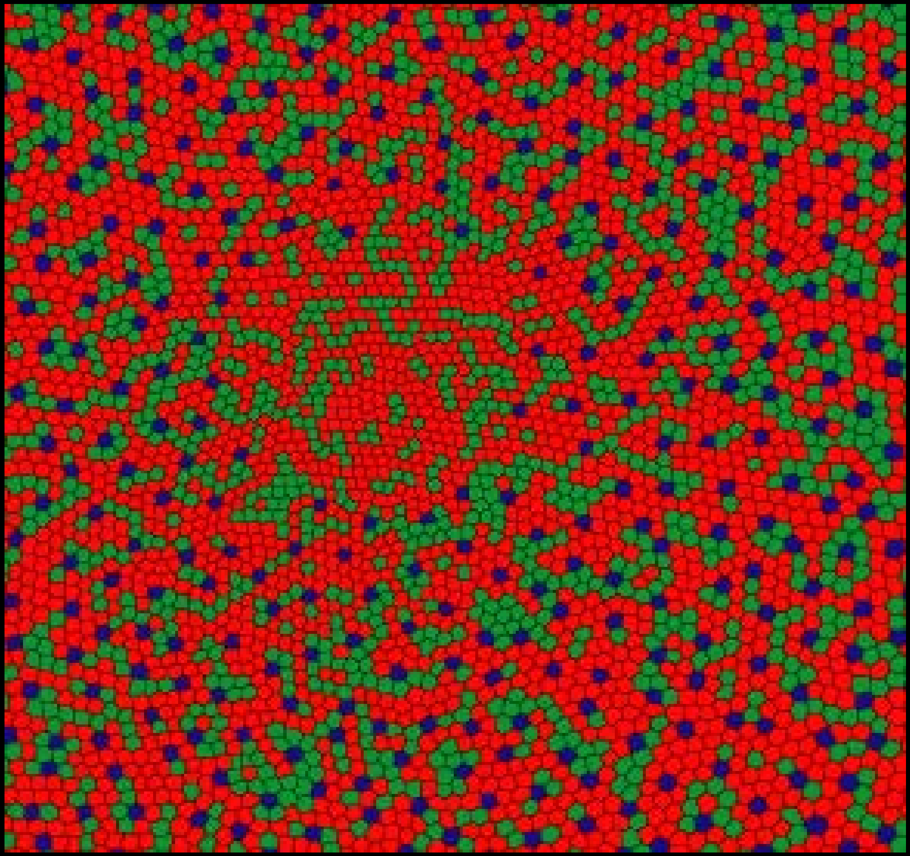
Physiological optics and the photoreceptor mosaic

Andrew Stockman

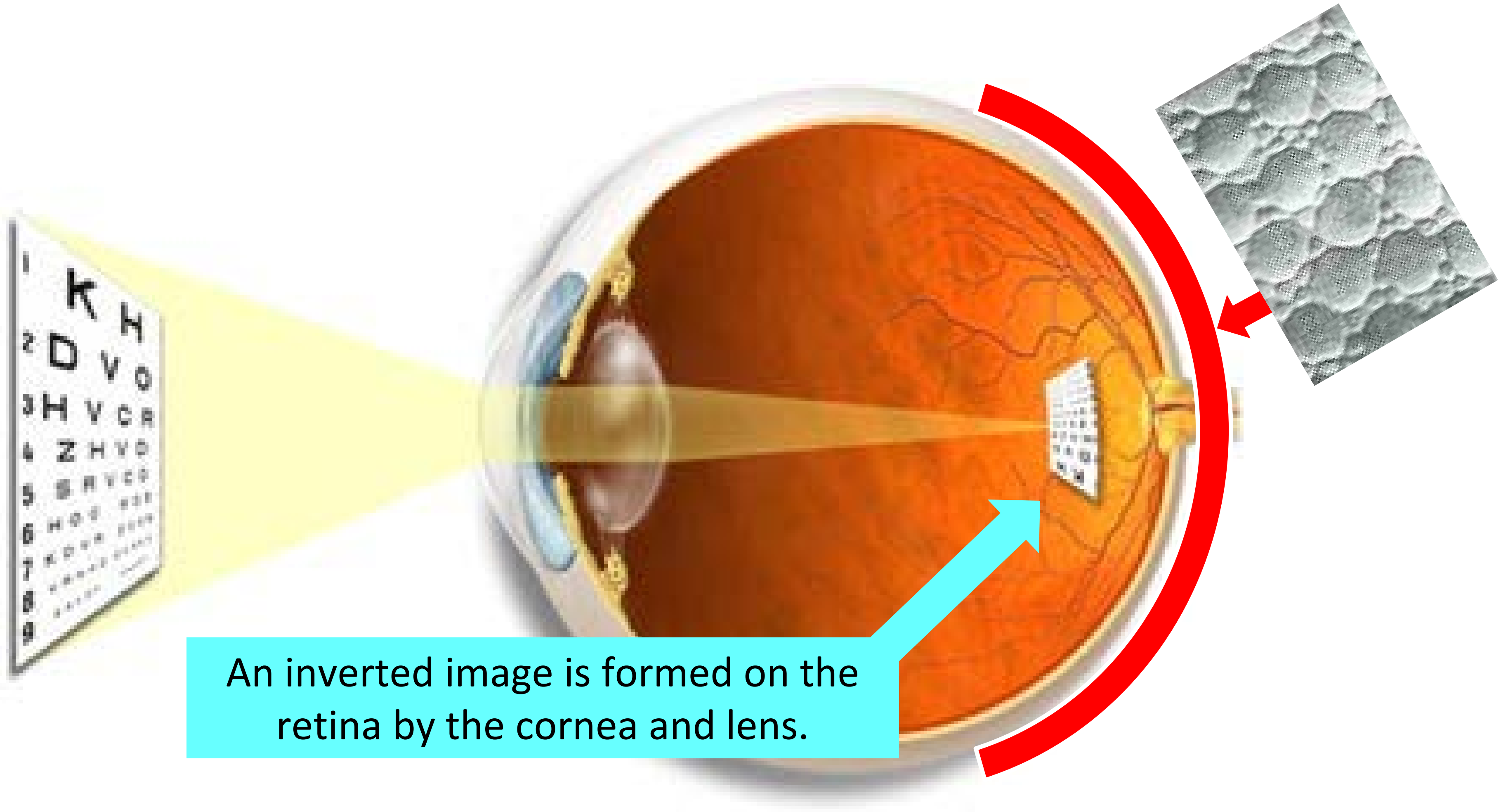


NEUR 3045
Visual Neuroscience

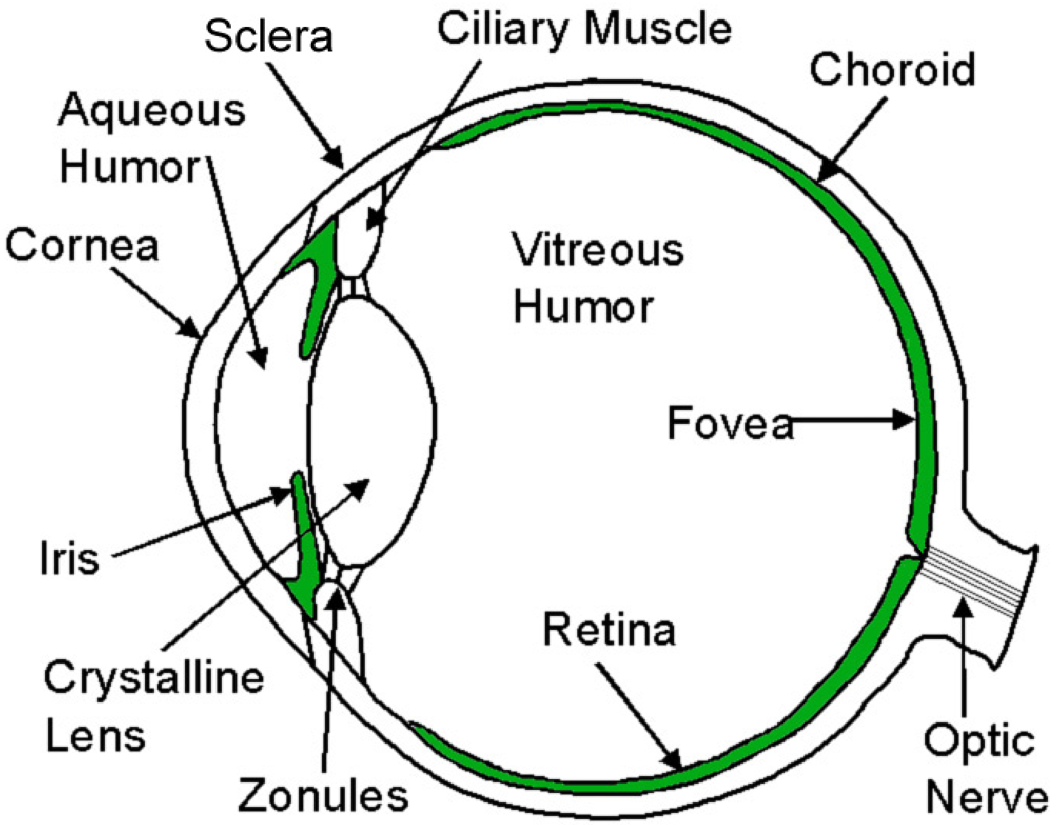
Outline

- 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.

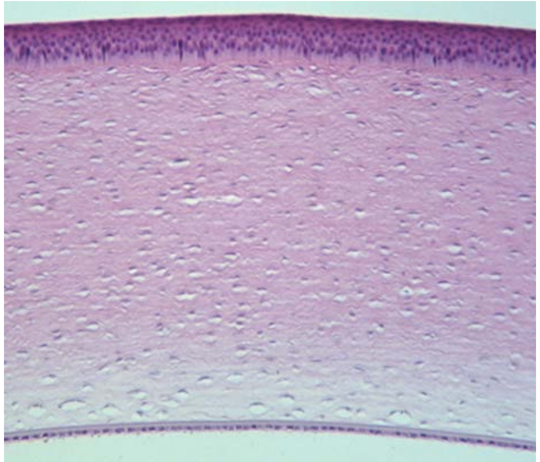
Optic Nerve – bundle of nerve fibers that carry information to the brain.

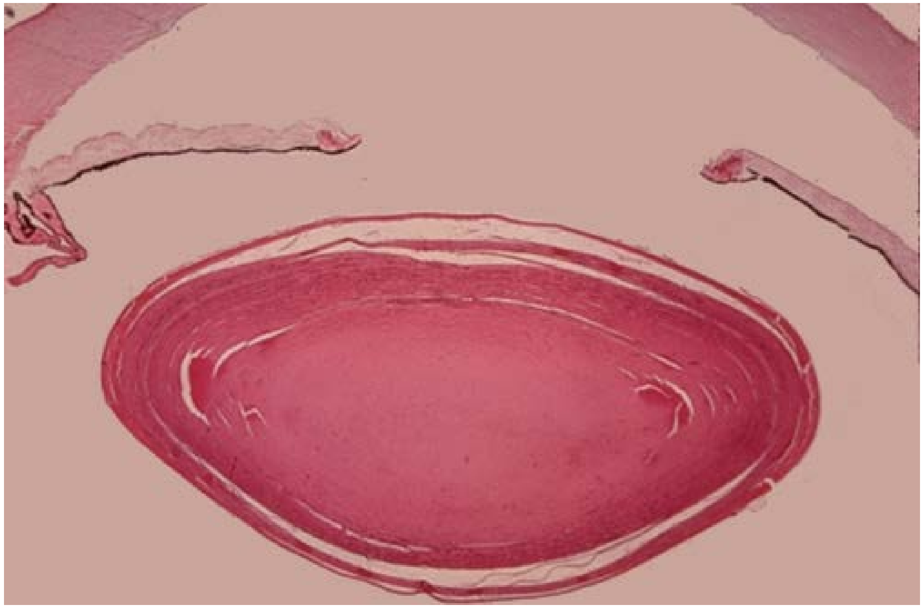
Jim Schwiegerling

Visual optics

Cornea

Crystalline lens



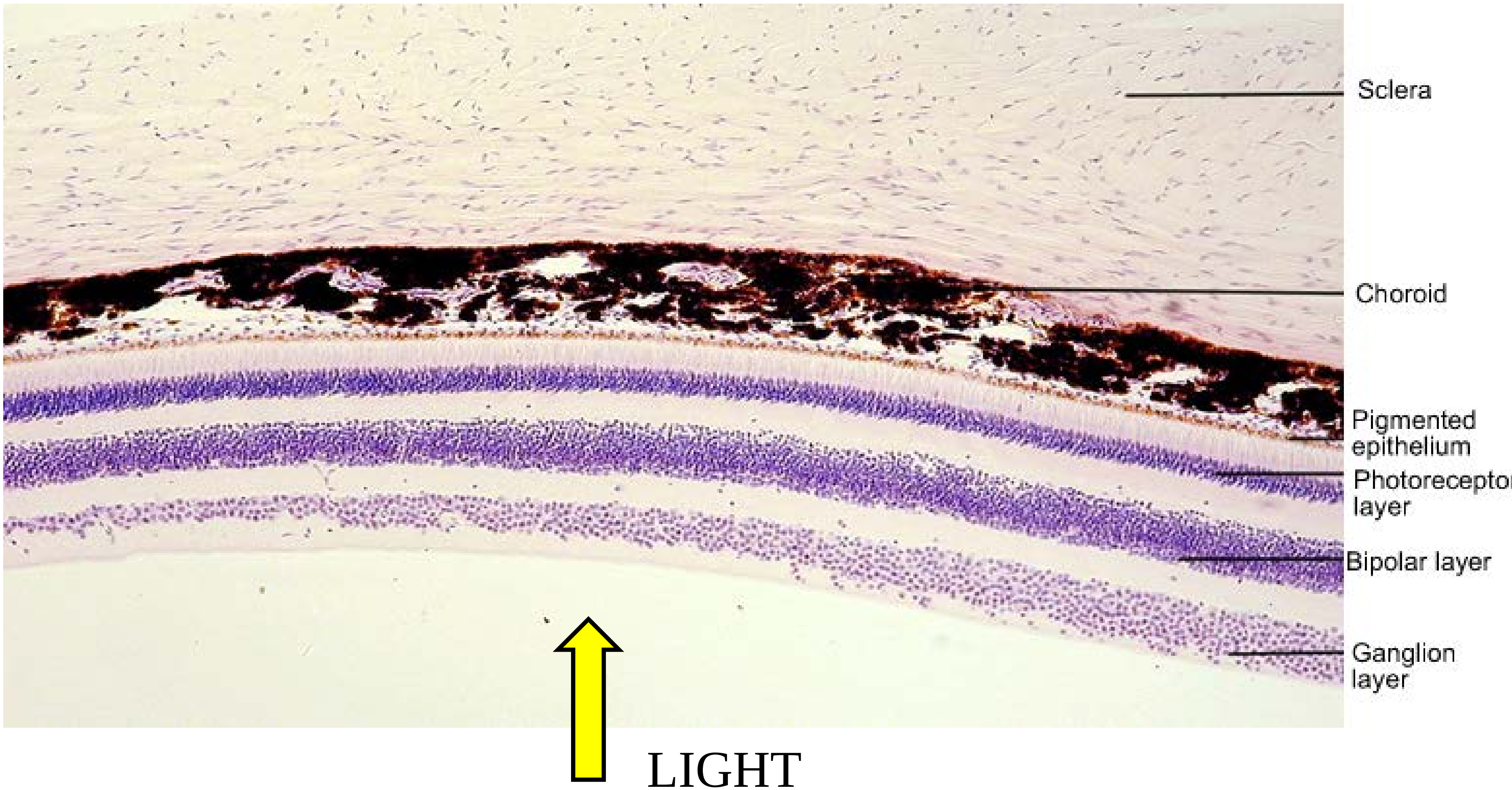


Jim Schwiegerling

Jim Bowmaker dissecting an eye…

BBC Horizon: Light Fantastic (2006)

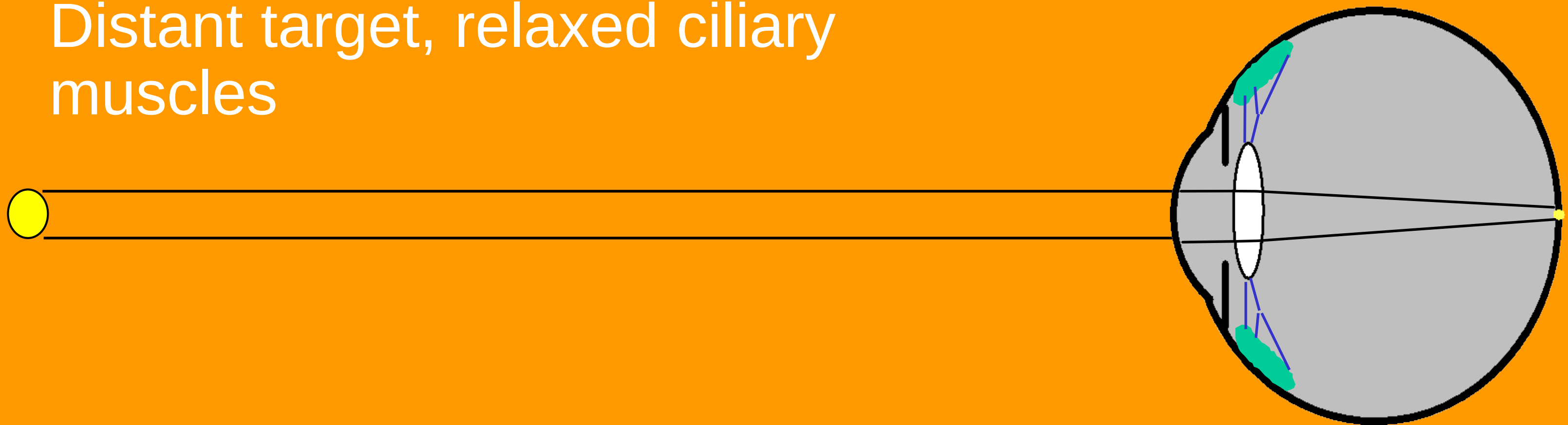
Retinal cross-section



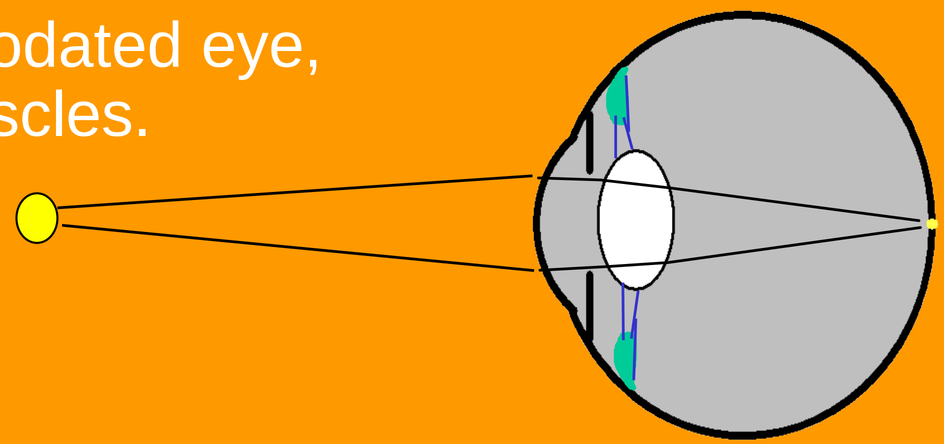
Retina 200 ×

Accommodation to Target Distance

Distant target, relaxed ciliary muscles

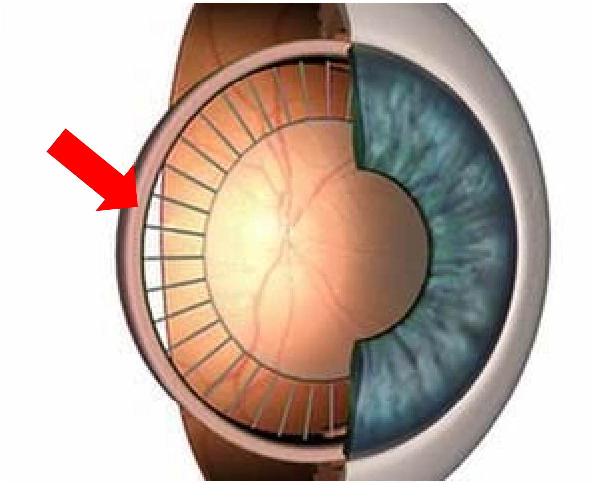


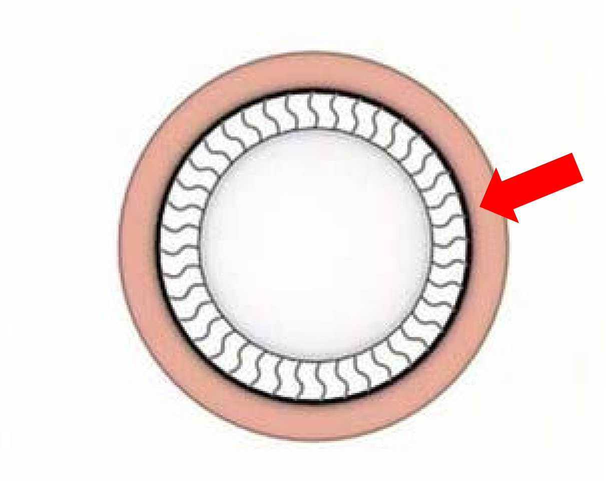
Near target, accommodated eye, constricted ciliary muscles.



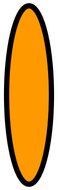
Larry Thibos

Accommodation

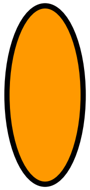




Relaxed ciliary muscle pulls zonules taut an flattens crystalline lens.



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



Jim Schwiegerling

Image quality

Point spread function

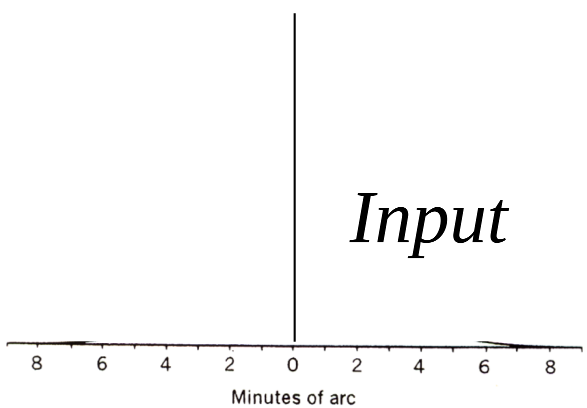
Optical systems are rarely ideal.

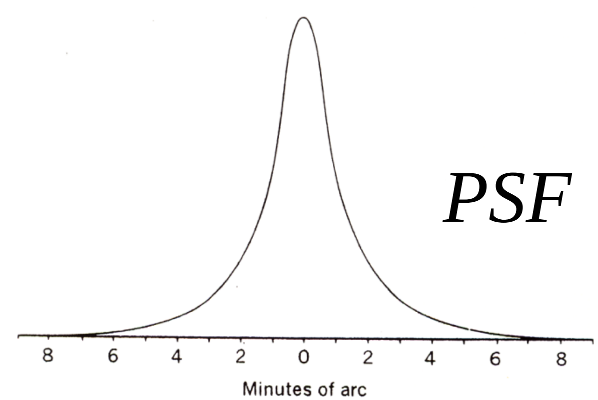
scene → **Optical System** → image

Point spread function of Human Eyes

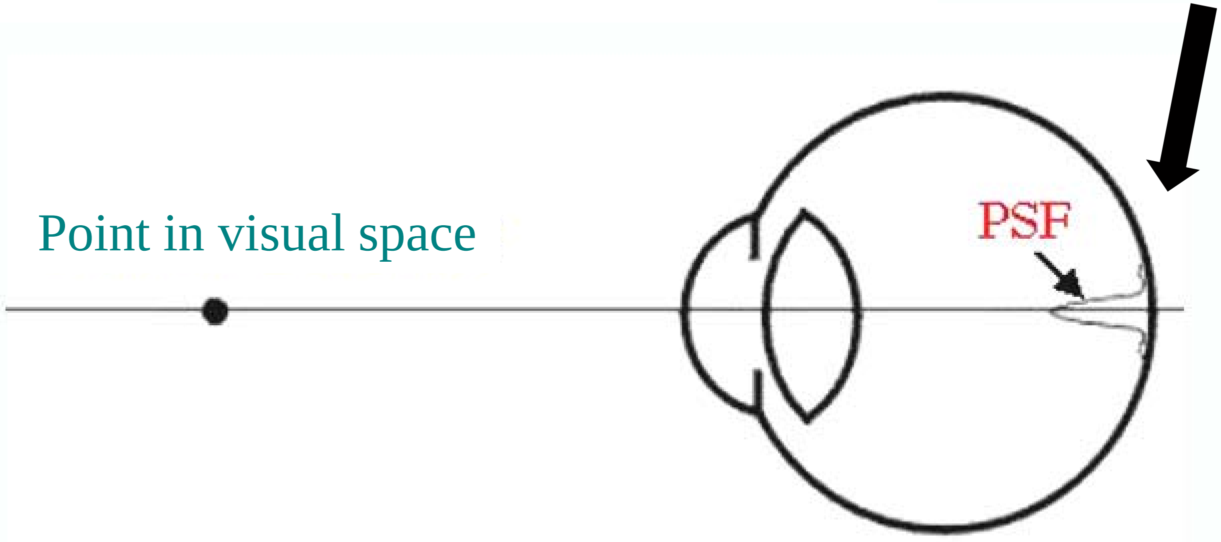
$\delta(x)$ → **Optical System** → $PSF(x)$

point source — point spread function





Point spread function (PSF)

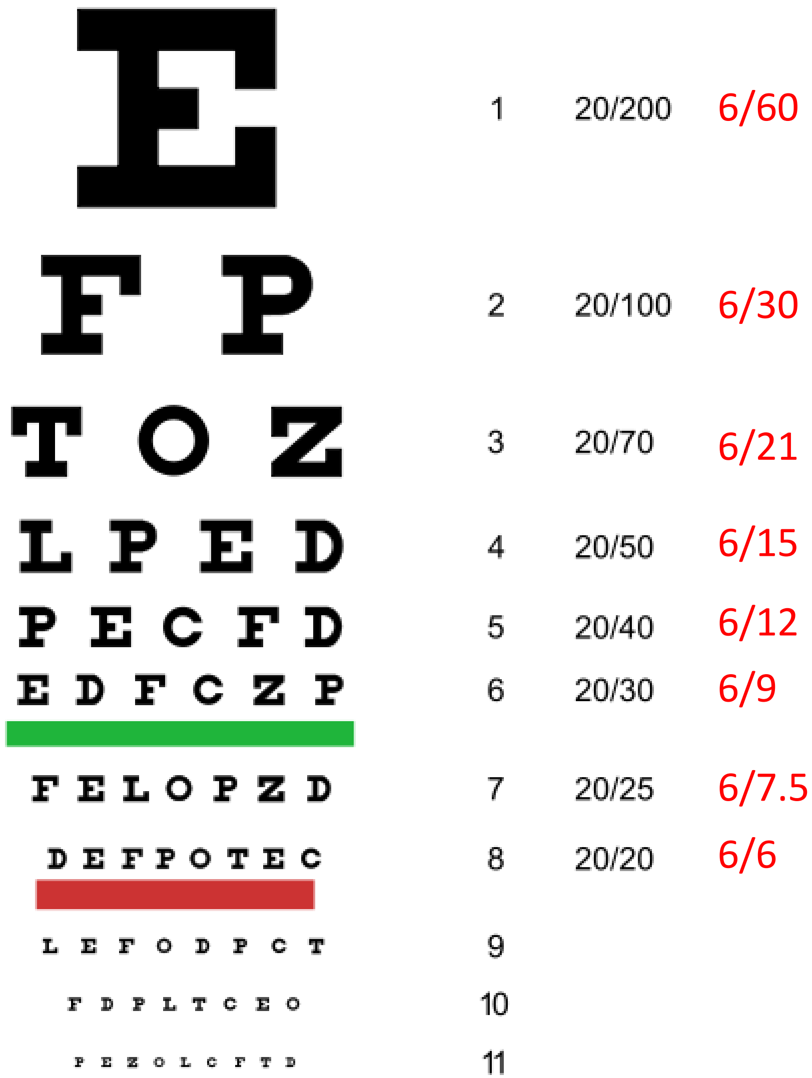


From Webvision, Michael Kalloniatis

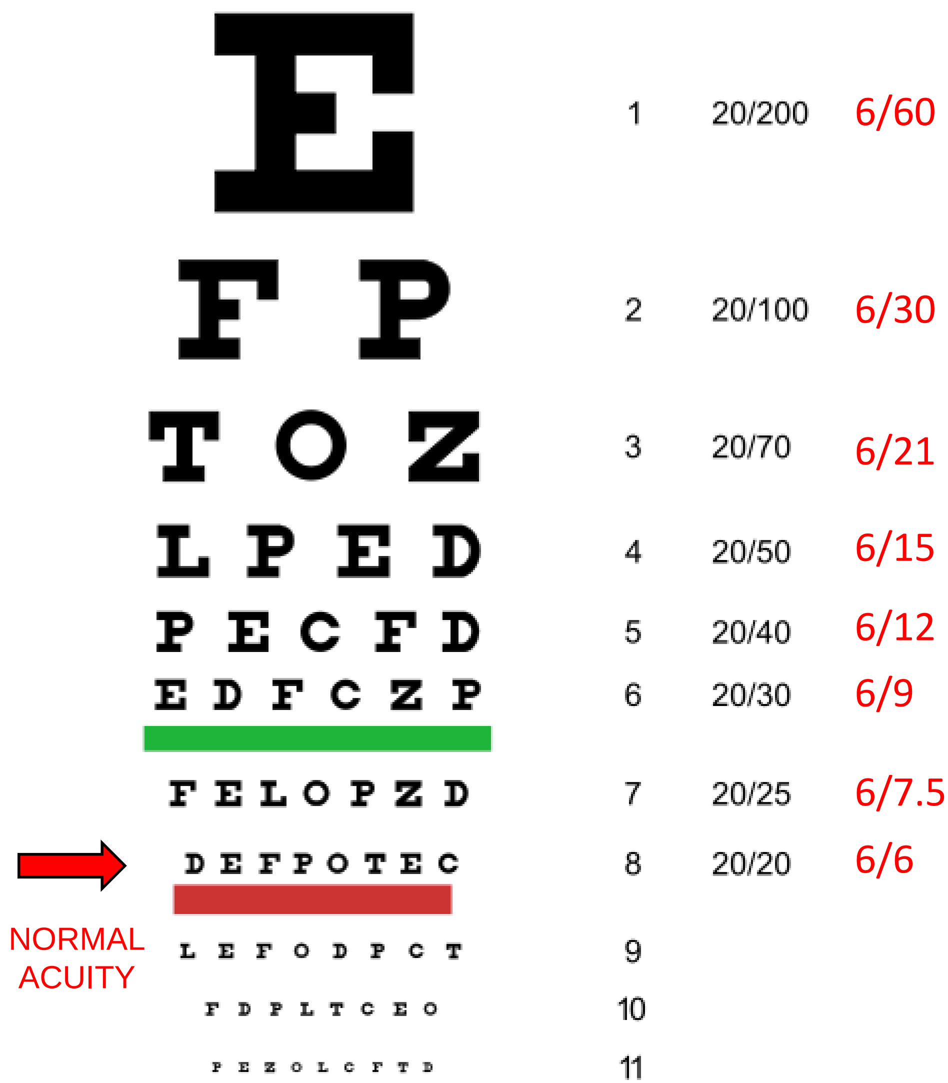
The Point Spread Function (PSF) characterizes the optical performance of the eye.

Measuring image quality “psychophysically”

1. Visual acuity measures



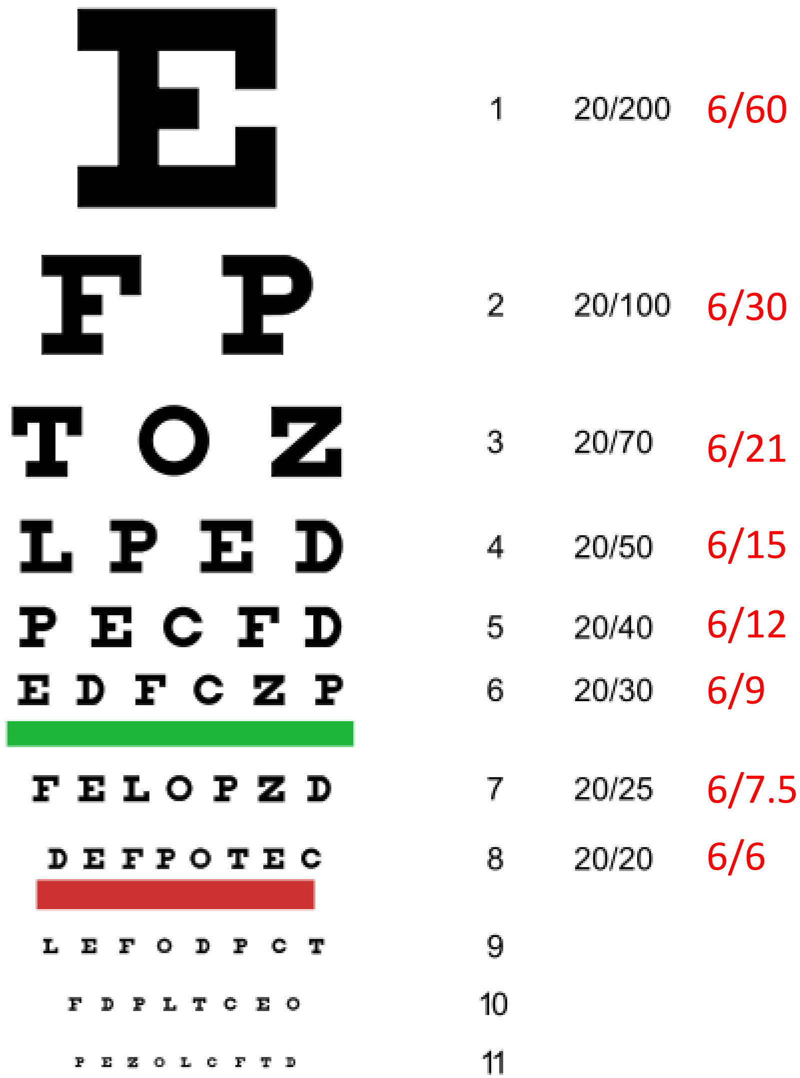
Smallest resolvable black and white target. Many different types of tests are available , but the letter chart introduced by Snellen in 1862 is the most common.

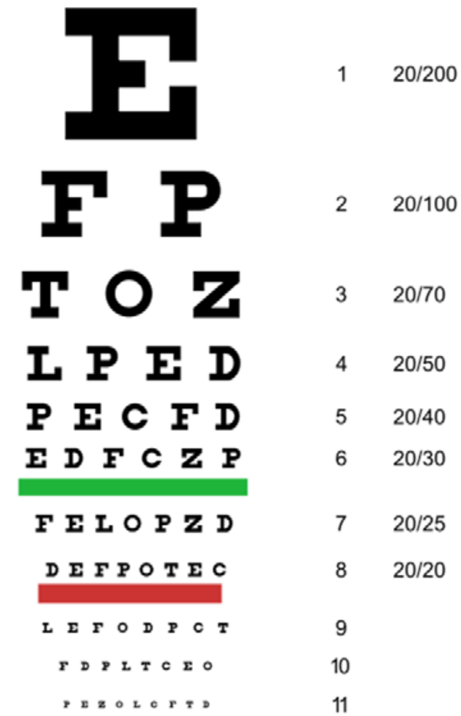


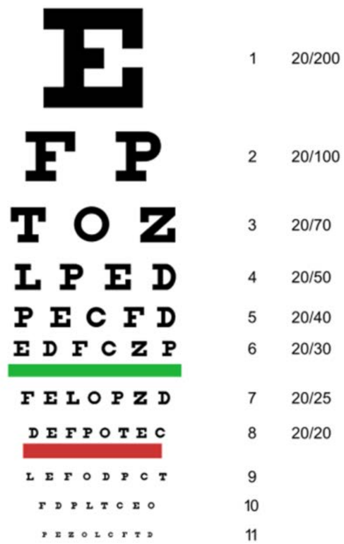
Snellen defined “standard vision” as the ability to recognize one of his optotypes when it subtended 5 minutes of arc. Thus, the optotype can only be recognized if the person viewing it can discriminate a spatial patterns separated by visual angles of 1 minute of arc.

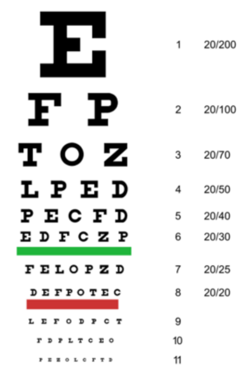
A Snellen chart is placed at a standard distance, twenty feet in the US (6 metres in Europe). At this distance, the symbols on the line representing "normal" acuity subtend an angle of five minutes of arc, and the thickness of the lines and of the spaces between the lines subtends one minute of arc.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

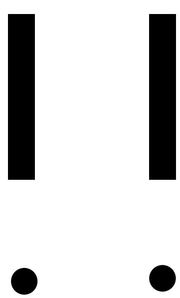
Grating acuity

Orientation resolution acuity

Detection acuity

2-line resolution

2-point resolution

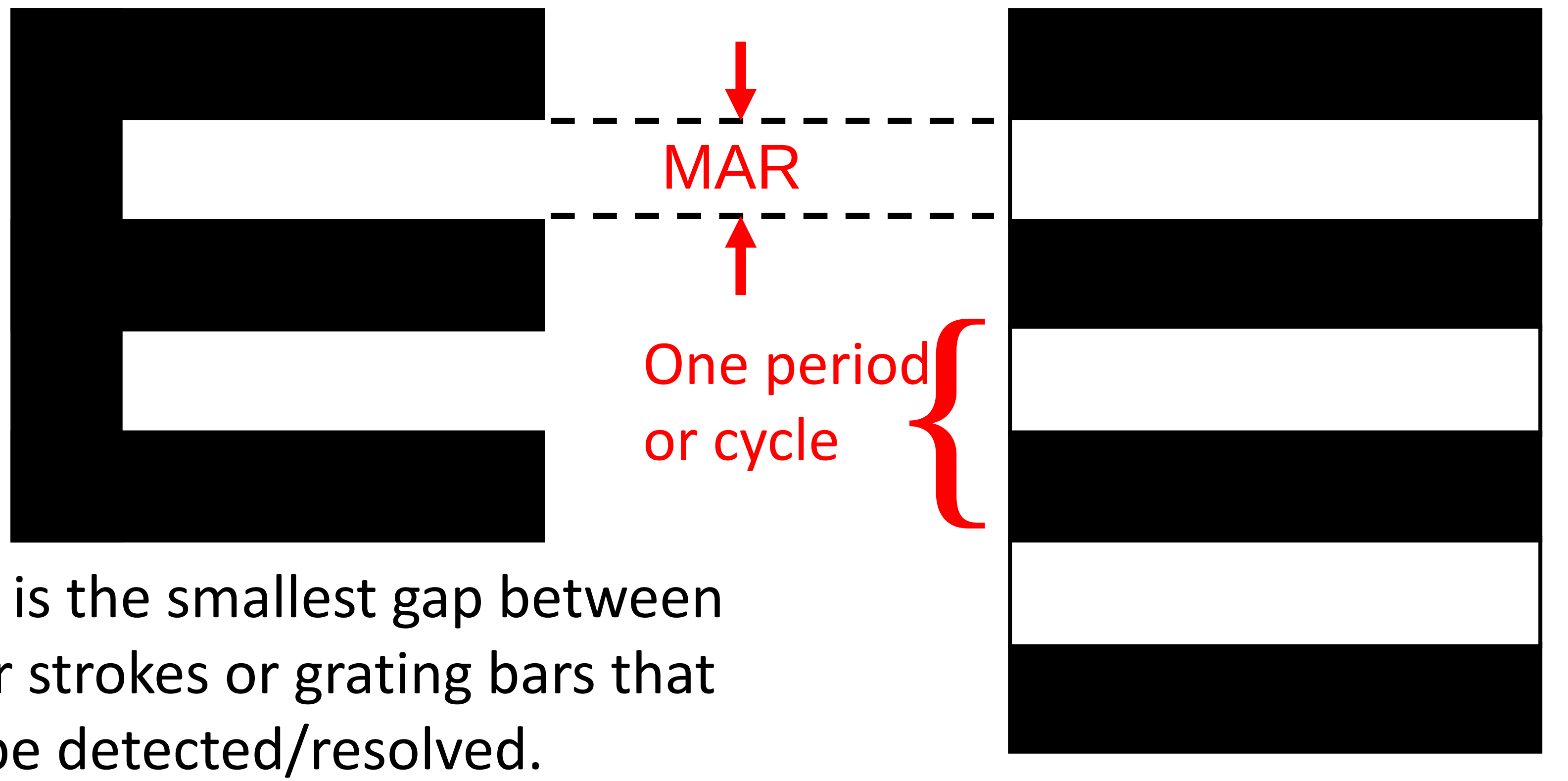


Can the subject see two lines or points rather than one?

Arthur Bradley

Arthur Bradley

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

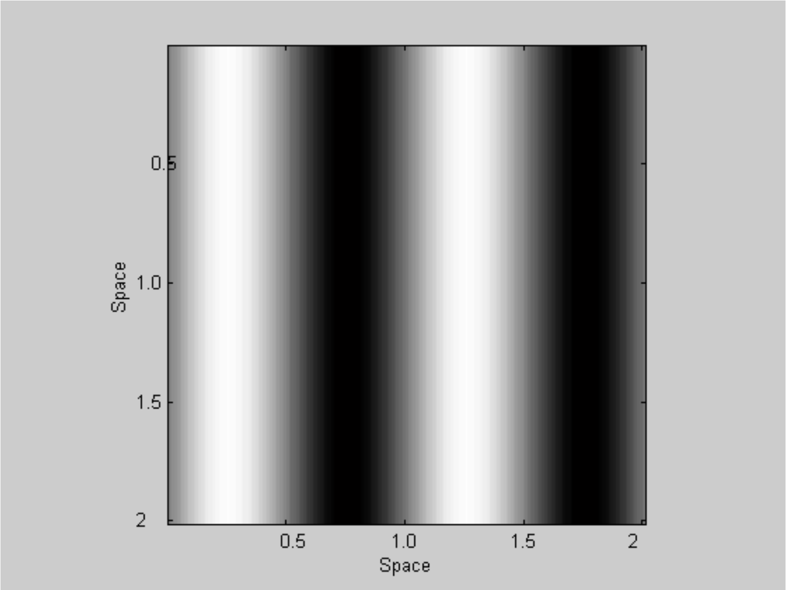
NORMAL ACUITY

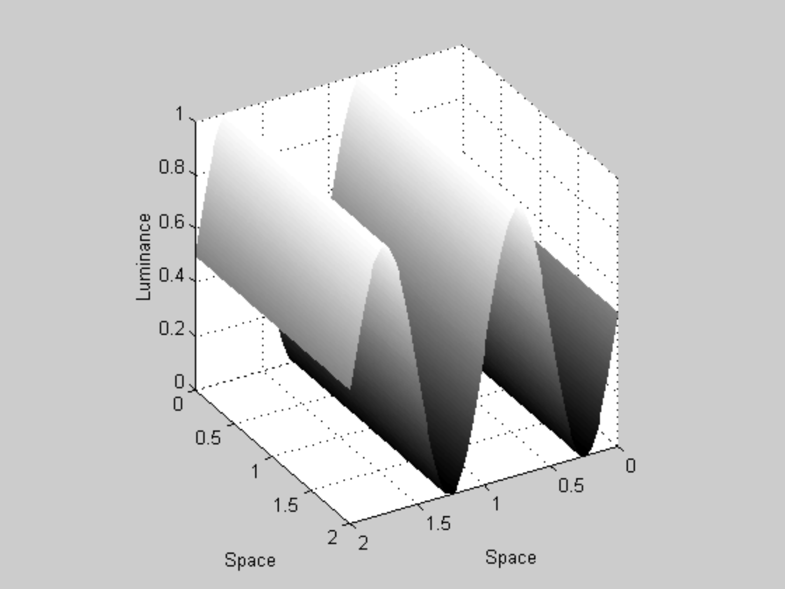
Arthur Bradley

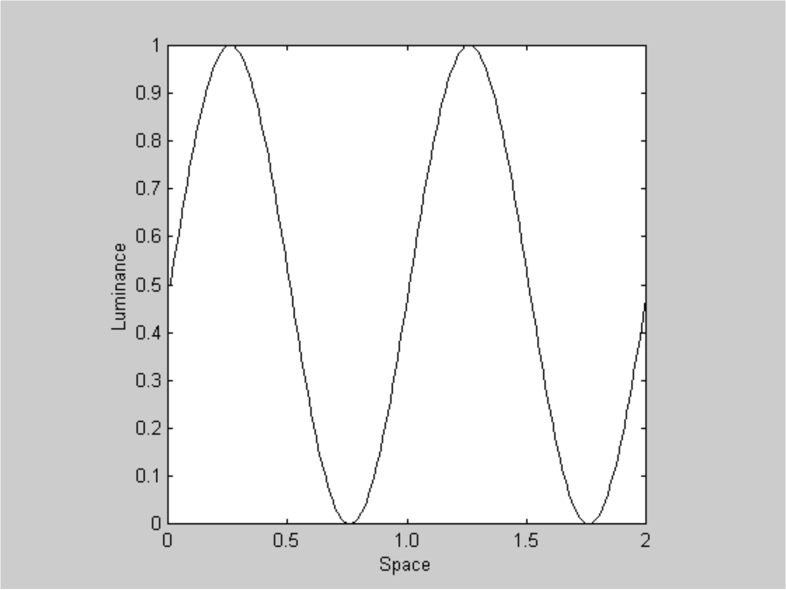
Measuring image quality psychophysically

2. Spatial contrast sensitivity measures

Spatial frequency

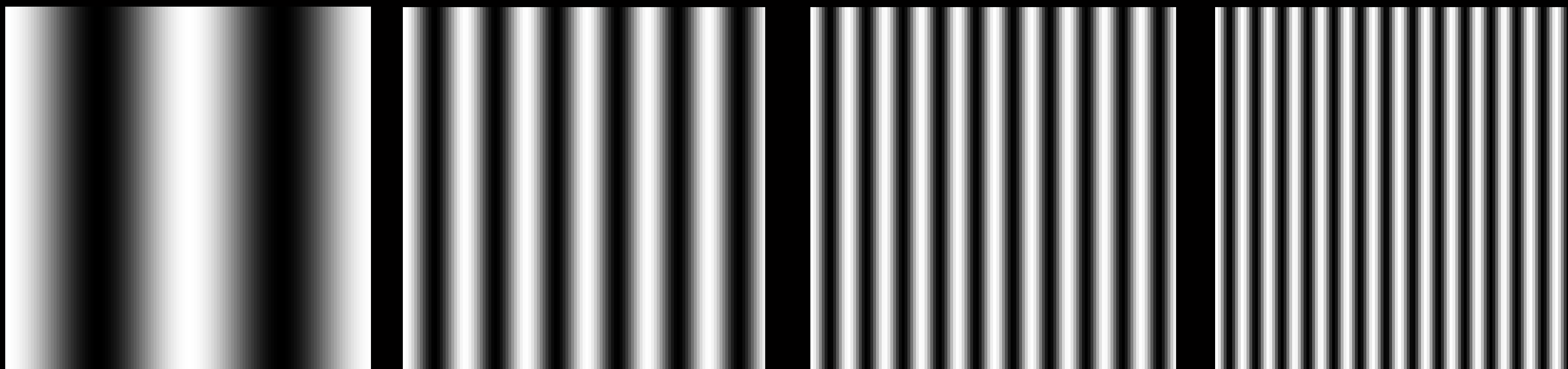




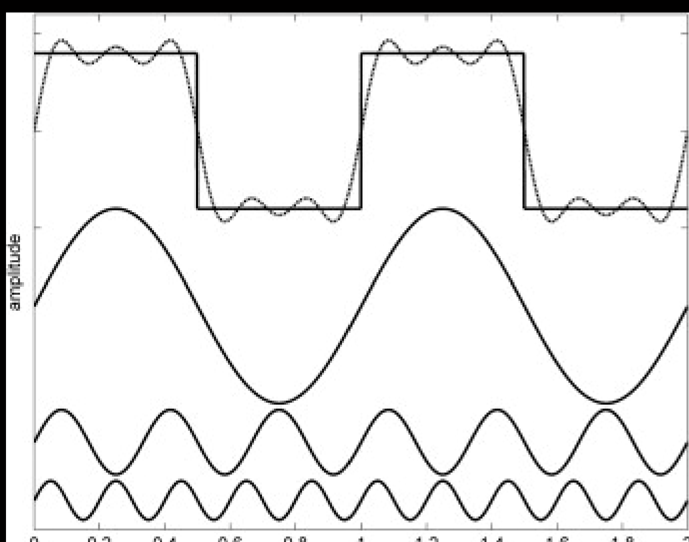


Harmonics of a square wave

1 3 5 7



Steven Lehars



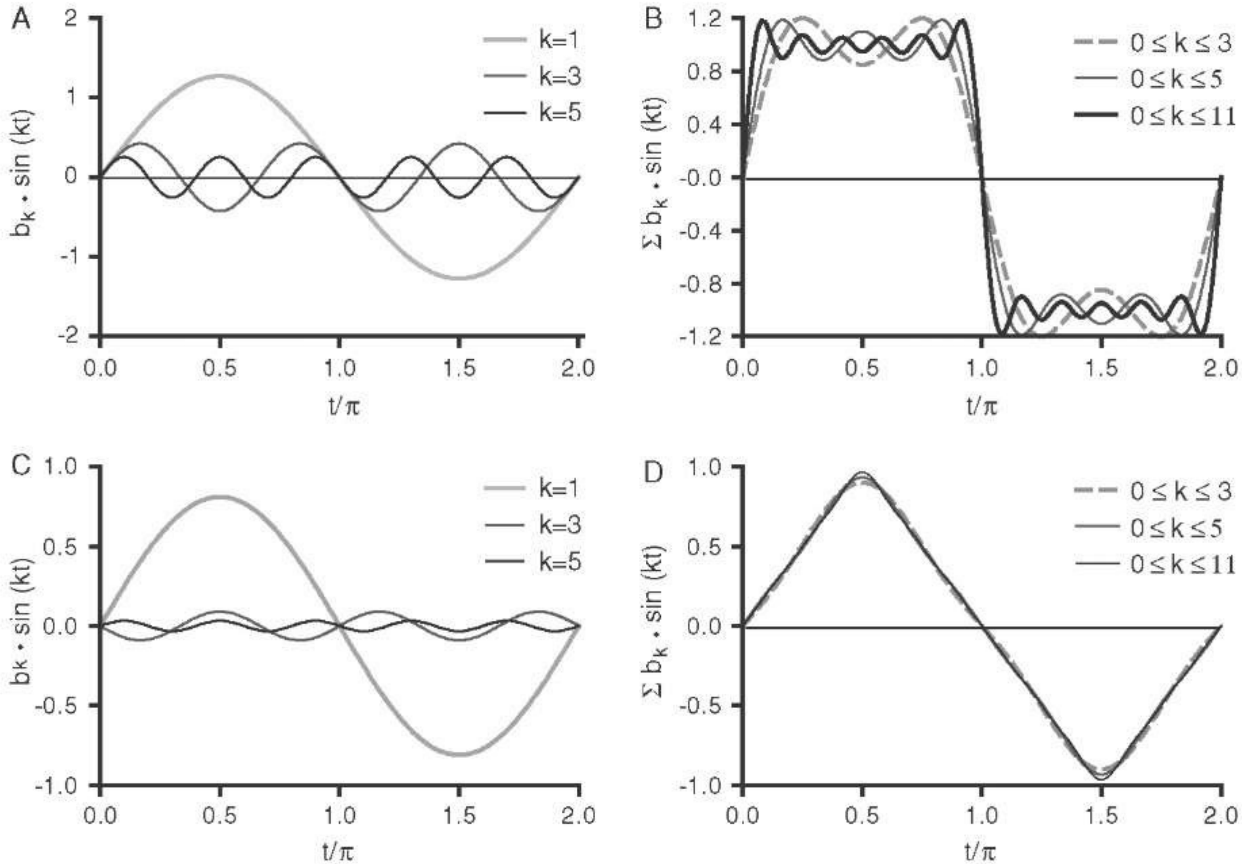
1+3+5

1

3

5

Harmonics of a square and triangle wave



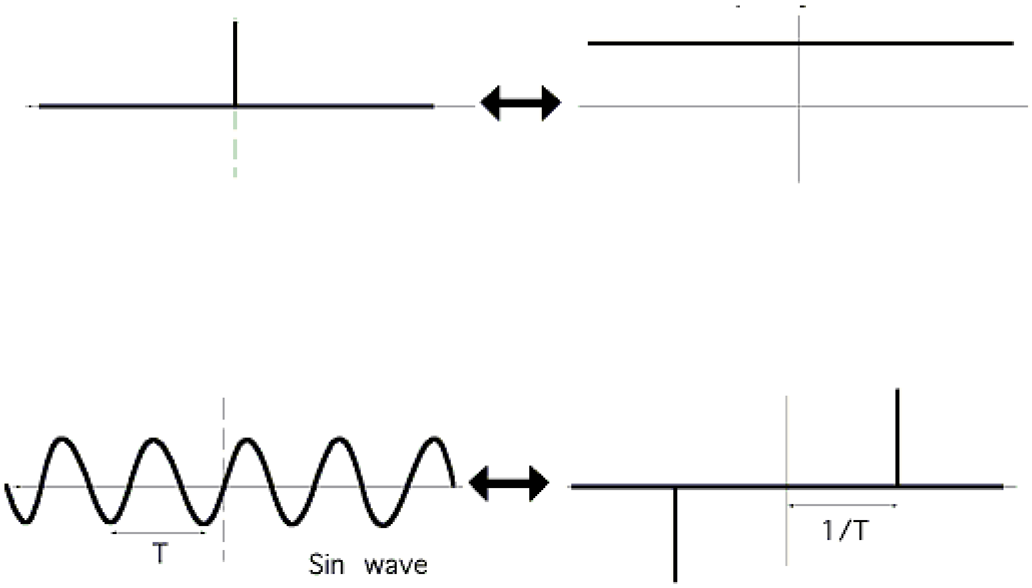
Square

Triangle

Fourier transform

Inverse Fourier transform

Space | Spatial Frequency



All frequencies

One frequency

Fourier transform

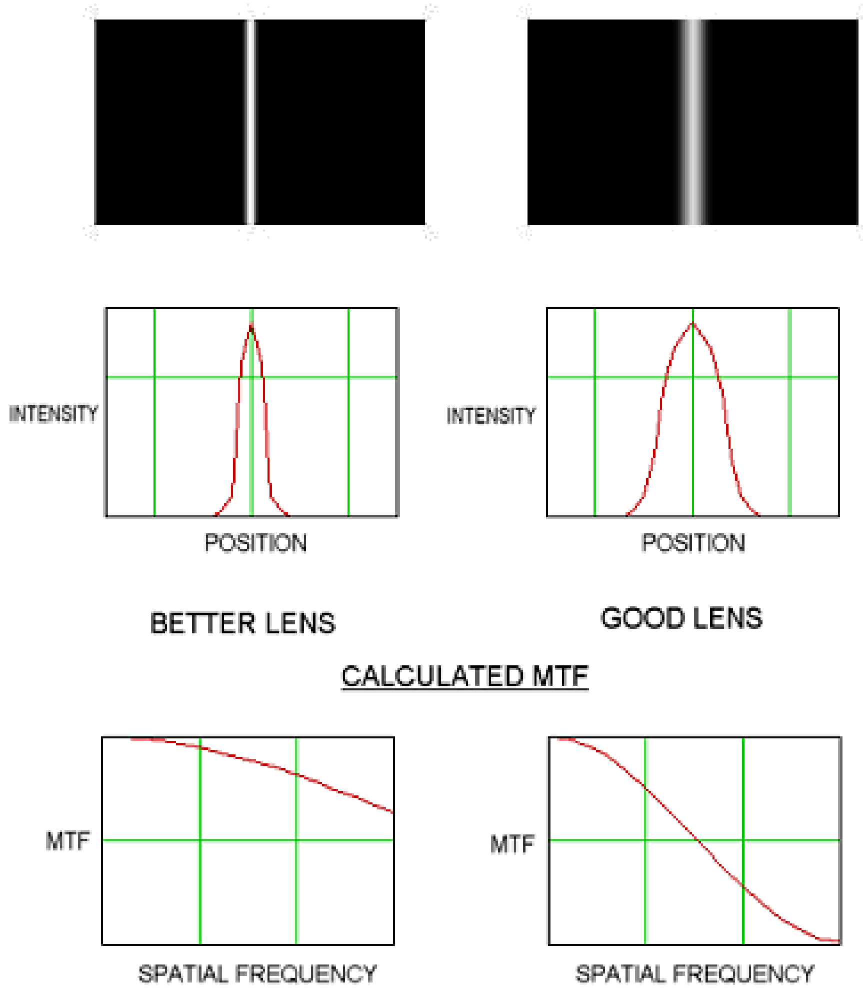


Image of line

PSF

Spatial MTF

Inverse Fourier transform

What would the results for a perfect lens look like?

Fourier transform

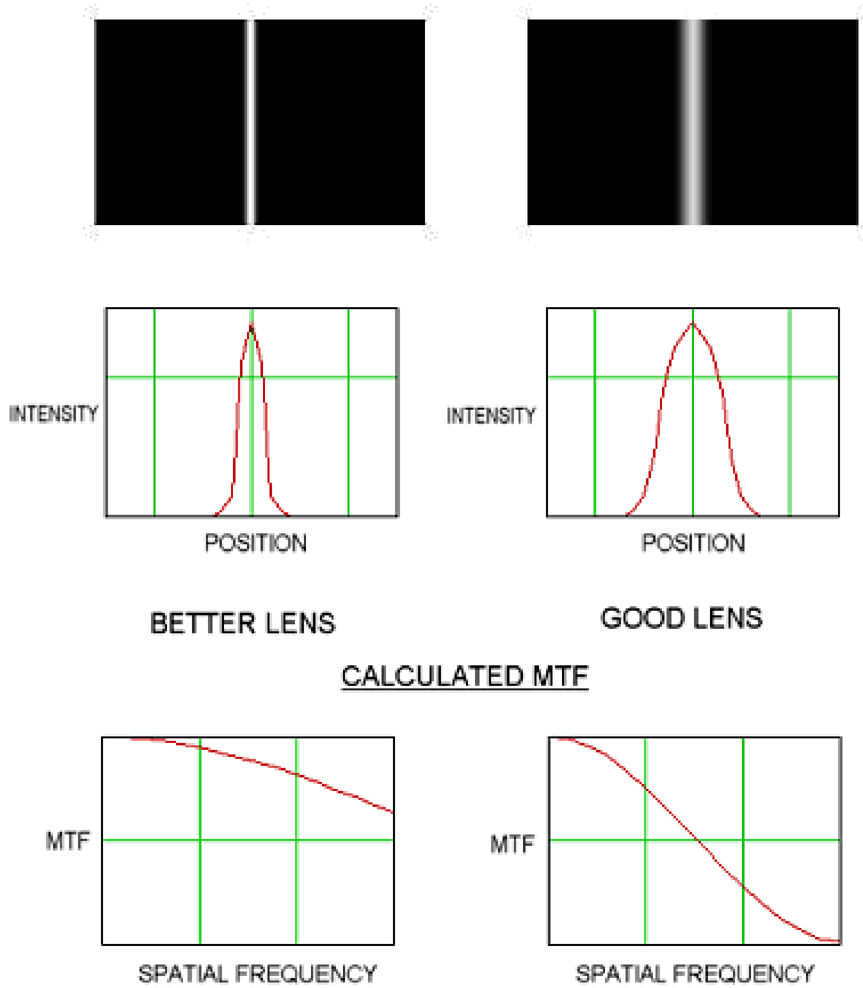


Image of line

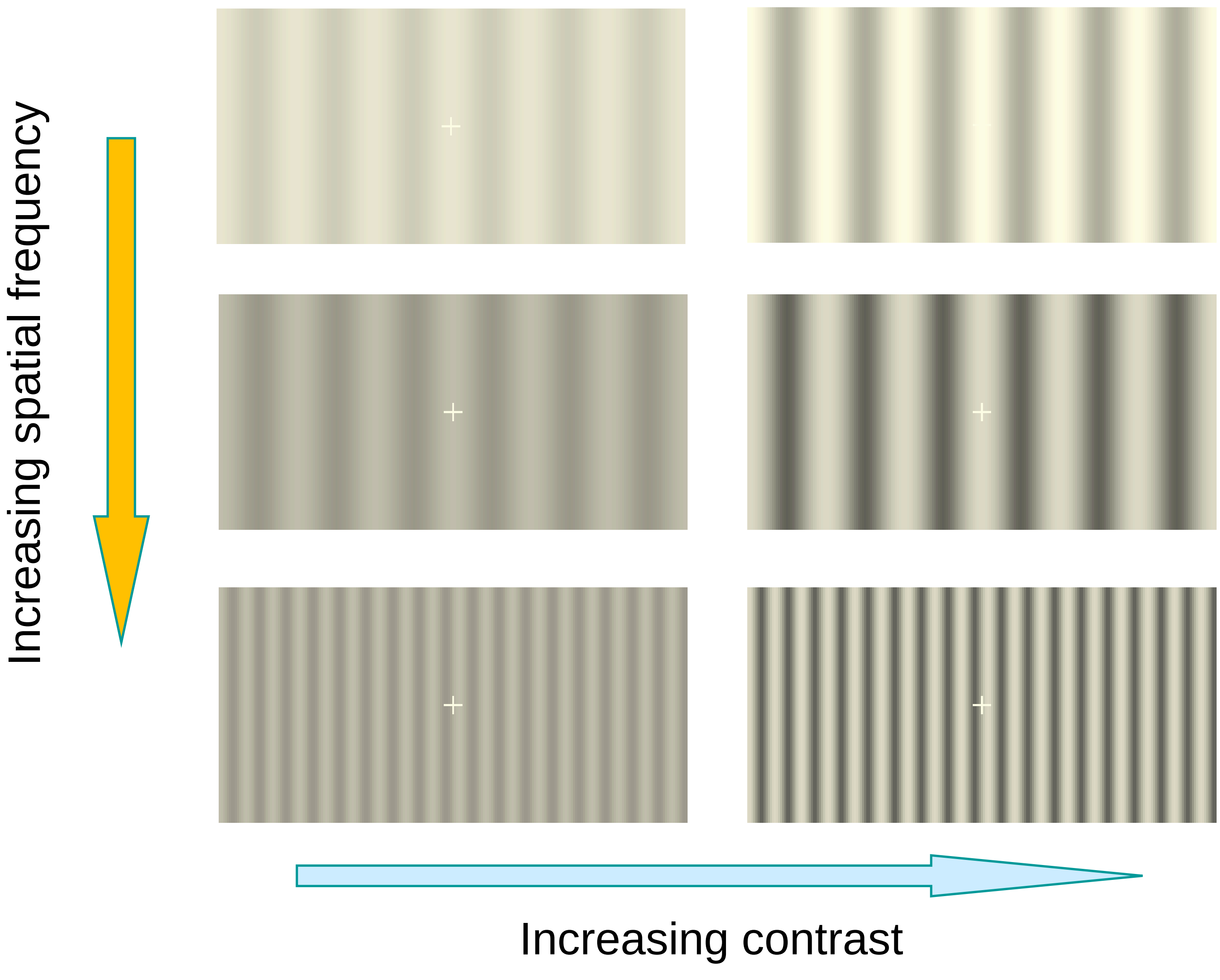
PSF

Spatial MTF

Inverse Fourier transform

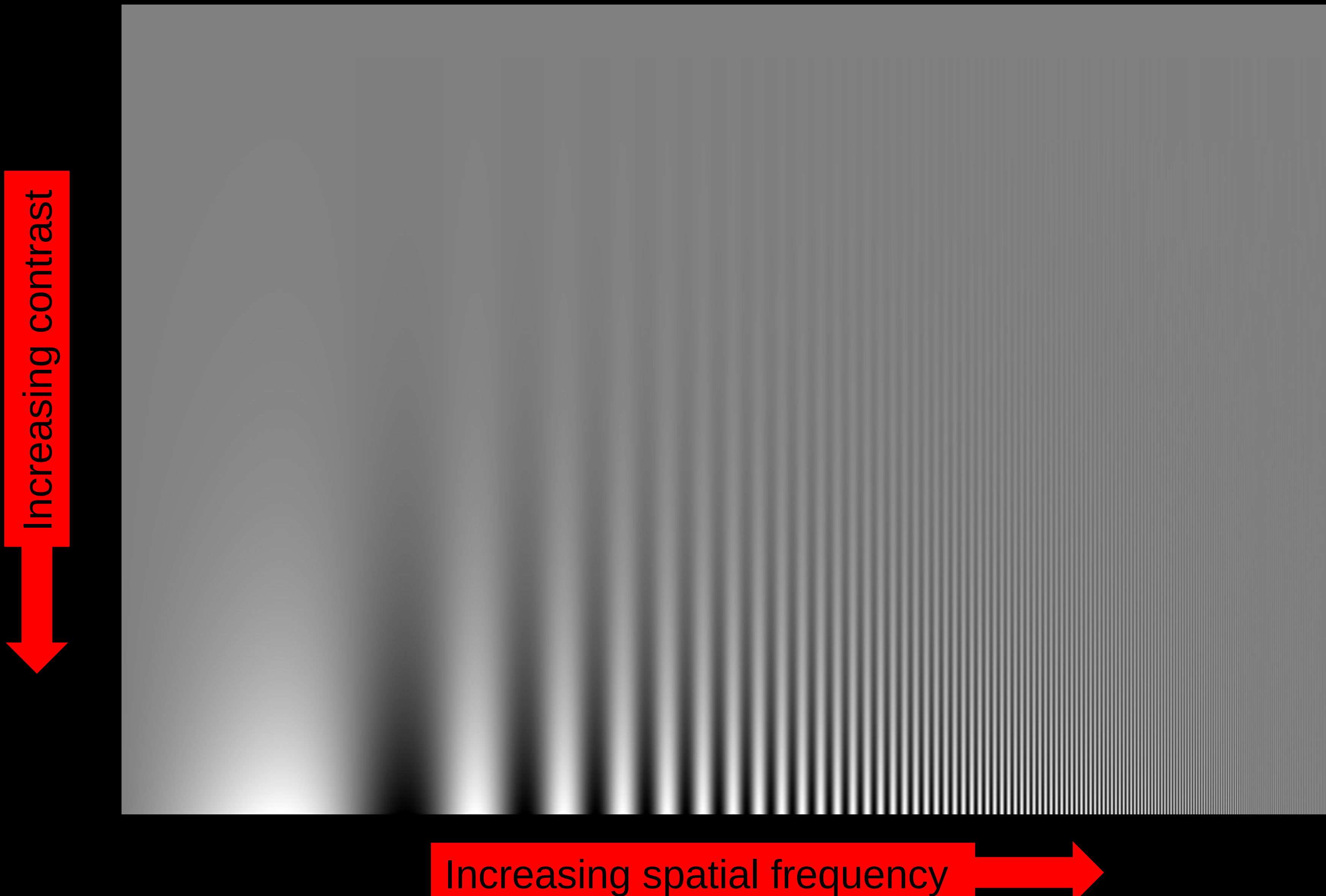
We can measure this “psychophysically”

Spatial frequency gratings



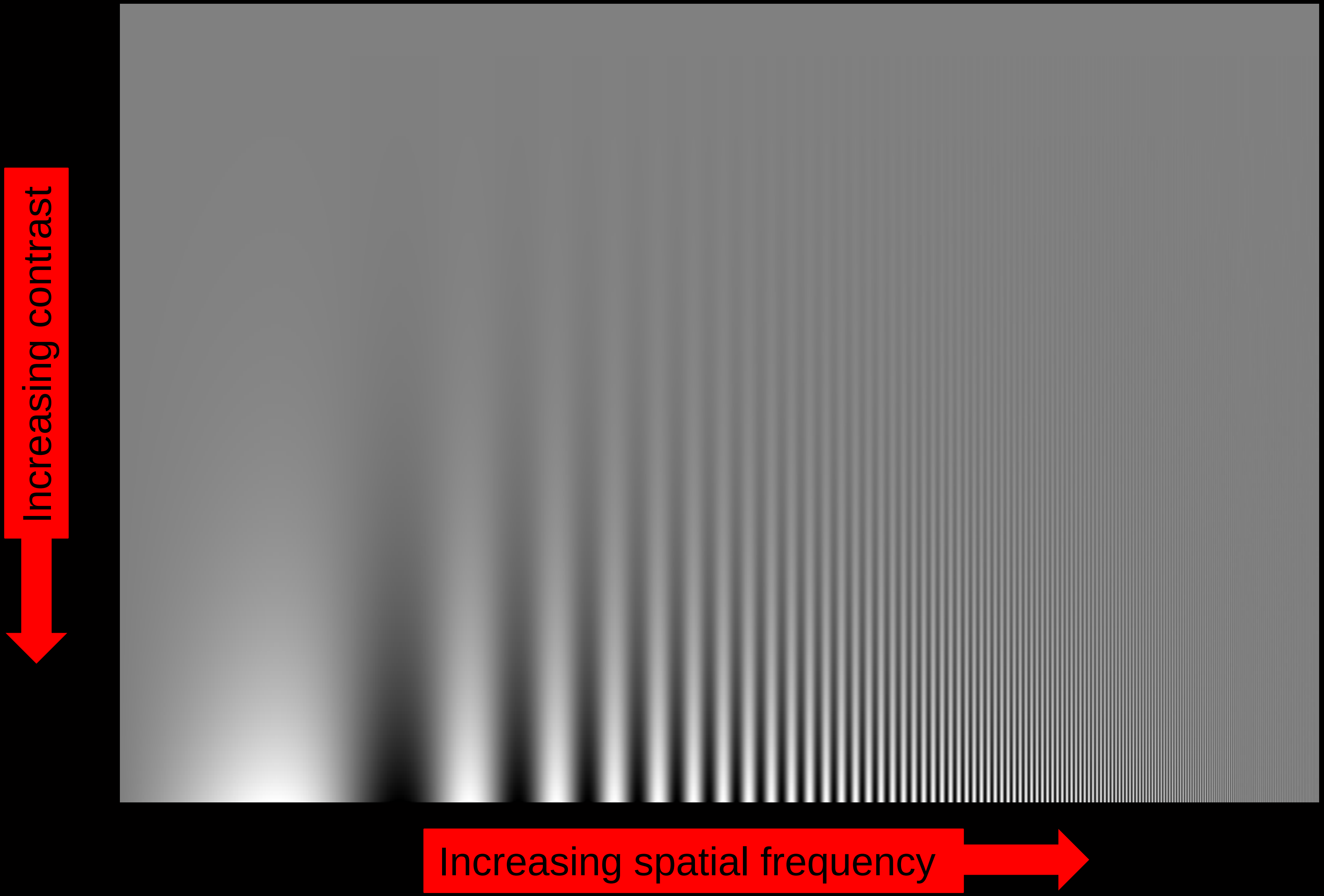
Spatial MTF

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



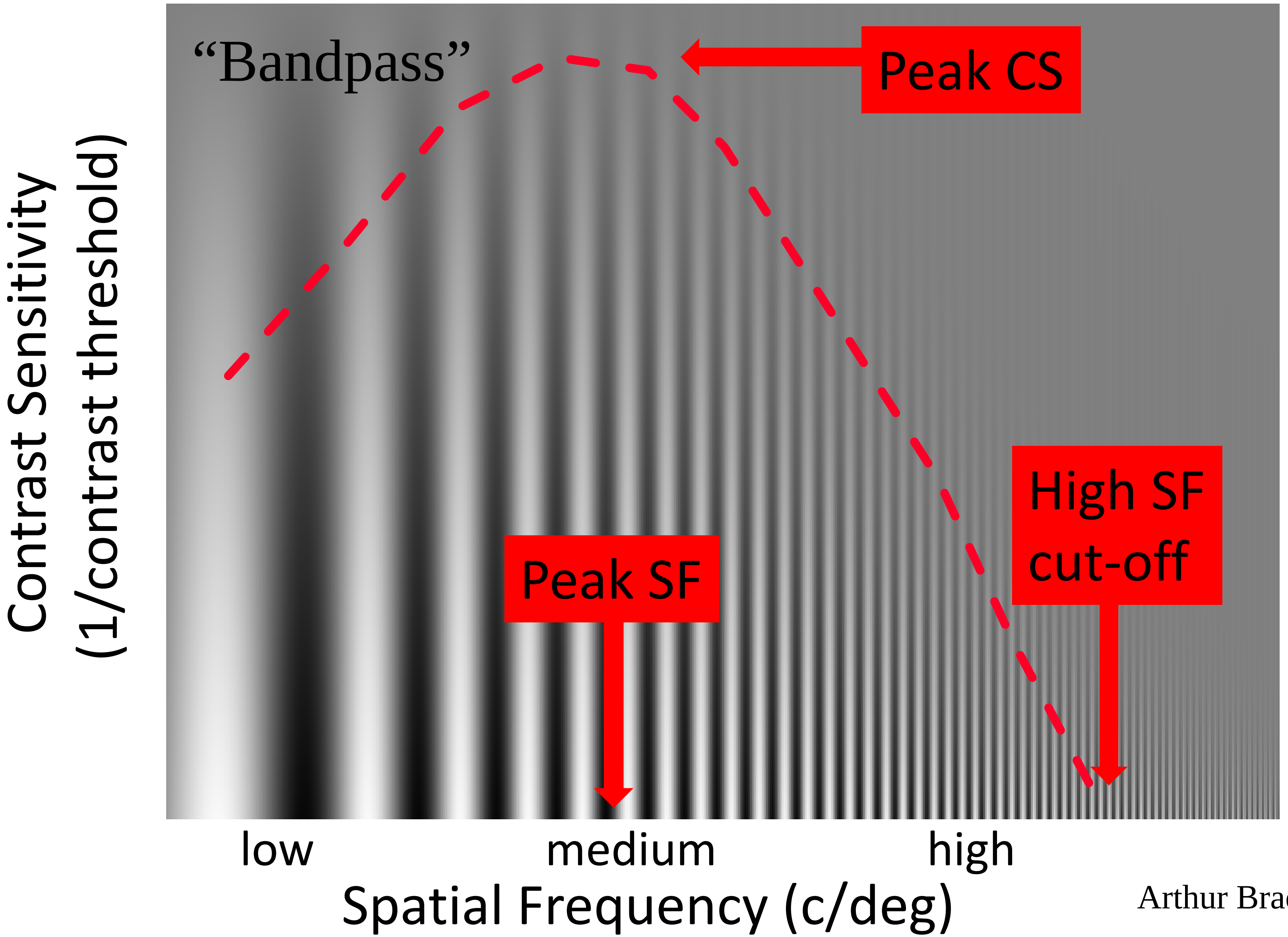
Spatial MTF

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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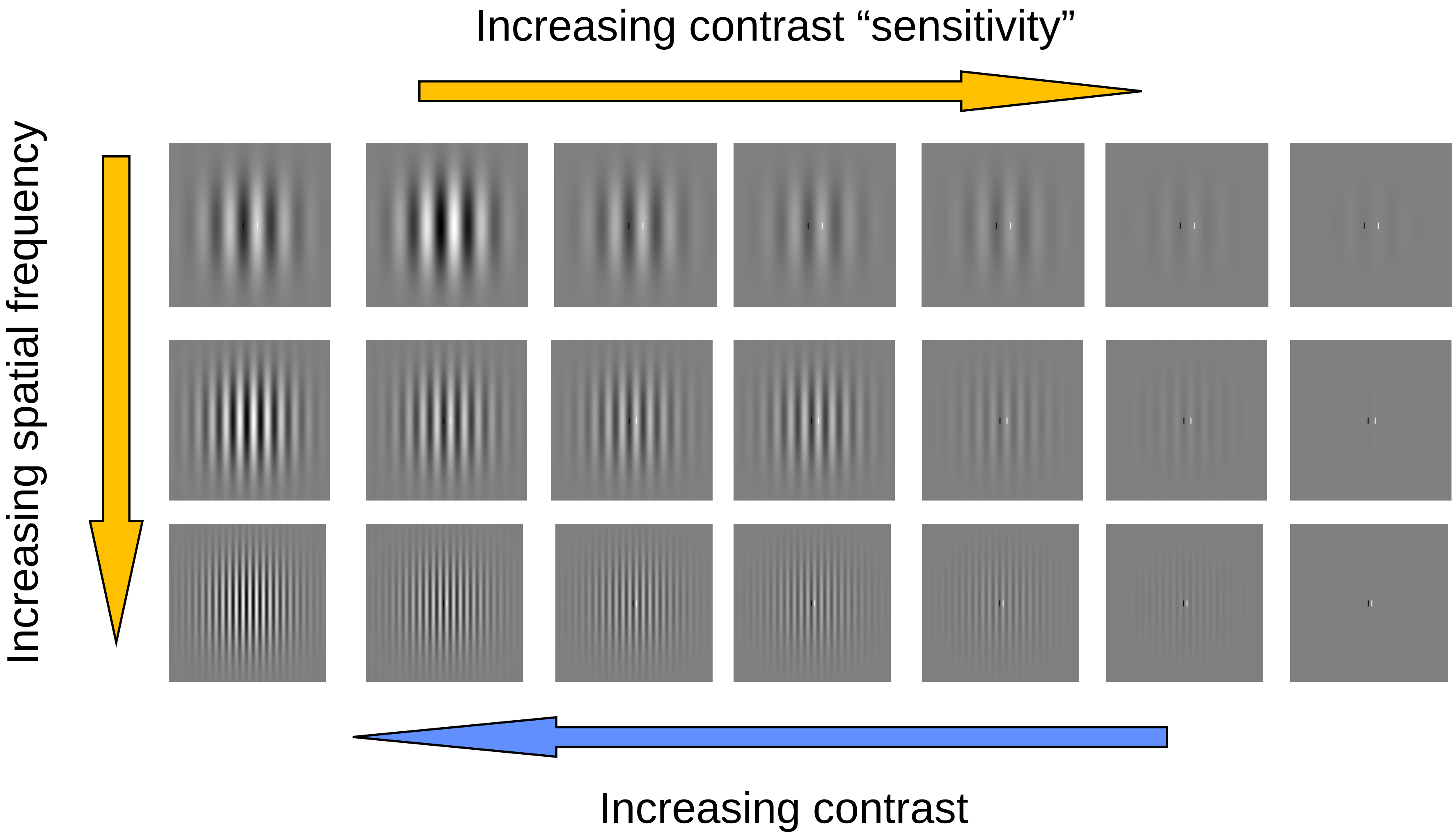
Example of grating contrast sensitivity test using printed gratings



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Spatial CSFs

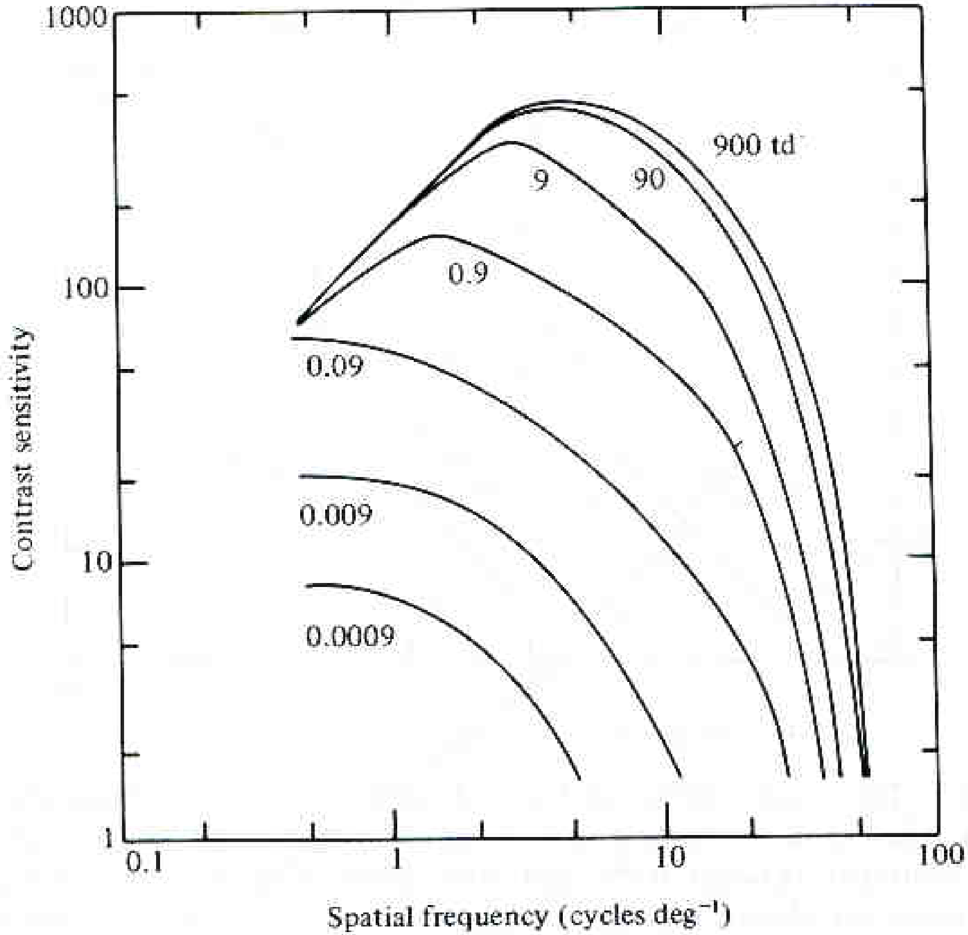
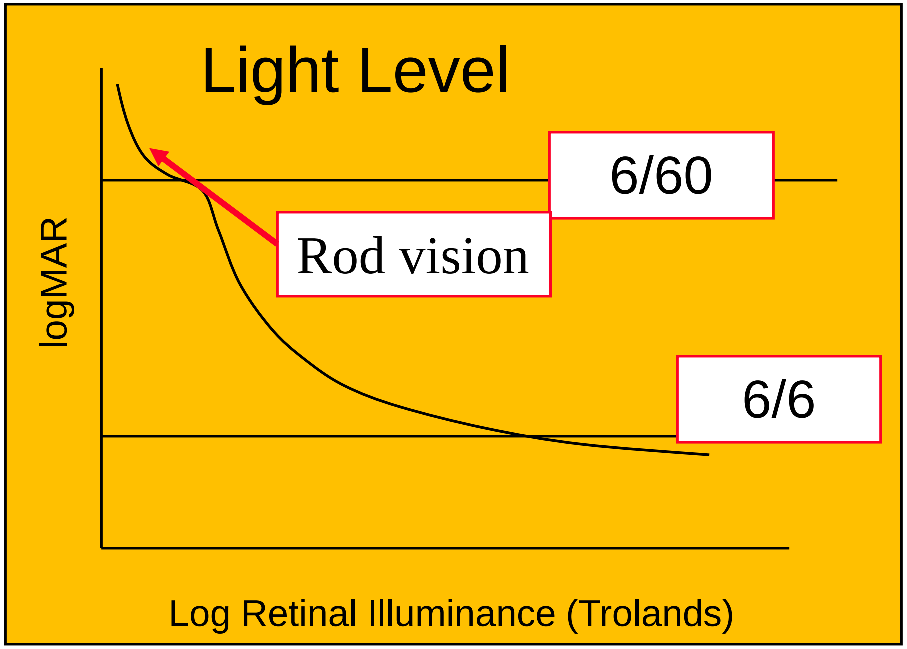
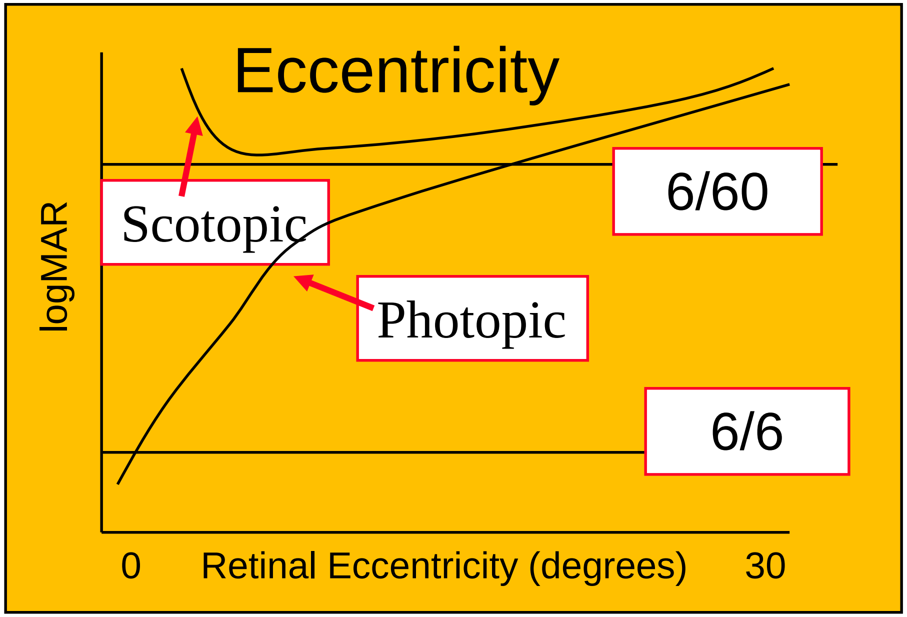


Fig. 8.4. Spatial contrast sensitivity curves at seven different retinal illuminance levels between 0.0009 and 900 trolands. The subject viewed the gratings through a 2 mm diameter artificial pupil. The wavelength of the light was 525 nm. Notice the loss of sensitivity for medium and high frequencies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

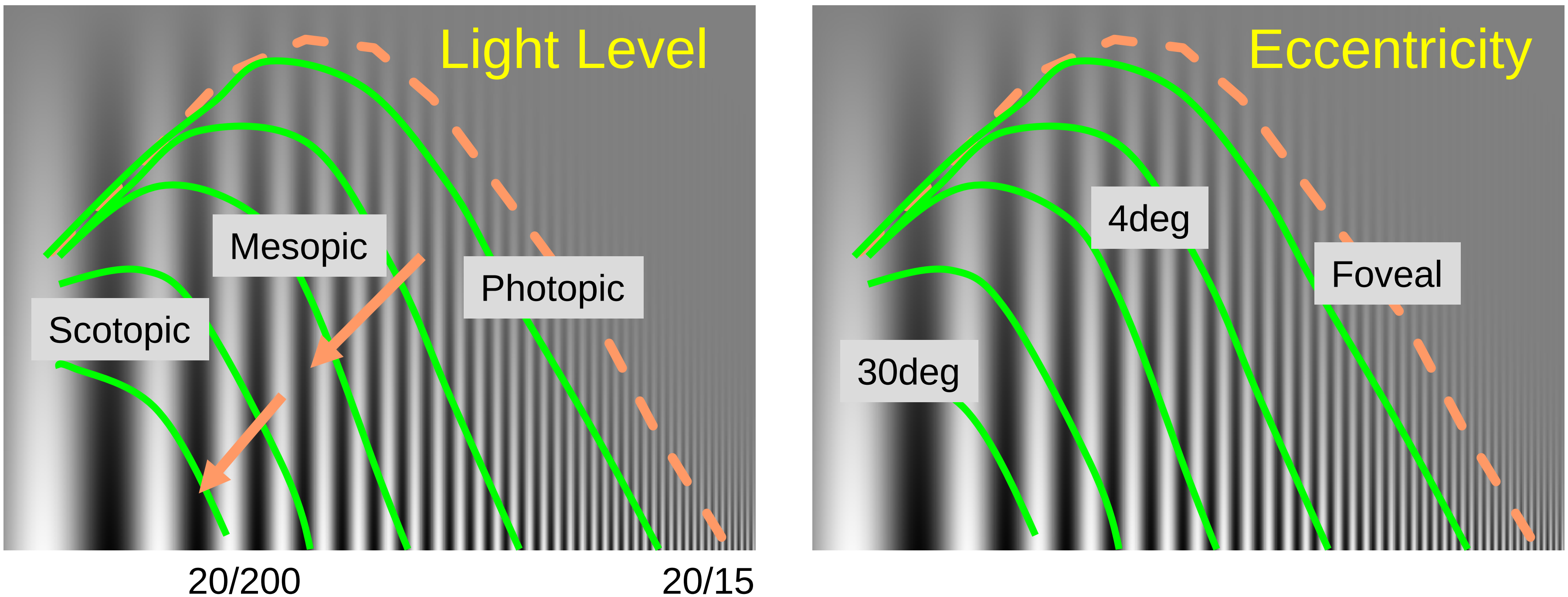




Vision is not always 6/6!

Arthur Bradley

Contrast Sensitivity is not constant!



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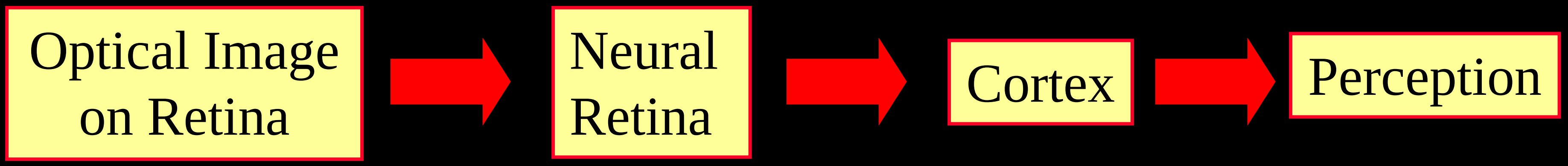
What limits visual performance?

Stages

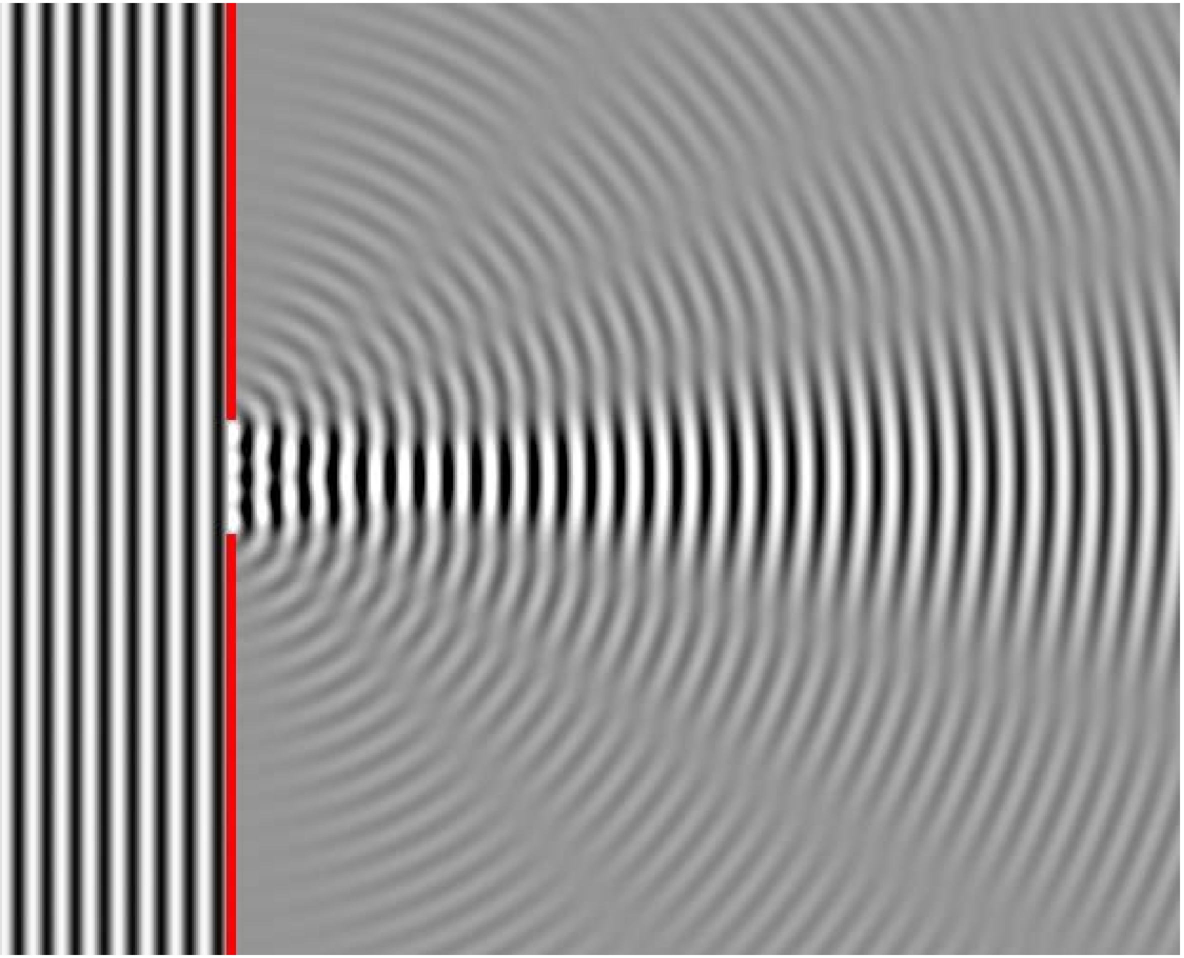


Stages

Optical Image on Retina ➡

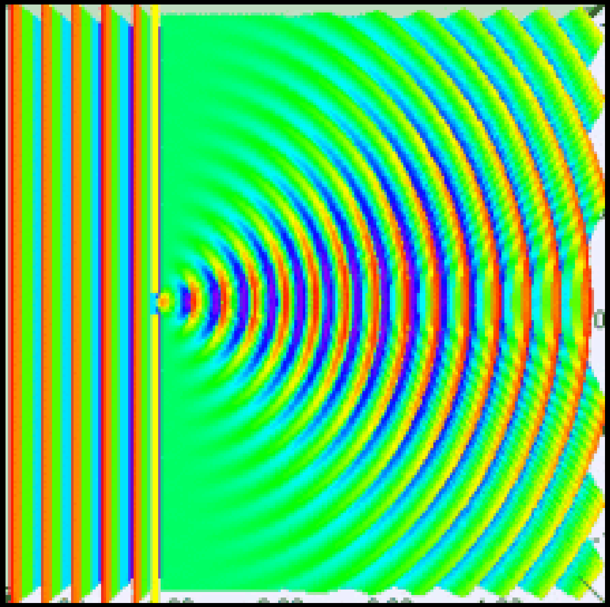
Consider optical limits first

The visual image is diffraction limited

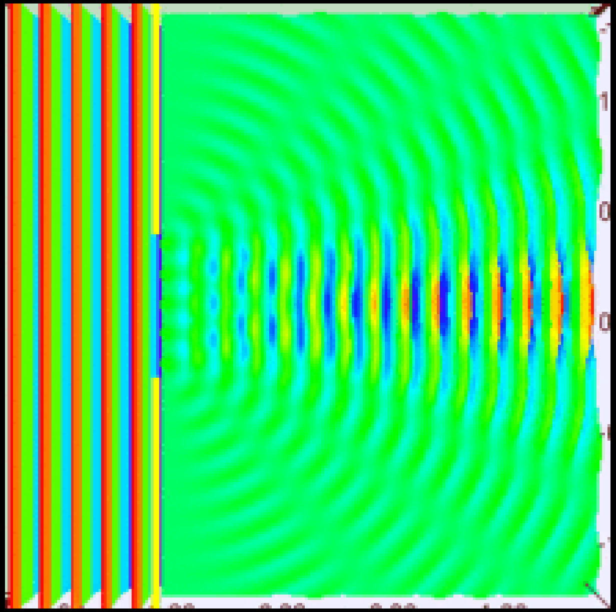


Approximation of diffraction pattern from a slit of width four wavelengths with an incident plane wave. The main central beam, nulls, and phase reversals are apparent (Wikipedia).

1-wavelength slit



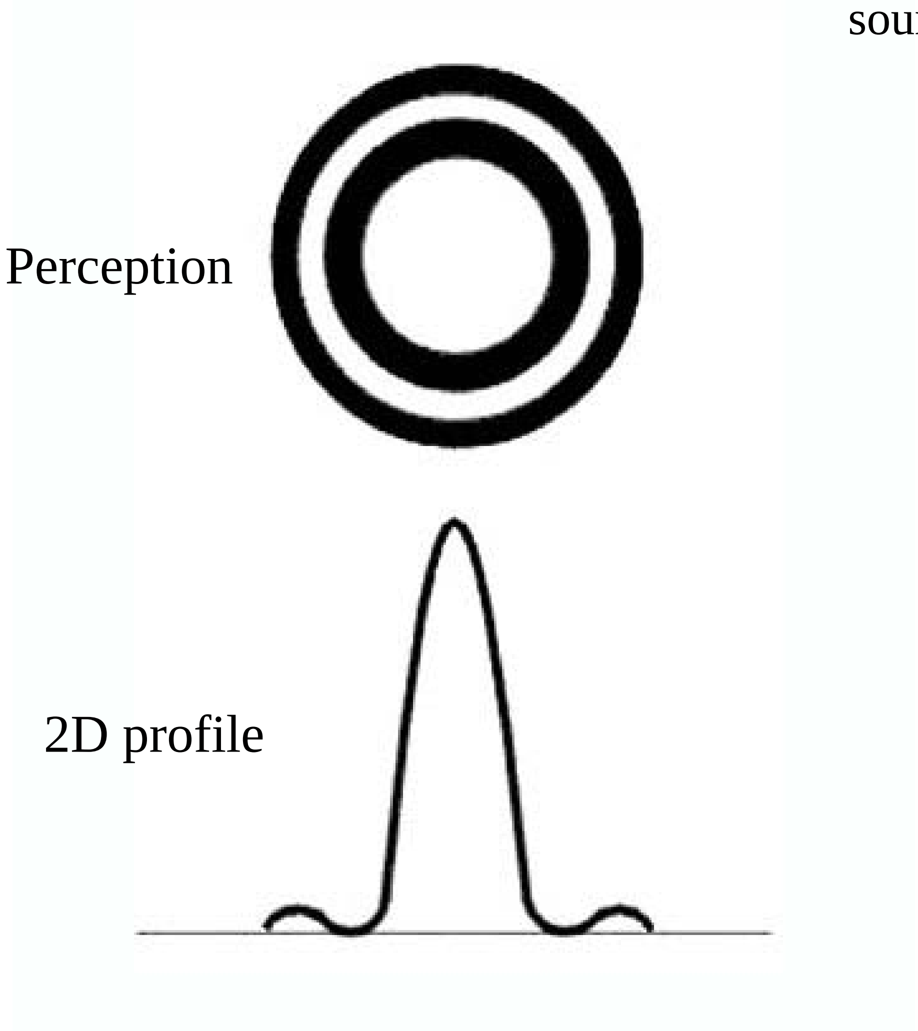
5-wavelength slit

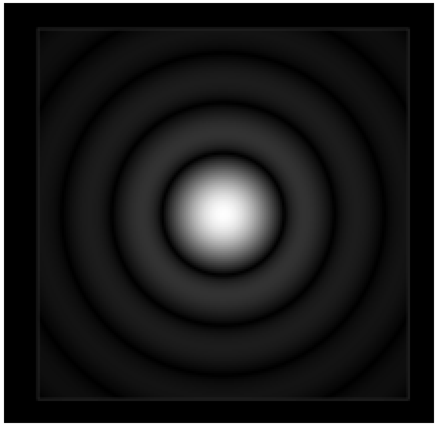


Wikipedia

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.

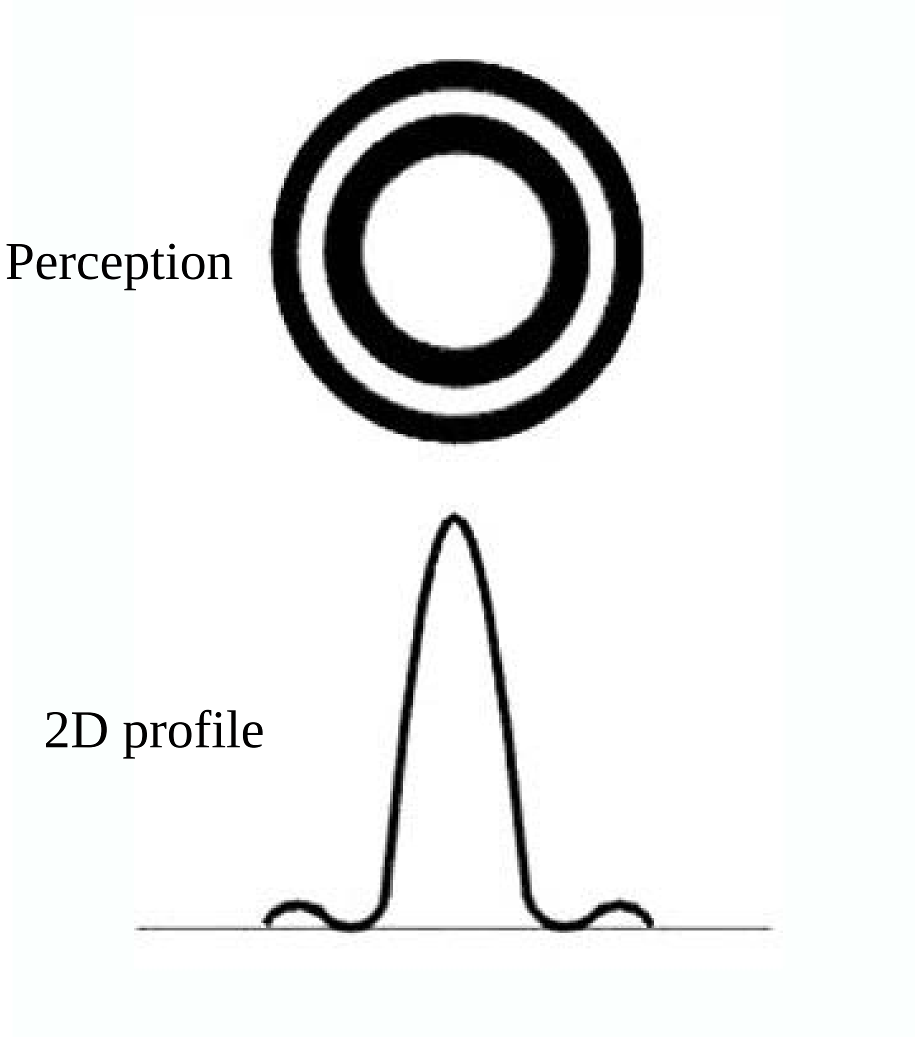


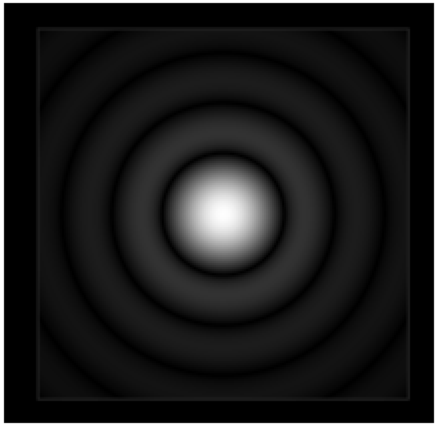


From Webvision, Michael Kalloniatis

Airy disc (PSF)

How does this affect spatial resolution?

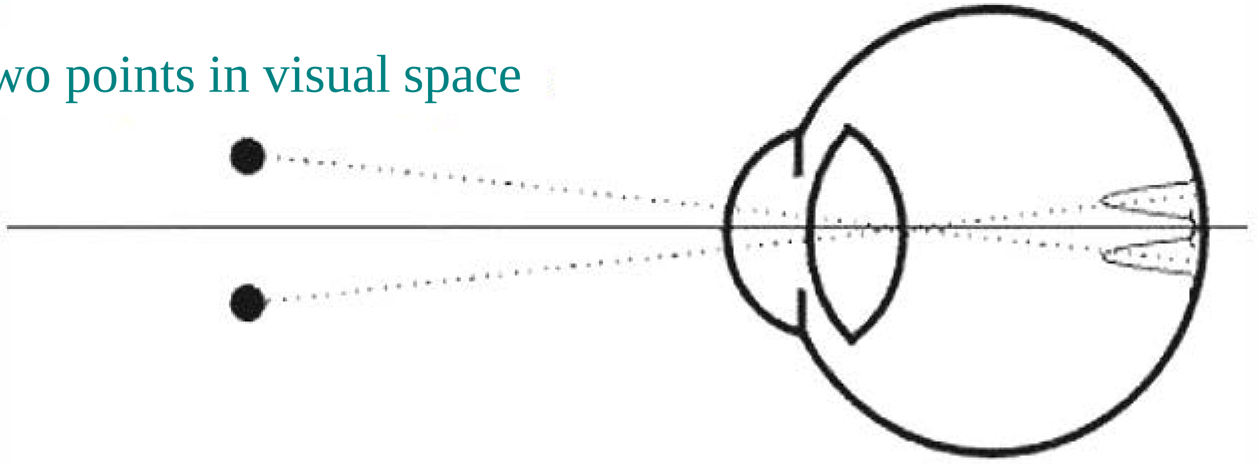




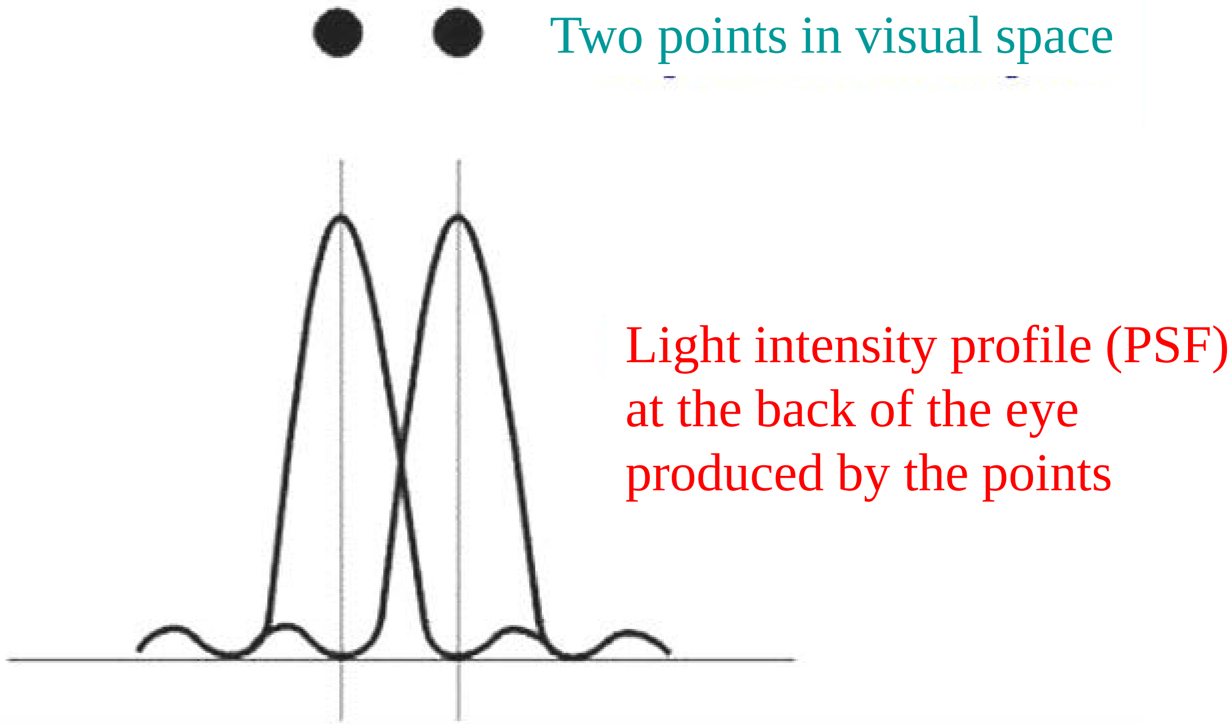
From Webvision, Michael Kalloniatis

Overlapping point spread functions (PSF)

Two points in visual space



From Webvision, Michael Kalloniatis

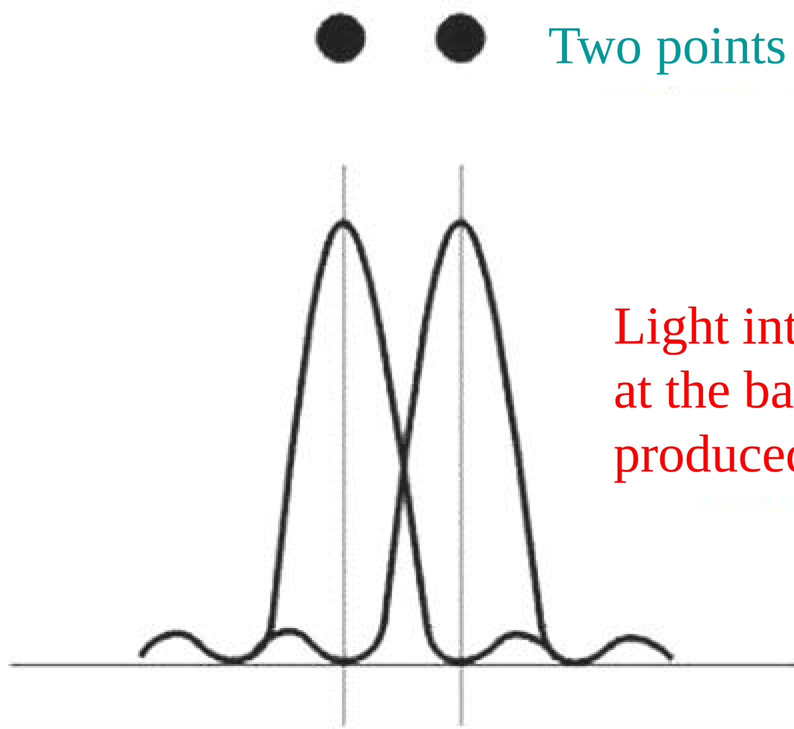


From Webvision,
Michael Kalloniatis

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:

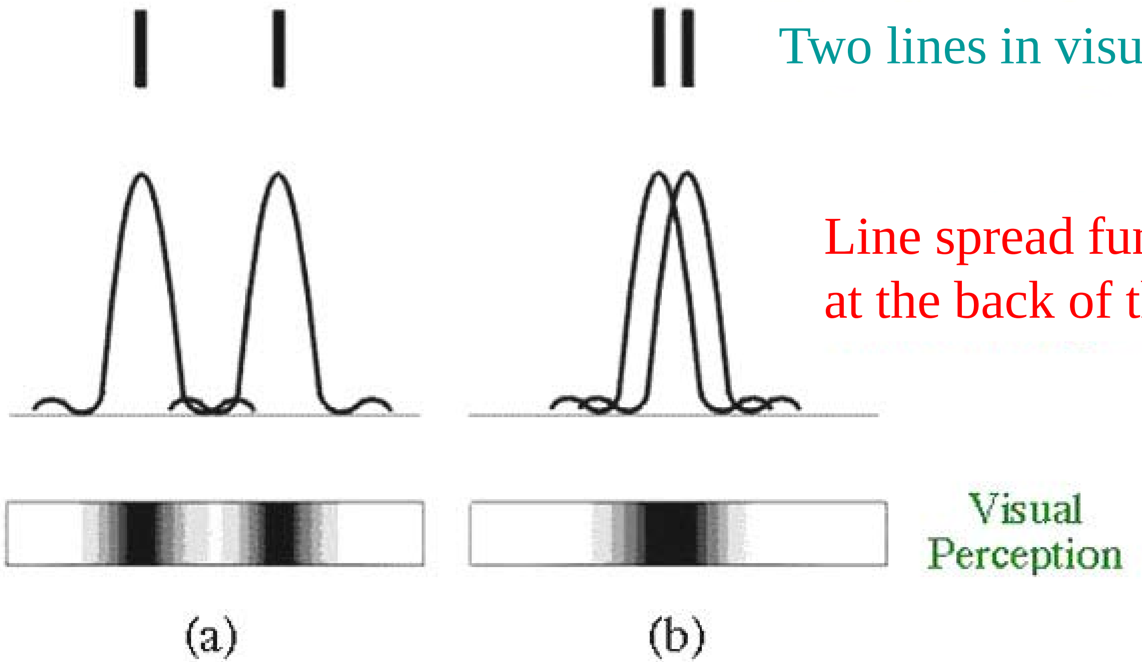
$$\Delta\theta = 1.22\frac{\lambda}{D}$$

where Δθ 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.



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

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.

From Webvision, Michael Kalloniatis

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

Snellen	Metric Snellen	MAR in arc minutes	LogMAR	Decimal	Grating VA c/deg	Jaeger Near VA
20/20	6/6	1	0.0	1.0	30	J1+

Normal acuity is well matched to the diffraction limited resolution for a 550 nm light and a 3 mm diameter pupil of 0.77 min of arc.

Pupil size

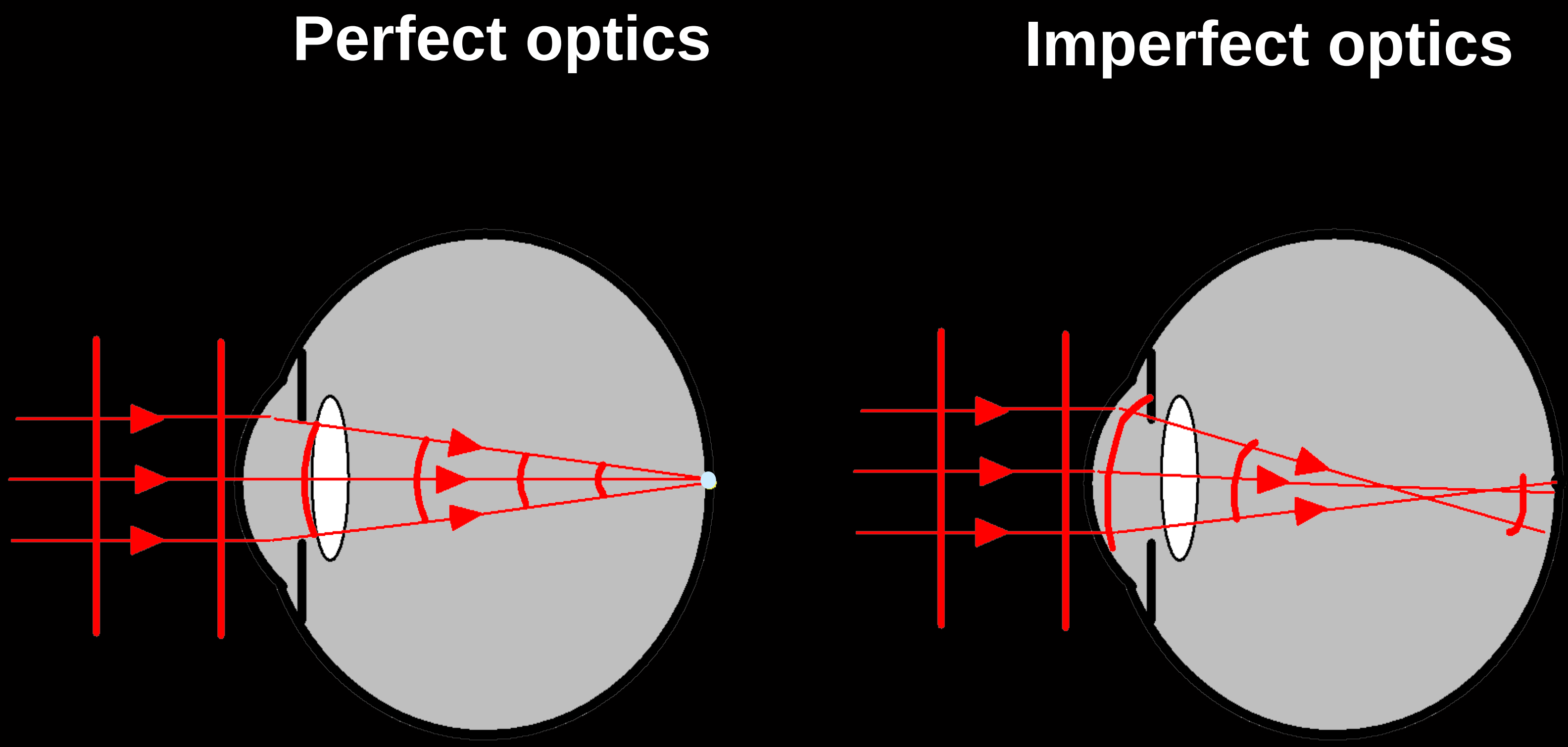
The size of the pupil is an important factor affecting visual acuity.

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

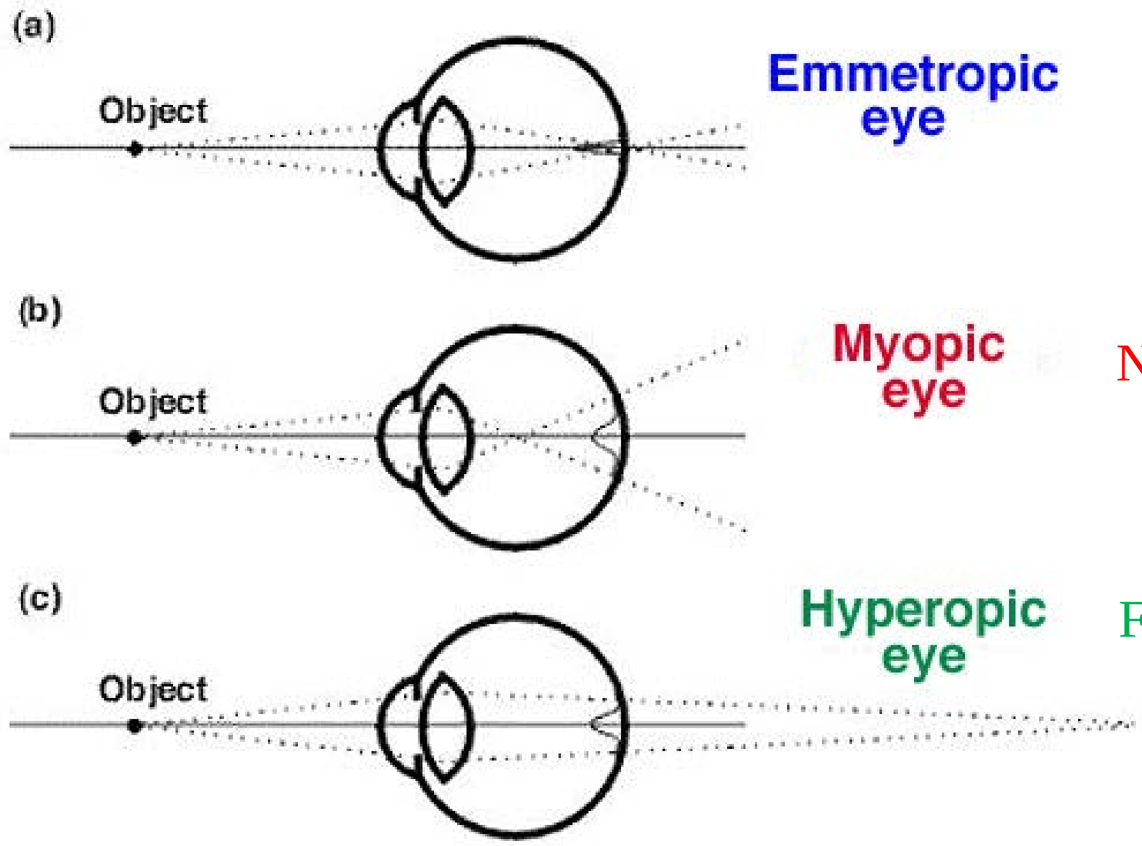


Larry Thibos

So far we have been talking about foveal vision at optimal light levels with optimal refraction…

Refractive errors

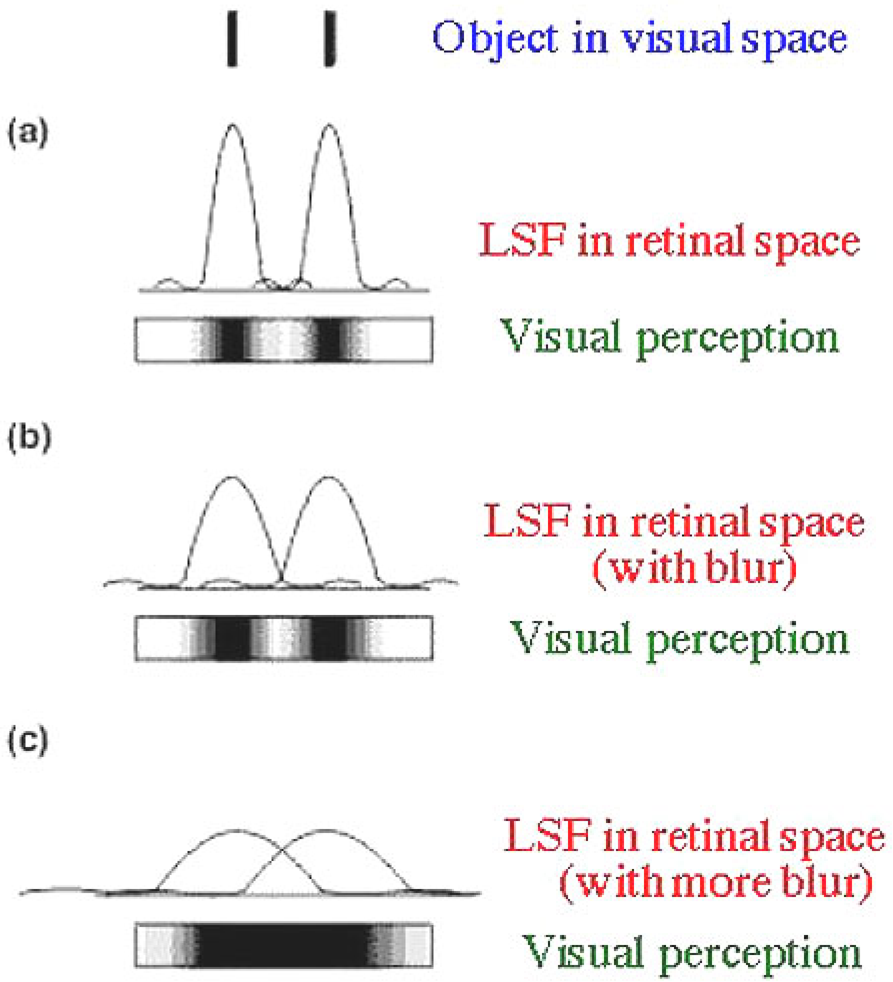
PSFs for different refractive errors



Nearsighted

Farsighted

From Webvision, Michael Kalloniatis

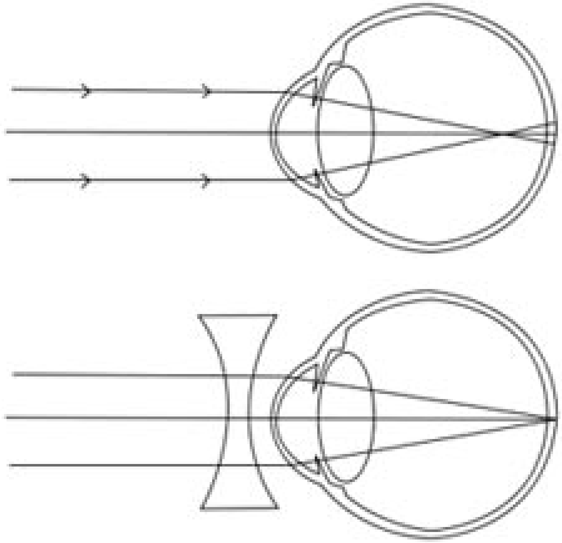


Line spread function (LSF) of two lines with varying amounts of blur. With increasing blur, the discrimination of the two lines is lost.

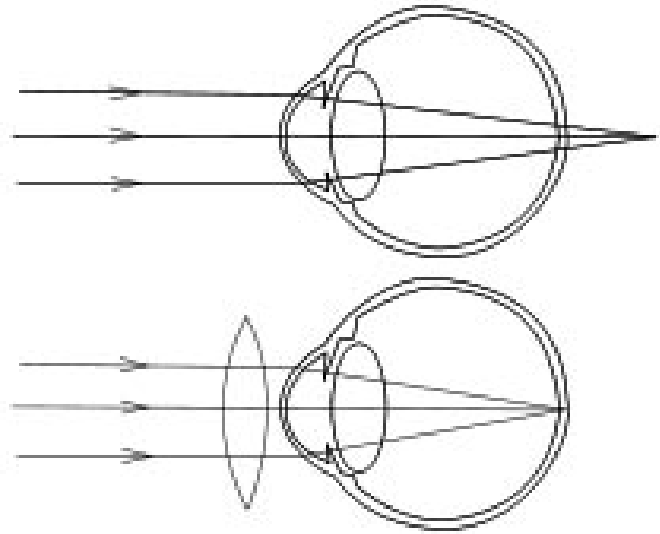
From Webvision, Michael Kalloniatis

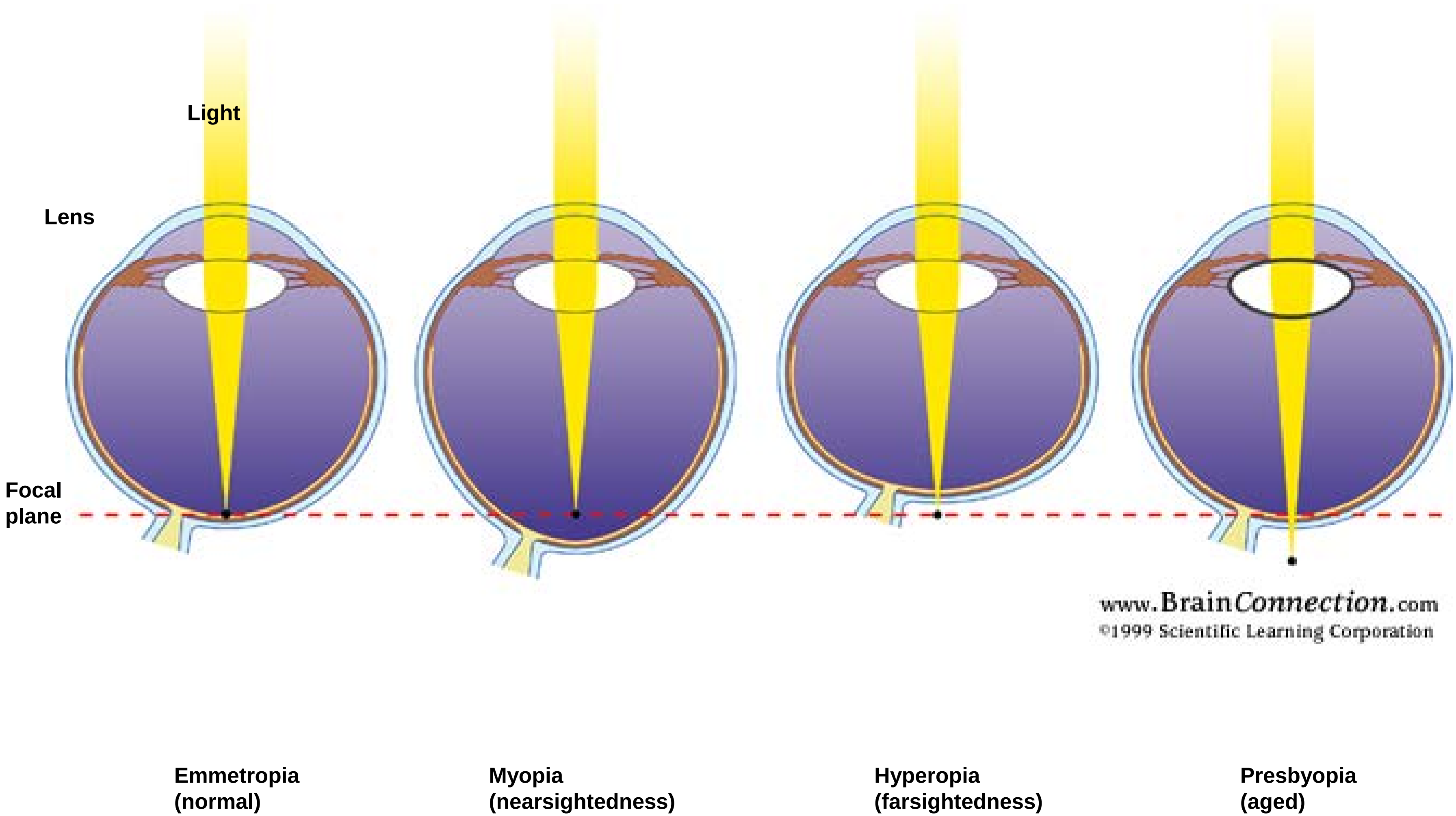
Corrective lenses

Myopia

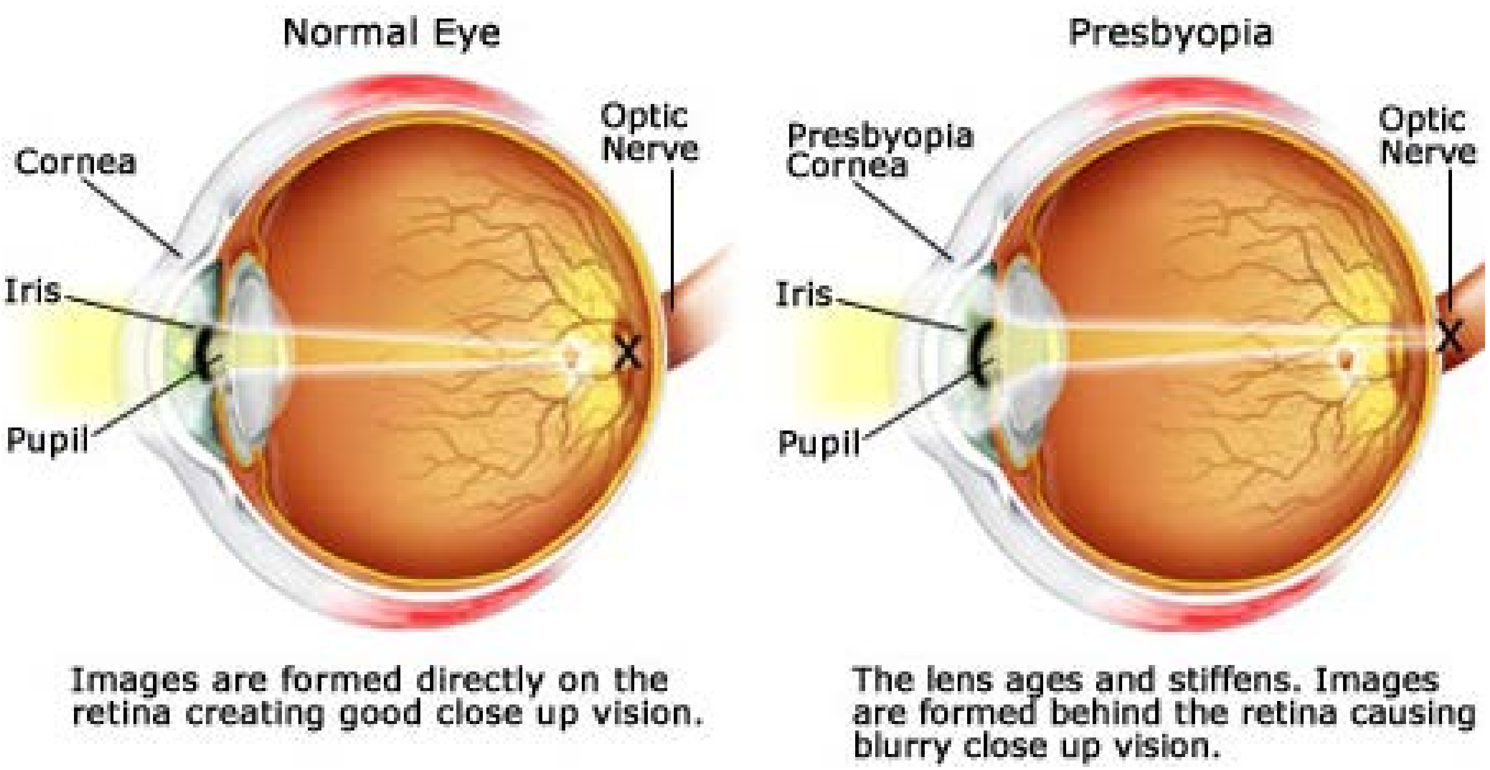


Hyperopia



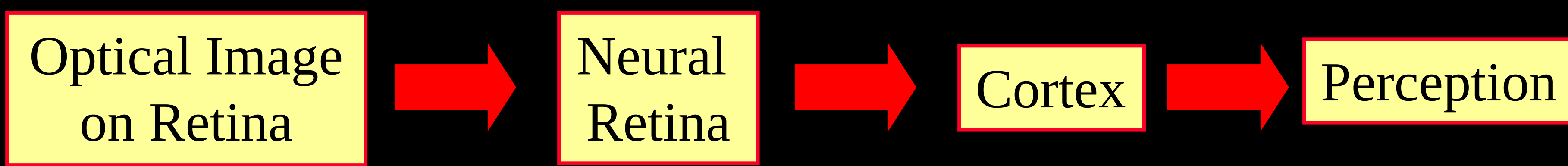

Light
Lens
Focal plane
www.BrainConnection.com
©1999 Scientific Learning Corporation
Emmetropia (normal)
Myopia (nearsightedness)
Hyperopia (farsightedness)
Presbyopia (aged)

Presbyopia (age related far-sightedness)

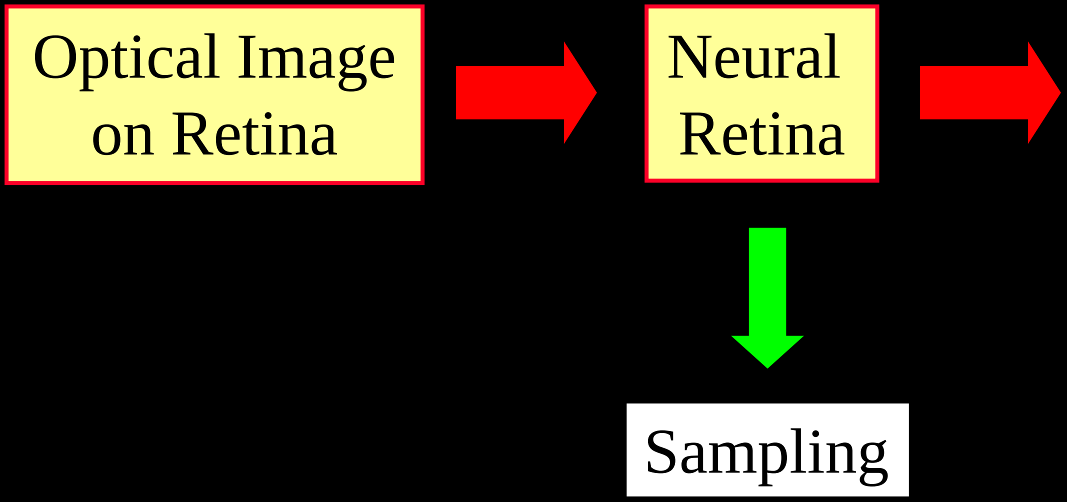


What else limits visual performance?

Stages



Stages



Retinal sampling

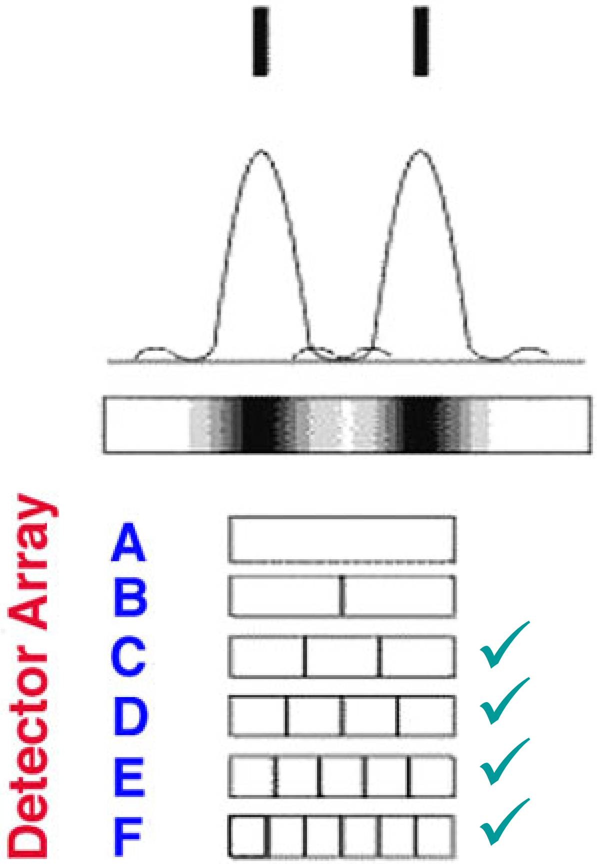
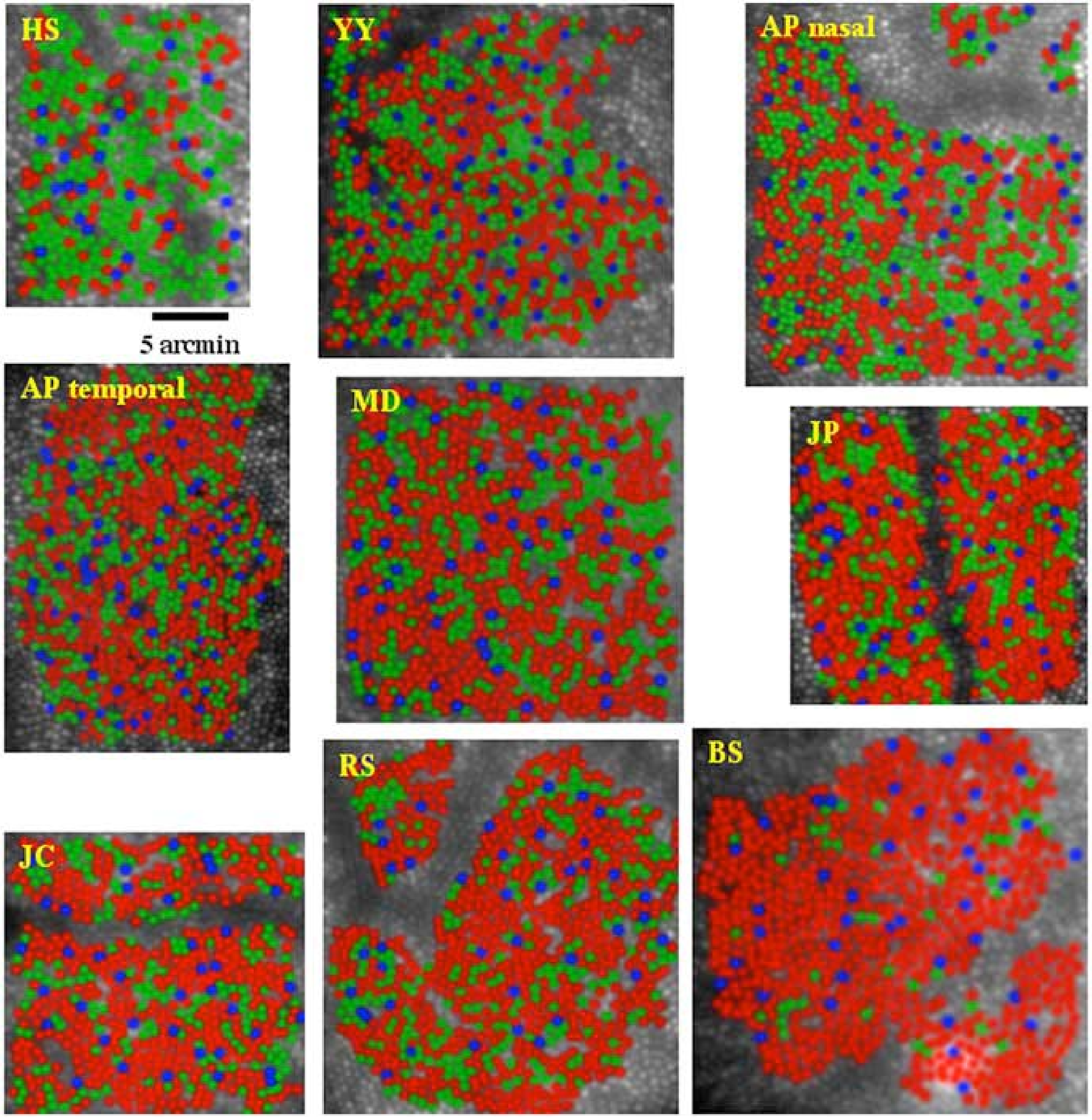


Figure 13. Two lines with their line spread function, person's perception of the two lines and various detector arrays. Only detector arrays C (3 detectors) through to F (6 detectors) have a fine enough detector density to resolve the two lines, i.e. detect the gap. Detector array A or B, that have one and two detectors, respectively, cannot signal a yes-no-yes response.

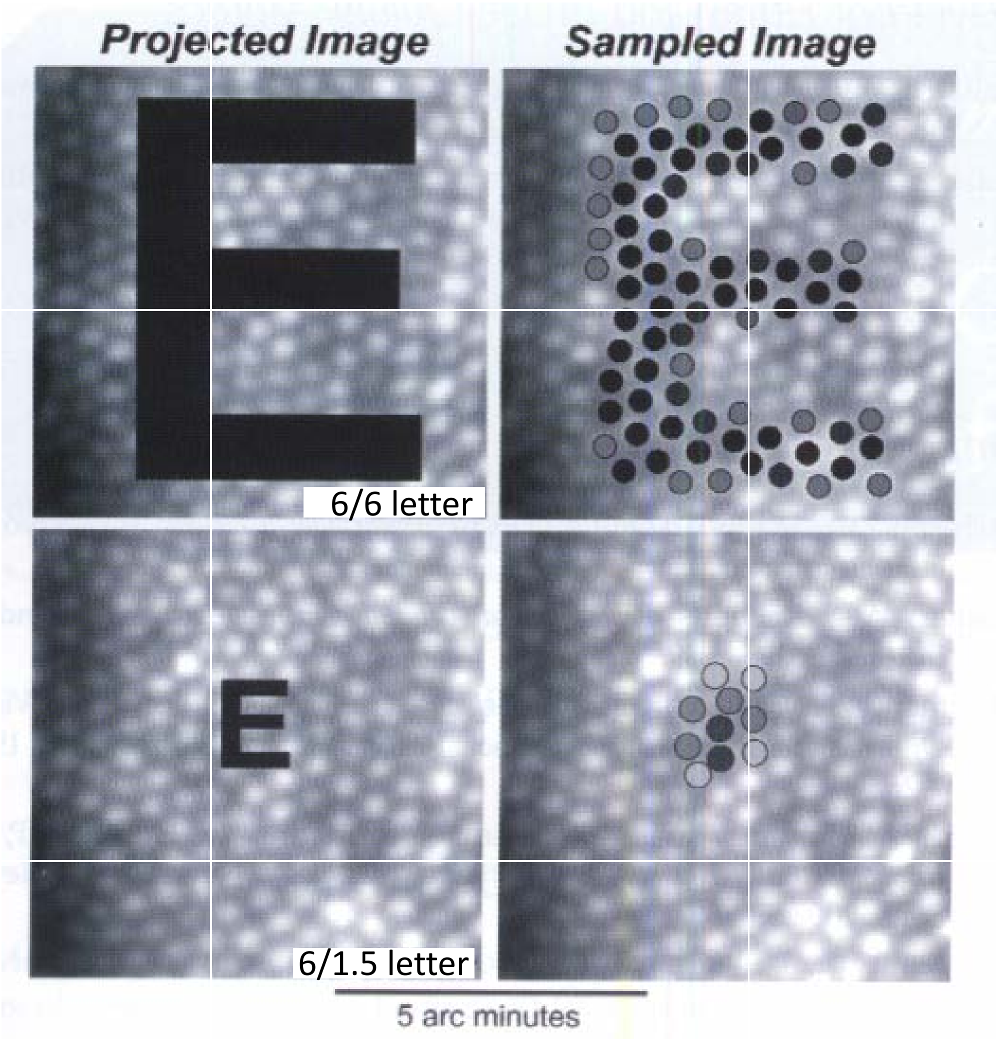
From Webvision, Michael Kalloniatis



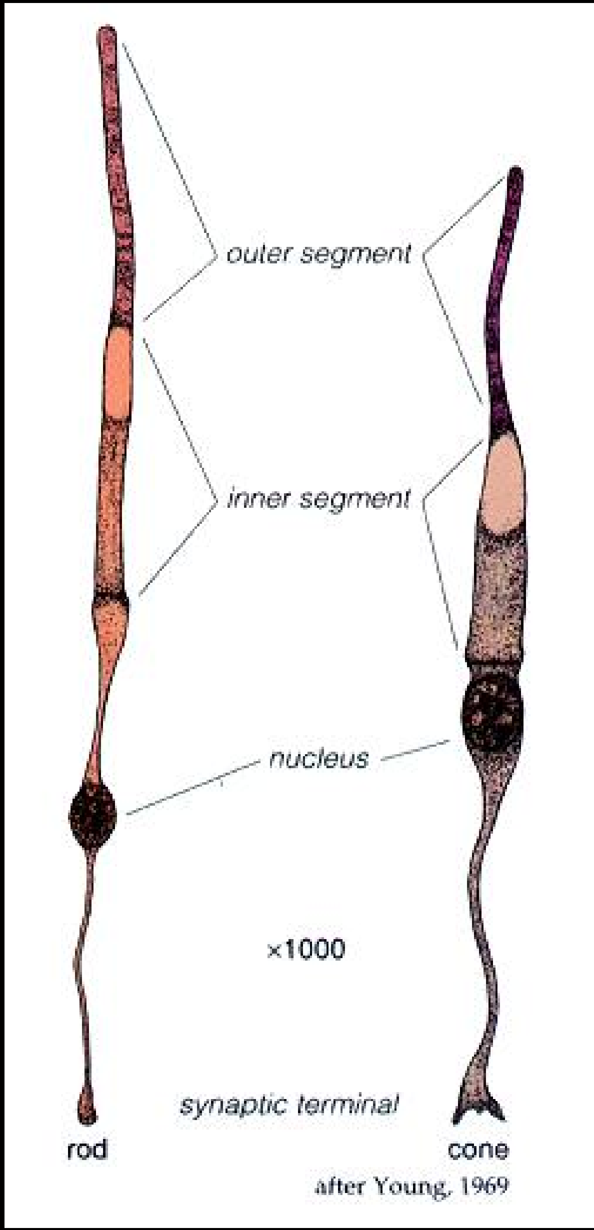
False color images showing the arrangement of L (red), M (green), and S (blue) cones in the retinas of different human subjects. All images are shown to the same scale.

Hofer et al., 2005

Impact of sampling on letter visual acuity: Notice that the foveal sampling is perfectly adequate to represent a 6/6 (20/20) letter, but inadequate to represent a 6/1.5 (20/5) letter.



Austin Roorda, 2004



Human photoreceptors

- <u>Rods</u>
  - Achromatic night vision
  - 1 type

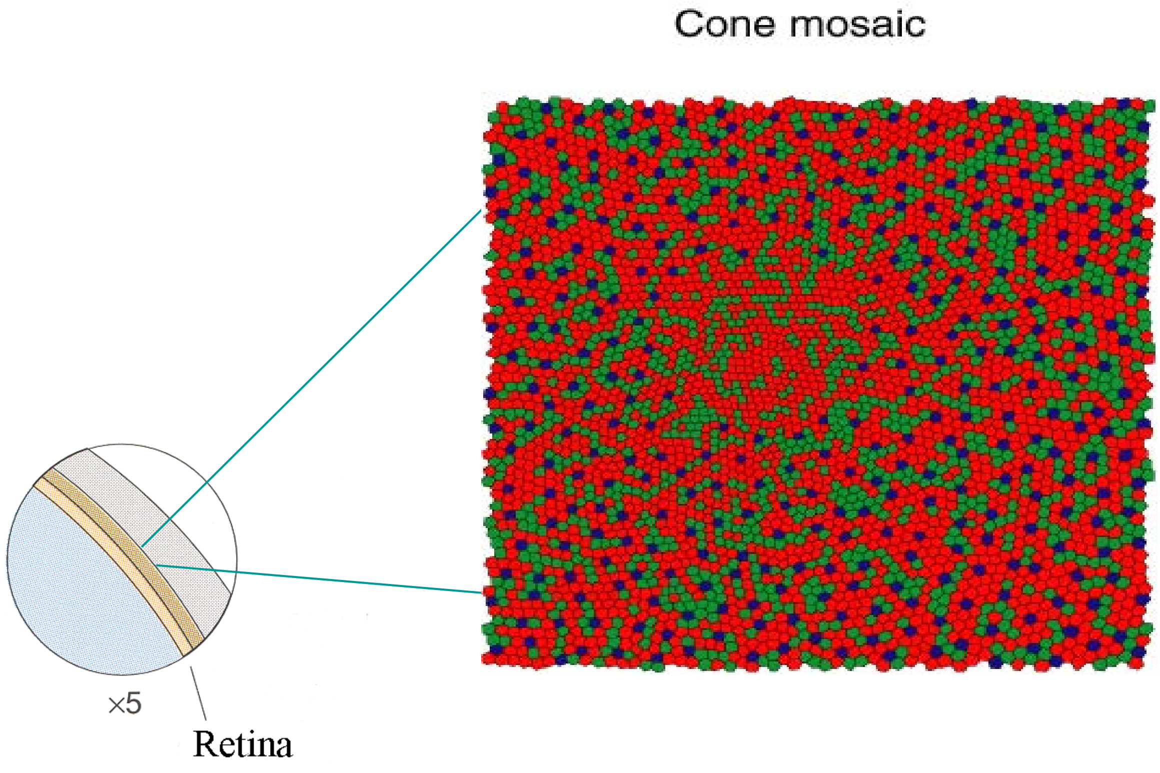
Rod

- <u>Cones</u>
  - Daytime, achromatic *and* chromatic vision
  - 3 types

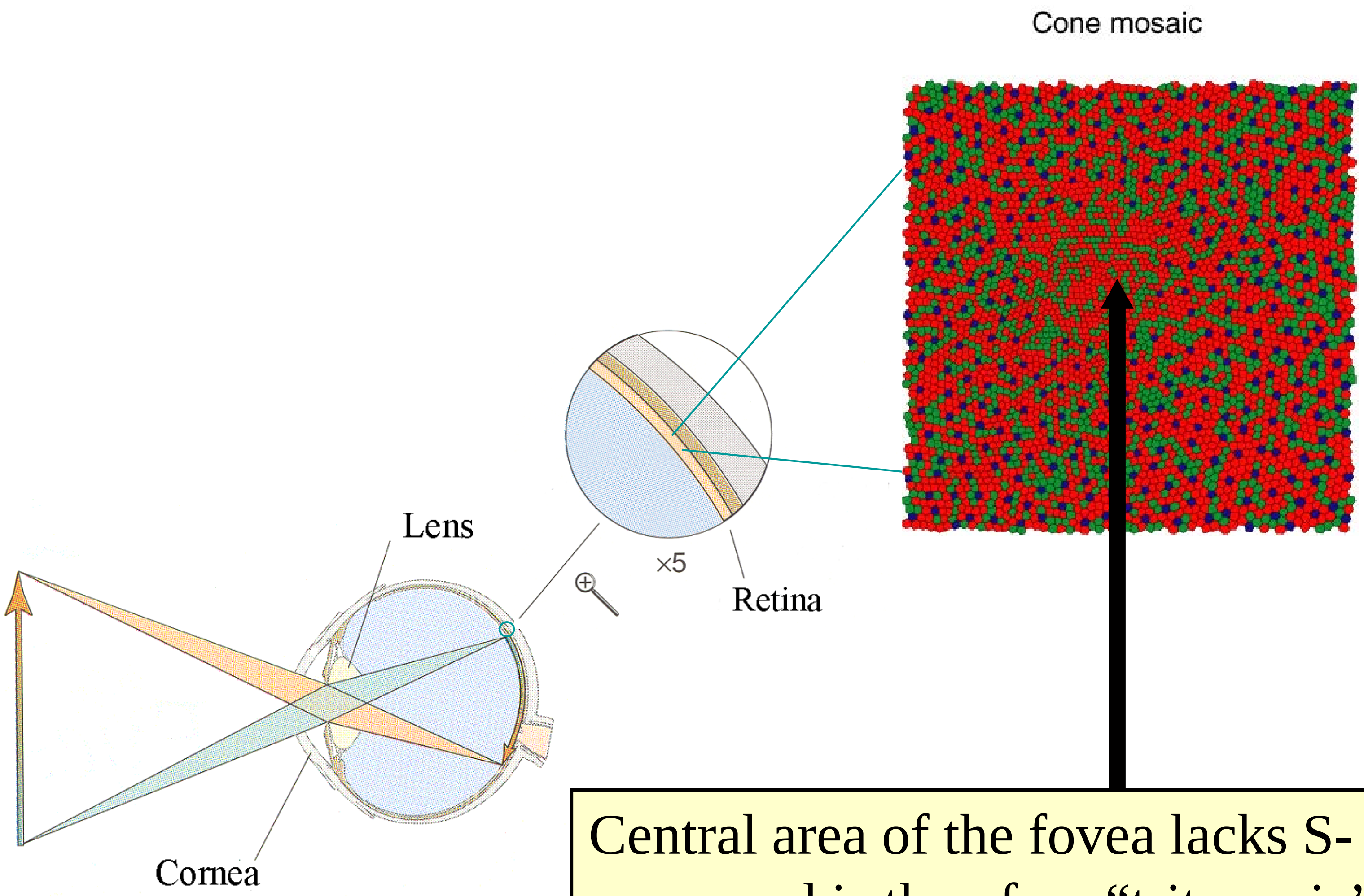
Long-wavelength-sensitive (L) or “red” cone

Middle-wavelength-sensitive (M) or “green” cone

Short-wavelength-sensitive (S) or “blue” cone

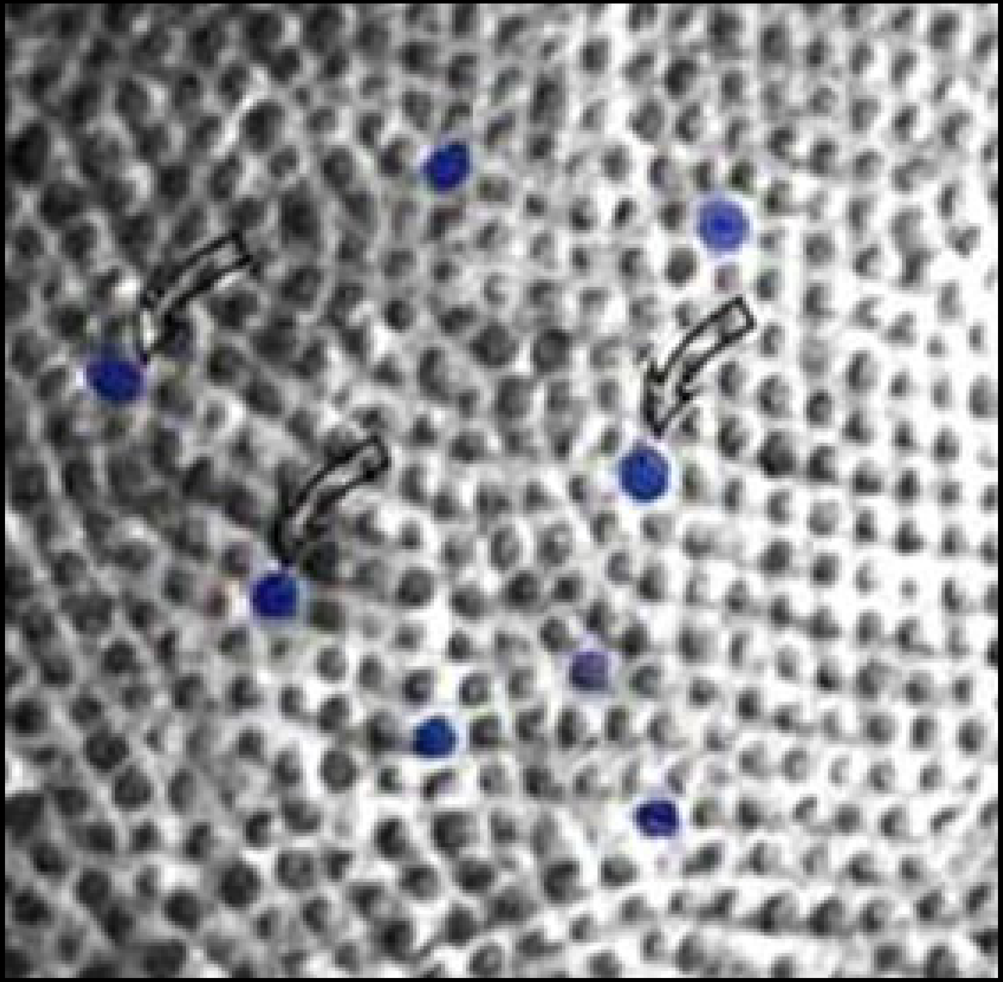


Central fovea is rod-free, and the very central foveola is rod- and S-cone free



Central area of the fovea lacks S-cones and is therefore "tritanopic".

In other retinal regions, the S-cone mosaic remains sparse.

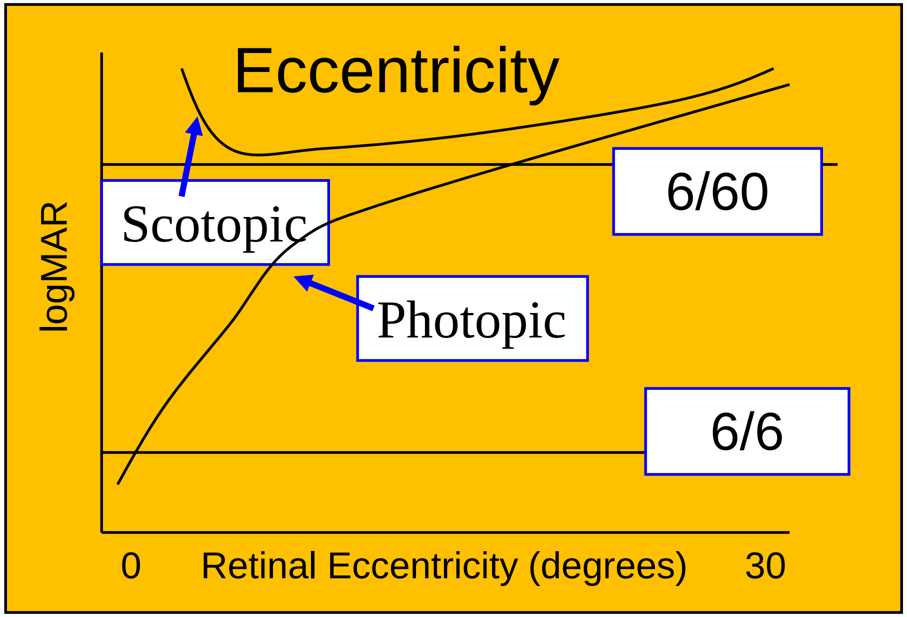


S-cones form between 5 and 10% of the cone population.

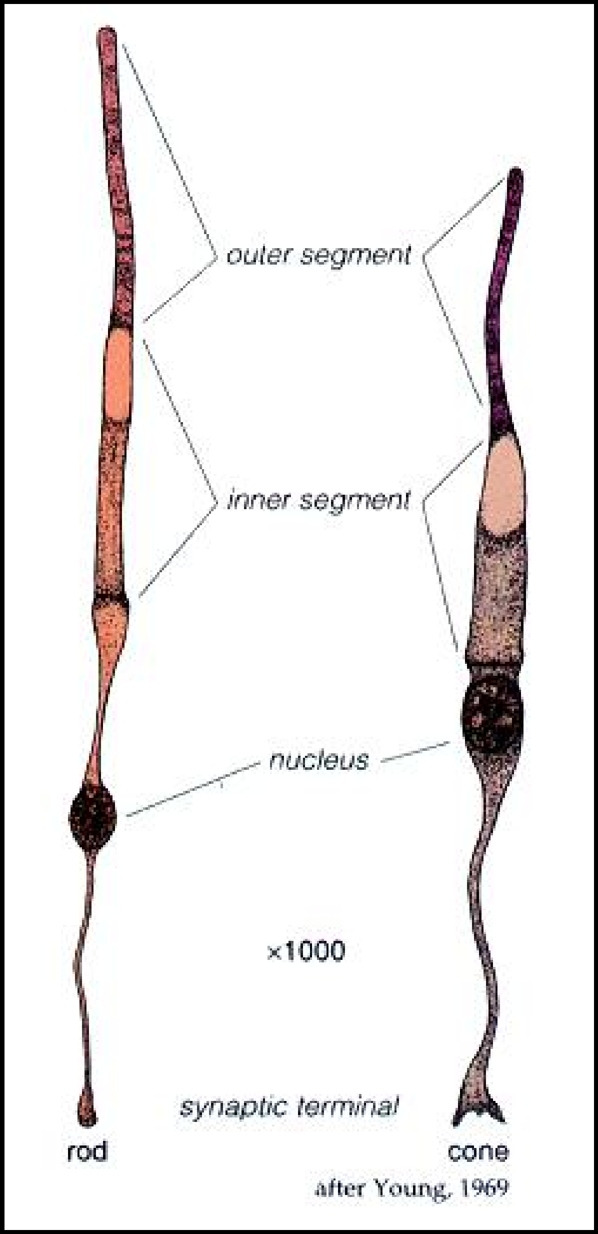
Curcio et al.

Small field tritanopia

Changes with eccentricity



Arthur Bradley



Human photoreceptors

- Rods
  - Achromatic night vision
  - 1 type

Rod

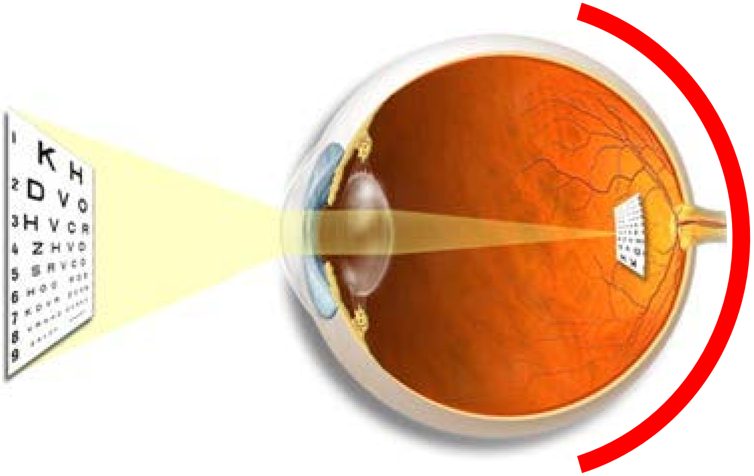
- Cones
  - Daytime, achromatic *and* chromatic vision
  - 3 types

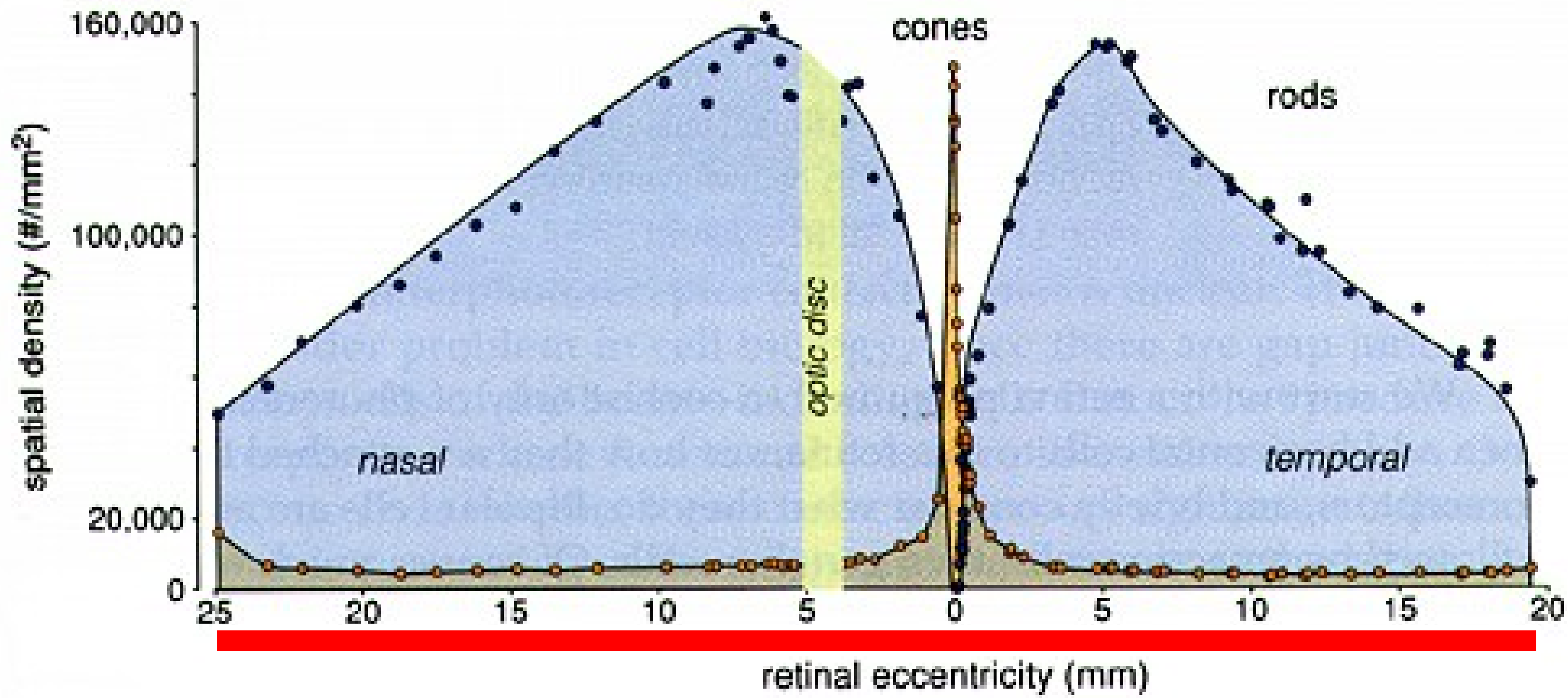
Long-wavelength-sensitive (L) or "red" cone

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

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

Rod and cone distribution

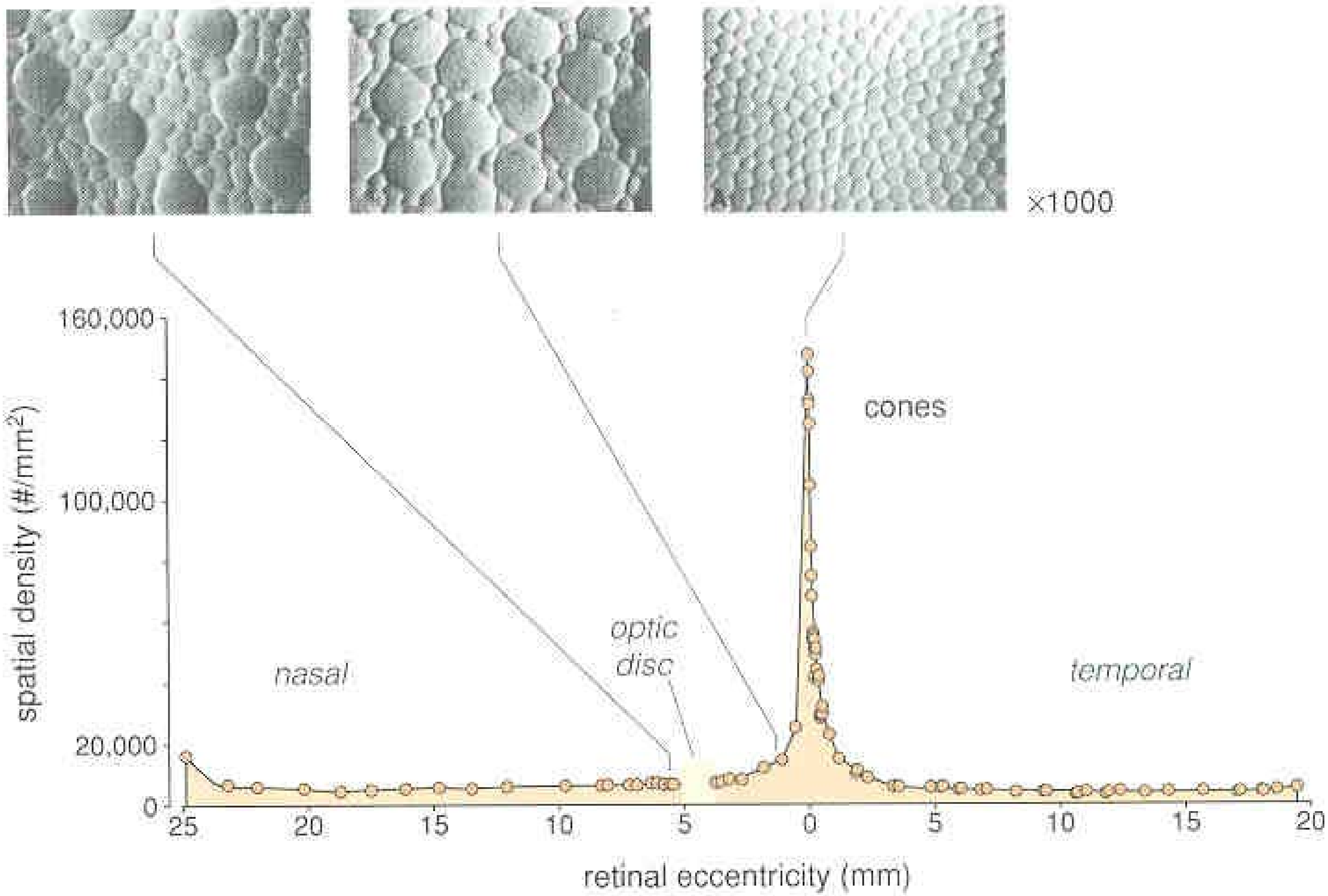




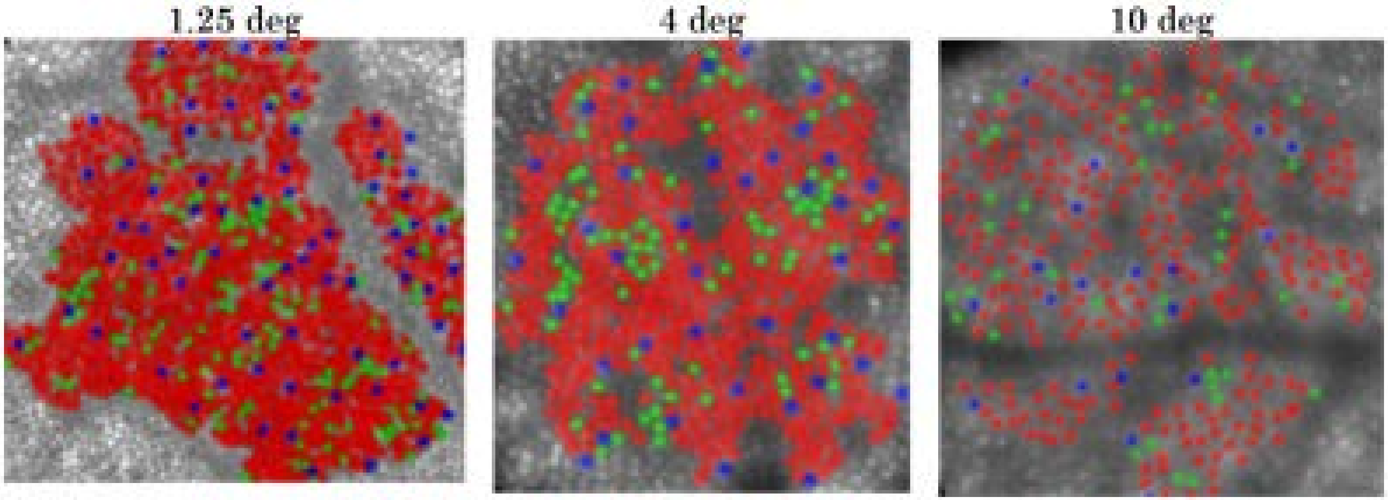
after Østerberg, 1935; as modified by Rodieck, 1988

0.3 mm of eccentricity is about 1 deg of visual angle

Cone distribution and photoreceptor mosaics



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



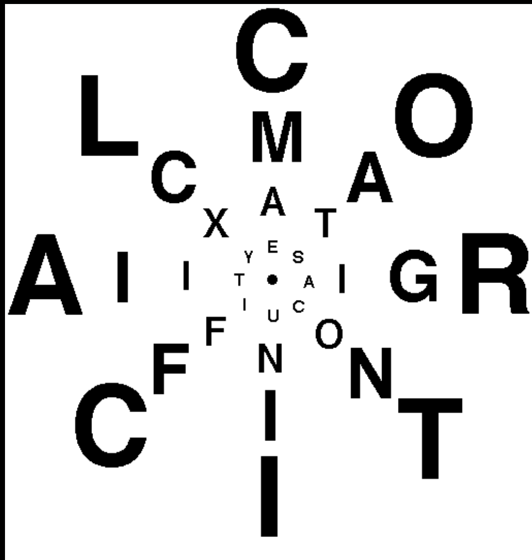
Primate retina

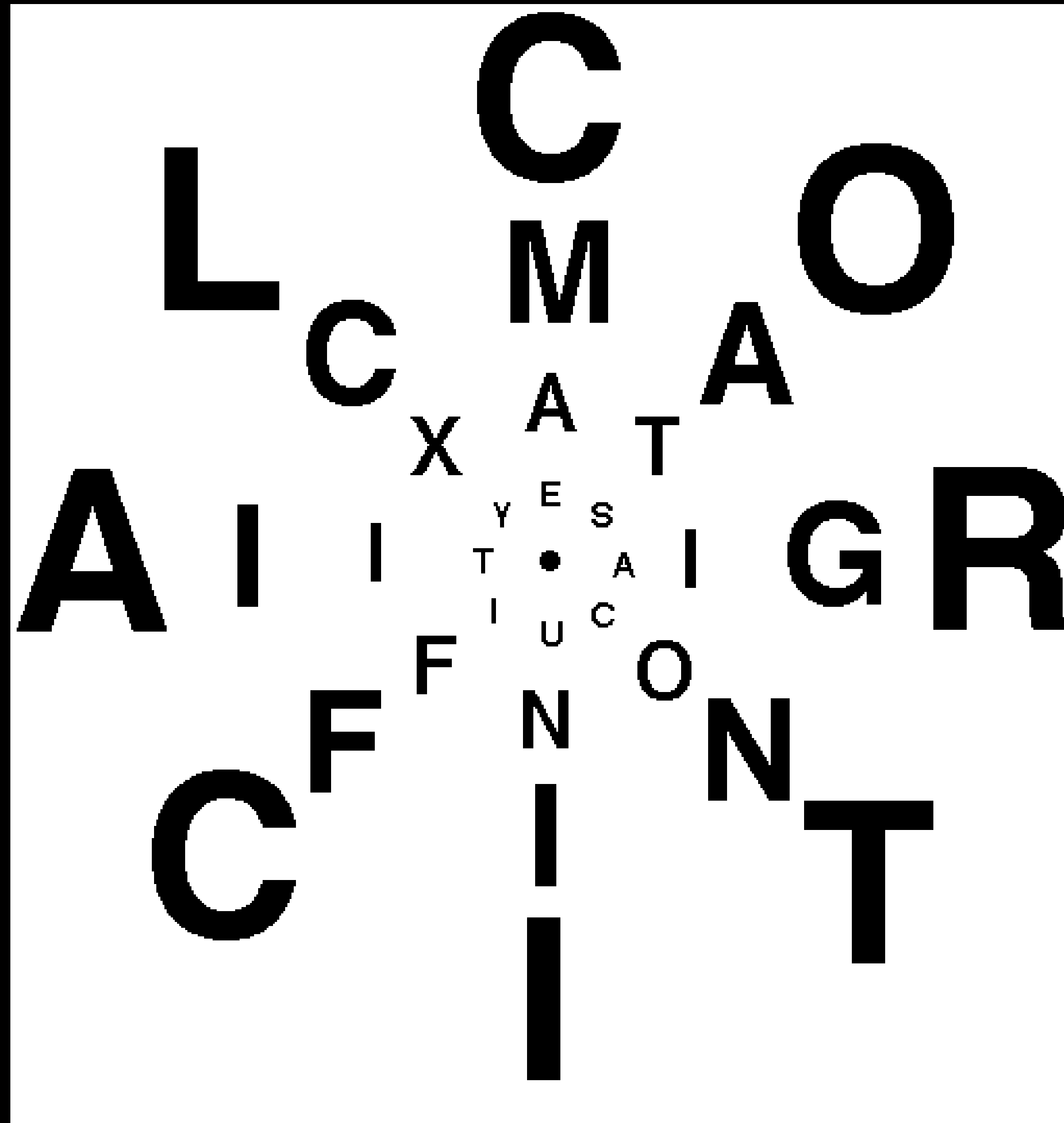
Roorda et al., 2001

The human visual system is a foveating system

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

Credit: Stuart Anstis, UCSD

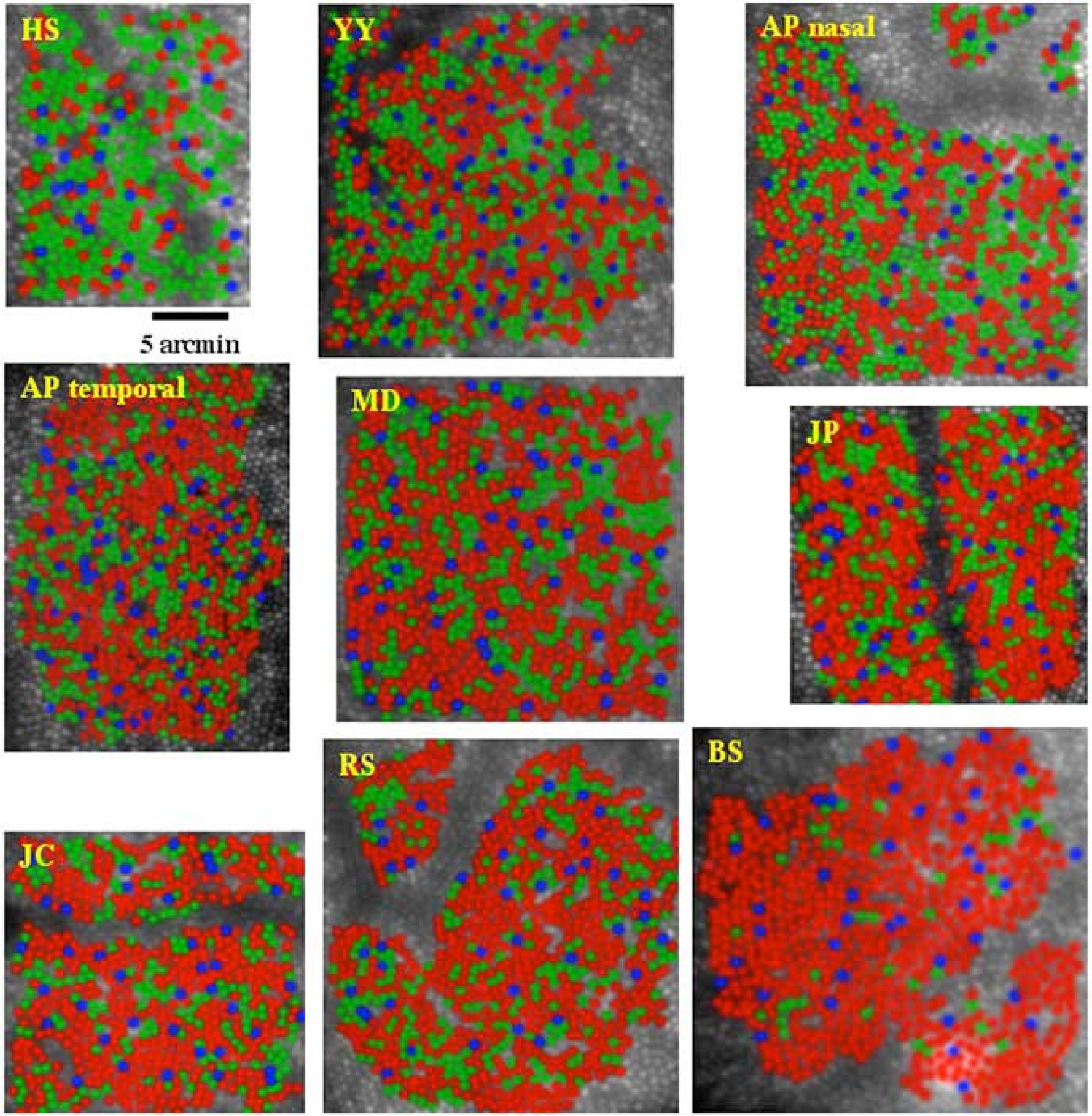




Visual acuity gets much poorer with eccentricity

Credit: Stuart Anstis, UCSD

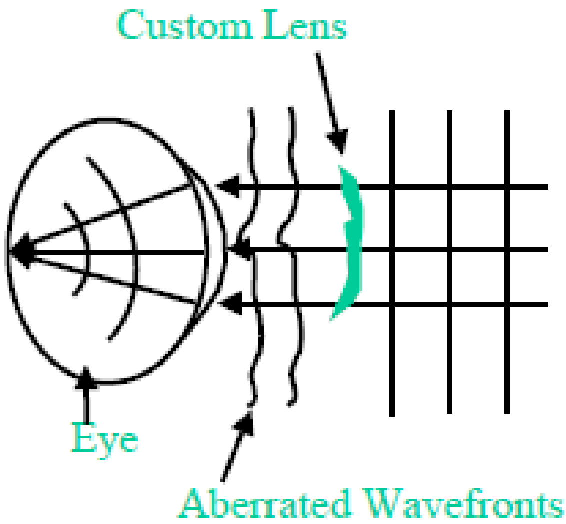
Adaptive optics: viewing the retina through the eye's optics



False color images showing the arrangement of L (red), M (green), and S (blue) cones in the retinas of different human subjects. All images are shown to the same scale.

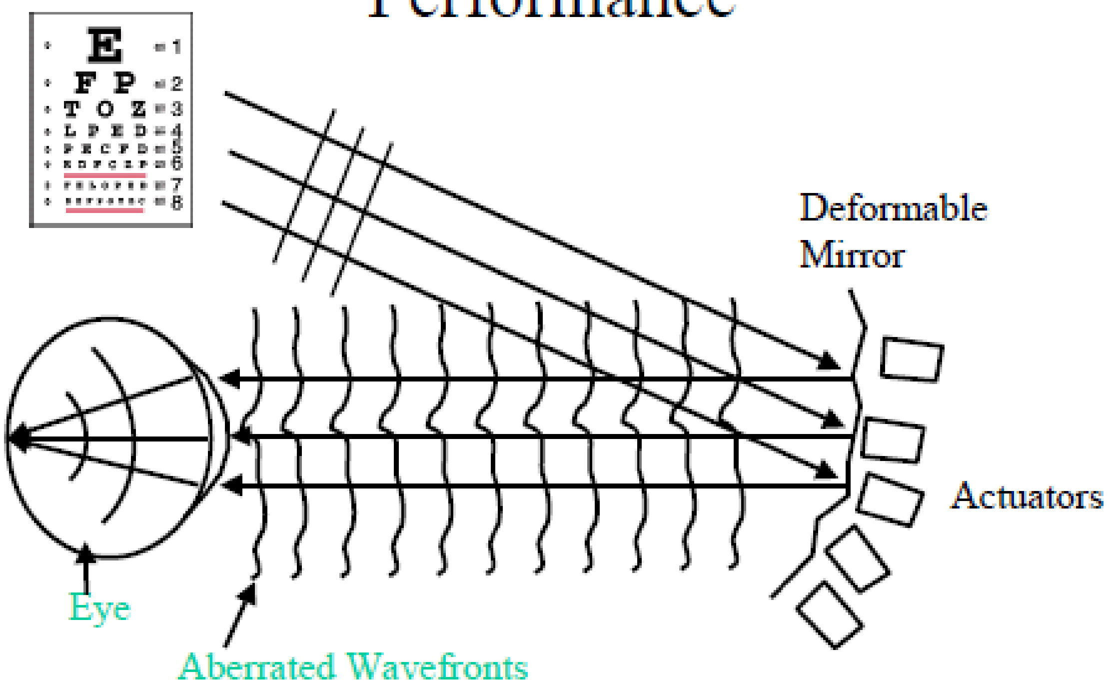
Hofer et al., 2005

Diffraction-Limited Eye

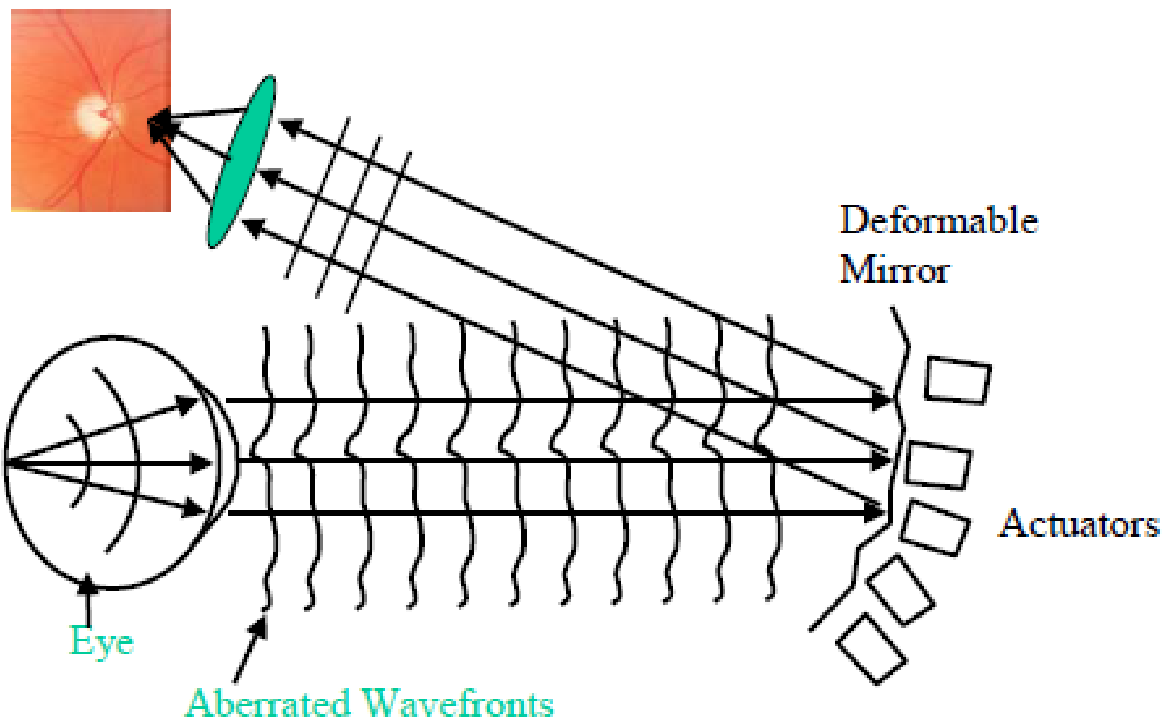


Knowledge of the aberration of the eye allows us to calculate a custom lens, which will compensate for the aberrations of the eye and form a diffraction-limited image on the retina. The results are improved visual acuity and contrast sensitivity.

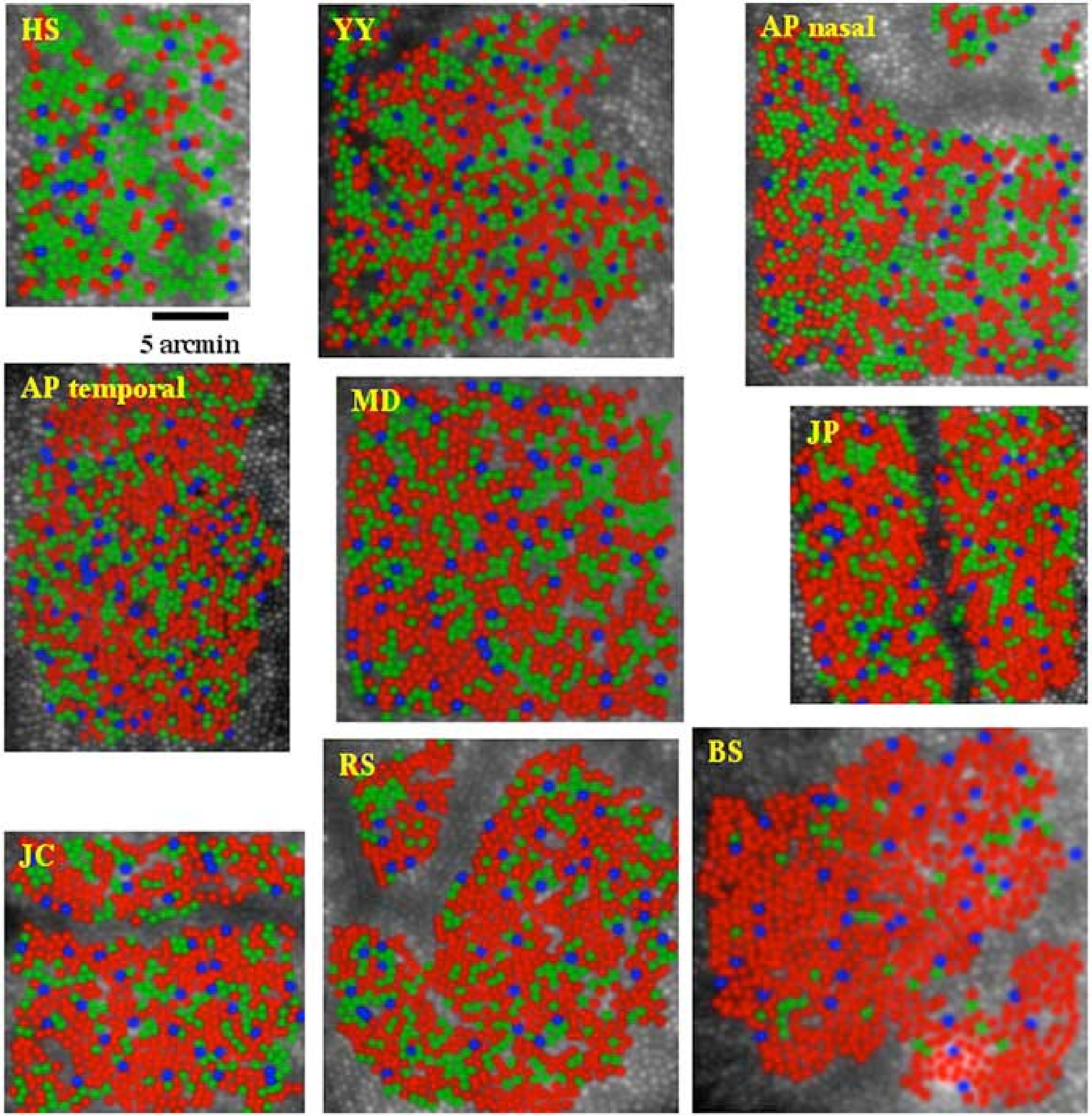
Improvements to Visual Performance



Improvements to Retinal Imaging

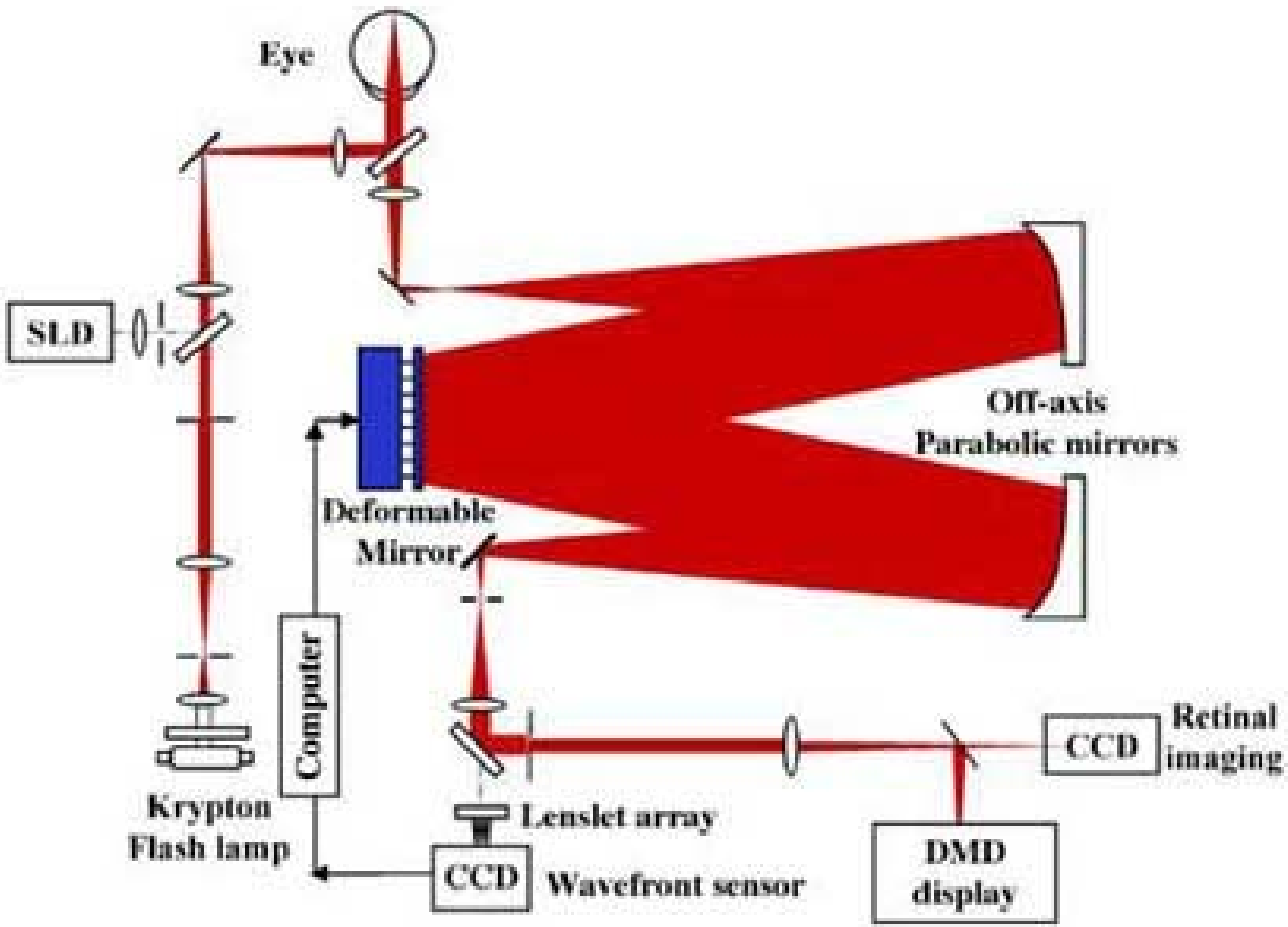


Jim Schwiegerling

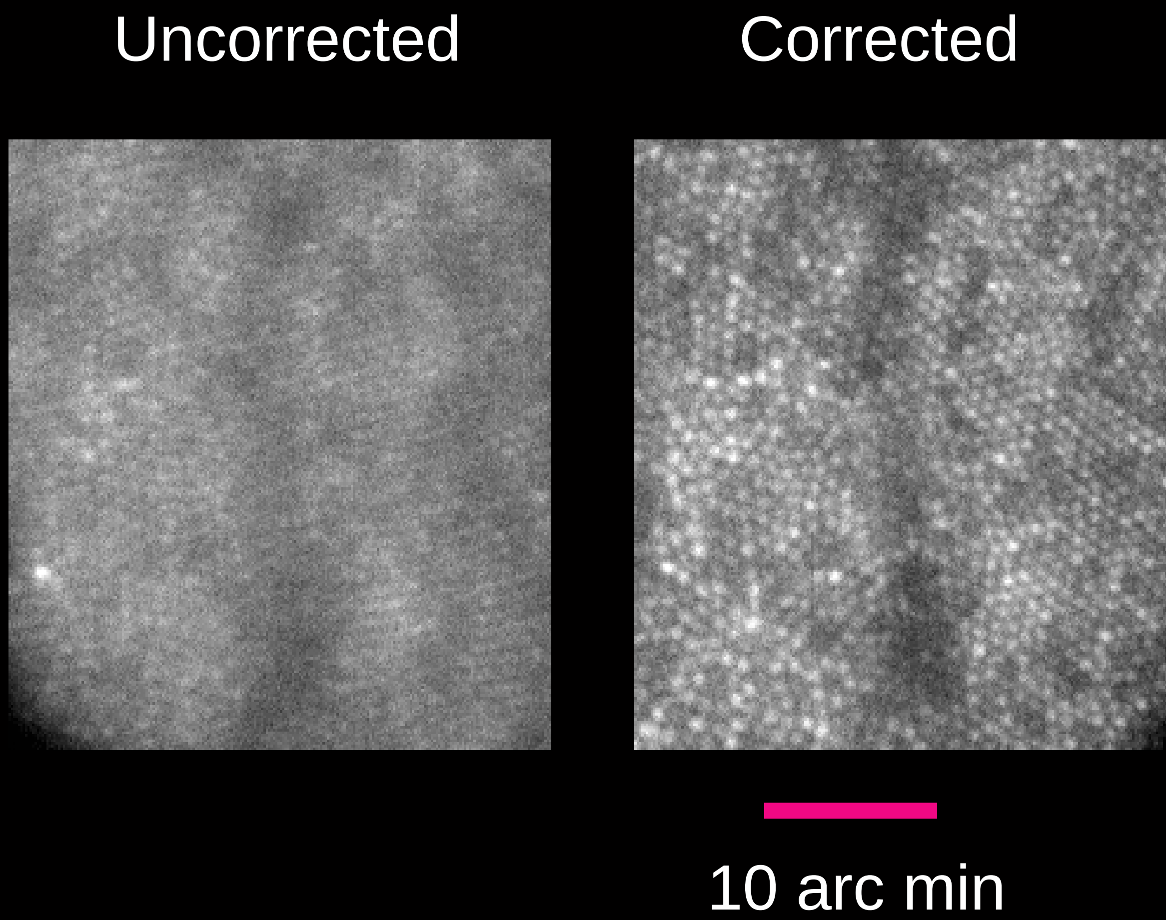


False color images showing the arrangement of L (red), M (green), and S (blue) cones in the retinas of different human subjects. All images are shown to the same scale.

Hofer et al., 2005



David Williams

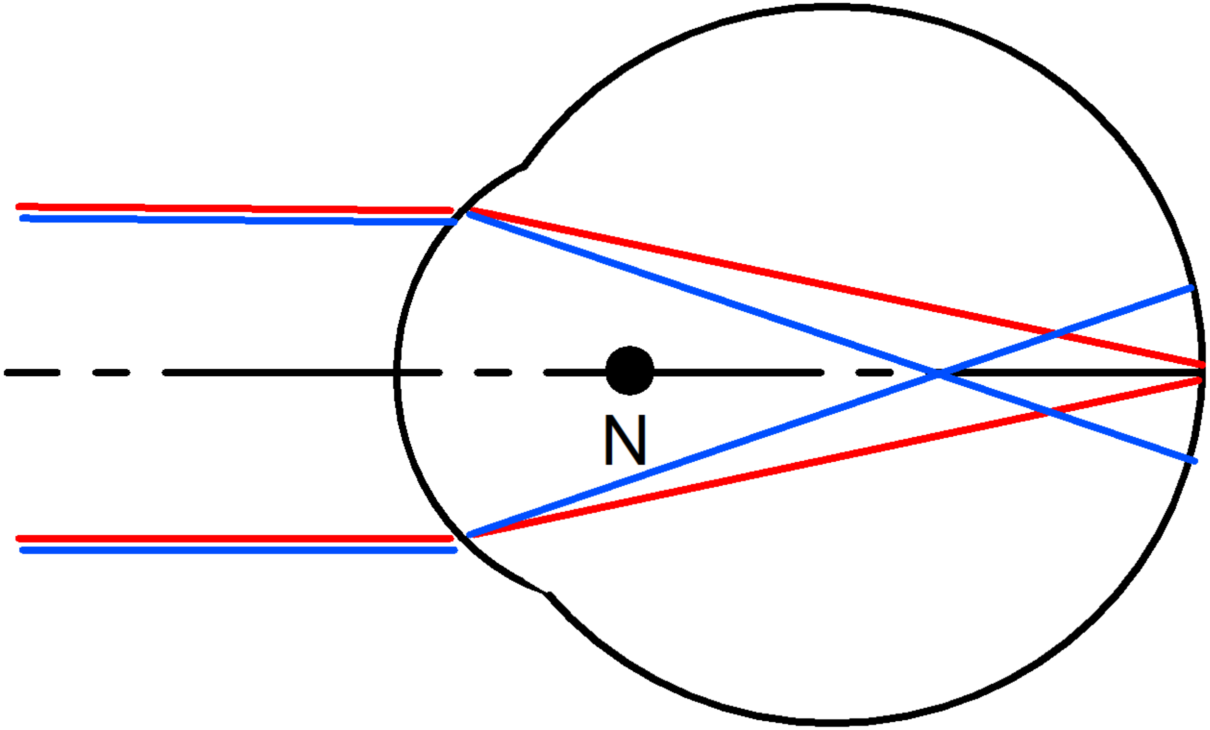


Photos courtesy of A. Roorda, D. Williams, U. Rochester

Chromatic aberrations

Chromatic aberration

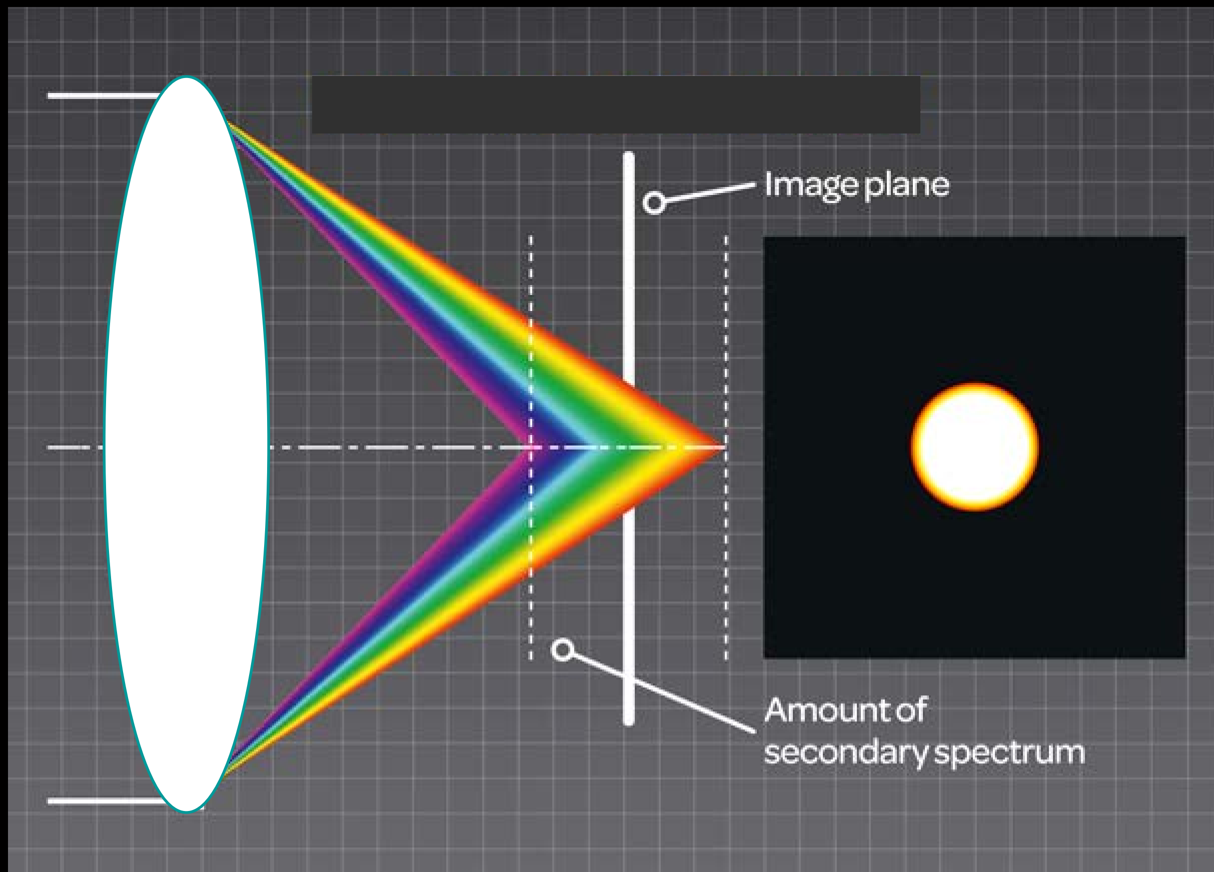
The focusing power of the eye varies with wavelength.



This phenomenon is called longitudinal (or axial) chromatic aberration (LCA)

Larry Thibos

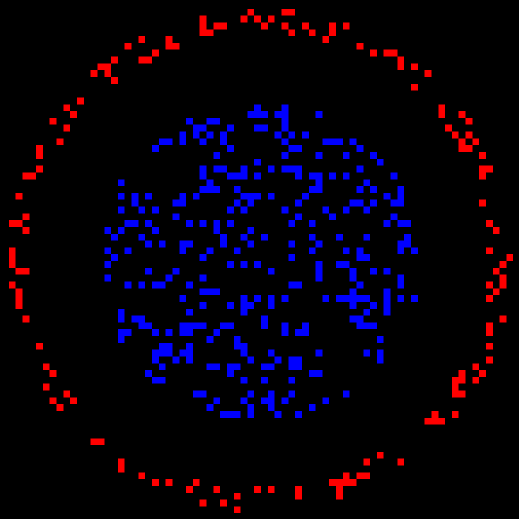
Chromatic aberration



Base picture: Digital camera world

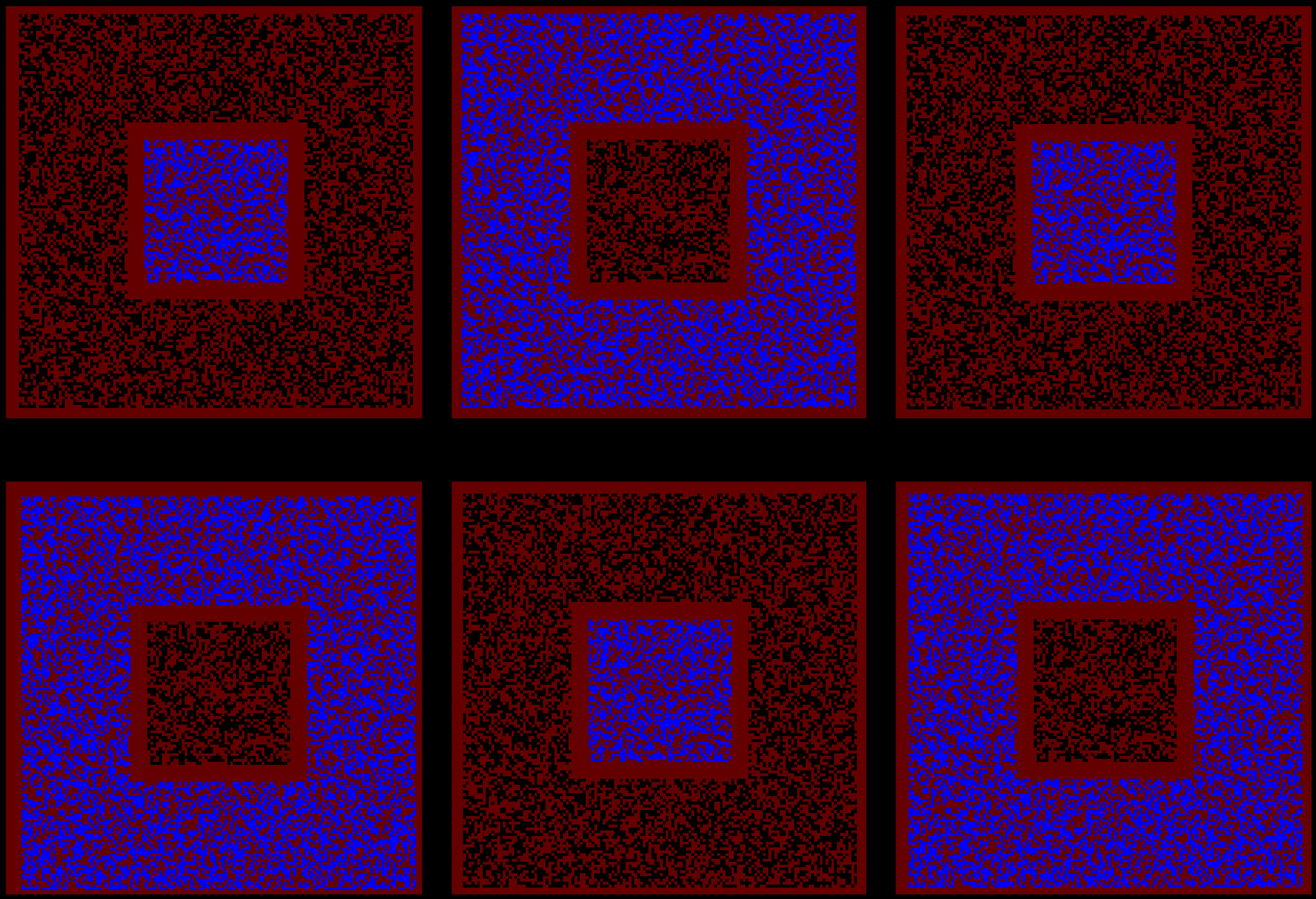
Effect of chromatic blur on eye chart

Jim Schwiegerling



Akitaoka Kitaoka

Chromostereoscopic windows



Akitaoka Kitaoka

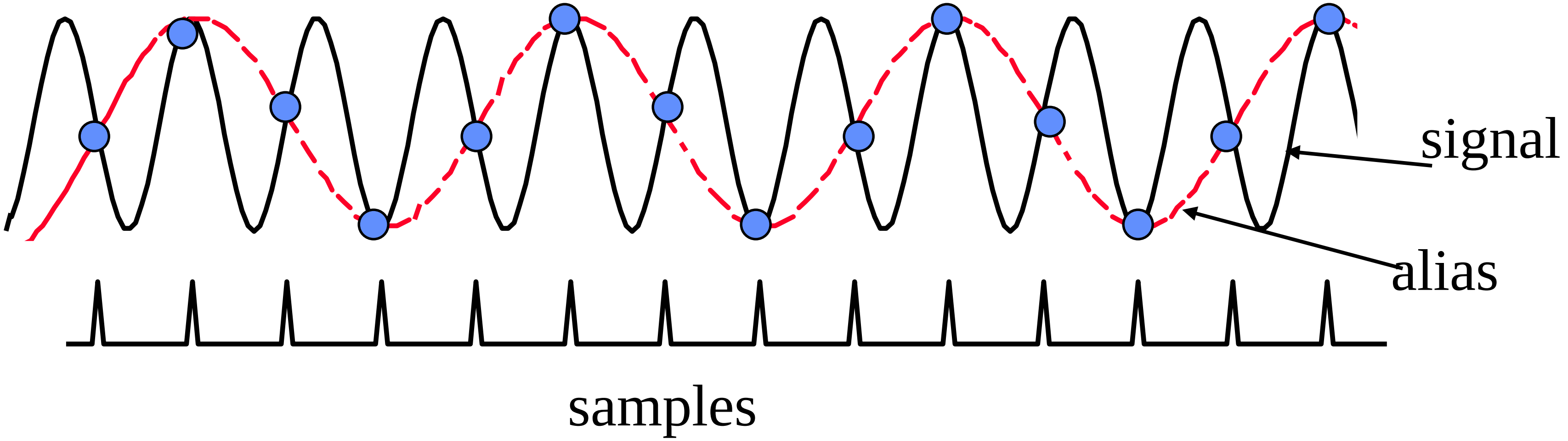
EXTRA SLIDES (not presented)

Why visual acuity should be limited by the optics and sampling

Undersampling and Aliases

Repetitive Grating Stimulus

If there are **less than 2 samples per period** of a repetitive signal, it will be **undersampled** by the array, and the resulting output will be indistinguishable from a lower frequency signal.

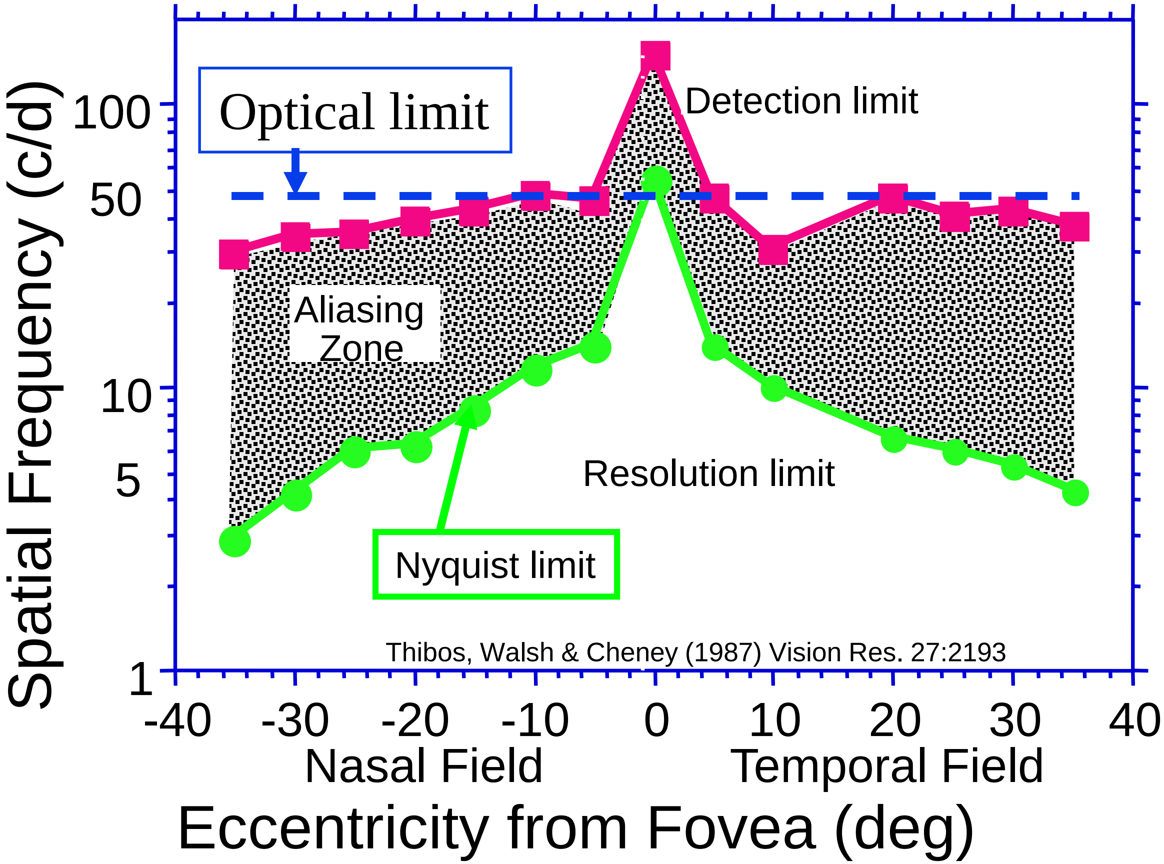


For resolution: sample separation(s) must be <= period/2.

For human fovea: cones separated by 1/2 arc minute, thus minimum resolvable period is 1 minute, or 60 c/deg. Above 60 c/deg, see aliases if these high frequencies existed in retinal image.

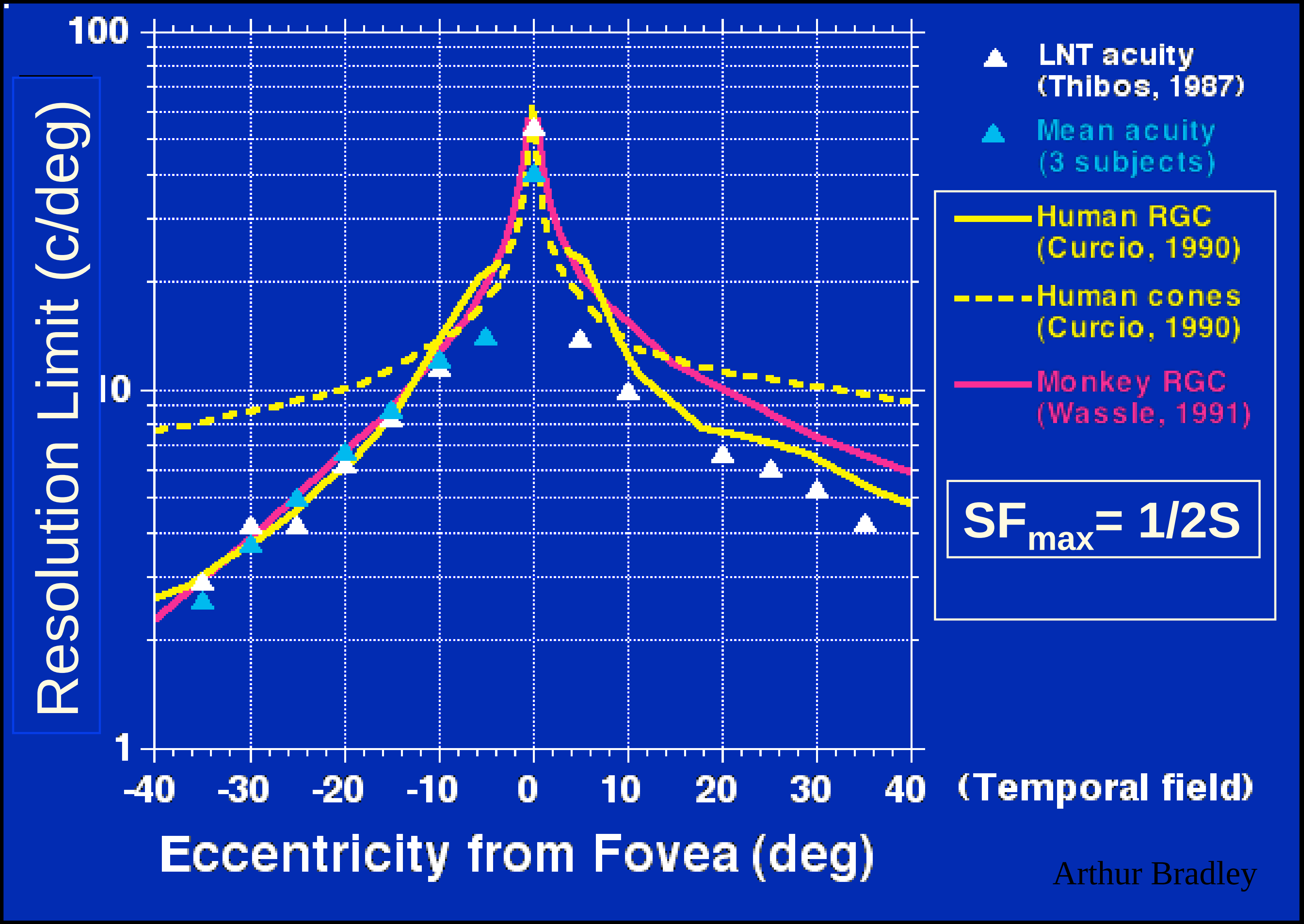
Arthur Bradley

The eye’s optics filters out all SF above Nyquist limit in fovea, since foveal nyquist (60 c/deg) is slightly higher than optical cut-off (about 50 c/deg). This is not so in the peripheral retina where the optical cut-off is higher than the nyquist limit, thus aliases can be seen.

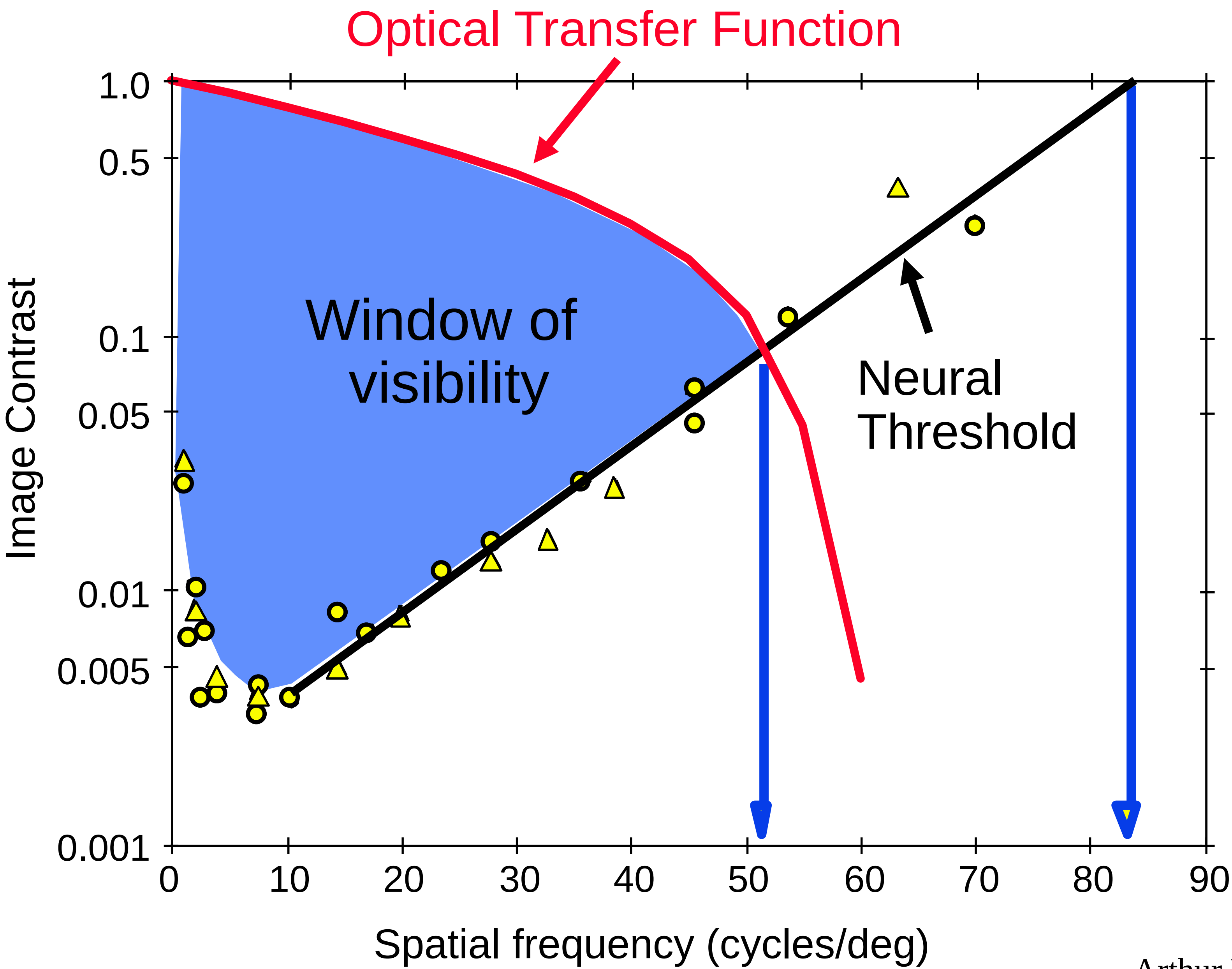


Arthur Bradley

Human peripheral resolution acuity matches RGC sampling density predictions



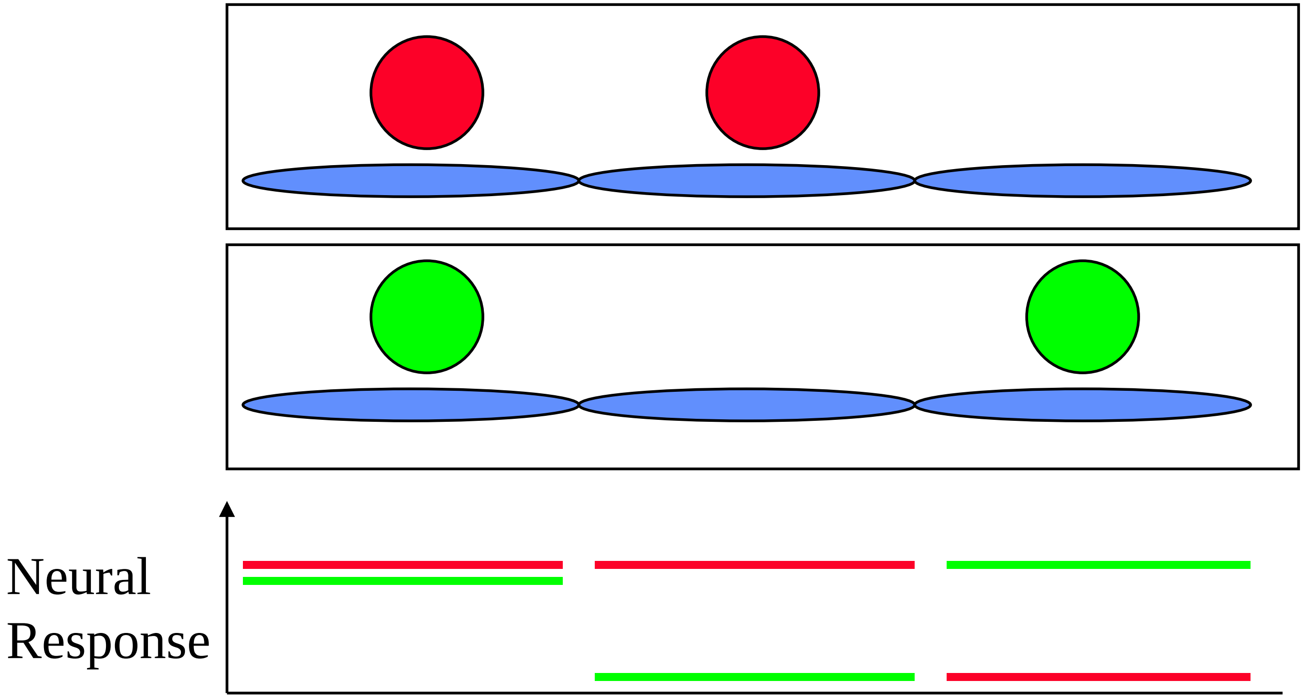
Foveal VA and CS are both limited by optical and neural factors



Arthur Bradley

Impact of sampling on spatial resolution: Helmholtz

Two point Resolution:



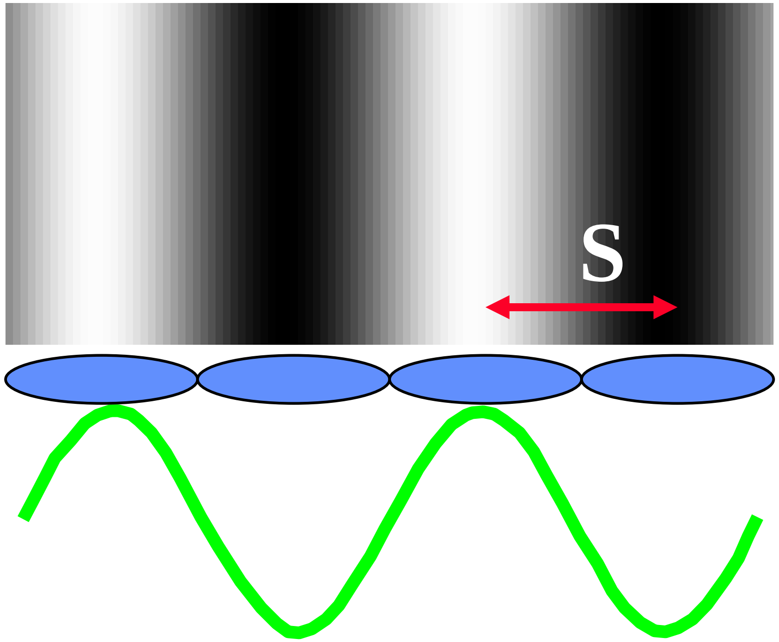
Must have sample between images of two points in order to know that there is a gap between the stimuli and thus be able to identify two points as two.

Arthur Bradley

Sampling and periodic patterns.

Shannon's sampling theorem: basically same idea as Helmholtz (need one sample between each line)

Notice that, at limit of just one sample between each bright line of grating, there will be exactly 2 samples per period of the grating.

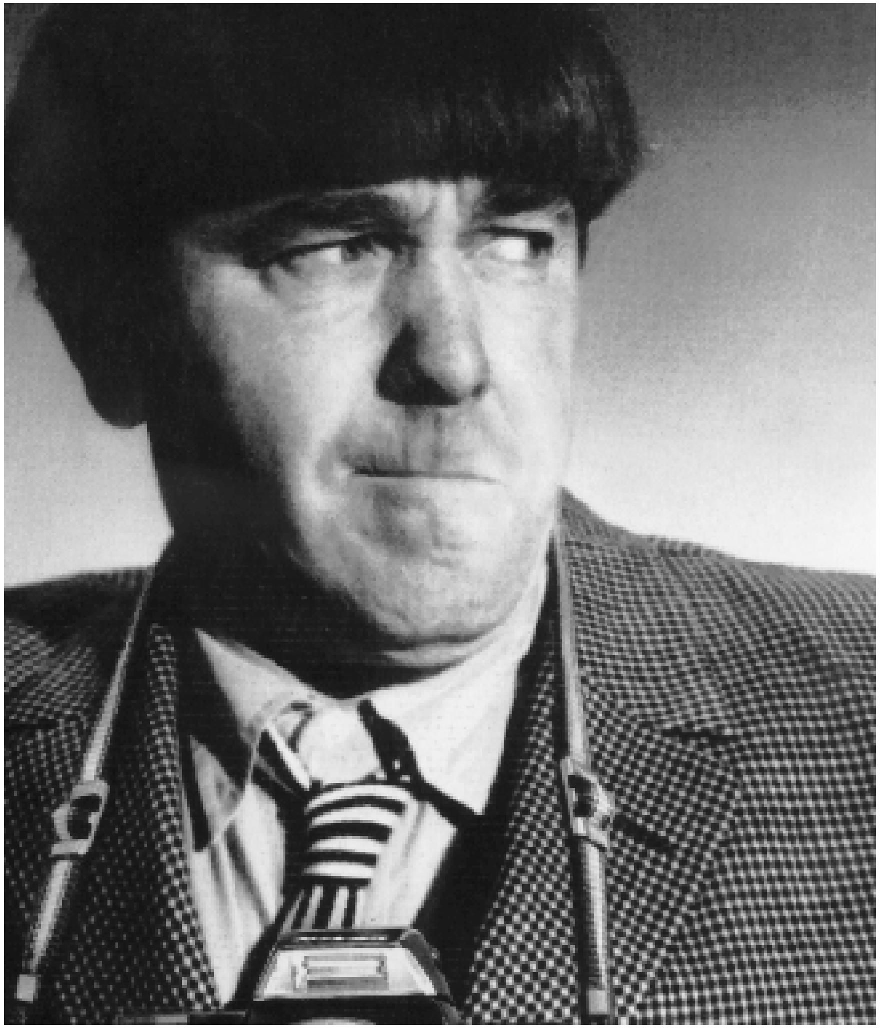


In order to resolve a periodic pattern there must be at least 2 samples per period. Therefore, if we know the spacing between samples, we know the maximum resolvable spatial frequency = f_{max} = 1/(2s), where s = separation between samples.

Arthur Bradley

Miscellaneous

What limits resolution acuity?



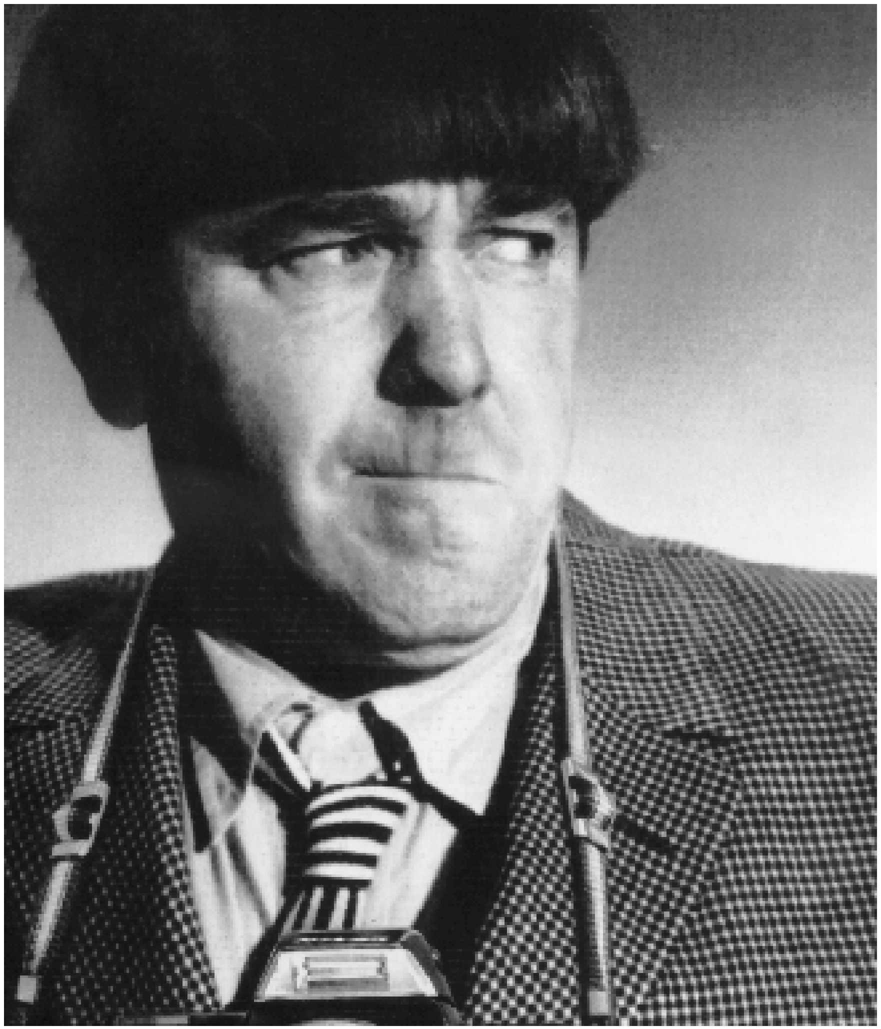
Two candidate mechanisms:

- filtering (optical or neural)
- undersampling

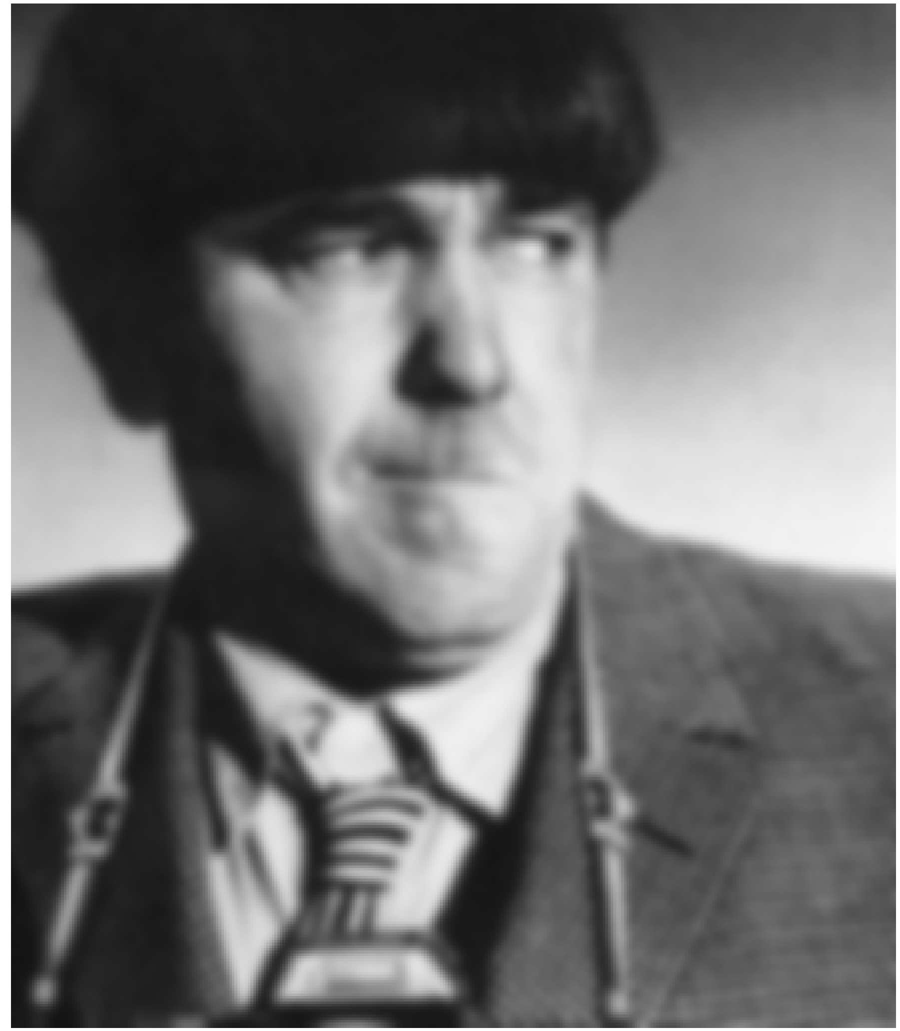
Arthur Bradley

Filtering Limit to Visual Resolution

Original



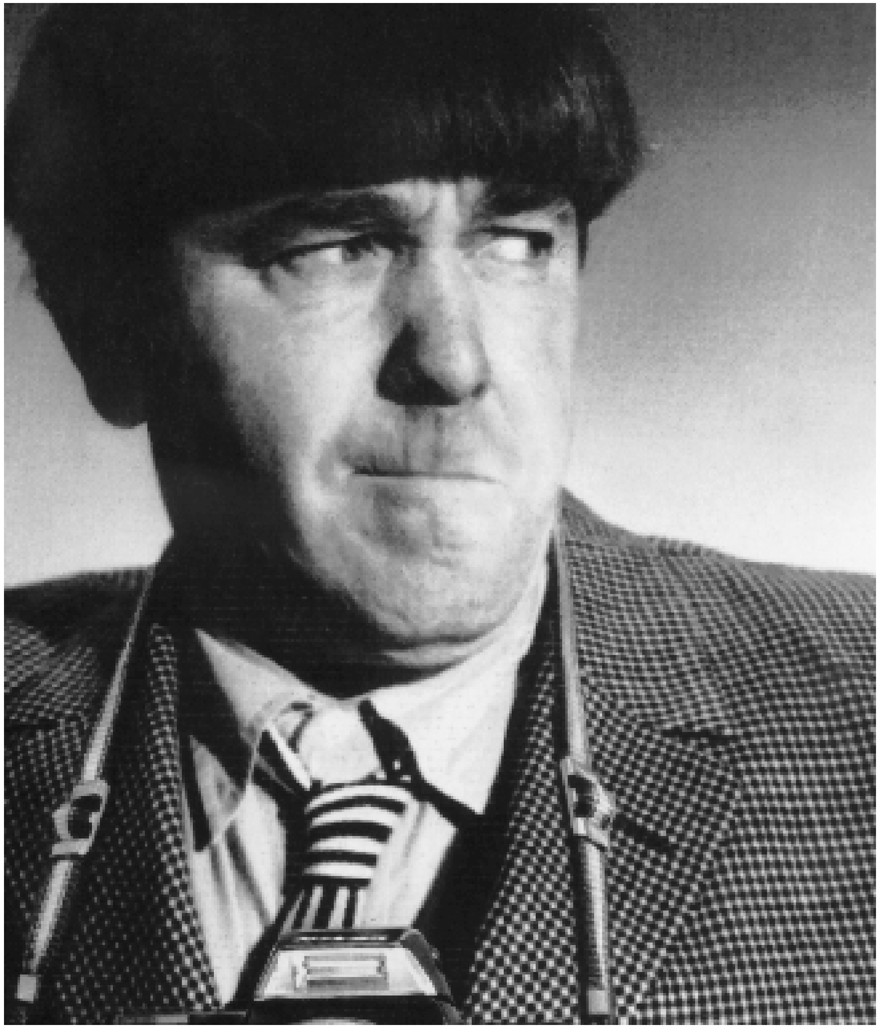
Low-pass Filtered



Arthur Bradley

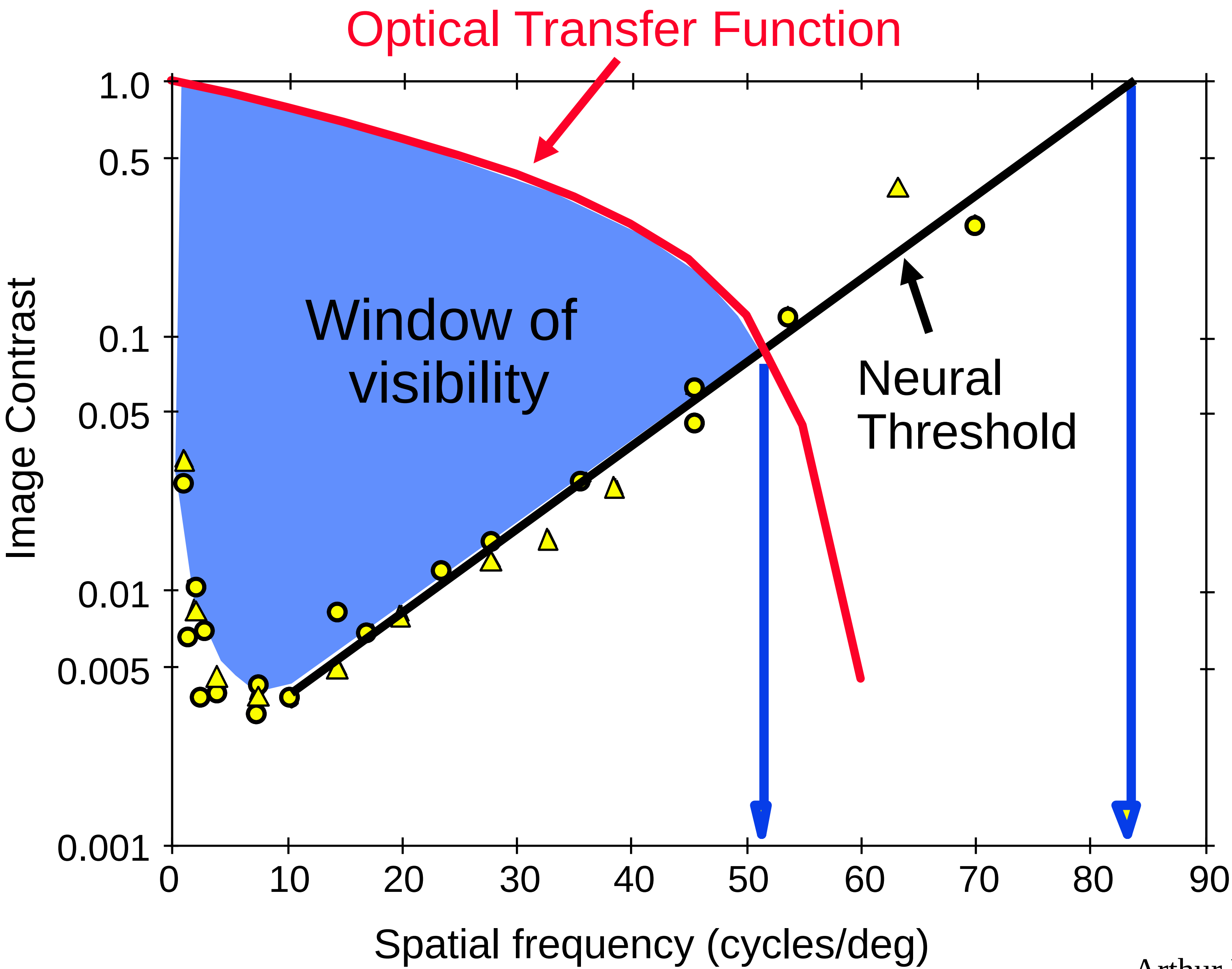
Sampling Limit to Visual Resolution

Original



Undersampled

Foveal VA and CS are both limited by optical and neural factors



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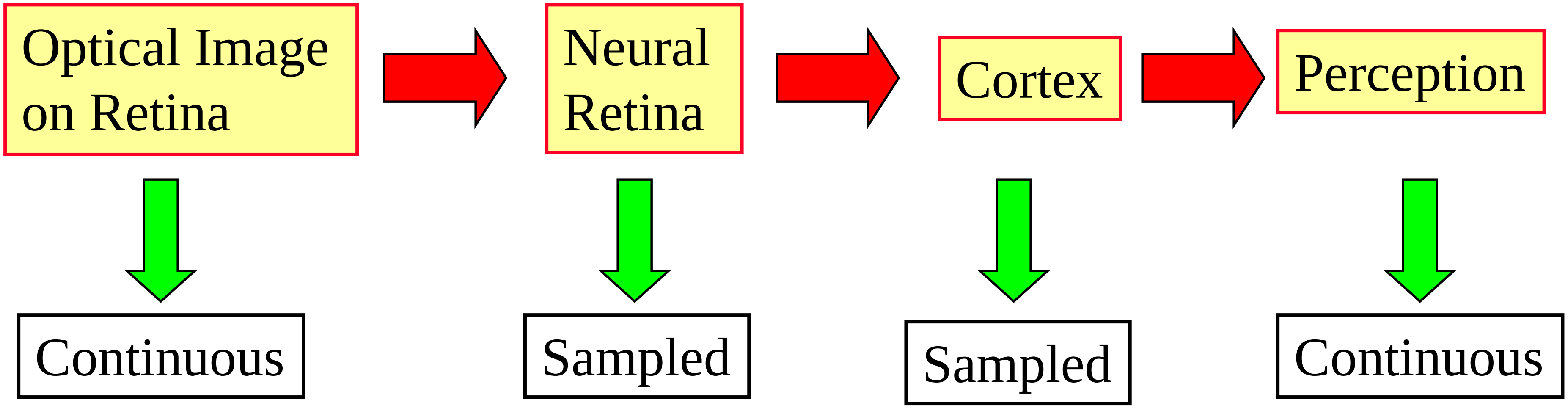
Neural sampling



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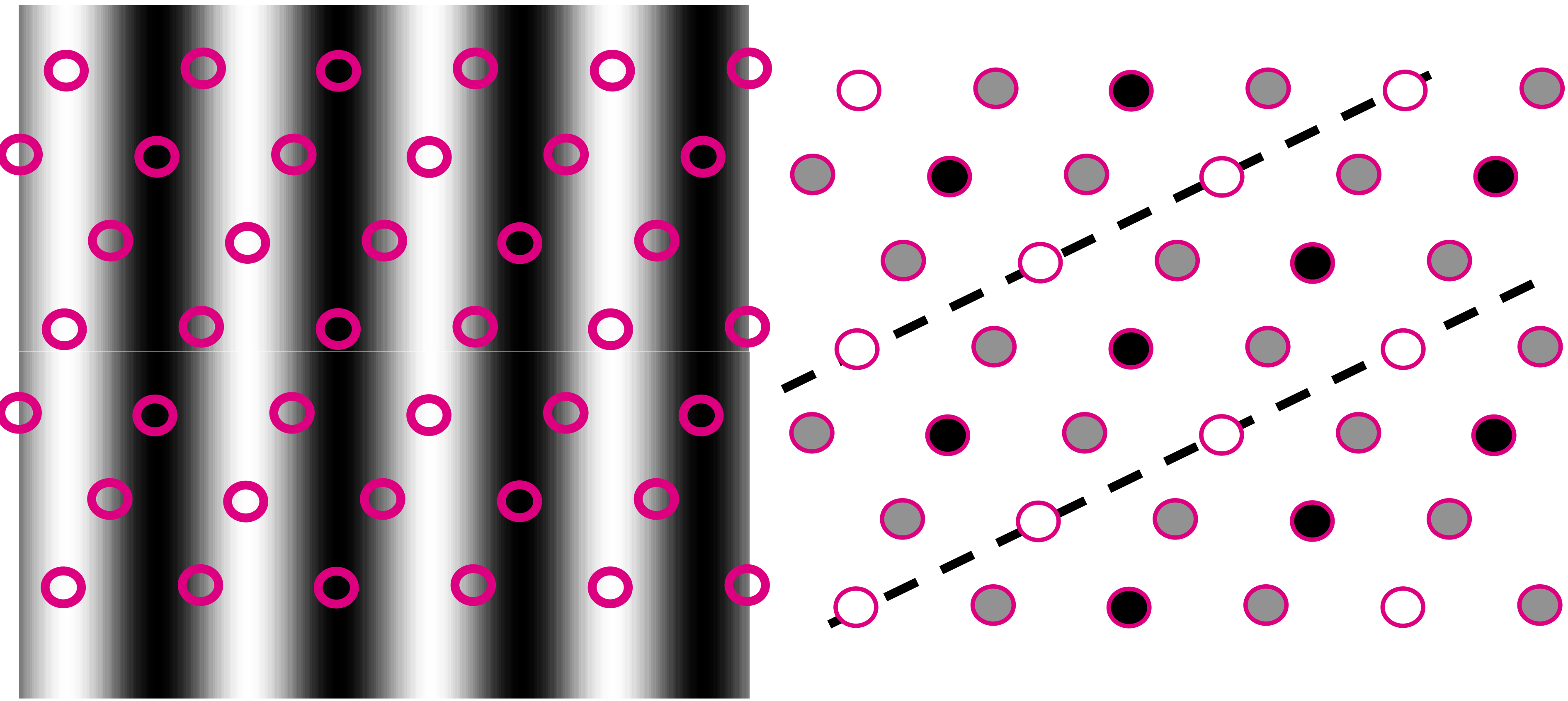
2-dimensional undersampling misrepresents spatial frequency <u>and</u> orientation of patterns



Example with less than 2 samples per period

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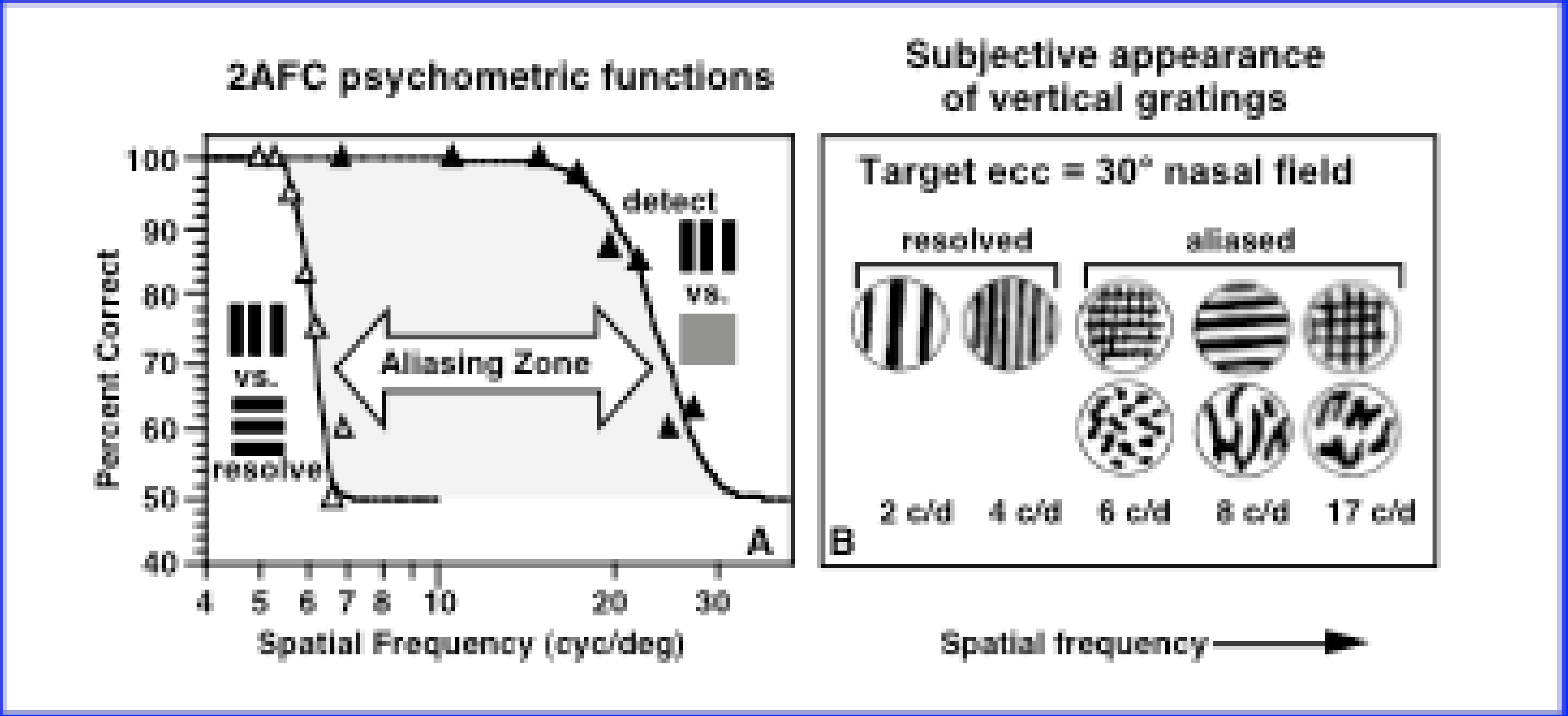
Psychophysical acuity data and perceived aliases from normal peripheral retina.



Arthur Bradley