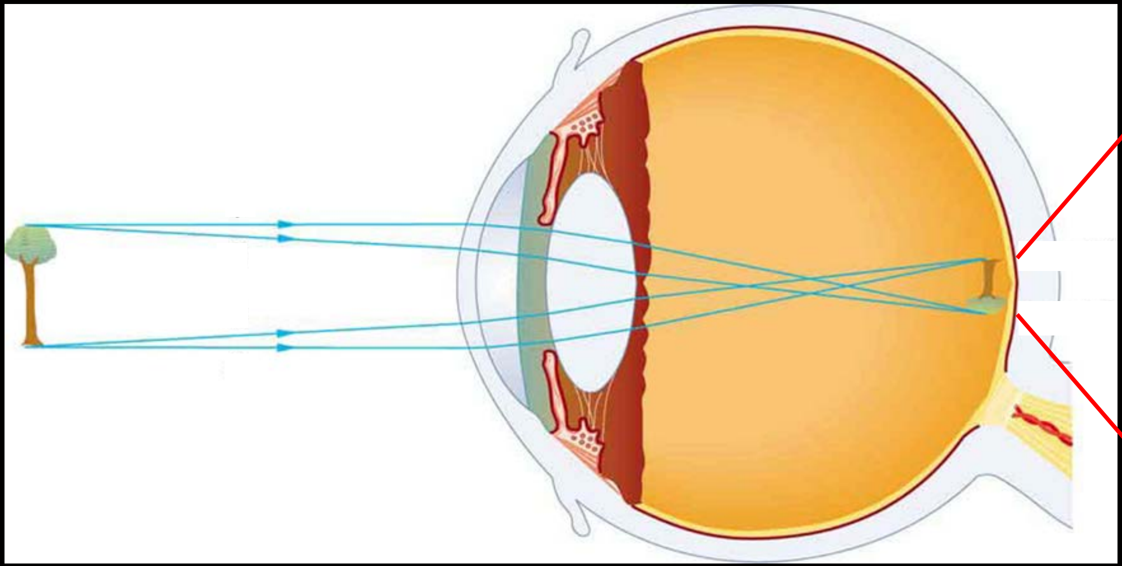
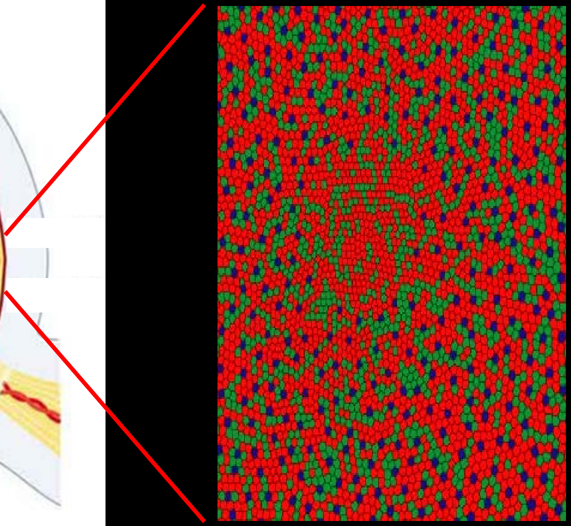




Fundamental Optics of the Eye and Rod and Cone vision

Andrew Stockman

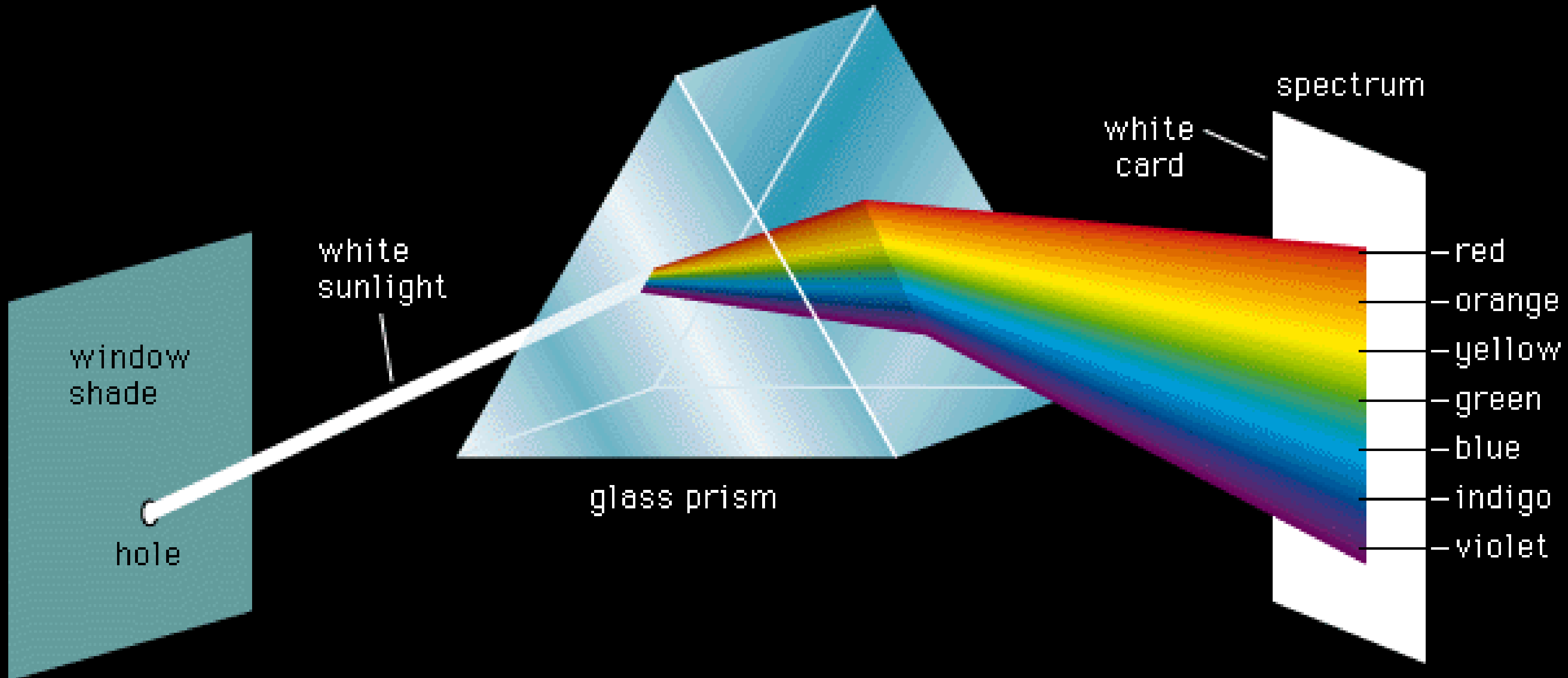
Revision Course in Basic Sciences for FRCOphth. Part 1

Outline

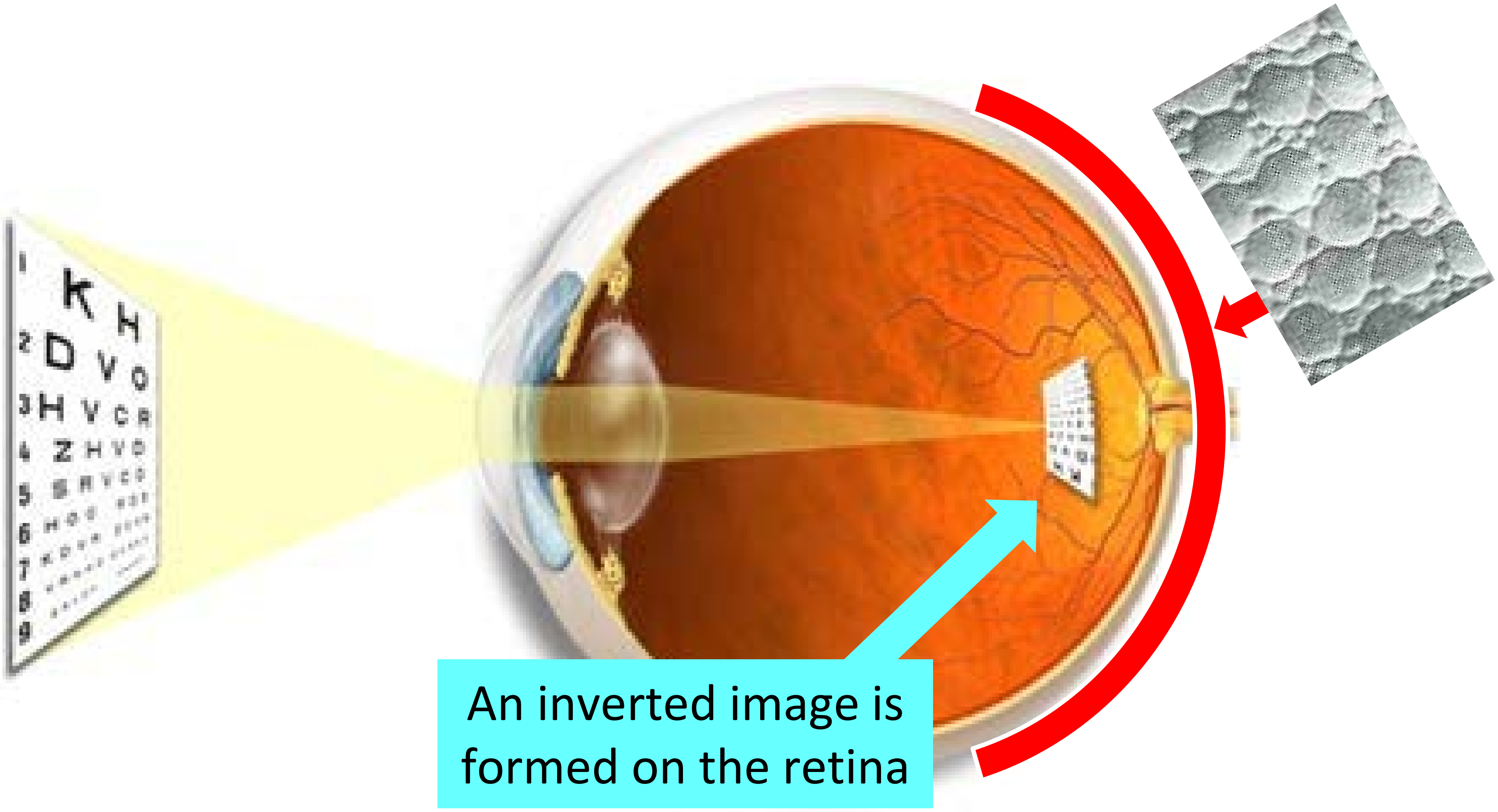
- The eye
- Visual optics
- Image quality
- Measuring image quality
- Refractive errors
- Rod and cone vision differences
- Rod vision is achromatic
- How do we see colour with cone vision?

Light

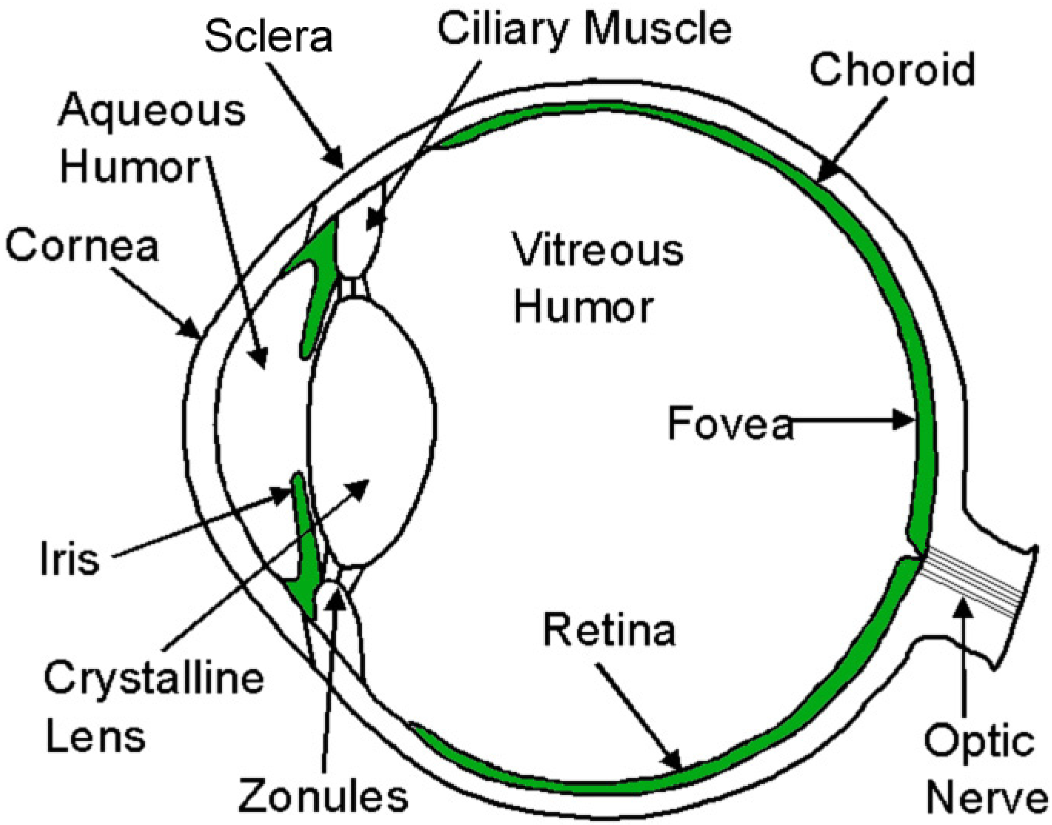
400 - 700 nm is important for vision



The retina is carpeted with light-sensitive rods and cones



Retinal cross-section



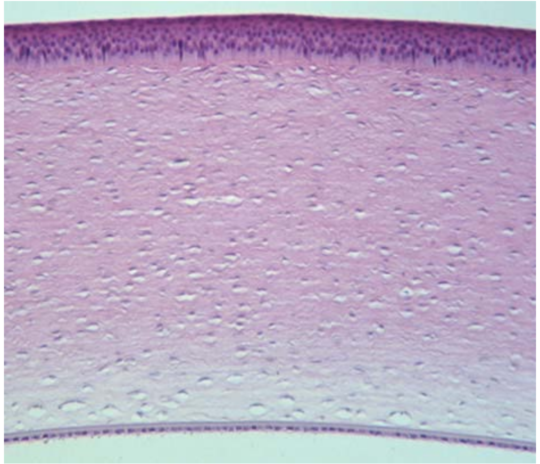
Cornea – Clear membrane on the front of the eye.
Crystalline Lens – Lens that
can change shape to alter focus.
Retina – Photosensitive inner lining of eye
Fovea – central region of retina with sharpest vision.
Optic Nerve – bundle of nerve fibers that carry information to the brain.

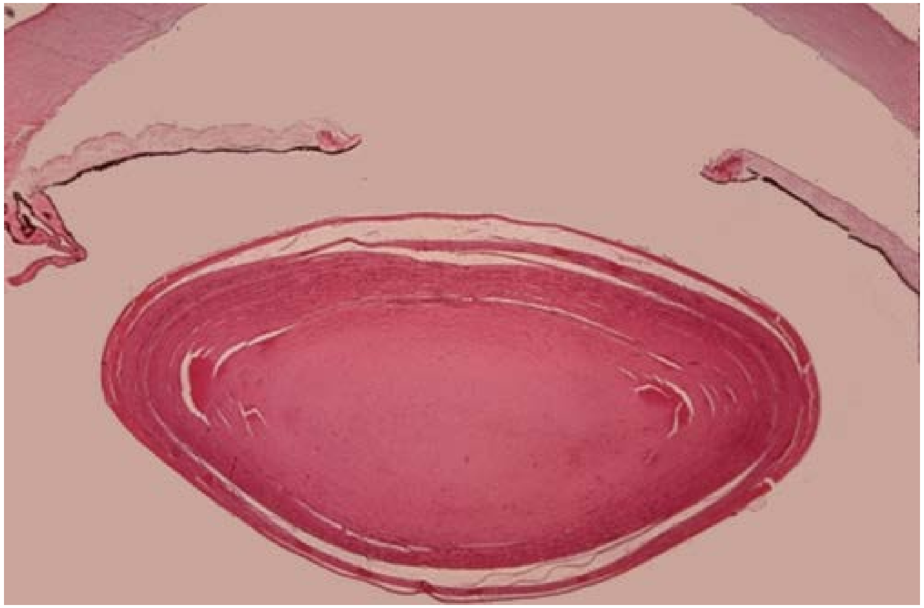
Jim Schwiegerling

Visual optics

Cornea

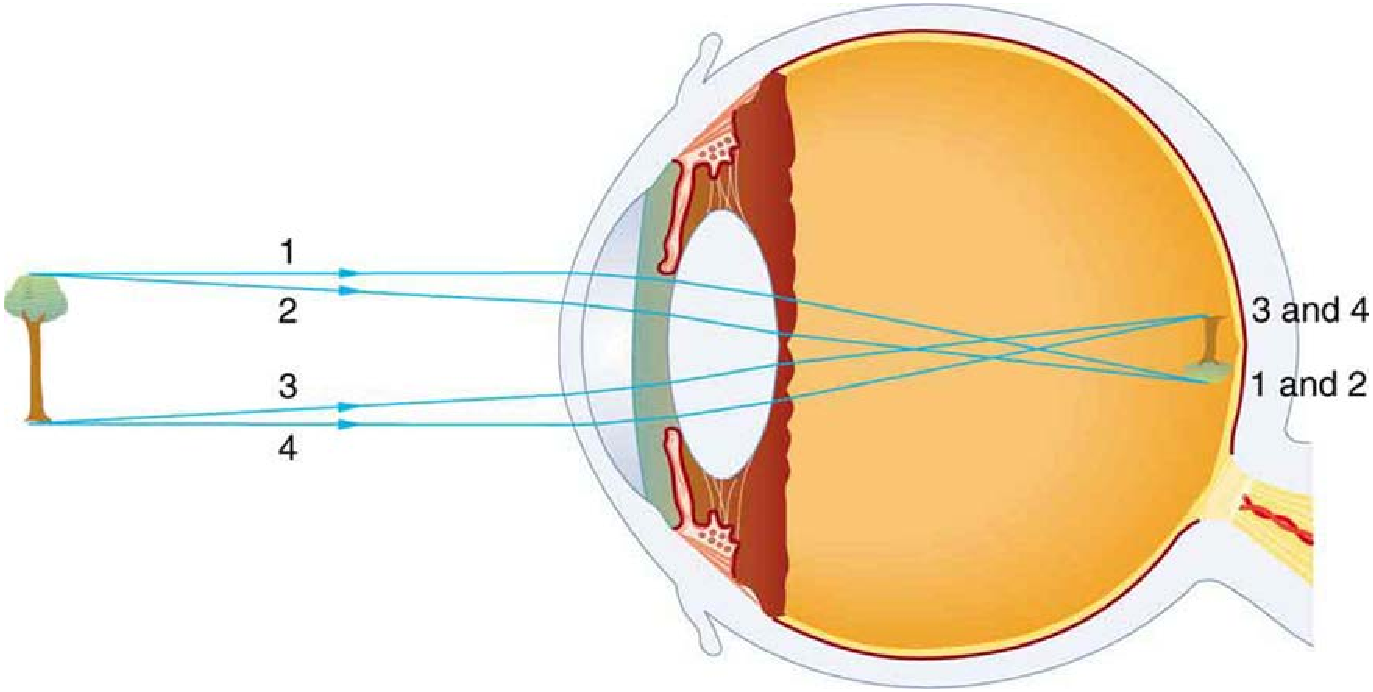
Crystalline lens





Jim Schwiegerling

Image formation

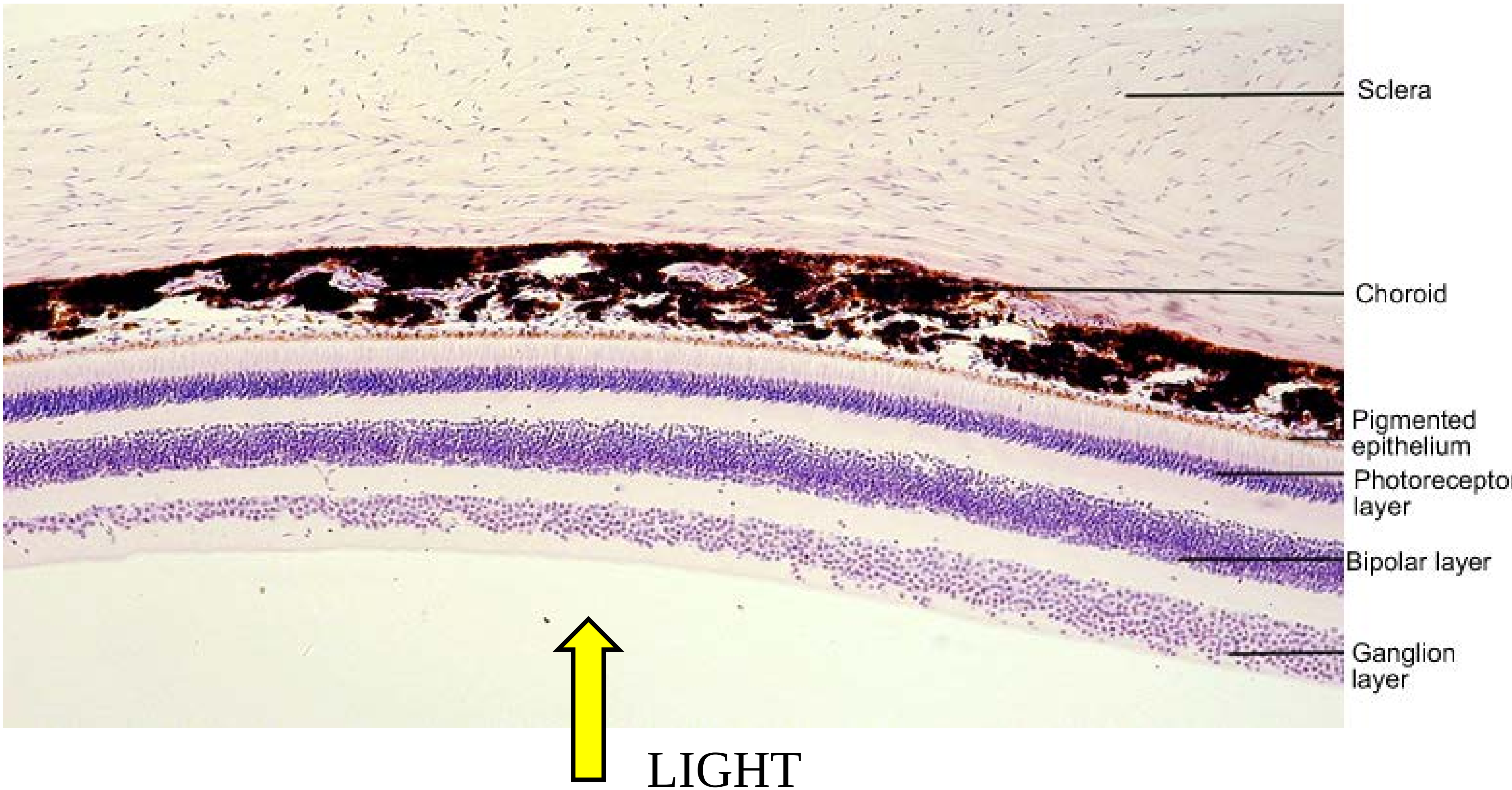


Openstax College Physics

Jim Bowmaker dissecting an eye…

BBC Horizon: Light Fantastic (2006)

Retinal cross-section

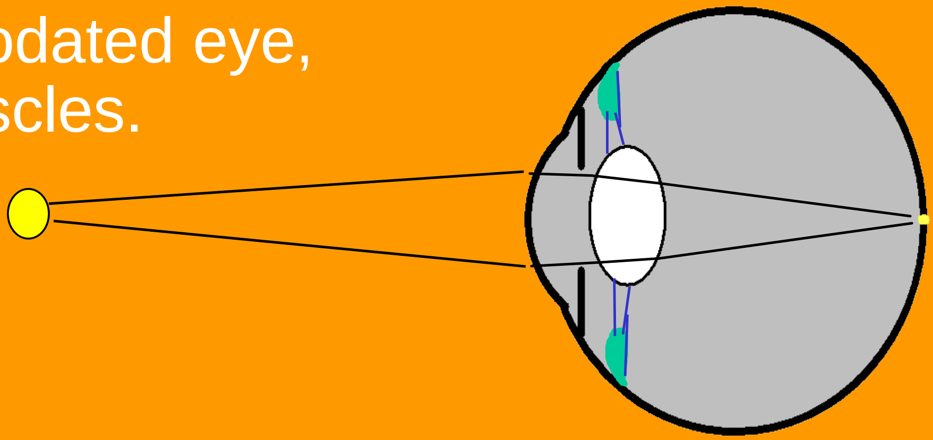


Retina 200 ×

Accommodation to target distance

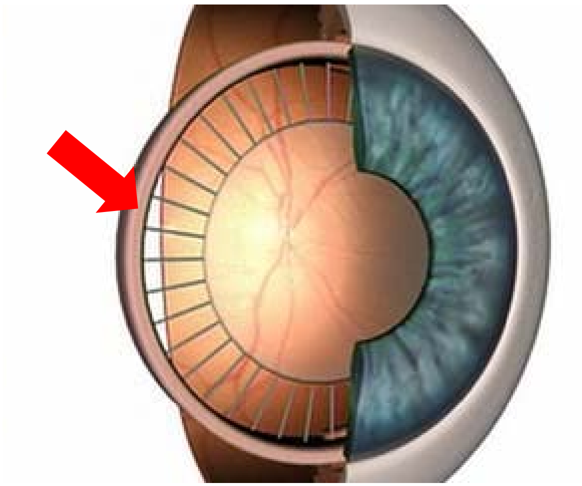
Distant target, relaxed ciliary muscles

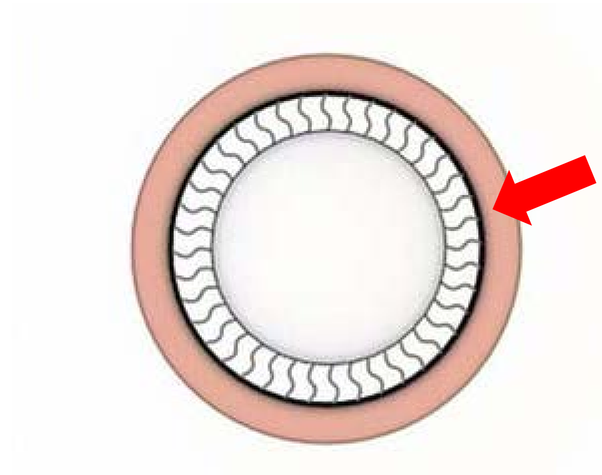
Near target, accommodated eye, constricted ciliary muscles.



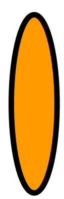
Larry Thibos

Accommodation

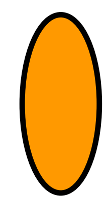




Relaxed ciliary muscle pulls zonules taut an flattens crystalline lens.



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



Jim Schwiegerling

Image quality

Point spread function

Optical systems are rarely ideal.

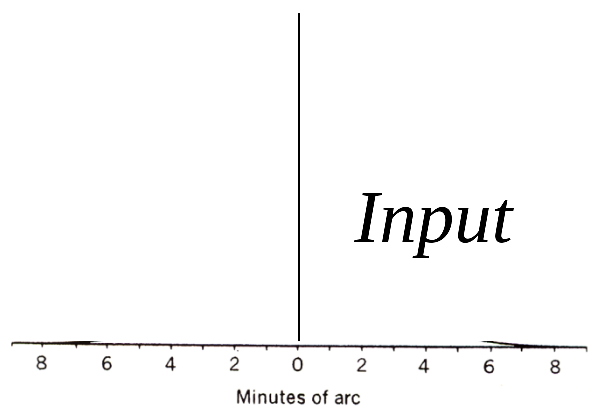
scene → Optical System → image

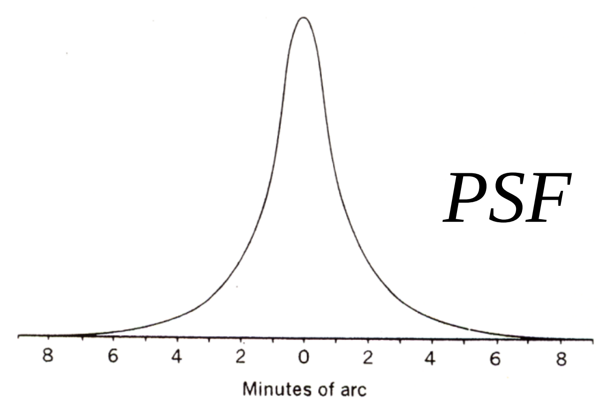
Point spread function of Human Eyes

$\delta(x)$ → Optical System → $PSF(x)$

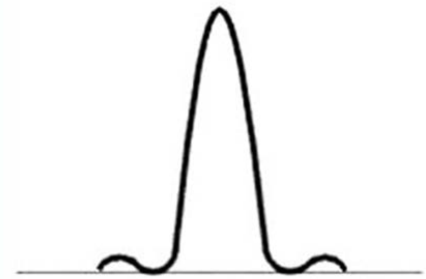
point source

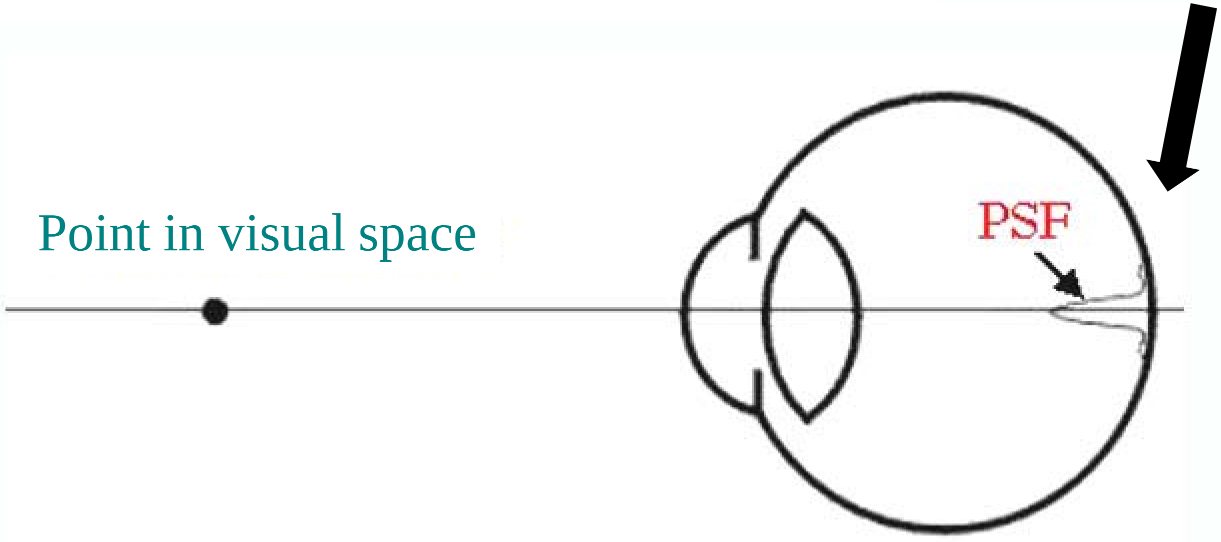
point spread function





Point spread function (PSF)



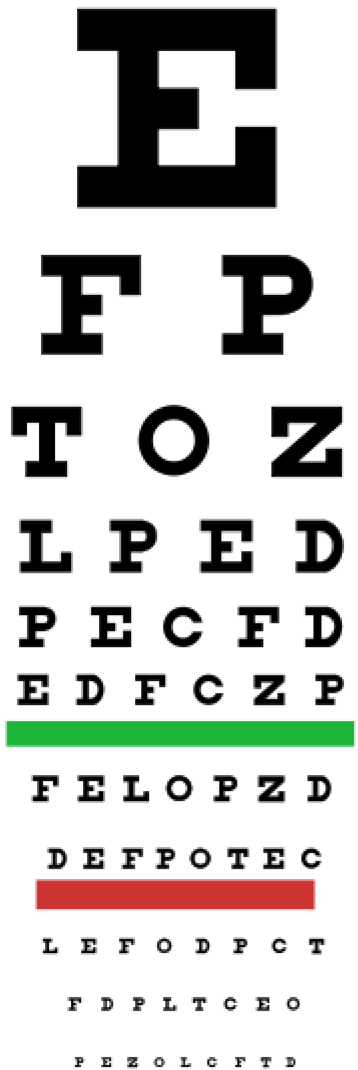


From Webvision, Michael Kalloniatis

If we know the Point Spread Function (PSF) or the Line Spread Function (LSF), then we can characterize the optical performance of the eye.

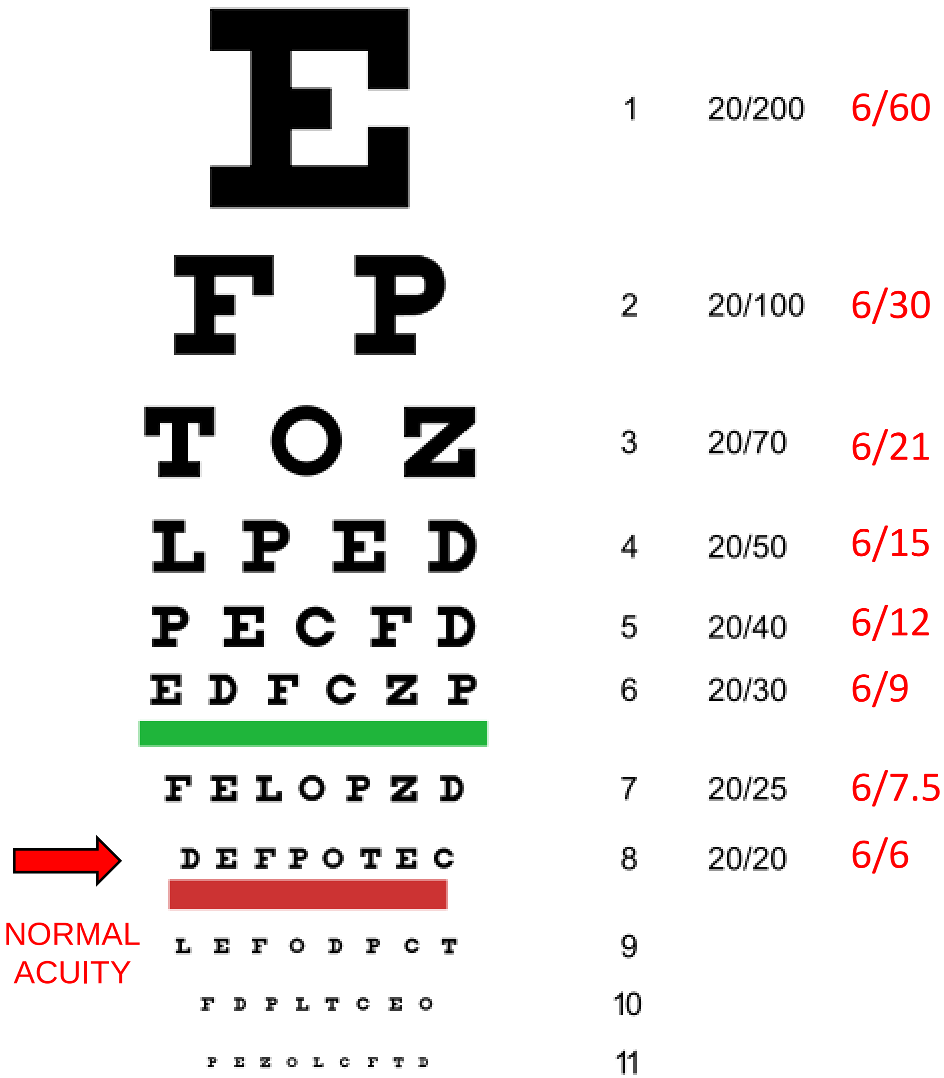
Measuring image quality psychophysically

1. Visual acuity measures



1	20/200	6/60
2	20/100	6/30
3	20/70	6/21
4	20/50	6/15
5	20/40	6/12
6	20/30	6/9
7	20/25	6/7.5
8	20/20	6/6
9		
10		
11		

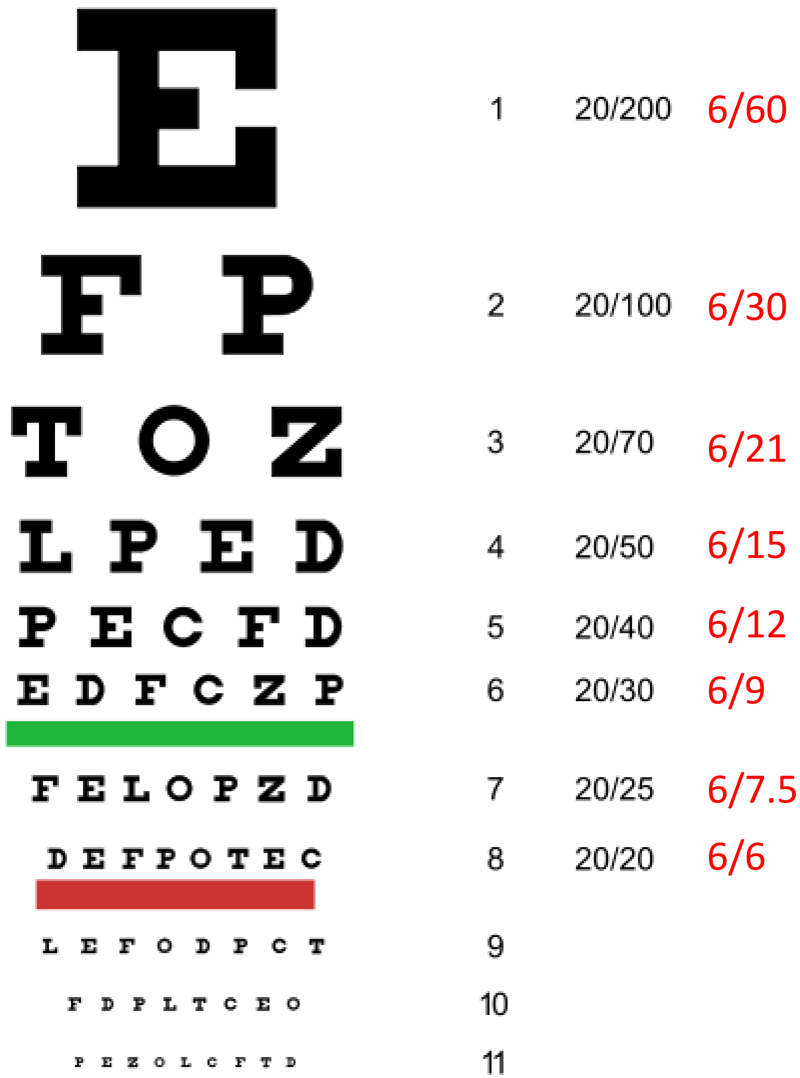
Smallest resolvable black and white target. Many different types of tests are available , but the letter chart introduced by Snellen in 1862 is the most common.

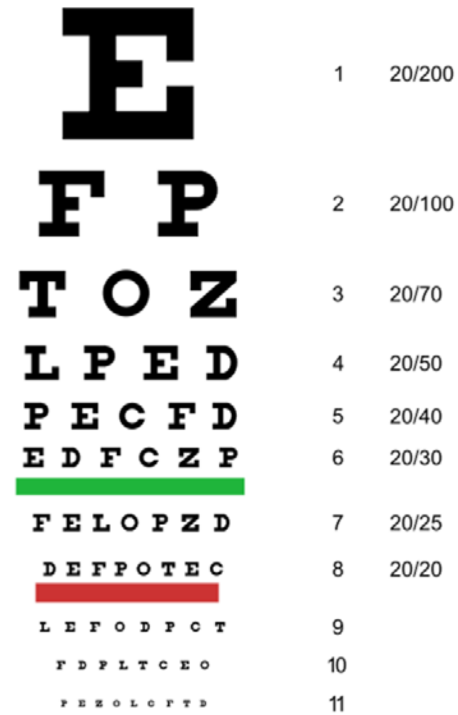


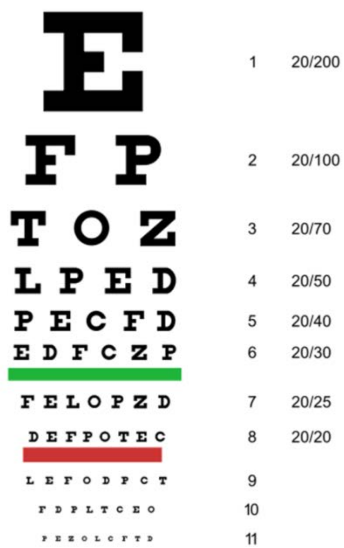
Snellen defined “standard vision” as the ability to recognize one of his optotypes when it subtended 5 minutes of arc. Thus, the optotype can only be recognized if the person viewing it can discriminate a spatial pattern separated by a visual angle of 1 minute of arc.

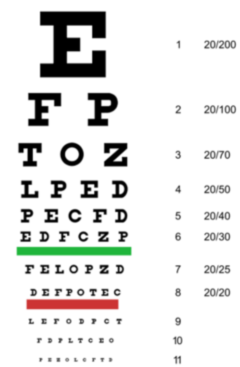
A Snellen chart is placed at a standard distance, twenty feet in the US (6 metres in Europe). At this distance, the symbols on the line representing "normal" acuity subtend an angle of five minutes of arc, and the thickness of the lines and of the spaces between the lines subtends one minute of arc.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


E 1 20/200 6/60
F P 2 20/100 6/30
T O Z 3 20/70 6/21
L P E D 4 20/50 6/15
P E C F D 5 20/40 6/12
E D F C Z P 6 20/30 6/9
F E L O P Z D 7 20/25 6/7.5
D E F P O T E C 8 20/20 6/6
L E F O D P C T 9
F D P L T C E O 10
P E Z O L C F T D 11


E 1 20/200
F P 2 20/100
T O Z 3 20/70
L P E D 4 20/50
P E C F D 5 20/40
E D F C Z P 6 20/30
F E L O P Z D 7 20/25
D E F P O T E C 8 20/20
L E F O D P C T 9
F D P L T C E O 10
P E Z O L C F T D 11


E 1 20/200
F P 2 20/100
T O Z 3 20/70
L P E D 4 20/50
P E C F D 5 20/40
E D F C Z P 6 20/30
F E L O P Z D 7 20/25
D E F P O T E C 8 20/20
L E F O D P C T 9
F D P L T C E O 10
P E Z O L C F T D 11

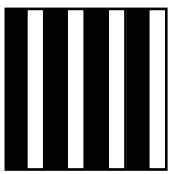

E 1 20/200
F P 2 20/100
T O Z 3 20/70
L P E D 4 20/50
P E C F D 5 20/40
E D F C Z P 6 20/30
F E L O P Z D 7 20/25
D E F P O T E C 8 20/20
9
10
11

Visual Acuity: four standard methods

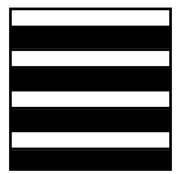
Letter acuity (Snellen)

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

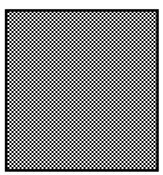
Grating acuity



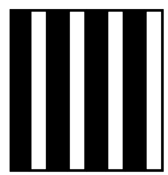
vs.



Orientation resolution acuity



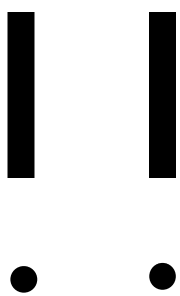
vs.



Detection acuity

2-line resolution

2-point resolution



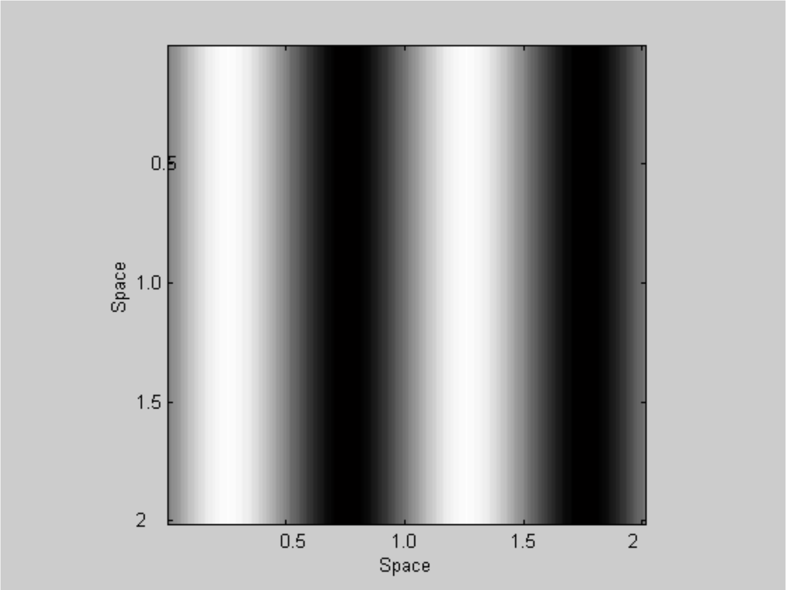
Can the subject see two lines or points rather than one?

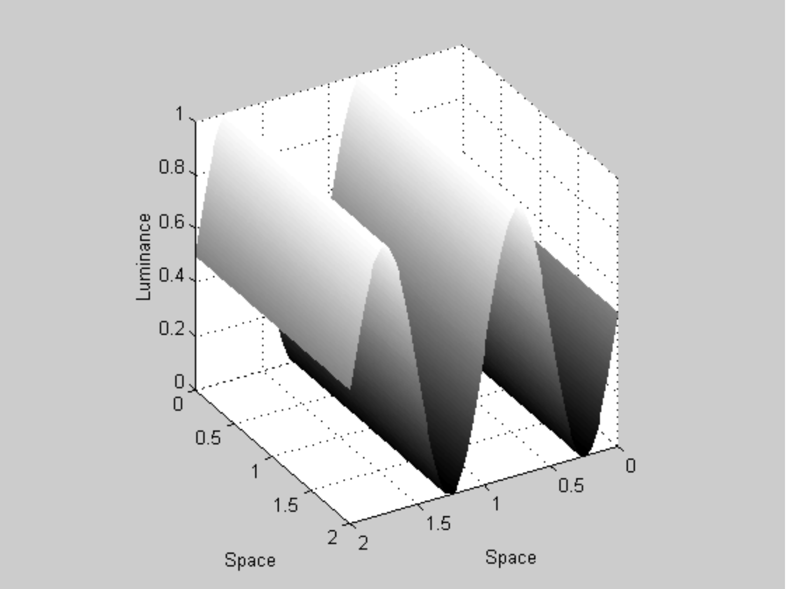
Arthur Bradley

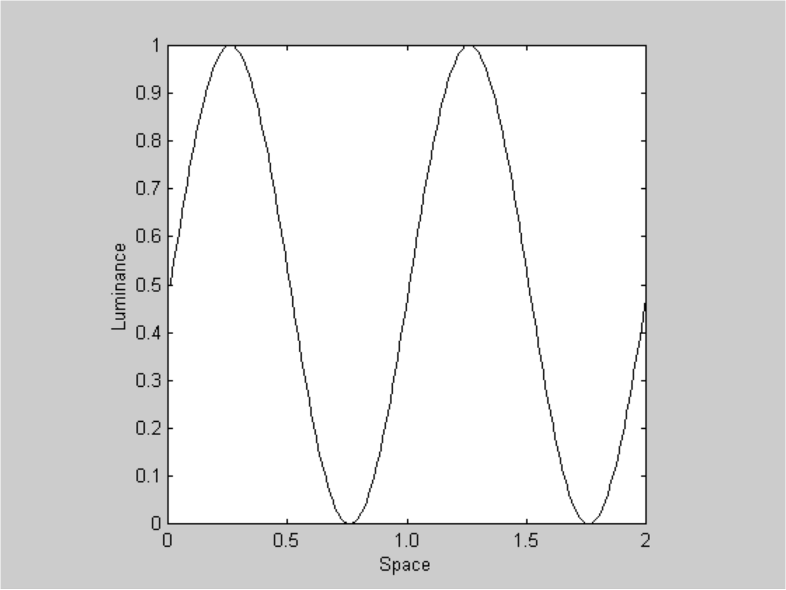
Measuring image quality psychophysically

2. Spatial contrast sensitivity measures

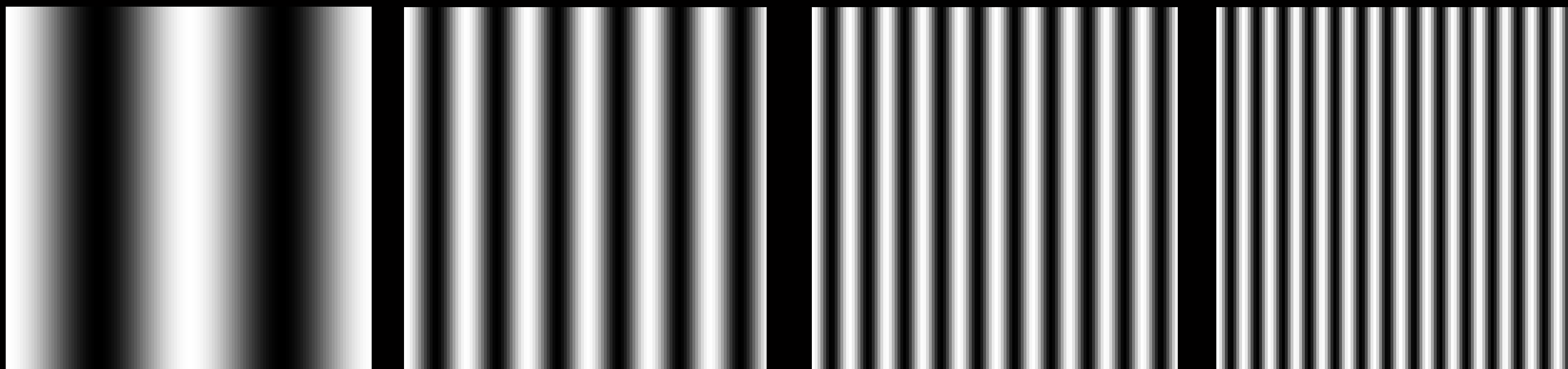
Spatial frequency



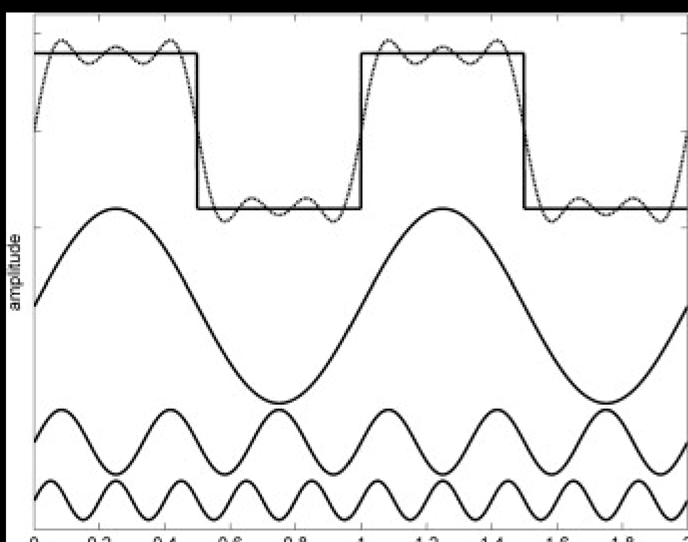




Harmonics of a square wave



Steven Lehars



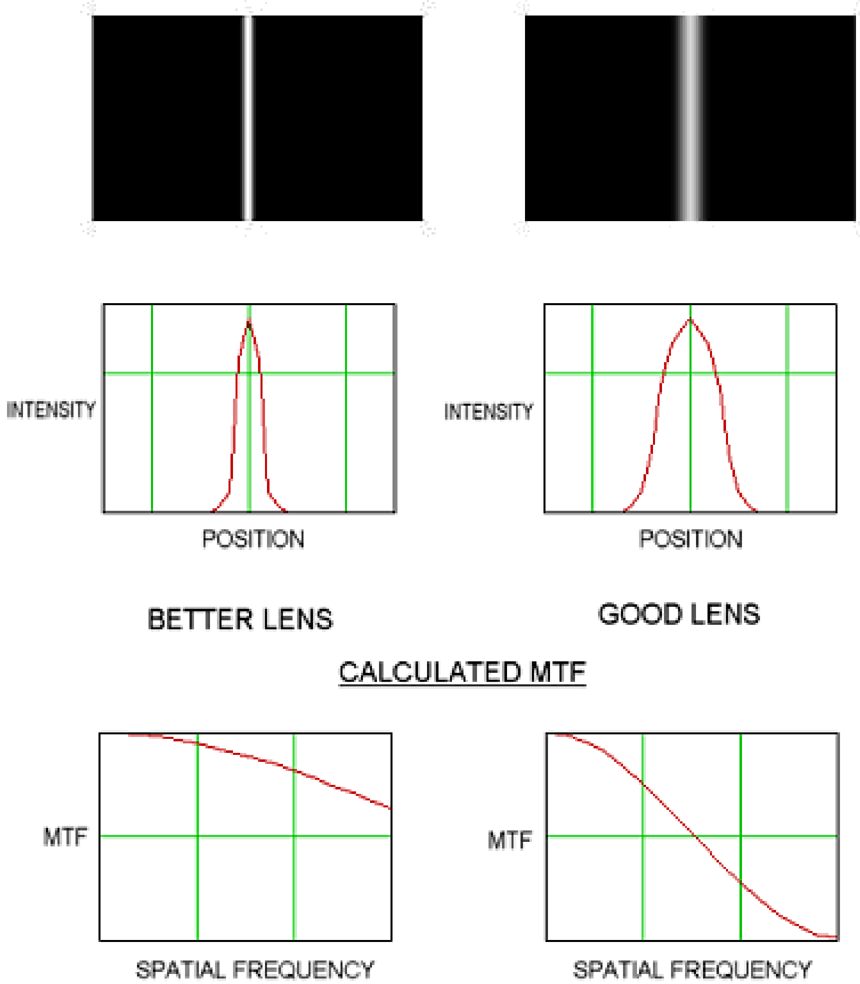


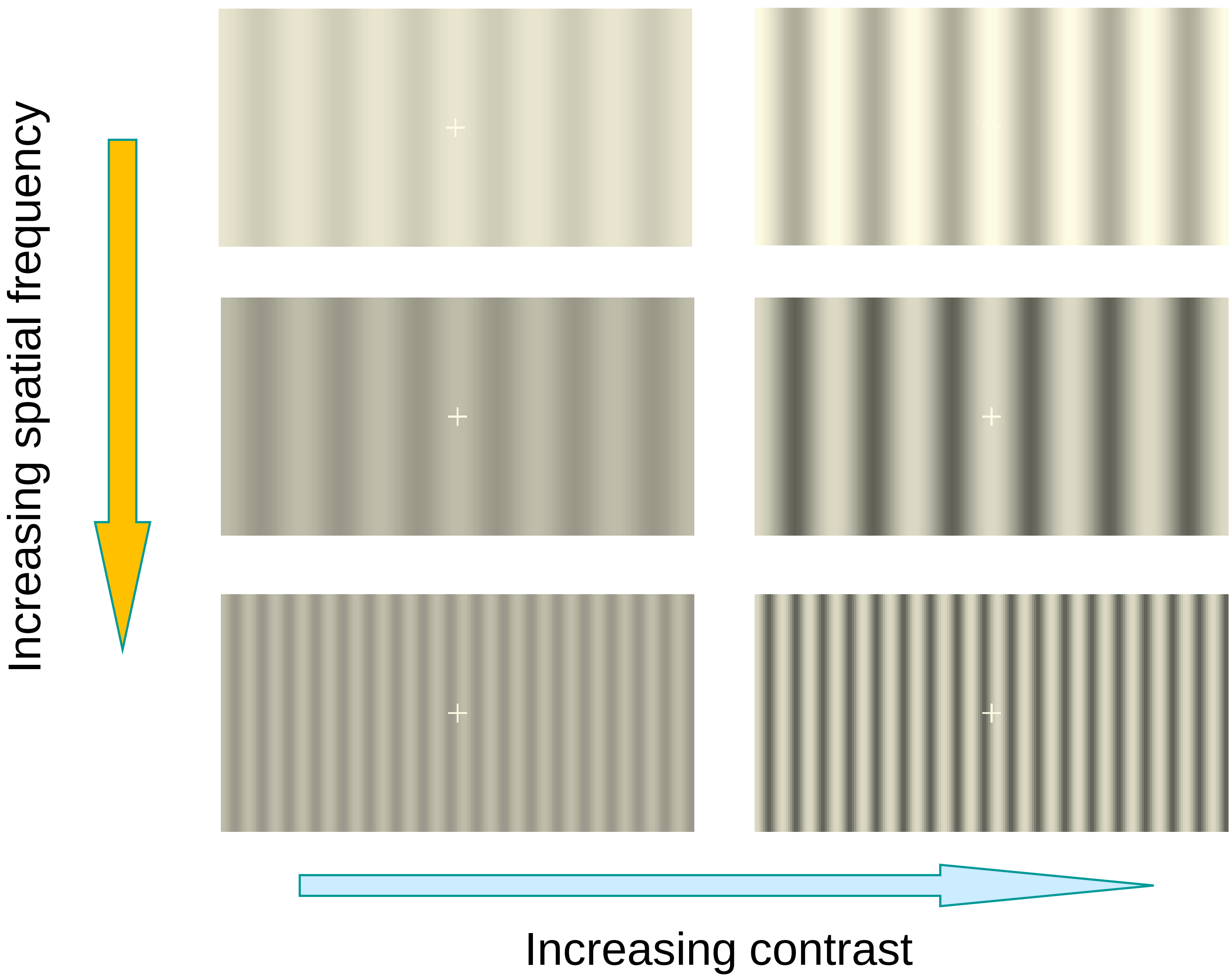
Image of line

PSF

Spatial MTF

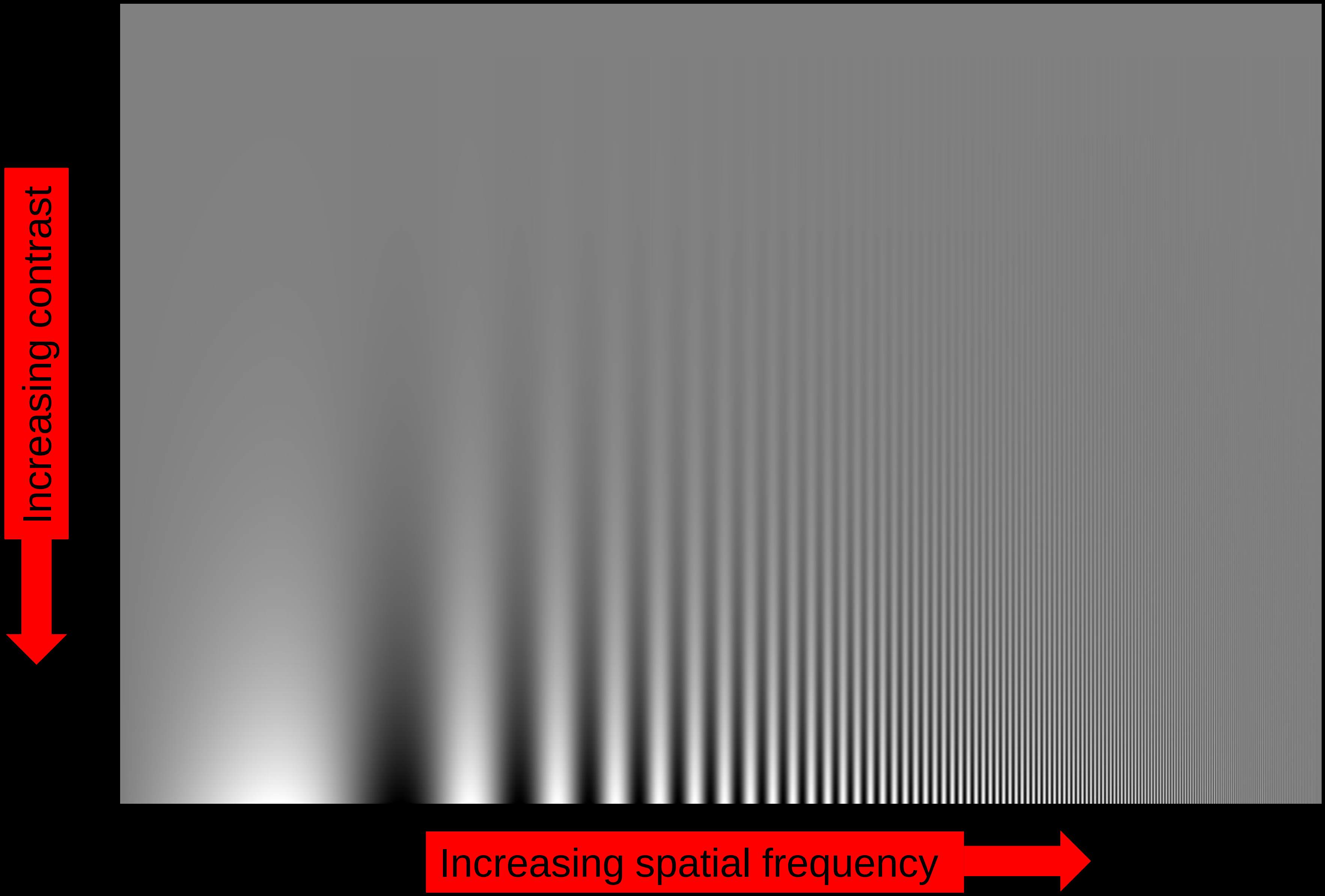
What would the results for a perfect lens look like?

Spatial frequency gratings



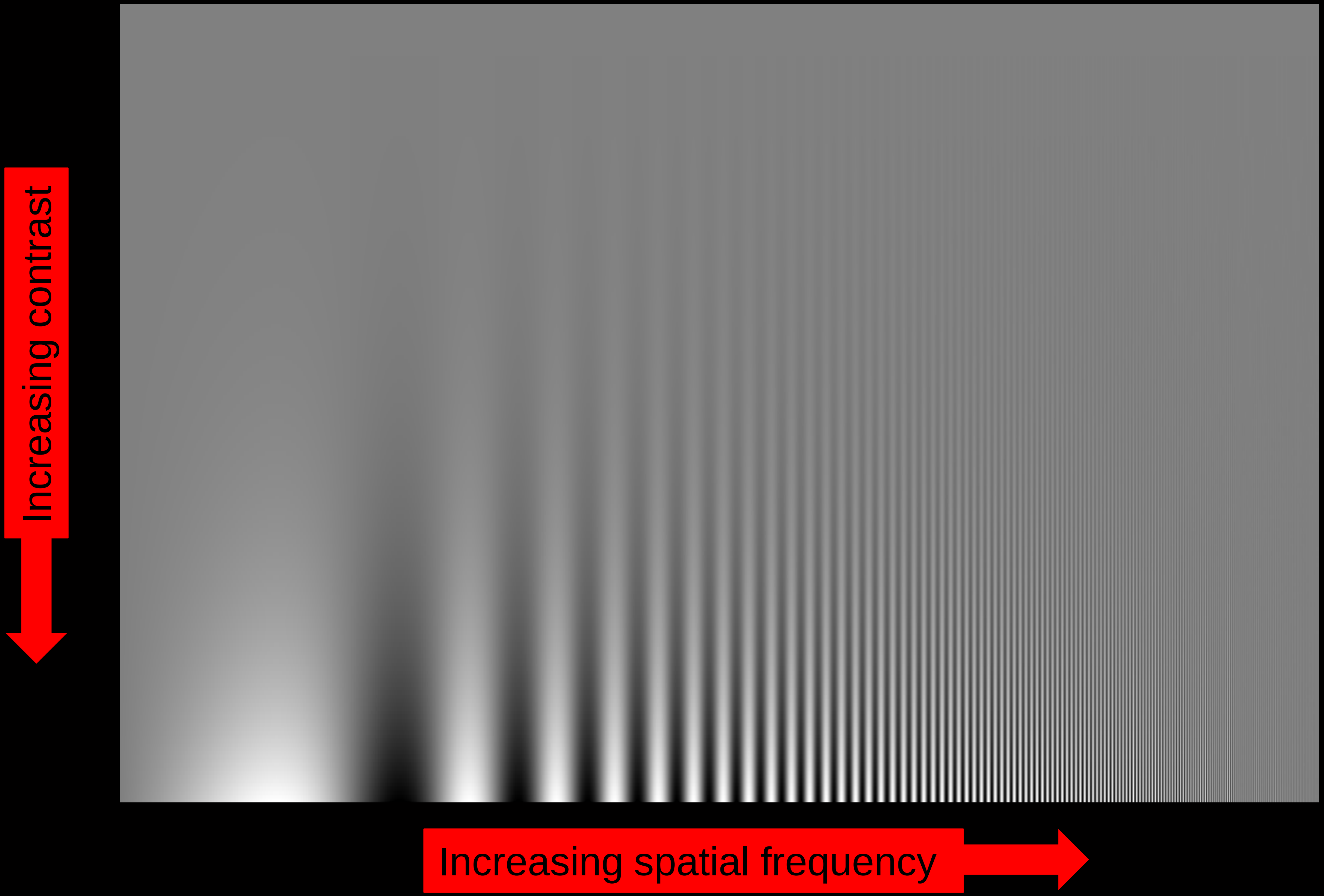
Spatial MTF

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



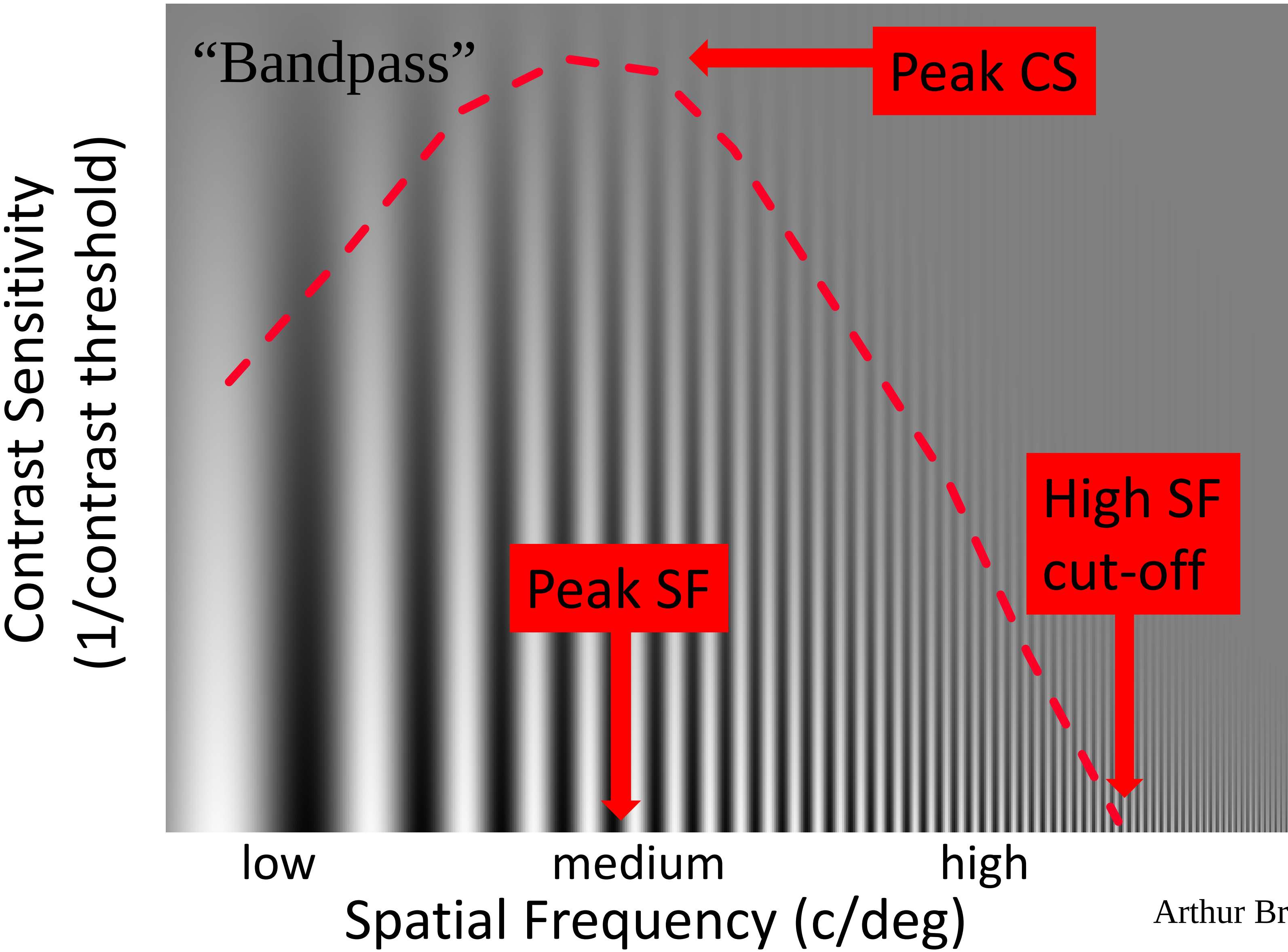
Spatial MTF

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



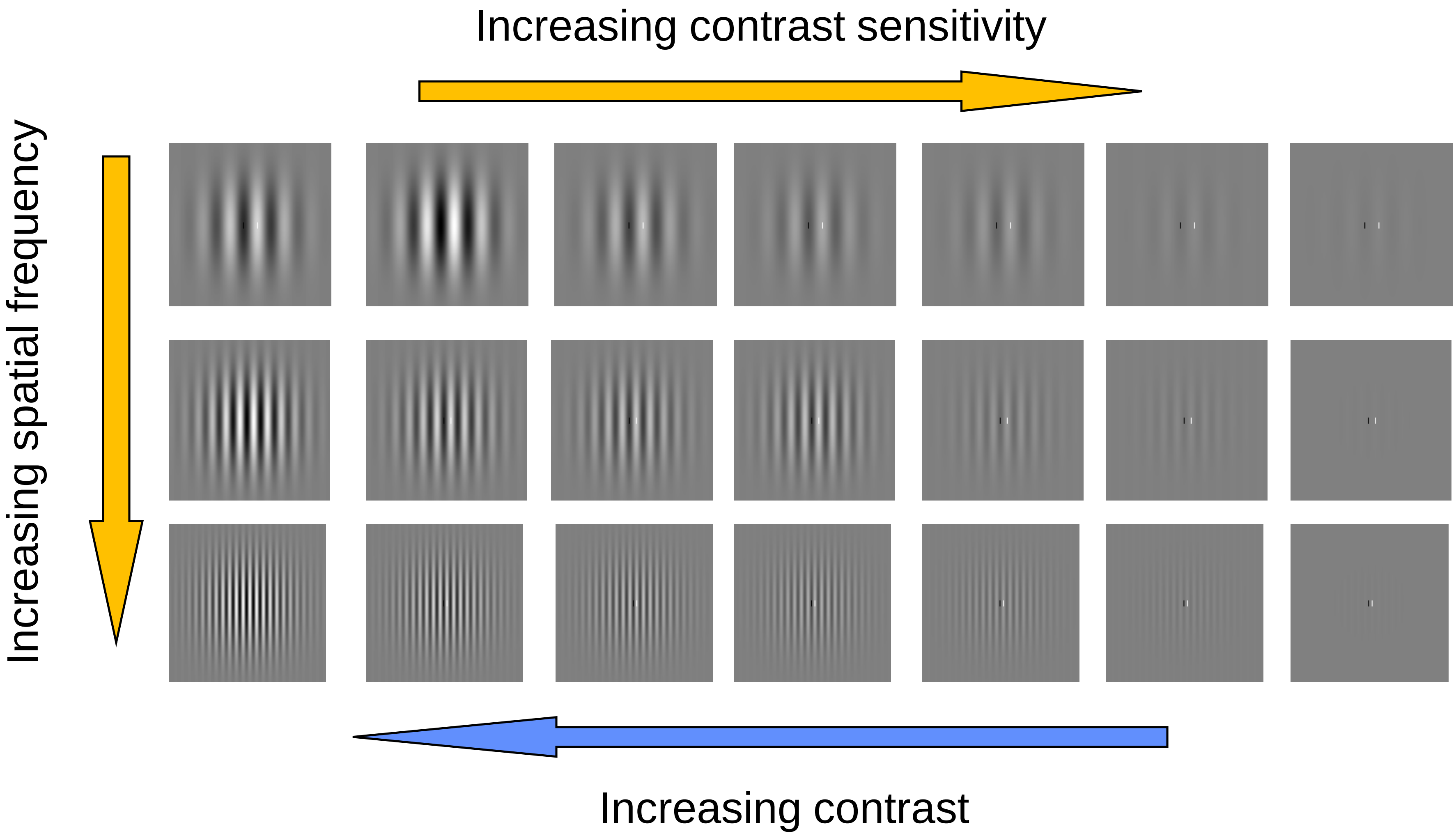
2. Grating Contrast Sensitivity

Contrast Sensitivity Function (CSF)



Arthur Bradley

Example of grating contrast sensitivity test using printed gratings



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Spatial CSFs

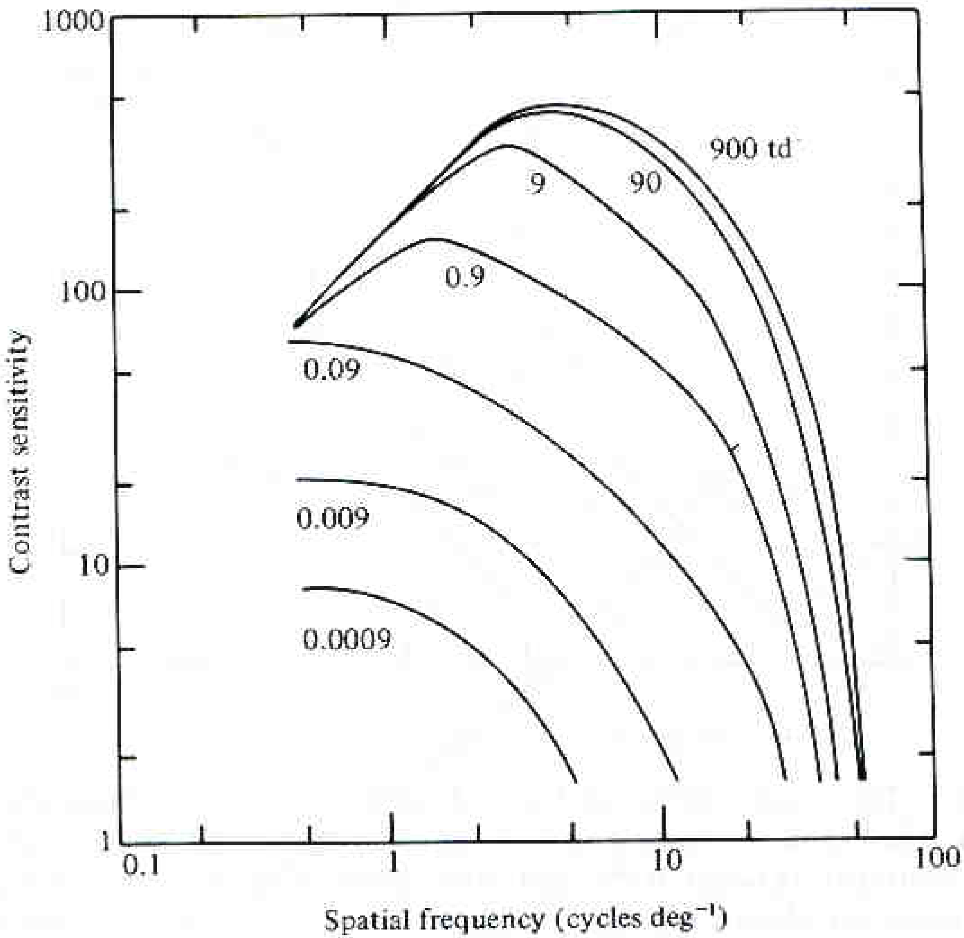
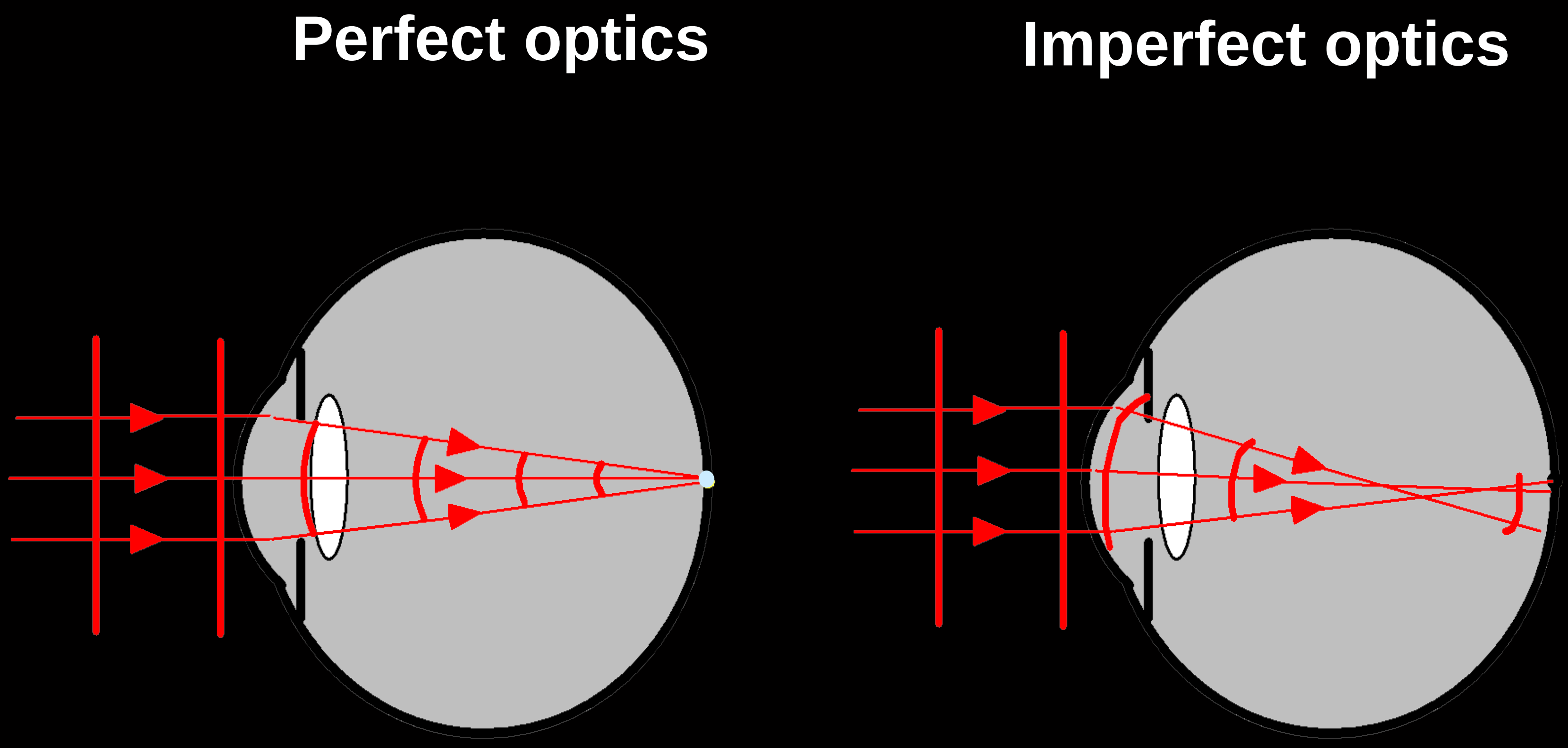


Fig. 8.4. Spatial contrast sensitivity curves at seven different retinal illuminance levels between 0.0009 and 900 trolands. The subject viewed the gratings through a 2 mm diameter artificial pupil. The wavelength of the light was 525 nm. Notice the loss of sensitivity for medium and high frequencies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

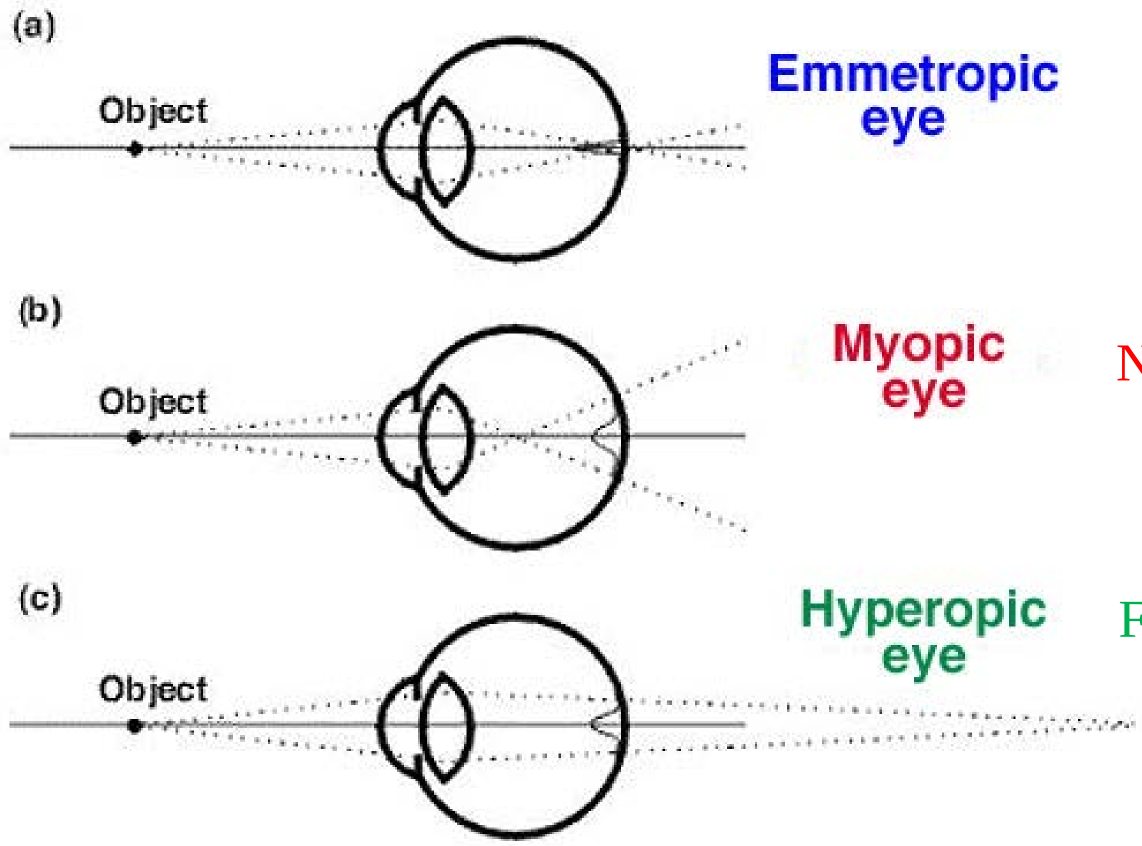
Refractive errors

Aberrations of the Eye



Larry Thibos

PSFs for different refractive errors



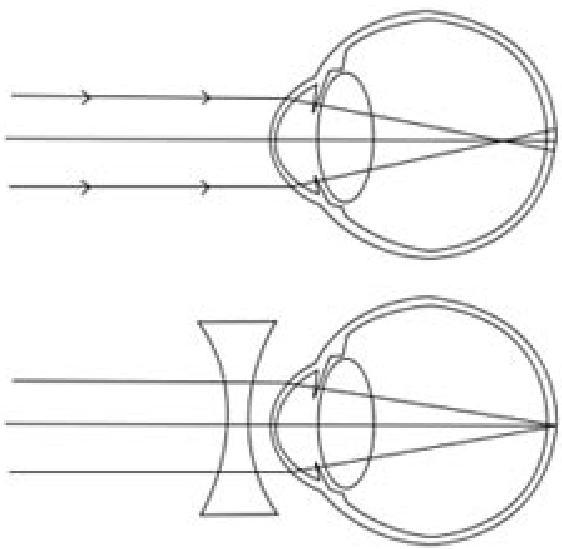
Nearsighted

Farsighted

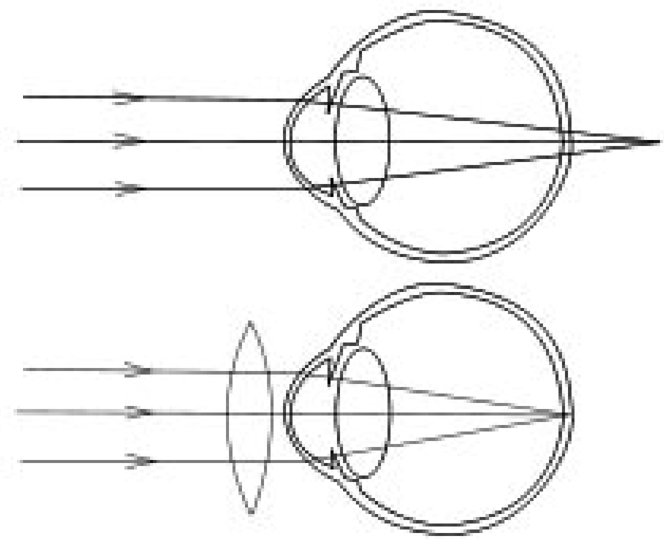
From Webvision, Michael Kalloniatis

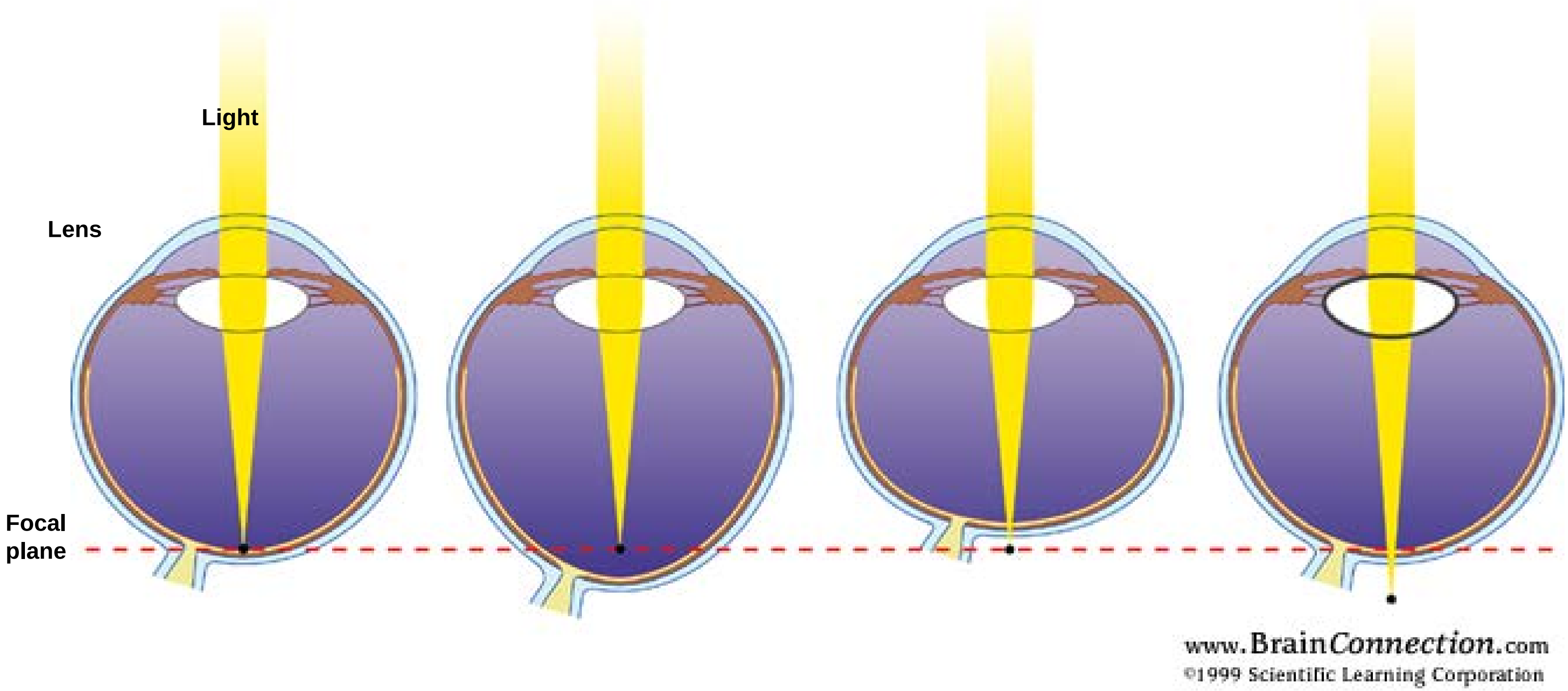
Corrective lenses

Myopia



Hyperopia





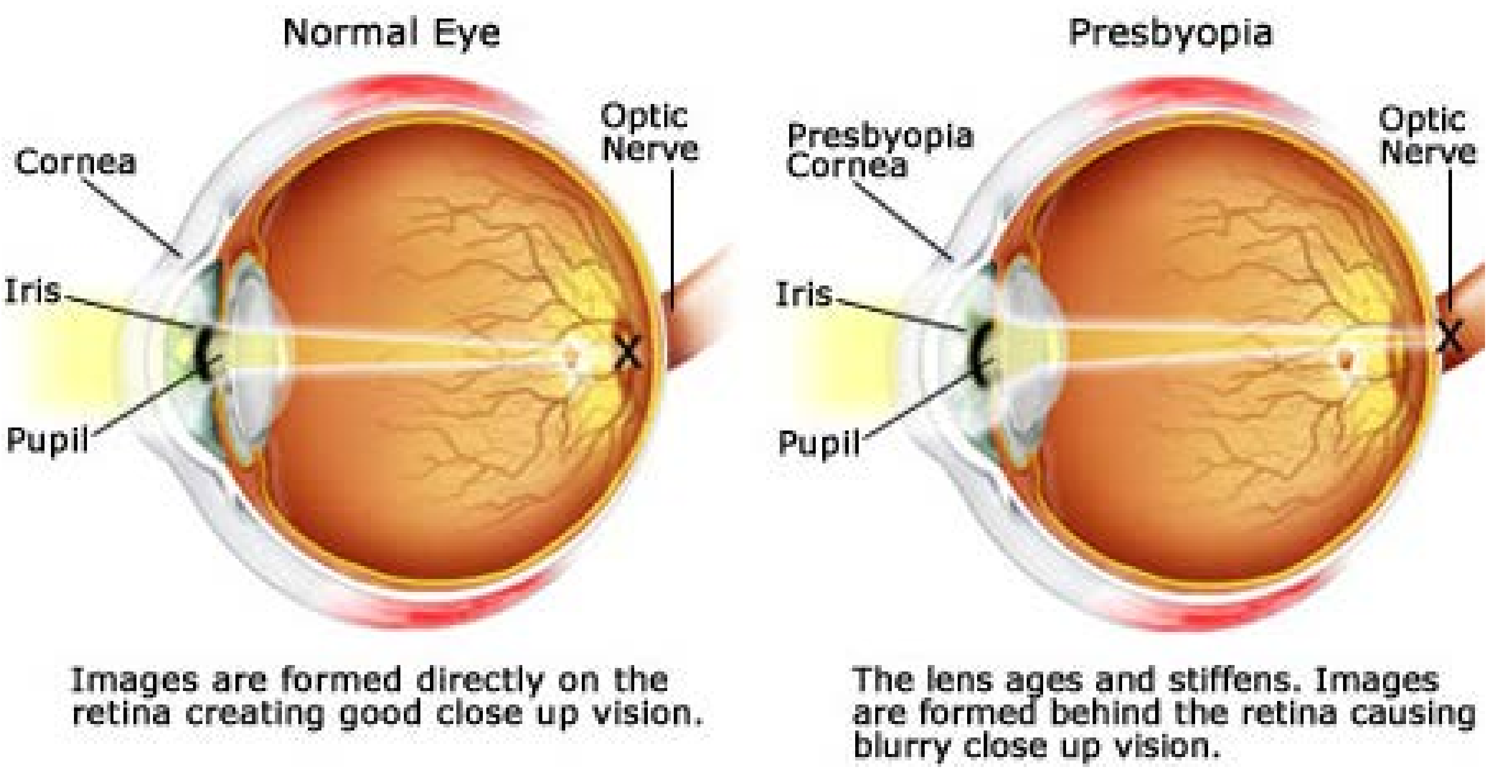
Emmetropia (normal)

Myopia (nearsightedness)

Hyperopia (farsightedness)

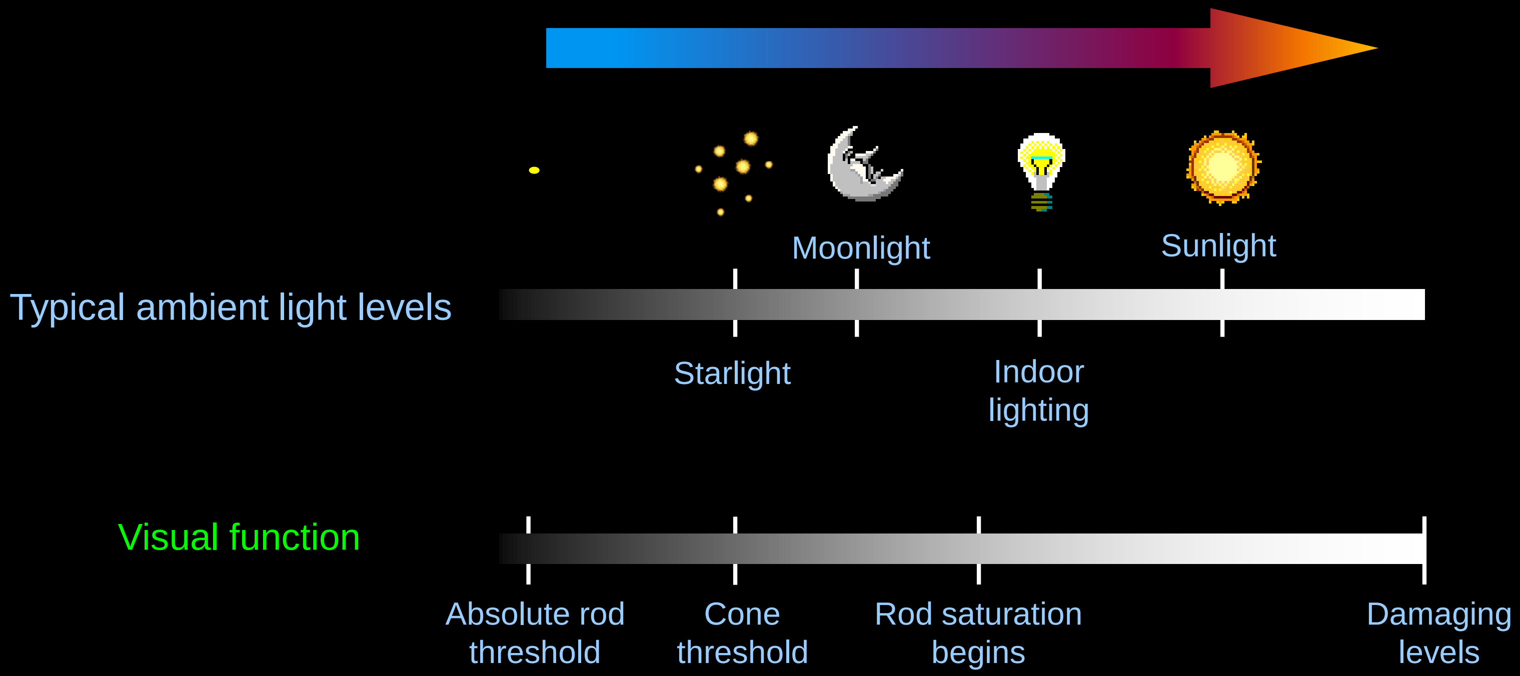
Presbyopia (aged)

Presbyopia (age related far-sightedness)



Rods and cones: why do we have two types of photoreceptor?

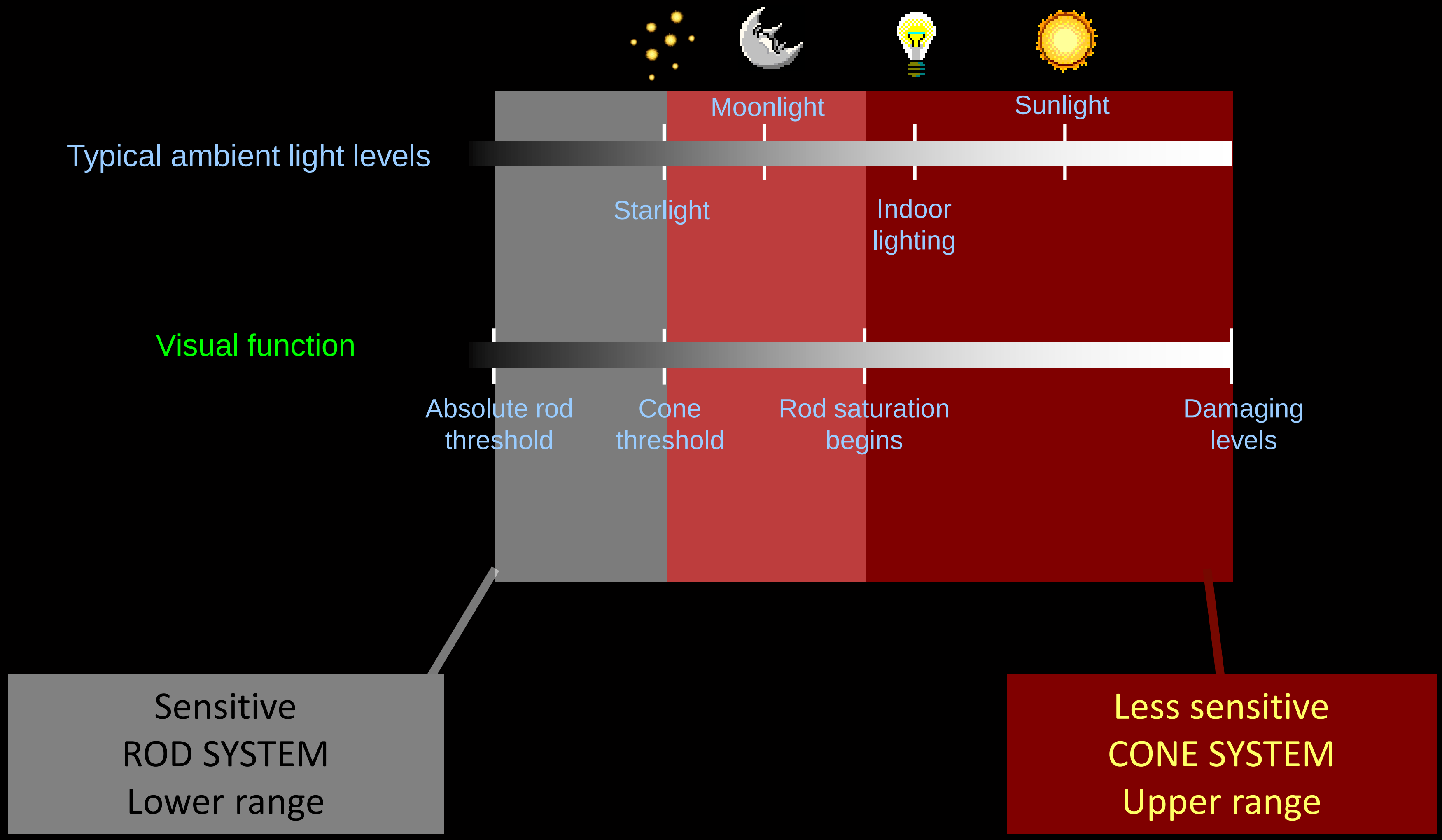
Our vision has to operate over an enormous range of 10^{12} (1,000,000,000,000) levels



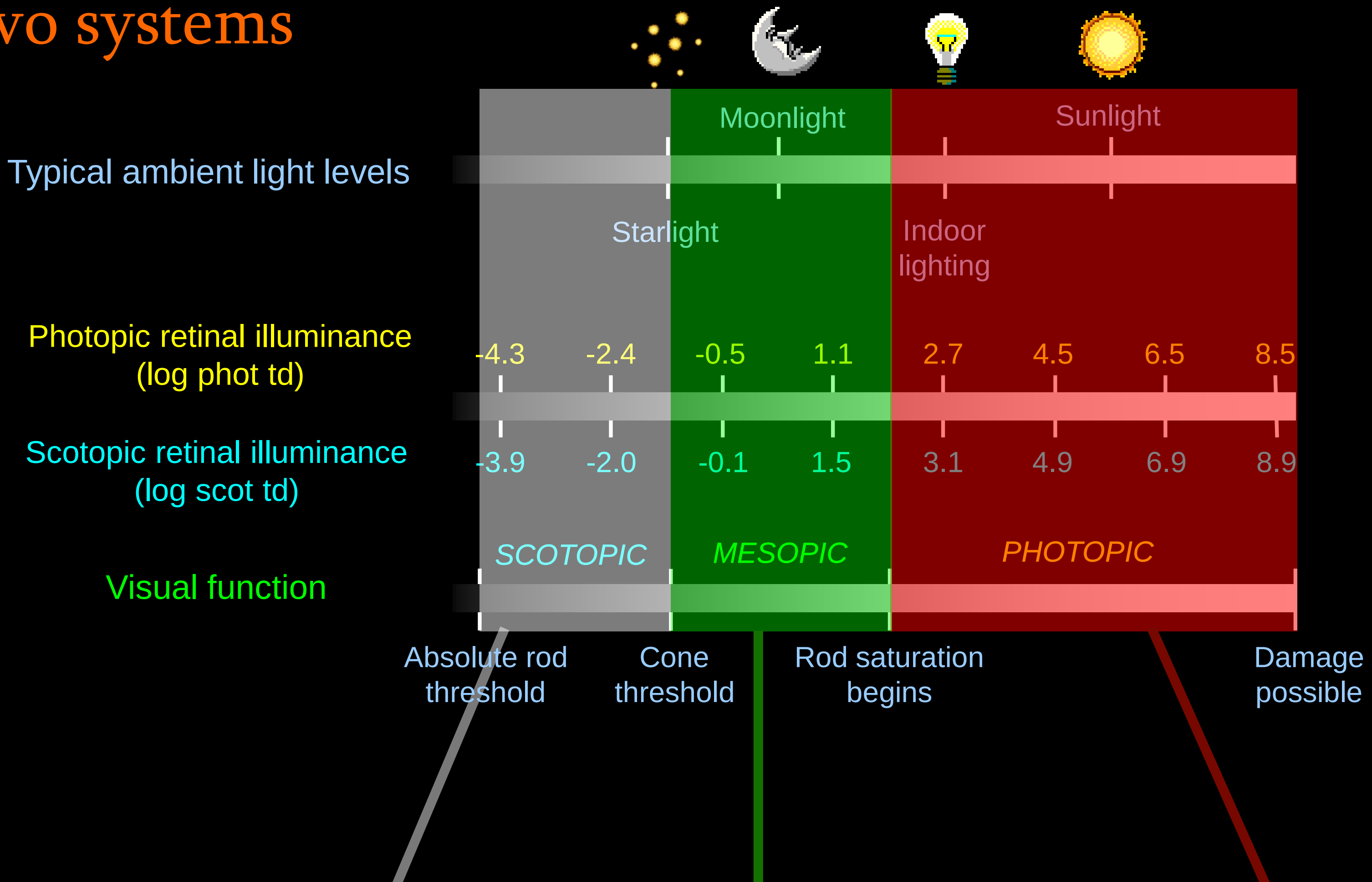
To cover that range we have two different types of photoreceptor...

Rods that are optimized for low light levels

Cones that are optimized for higher light levels



Two systems



Scotopic levels
(below cone threshold)
where rod vision functions alone.
A range of c. $10^{3.5}$

Mesopic levels
where rod and cone vision function together.
A range of c. 10^{3}

Photopic levels
(above rod saturation)
where cone vision functions alone.
A range of > 10^{6}

Rod vision

- Achromatic
- High sensitivity
- Poor detail and no colour

Cone vision

- Achromatic and chromatic
- Lower sensitivity
- Detail and good colour

ROD AND CONE DIFFERENCES

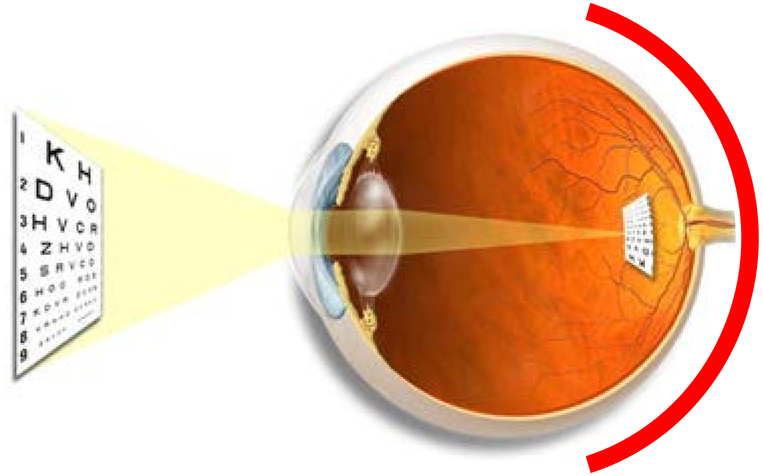
Differences in the number and distribution of cone and rod photoreceptors

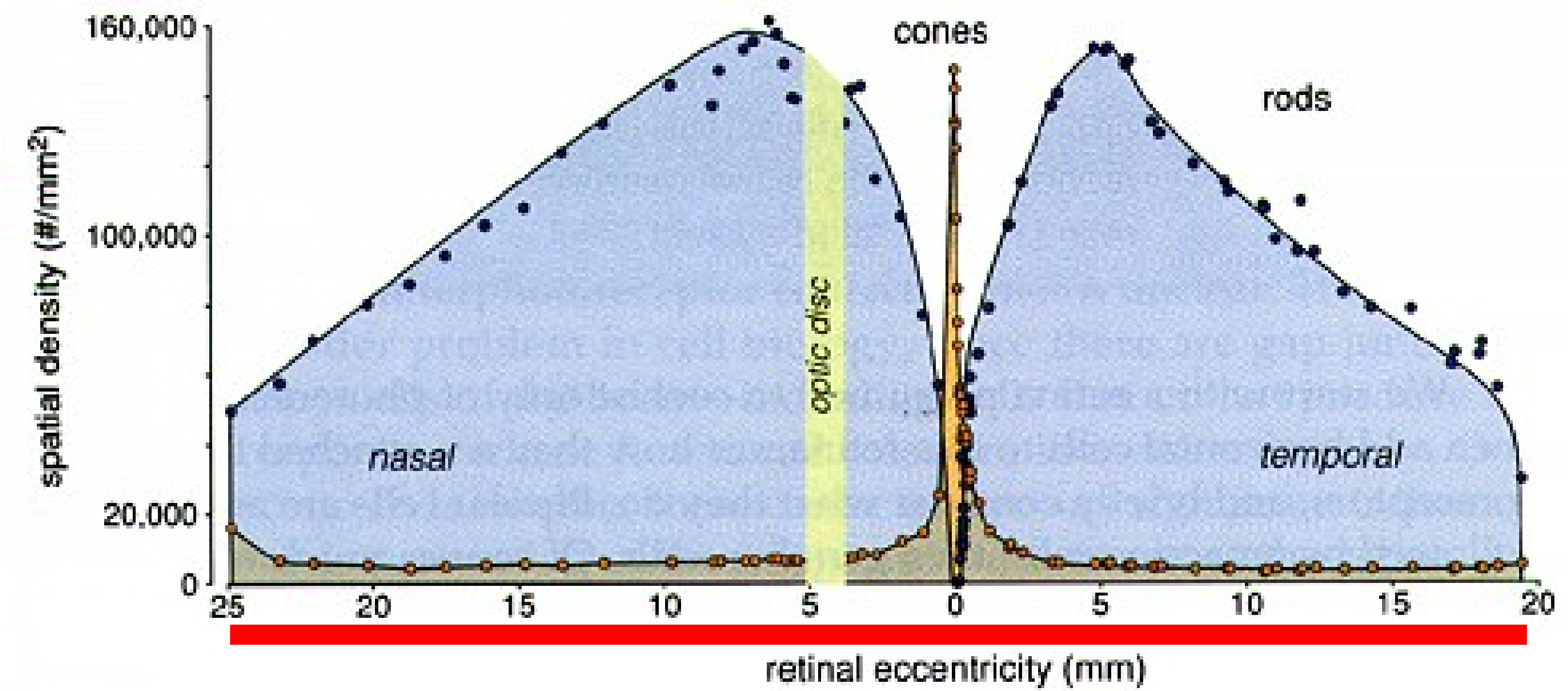
Facts and figures

There are about 120 million rods. They are absent in the central 0.3 mm diameter area of the fovea, known as the *fovea centralis*.

There are only about 6 to 7 million cones. They are much more concentrated in the fovea.

Rod and cone distribution

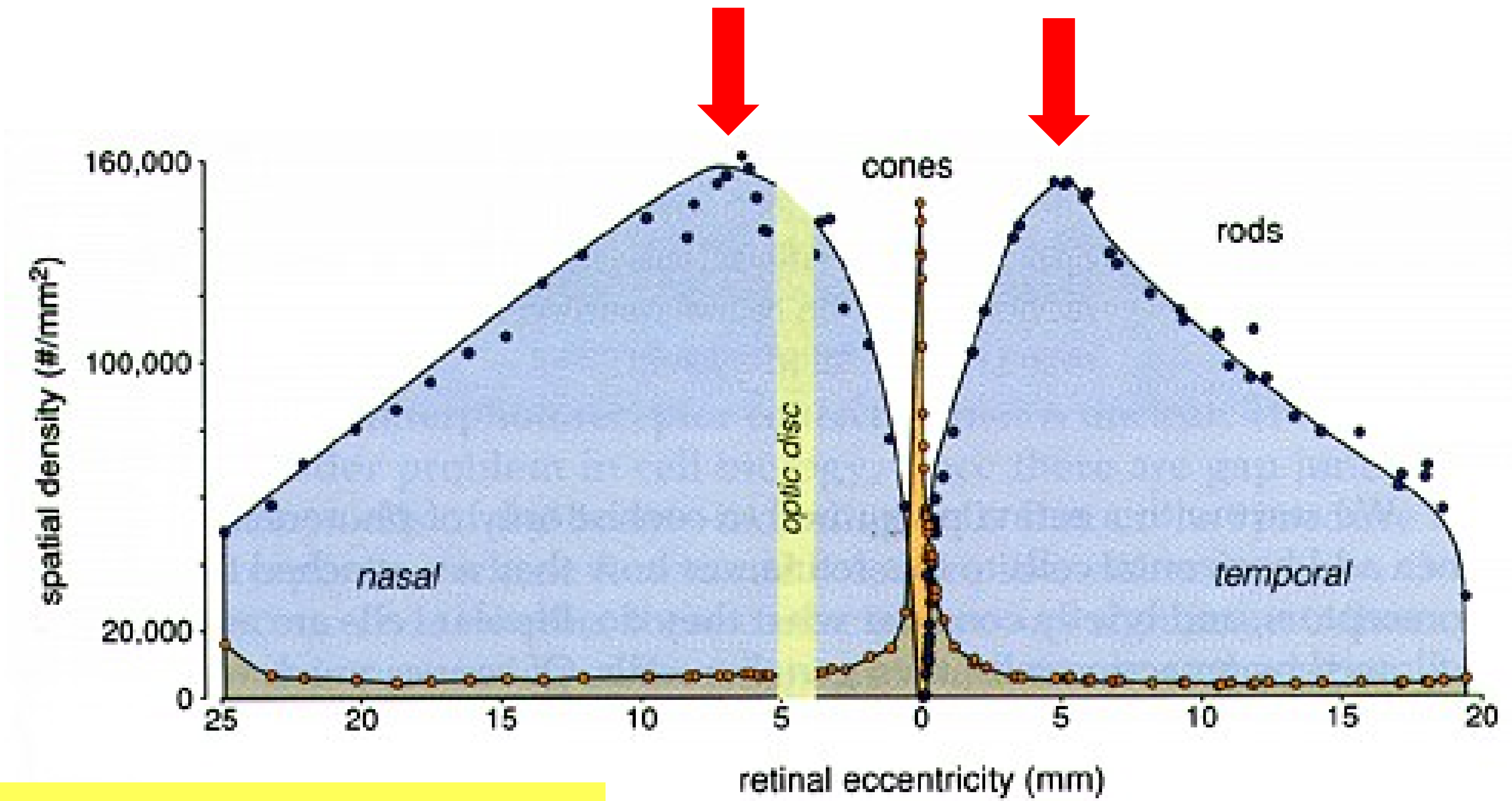




after Østerberg, 1935; as modified by Rodieck, 1988

0.3 mm of eccentricity is
about 1 deg of visual angle

Rod density peaks at about
20 deg eccentricity

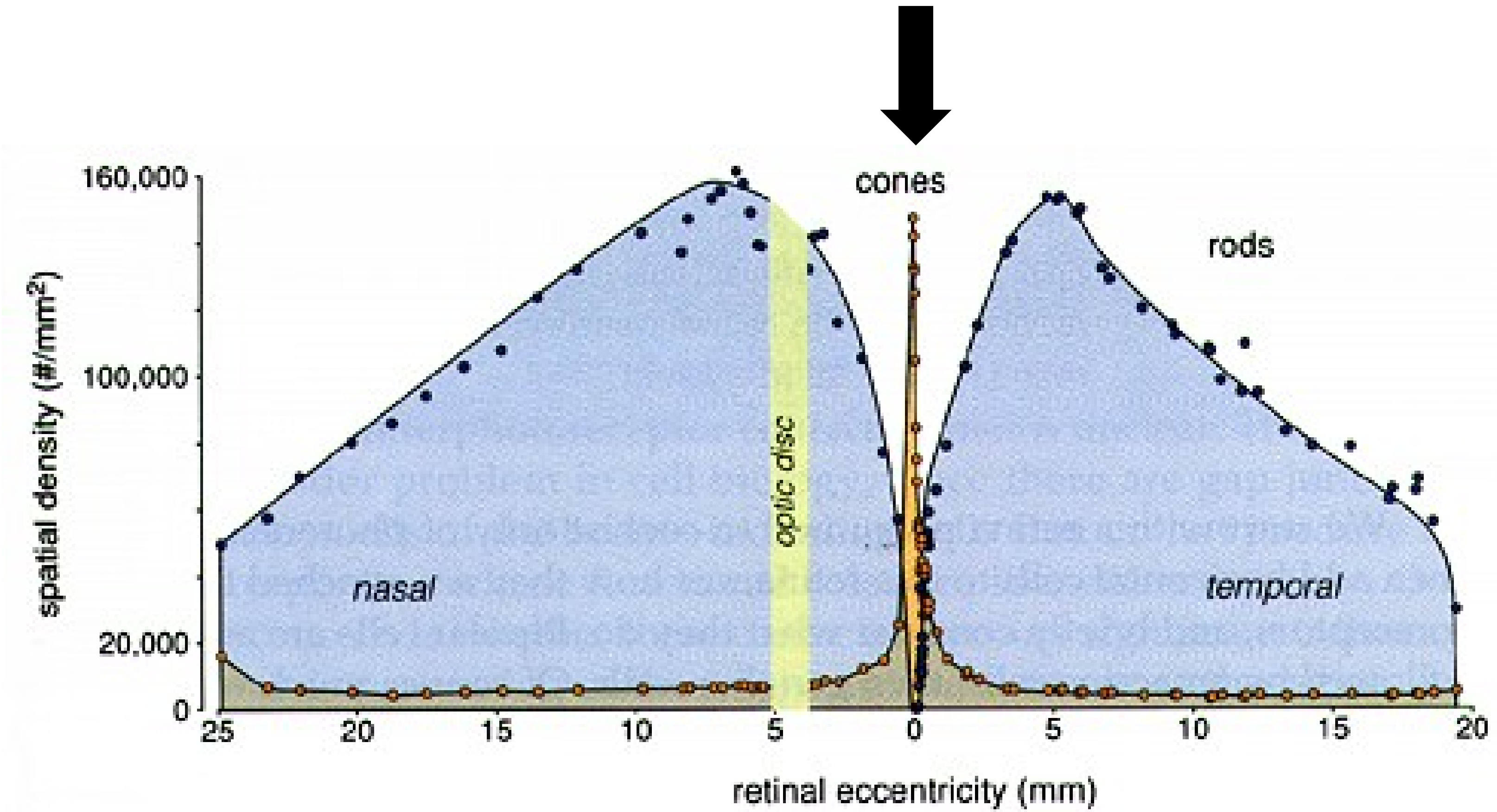


after Østerberg, 1935; as modified by Rodieck, 1988

At night, you have to look away from things to see them in more detail

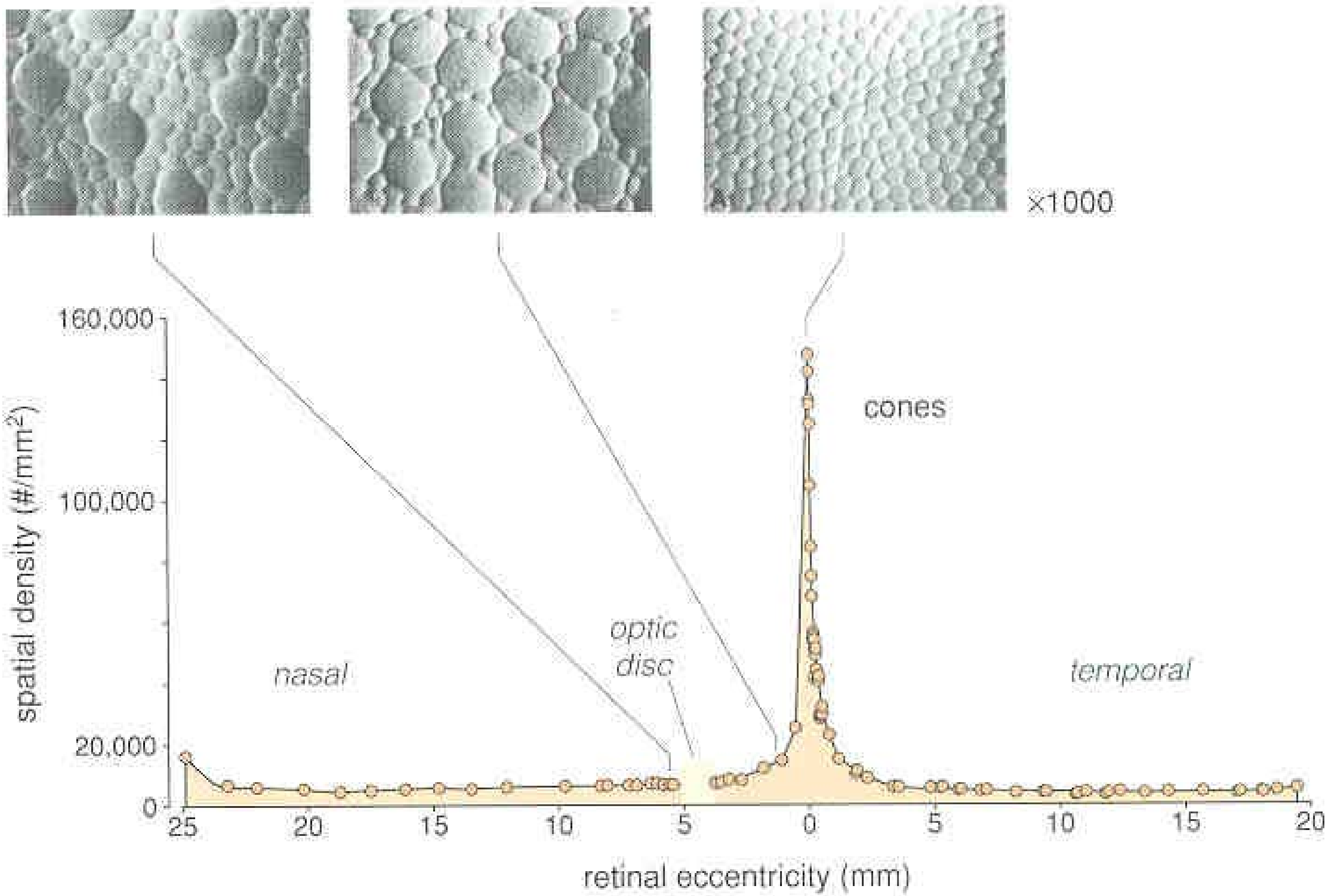
During the day, you have to look at things directly to see them in detail

Cones peak at the centre of vision at 0 deg



after Østerberg, 1935; as modified by Rodieck, 1988

Cone distribution and photoreceptor mosaics

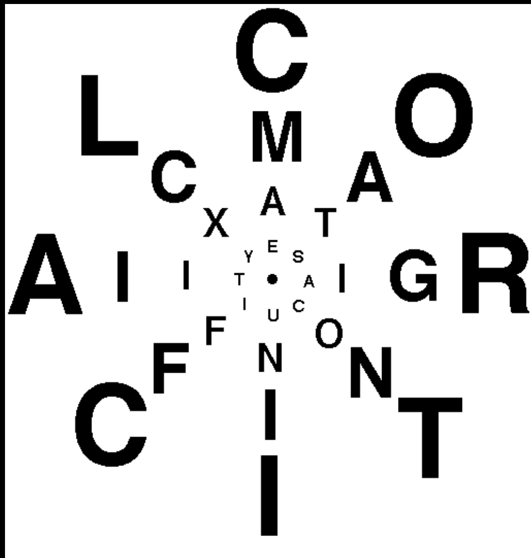


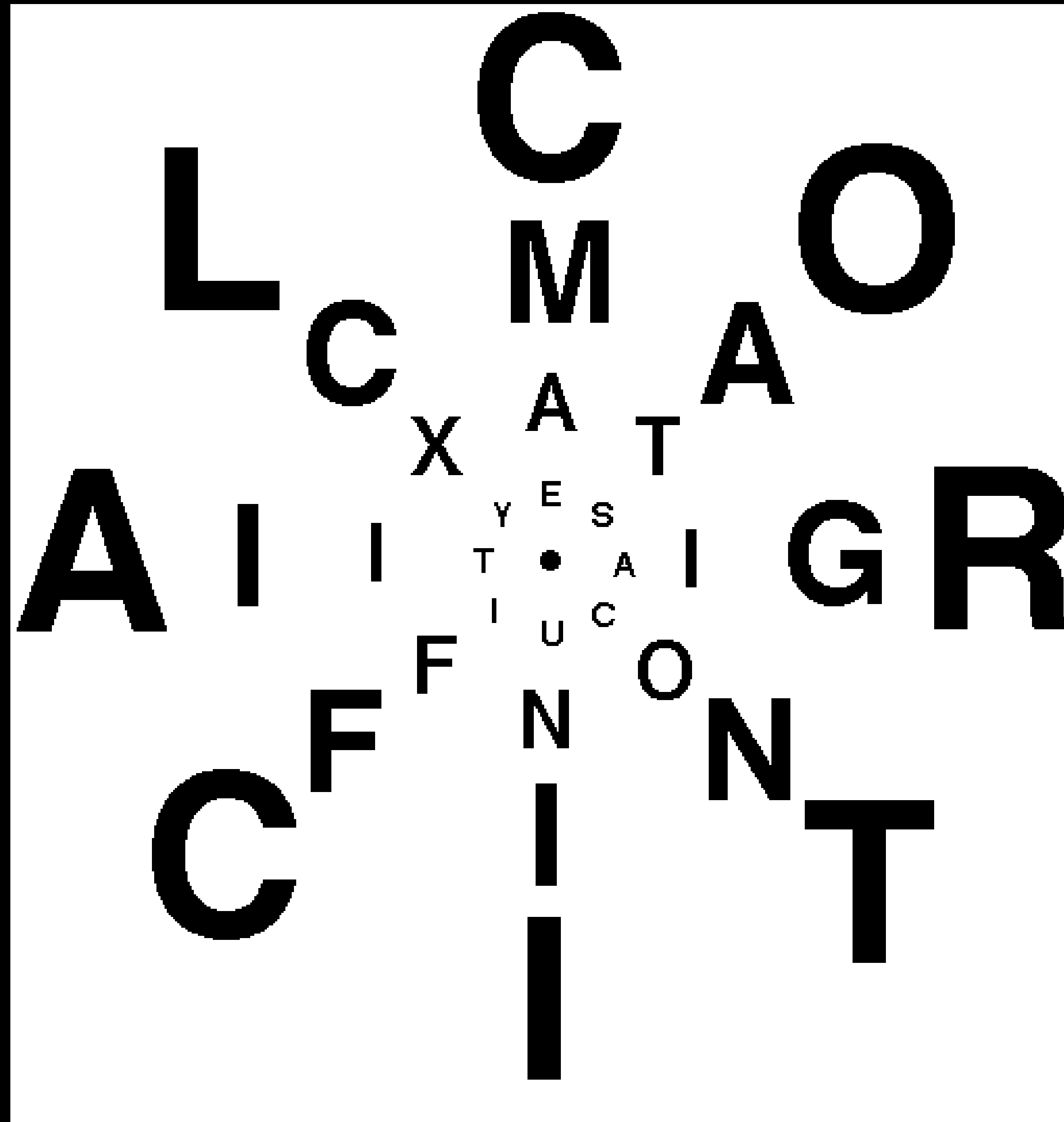
after Østerberg, 1935; as modified by Rodieck 1988;
micrographs from Curcio et al., 1990

The human cone visual system is a foveating system

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

Credit: Stuart Anstis, UCSD

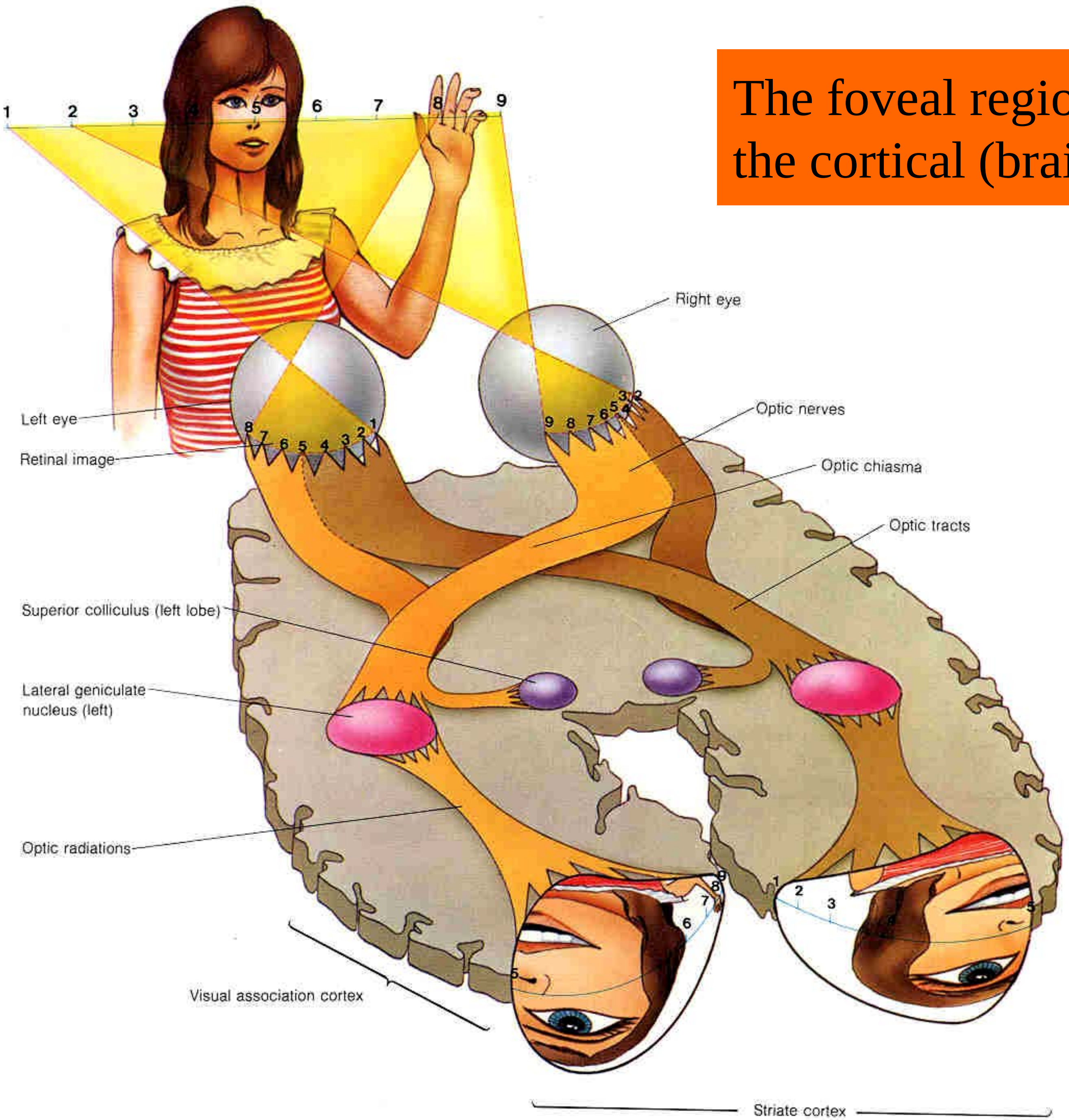




Visual acuity gets much poorer with eccentricity

Credit: Stuart Anstis, UCSD

The foveal region is magnified in the cortical (brain) representation



Rod vision is more sensitive than cone vision

Rod and cone differences can be demonstrated using tests of visual performance.

Rod and cone threshold versus intensity curves

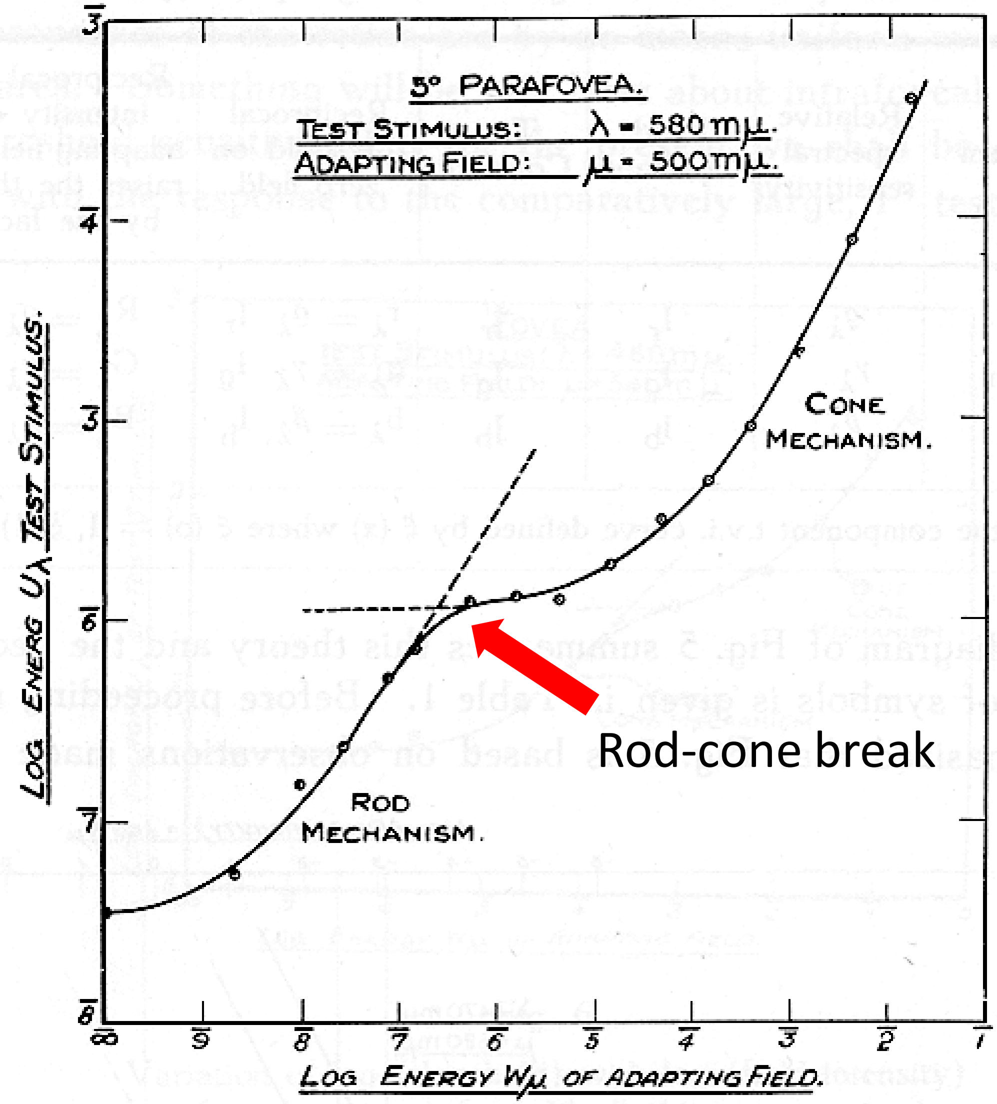


Fig. 4.

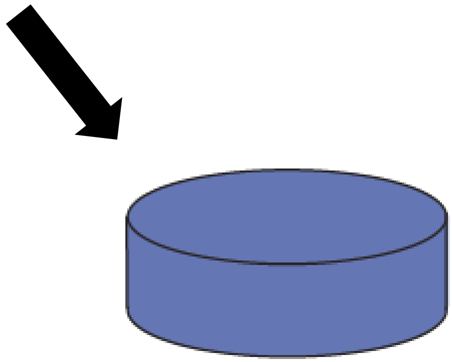
Variation of log (threshold) with log (field intensity) for a 1° flashing test stimulus of yellow light (exposure time 0.063 sec.) on a blue-green field: 5°- parafoveal vision. (Stiles, 1939)

Rods are about one thousand times more sensitive than cones. They can be triggered by individual photons.

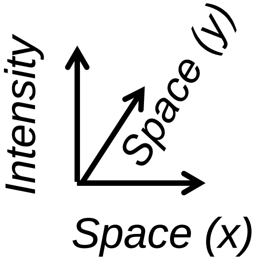
Rod and cone spectral sensitivity differences

Threshold versus target wavelength measurements

Incremental flash

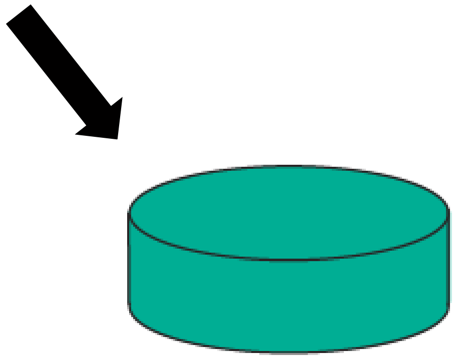


10-deg eccentric fixation

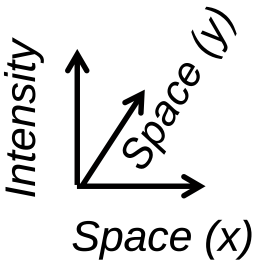


Threshold versus target wavelength measurements

Incremental flash

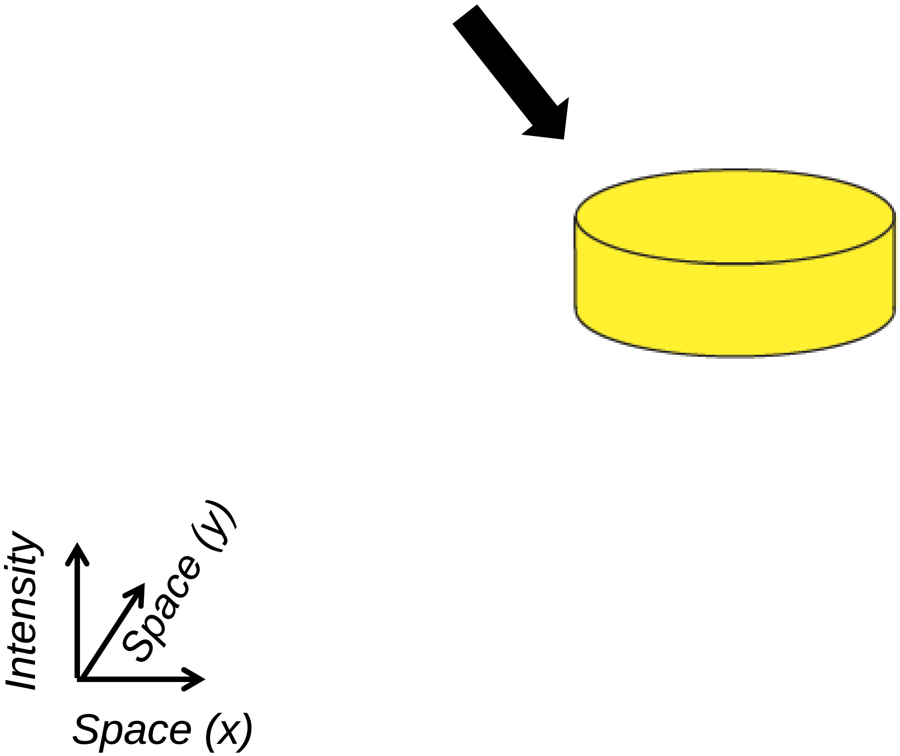


10-deg eccentric fixation



Threshold versus target wavelength measurements

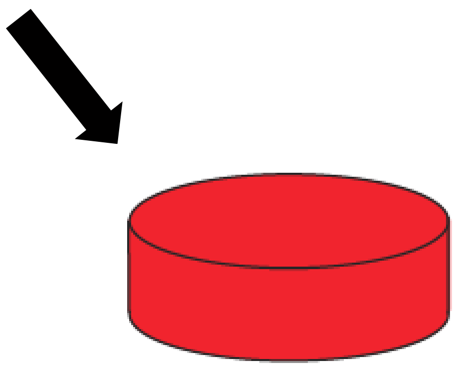
Incremental flash



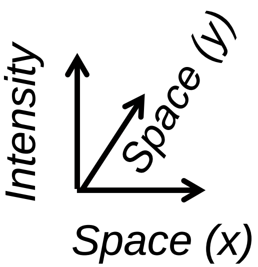
10-deg eccentric fixation

Threshold versus target wavelength measurements

Incremental flash



10-deg eccentric fixation



Rod and cone spectral sensitivity curves

Plotted as "thresholds" versus wavelength curves

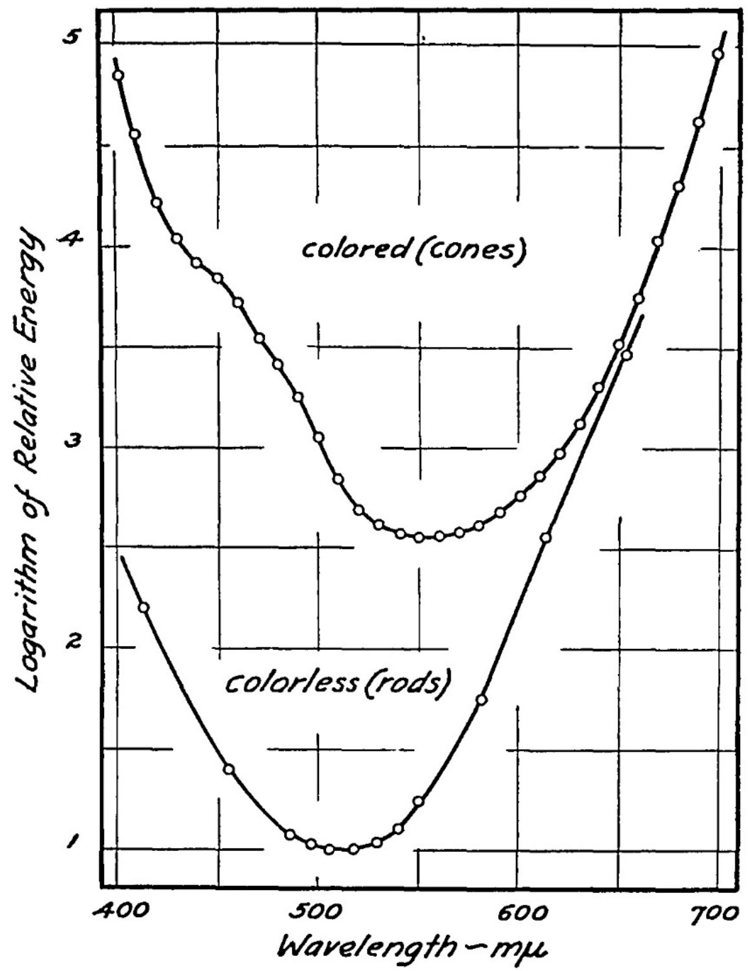
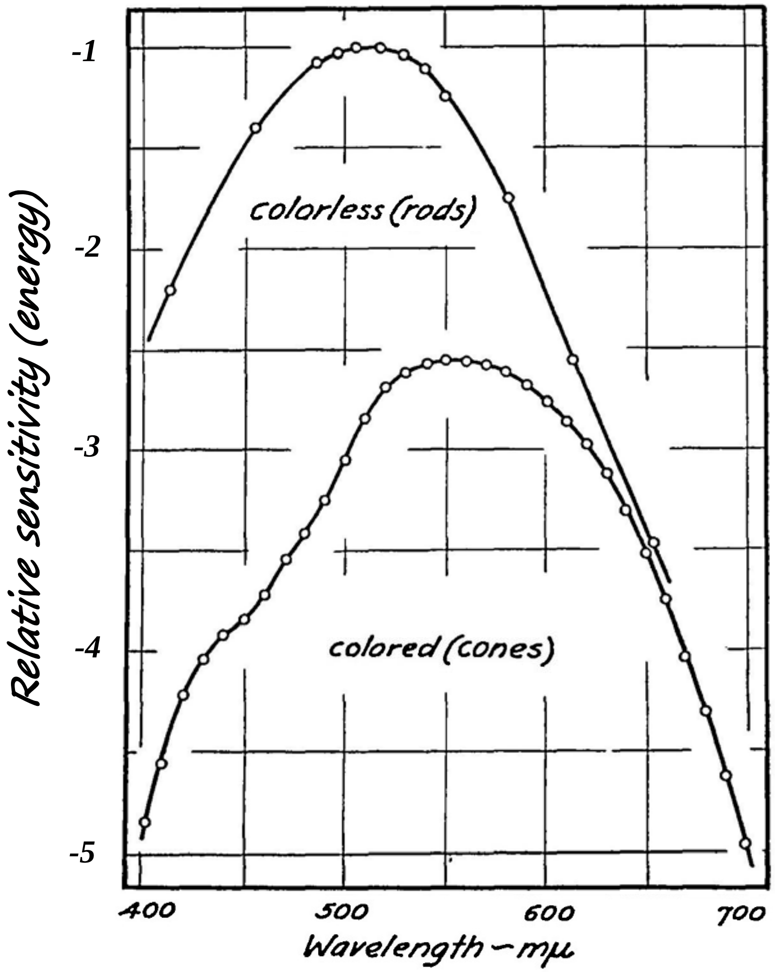


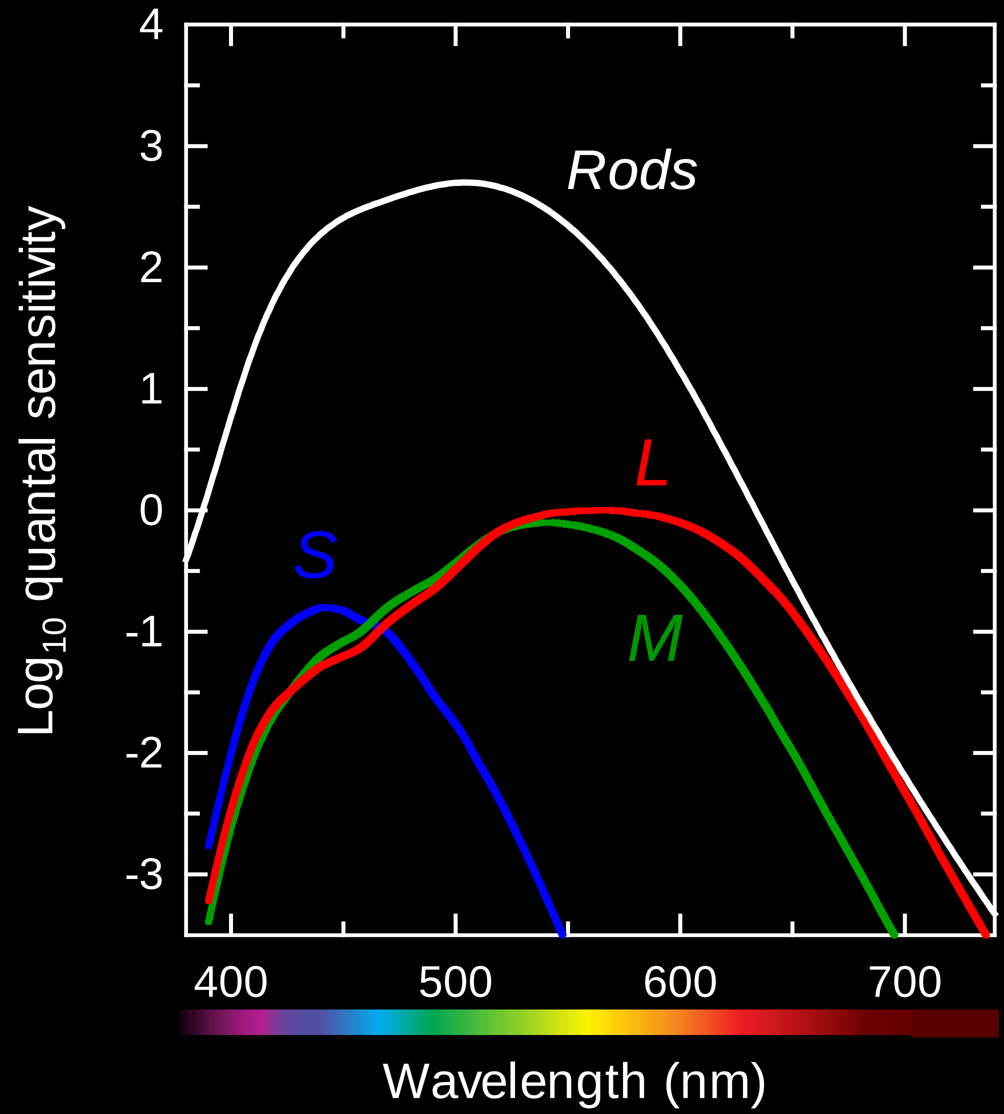
FIG. 2. Spectrum sensibility curves for rod and cone vision on a real energy basis. The data for the separate curves are from the same sources as in Fig. 1. The position of the two curves on the ordinates corresponds to the fact that after complete dark adaptation, any region of the retina outside the fovea sees red light of 650 mμ as colorless at the threshold, and as colored only above the threshold. The precise energy increment above the threshold for the appearance of color (cone function) varies for different parts of the retina; in the parafovea it lies between 0.1 and 1.0 log unit.

Plotted as the more conventional spectral "sensitivity" curve

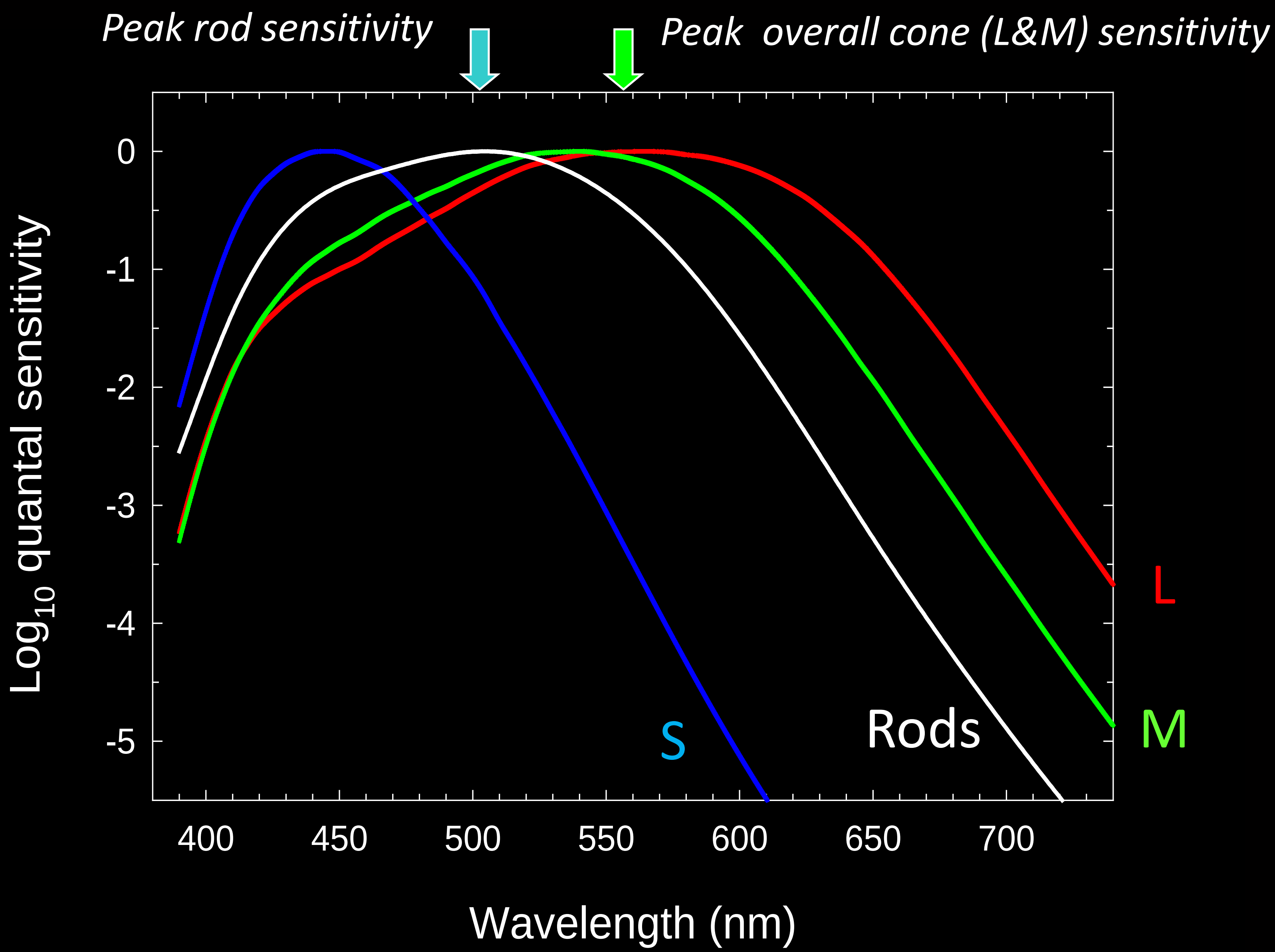


Sensitivity = 1/threshold
or
log (sensitivity) = -log(threshold)

Approximate dark-adapted photoreceptor sensitivities.



Spectral sensitivities and the Purkinje shift



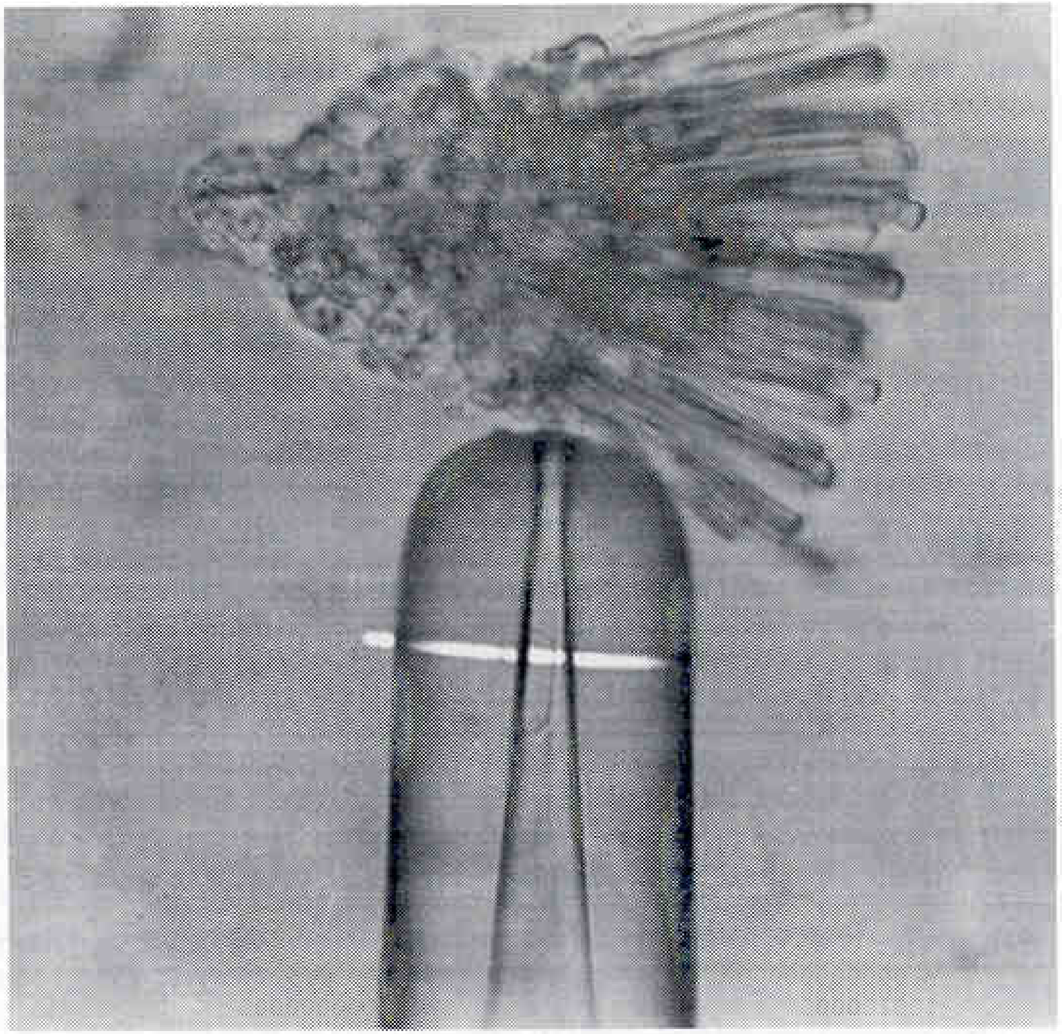
The Purkinje Shift

A change in the relative brightness of colours as the light level changes because of the difference in spectral sensitivity between rod and cone vision (*e.g.,* reds and oranges become darker as rods take over)

Simulated: Dick Lyon & Lewis Collard at Wikimedia

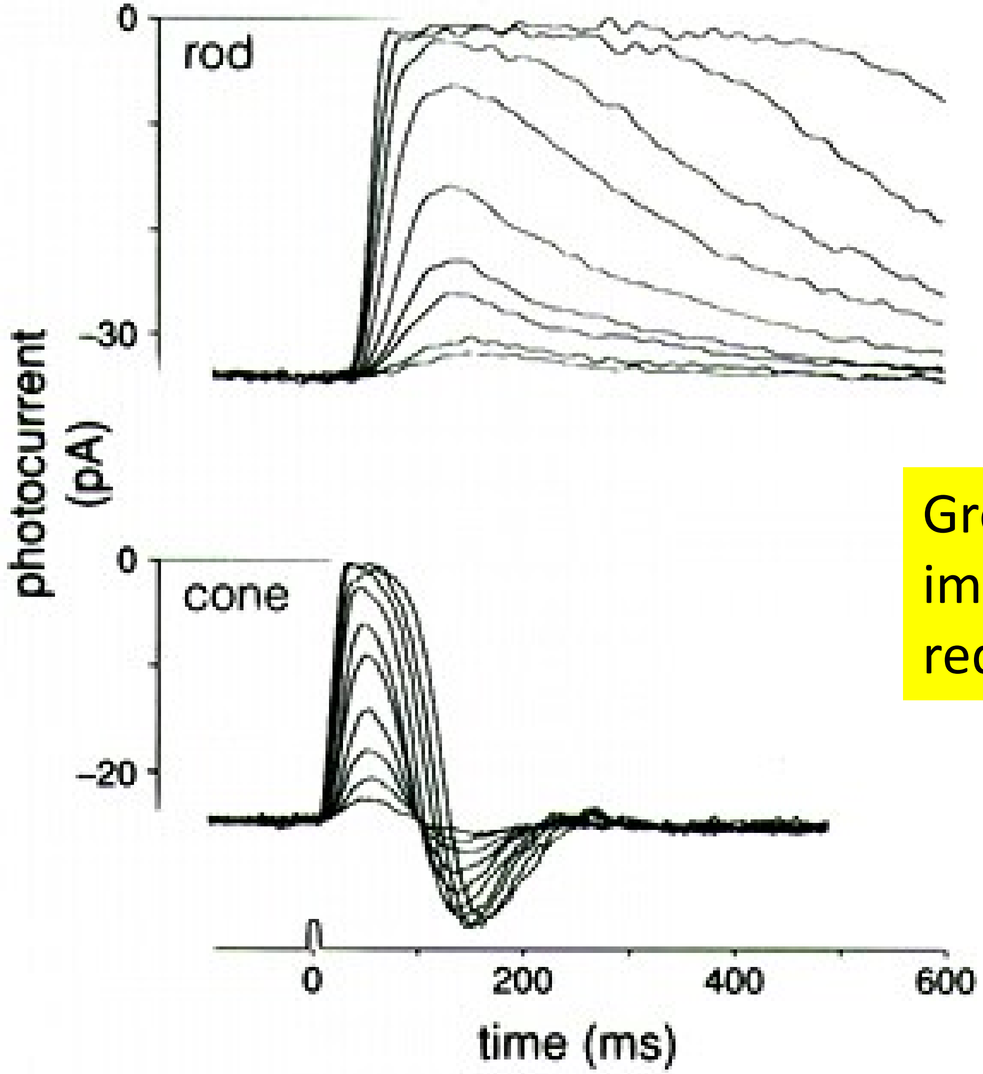
Rod and cone temporal differences

Suction electrode recording



4.15 MEASURING CONE PHOTOCURRENTS. The image shows a portion of macaque retina suspended in solution. A single photoreceptor from this retinal section has been drawn into a micropipette and is being stimulated by a beam of light passing transversely through the photoreceptor and micropipette. Courtesy of Denis Baylor.

Photocurrent responses



Greater temporal integration improves rod sensitivity (but reduces temporal acuity)

source: Baylor, 1987

Highest flicker rates that can just be seen (c.f.f.)

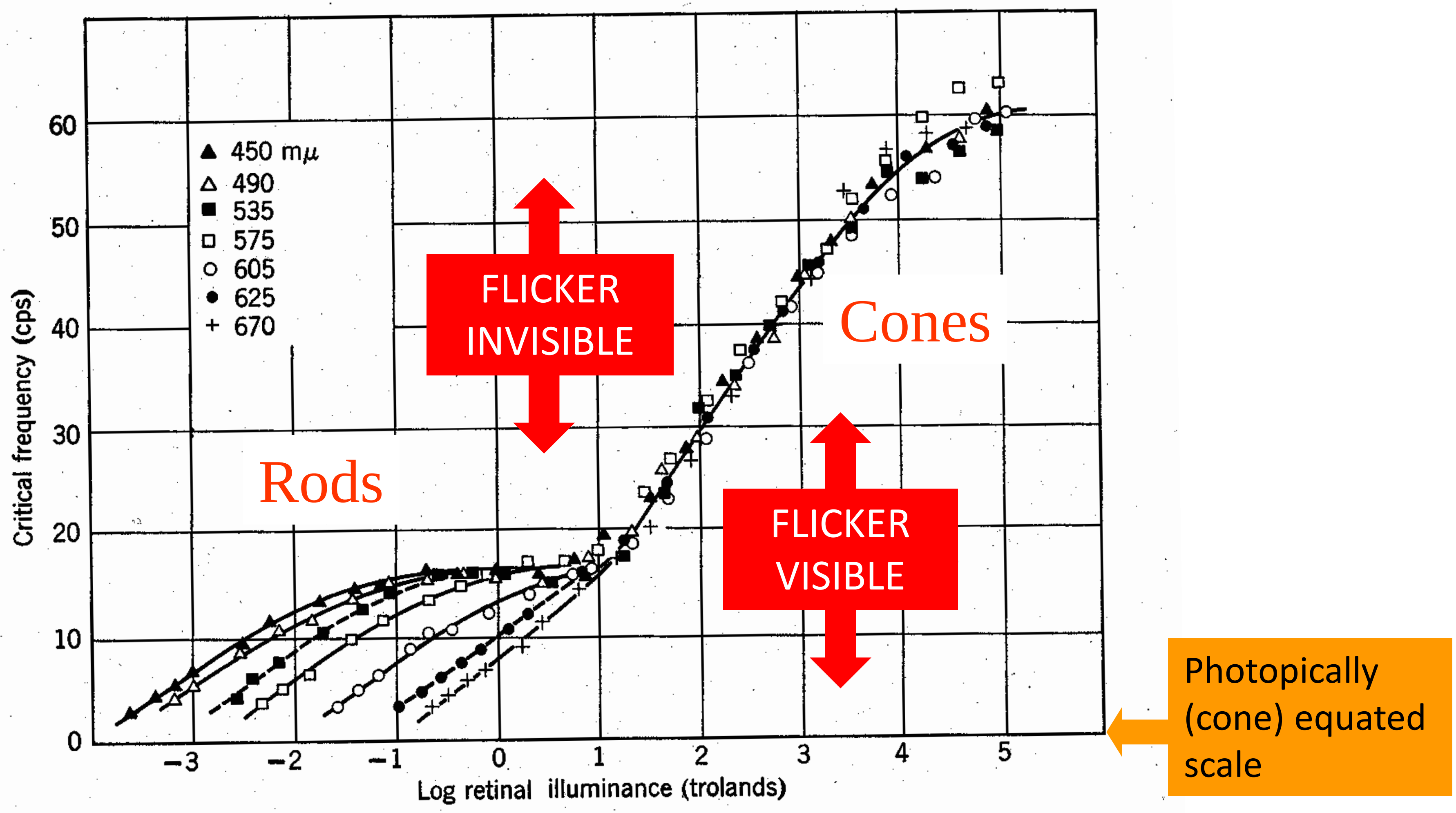
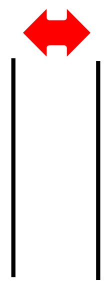


FIG. 10.6 Relation of CFF to log retinal illuminance for seven spectral regions. (Hecht and Shlaer, 1936. Reprinted by permission of The Rockefeller Institute Press from *The Journal of General Physiology*, 1936, **19**, 956–979; Fig. 3.)

Rod and cone spatial differences
(visual acuity)

Rod and cone visual acuities



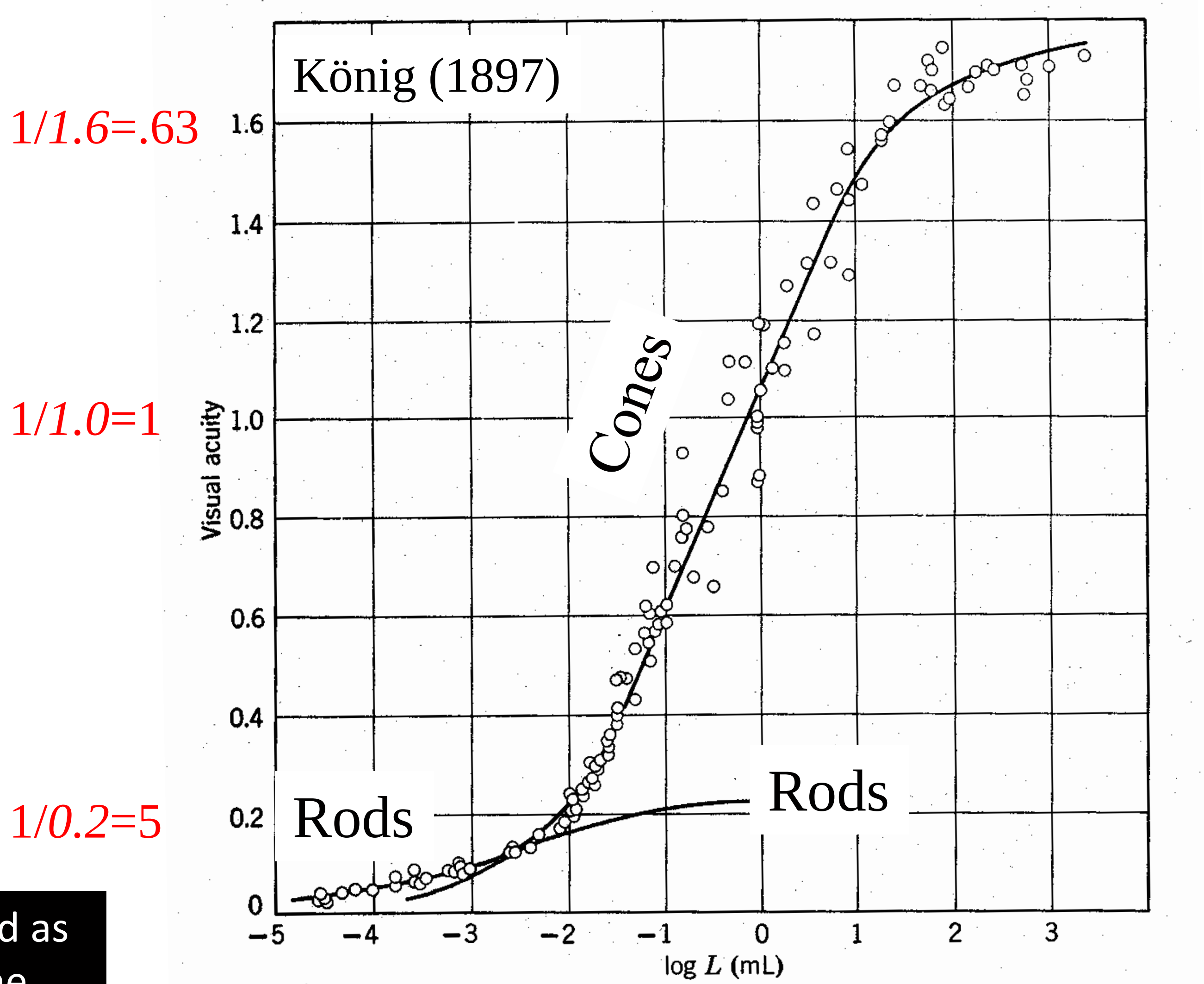


FIG. 11.14 König's data for the relation between visual acuity and illumination, as replotted by Hecht (1934). The shallow curve for the lower limb of the data is an equation for rods, whereas the upper curve is for cones. The task is one of recognizing the orientation of a hook form of test object.

The acuity here is defined as the *reciprocal* value of the size of the gap (measured in arc minutes) that can be reliably identified.

Rod and cone visual acuities

Greater spatial integration improves rod sensitivity but reduces acuity

The loss must be postreceptoral because the rods are smaller than cones in the periphery)

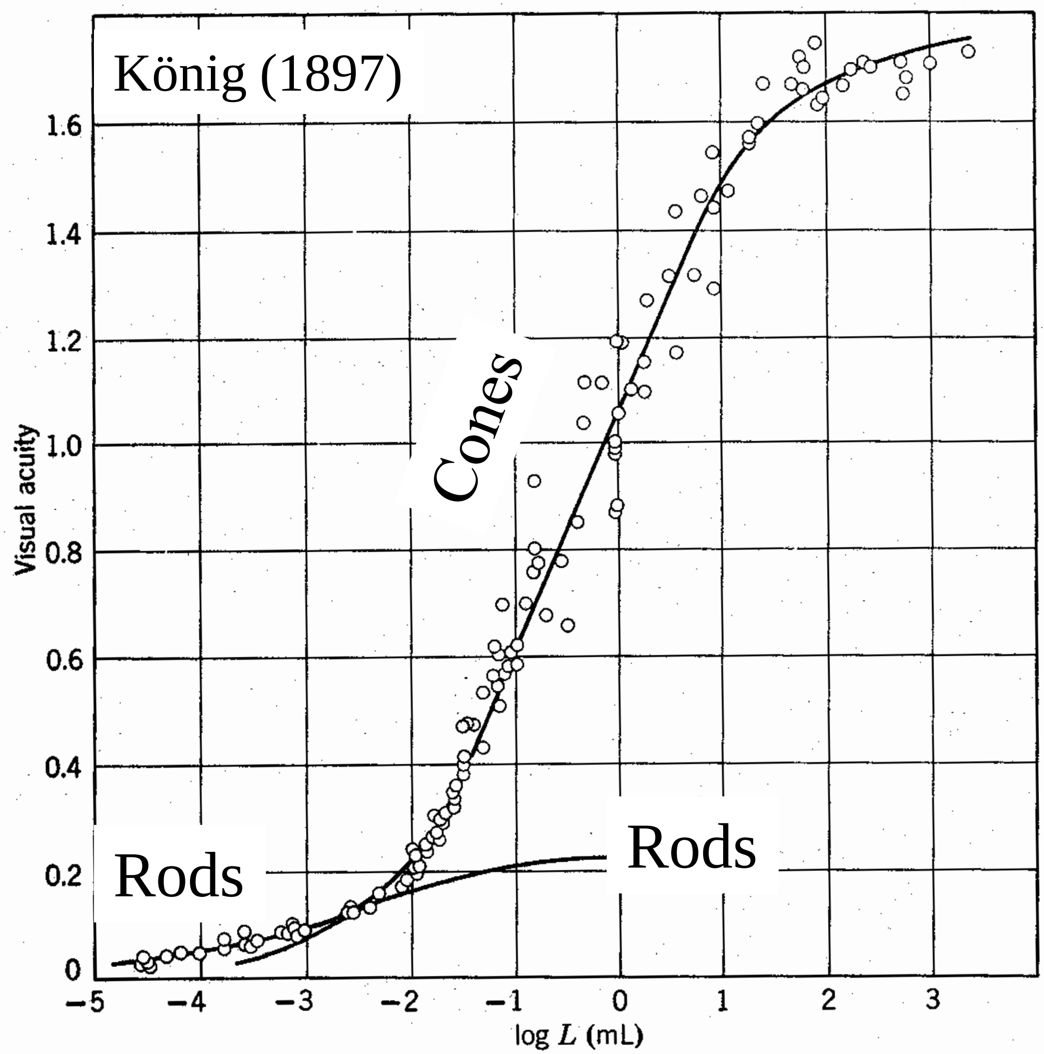
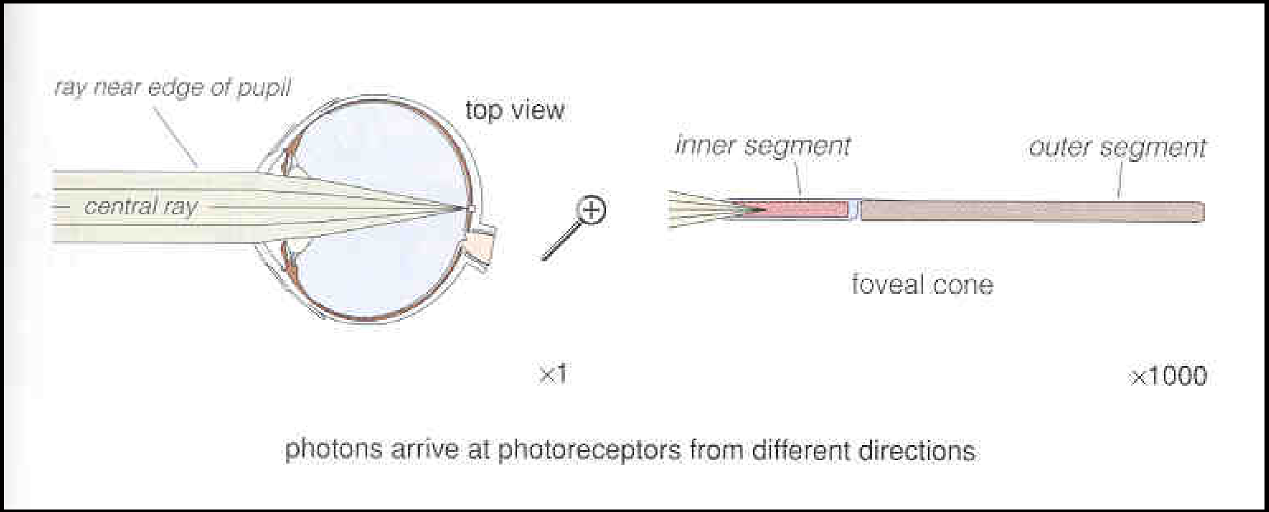
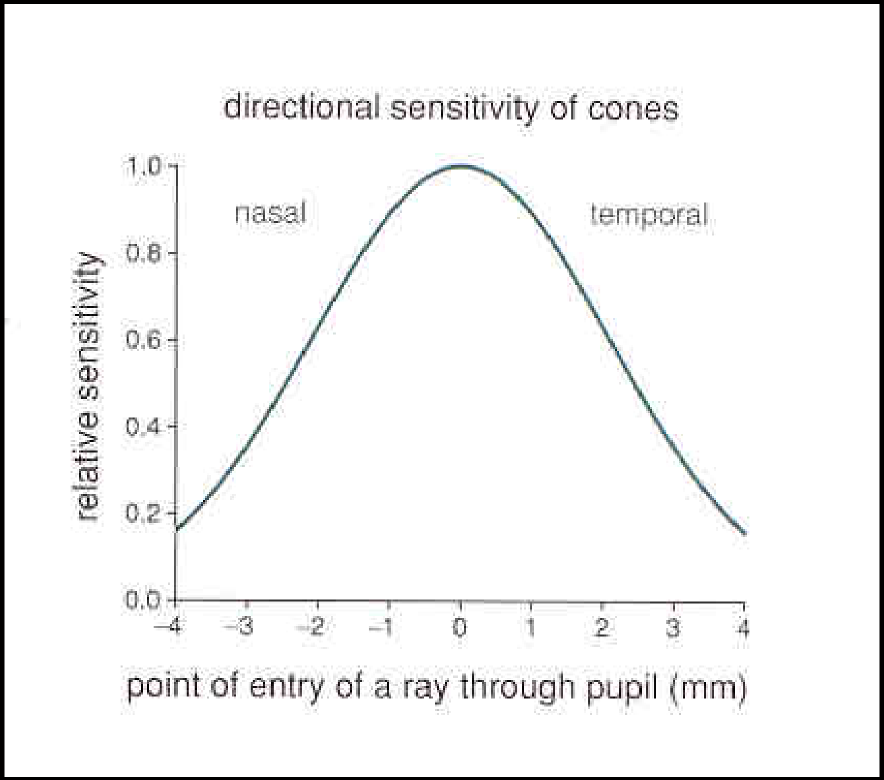


FIG. 11.14 König's data for the relation between visual acuity and illumination, as replotted by Hecht (1934). The shallow curve for the lower limb of the data is an equation for rods, whereas the upper curve is for cones. The task is one of recognizing the orientation of a hook form of test object.

Rod and cone directional sensitivity differences

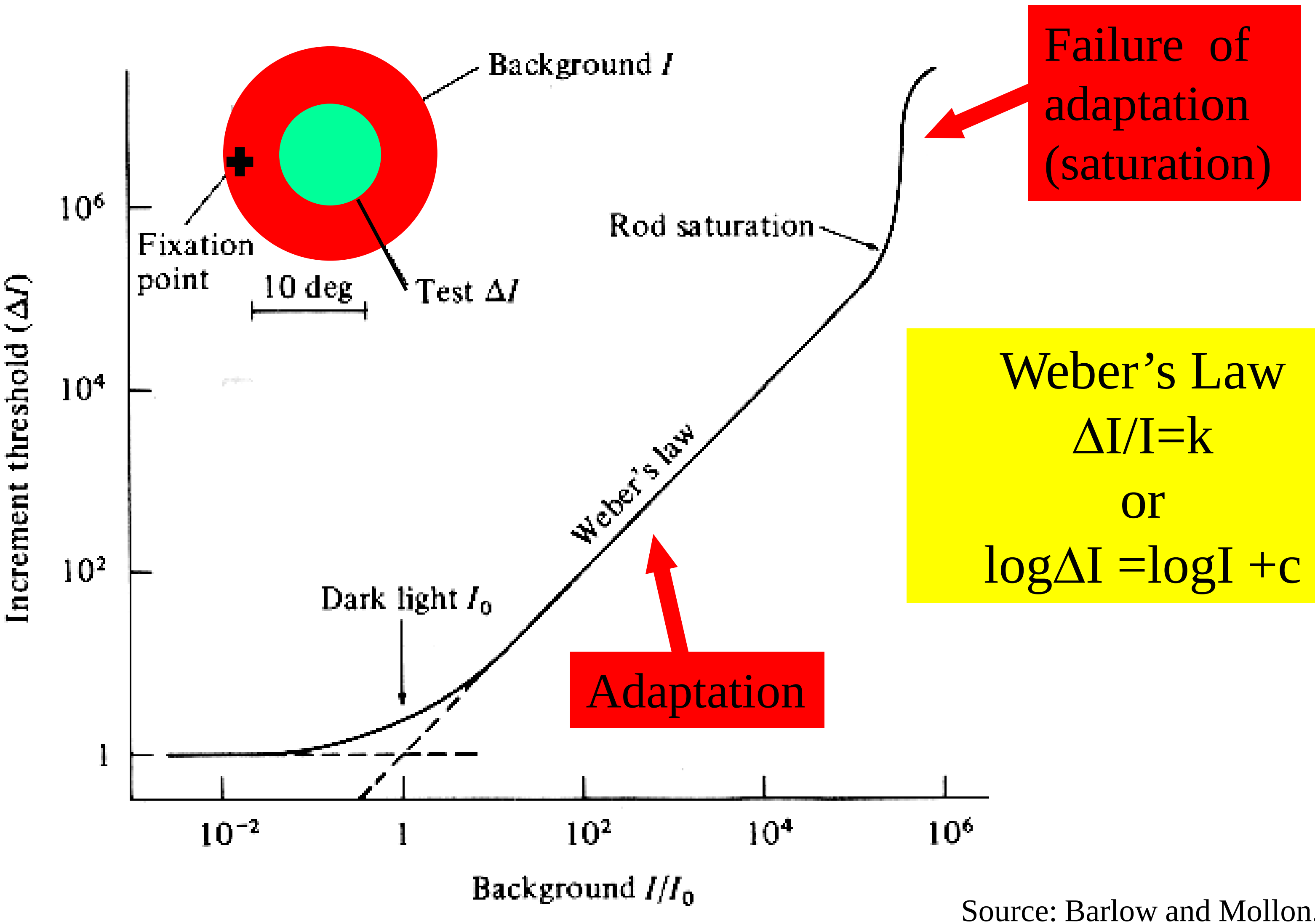


Stiles-Crawford effect



Rod vision saturates – under most conditions cone vision does not.

Rod threshold versus intensity (tvi) curves



Weber's Law

$\Delta I/I=k$

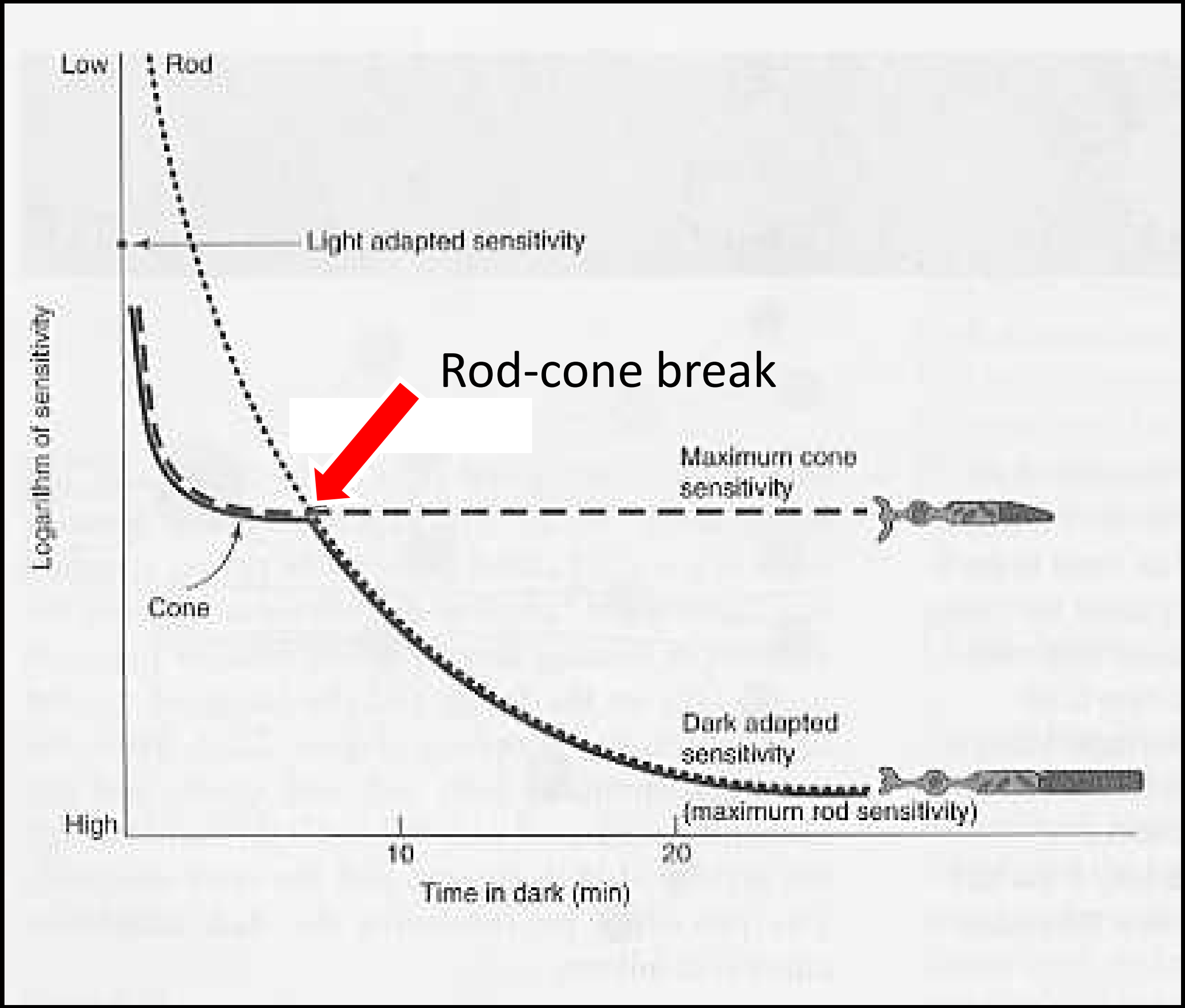
or

$\log\Delta I = \log I + c$

Source: Barlow and Mollon, 1982

Rod dark adaptation takes much longer than cone dark adaptation

Rod-cone dark adaptation curves



Rod-cone dark adaptation curves

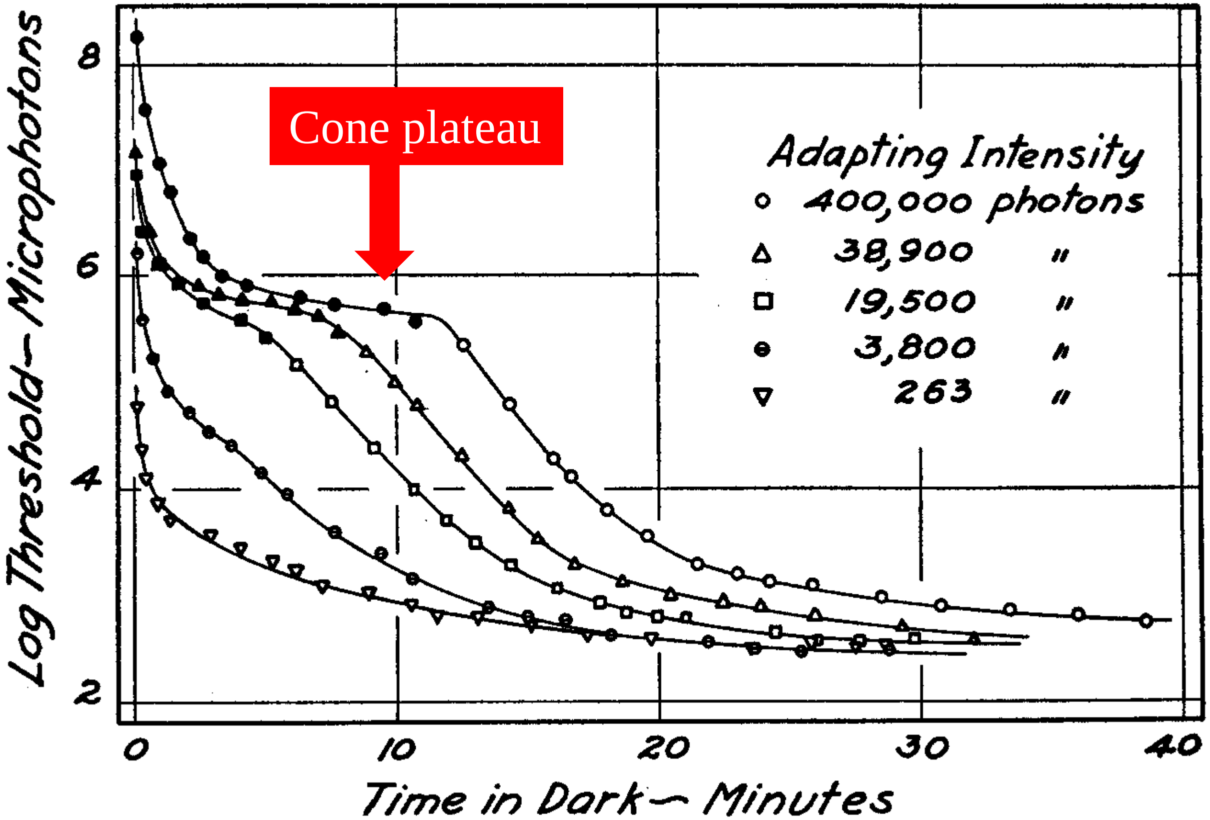
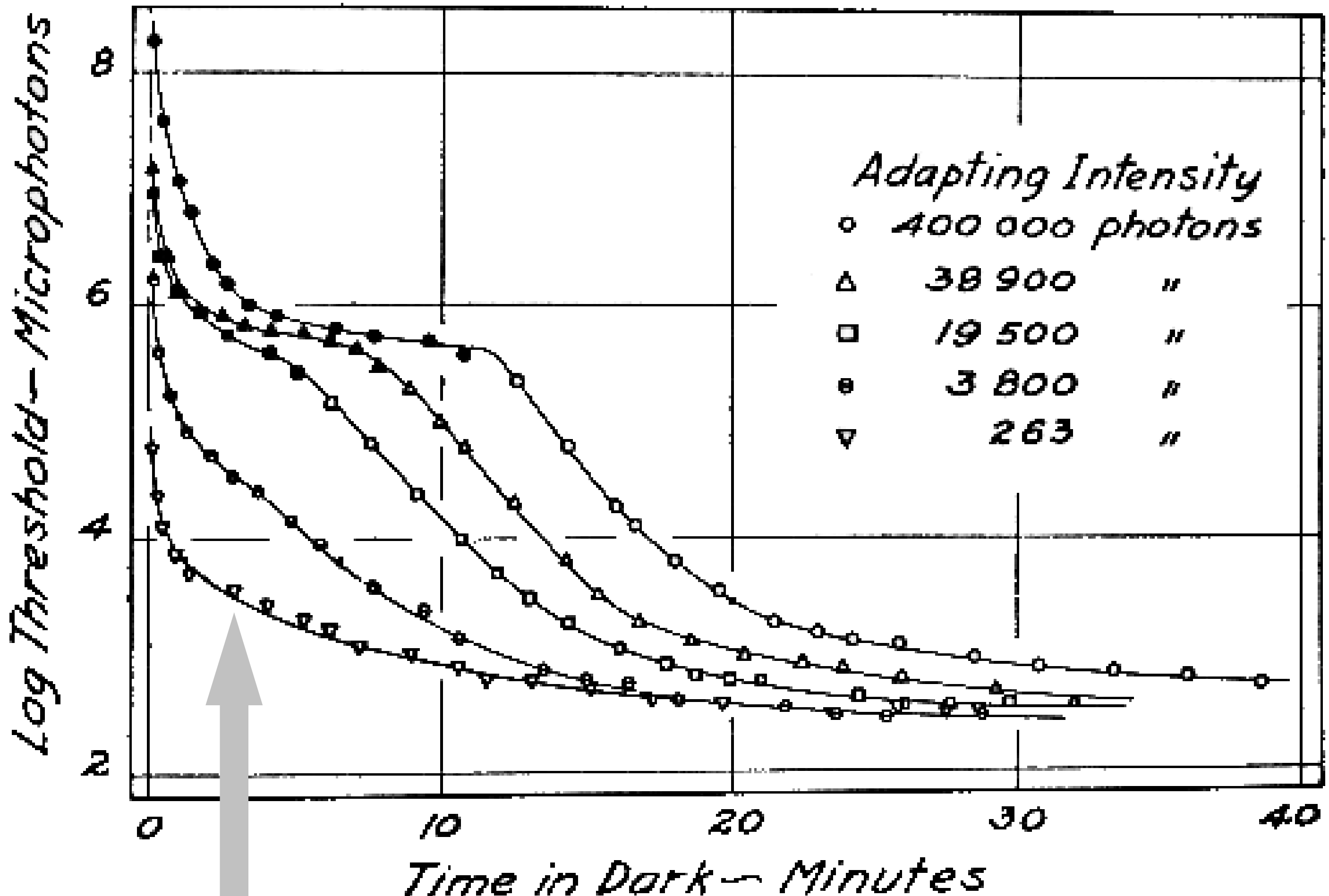


FIG. 2. The course of dark adaptation as measured with violet light following different degrees of light adaptation. The filled-in symbols indicate that a violet color was apparent at the threshold, while the empty symbols indicate that the threshold was colorless.

Rods take much longer to recover after a bleach than cones

From Hecht, Haig & Chase (1937)



The sensitivity loss during dark adaptation is much greater than the fraction of pigment bleached. For example, with a bleach of about 5% the sensitivity loss is more than 1000-fold. Rather than the lack of photopigment, it is the presence of a photoproduct that causes the sensitivity loss.

Cone vision is chromatic and rod vision is achromatic

Rod vision

- Achromatic
- High sensitivity
- Poor detail and no colour

Cone vision

- Achromatic and chromatic
- Lower sensitivity
- Detail and good colour

Rod vision is achromatic

Why?

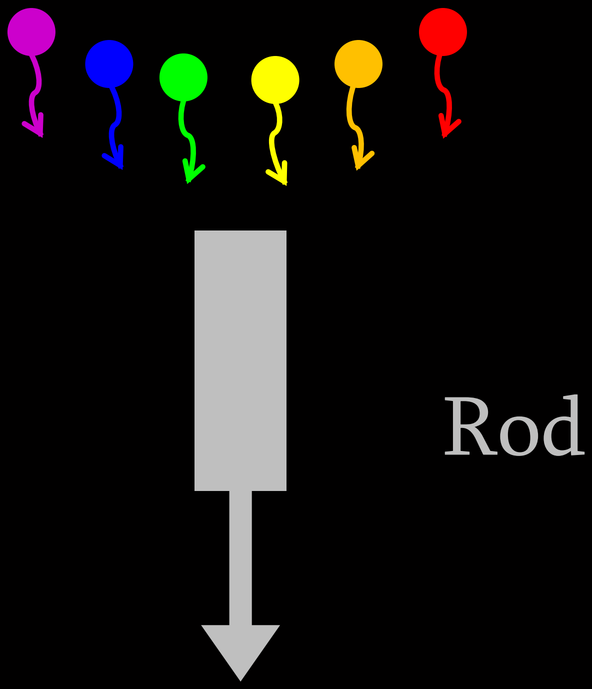
Vision at the photoreceptor stage is relatively simple because the output of each photoreceptor is:

UNIVARIANT

What does univariant mean?

UNIVARIANCE

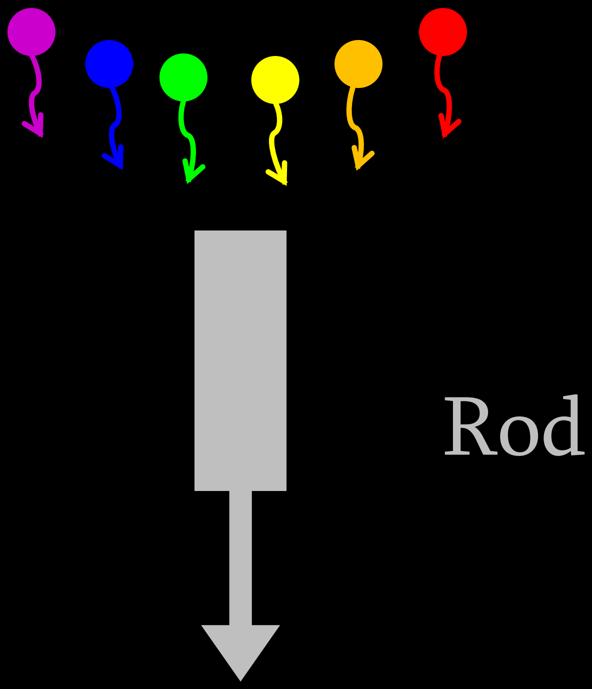
Crucially, the effect of any absorbed photon is *independent* of its wavelength.



Once absorbed a photon produces the *same* change in photoreceptor output whatever its wavelength.

UNIVARIANCE

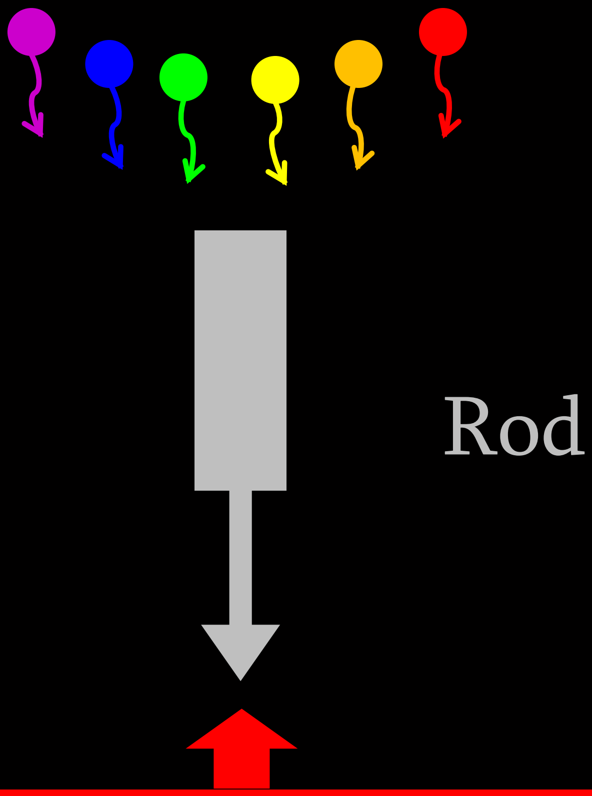
Crucially, the effect of any absorbed photon is *independent* of its wavelength.



So, if you monitor the rod output, you can't tell which "colour" of photon has been absorbed.

UNIVARIANCE

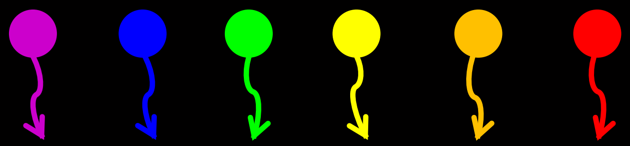
Crucially, the effect of any absorbed photon is *independent* of its wavelength.



All the photoreceptor effectively does is to count photons.

UNIVARIANCE

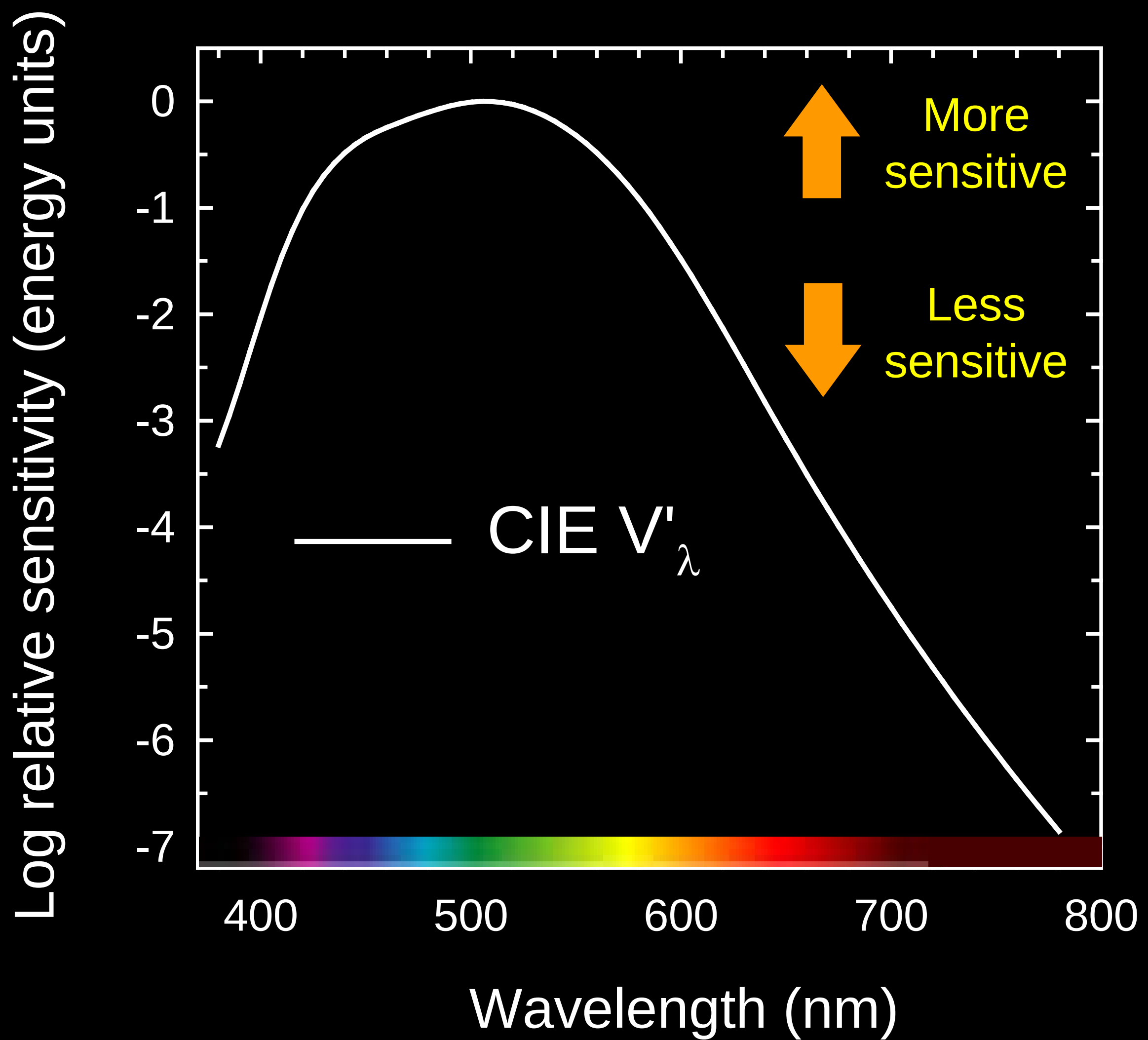
What does vary with wavelength is the probability that a photon will be absorbed.



This is reflected in what is called a "spectral sensitivity function".

Rod spectral sensitivity function

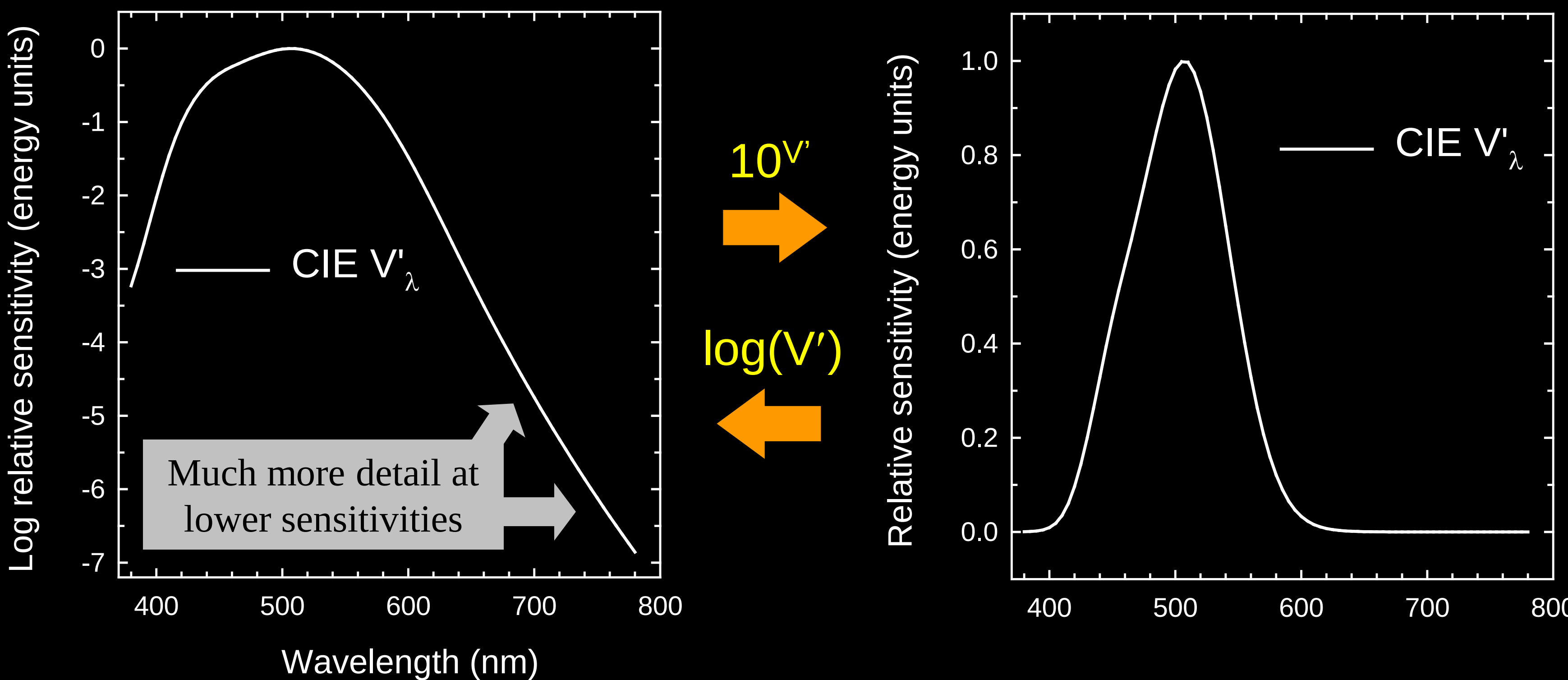
(also known as the scotopic luminosity curve, CIE V'_λ)



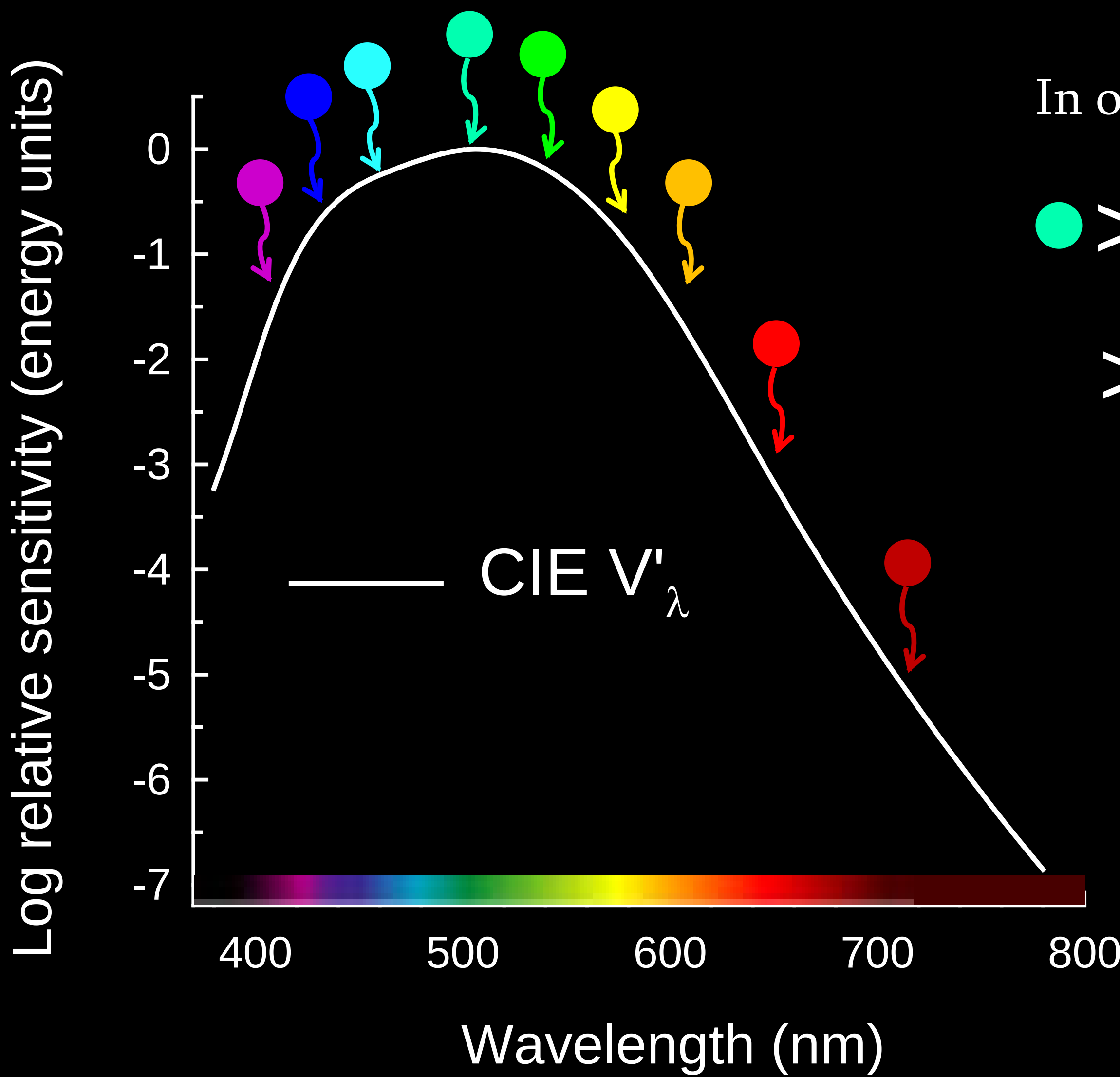
Rod spectral sensitivity function (V'_λ)

Logarithmic sensitivity plot

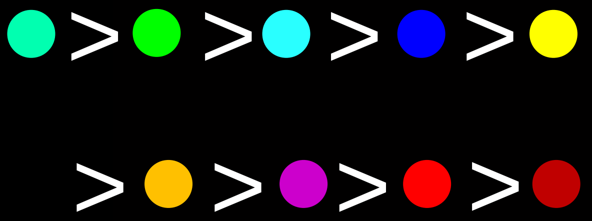
Linear sensitivity plot

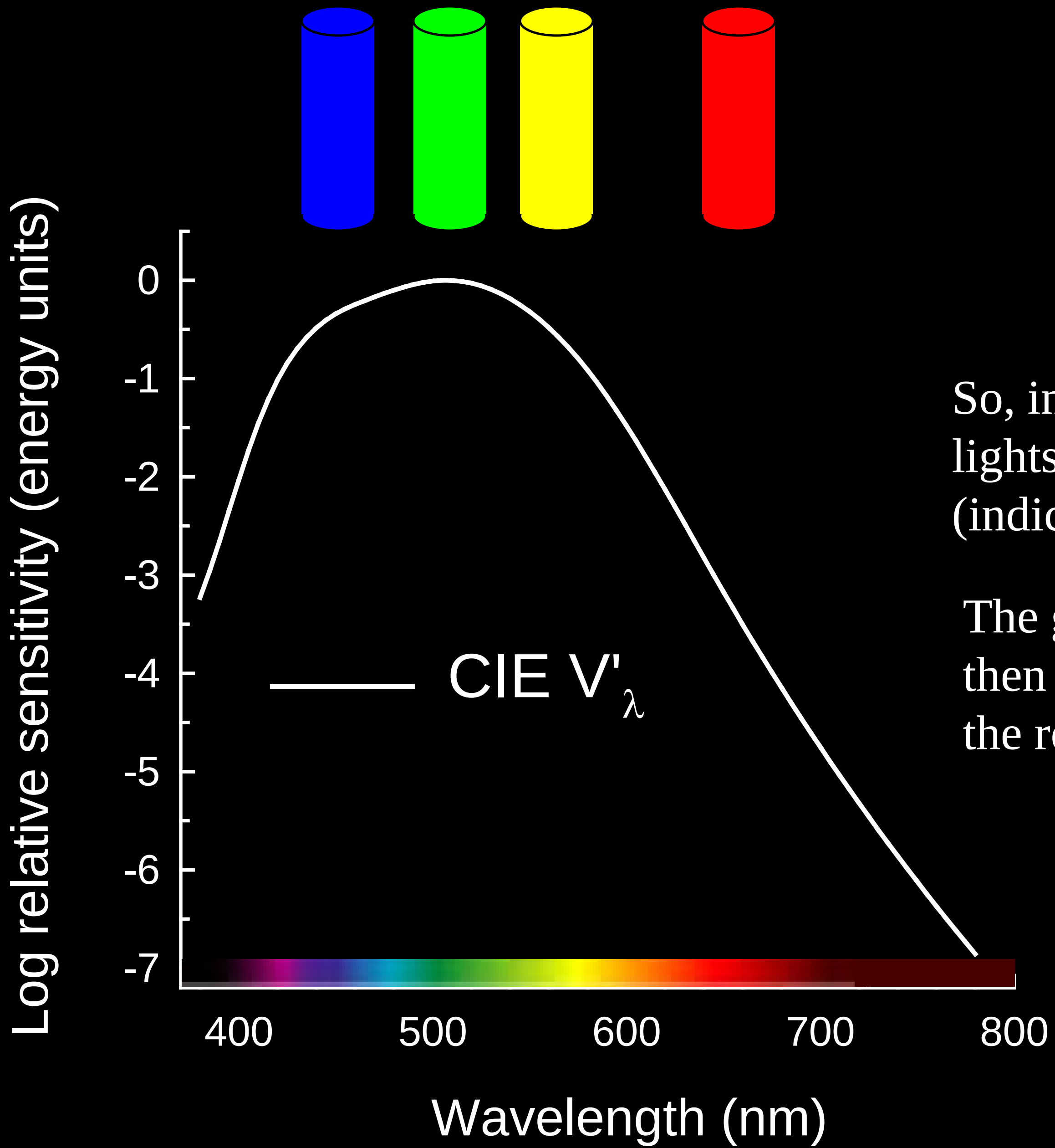


Rod spectral sensitivity function (V'_λ)



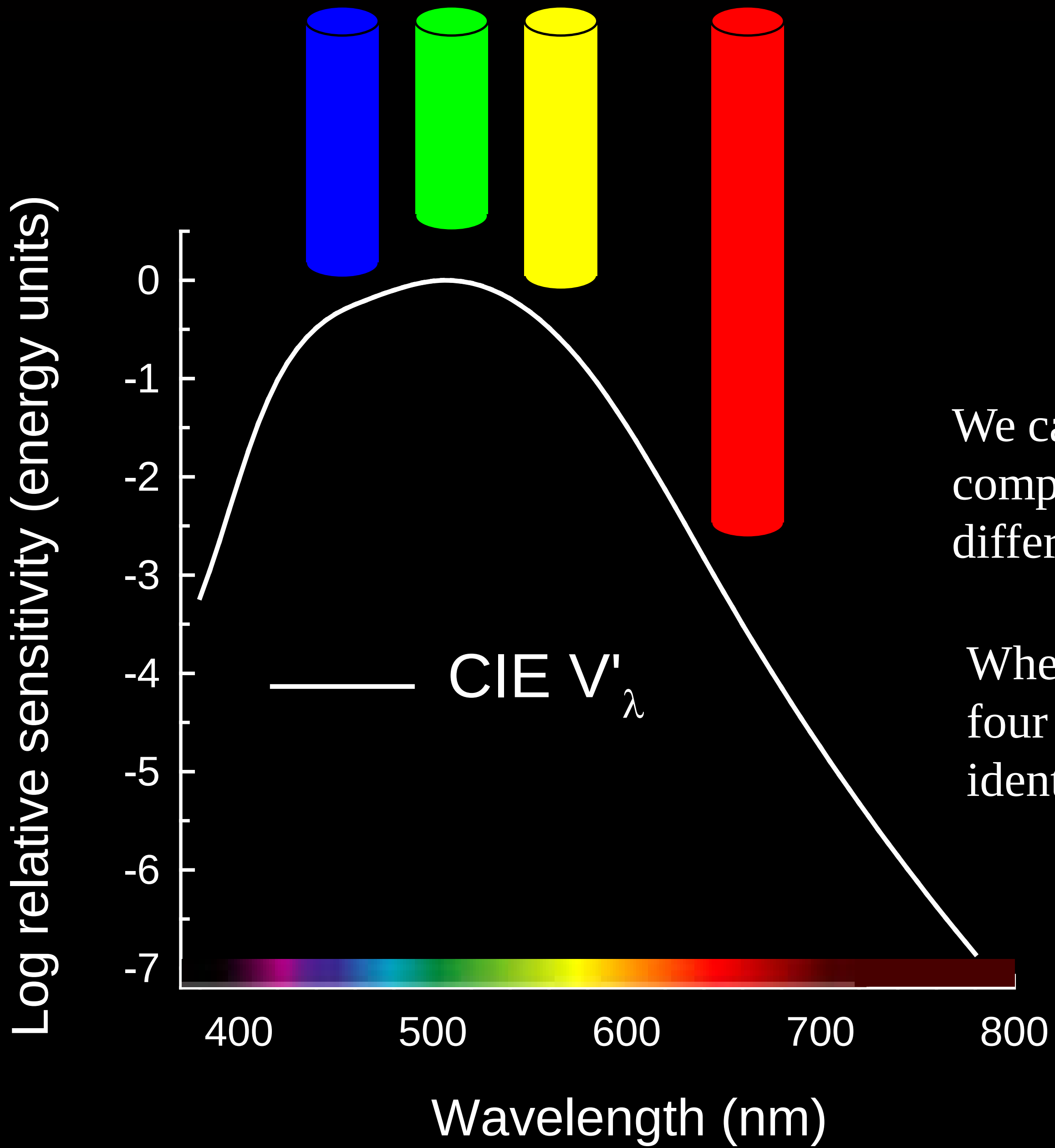
In order of rod sensitivity:





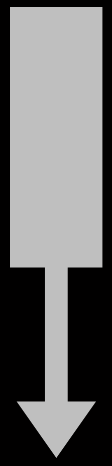
So, imagine you have four lights of the same intensity (indicated here by the height)

The green will look brightest, then blue, then yellow and lastly the red will be the dimmest



We can adjust the intensities to compensate for the sensitivity differences.

When this has been done, the four lights will look completely identical.

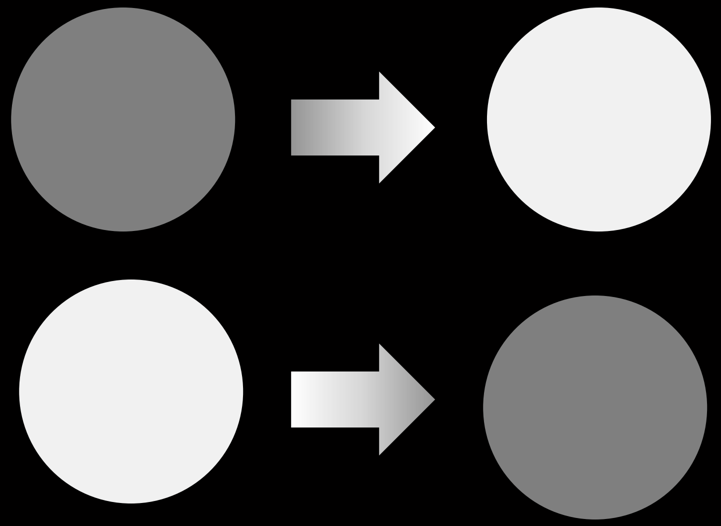


Rod

Changes in light intensity are confounded with changes in colour (wavelength)

UNIVARIANCE

A change in photoreceptor output can be caused by a change in intensity or by a change in colour. There is no way of telling which.



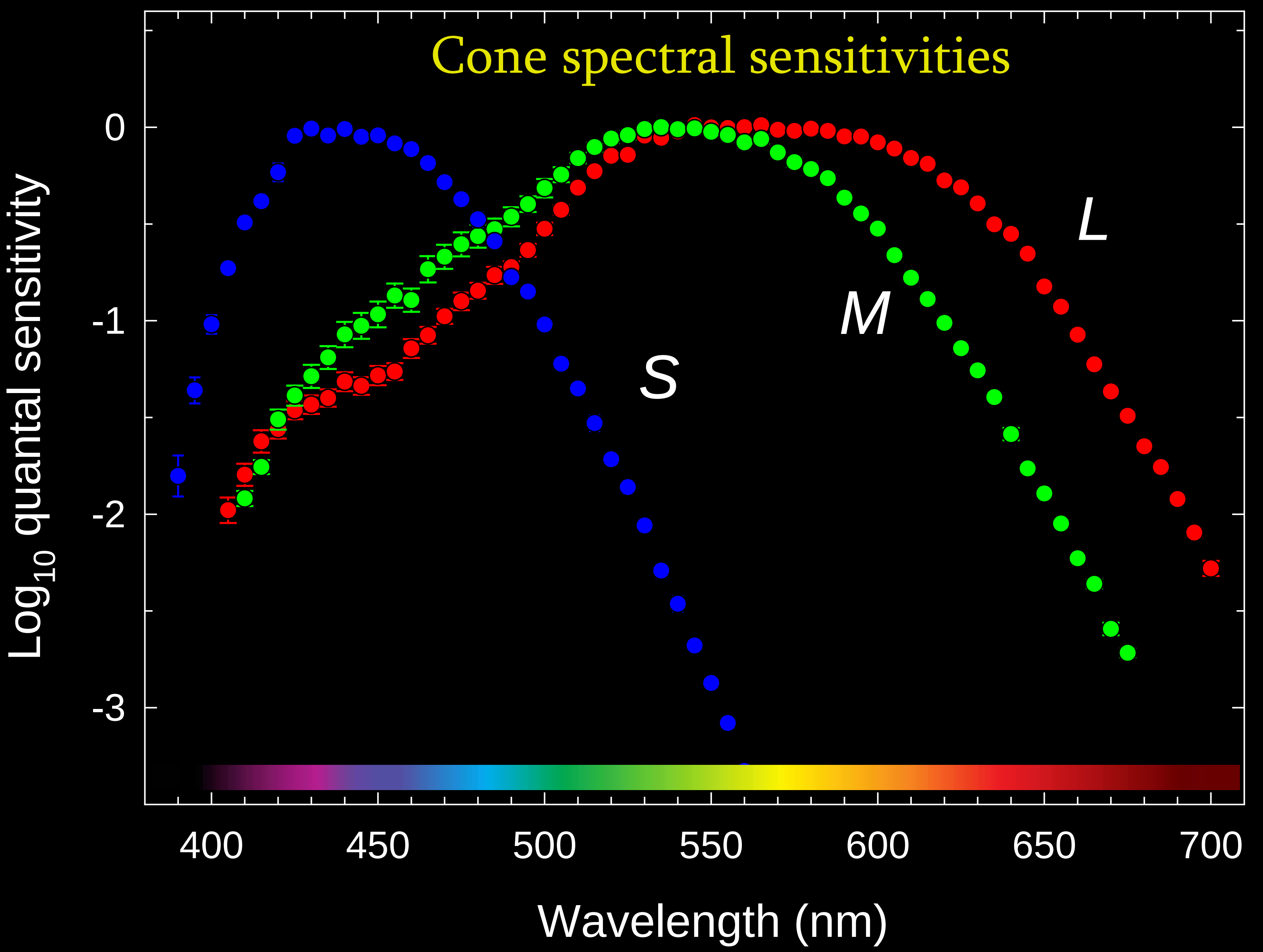
Colour or intensity change??

Each photoreceptor is therefore ‘colour blind’, and is unable to distinguish between changes in colour and changes in intensity.

A consequence of univariance is that we are colour-blind when only one photoreceptor operates…

Examples: SCOTOPIC VISION, cone monochromacy

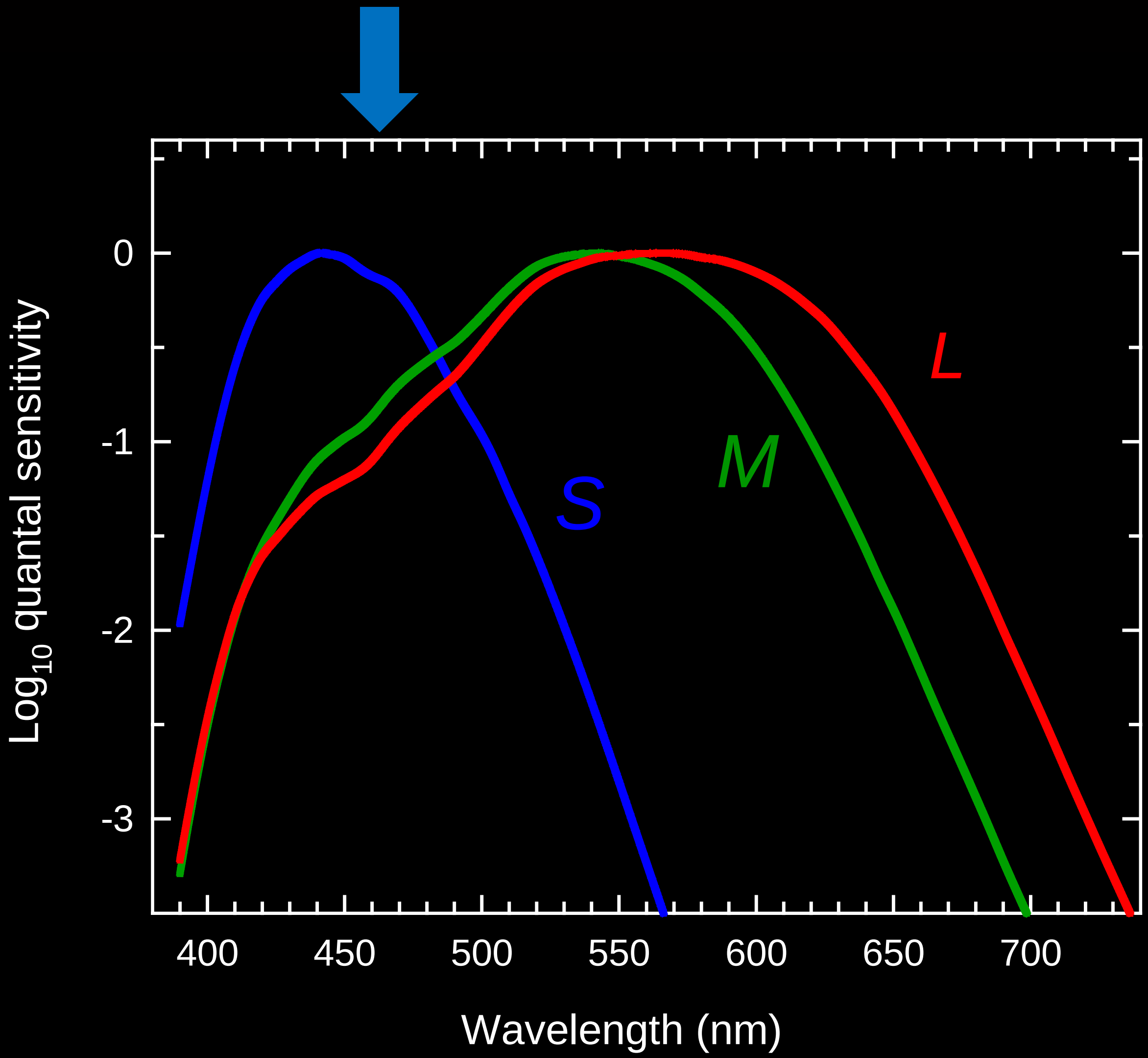
With three cone photoreceptors, our colour vision is chromatic…


Cone spectral sensitivities
0
-1
-2
-3
Log10 quantal sensitivity
S
M
L
400
450
500
550
600
650
700
Wavelength (nm)

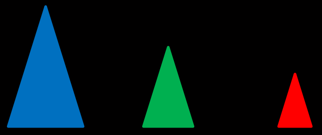
So, if each photoreceptor is colour-blind, how do we see colour?

Or to put it another way: How is colour encoded?

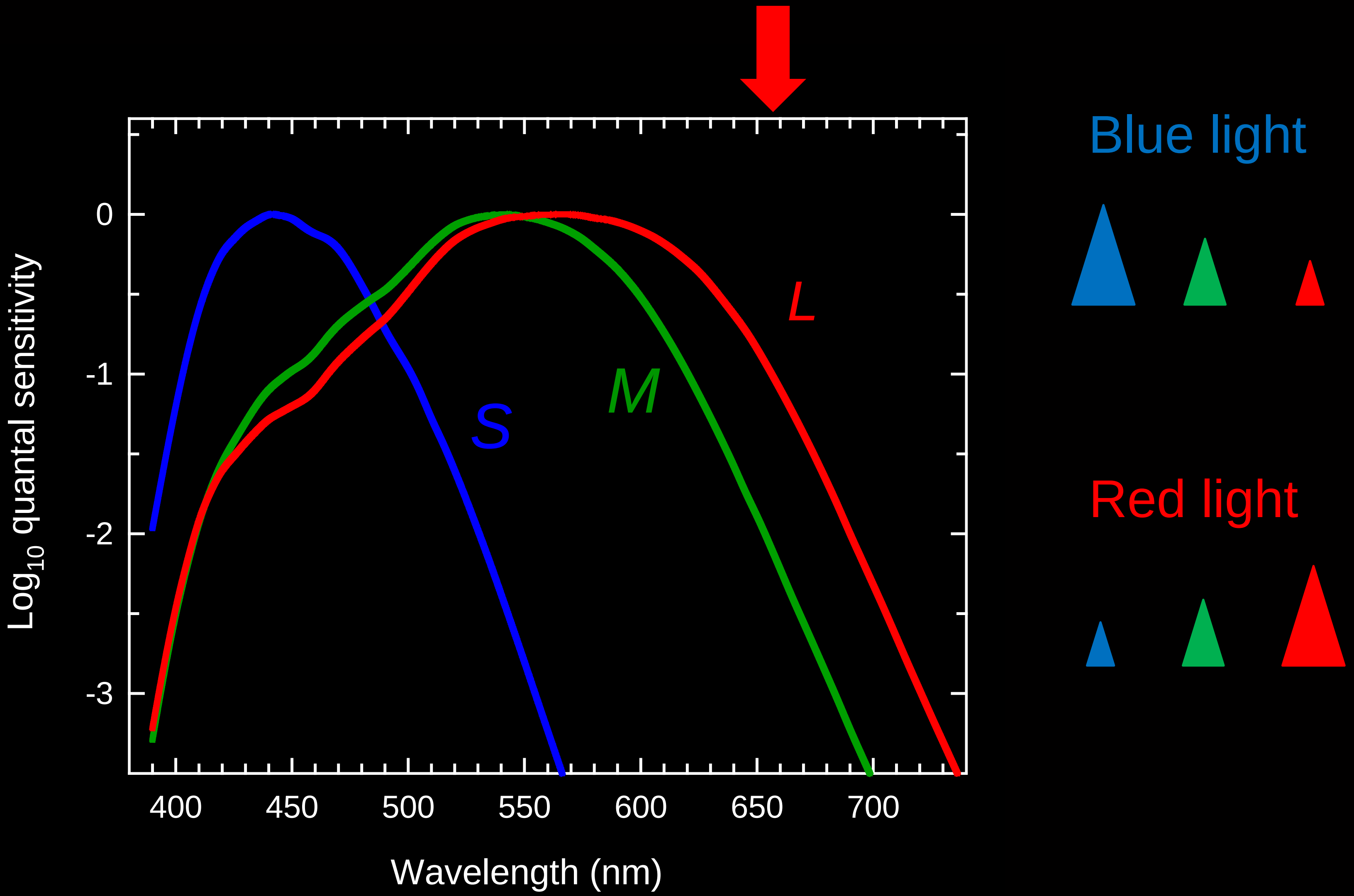
Colour is encoded by the relative cone outputs



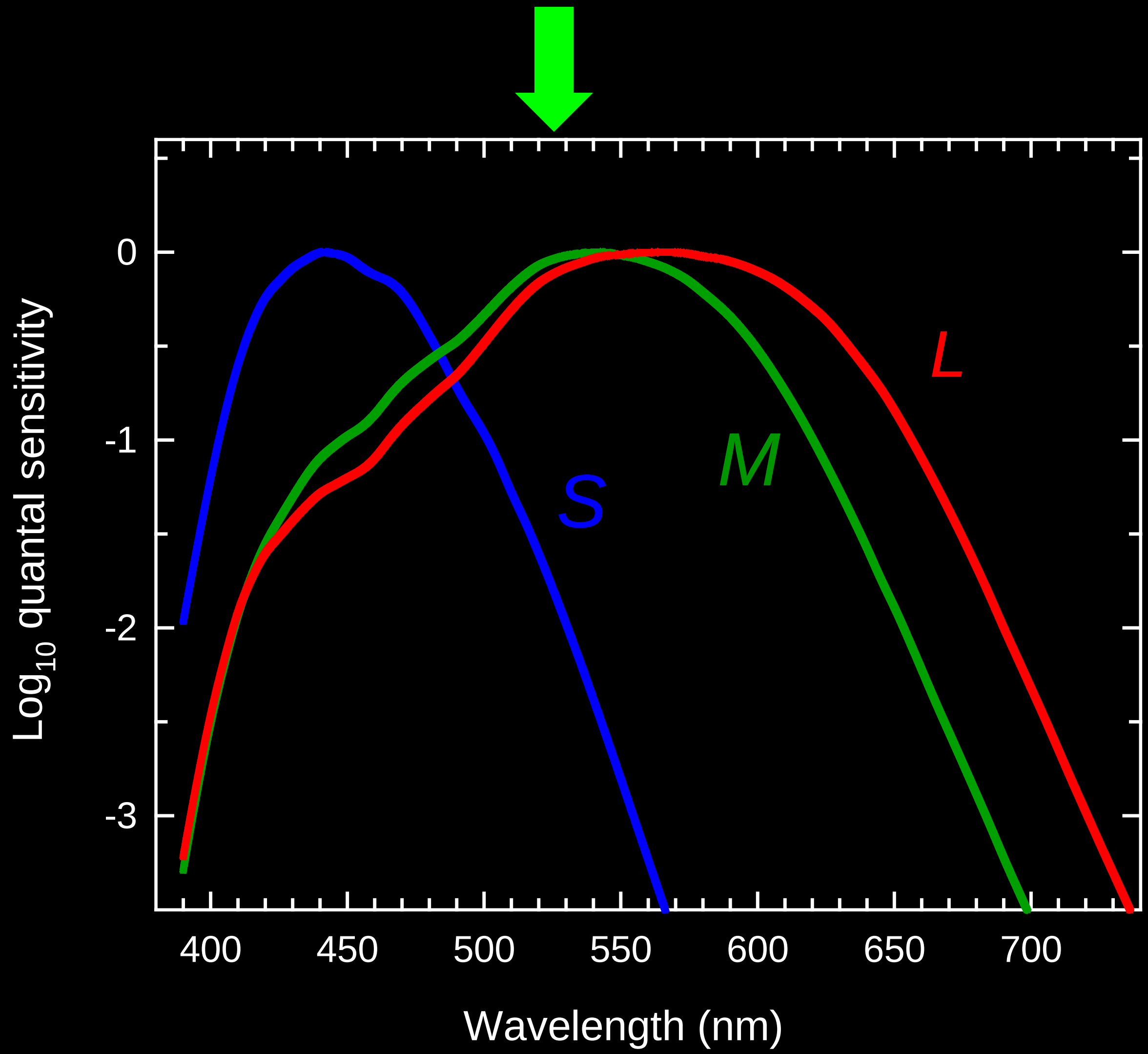
Blue light

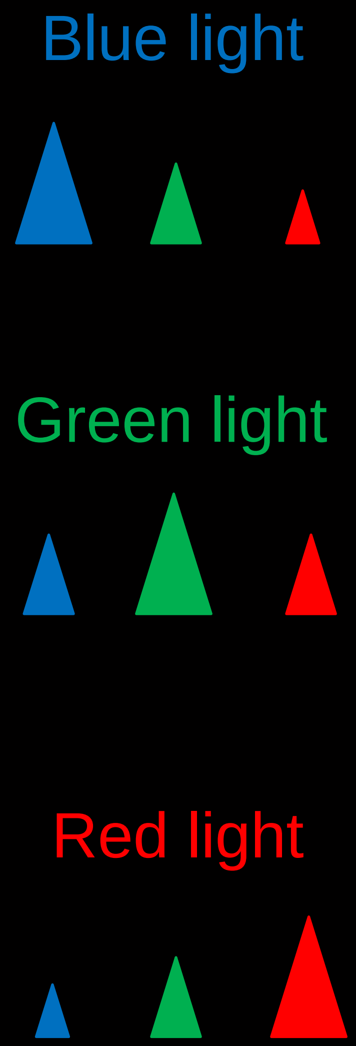


Colour is encoded by the relative cone outputs

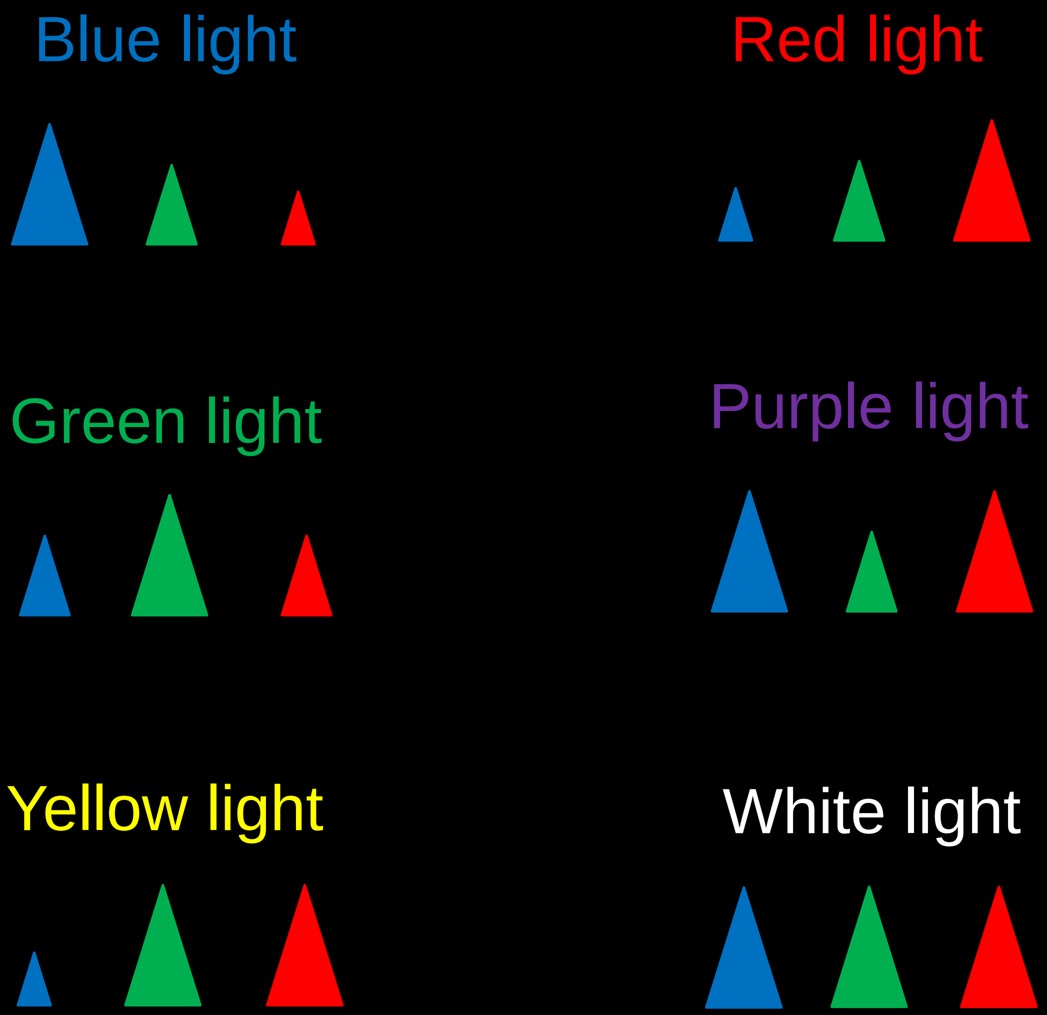


Colour is encoded by the relative cone outputs





Colour is encoded by the relative cone outputs



Rod vision

- Achromatic
- High sensitivity
- Poor detail and no colour

Cone vision

- Achromatic and chromatic
- Lower sensitivity
- Detail and good colour