Hearing & Seeing 2009

Lecture 1 - Anatomy and Optics of the Eye

October 26, 2009

Frank Schaeffel, Tel 29-80739
E-mail: frank.schaeffel@uni-tuebingen.de
http://www.uak.medizin.uni-tuebingen.de/frank/

Ray tracing ??

2005

Scharf sehen
ohne Brille

Das Neueste über | Augenlasern | Kontaktlinsen | OP-Methoden

Sind Sie ein Kandidat?

hr Geld in der Finanzkrise

Der Machtk(r)ampf

PLUS Extra-Heft
BAYERN

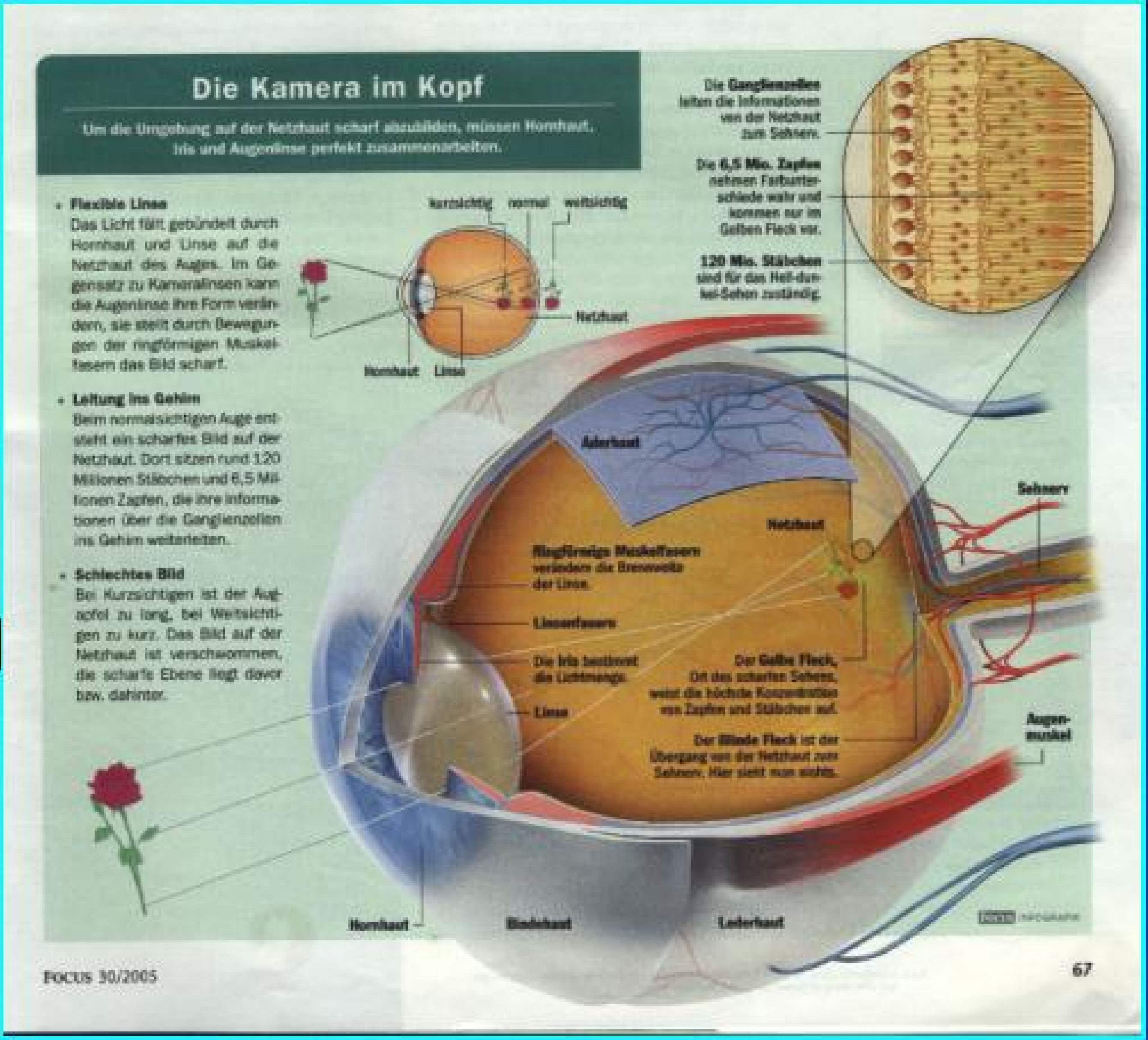
2008

Nie
wieder
Brille!

... auch nicht zum Lesen

Alles über die neuen, sicheren
Linsen- und Laser-Techniken

TIPPS FÜR ALLE ALTERSGRUPPEN



Die Kamera im Kopf

Um die Umgebung auf der Netzhaut scharf abzubilden, müssen Hornhaut, Iris und Augenlinse perfekt zusammenarbeiten.

- **Flexible Linse**
  Das Licht fällt gebündelt durch Hornhaut und Linse auf die Netzhaut des Auges. Im Gegensatz zu Kameralinsen kann die Augenlinse ihre Form verändern, sie stellt durch Bewegungen der ringförmigen Muskelfasern das Bild scharf.
- **Leitung ins Gehirn**
  Beim normalsichtigen Auge entsteht ein scharfes Bild auf der Netzhaut. Dort sitzen rund 120 Millionen Stäbchen und 6,5 Millionen Zapfen, die ihre Informationen über die Ganglienzellen ins Gehirn weiterleiten.
- **Schlechtes Bild**
  Bei Kurzsichtigen ist der Augapfel zu lang, bei Weitsichtigen zu kurz. Das Bild auf der Netzhaut ist verschwommen, die scharfe Ebene liegt davor bzw. dahinter.

Die **Ganglienzellen** leiten die Informationen von der Netzhaut zum Sehnerv.

Die **6,5 Mio. Zapfen** nehmen Farbunterschiede wahr und kommen nur im Gelben Fleck vor.

120 Mio. Stäbchen sind für das Hell-dunkel-Sehen zuständig.

Ringförmige Muskelfasern verändern die Brennweite der Linse.

Die **Iris** bestimmt die Lichtmenge.

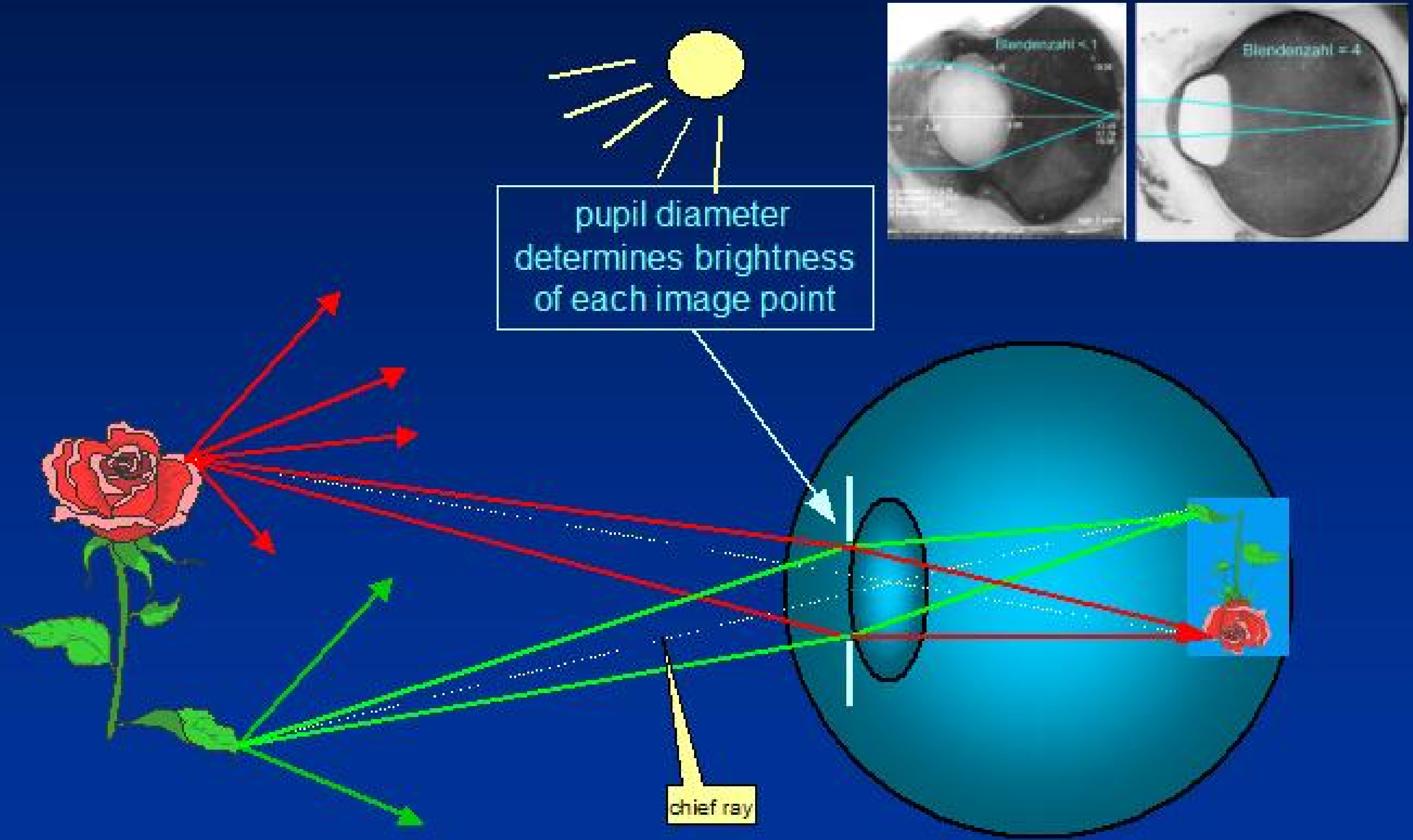
Der **Gelbe Fleck**, Ort des scharfen Sehens, weist die höchste Konzentration von Zapfen und Stäbchen auf.

Der **Blinde Fleck** ist der Übergang von der Netzhaut zum Sehnerv. Hier sieht man nichts.

FOCUS 30/2005

67

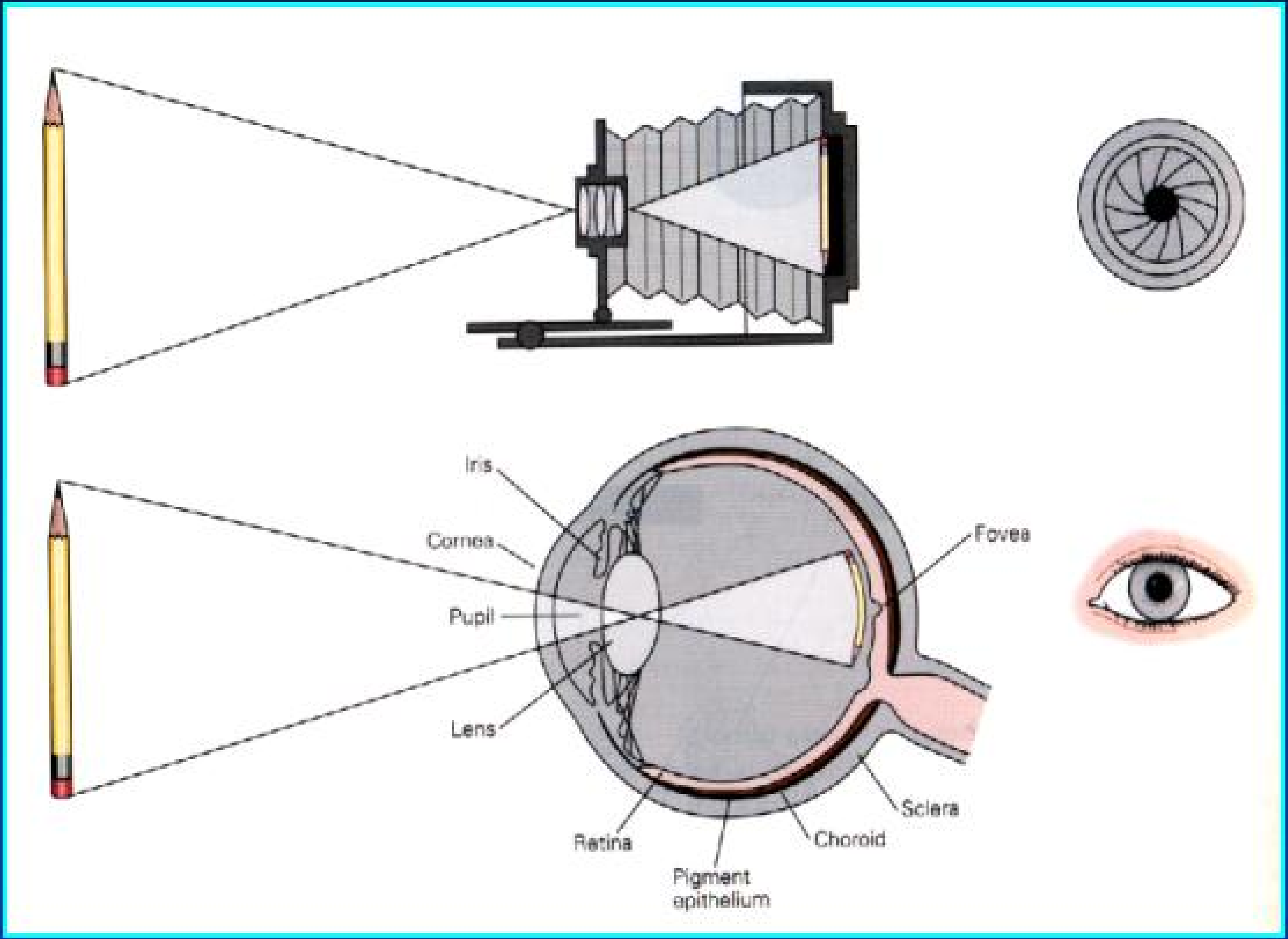
Image formation



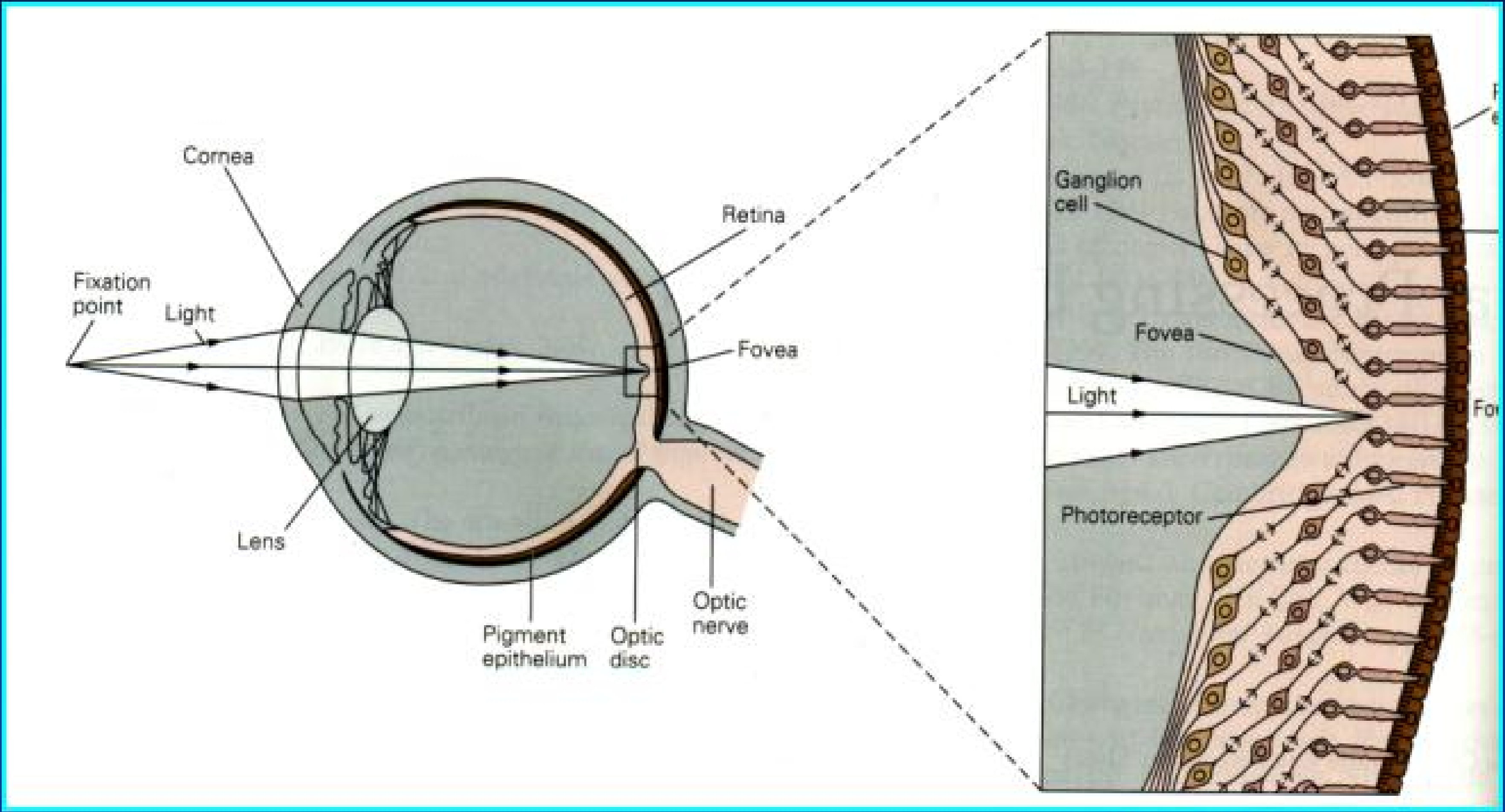
pupil diameter determines brightness of each image point

chief ray

Image formation



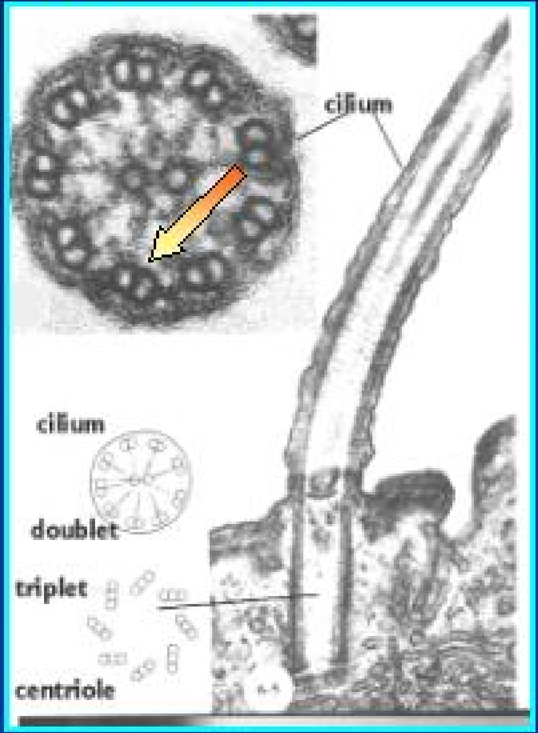
Inverted retina and fovea

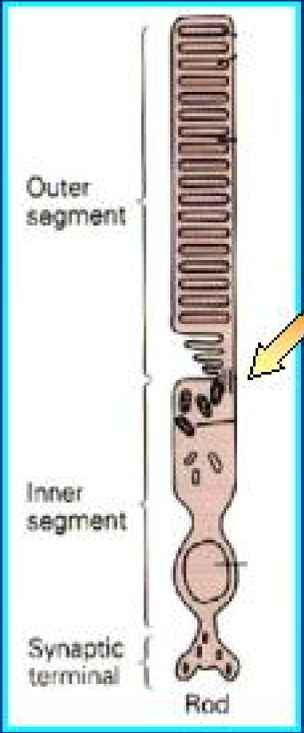


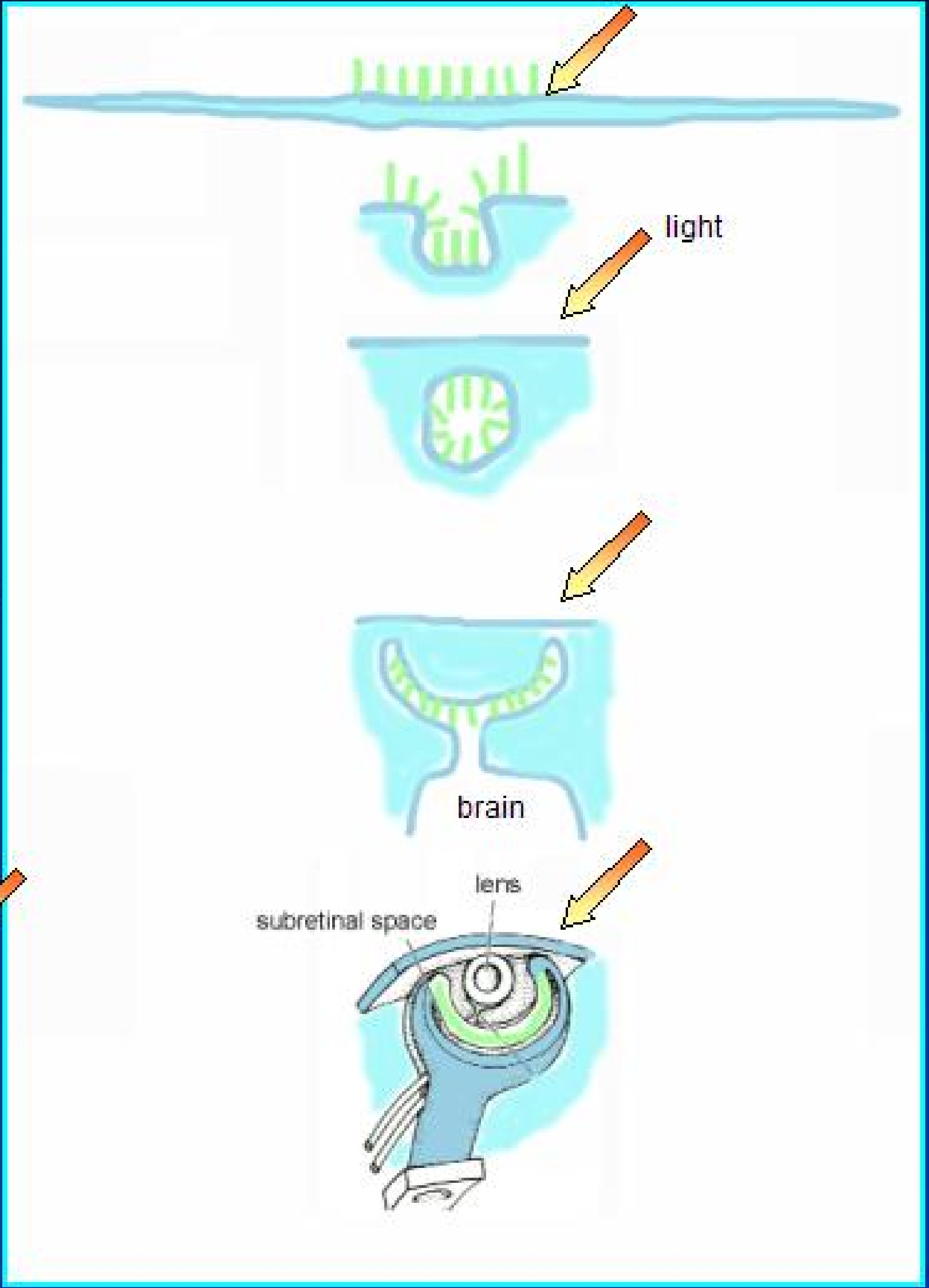
Why is the vertebrate retina inverted ?

Why is the vertebrate retina <u>inverted</u> ?

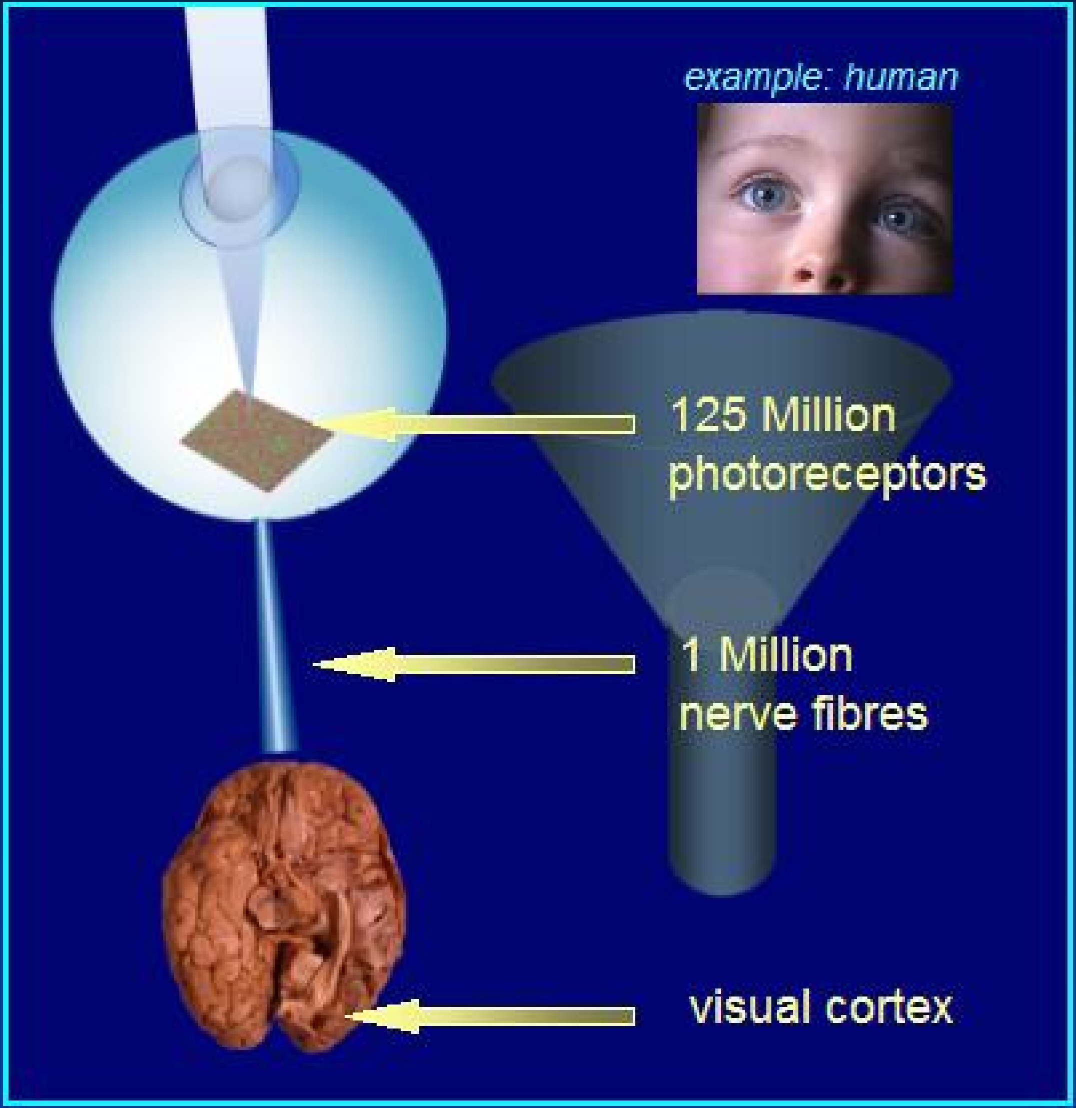
photoreceptors are neurons but
share features of cilia
(see 9*2 + 2 pattern
of microtubuli between outer
and inner segment)







Problem of most visual systems:
Information overflux !



example: human

125 Million photoreceptors

1 Million nerve fibres

visual cortex

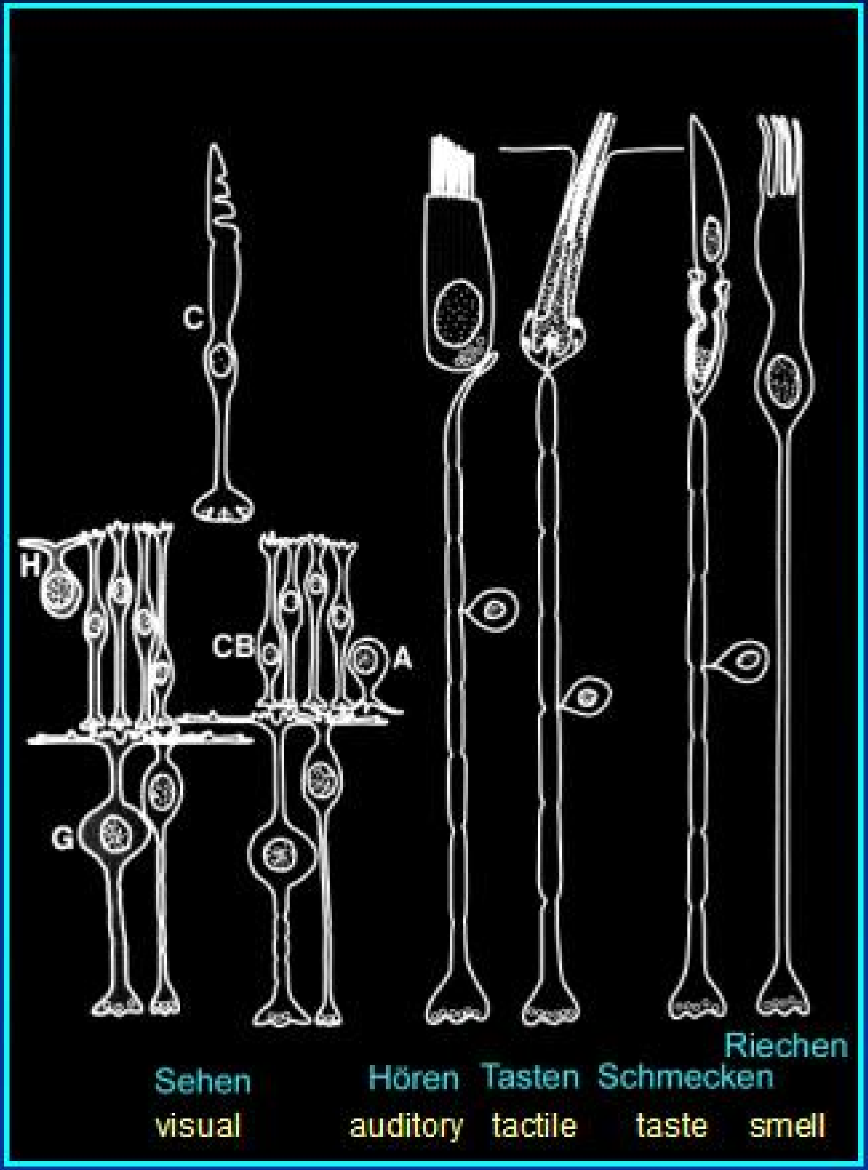
~100 mg retina

keep busy

50% of the entire cortex

information reduction necessary at the beginning

peripheral processing in different sensory systems



- extensive pre-processing outside the cortex in the visual system

this is achieved by analyzing only "changes" and confining high resolutions to small areas
example: Troxler effect

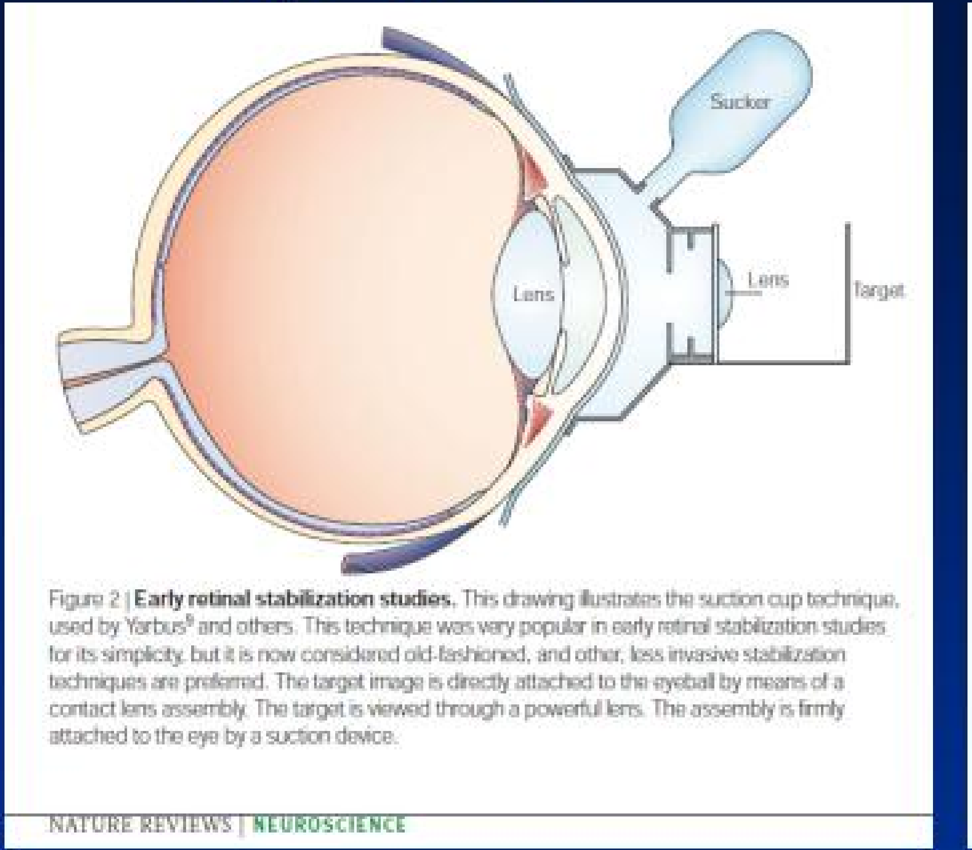
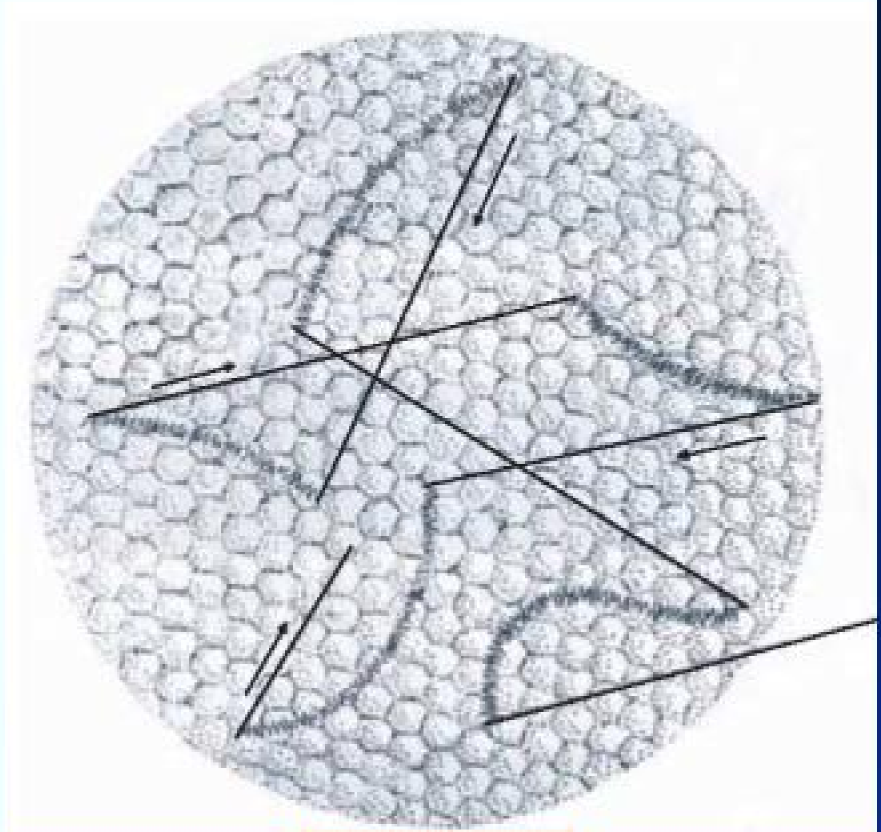
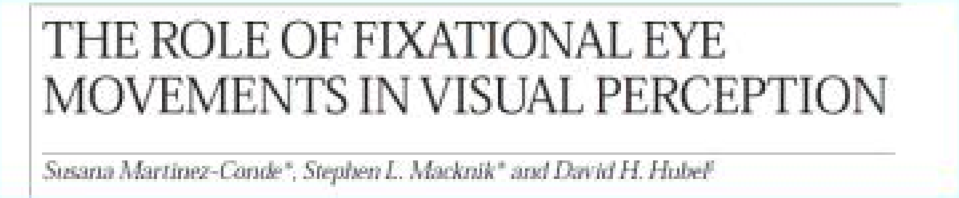


Figure 2 | **Early retinal stabilization studies.** This drawing illustrates the suction cup technique, used by Yarbus[9] and others. This technique was very popular in early retinal stabilization studies for its simplicity, but it is now considered old-fashioned, and other, less invasive stabilization techniques are preferred. The target image is directly attached to the eyeball by means of a contact lens assembly. The target is viewed through a powerful lens. The assembly is firmly attached to the eye by a suction device.

NATURE REVIEWS | NEUROSCIENCE

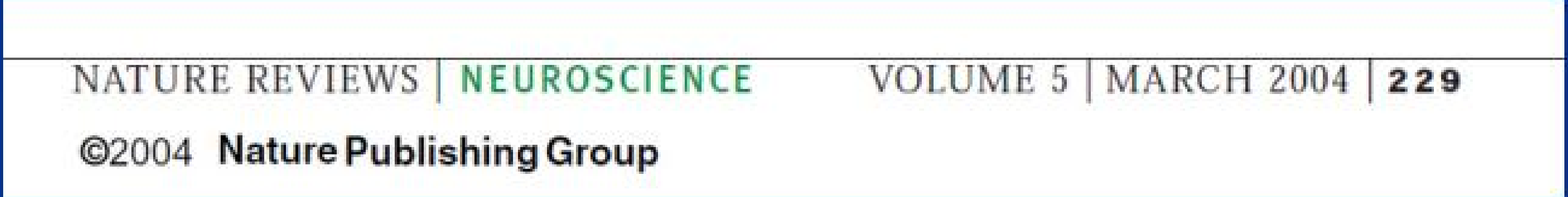


50 µm on the retina



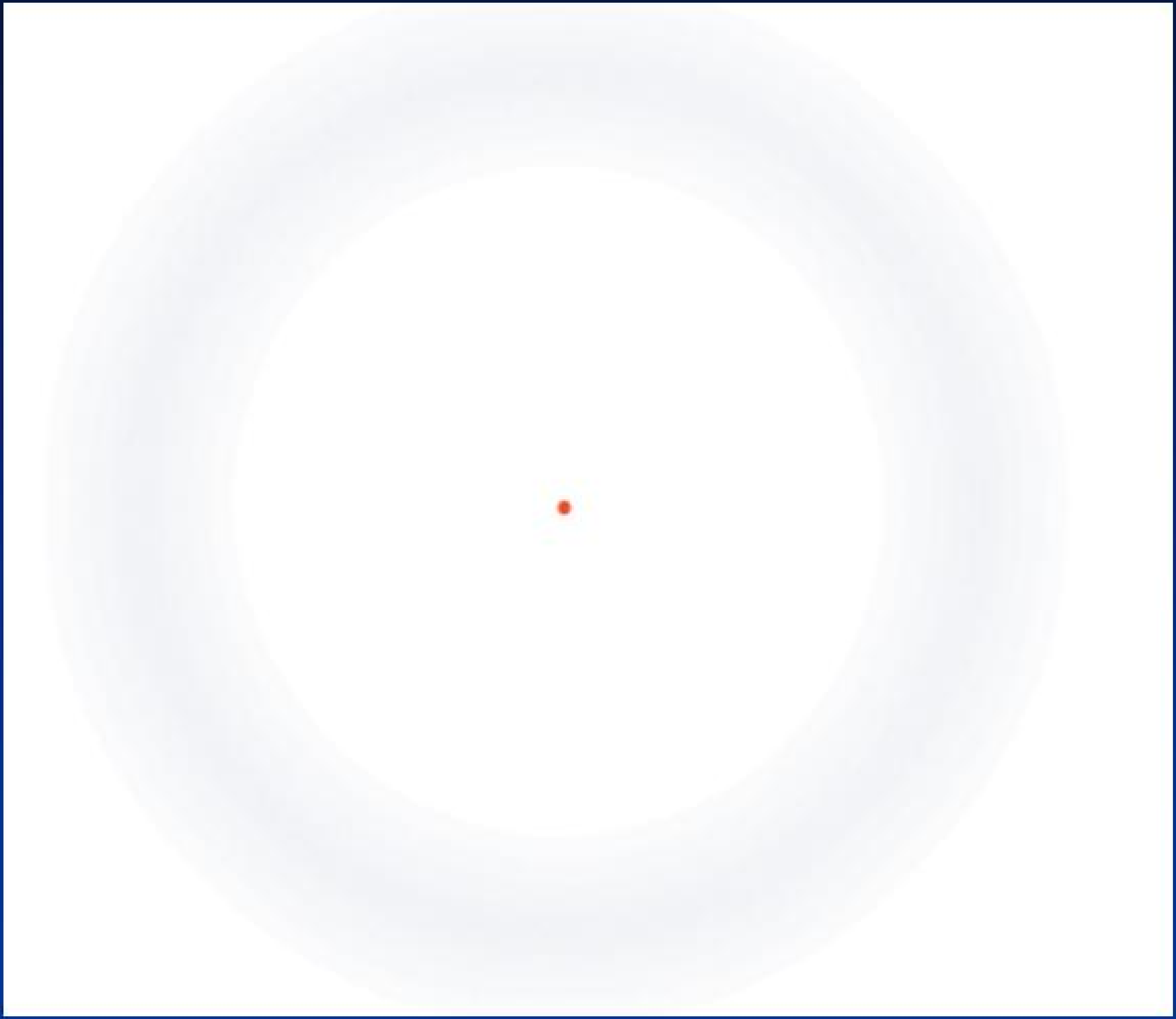
THE ROLE OF FIXATIONAL EYE MOVEMENTS IN VISUAL PERCEPTION

Susana Martinez-Conde, Stephen L. Macknik* and David H. Hubel[‡]*

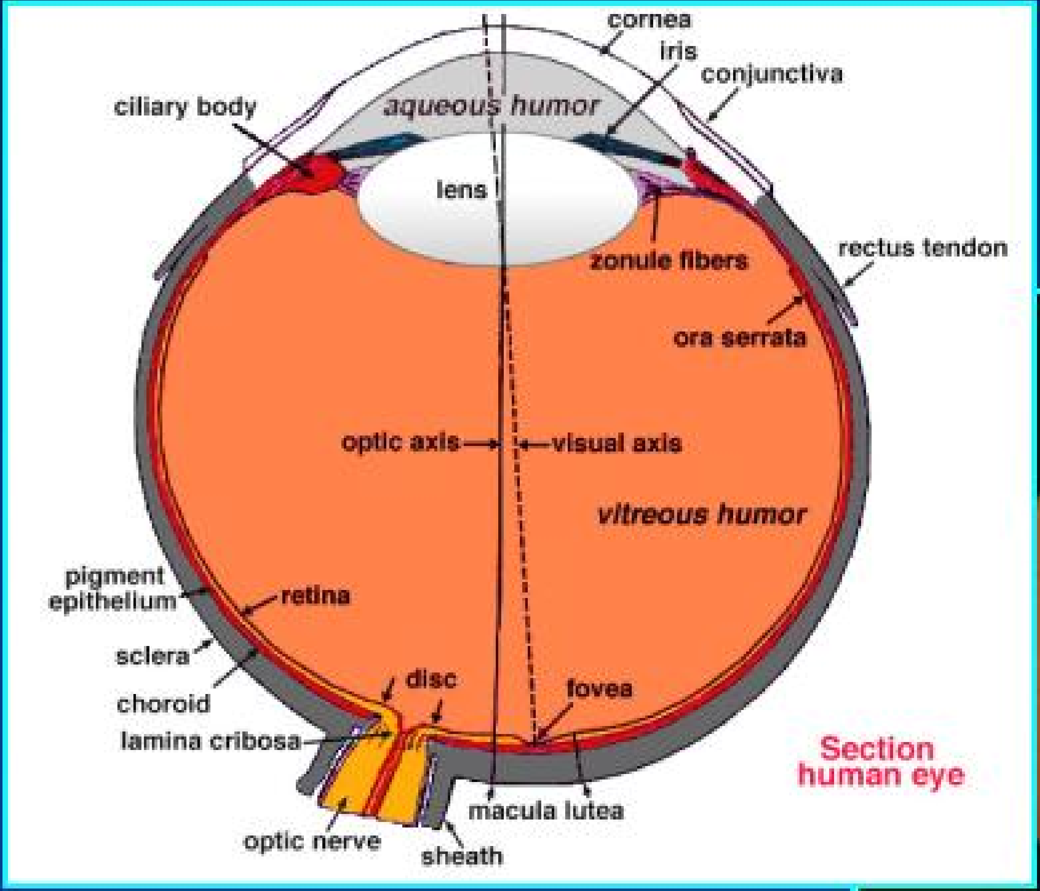


NATURE REVIEWS | NEUROSCIENCE VOLUME 5 | MARCH 2004 | 229

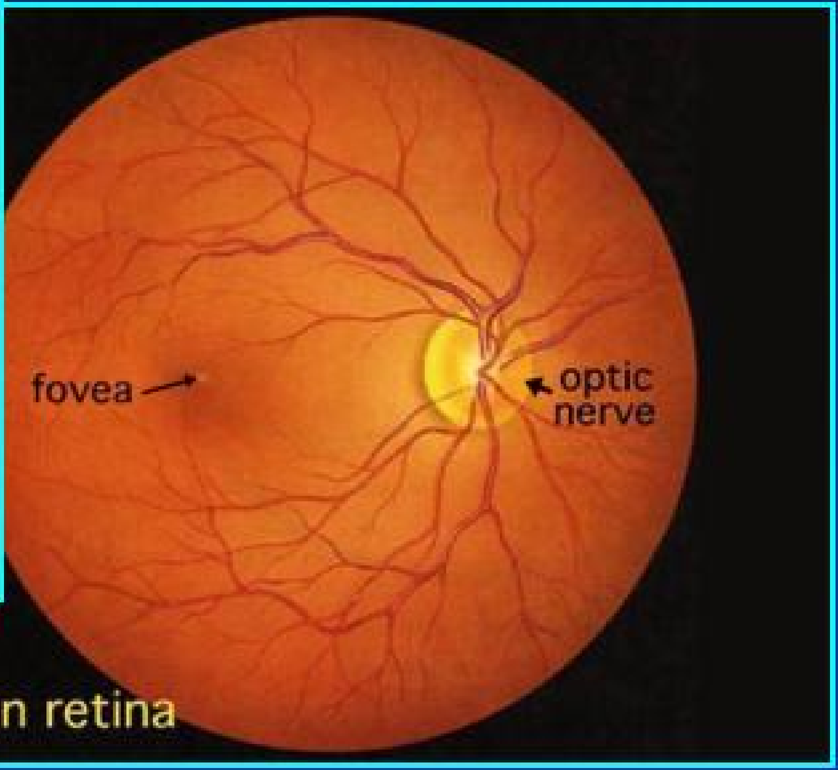
Troxler effect



appearance of the "fundus" by clinical ophthalmoscopy

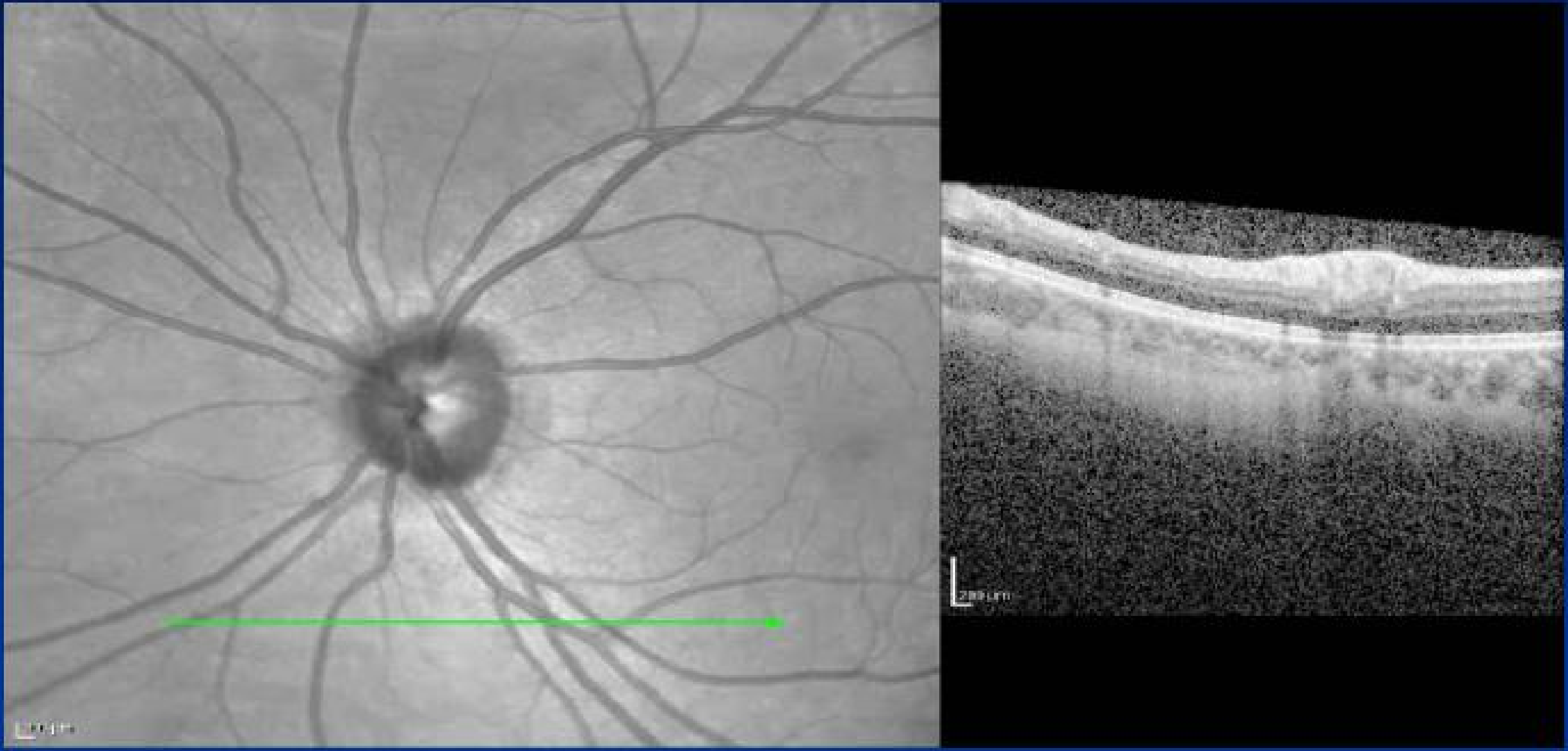


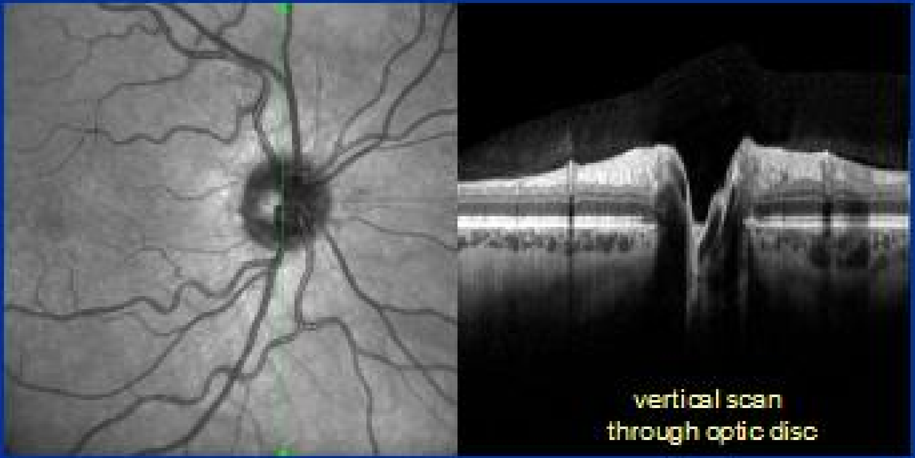
Section human eye



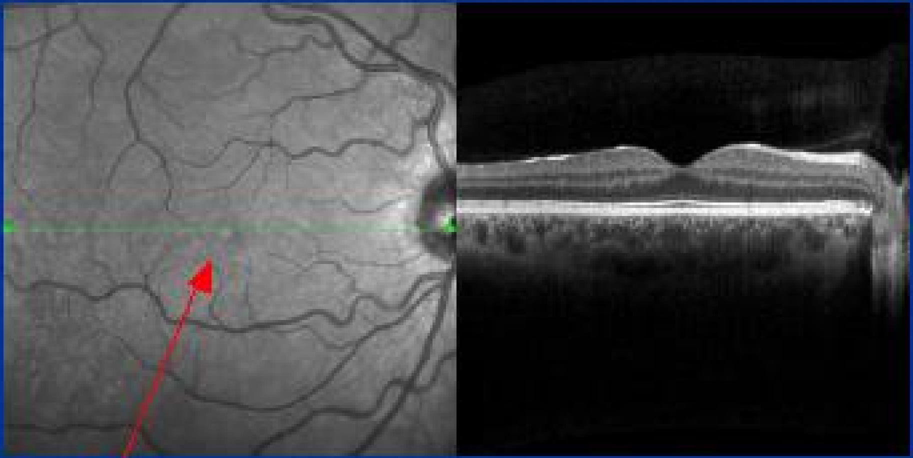
Human retina

OCT scan through optic disc



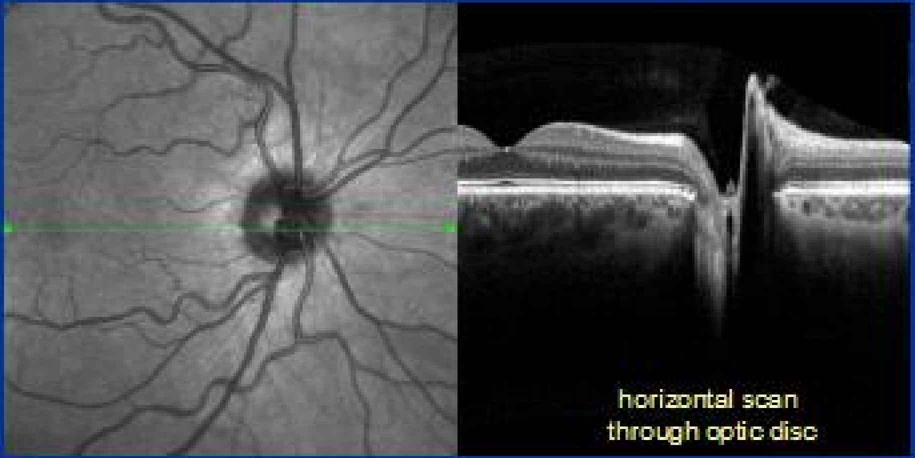


vertical scan
through optic disc

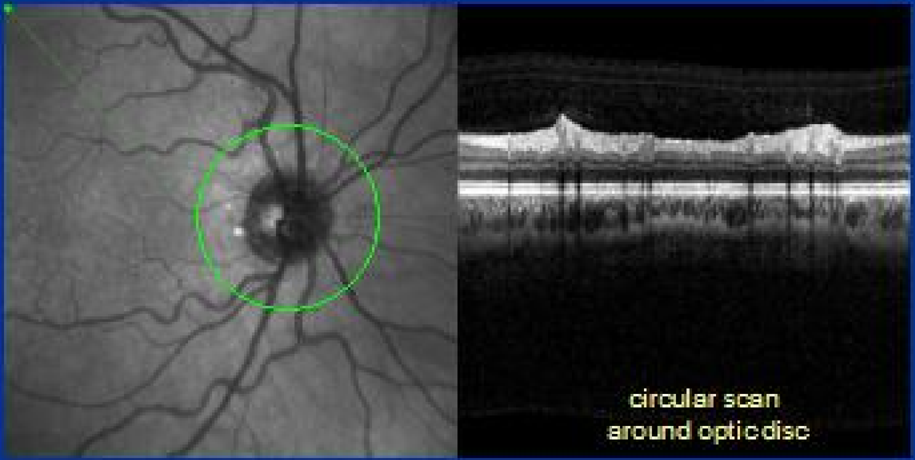


scan through fovea

fovea



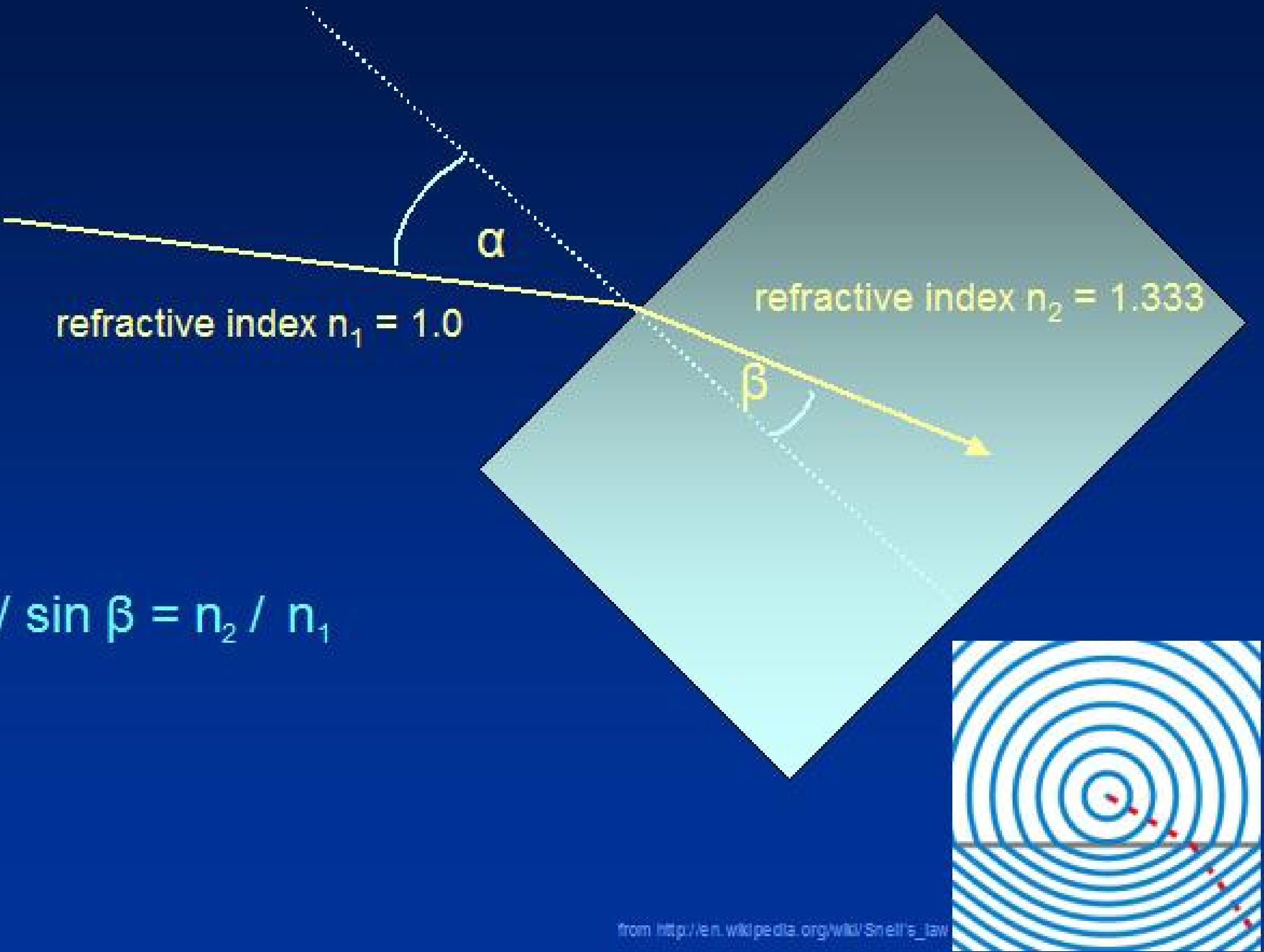
horizontal scan
through optic disc



circular scan
around optic disc

Snell's law (1621)

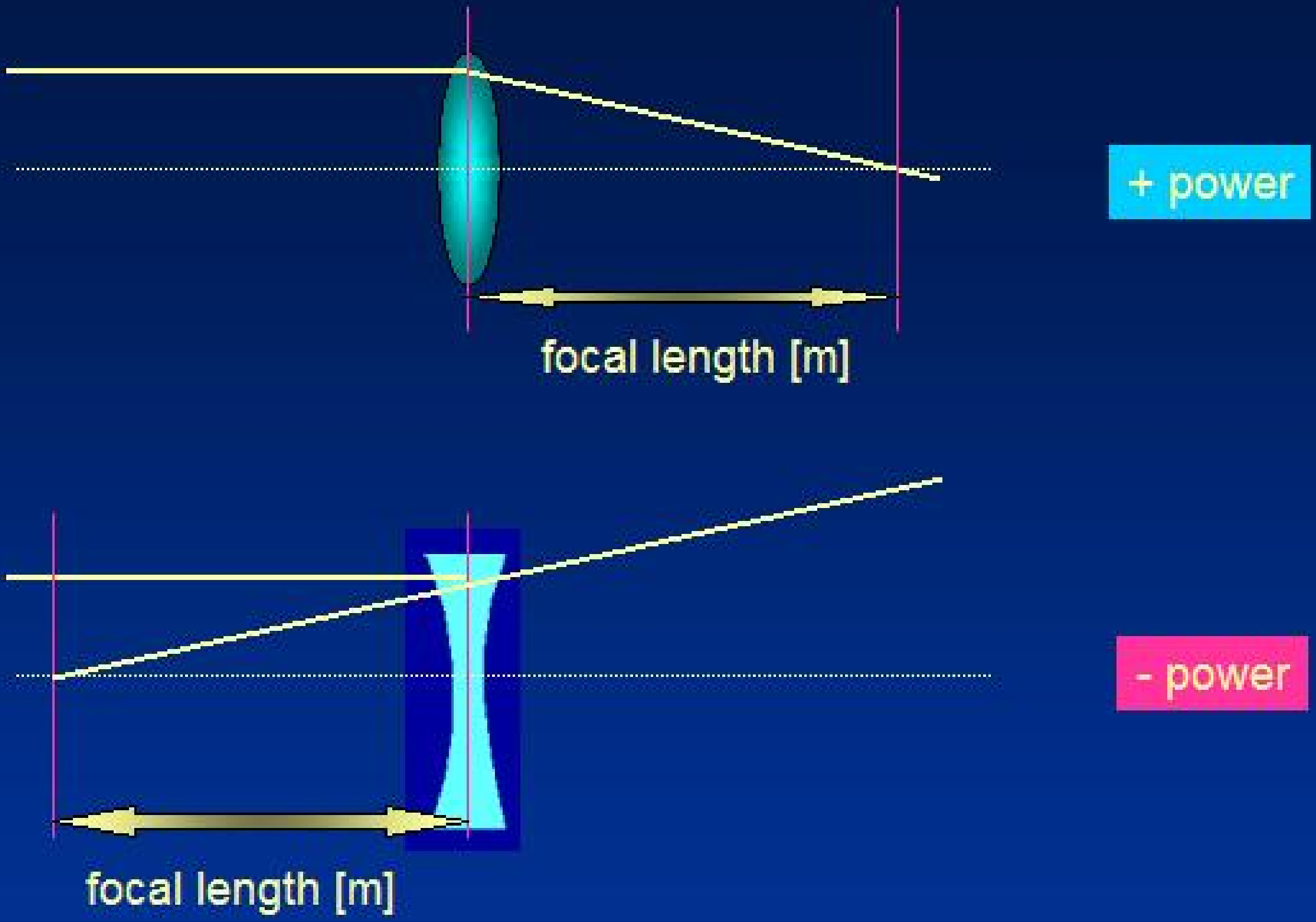
(remained unpublished during the lifetime of Willebrord Snellius)



$\sin \alpha / \sin \beta = n_2 / n_1$

from http://en.wikipedia.org/wiki/Snell's_law

Basic lens equation



focal length [m]

+ power

- power

focal length [m]

refractive power [D] = 1 / focal length [m]

Ray tracing

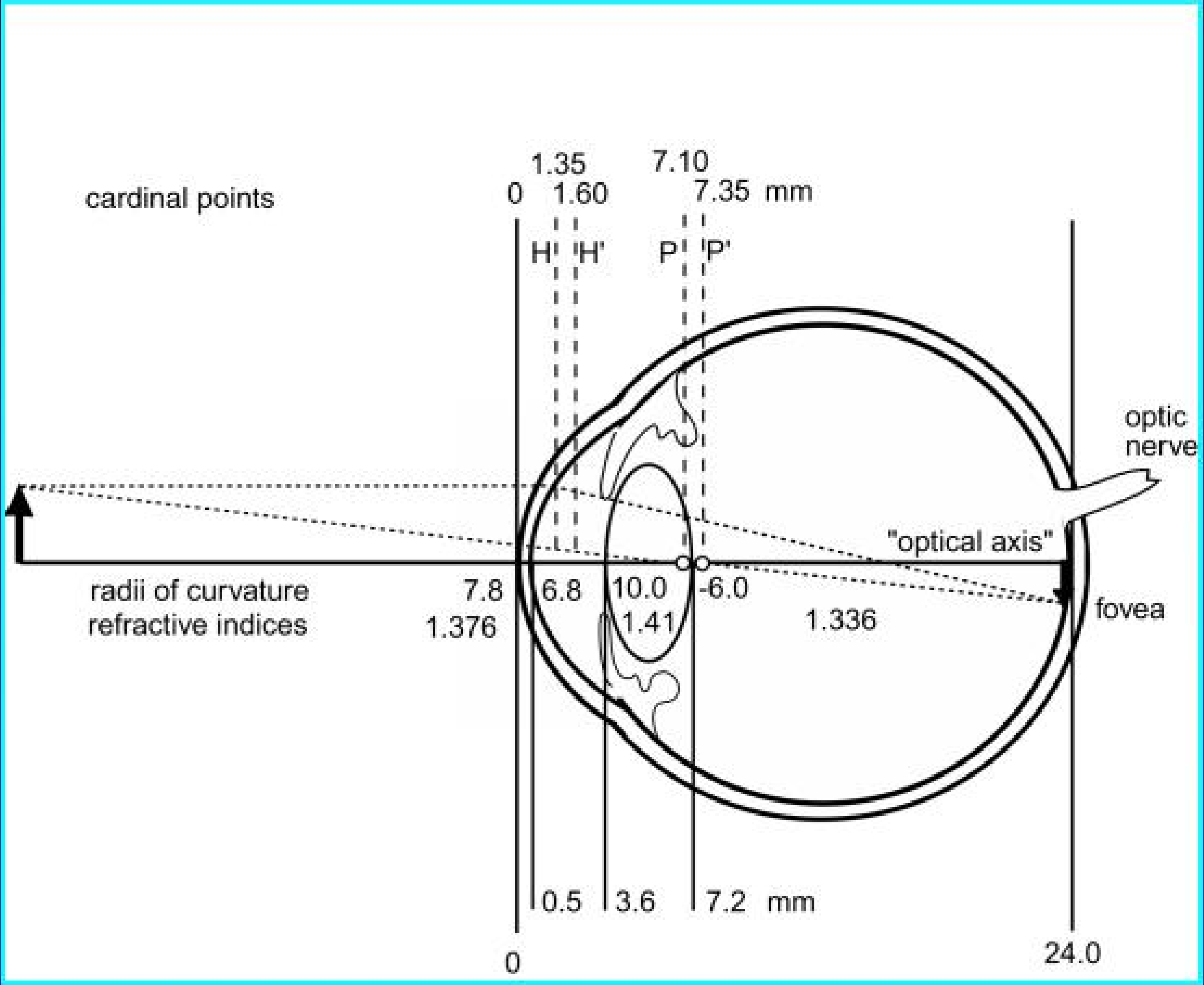
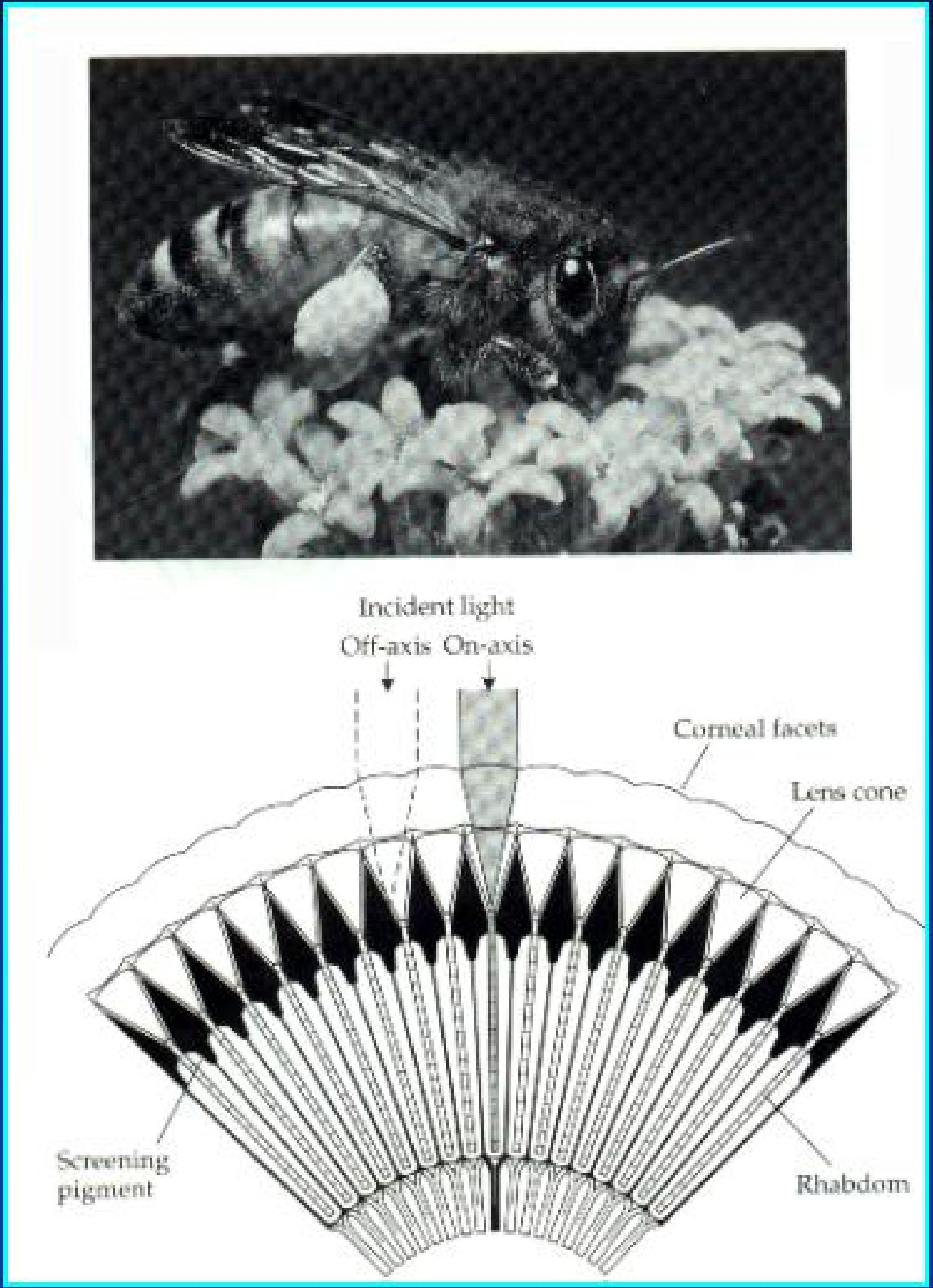
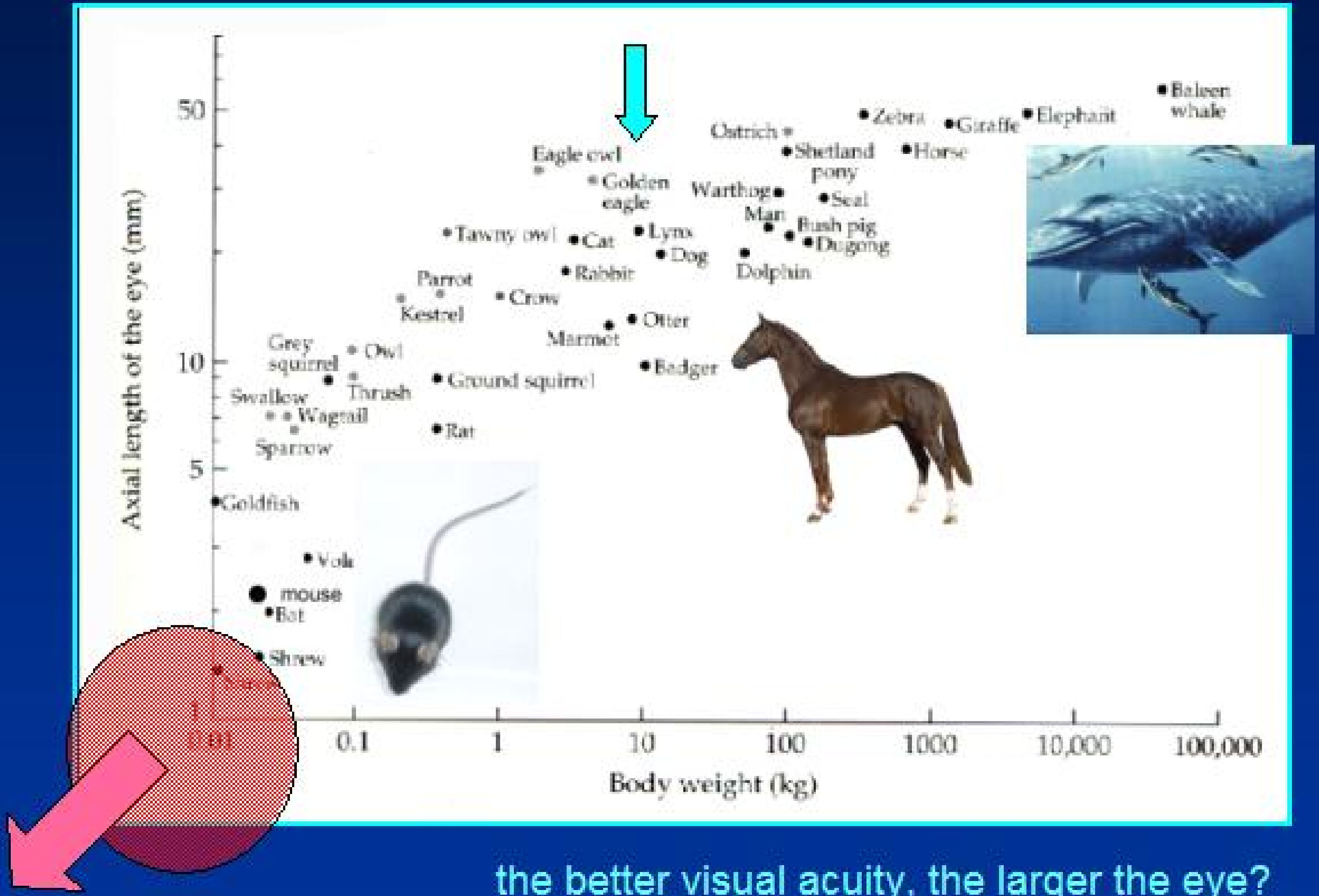

cardinal points
1.35
7.10
0
1.60
7.35 mm
H
H'
P
P'
optic
nerve
"optical axis"
fovea
radii of curvature
refractive indices
7.8
6.8
10.0
-6.0
1.376
1.41
1.336
0.5
3.6
7.2 mm
0
24.0

Image formation in an insect eye

(assuming equal spatial resolution across the visual field)



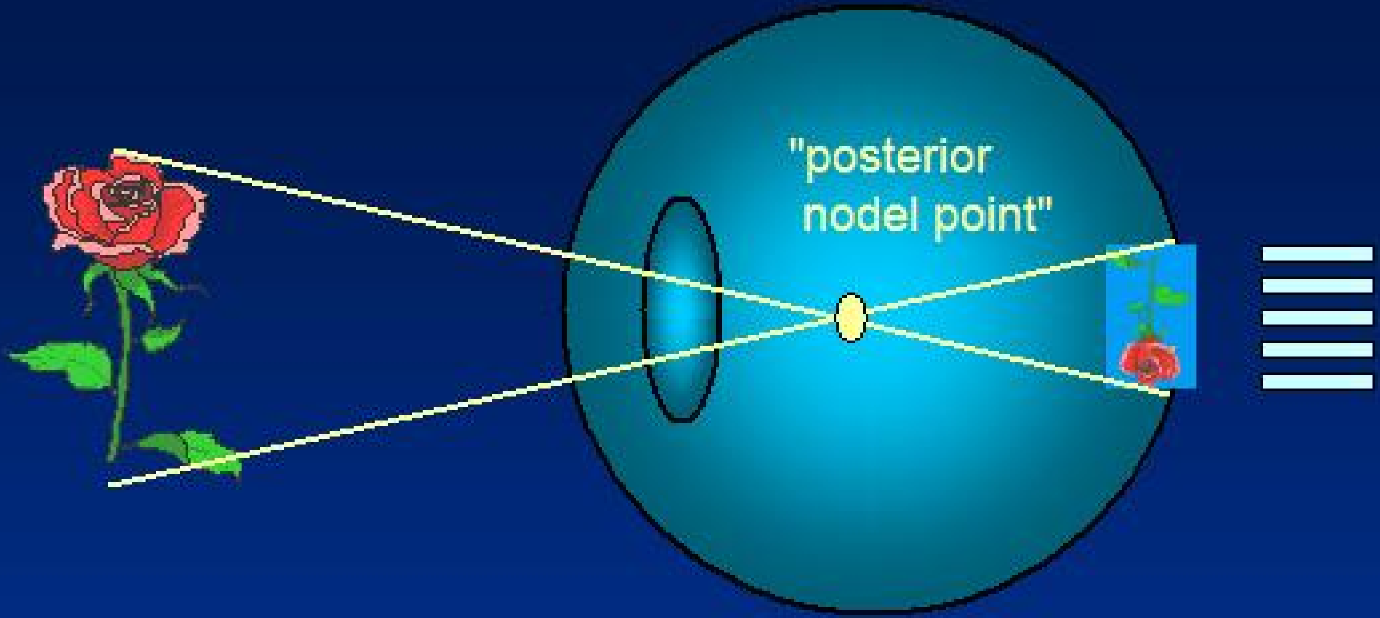
large eye <-----> large image !

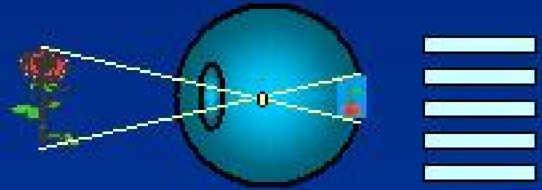


the better visual acuity, the larger the eye?

from here only complex eyes

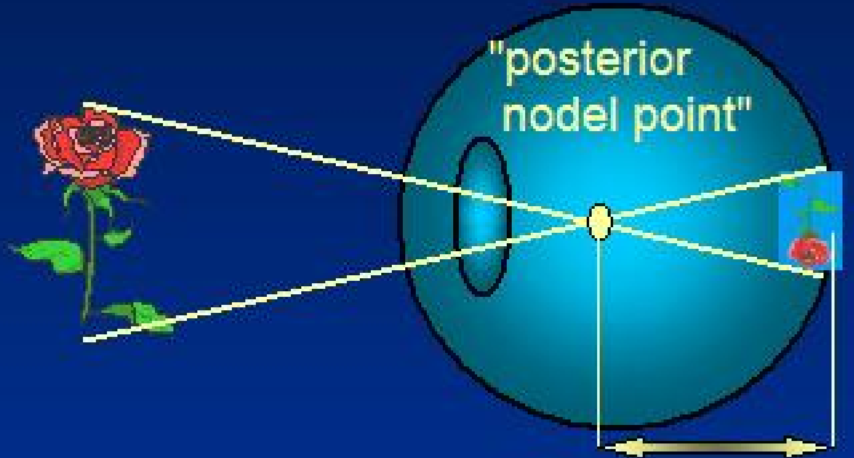
- why compound eyes and camera eyes ?





- smaller eyes have smaller image but not smaller receptors --> small animals have poorer visual acuity
- image brightness in camera eye remains the same despite small pupil :
  image brightness ~ (pupil diameter / focal length)^2
- large animals need camera eyes because resolution ~ axial length (compound eyes ~ $\sqrt{ax}$)
- **but: (1) compounds eyes have many pupils -> more light ! (2) larger visual field**

the size of the retinal image



PND (posterior nodal distance)

necessary for calculation: the posterior nodal distance
(PND, about 0.6 of axial eye length)

the size of the retinal image

example human eye: PND about 16.7 mm

(1) How big is the image of the moon?

tan 1° = image size / PND

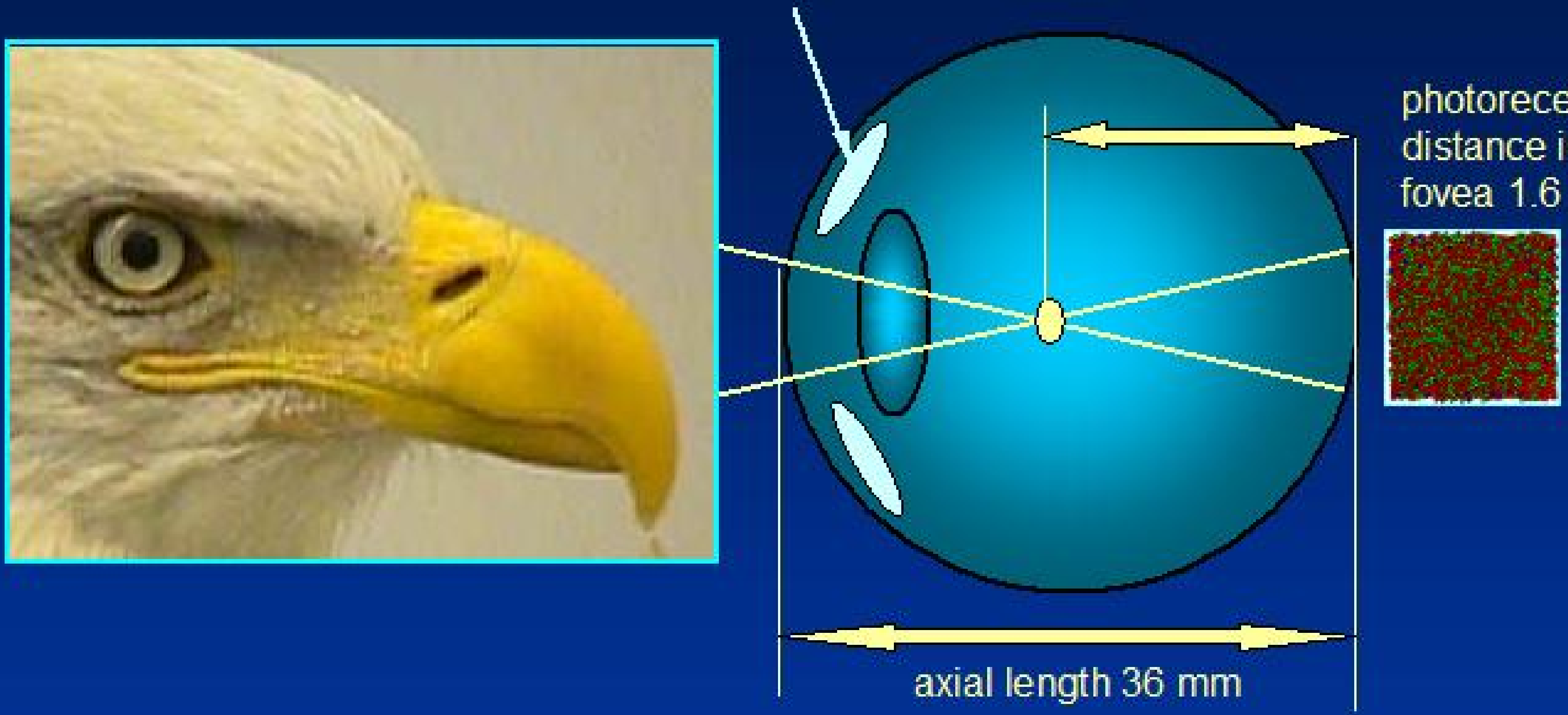
image size = tan 1° * PND = 0.29 mm

(2) What is the minimal visual angle that can be resolved?

photoreceptor diameter ~ 2 µm

minimal angle = arctan (4 µm / 16700 µm) = 0.014° ~ 1/ 60° = 1'

highest visual acuity in the animal kingdom: golden eagle



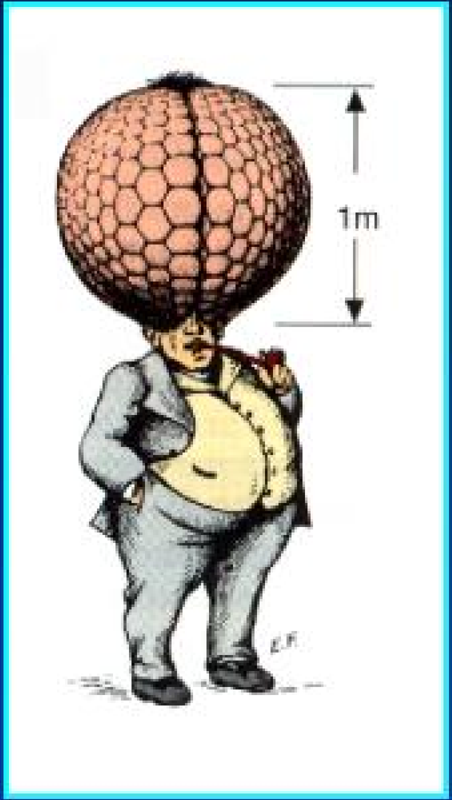
bones for mechanical stabilization of the globe ("scleral ossicles")

photoreceptor distance in fovea 1.6 µm

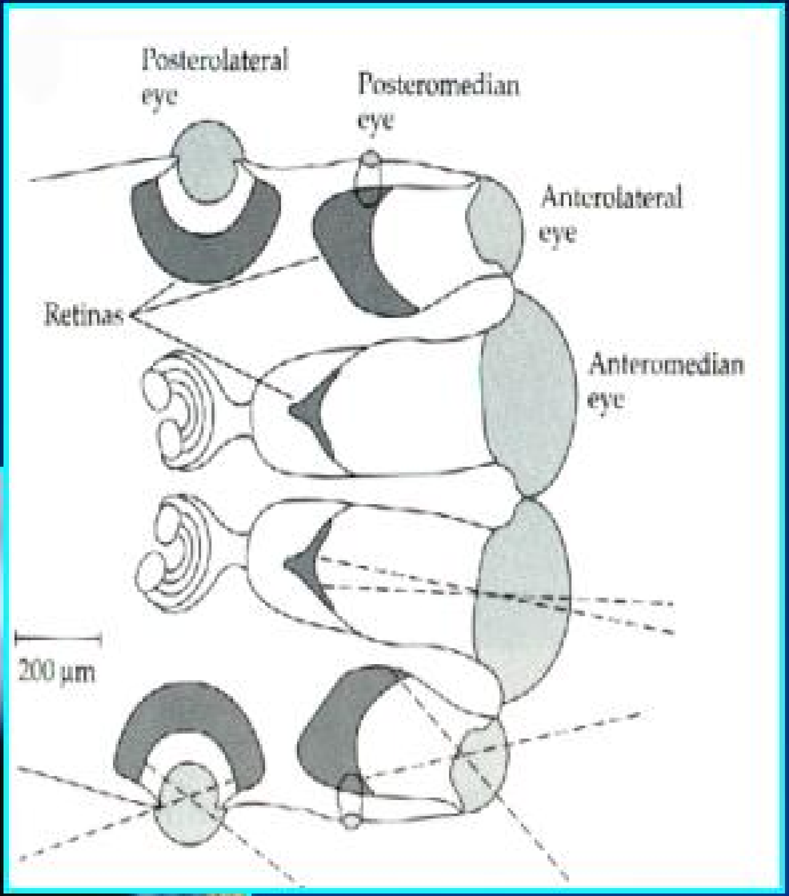
axial length 36 mm

- perfect optics up to 4 mm pupil diameter (human: about up to 2 mm)
- 1 deg of visual angle = 380 µm on the retina (human 290 µm)
spatial resolution 130 cycles / deg (human 50 - 60)

high visual acuity and reasonable eye size only possible with camera lens eyes

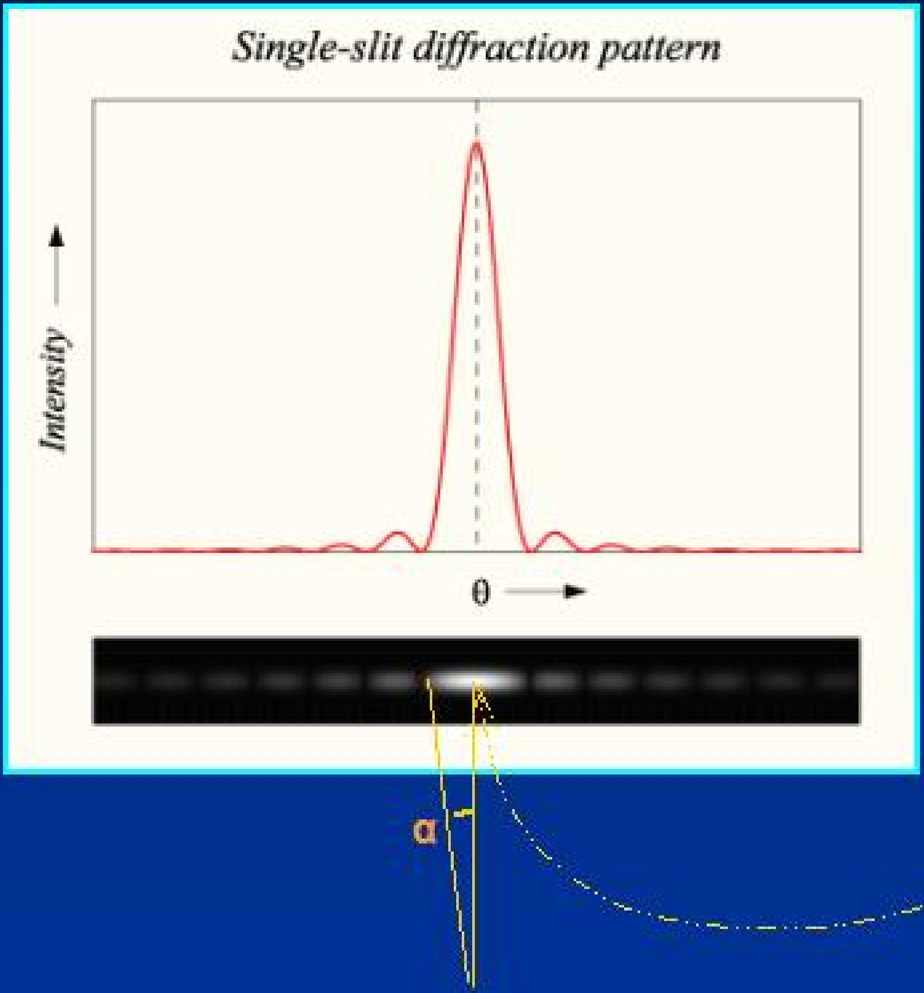


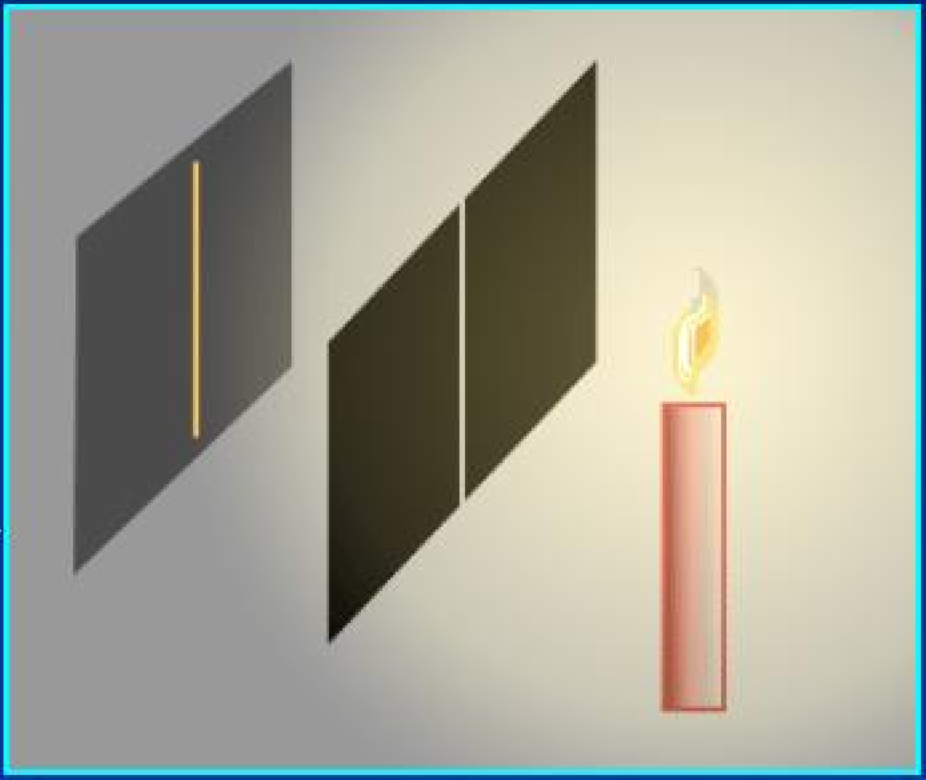
nevertheless, back to the camera eye
in the jumping spider



Physical and optical limits of vertebrate eyes

physical limits of the camera lens eye
- diffraction

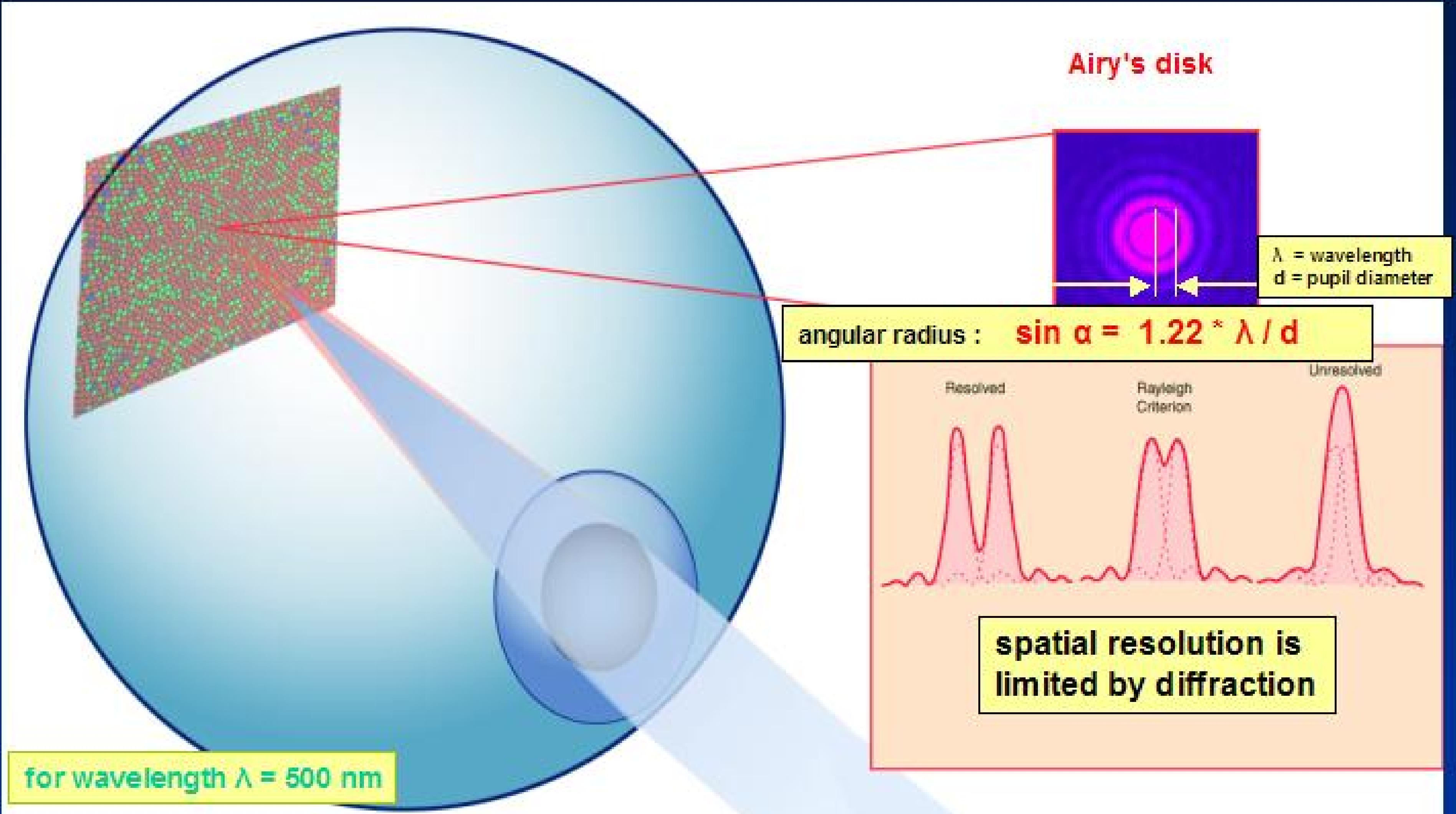




angular distance : **$\sin \alpha = \lambda / d$**

λ = wavelength
d = slit diameter

physical limits of the camera lens eye
- diffraction



λ = wavelength
d = pupil diameter

angular radius : **$\sin\alpha = 1.22 * \lambda / d$**

spatial resolution is limited by diffraction

for wavelength λ = 500 nm

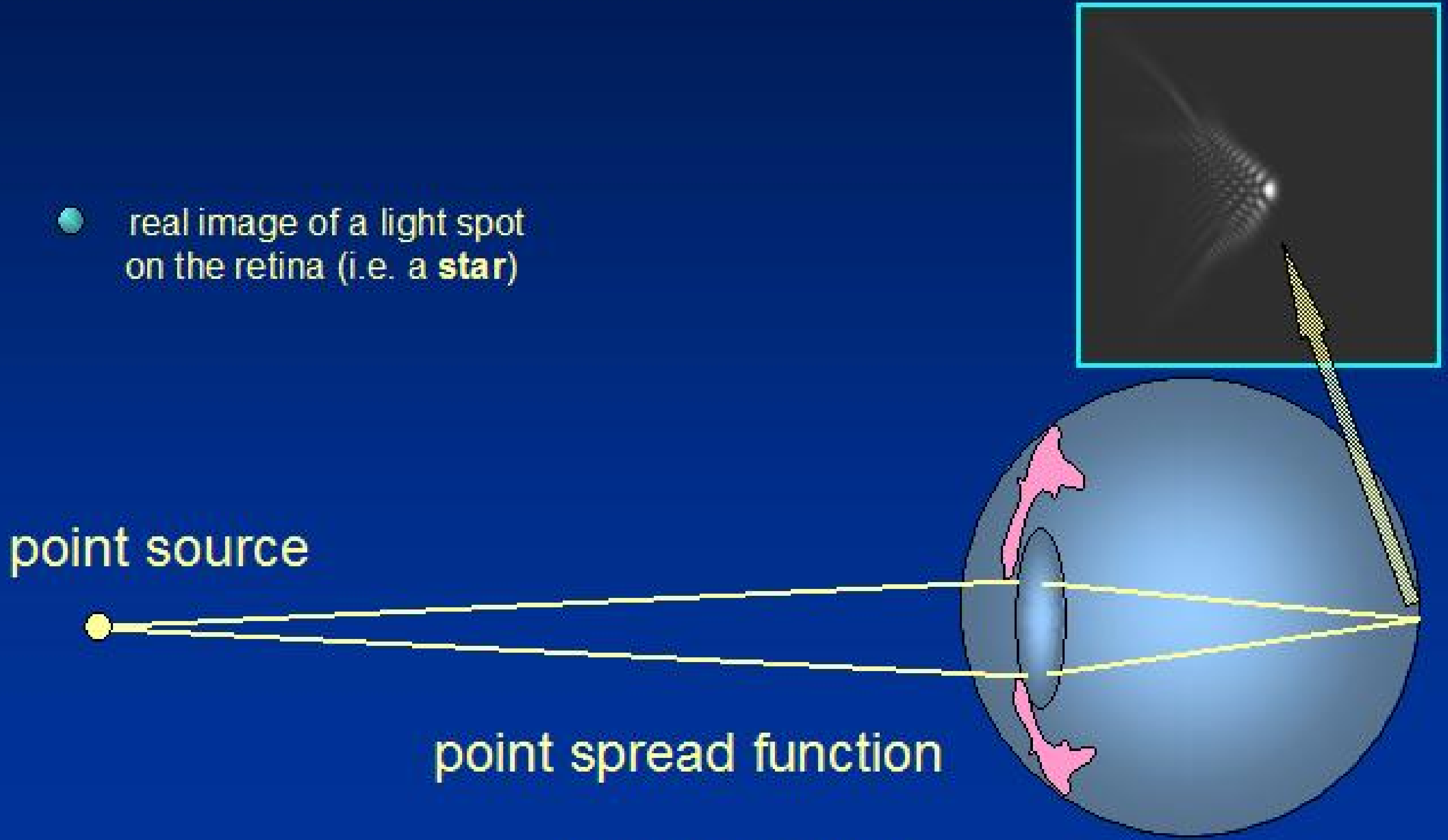
2 mm pupil : $\alpha = 1.22 * (0.5\ \mu m / 2000\ \mu m) = 0.035$ deg **~ 2 min**

5 mm pupil : $\alpha = 1.22 * (0.5 / 5000) = 0.014$ deg **~ 1 min**

range of the diameter of a cone photoreceptor

optical limits of the camera lens eye

- real image of a light spot on the retina (i.e. a **star**)

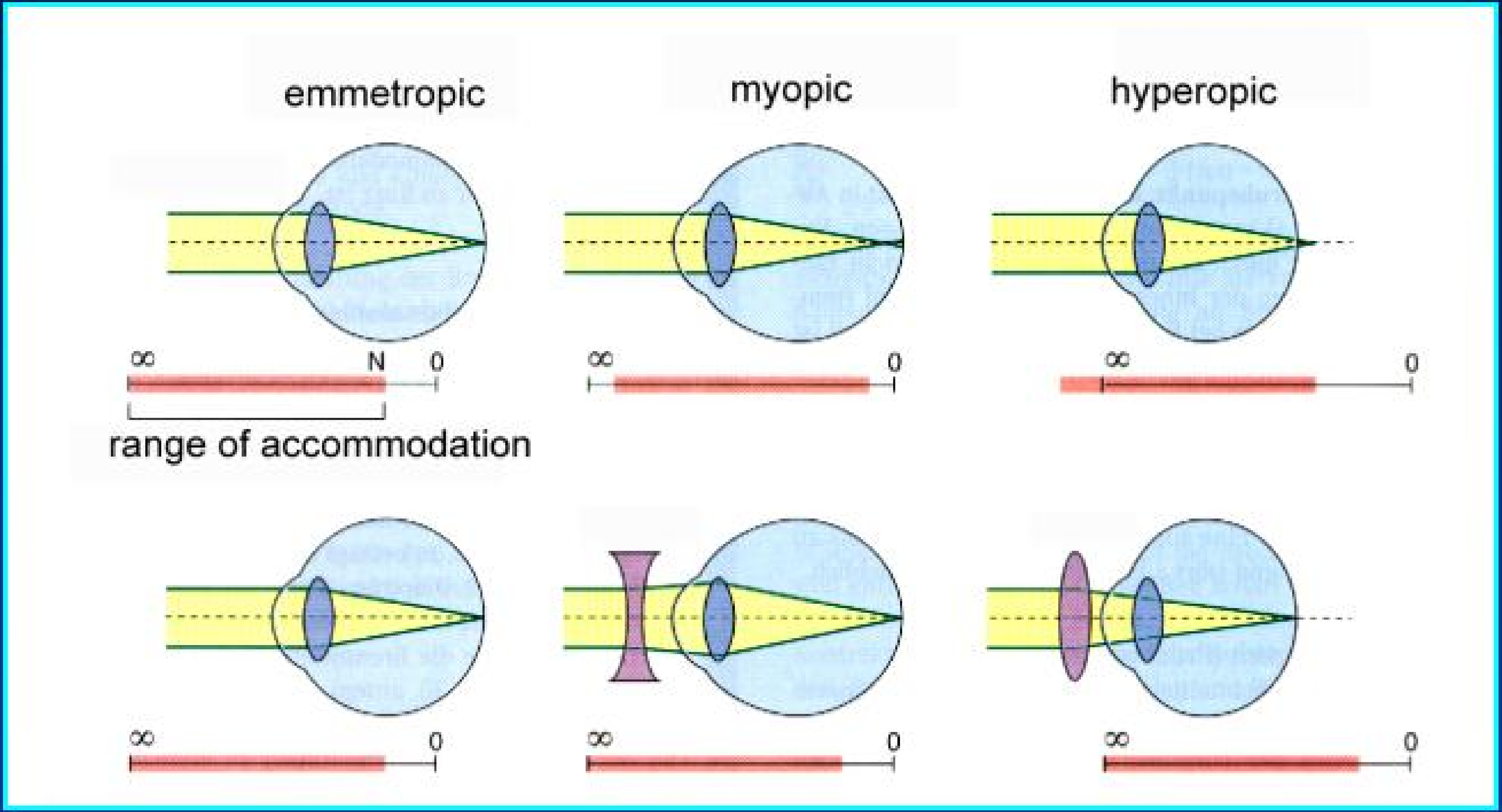


point source

point spread function

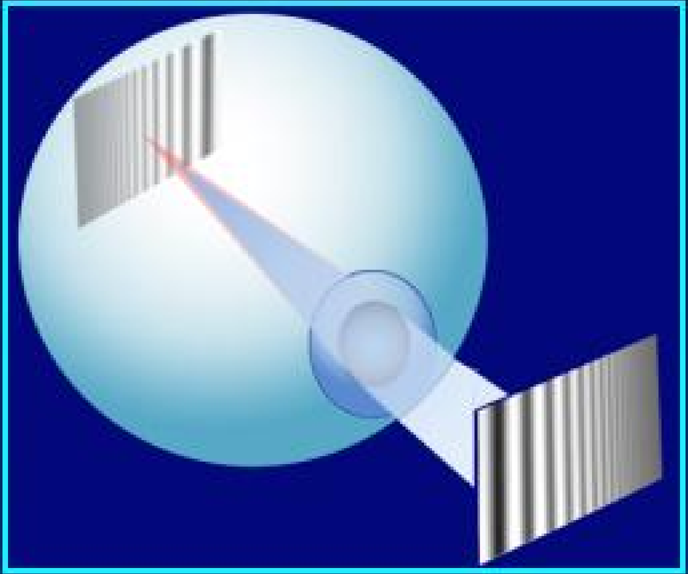
Why not a nice point?

Spherical refractive errors



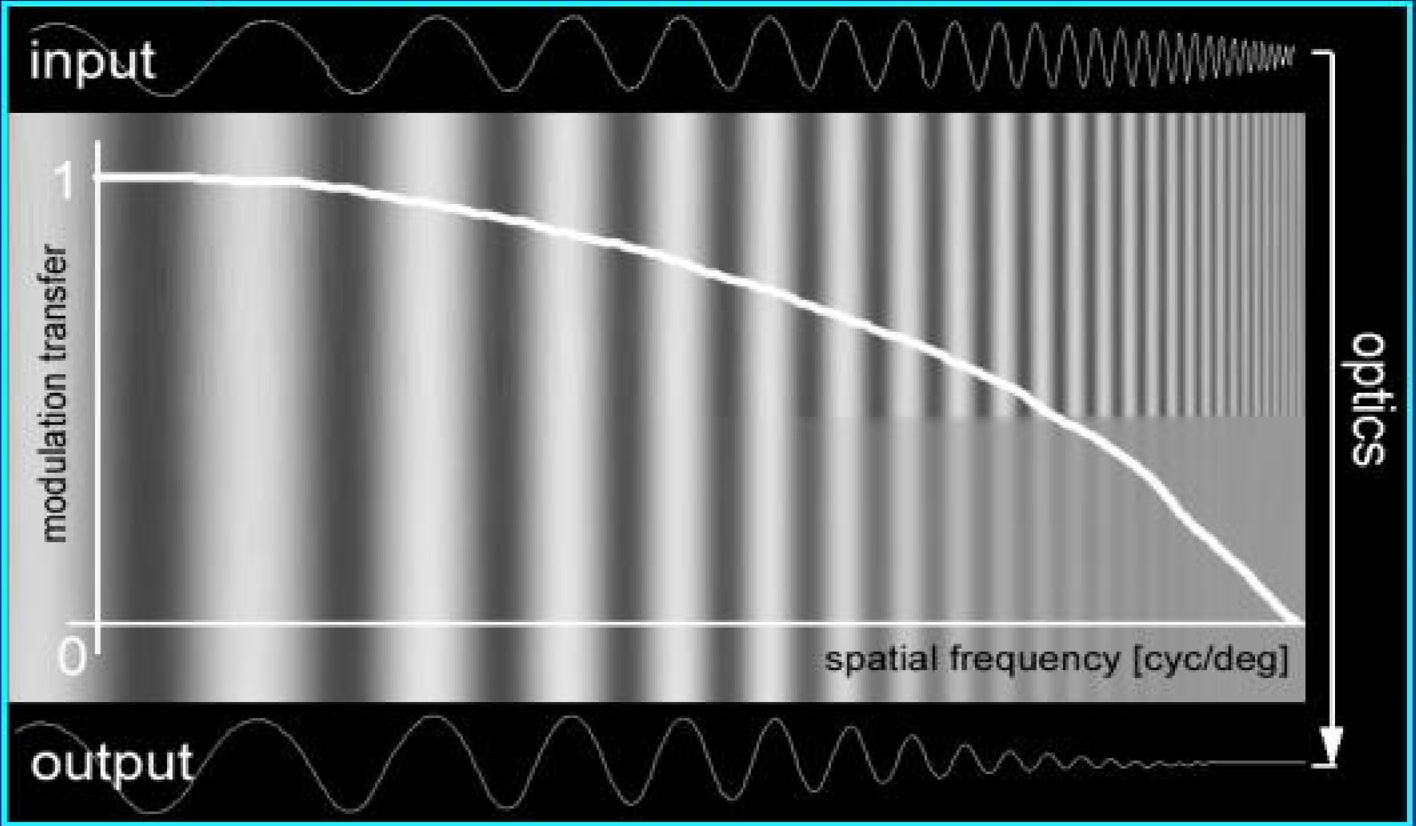
- power

+ power



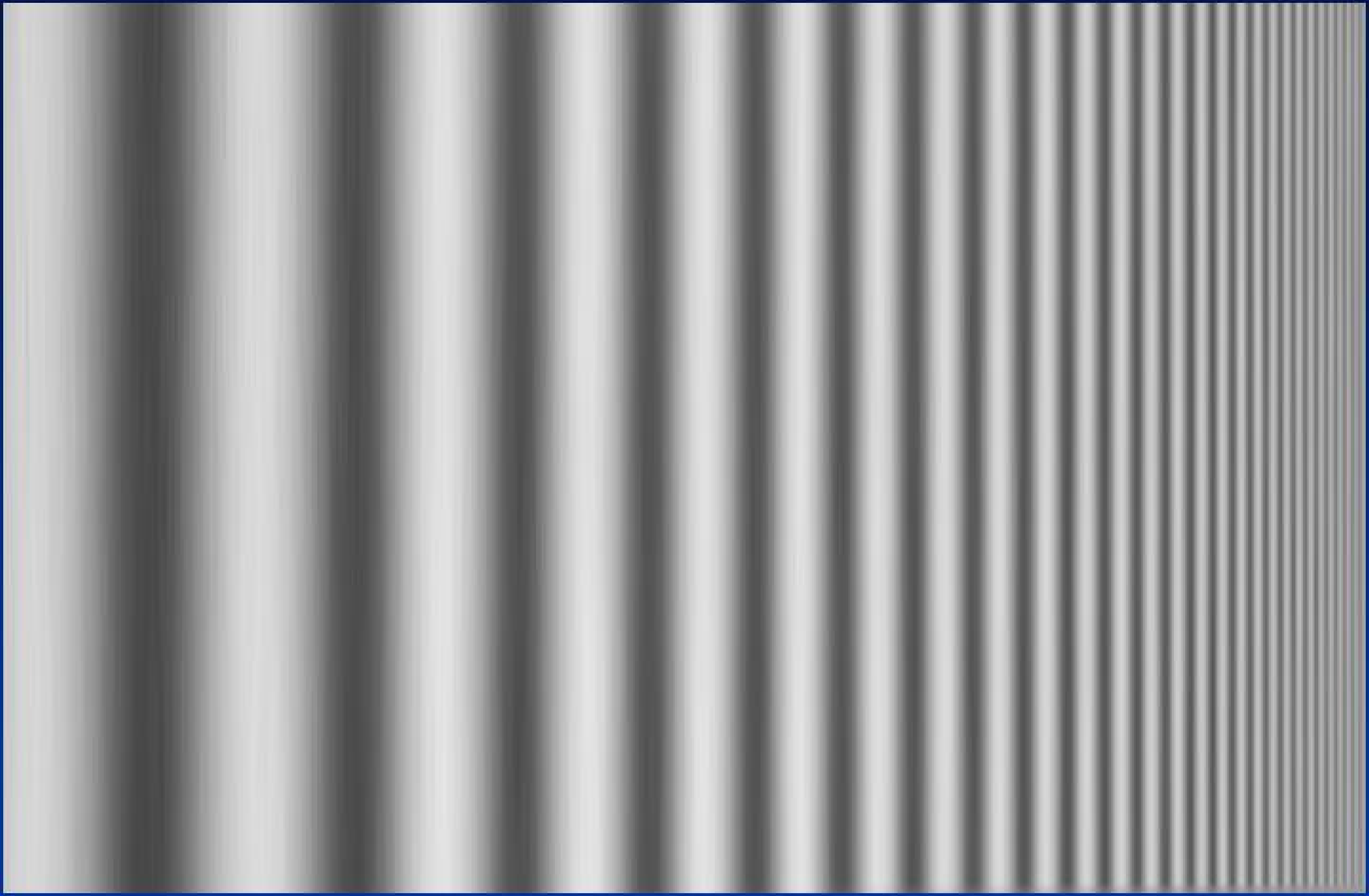
modulation transfer function

The optical system is a "low pass filter"



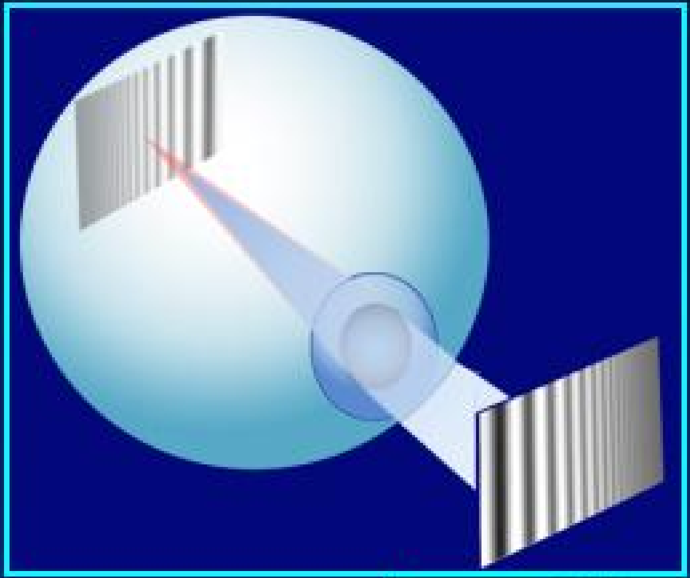
modulation transfer

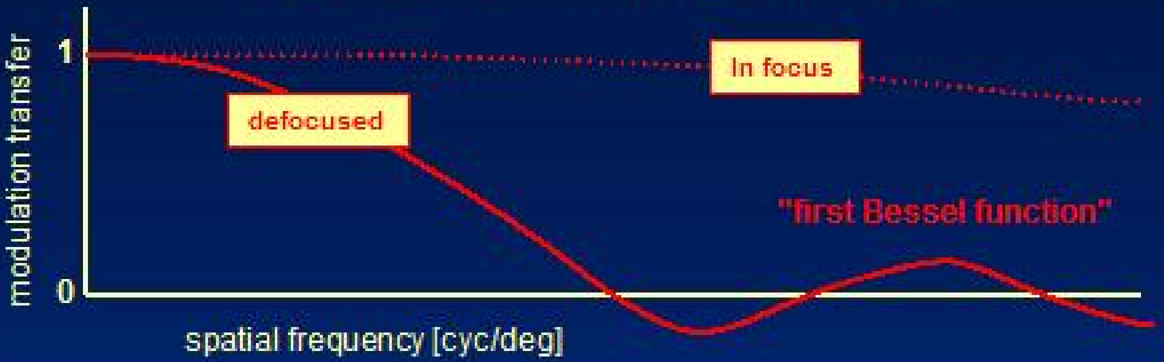
$$= \frac{\text{contrast (out)}}{\text{contrast (in)}}$$

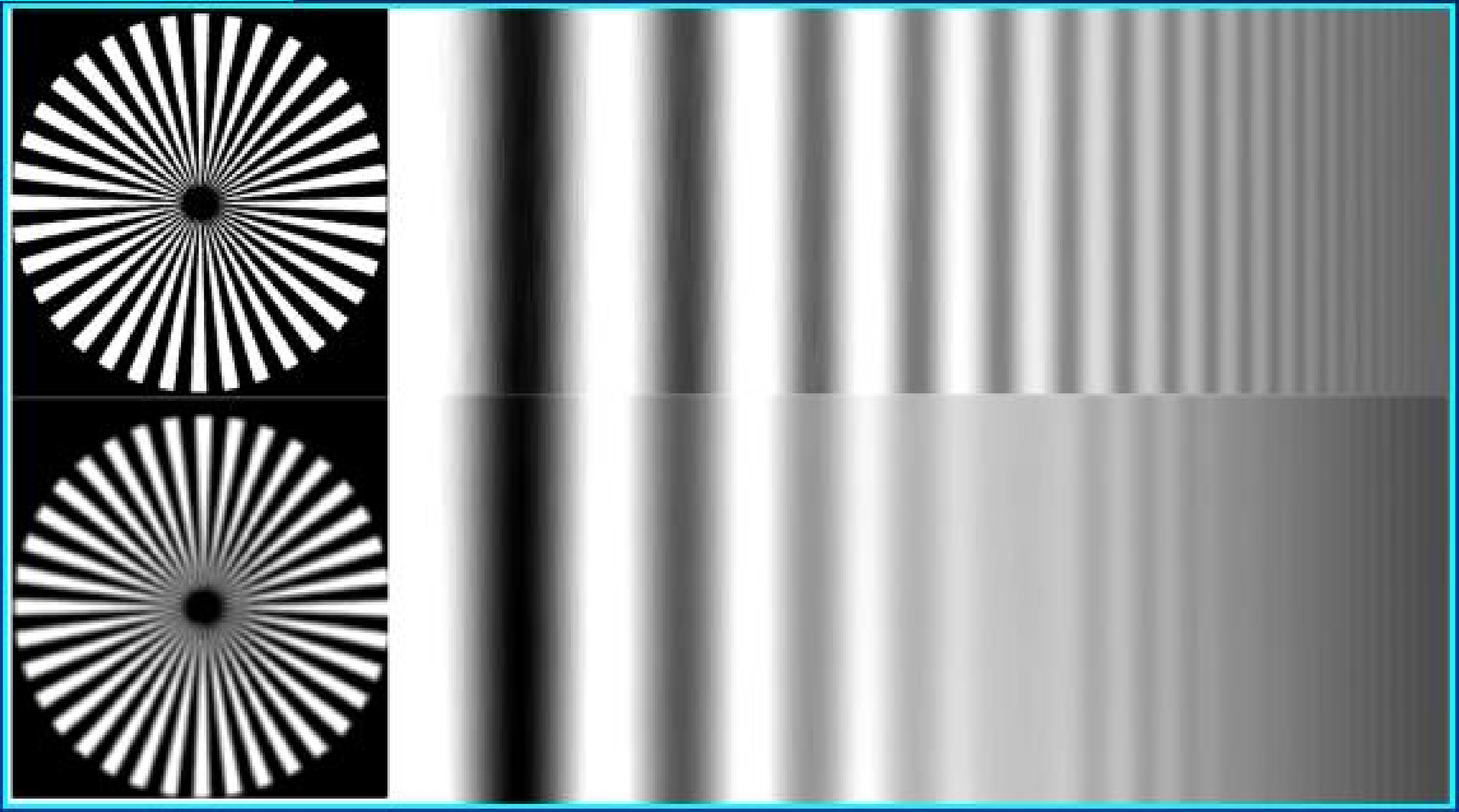


Modulation transfer function

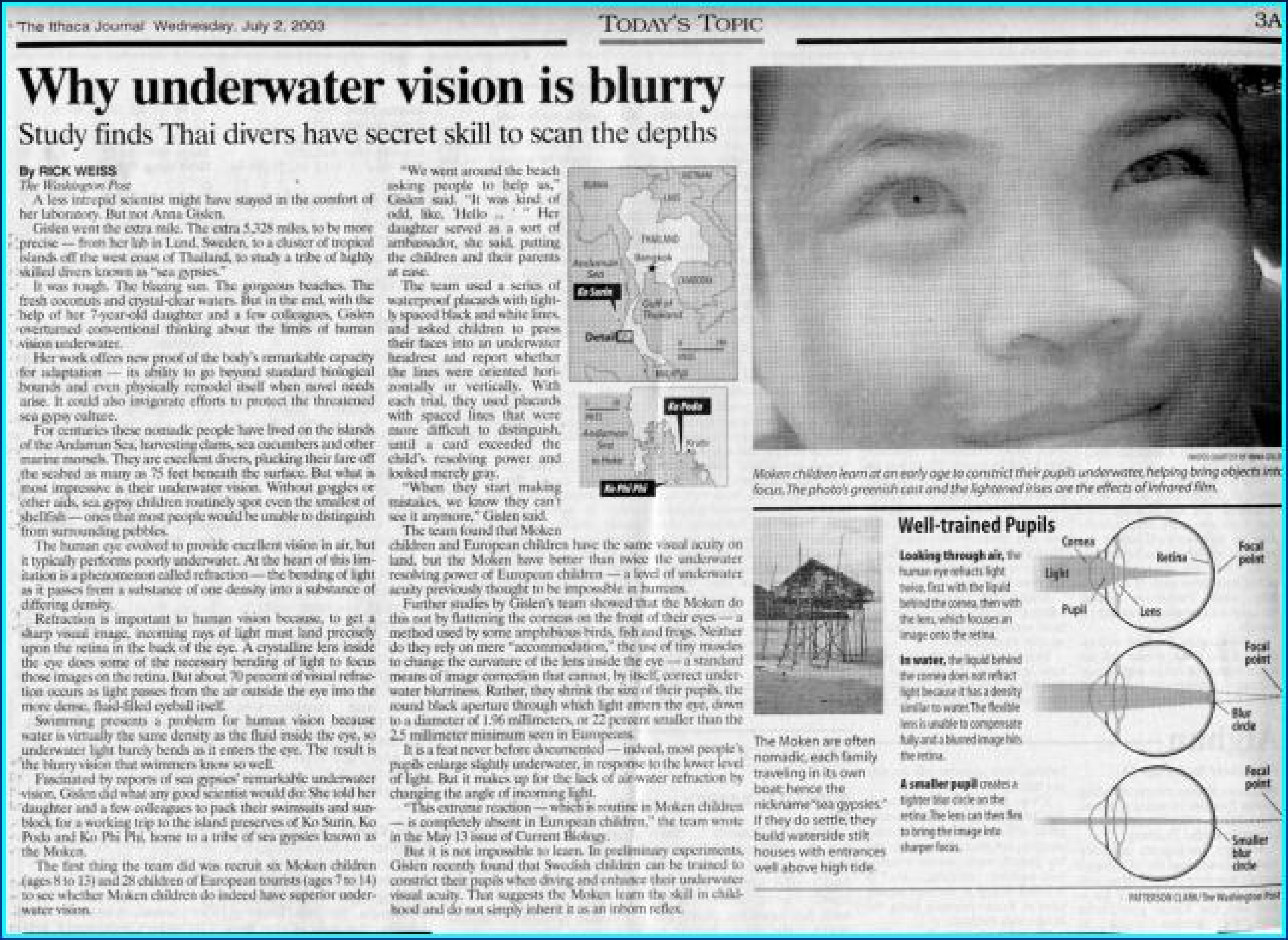
with defocus: "spurious resolution"







Extreme underwater visual acuity in Thai children?



The Ithaca Journal Wednesday, July 2, 2003 TODAY'S TOPIC 3A

Why underwater vision is blurry

Study finds Thai divers have secret skill to scan the depths

By RICK WEISS
The Washington Post

A less intrepid scientist might have stayed in the comfort of her laboratory. But not Anna Gislen.

Gislen went the extra mile. The extra 5,328 miles, to be more precise — from her lab in Lund, Sweden, to a cluster of tropical islands off the west coast of Thailand, to study a tribe of highly skilled divers known as "sea gypsies."

It was tough. The blazing sun. The gorgeous beaches. The fresh coconuts and crystal-clear waters. But in the end, with the help of her 7-year-old daughter and a few colleagues, Gislen overturned conventional thinking about the limits of human vision underwater.

Her work offers new proof of the body's remarkable capacity for adaptation — its ability to go beyond standard biological bounds and even physically remodel itself when novel needs arise. It could also invigorate efforts to protect the threatened sea gypsy culture.

For centuries these nomadic people have lived on the islands of the Andaman Sea, harvesting clams, sea cucumbers and other marine morsels. They are excellent divers, plucking their fare off the seabed as many as 75 feet beneath the surface. But what is most impressive is their underwater vision. Without goggles or other aids, sea gypsy children routinely spot even the smallest of shellfish — ones that most people would be unable to distinguish from surrounding pebbles.

The human eye evolved to provide excellent vision in air, but it typically performs poorly underwater. At the heart of this limitation is a phenomenon called refraction — the bending of light as it passes from a substance of one density into a substance of differing density.

Refraction is important to human vision because, to get a sharp visual image, incoming rays of light must land precisely upon the retina in the back of the eye. A crystalline lens inside the eye does some of the necessary bending of light to focus those images on the retina. But about 70 percent of visual refraction occurs as light passes from the air outside the eye into the more dense, fluid-filled eyeball itself.

Swimming presents a problem for human vision because water is virtually the same density as the fluid inside the eye, so underwater light barely bends as it enters the eye. The result is the blurry vision that swimmers know so well.

Fascinated by reports of sea gypsies' remarkable underwater vision, Gislen did what any good scientist would do: She told her daughter and a few colleagues to pack their swimsuits and sunblock for a working trip to the island preserves of Ko Surin, Ko Poda and Ko Phi Phi, home to a tribe of sea gypsies known as the Moken.

The first thing the team did was recruit six Moken children (ages 8 to 13) and 28 children of European tourists (ages 7 to 14) to see whether Moken children do indeed have superior underwater vision.

"We went around the beach asking people to help us," Gislen said. "It was kind of odd, like, 'Hello ... .'" Her daughter served as a sort of ambassador, she said, putting the children and their parents at ease.

The team used a series of waterproof placards with tightly spaced black and white lines and asked children to press their faces into an underwater headrest and report whether the lines were oriented horizontally or vertically. With each trial, they used placards with spaced lines that were more difficult to distinguish, until a card exceeded the child's resolving power and looked merely gray.

"When they start making mistakes, we know they can't see it anymore," Gislen said.

The team found that Moken children and European children have the same visual acuity on land, but the Moken have better than twice the underwater resolving power of European children — a level of underwater acuity previously thought to be impossible in humans.

Further studies by Gislen's team showed that the Moken do this not by flattening the corneas on the front of their eyes — a method used by some amphibious birds, fish and frogs. Neither do they rely on mere "accommodation," the use of tiny muscles to change the curvature of the lens inside the eye — a standard means of image correction that cannot, by itself, correct underwater blurriness. Rather, they shrink the size of their pupils, the round black aperture through which light enters the eye, down to a diameter of 1.96 millimeters, or 22 percent smaller than the 2.5 millimeter minimum seen in Europeans.

It is a feat never before documented — indeed, most people's pupils enlarge slightly underwater, in response to the lower level of light. But it makes up for the lack of air-water refraction by changing the angle of incoming light.

"This extreme reaction — which is routine in Moken children — is completely absent in European children," the team wrote in the May 13 issue of Current Biology.

But it is not impossible to learn. In preliminary experiments, Gislen recently found that Swedish children can be trained to constrict their pupils when diving and enhance their underwater visual acuity. That suggests the Moken learn the skill in childhood and do not simply inherit it as an inborn reflex.

Moken children learn at an early age to constrict their pupils underwater, helping bring objects int
focus. The photo's greenish cast and the lightened irises are the effects of infrared film.

The Moken are often nomadic, each family traveling in its own boat: hence the nickname "sea gypsies." If they do settle, they build waterside stilt houses with entrances well above high tide.

Well-trained Pupils

Looking through air, the human eye refracts light twice, first with the liquid behind the cornea, then with the lens, which focuses an image onto the retina.

In water, the liquid behind the cornea does not refract light because it has a density similar to water. The flexible lens is unable to compensate fully and a blurred image hits the retina.

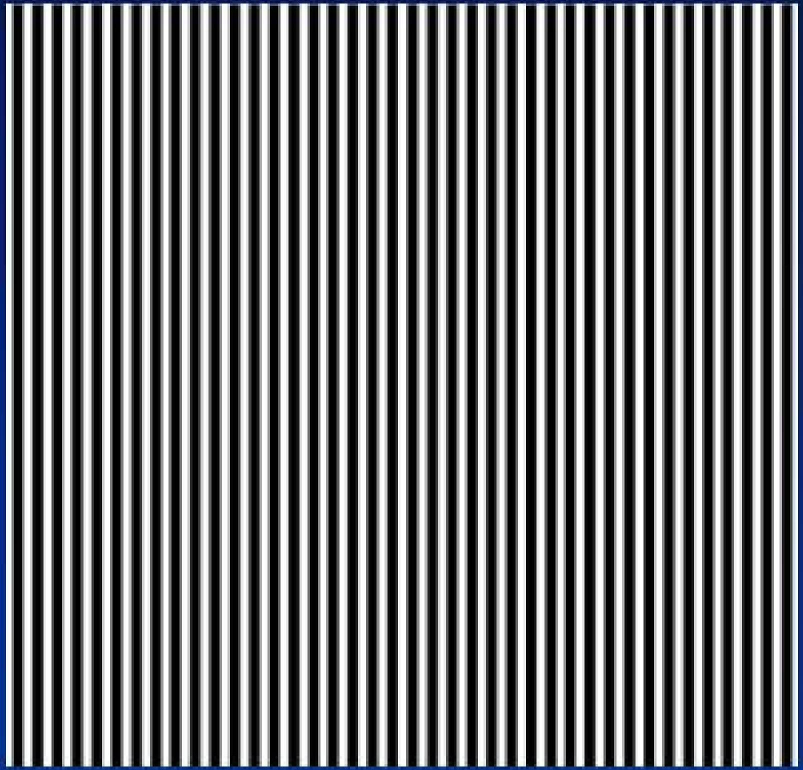
A smaller pupil creates a tighter blur circle on the retina. The lens can then flex to bring the image into sharper focus.

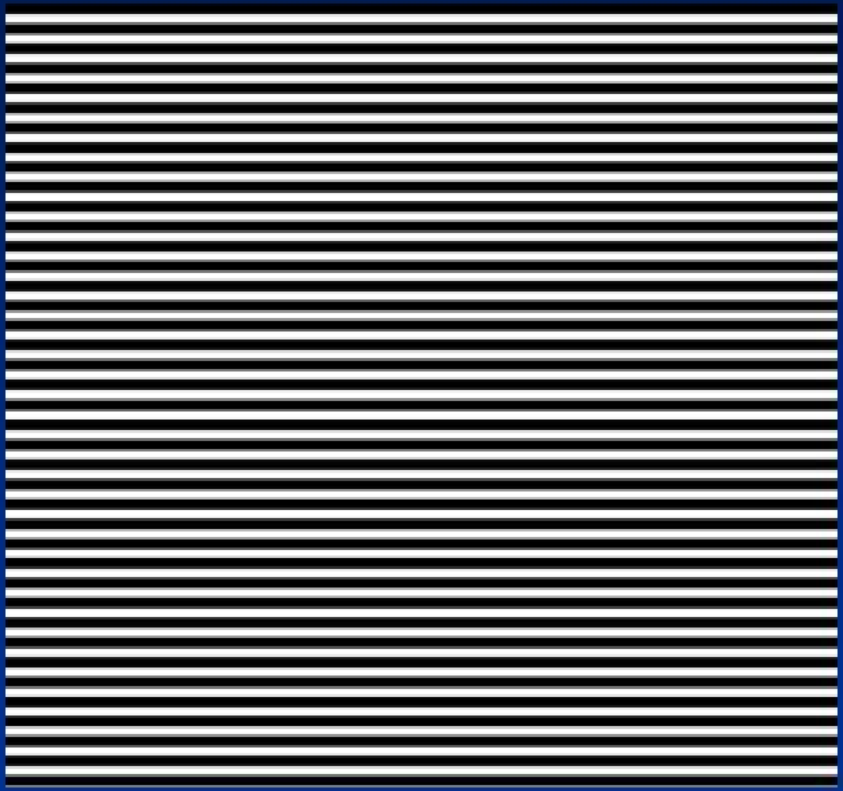
PATTERSON CLARK/The Washington Post

Modulation transfer function

orientation of stripes can be seen even with severe defocus

(spurious resolution)

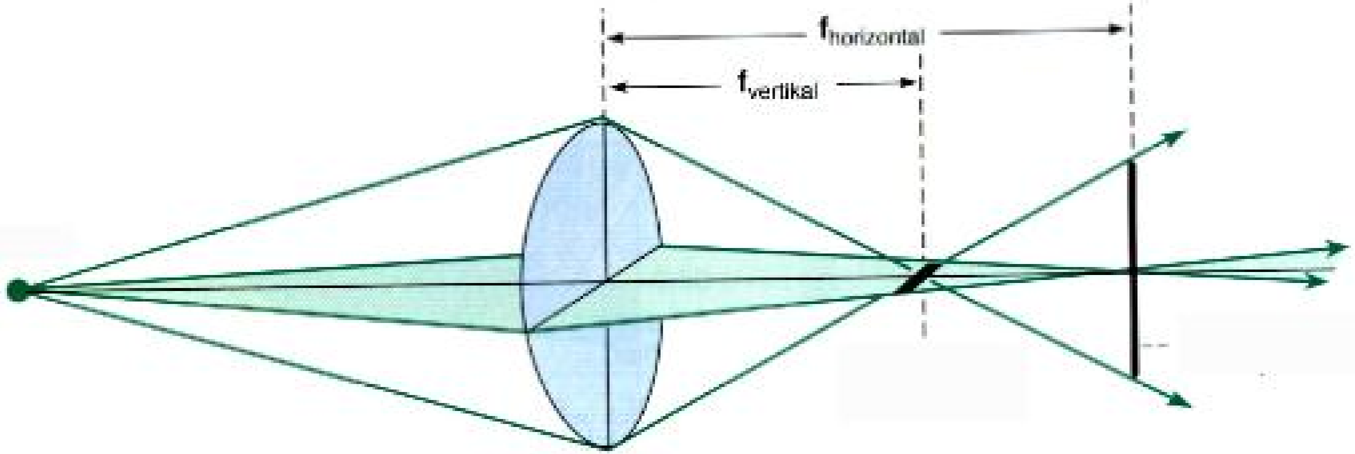


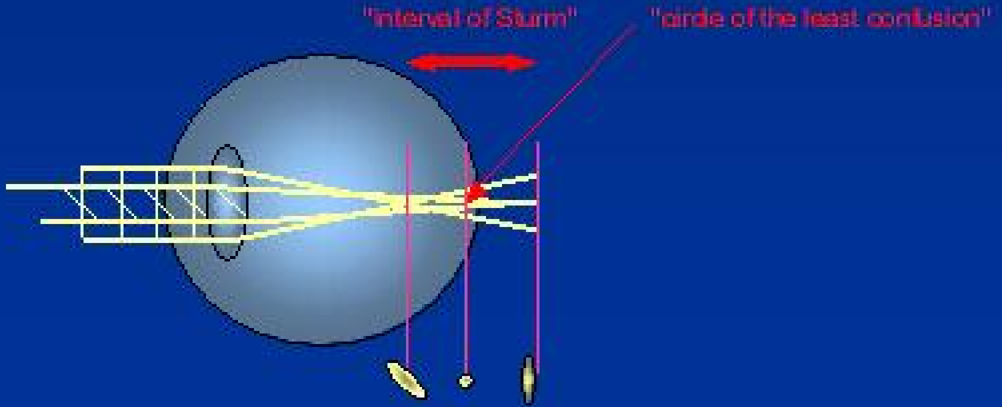


Astigmatism

for instance:

radius of curvature smaller in vertical than in horizontal meridian





How does this look in real images?

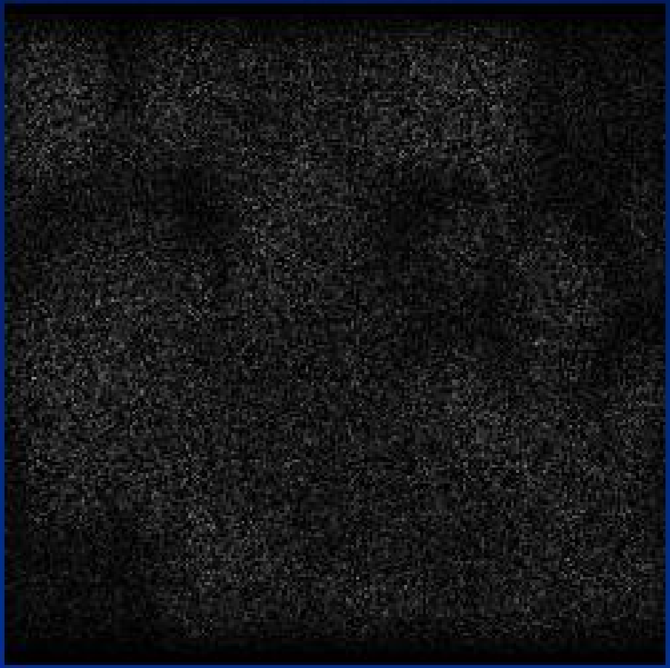
+5.5 D defocus

Spherical defocus

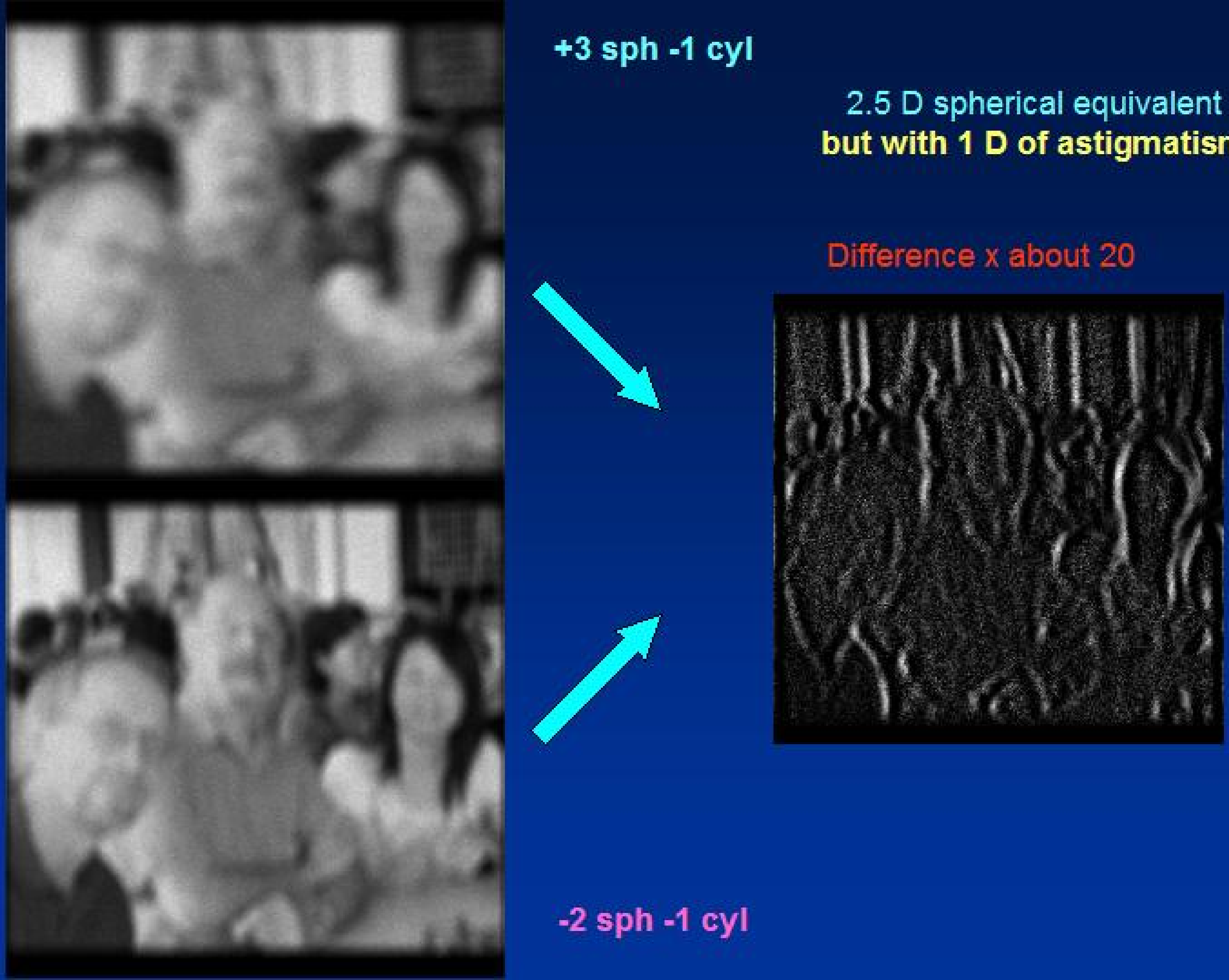
-5.5 D defocus

+5.5 D defocus

Difference x about 20



-5.5 D defocus



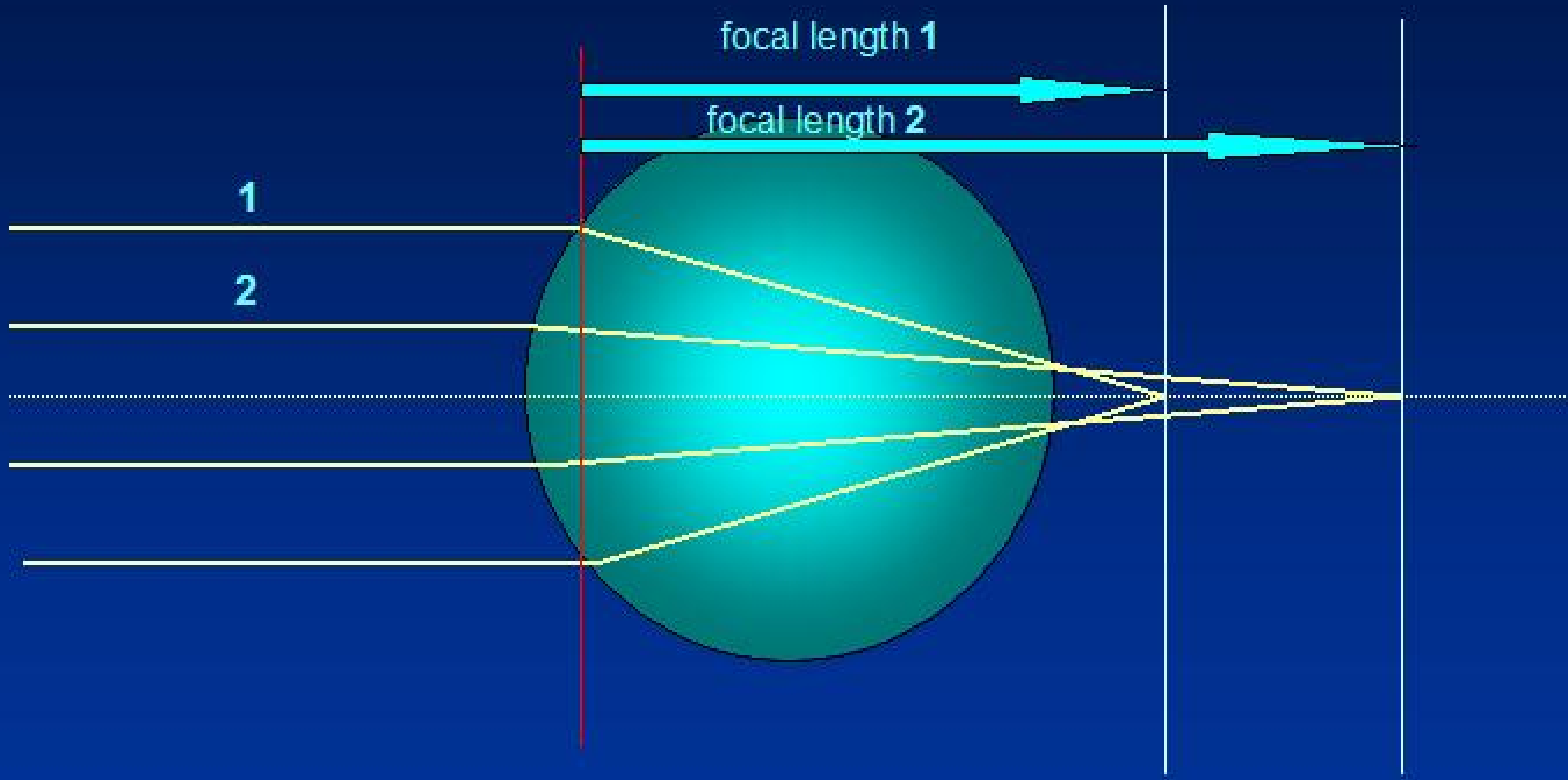
+3 sph -1 cyl

2.5 D spherical equivalent
but with 1 D of astigmatism

Difference x about 20

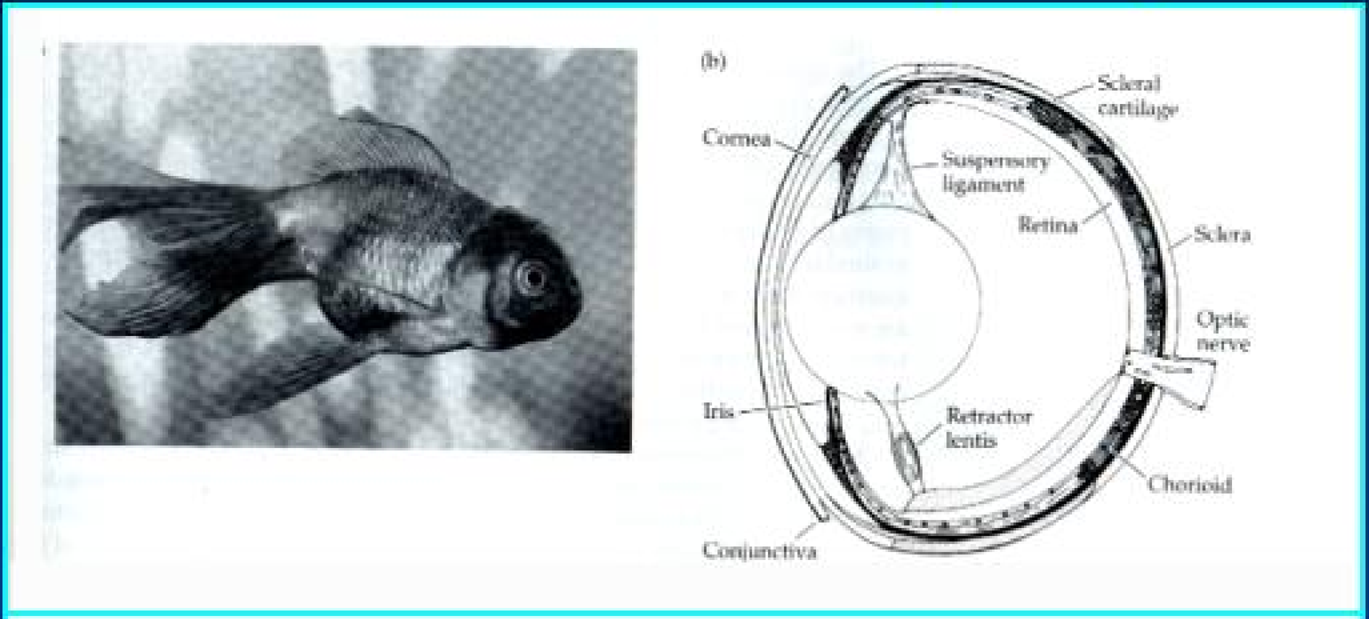
-2 sph -1 cyl

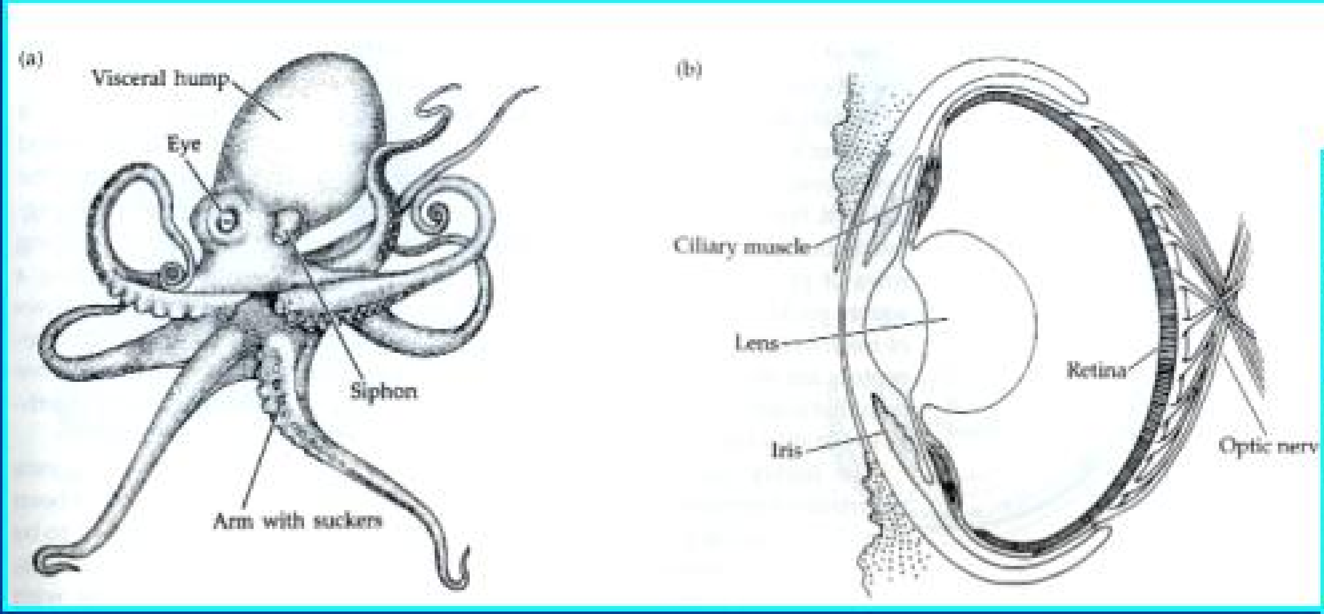
Spherical aberration



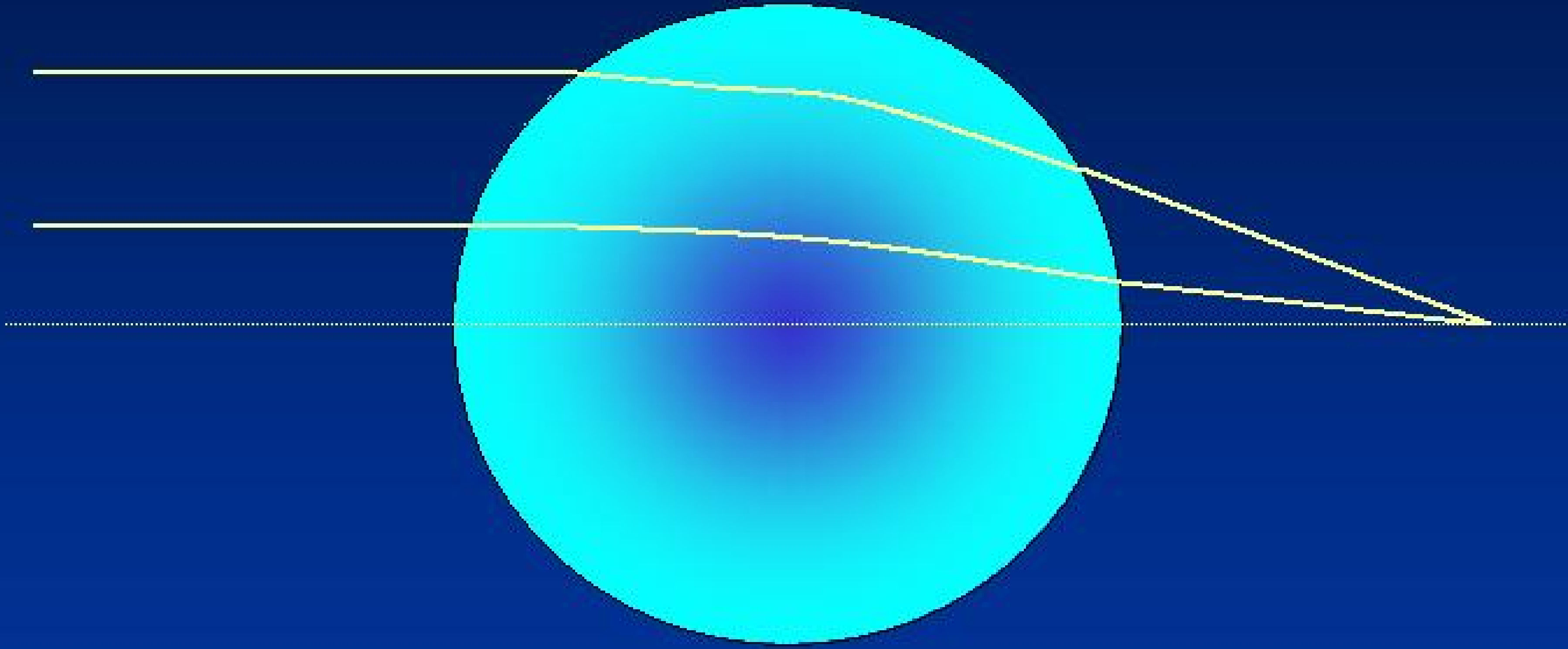
general : refractive power [D] = 1 / focal length [m]

- spherical aberration of the lens is particularly critical in fish and other aquatic eyes



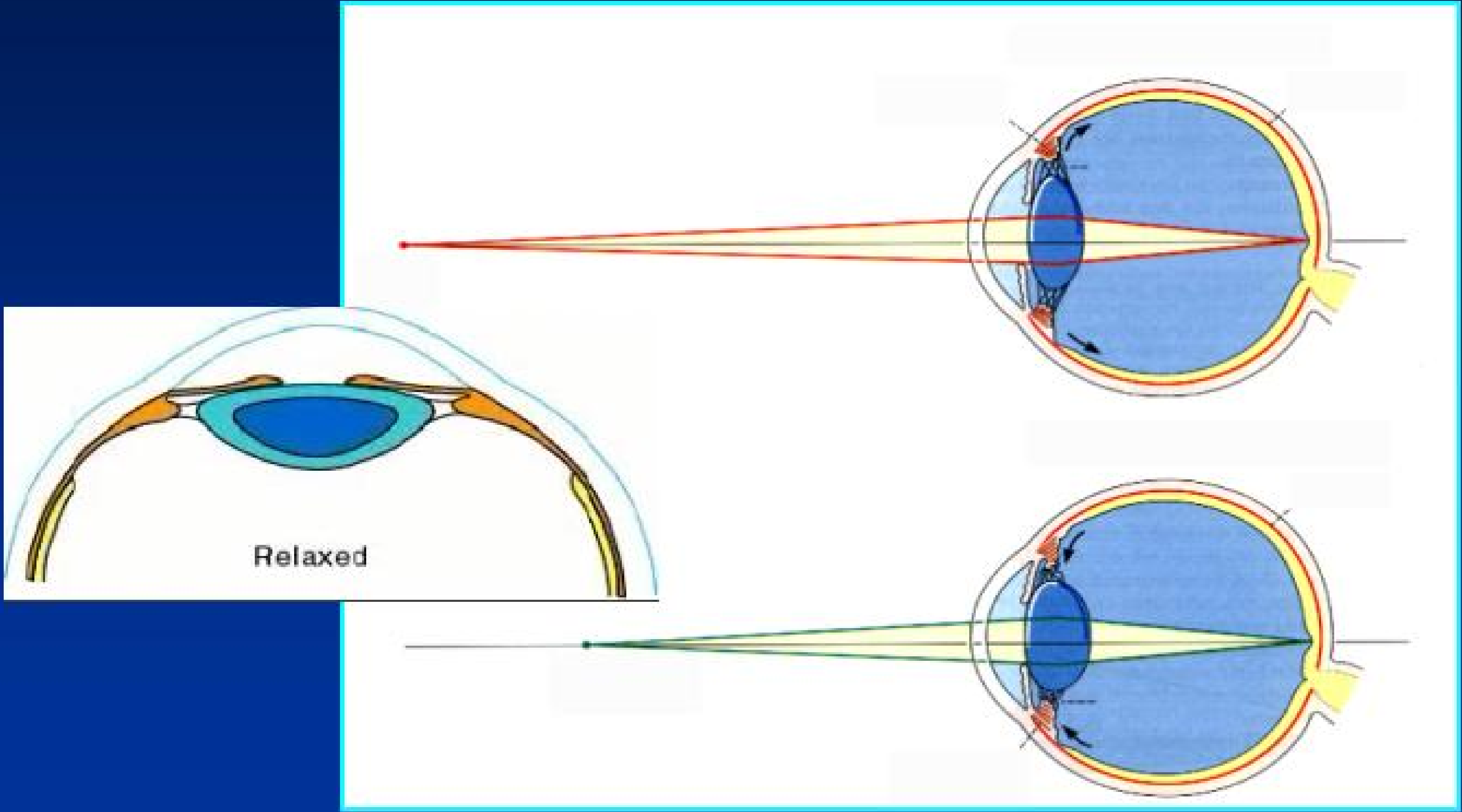


- solution for spherical aberration



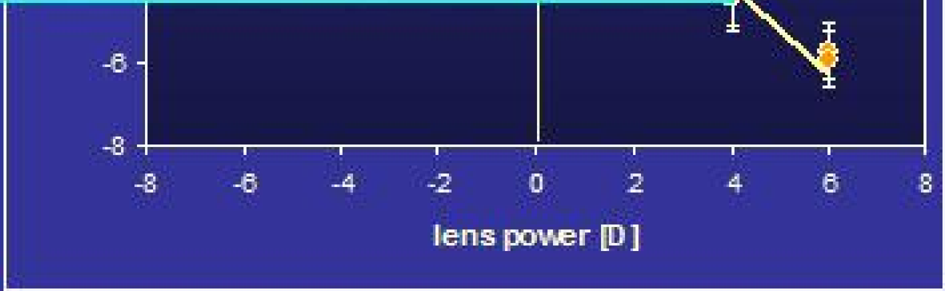
gradient index lens (GRIN lens)

Optimizing image focus at different viewing distances - accommodation

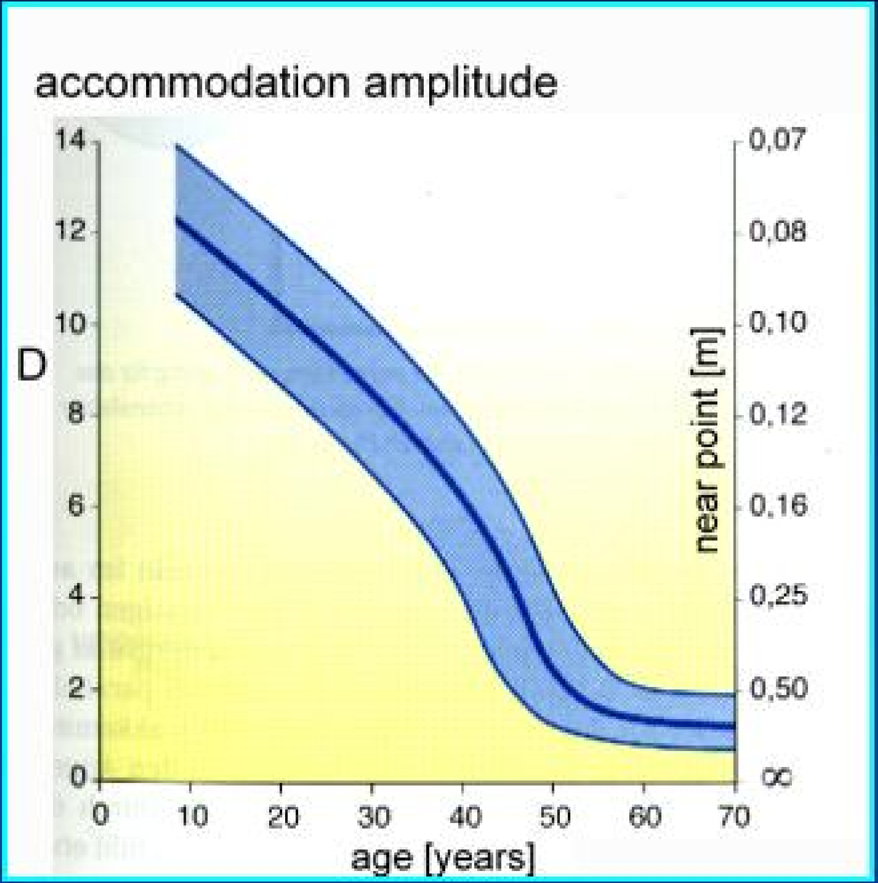


reading ta


ANALYZE
Pupillen
links
rechts
mm
8
6
4
2
0
2
4
Zeit [s]
8
10
Refraktionen
D
+2
0
-2
-4
-6
+20
0
-20
-40
-60
0
2
4
Zeit [s]
8
10

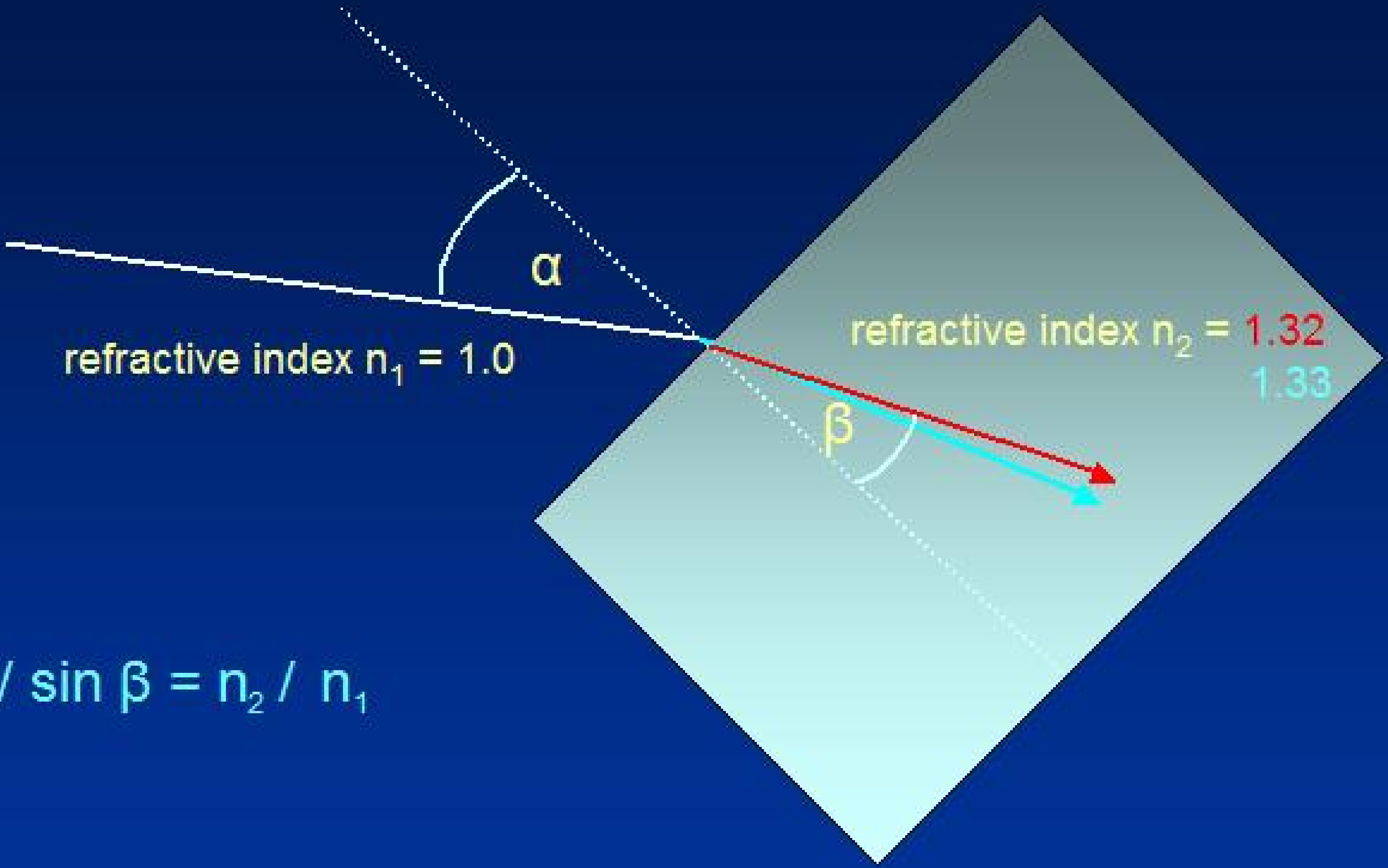

ction =
action - 0.0329
7
-6
-8
-8
-6
-4
-2
0
2
4
6
8
lens power [D]

but this does no longer work beyond 45 of age: presbyopia



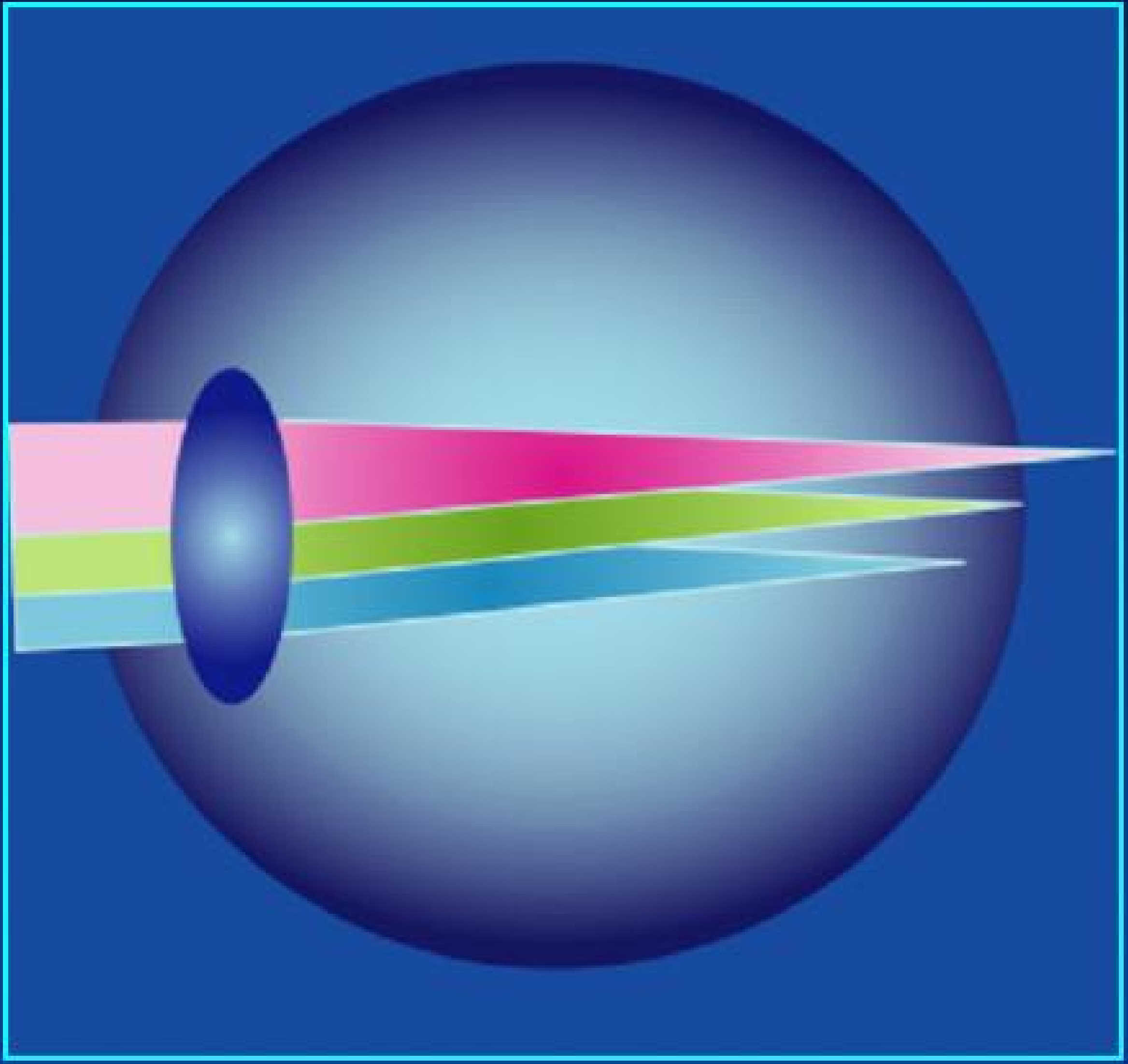
Chromatic Aberration

Snell's law

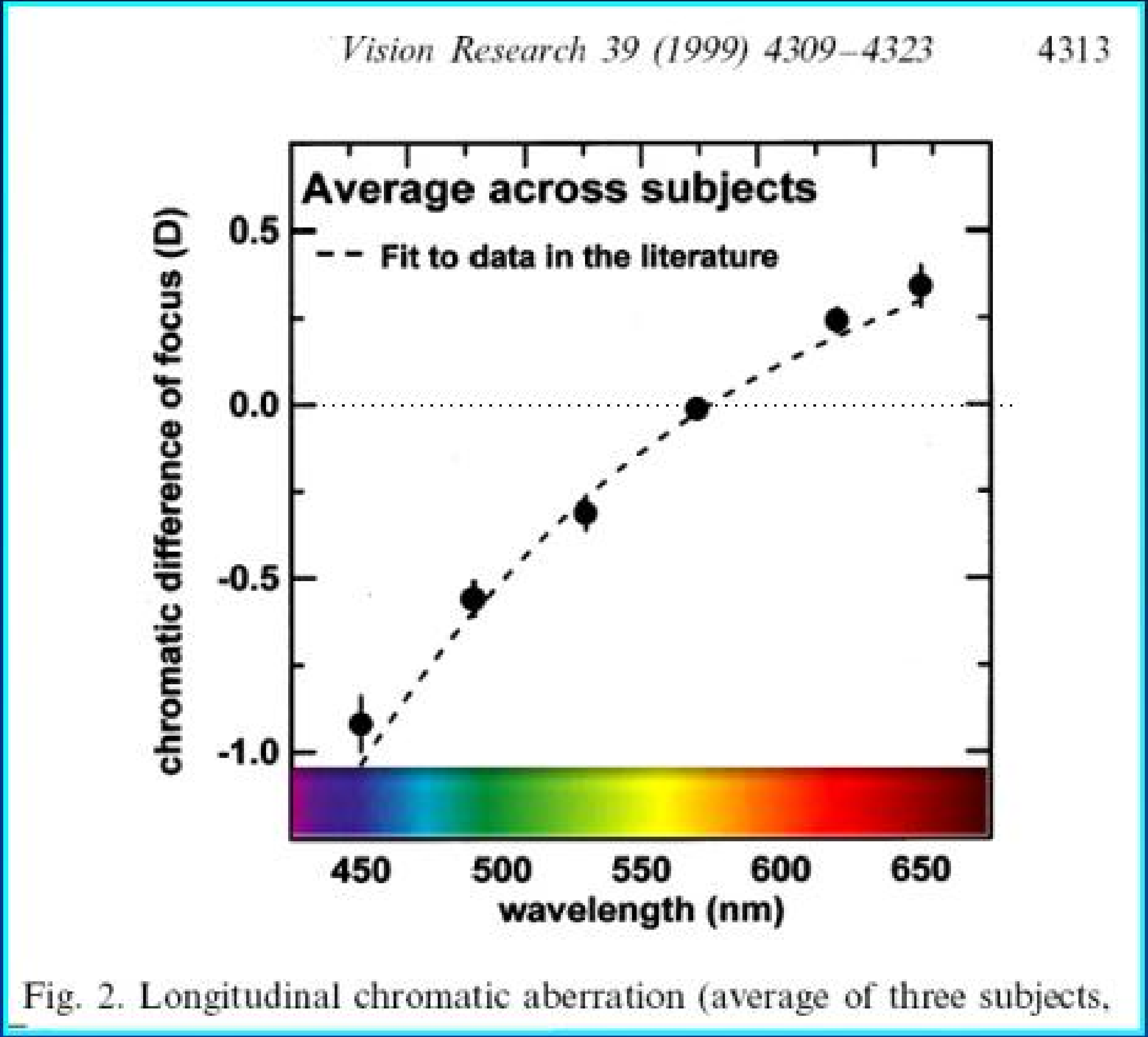


$\sin \alpha / \sin \beta = n_2 / n_1$

Longitudinal chromatic aberration



Dioptric amount of longitudinal chromatic aberration in humans

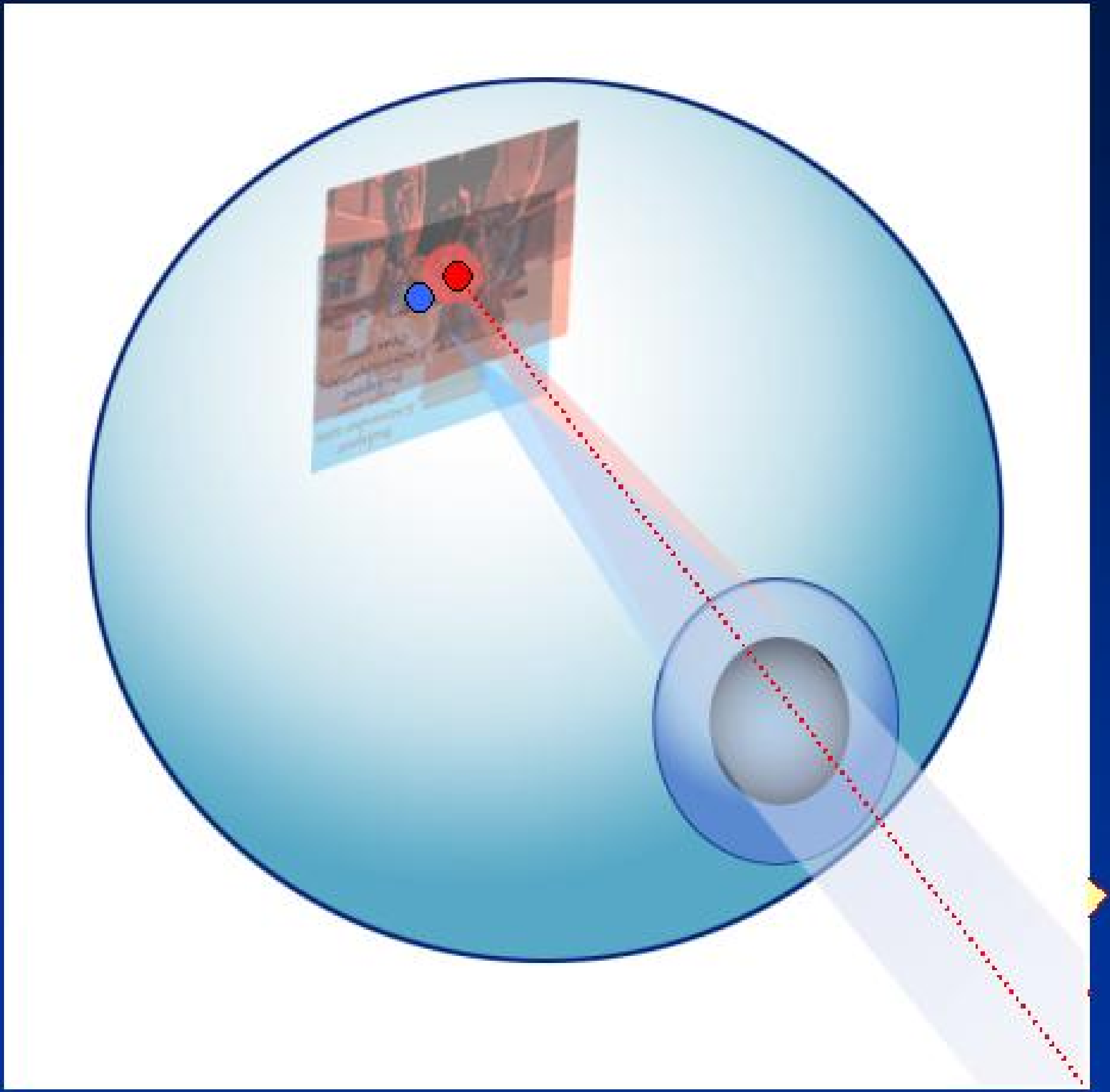


Vision Research 39 (1999) 4309–4323 4313

Fig. 2. Longitudinal chromatic aberration (average of three subjects,

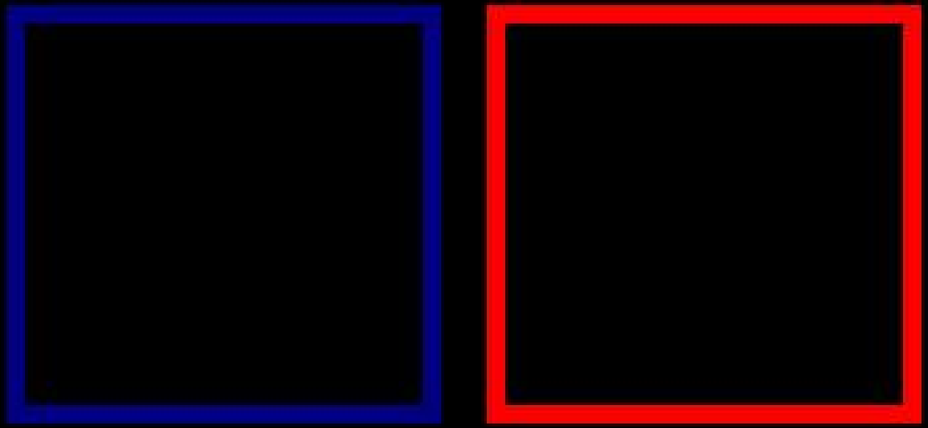
Marcos S, Burns SA, Moreno-Barriusop E, Navarro R
Vision Research 39, 4309-4323 (1999)

transverse chromatic aberration

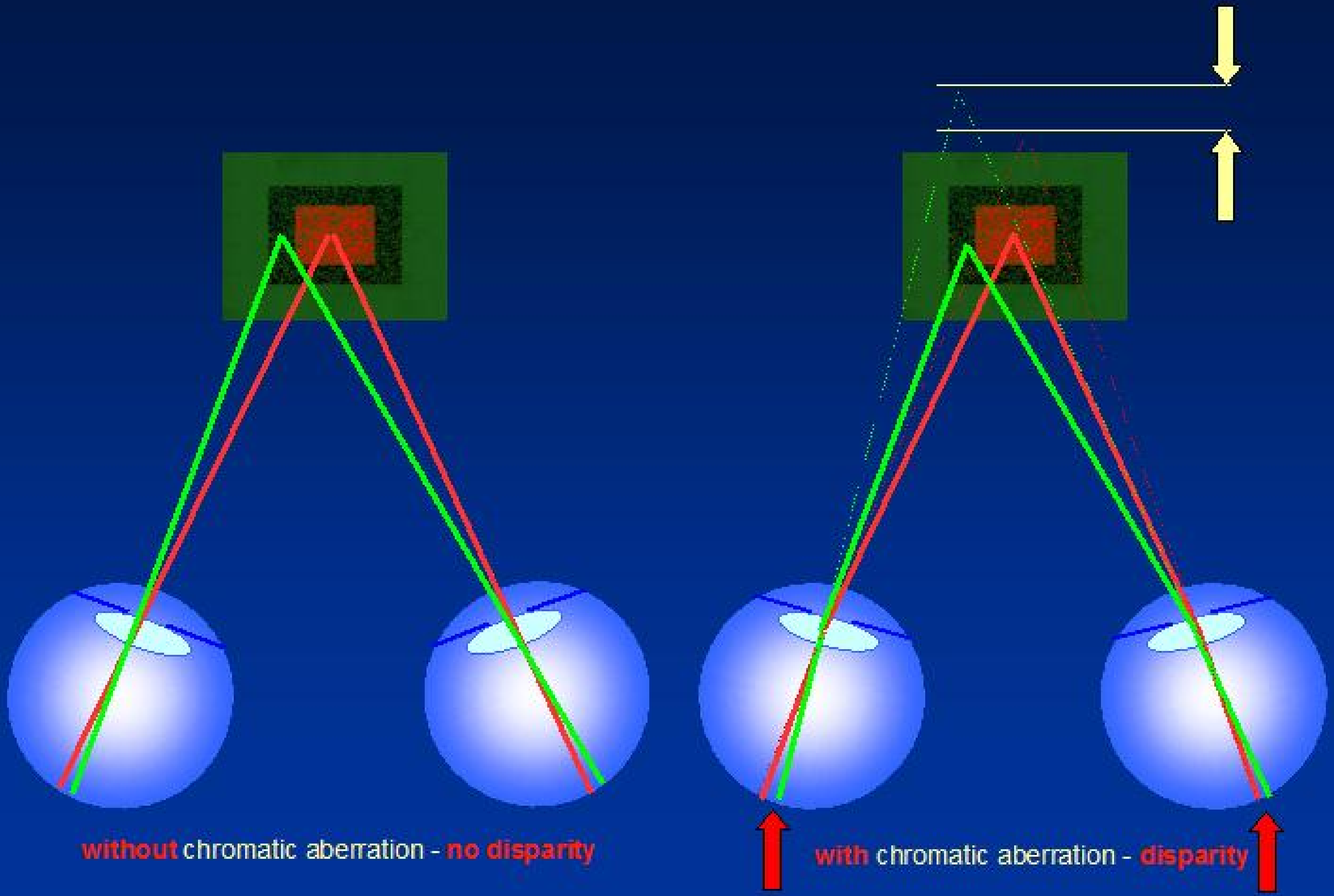


transverse chromatic aberration (3% difference in magnification from blue to red))

bei der Arbeit ....ARVO 2004
(damit jeder in seinen Vorurteilen bestätigt wird)

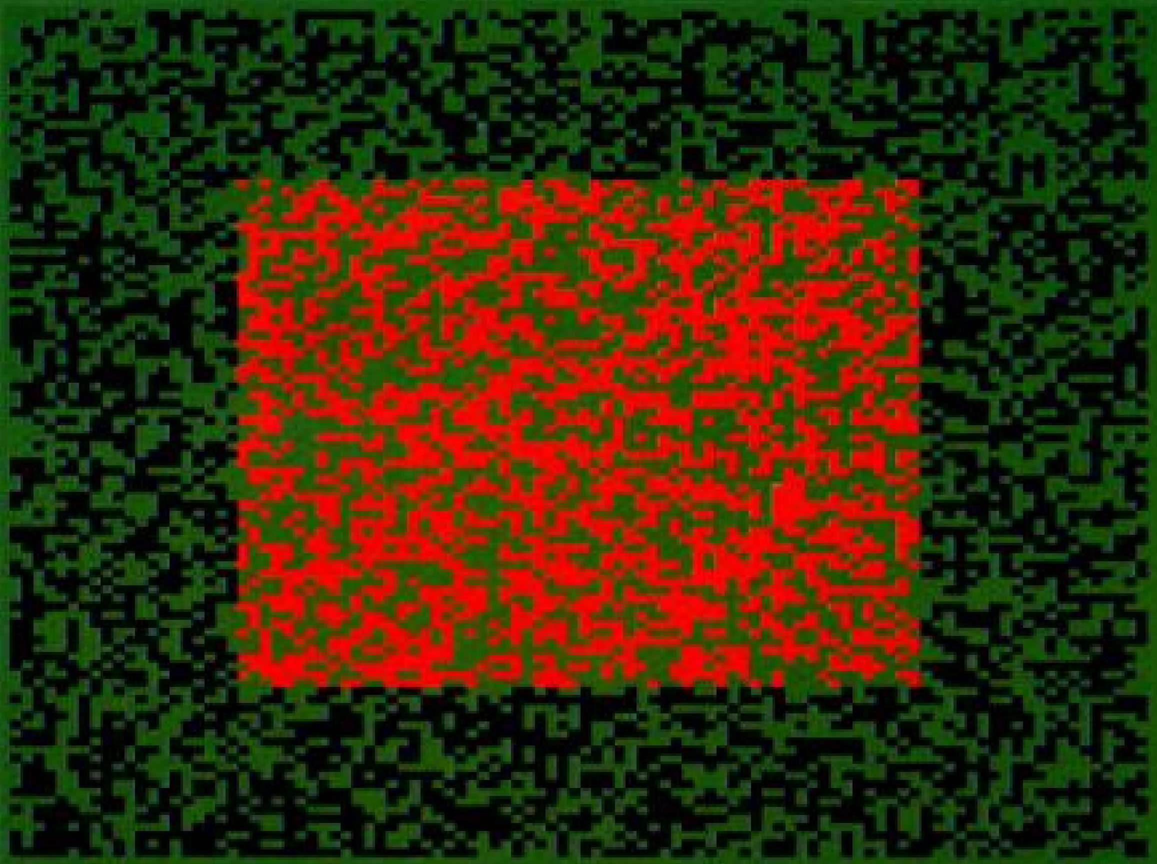


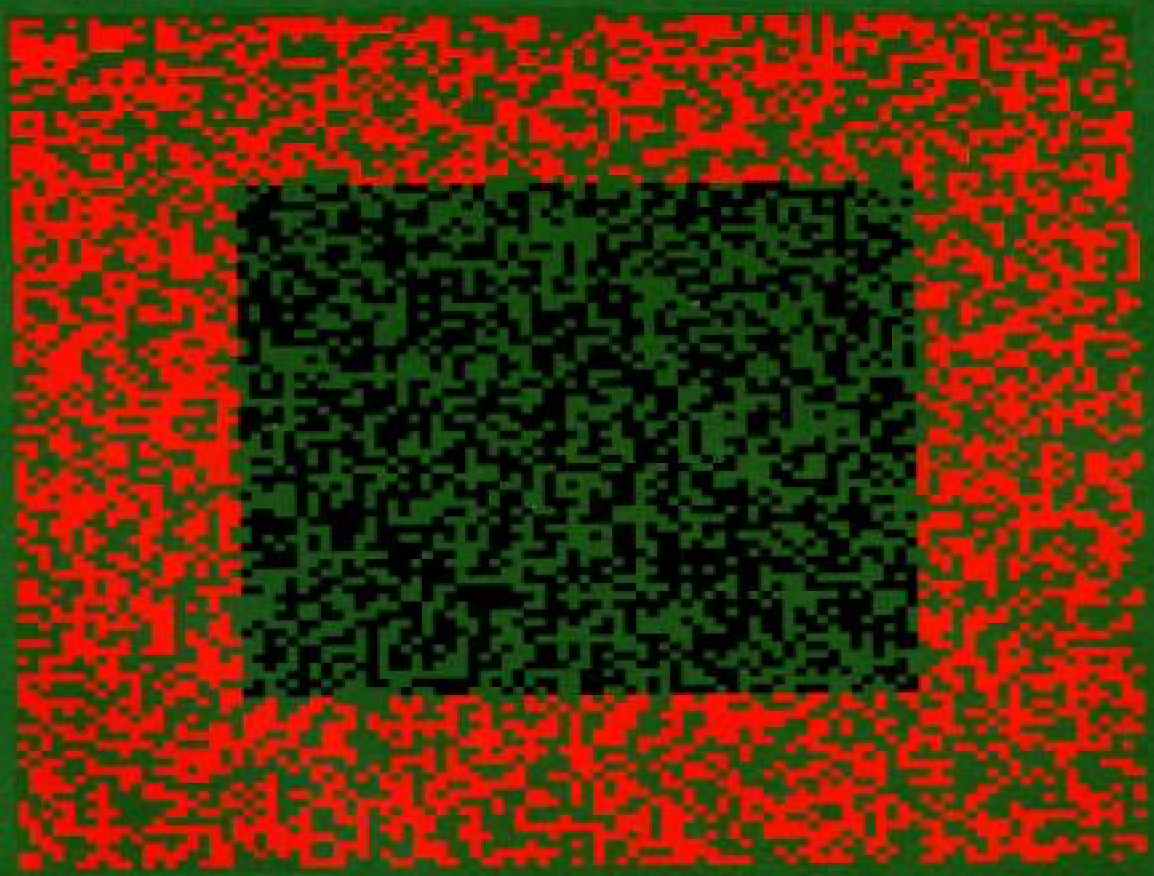
Chromostereopsis



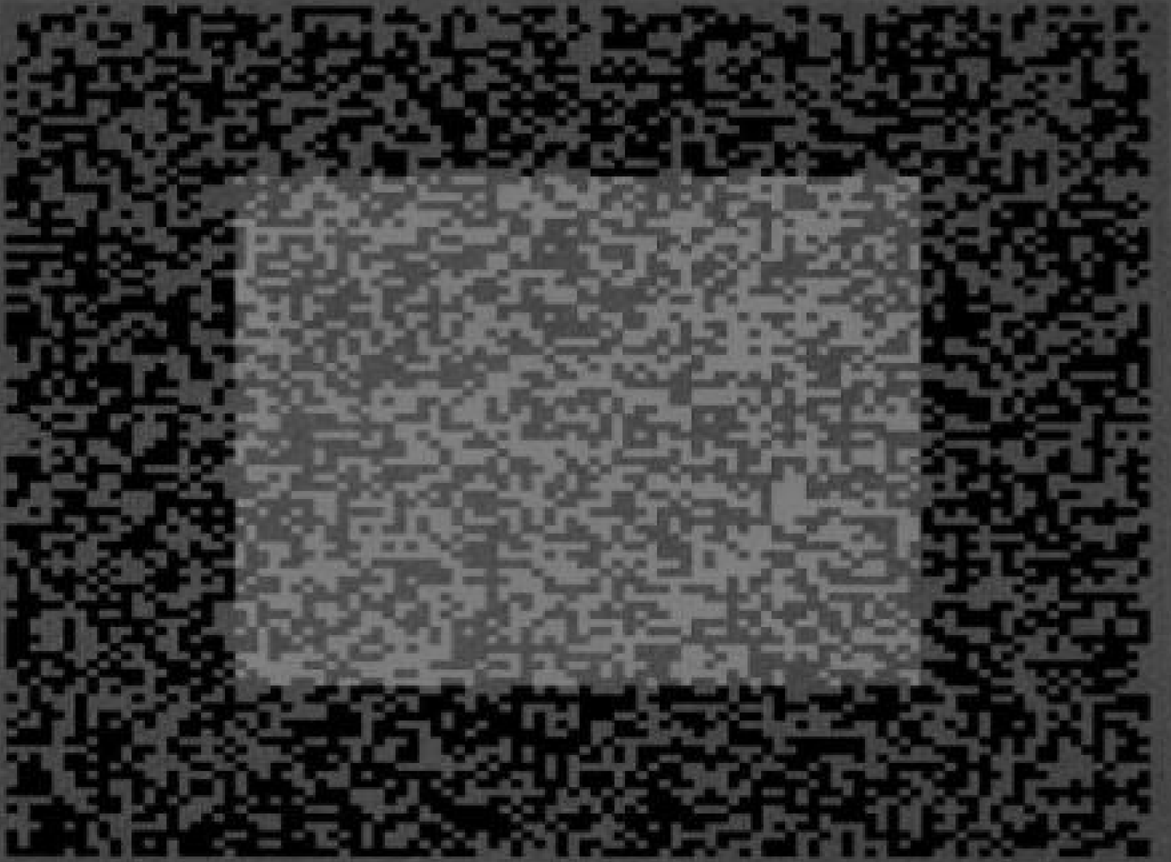
without chromatic aberration - **no disparity**

with chromatic aberration - **disparity**

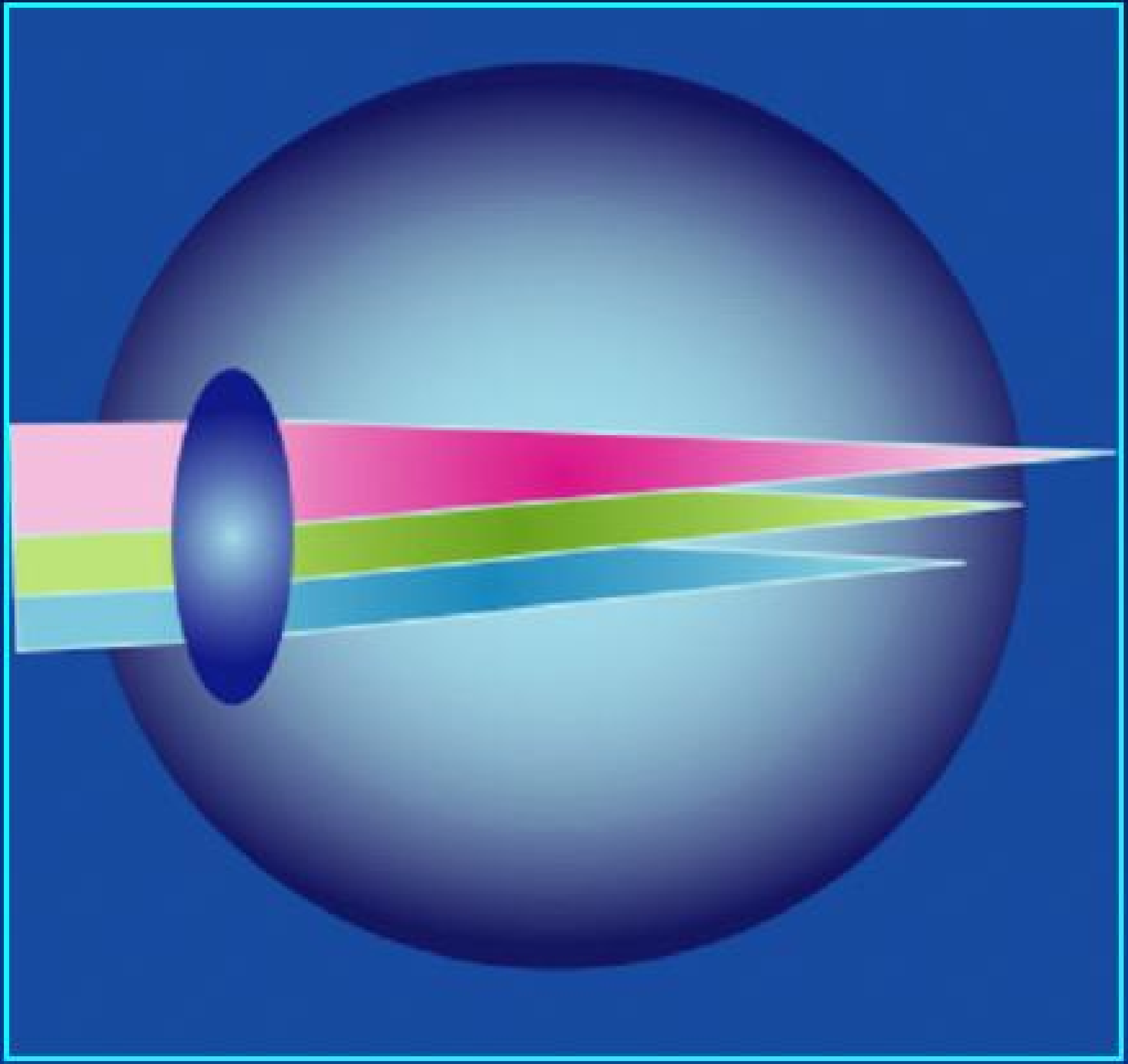




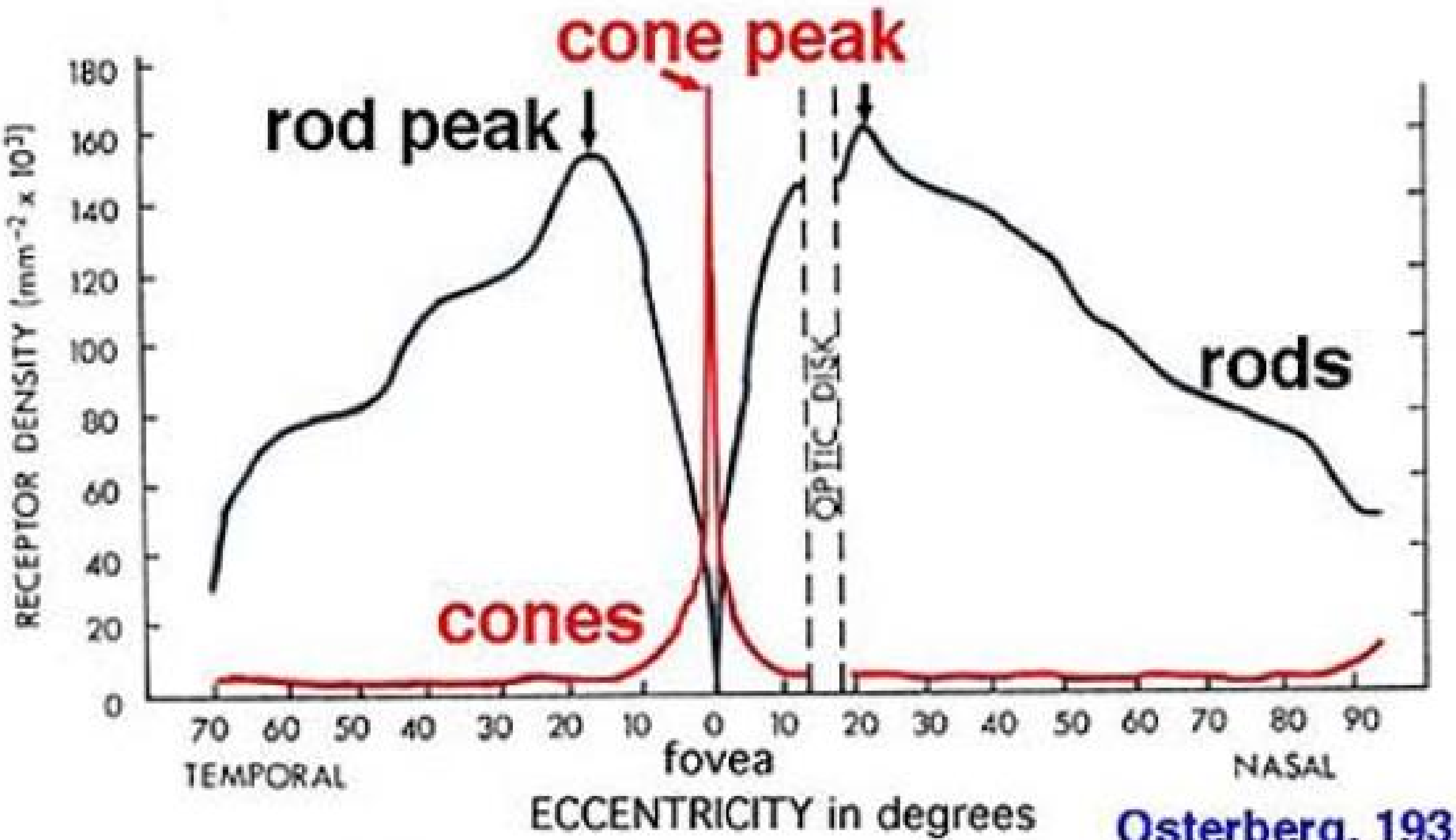
Faubert, *Vision Research* **34**, 1165-1186 (1994)



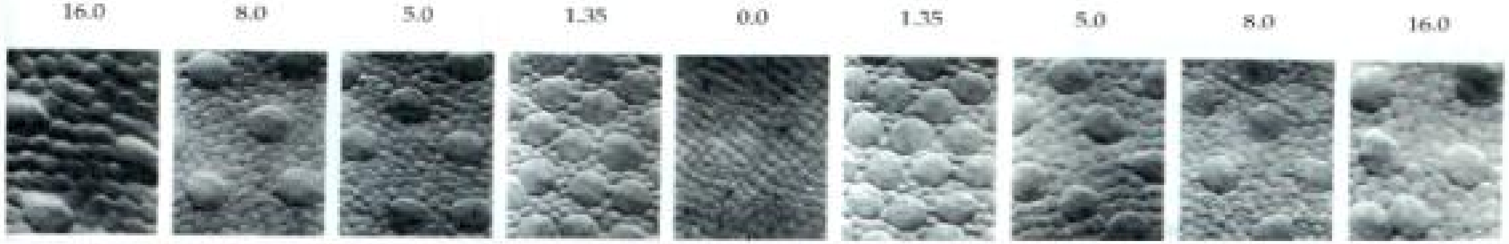
Visual acuity and chromatic aberration



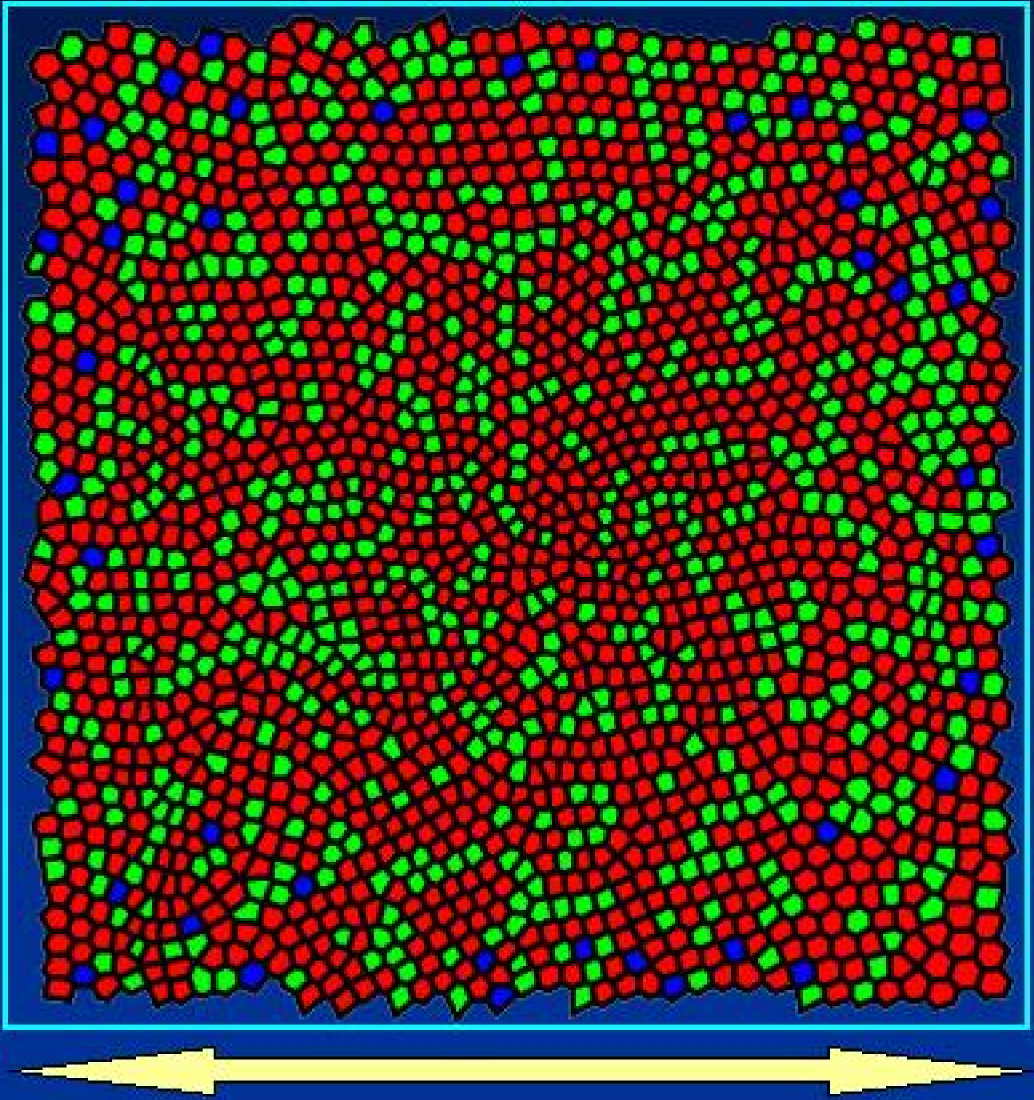
distribution of rods and cones over the visual field



Osterberg, 1935



foveal cone mosaic



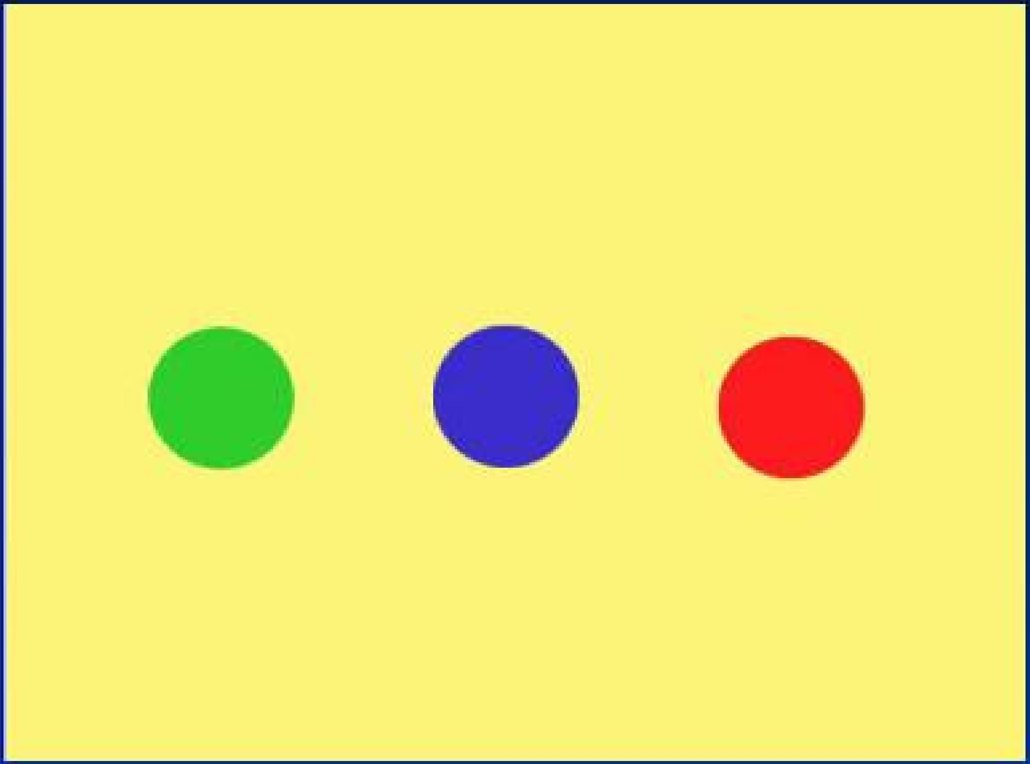
S cone = short wavelength cone ("blue cone")
M cone = mid wavelength cone ("green cone")
L cone = long wavelength cone ("red cone")

The computer simulated model shows the cone mosaic of the fovea of an adult human retina.
A red/green cone ratio of 1.7:1 is shown.
Only 7% of all cones are blue cones.

(tangential section on the level of inner segments, mosaic approx. 0.4° in diameter)

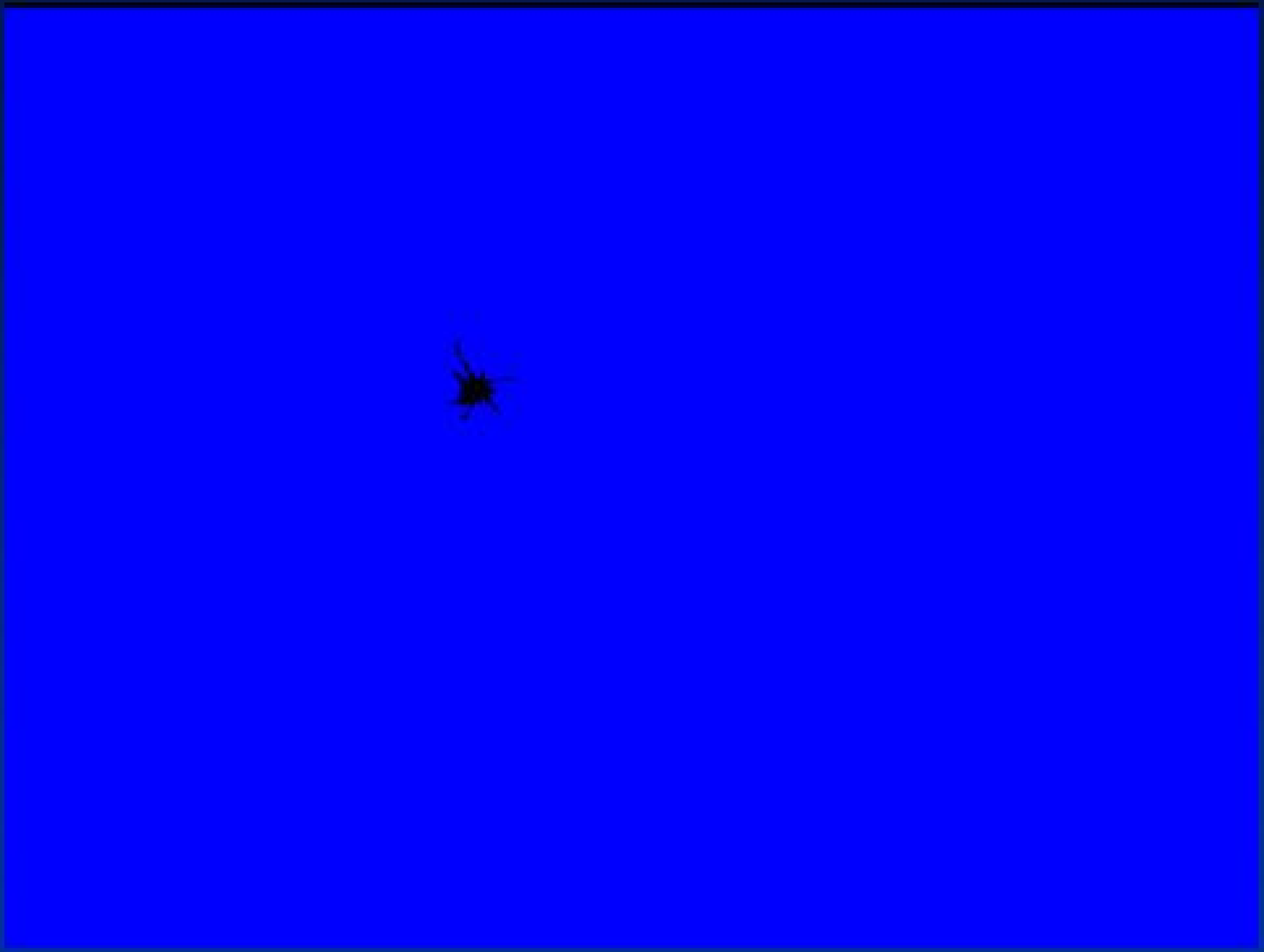
courtesy Lindsay T Sharpe (1999)

The fovea cannot distinguish blue



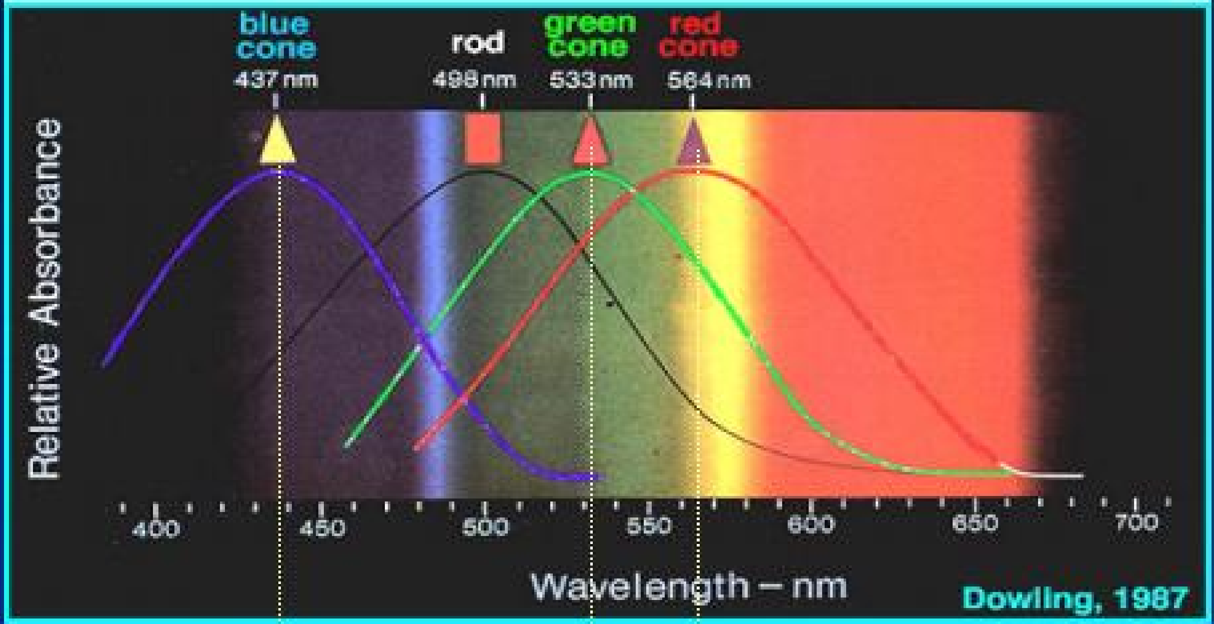
Demonstration of the lack of blue cones in the fovea

(monocular viewing)

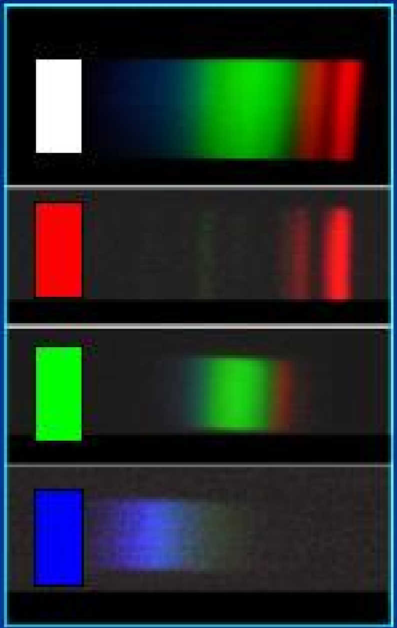


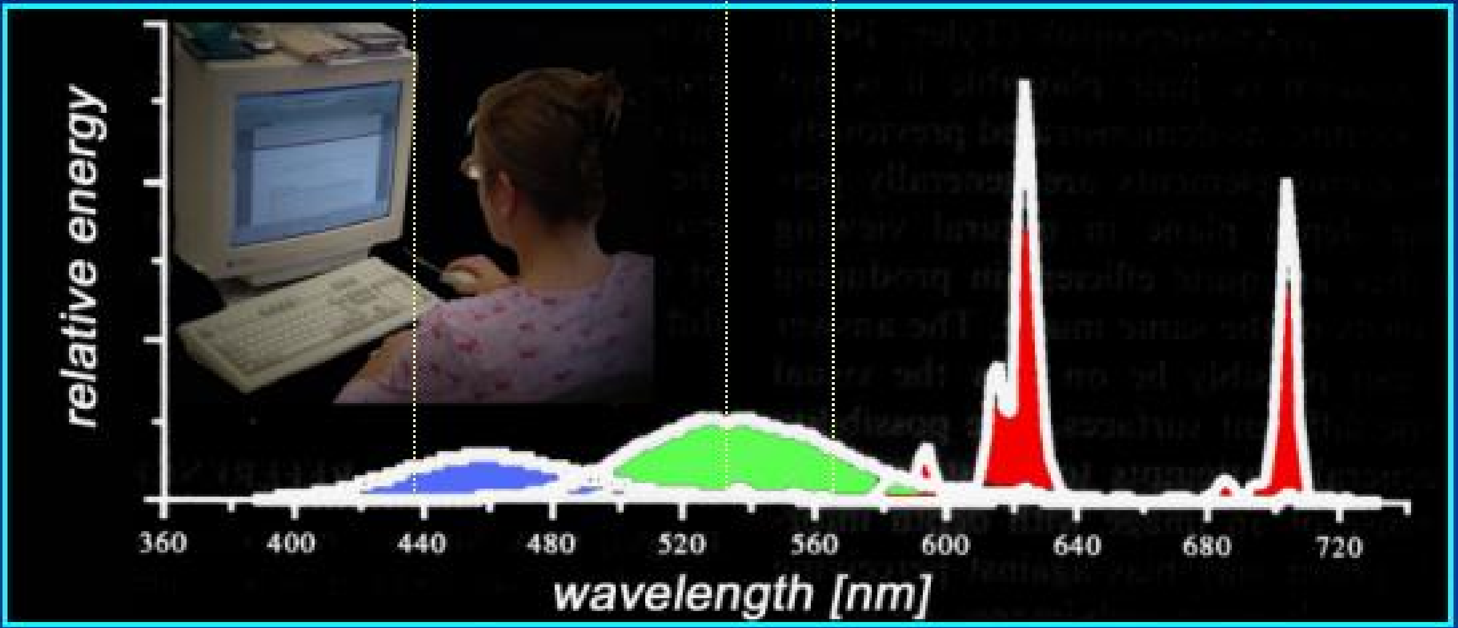
(requires Balzers filter K45 or Kodak BG12 for full effect)

Cone spectra and "guns" of the computer monitor

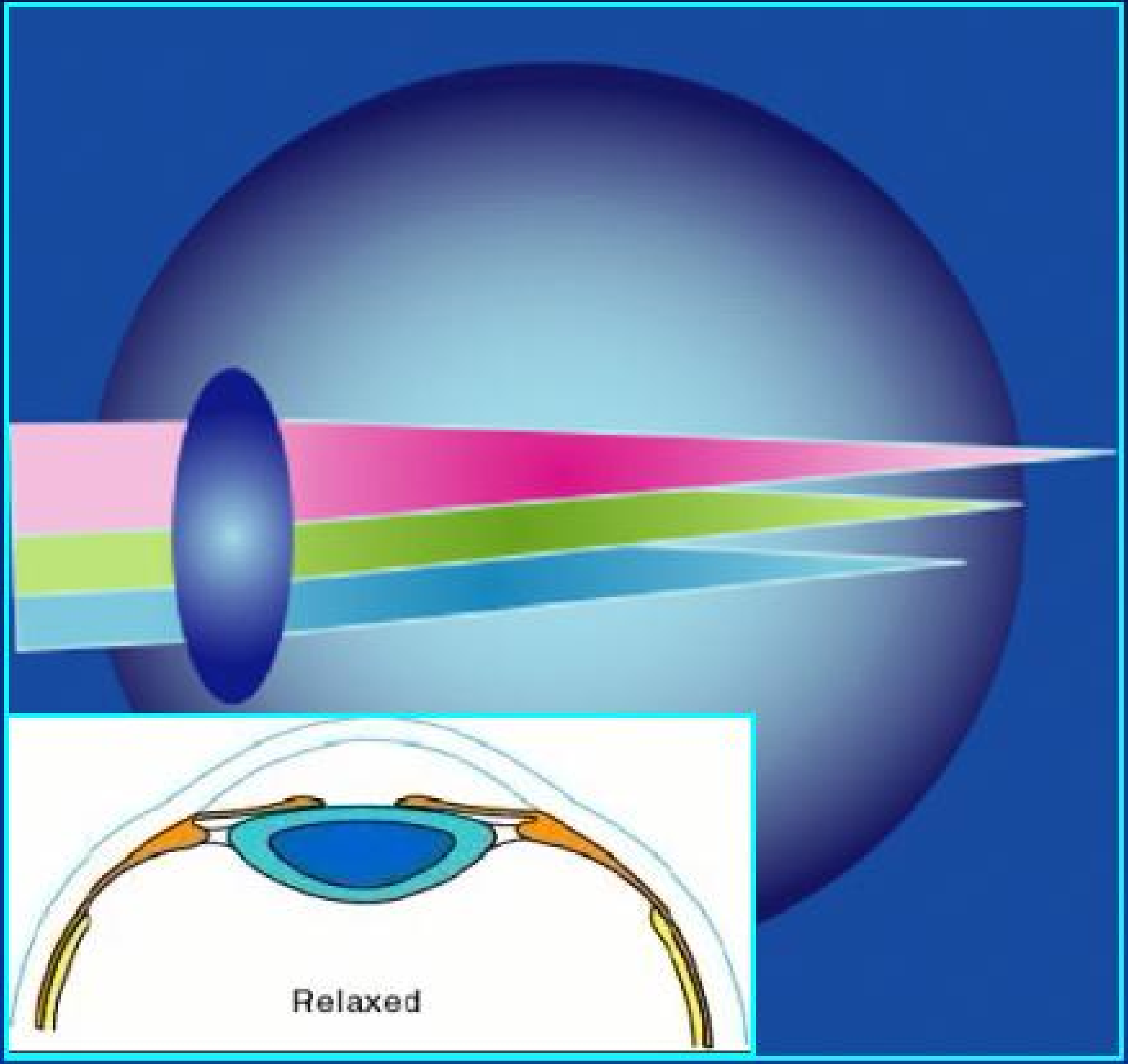


Dowling, 1987



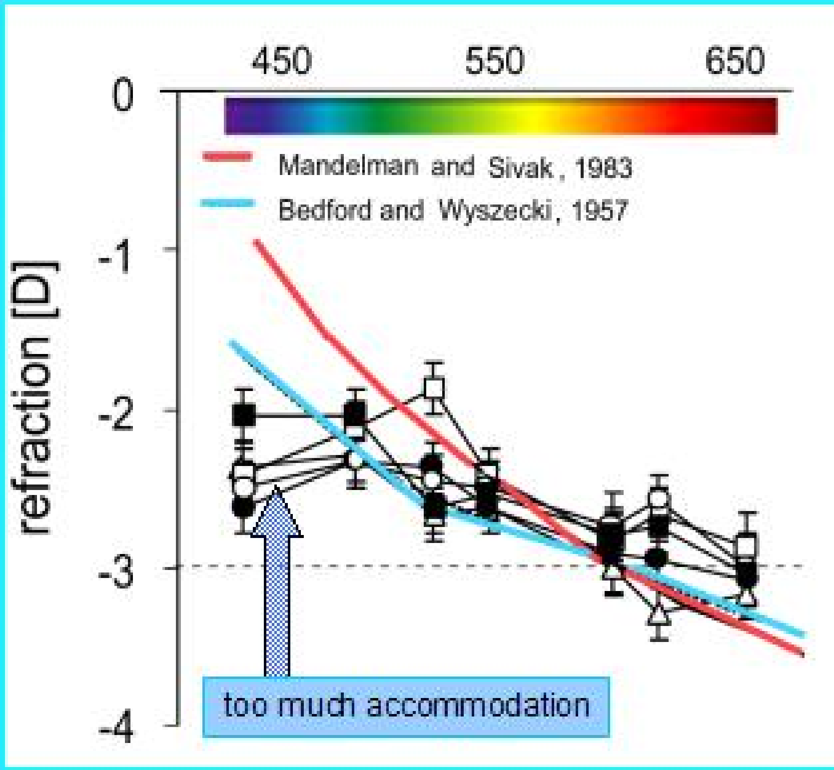


Accommodation and chromatic aberration

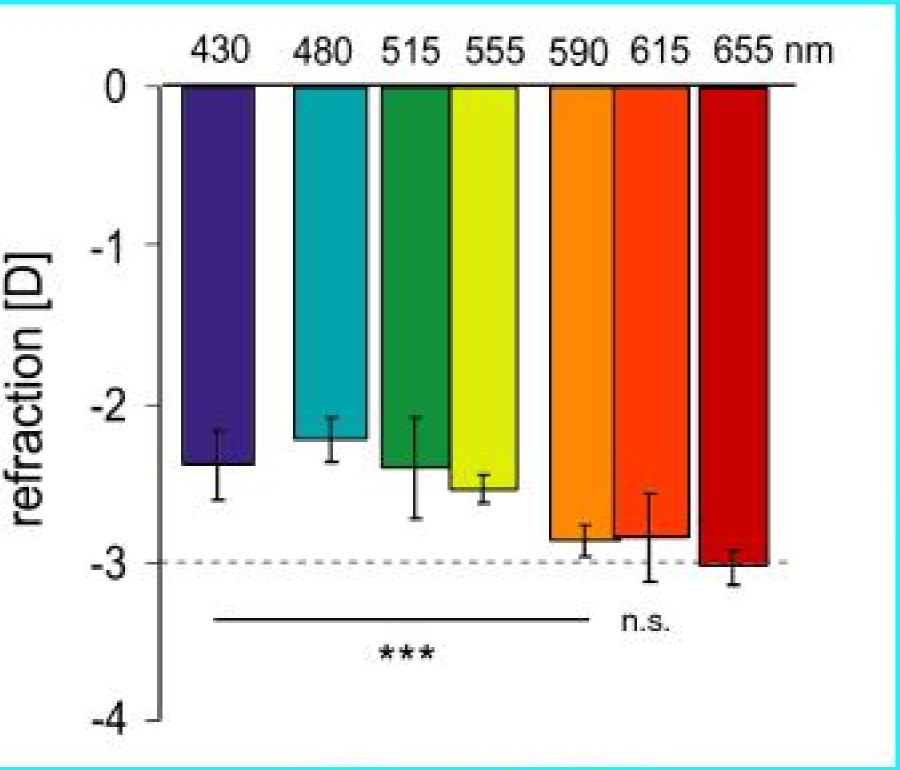


Accommodation in monochromatic light in humans

reading target at 3 D distance

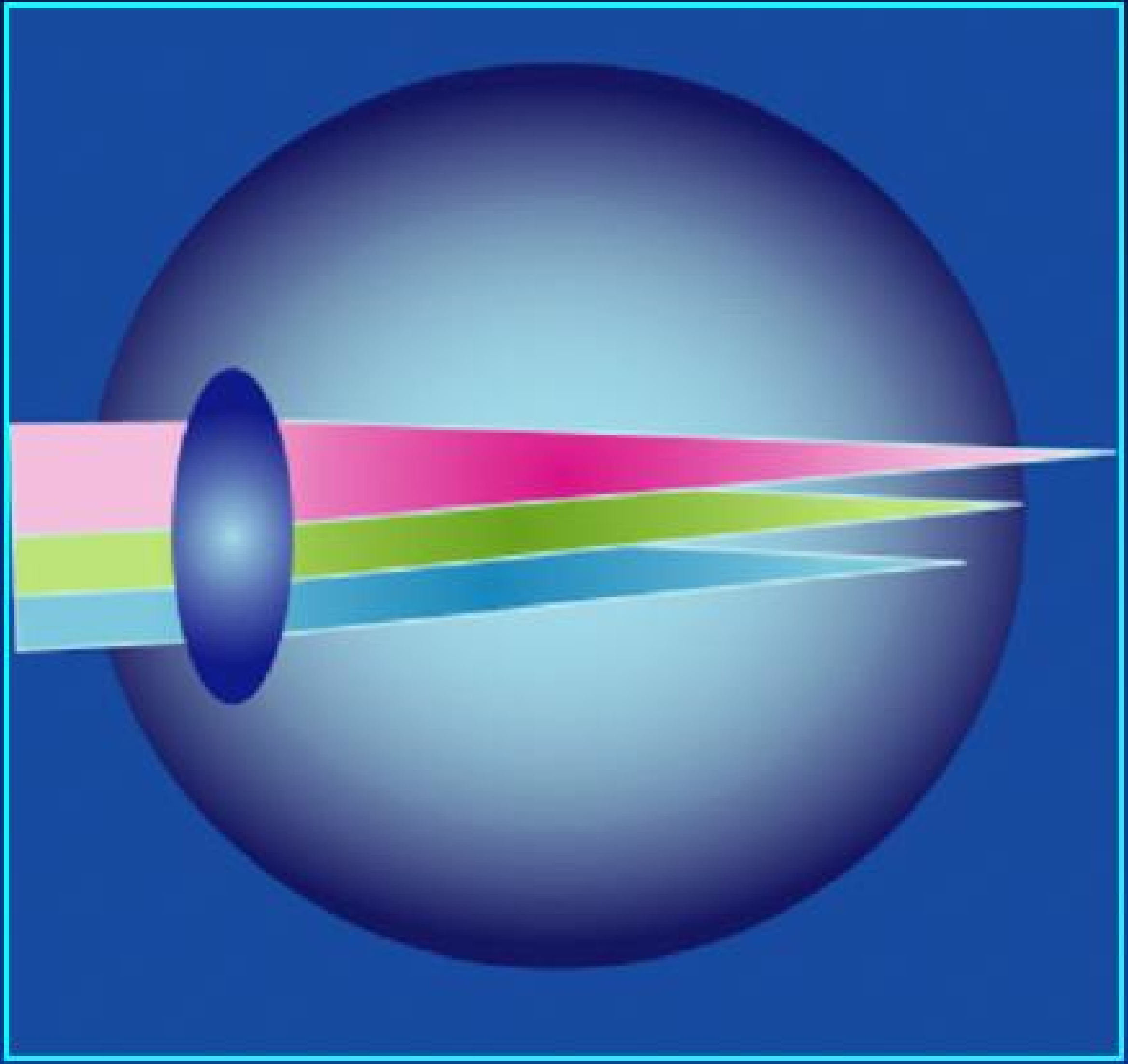


too much accommodation

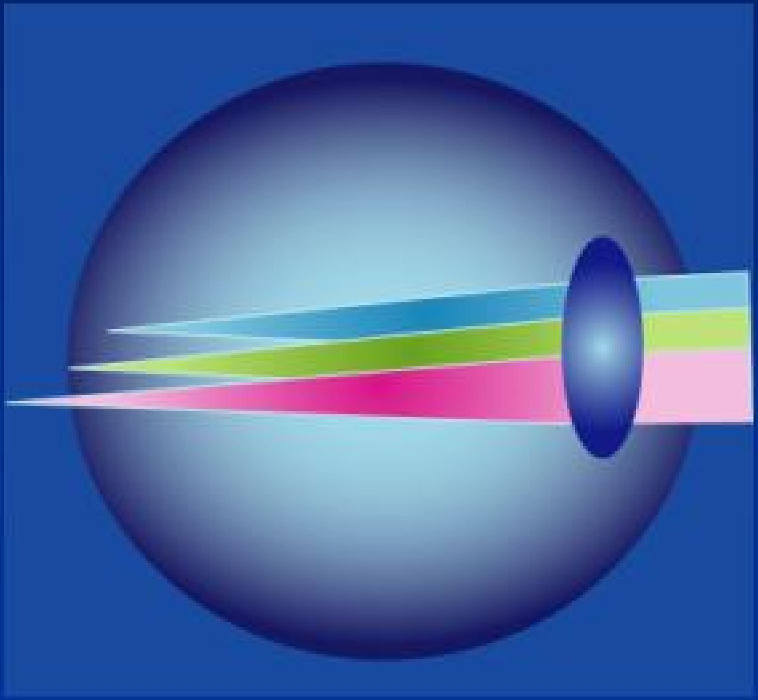


Seidemann & Schaeffel
Vision Reseach **42**, 2409-2417 (2002)

Emmetropization and chromatic aberration



blue light is focused in front
of the retina which could
inhibit axial elongation of the eye



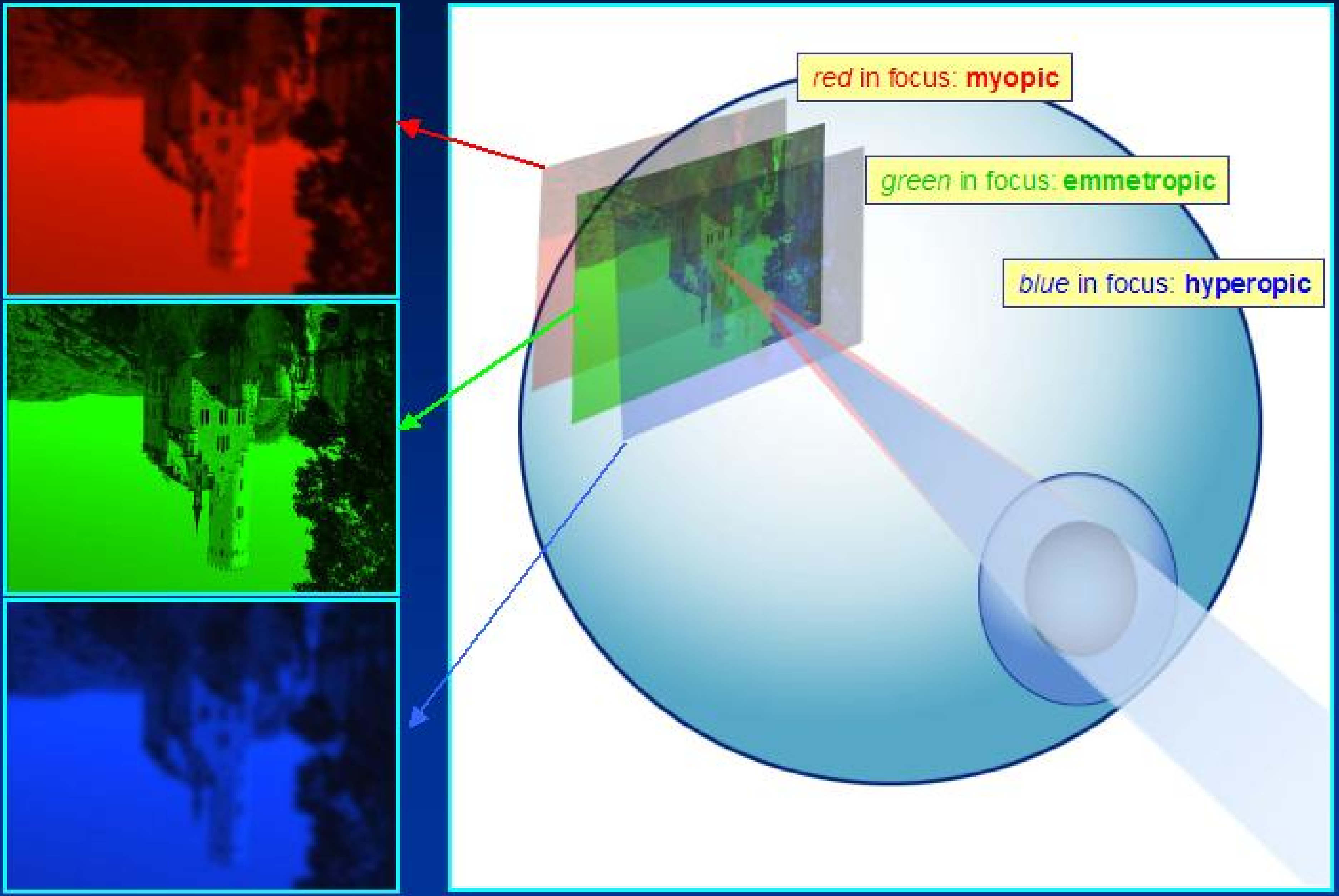
"Der Spiegel" 33/2000, p.161

MEDIZIN

Blaulicht statt Brille

Kurzsichtigkeit ließe sich bei vielen Menschen vermeiden, wenn Schulbücher auf hellblauem statt auf weißem Papier gedruckt würden. Zu diesem Ergebnis kommt der Tübinger Biologe Ronald Kröger im „British Journal of Ophthalmology". Der Trick: Licht verschiedener Wellenlänge wird im Auge unterschiedlich stark gebrochen. Kurzwelliges blaues Licht, so Kröger, führe dazu, dass die Augen beim Lesen auf eine größere Distanz fokussieren: „Bei Kindern mit einer schwachen Veranlagung zur Kurzsichtigkeit könnte die Brille so ganz vermieden werden."

Comparison of different cone contrasts indicates the sign of defocus

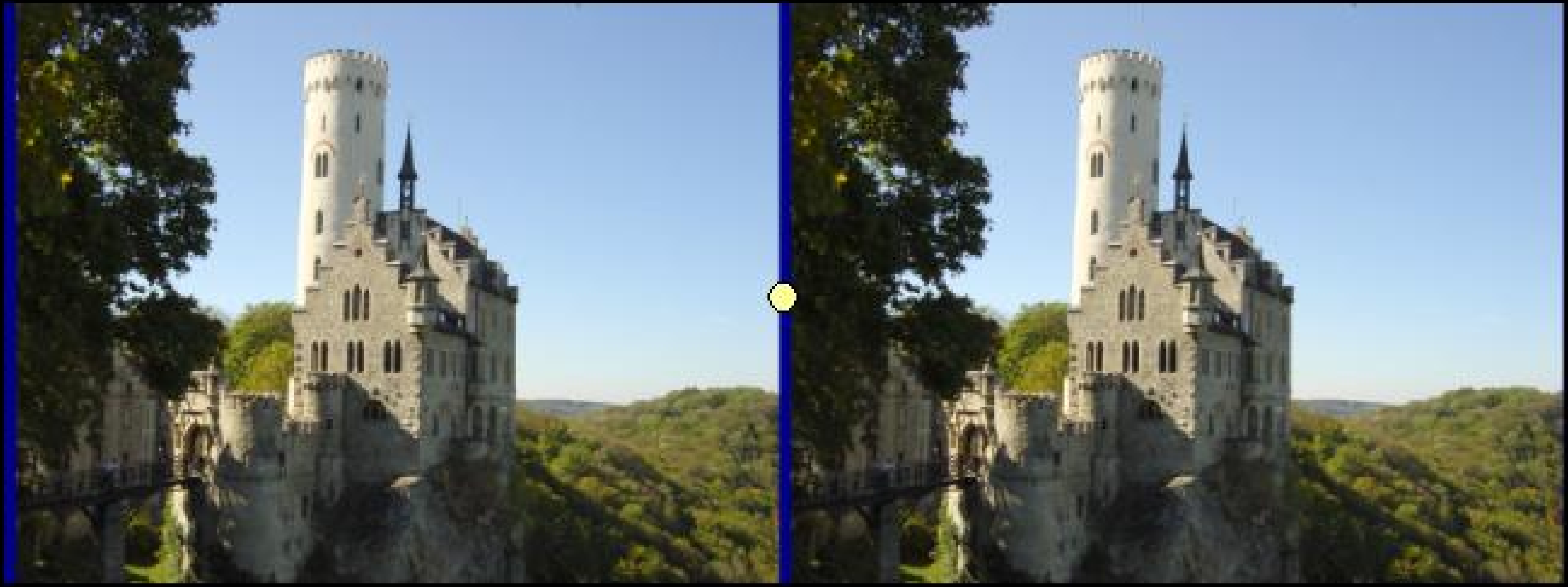


red in focus: **myopic**

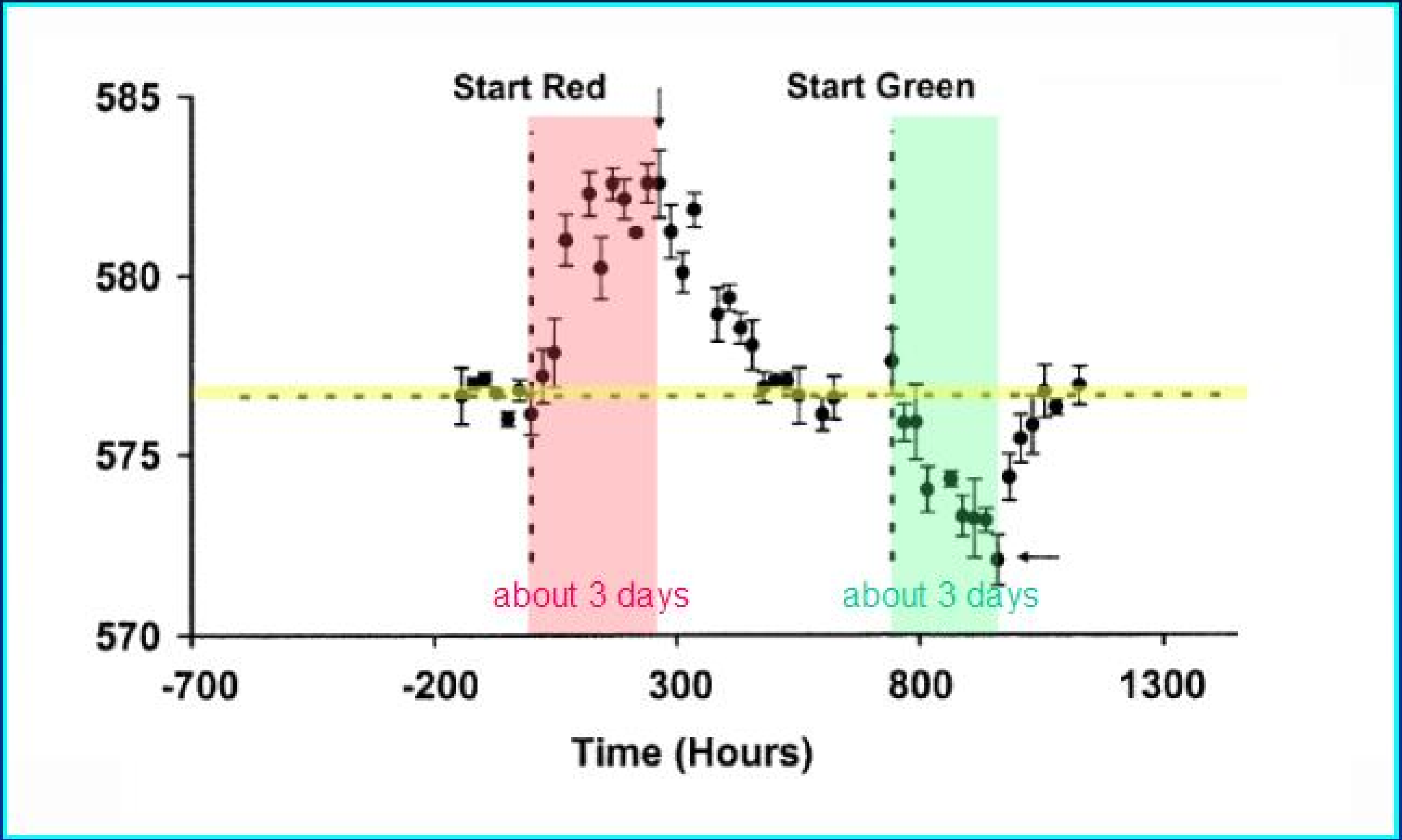
green in focus: **emmetropic**

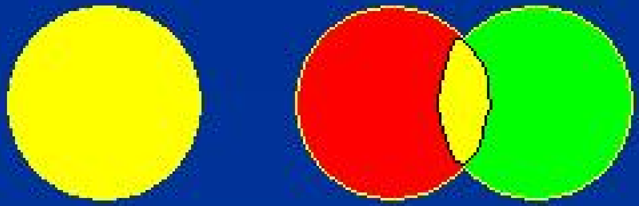
blue in focus: **hyperopic**

Short and long term changes in color perception

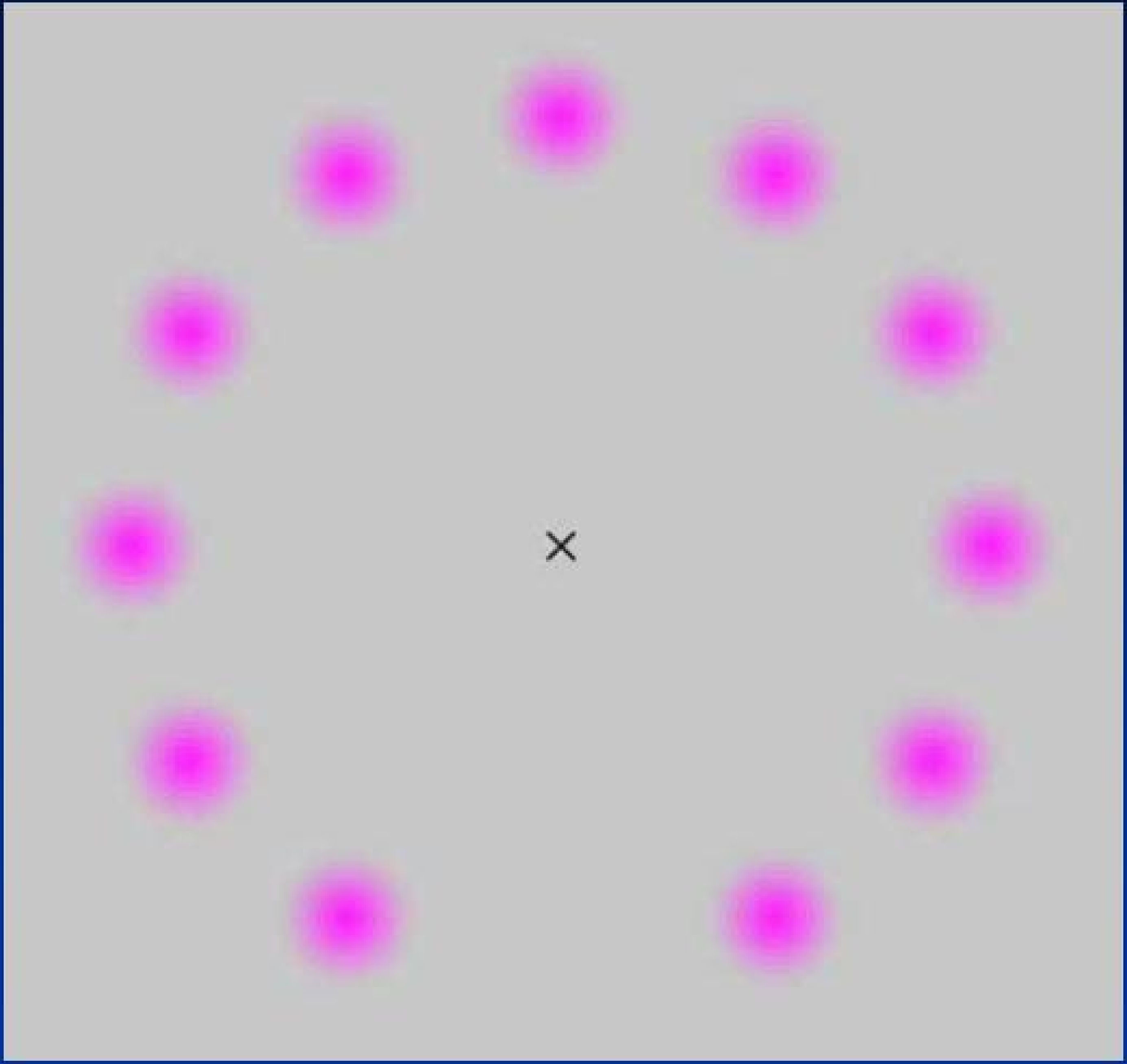


Long term changes in color perception

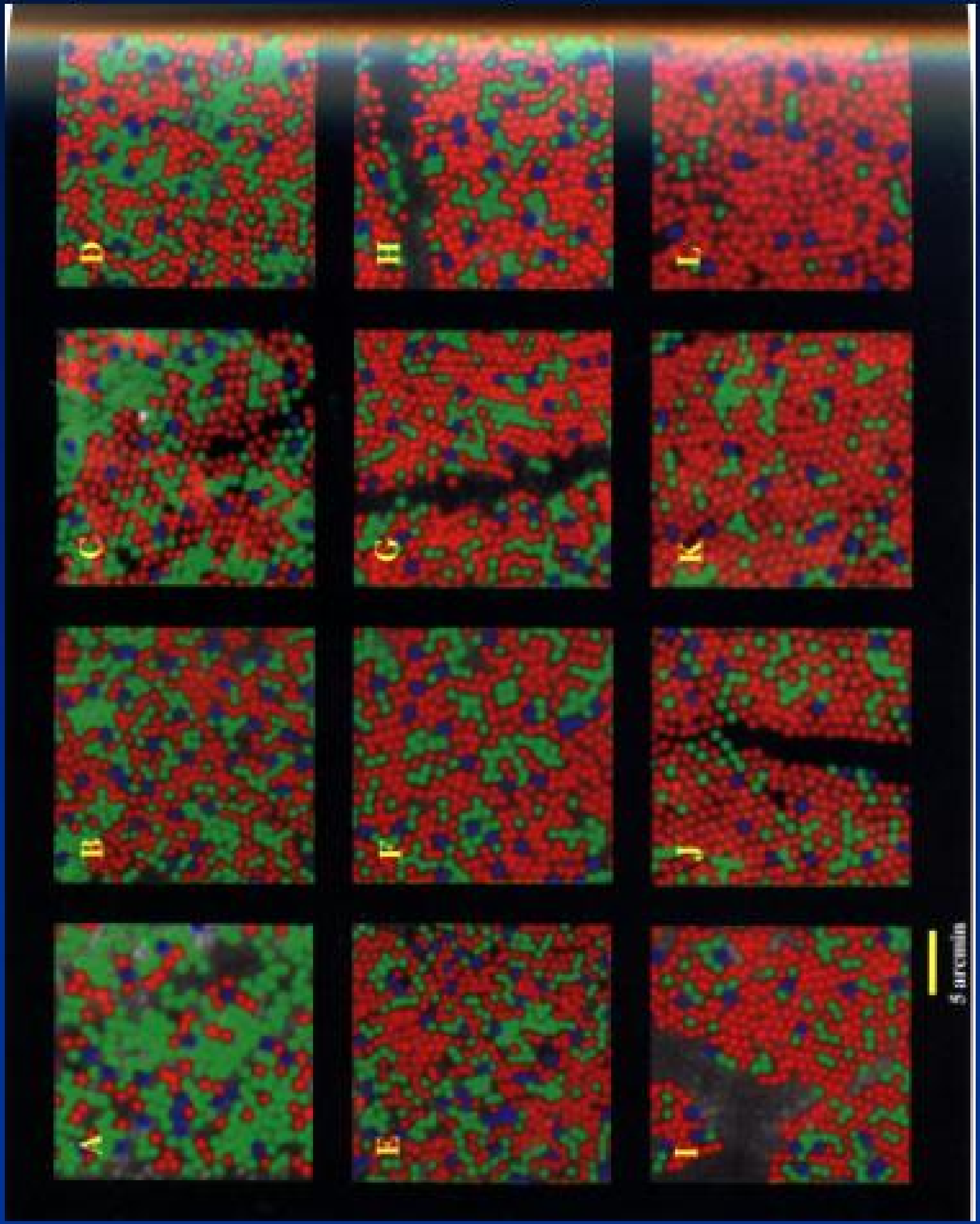




Neitz et al,
Neuron 35,
783-792 (2002)



Variability of cone mosaics in people with normal color vision



Roorda and Williams,
Nature **397**,
520-522 (1999)
and additional data by
Heidi Hofer

key words

- Snell's law, refractive power, focal length
- image formation and advantages in vertebrate and insect compound eyes
- image magnification, posterior nodal distance
- optical limits of vertebrate eyes, diffraction, refractive errors, astigmatism and spherical aberration
- accommodation and presbyopia
- chromatic aberration and the adaptations of the eye to deal with it