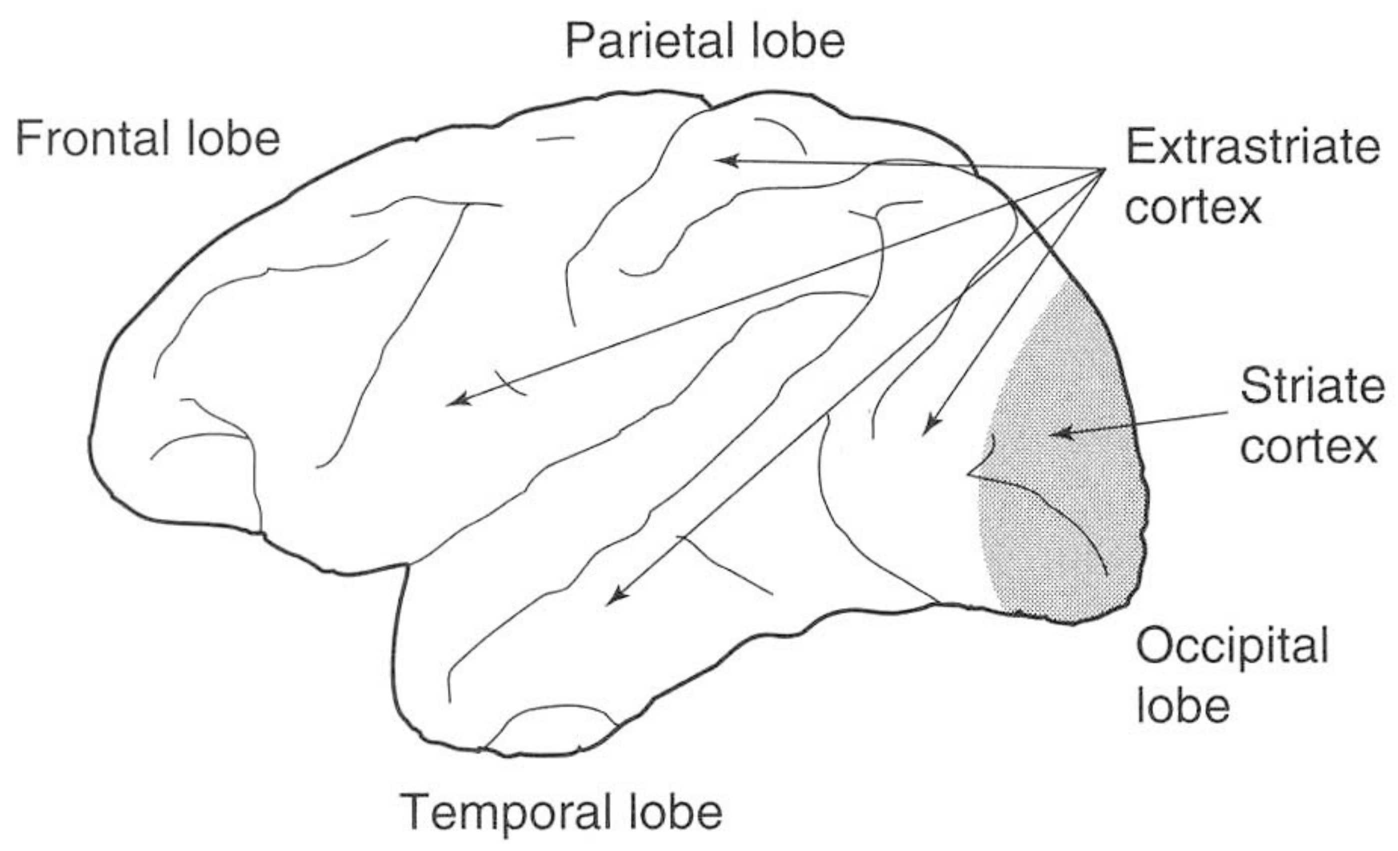
Perception: Psychophysics and Modeling

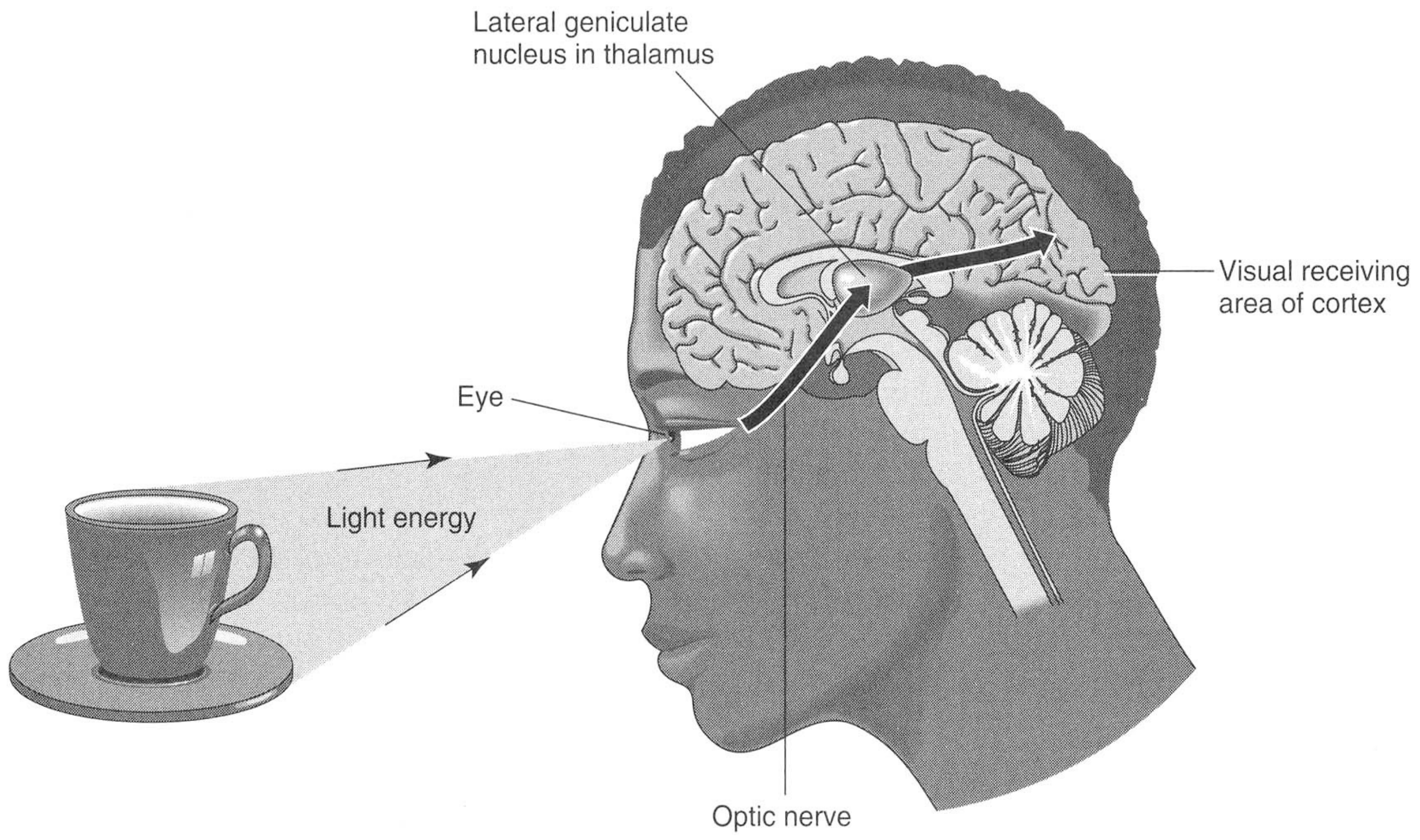
03 | Human eye and retina

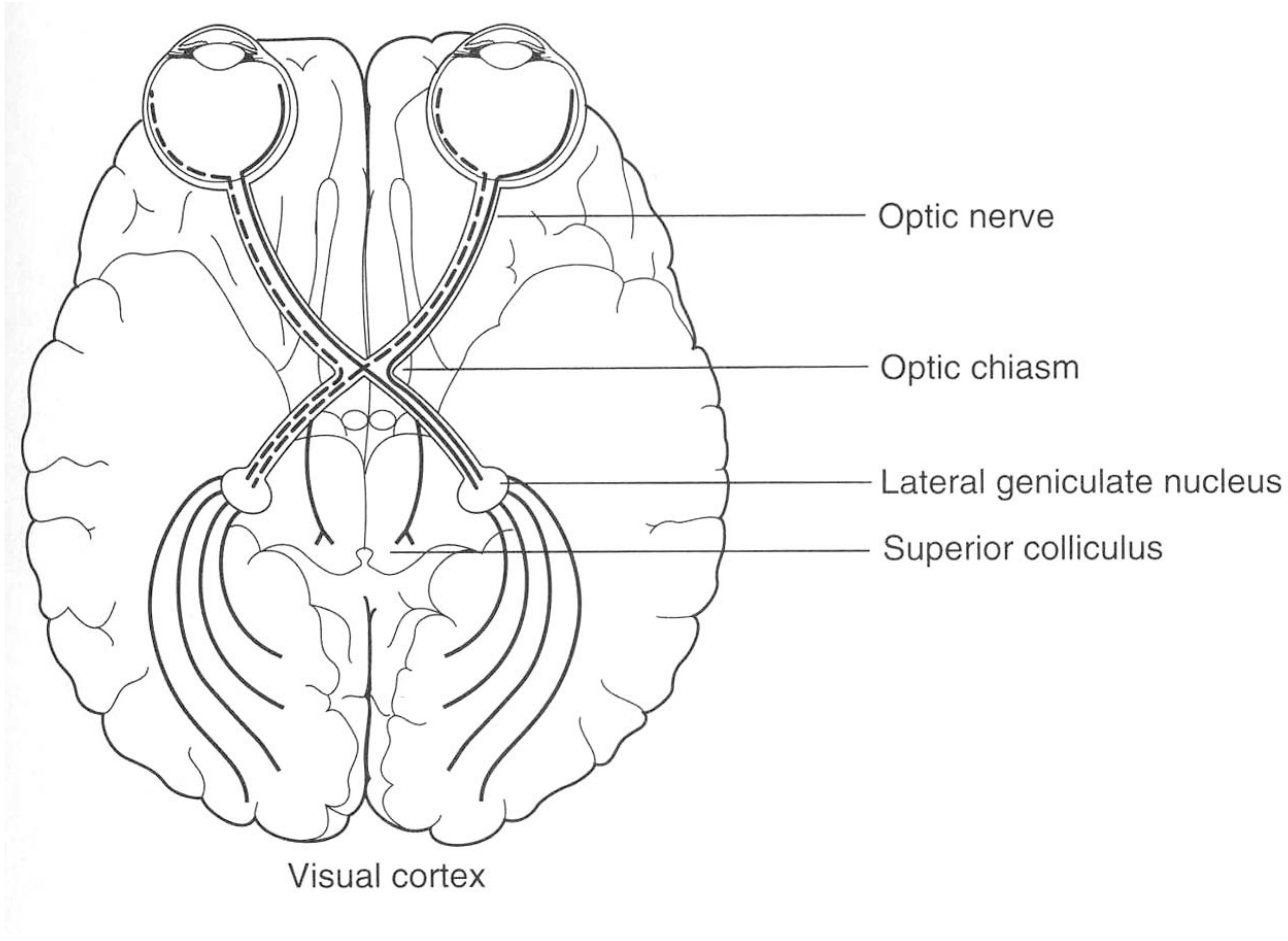
Felix Wichmann

Neural Information Processing Group
Eberhard Karls Universität Tübingen

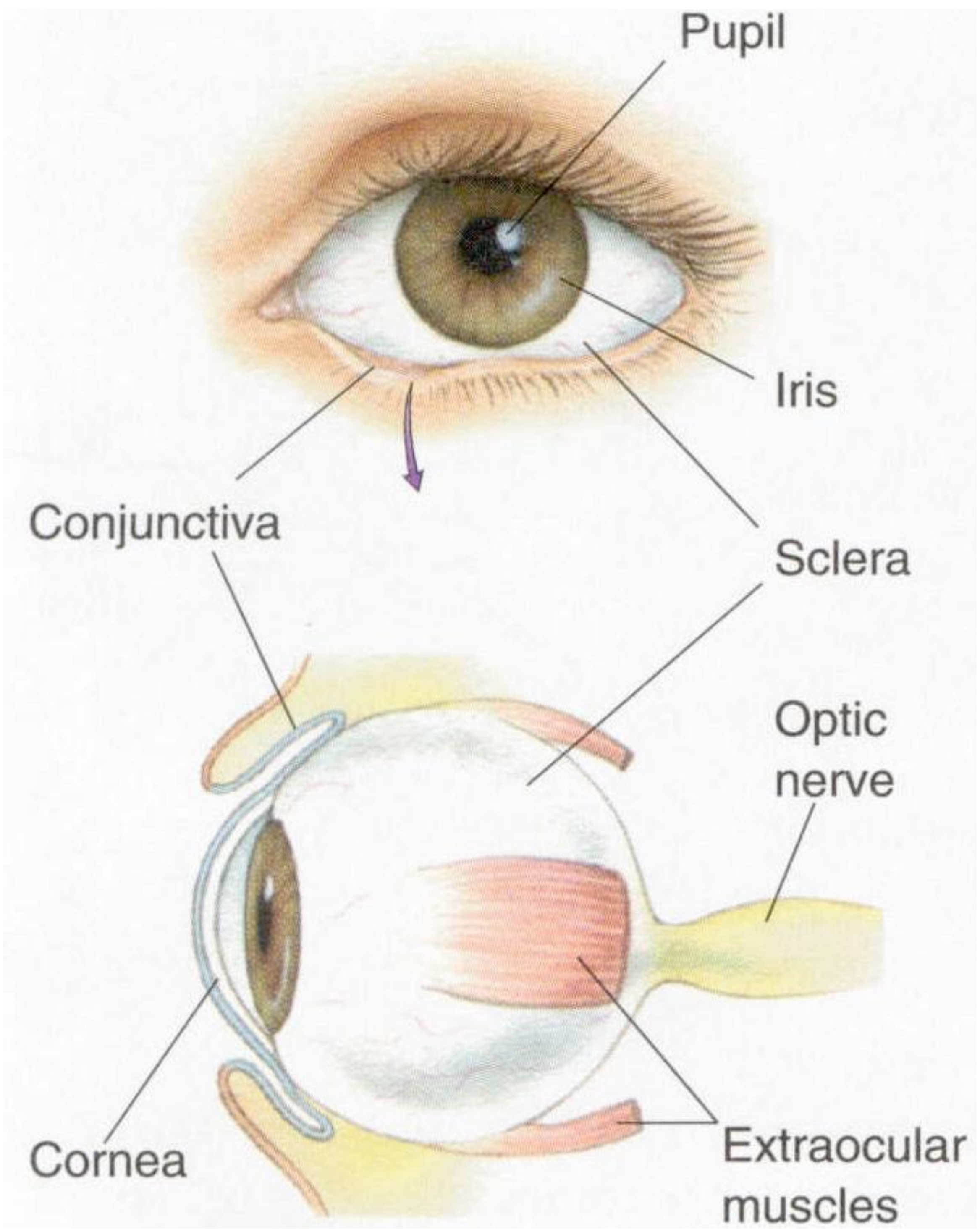
Structure of the visual system

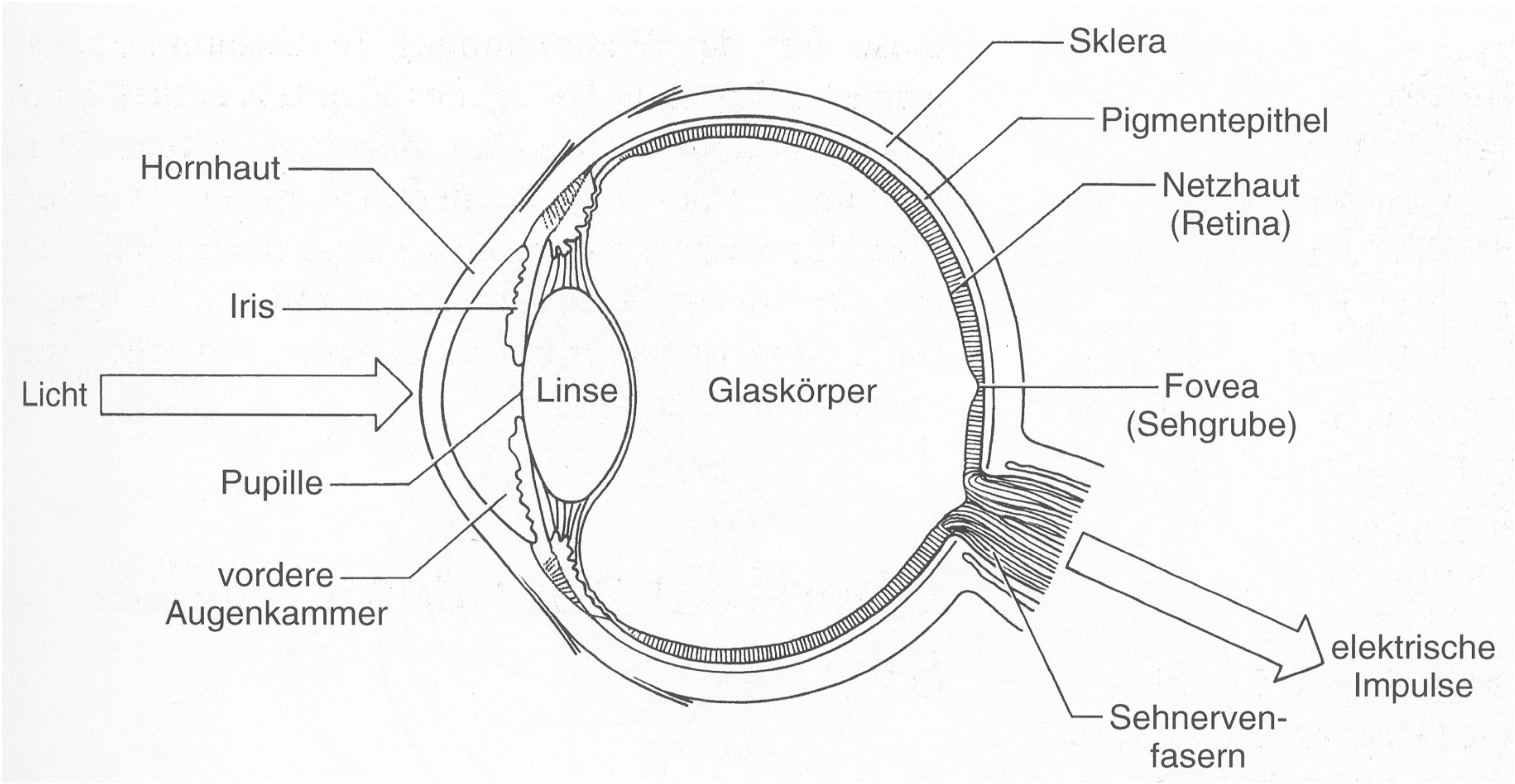




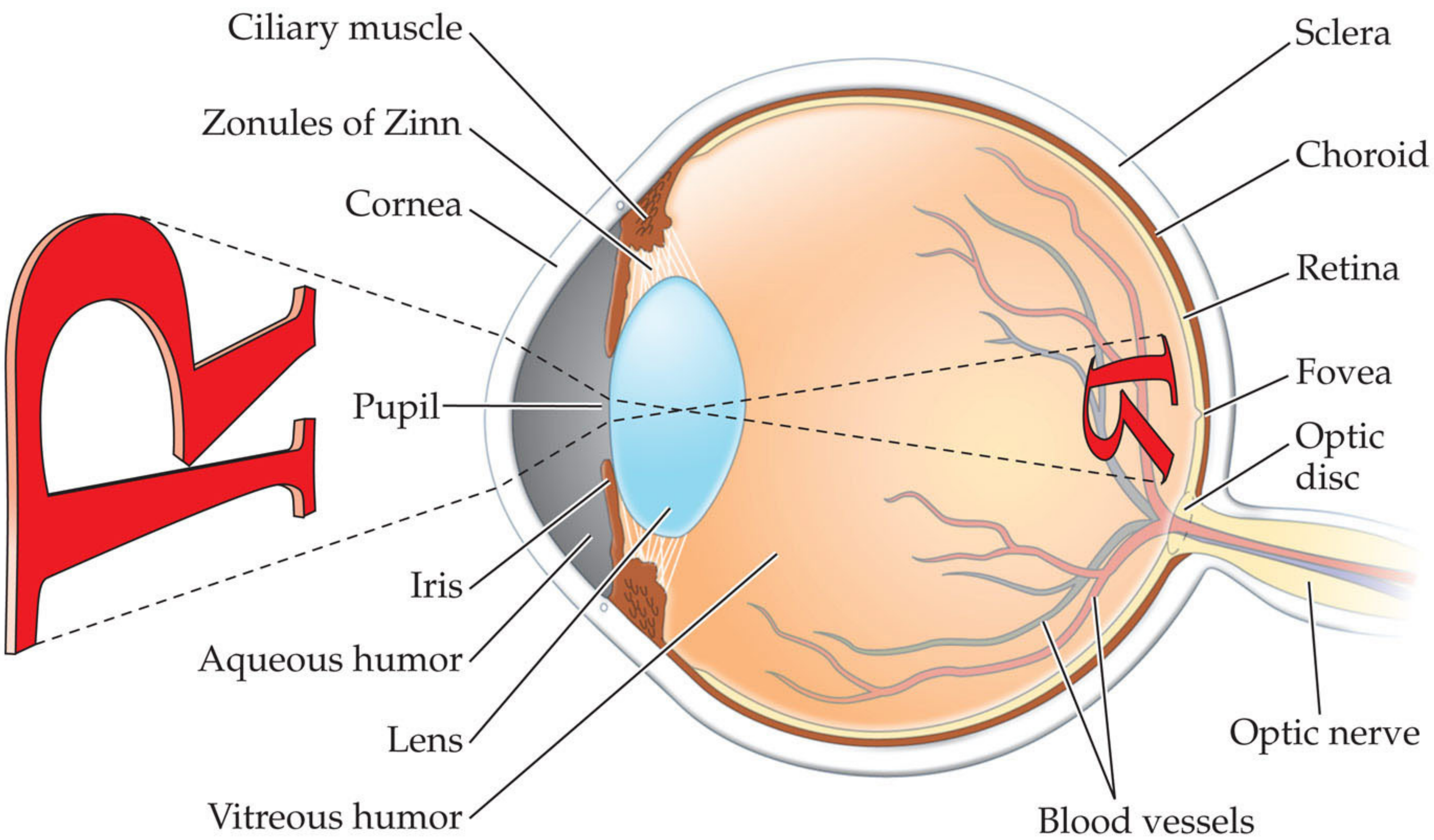


Anatomy of the eye



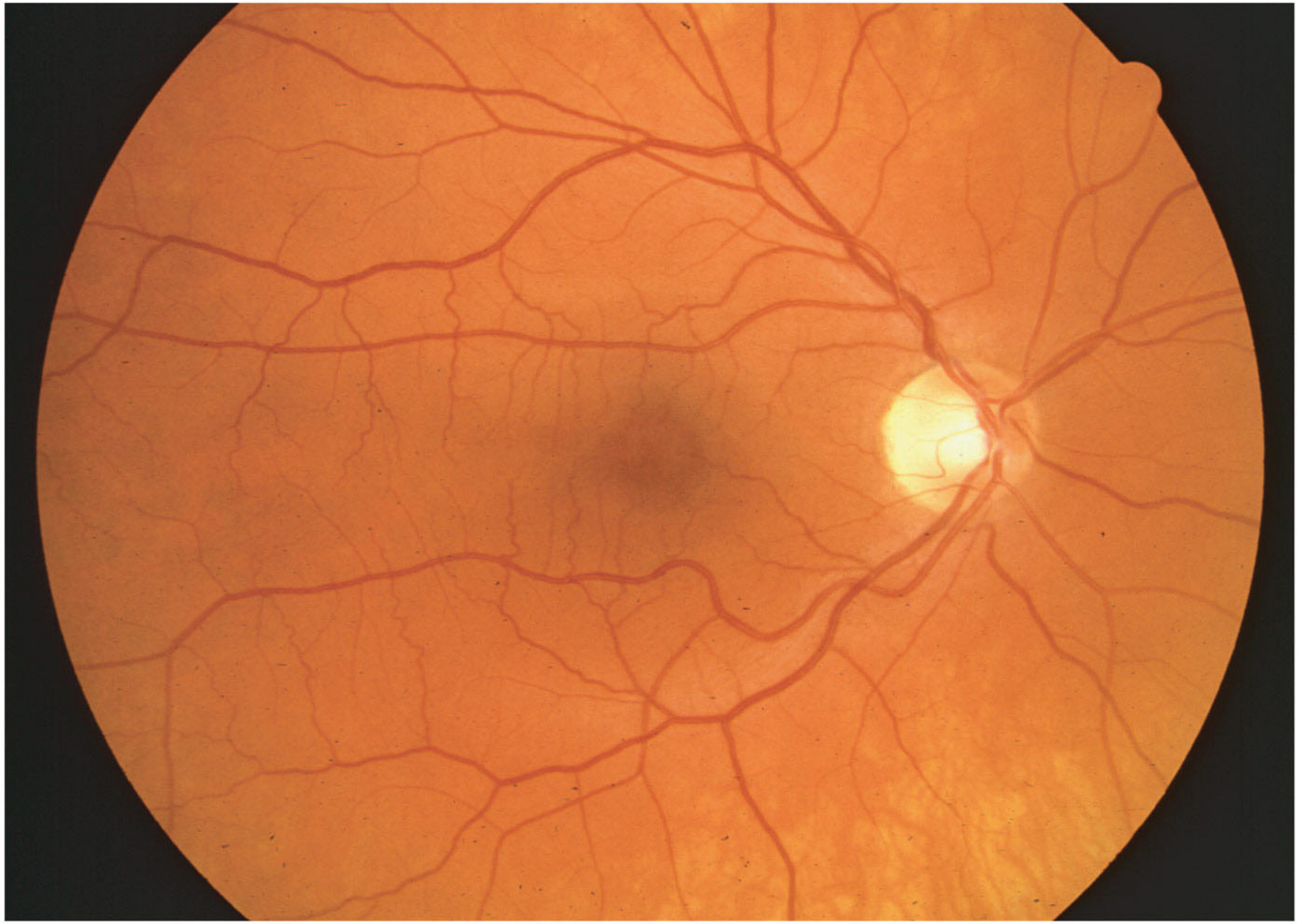


Anatomy of the eye



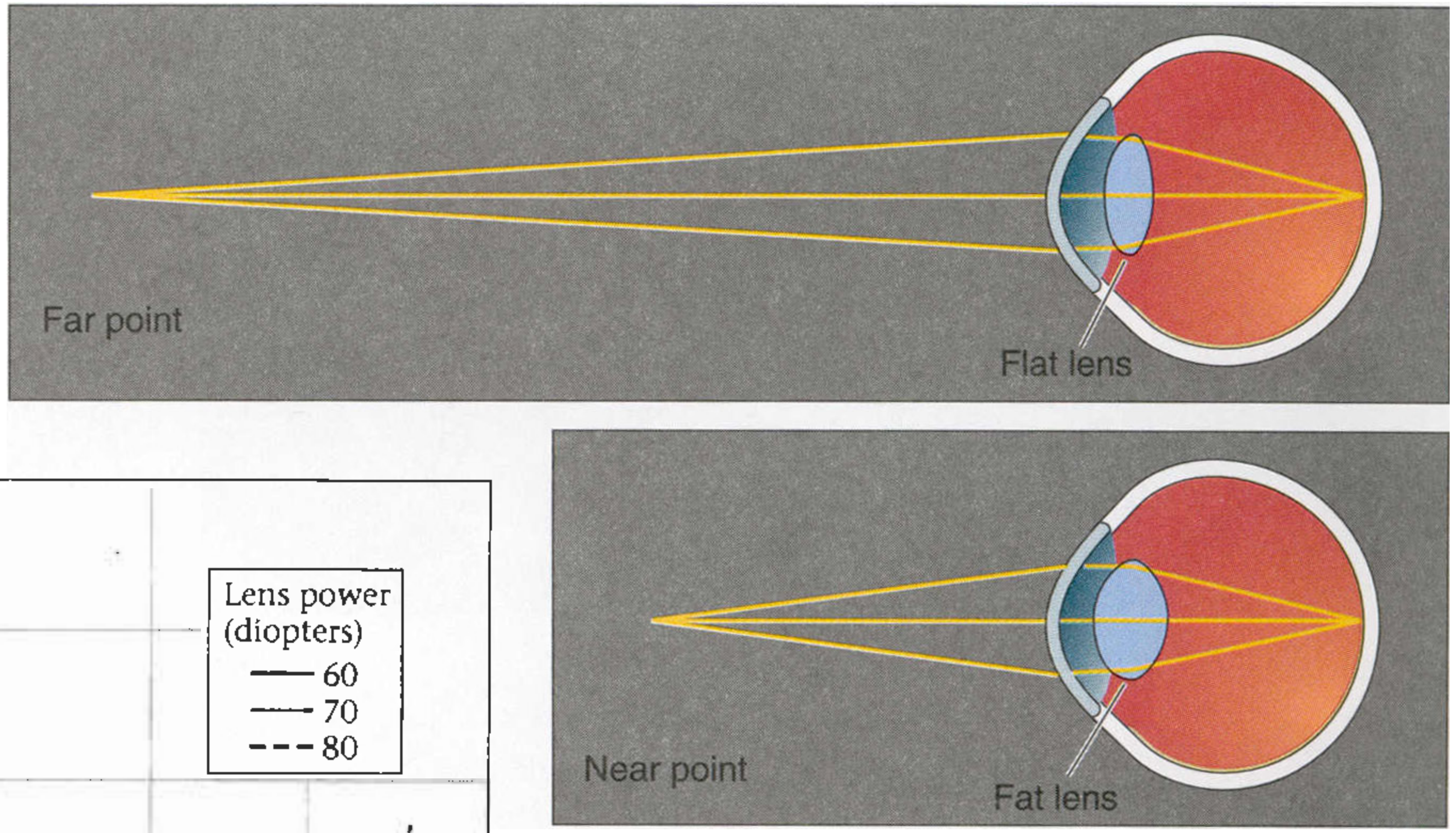
SENSATION & PERCEPTION 4e, **Figure 2.2**

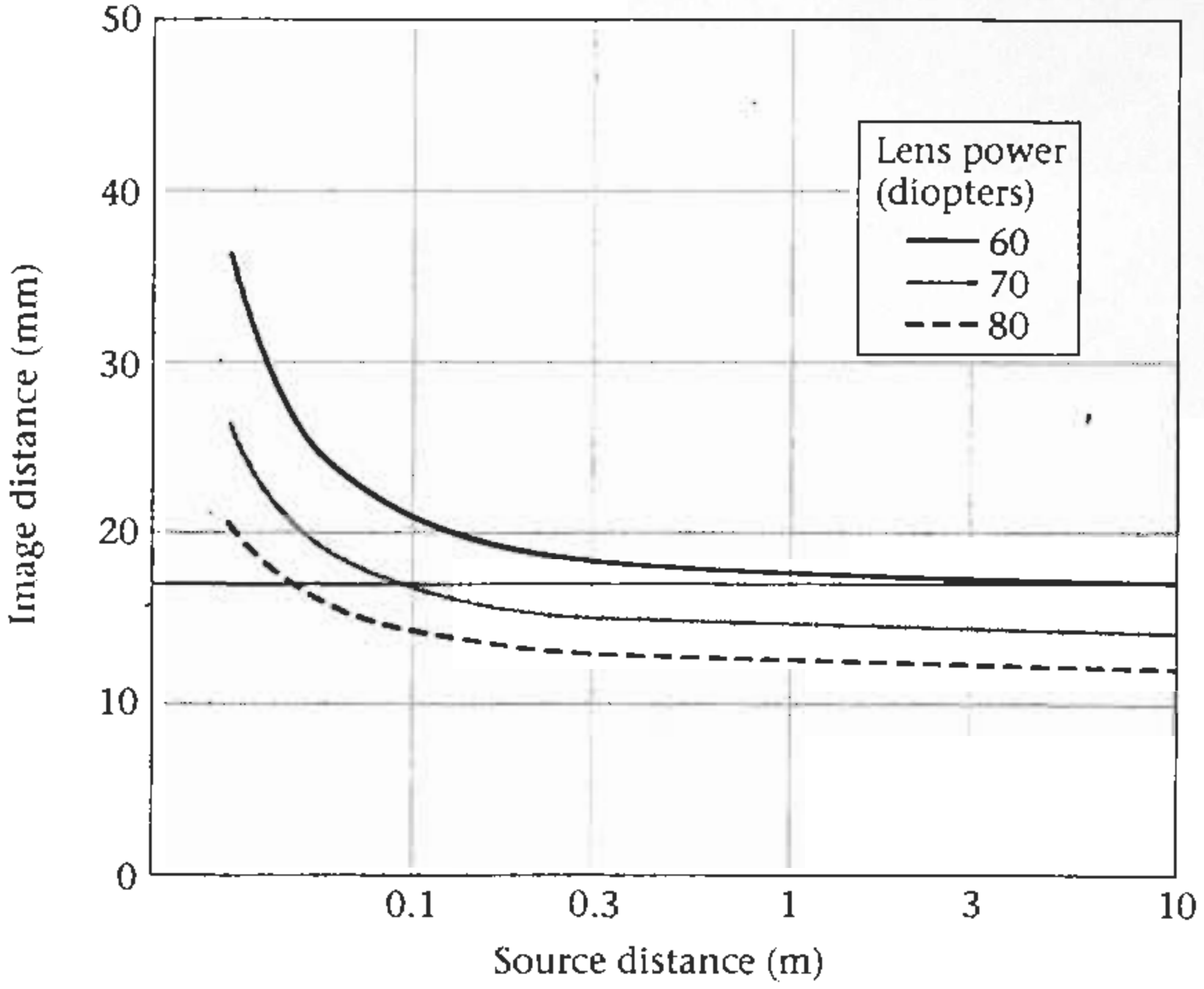
Fundus of the right eye of a human



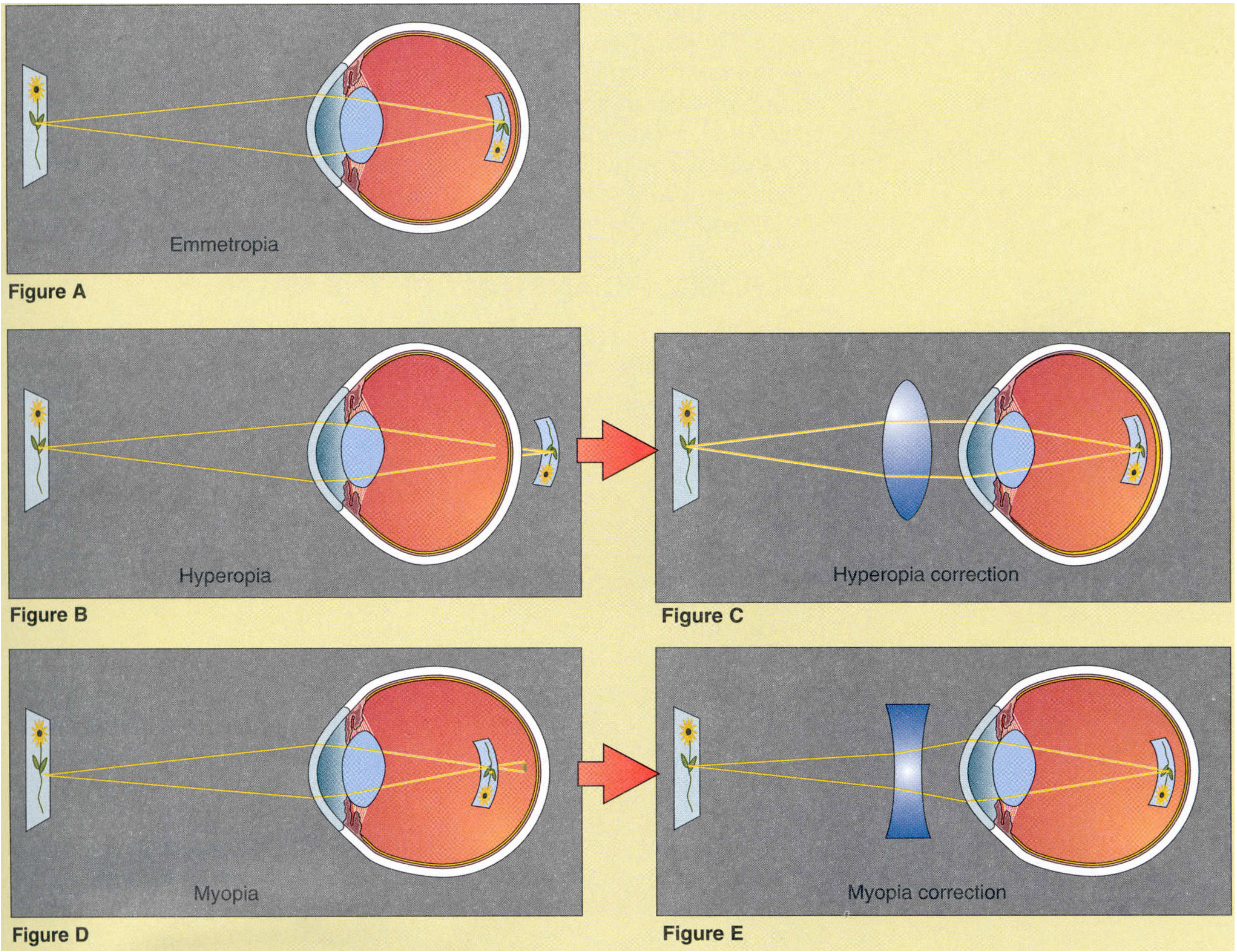
***SENSATION & PERCEPTION 4e*, Figure 2.6**

Accommodation





Defective refraction

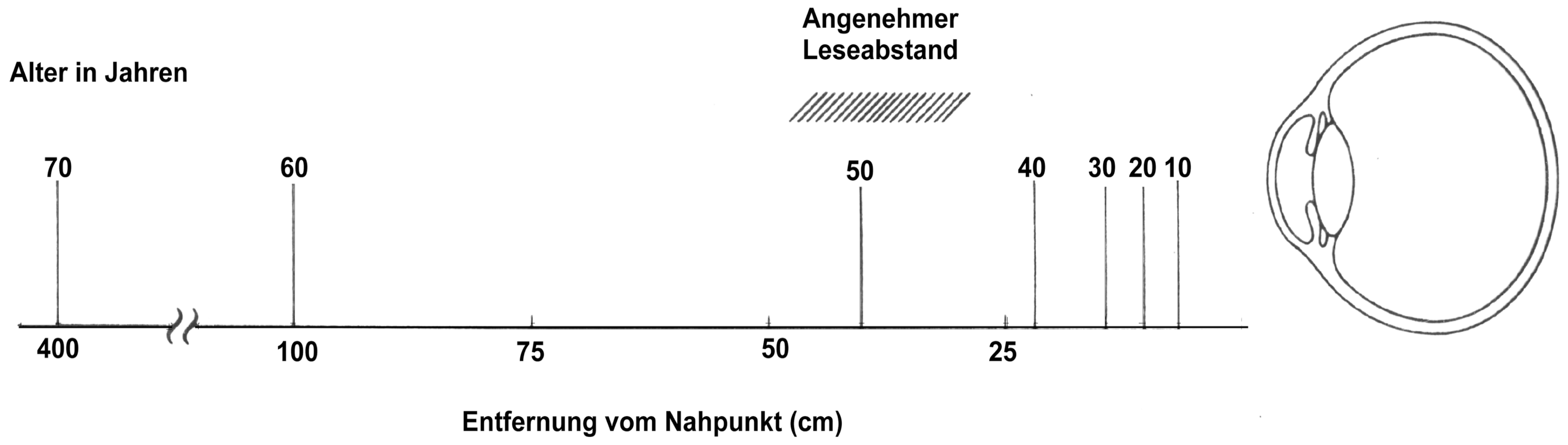


Normal

Far-sighted
(Weitsichtig)

Near-sighted
(Kurzsichtig)

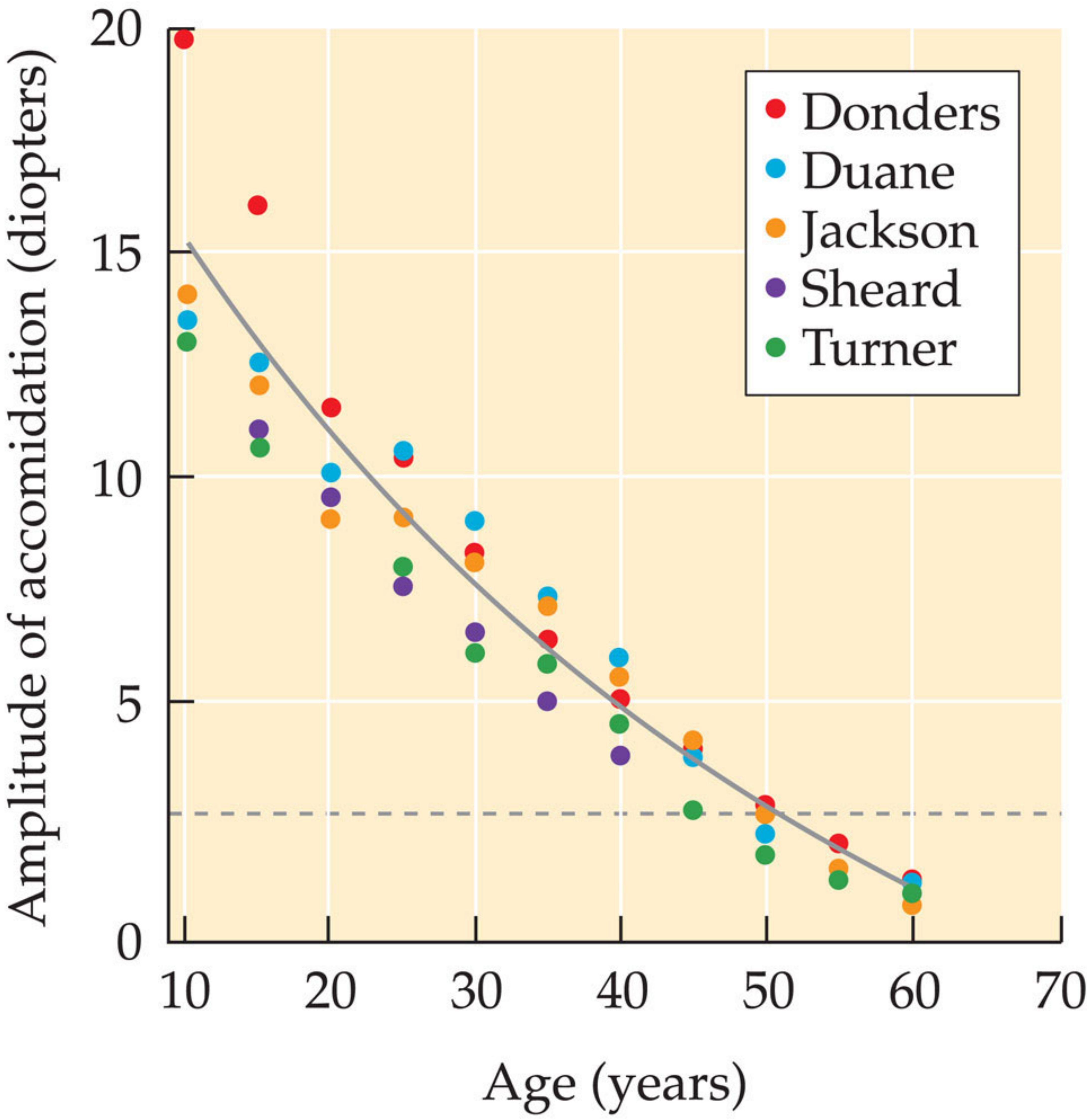
Nearest focal point and age (presbyopia)



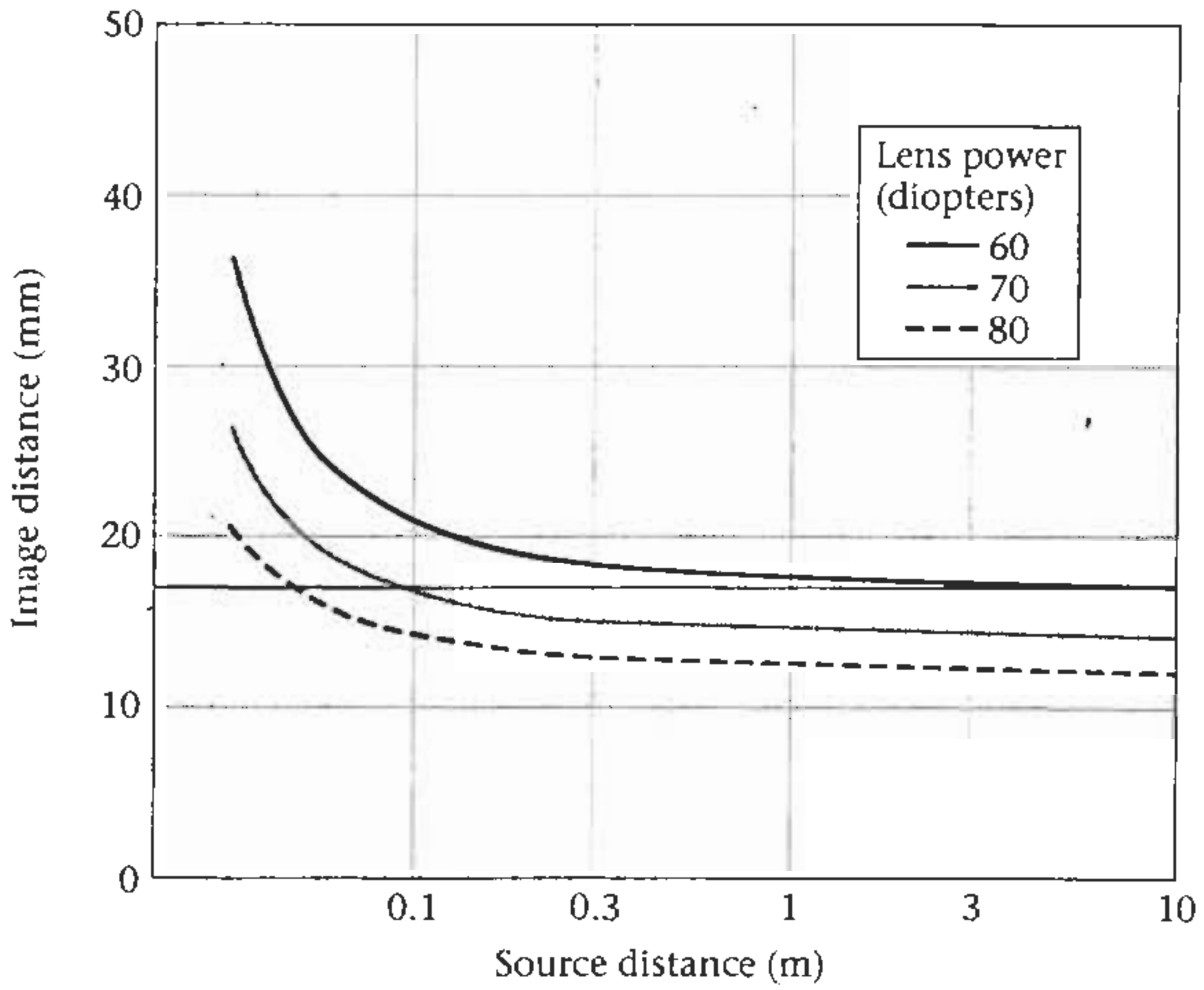
Objects closer than the nearest focal point can no longer be focussed by accommodation.

In old age, the flexibility of the lens decreases, meaning you can no longer accommodate. Reading glasses needed.

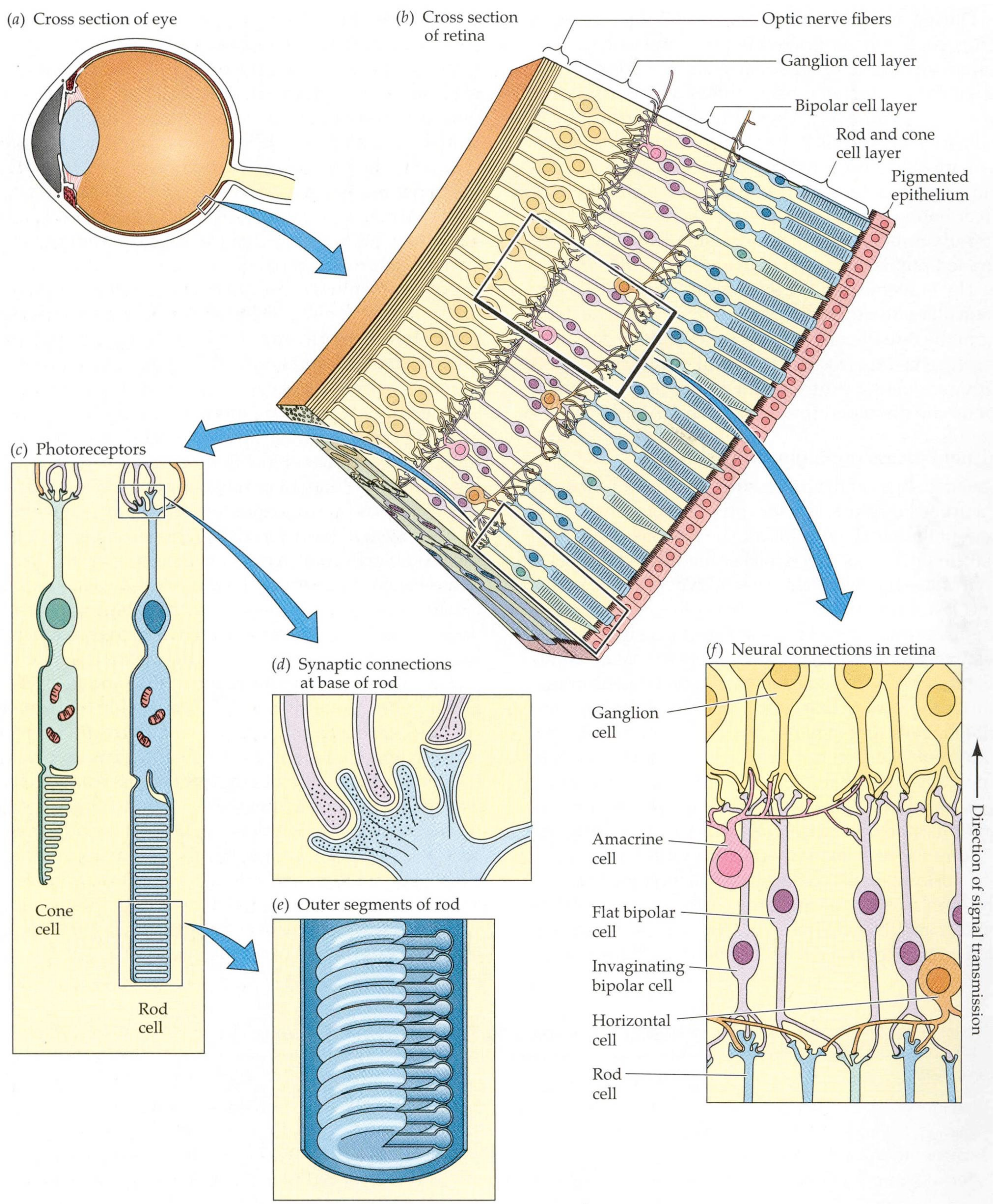
Nearest focal point and age (presbyopia)



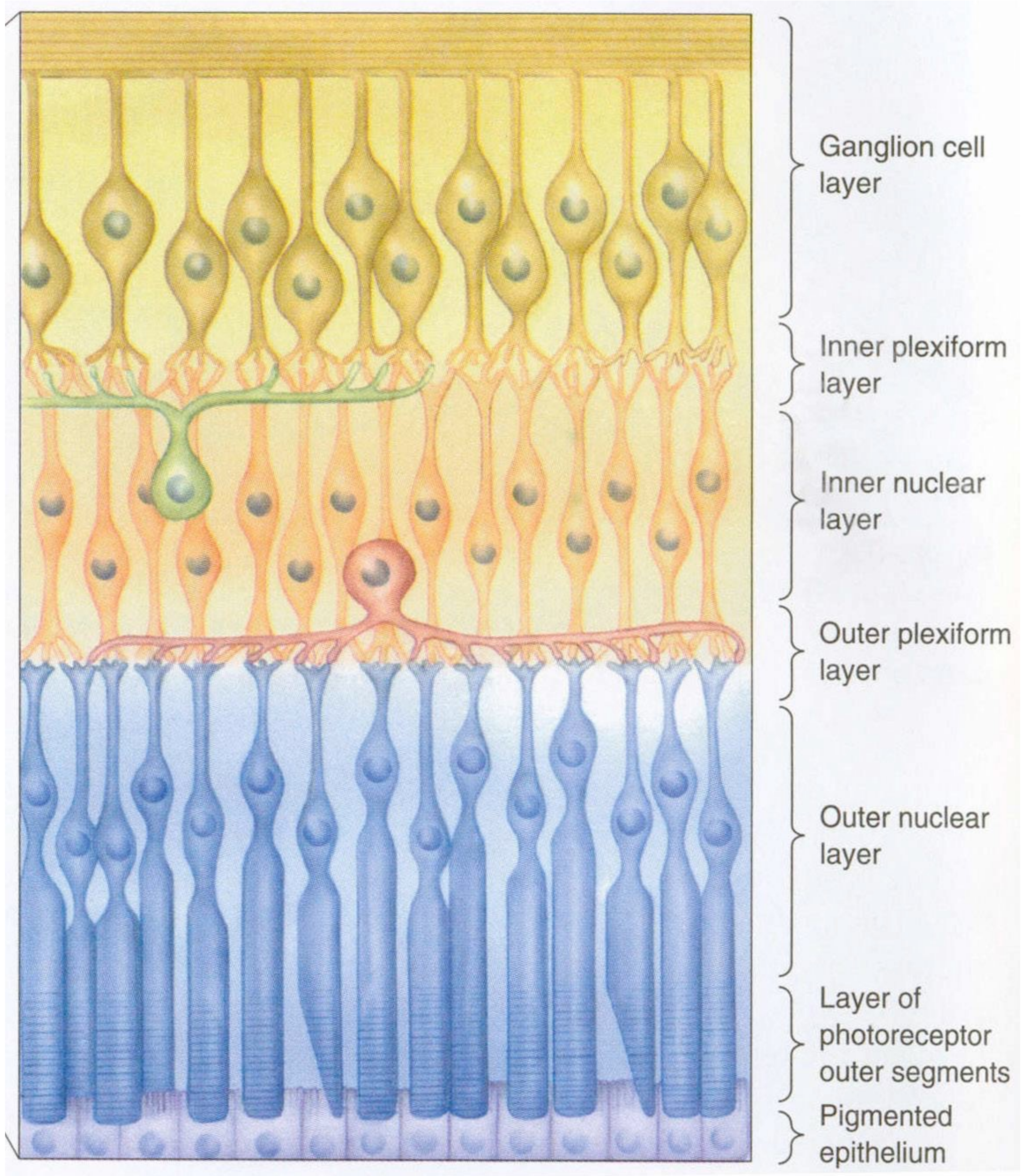
SENSATION & PERCEPTION 4e, Figure 2.5



Retinal processing



The retinal network

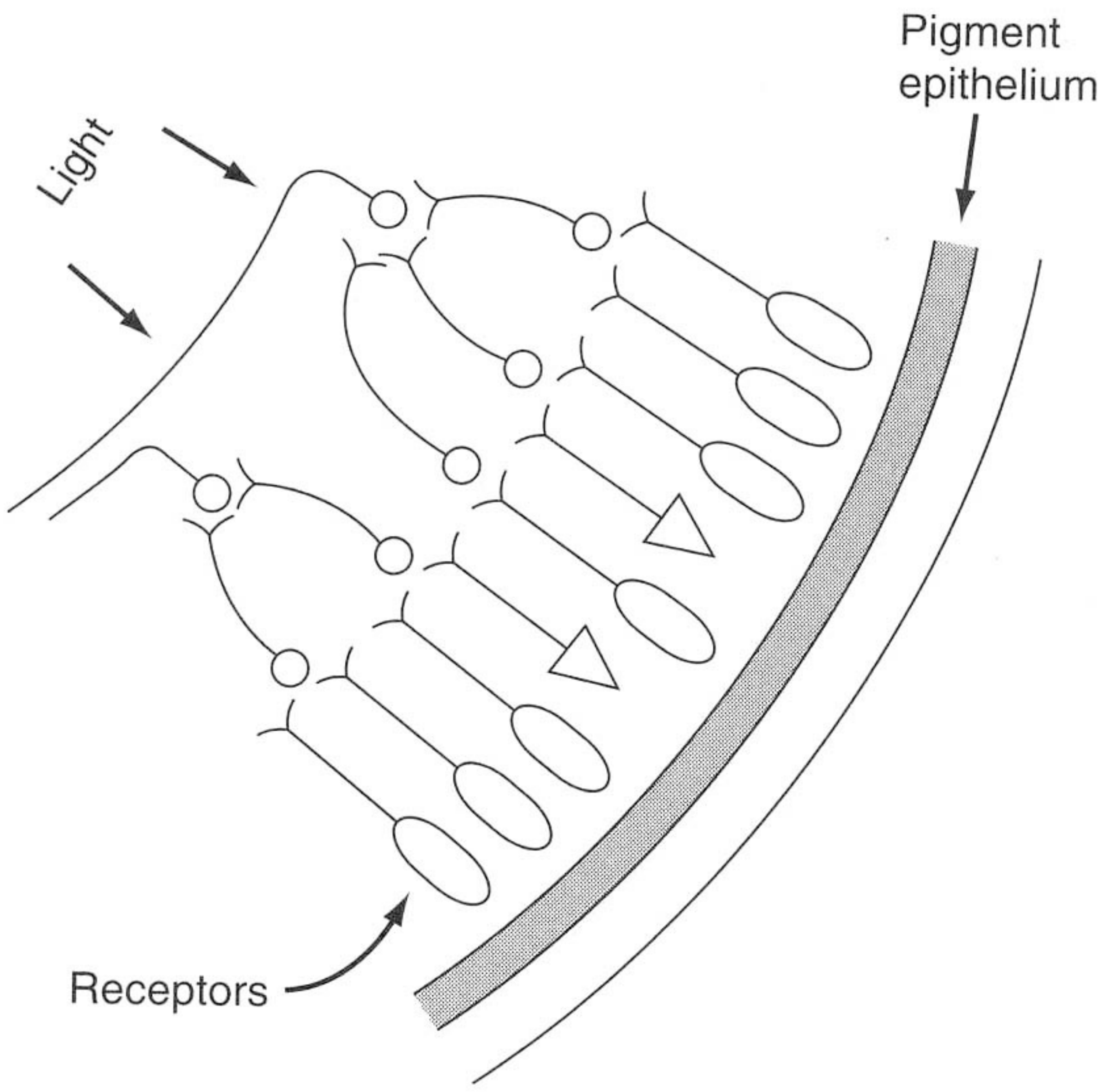


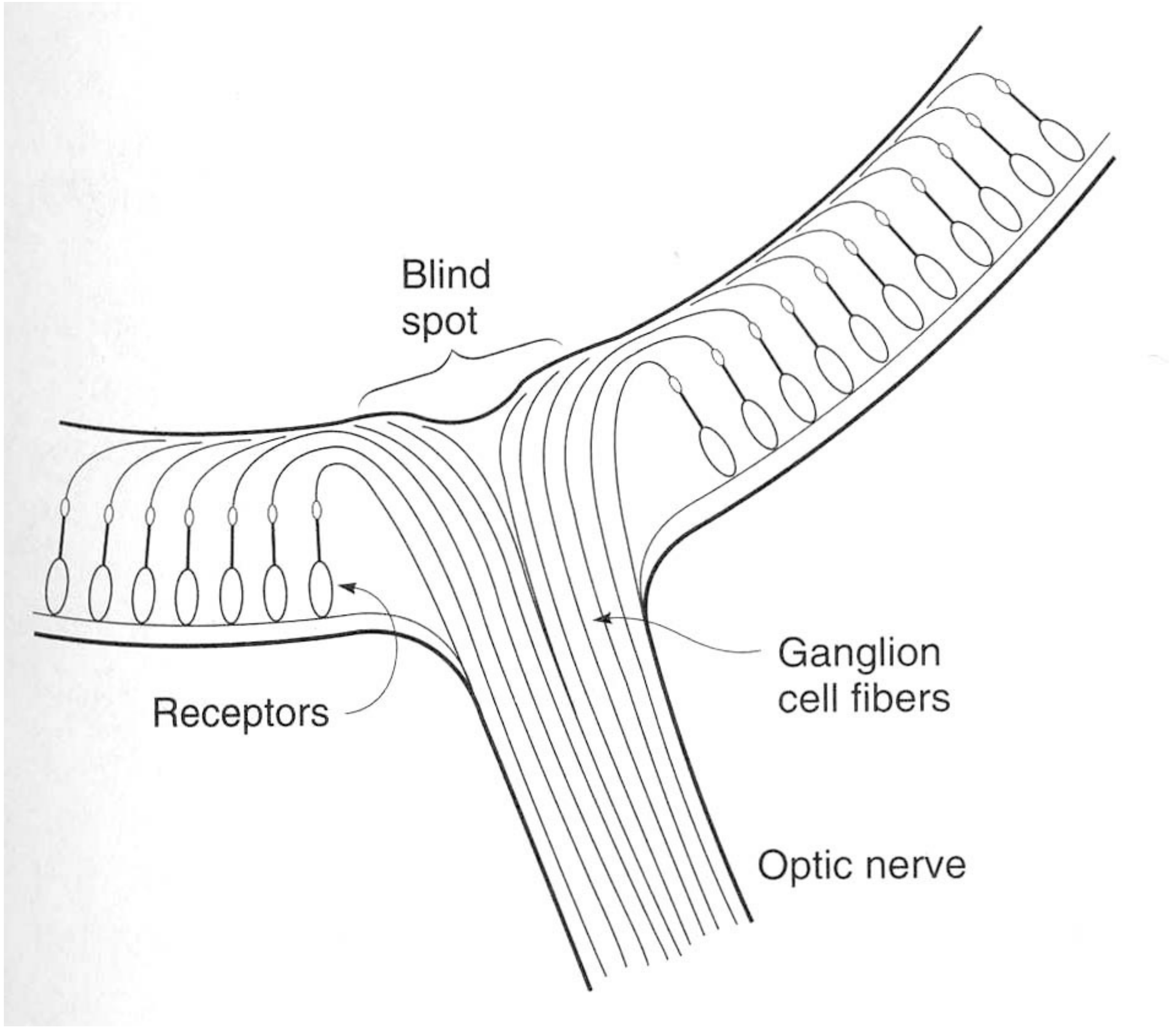
The ganglion cells conduct electrical signals from the eye to the brain.

There is a network of vertical (bipolar) and horizontal (amacrine and horizontal) connections between receptors and ganglion cells

Cones and rods project onto the same ganglion cells!

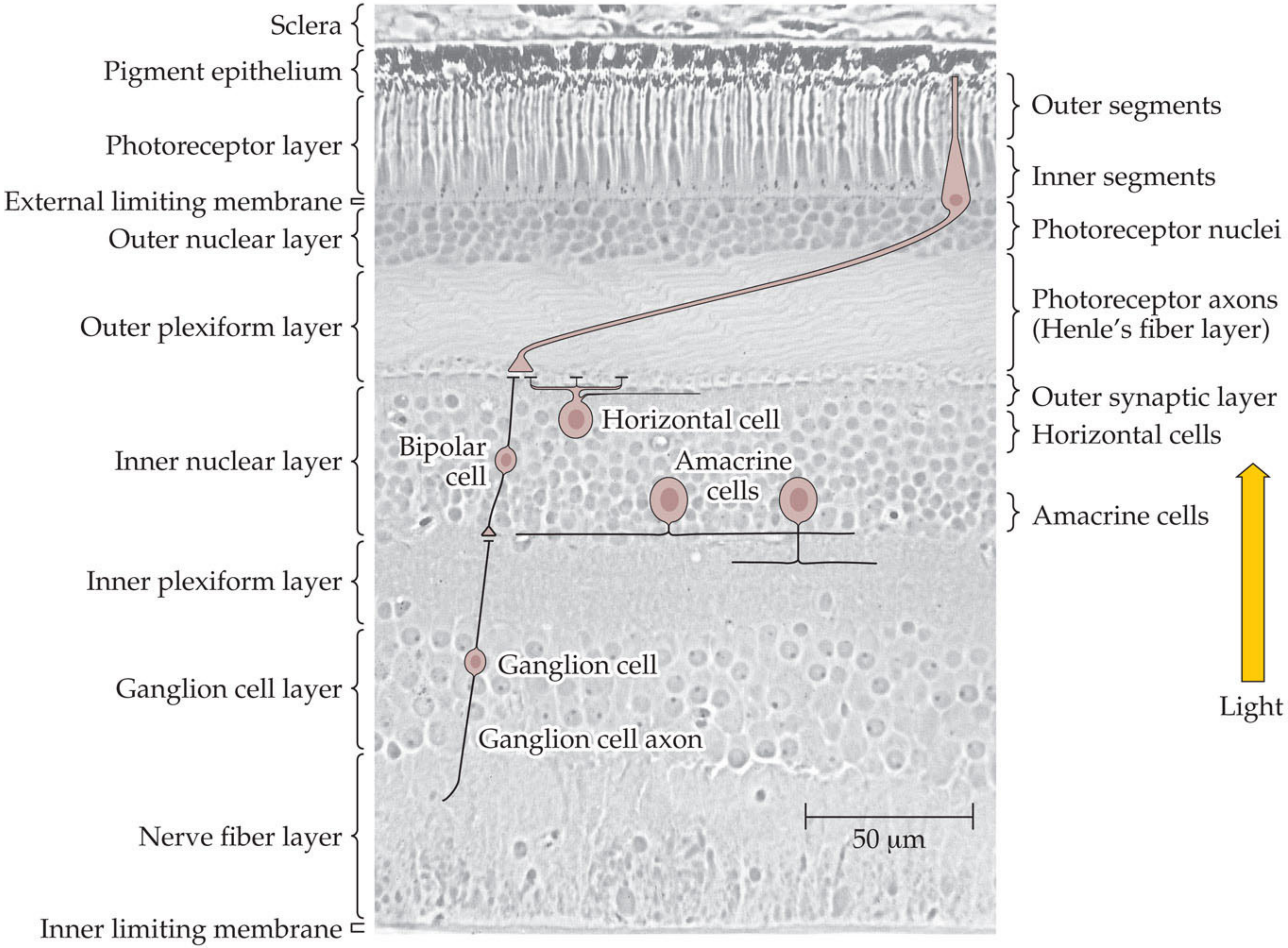
The light path in the eye



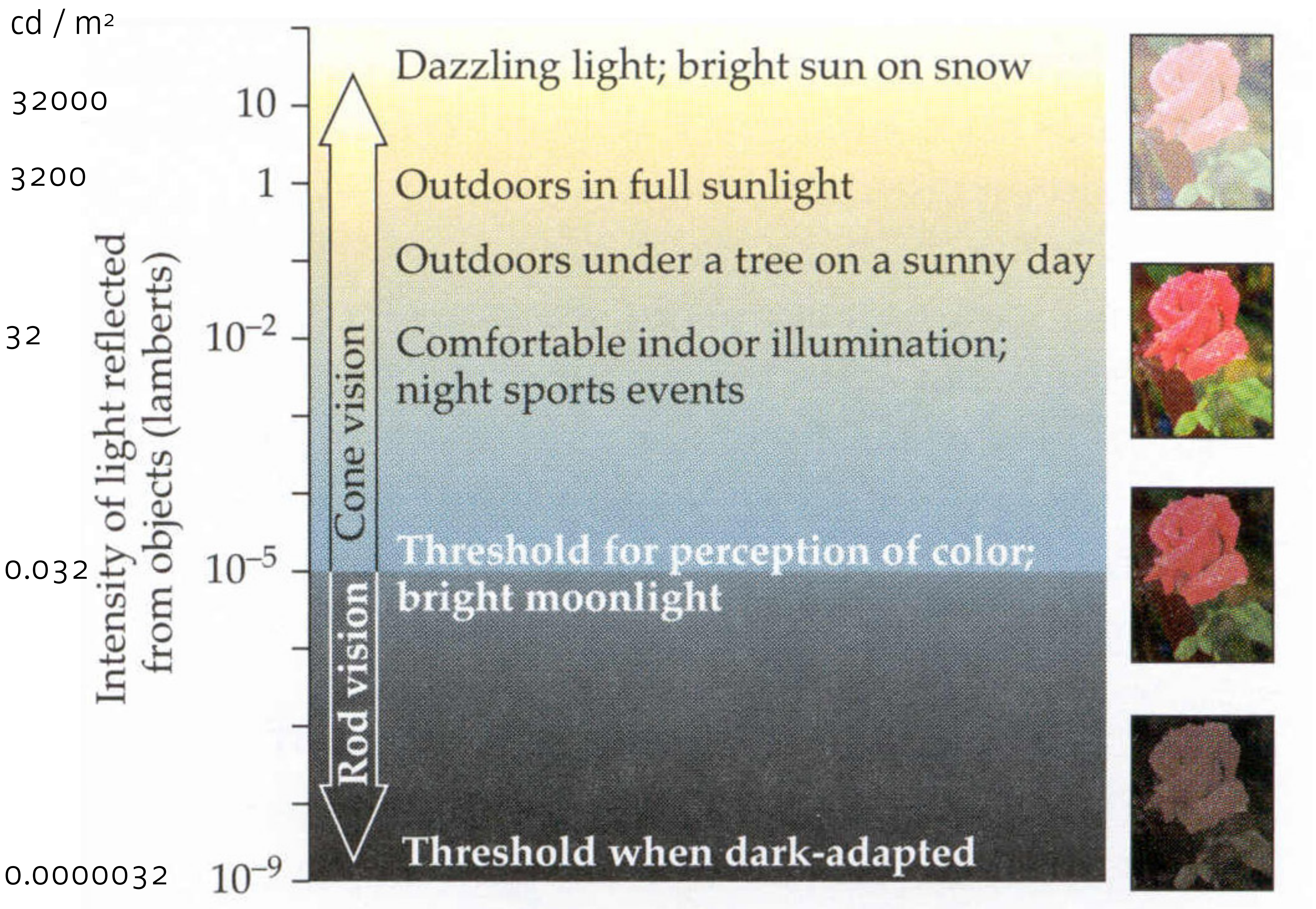


Light travels through the cells to reach the photoreceptors. The site where the axons of the ganglion cells leave the eye has no photoreceptors and is called "blind spot".

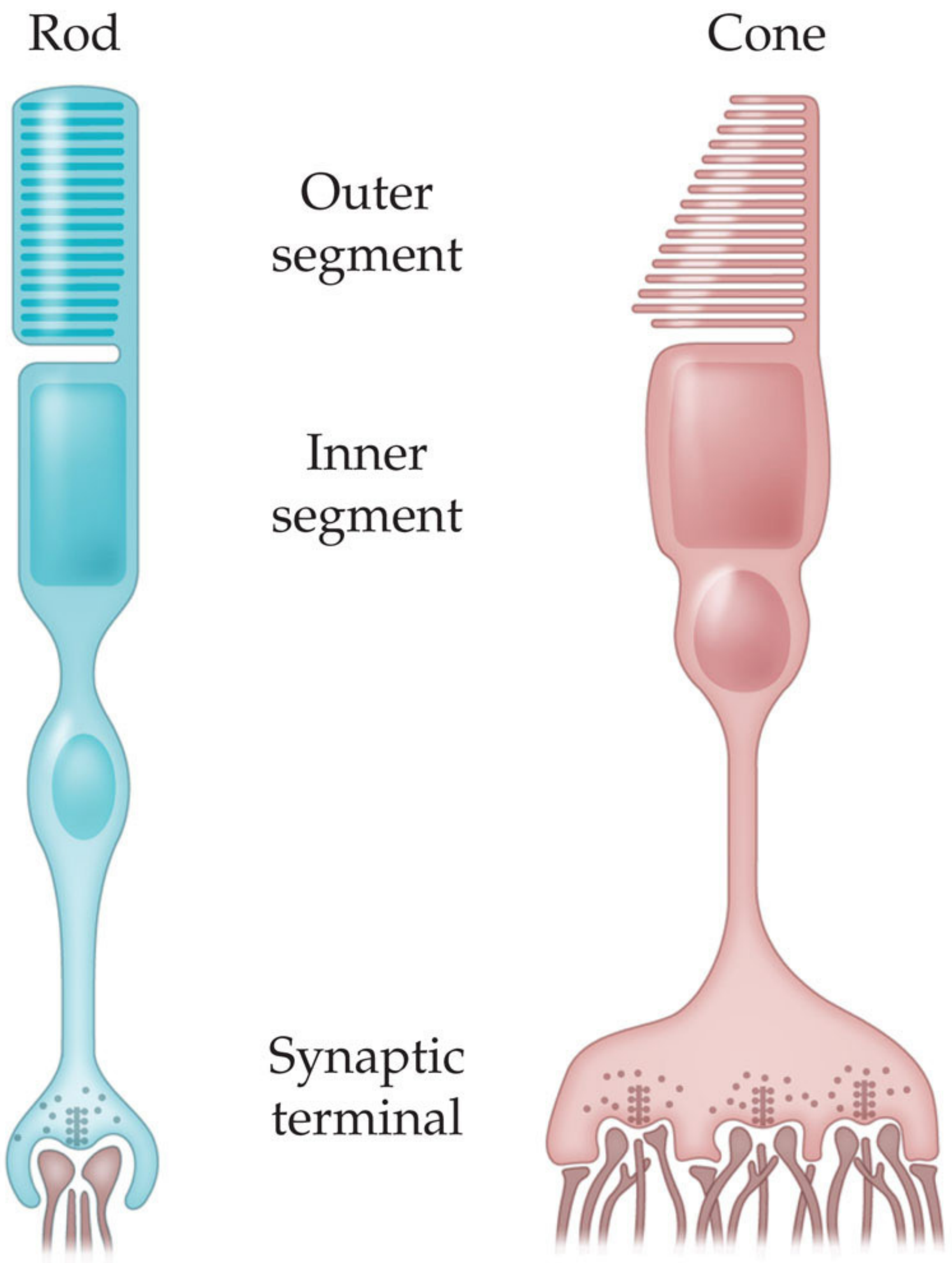
The light path in the eye



SENSATION & PERCEPTION 4e, Figure 2.8

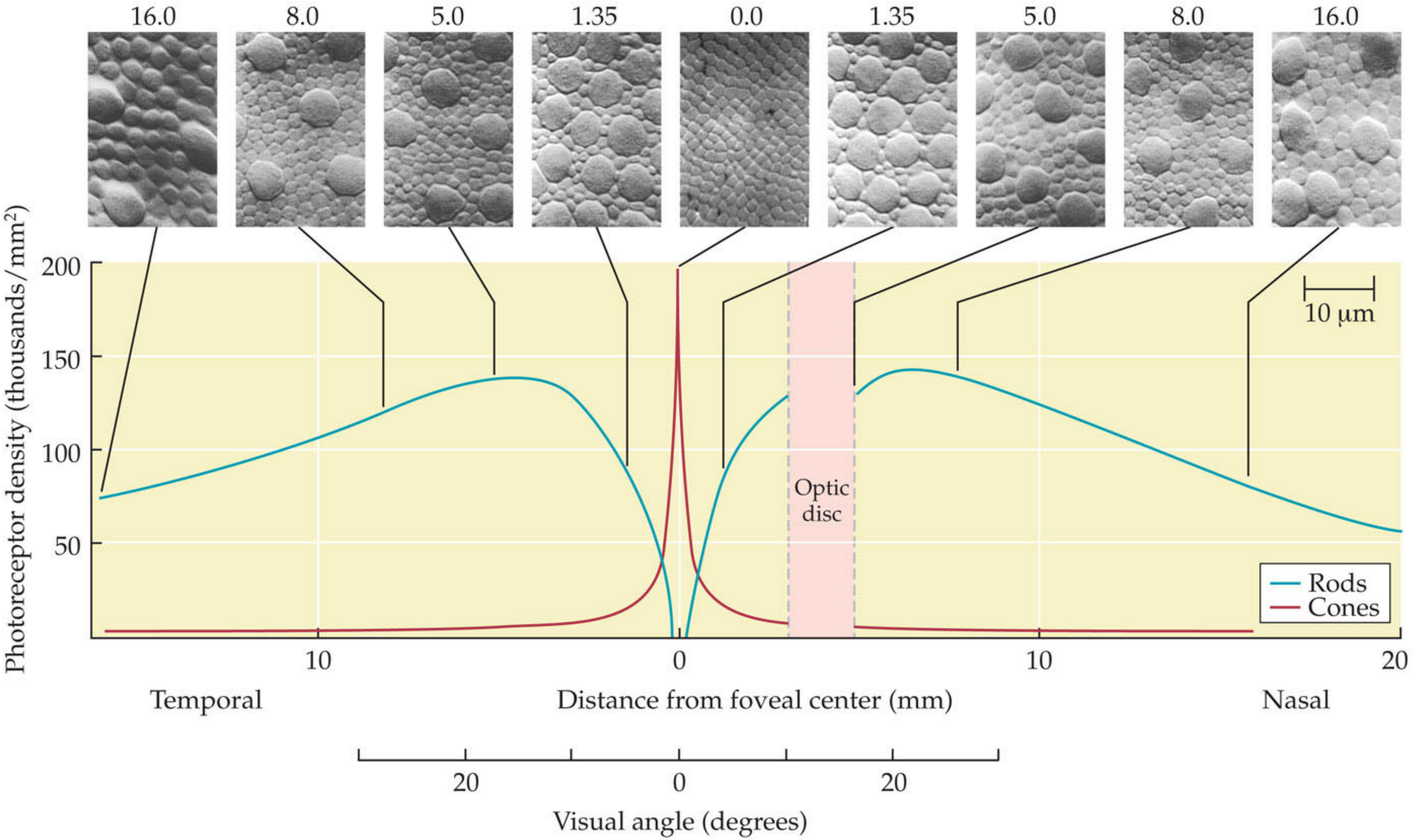


cd / m²
32000
3200
32
0.032
0.0000032
Intensity of light reflected from objects (lamberts)
10
1
10−2
10−5
10−9
Cone vision
Rod vision
Dazzling light; bright sun on snow
Outdoors in full sunlight
Outdoors under a tree on a sunny day
Comfortable indoor illumination; night sports events
Threshold for perception of color; bright moonlight
Threshold when dark-adapted

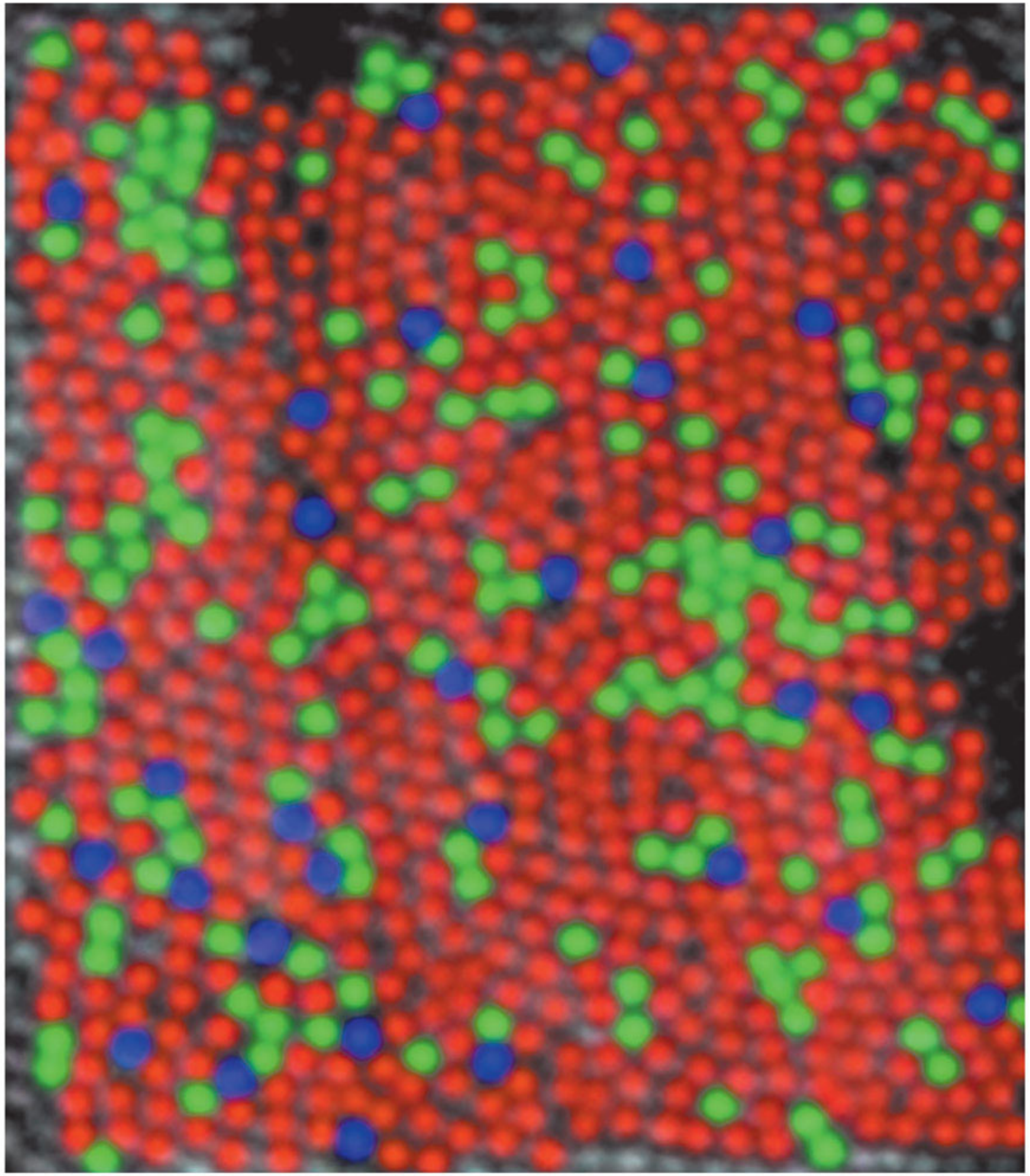


SENSATION & PERCEPTION 4e, Figure 2.9

Receptor distribution across the retina

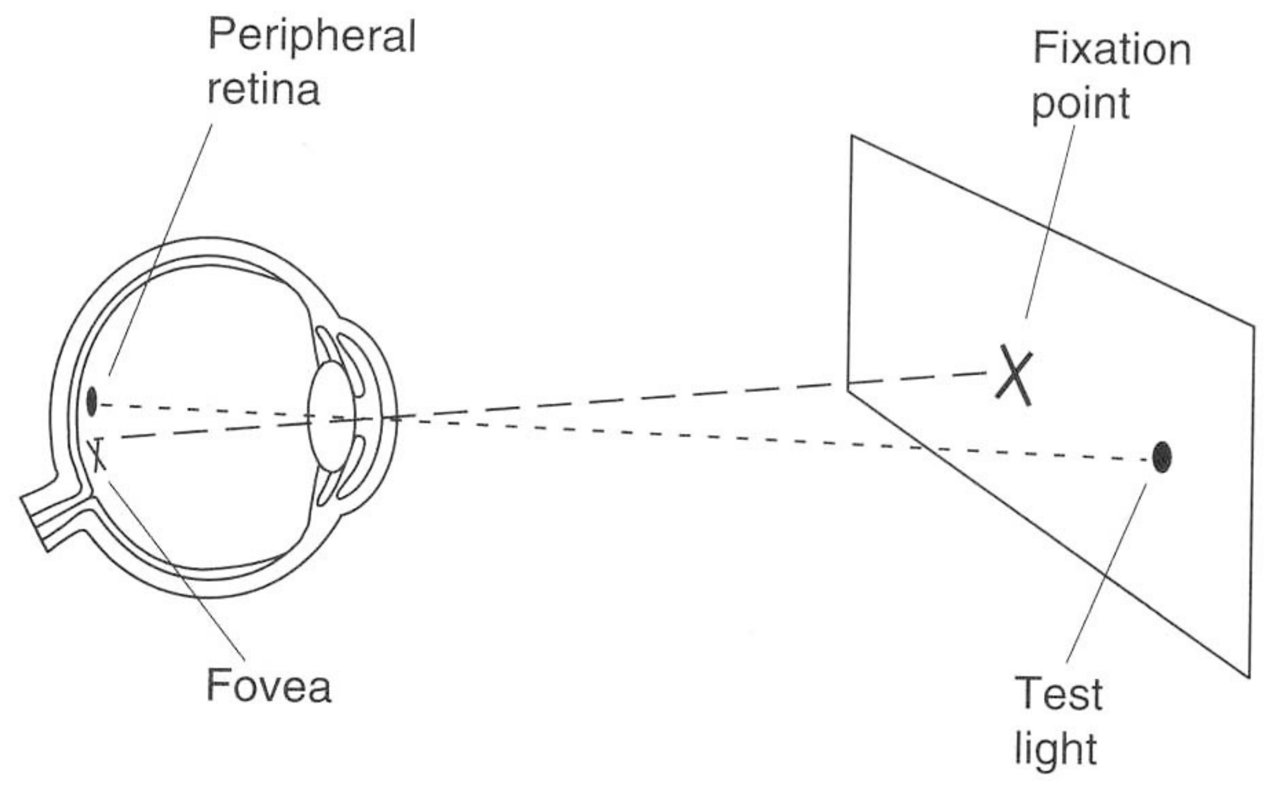


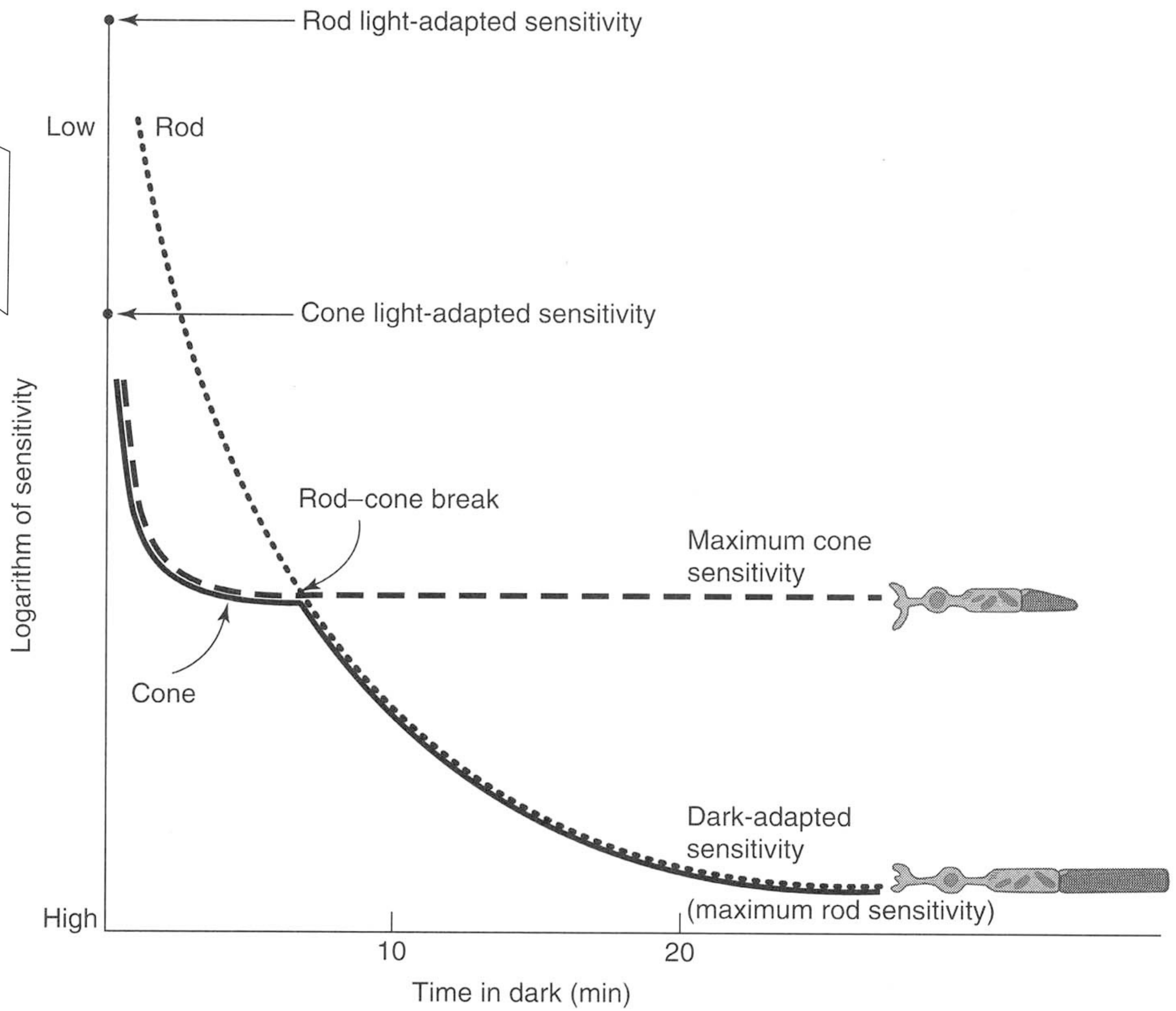
SENSATION & PERCEPTION 4e, Figure 2.10



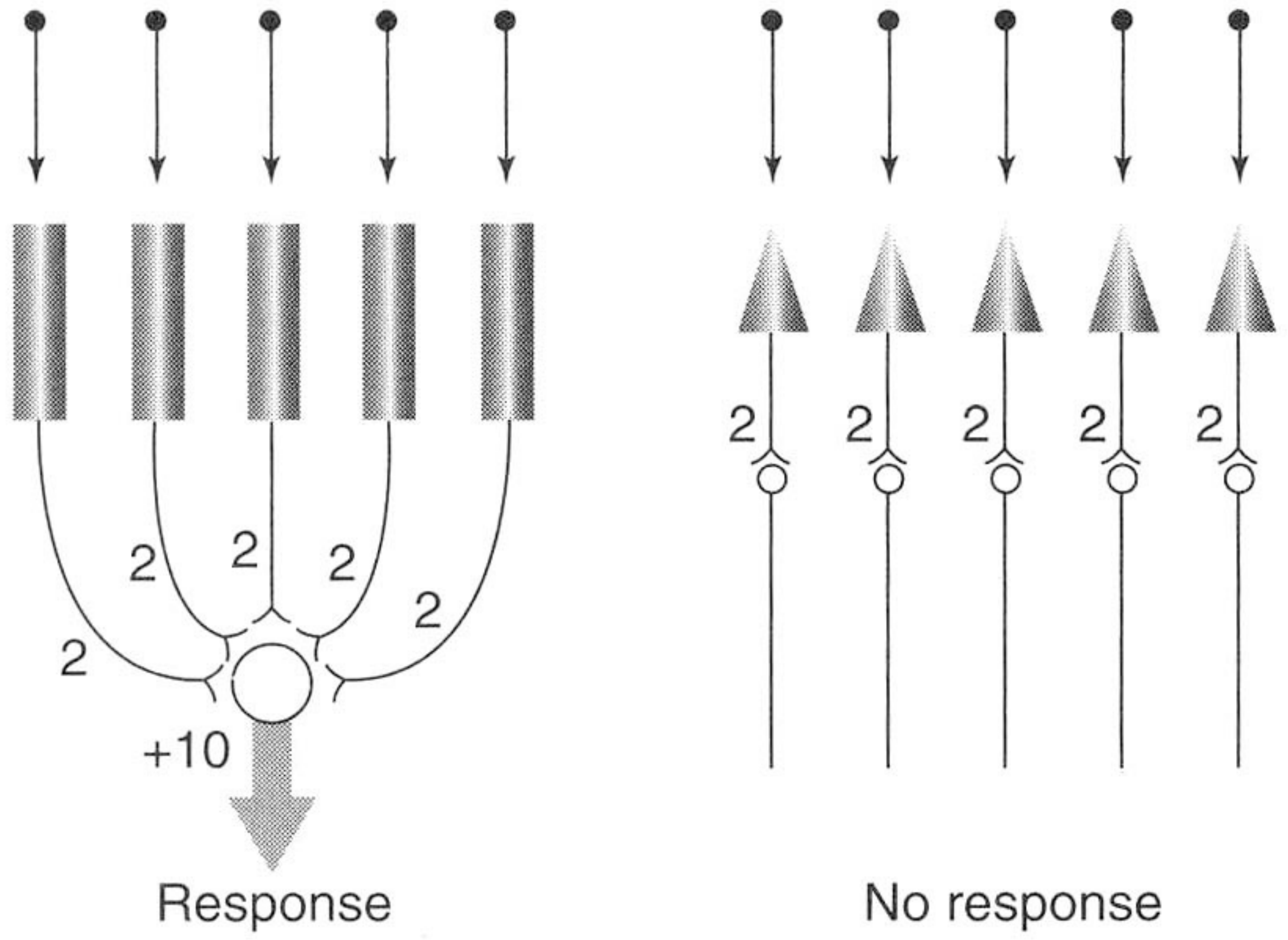
SENSATION & PERCEPTION 4e, Figure 2.12

Dark adaptation

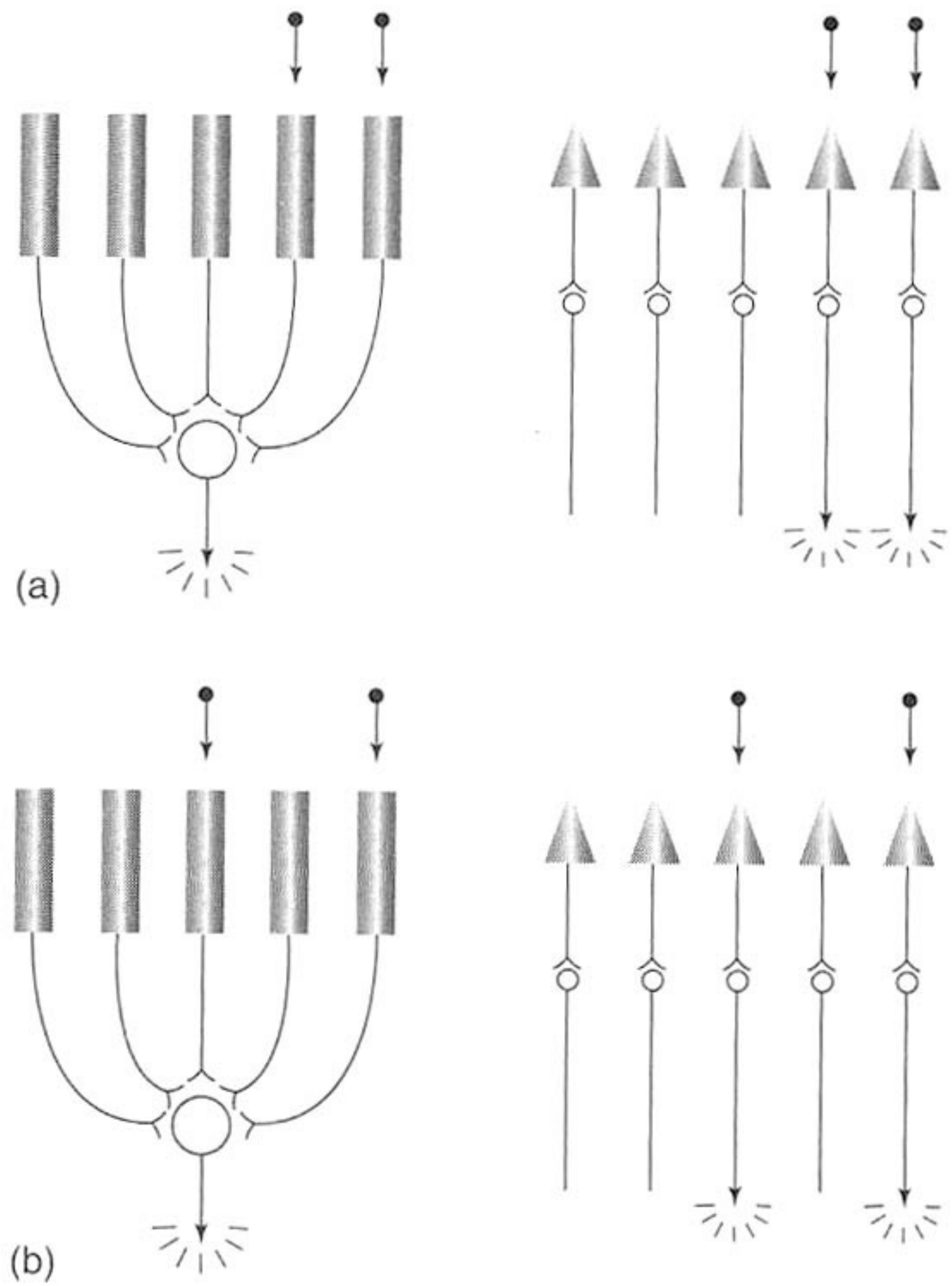




Summation increases sensitivity



… and worsens visual acuity



Stimulus (luminance) gain

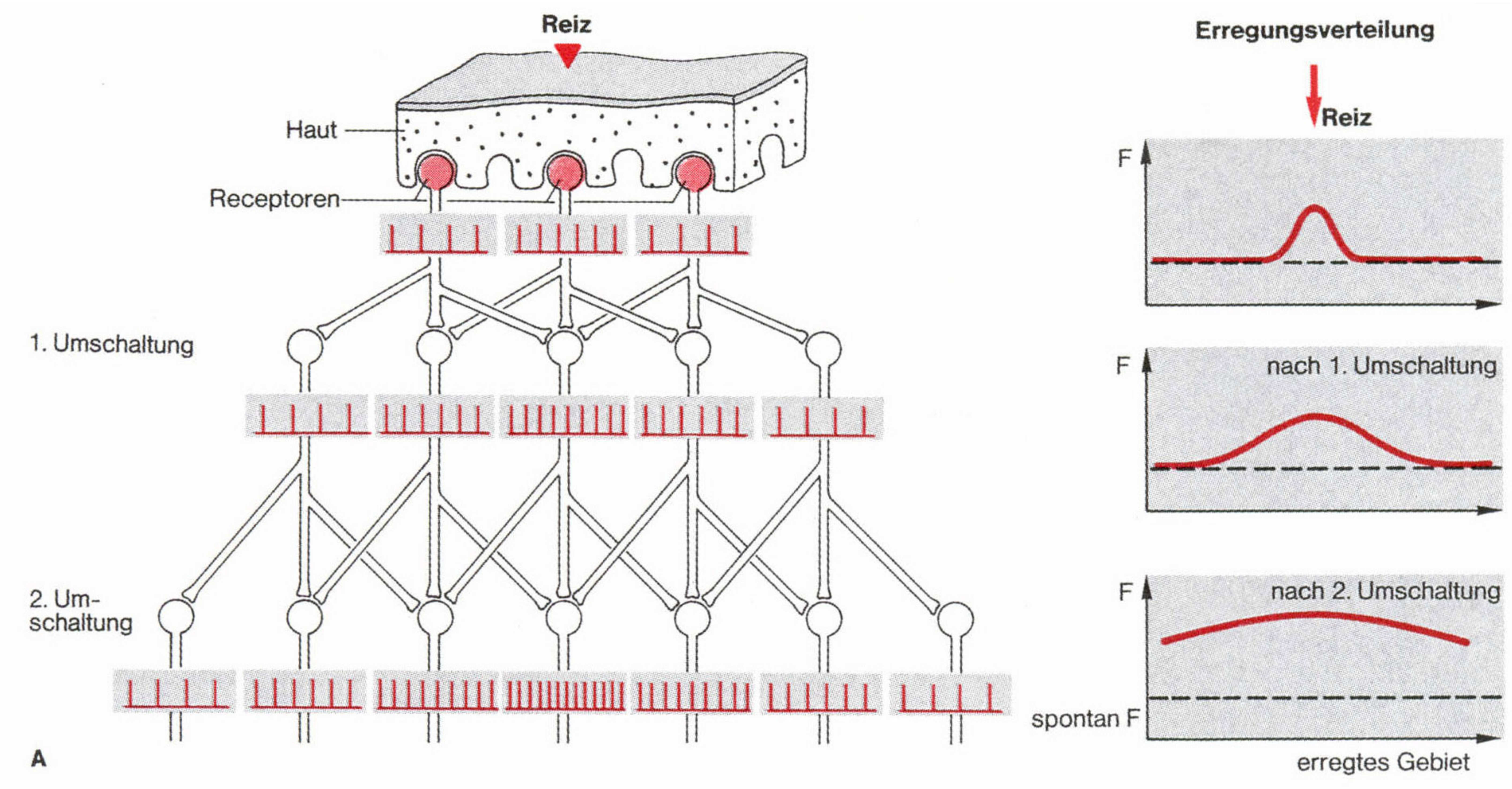


Illustration from skin example; same principle for rods (night vision)

Contrast gain

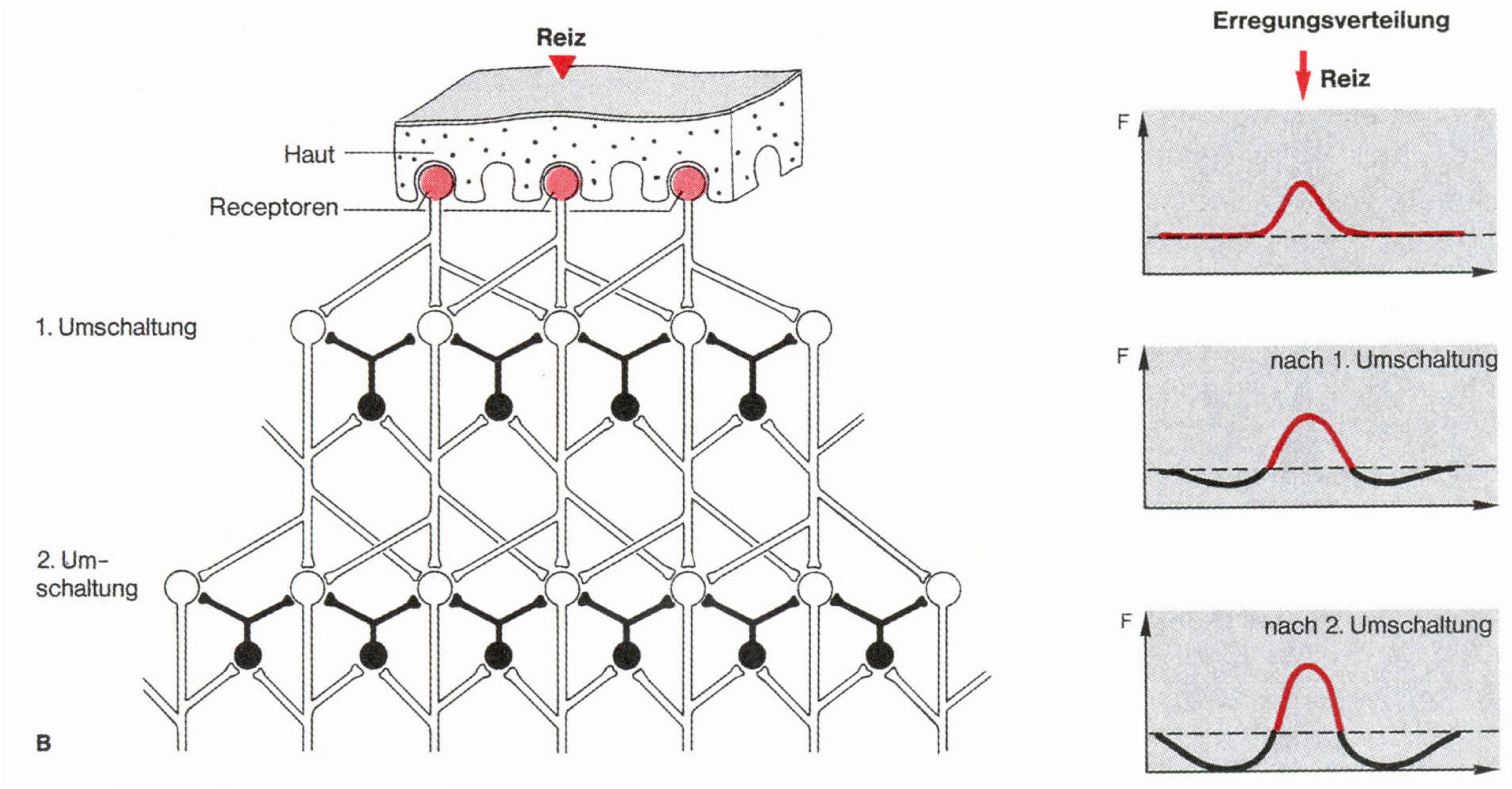


Illustration from skin example; same principle for cones (day vision)

Two visual systems

Feature	Photopic	Scotopic
Receptors	Cones (4-5 million)	Rods (90-100 million)
Photopigment	Three different cone opsins	Rhodopsin
Light sensitivity	Low, for day vision	High, also useful at night
Retinal location	Concentrated in the fovea	Outside the fovea
Acuity (highest resolution)	Very good in the fovea, lower in the periphery	Low

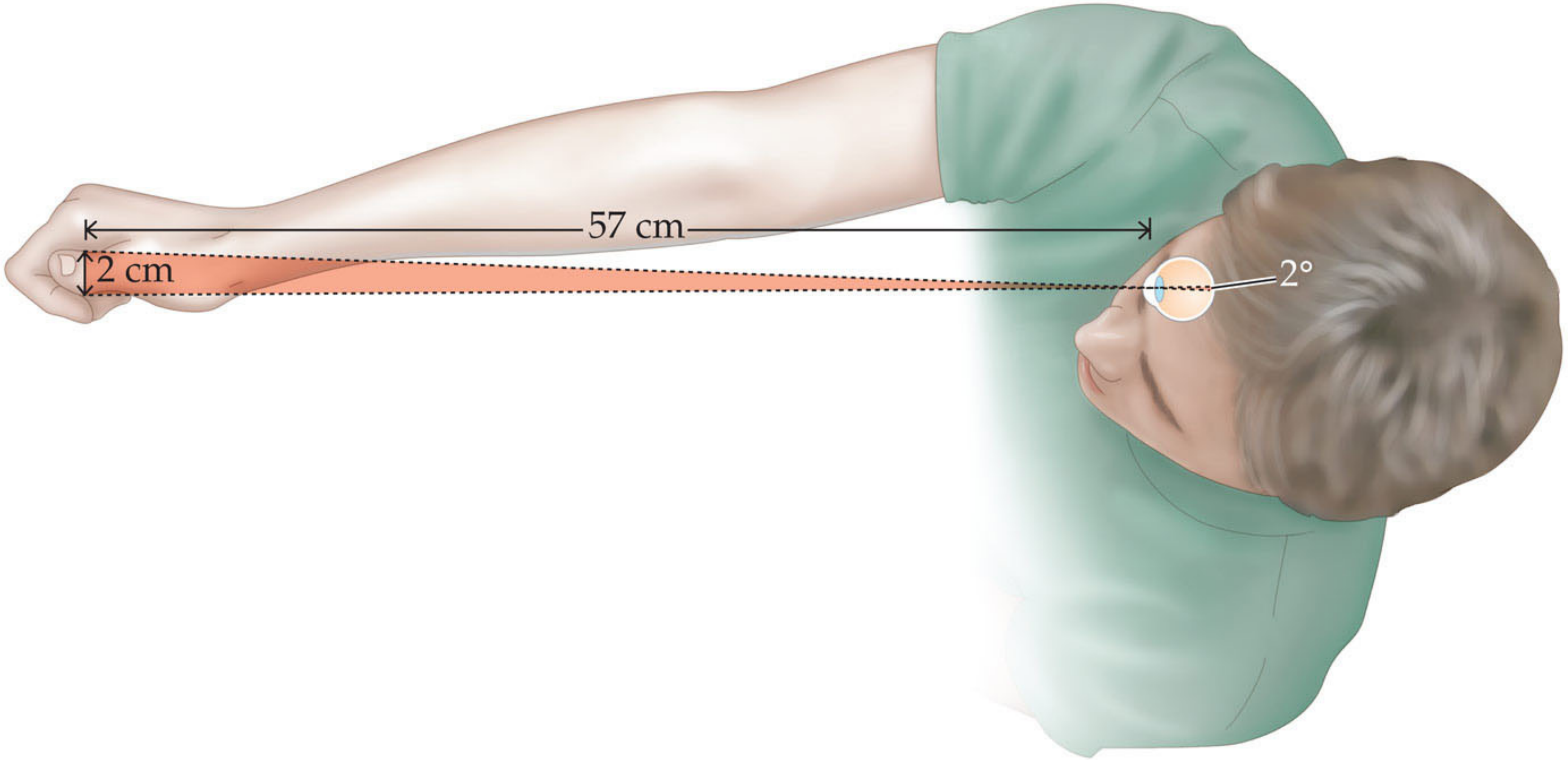
Properties of the fovea and periphery in human vision

TABLE 2.1
Properties of the fovea and periphery in human vision

Property	Fovea	Periphery
Photoreceptor type	Mostly cones	Mostly rods
Bipolar cell type	Midget	Diffuse
Convergence	Low	High
Receptive-field size	Small	Large
Acuity (detail)	High	Low
Light sensitivity	Low	High

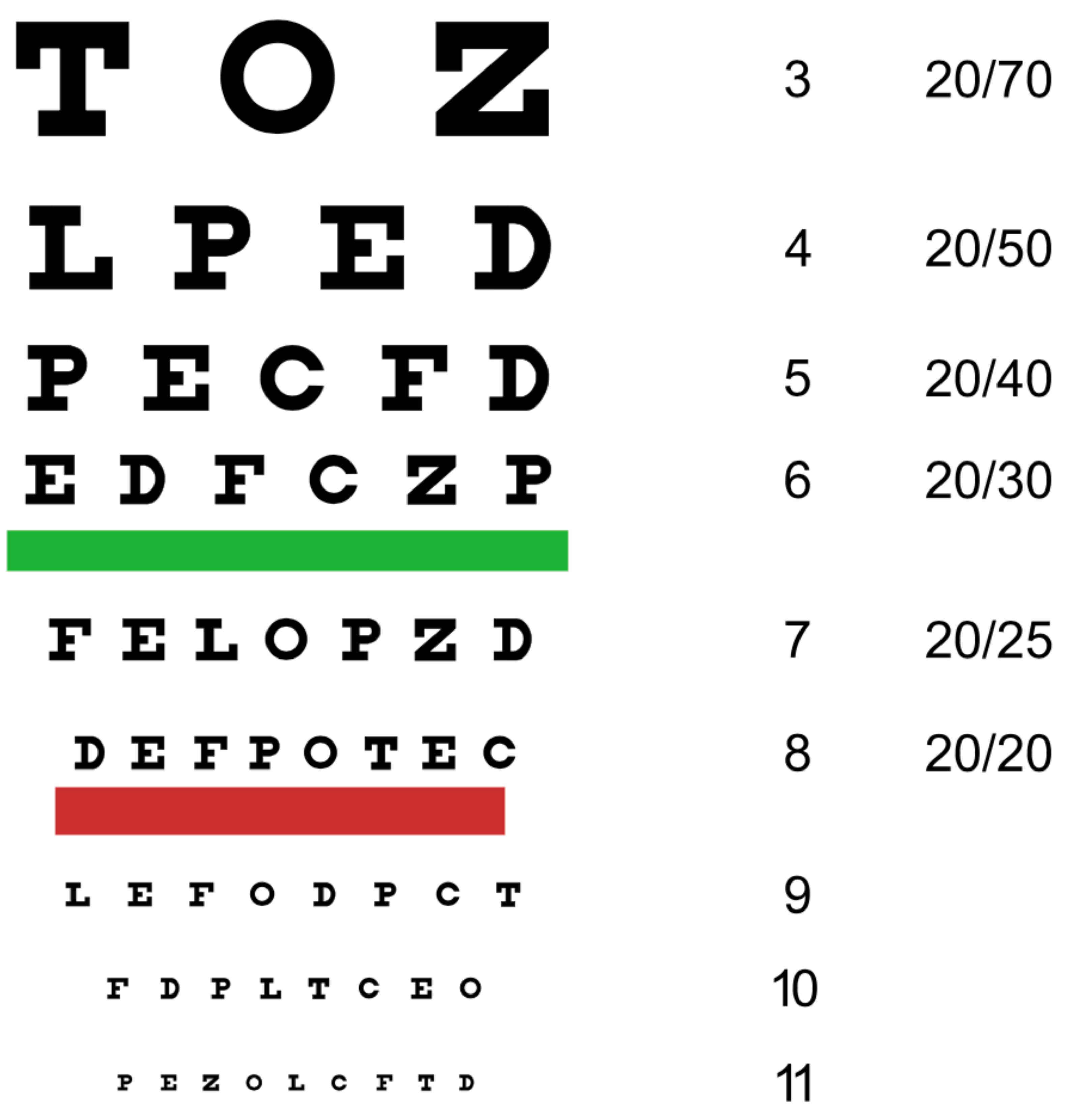
SENSATION & PERCEPTION 4e, Table 2.1

The “rule of thumb”:
when viewed at arm’s length, your thumb subtends an angle of about 1–2 degrees on the retina



SENSATION & PERCEPTION 4e, **Figure 2.11**

Visual acuity: Snellen test chart



Visual acuity refers to the quantification of the sharpest point of vision.

Snellen charts one of the first systematic measurement devices:

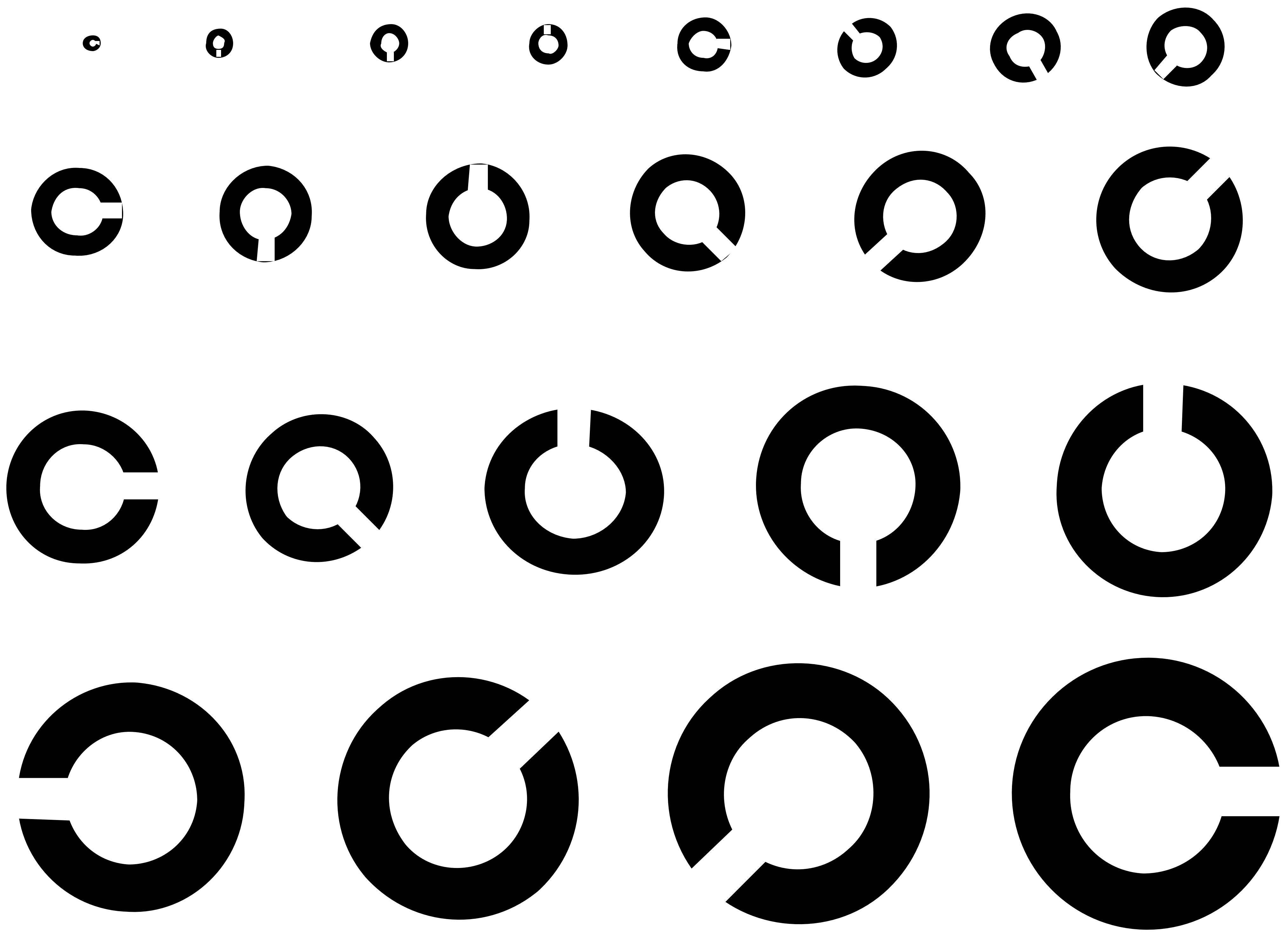
"Standard vision" = ability to recognise an optotype at 5 arcmin (line length = 1 arcmin)

"20/20" vision: this person can recognise letters at 20 ft, and an average person can recognise letters at 20 ft.

Metric "6/6"

e.g. "6/12" = you need to be at 6 meters to recognise what an average person could see at 12 meters

Visual acuity: Landolt C

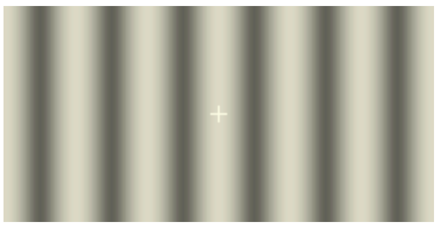


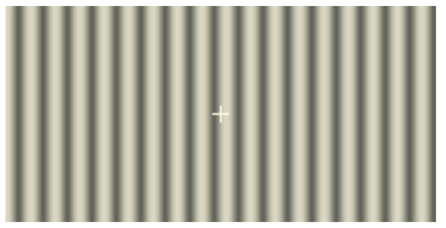
At which "clock position" is the gap?

Result: The viewing angle of the smallest discernible opening is approximately 1 arcmin under optimal conditions.

Visual acuity: sinusoidal gratings

How fine does a grating need to be (high frequency) before you can’t tell it apart from a homogenous grey field?

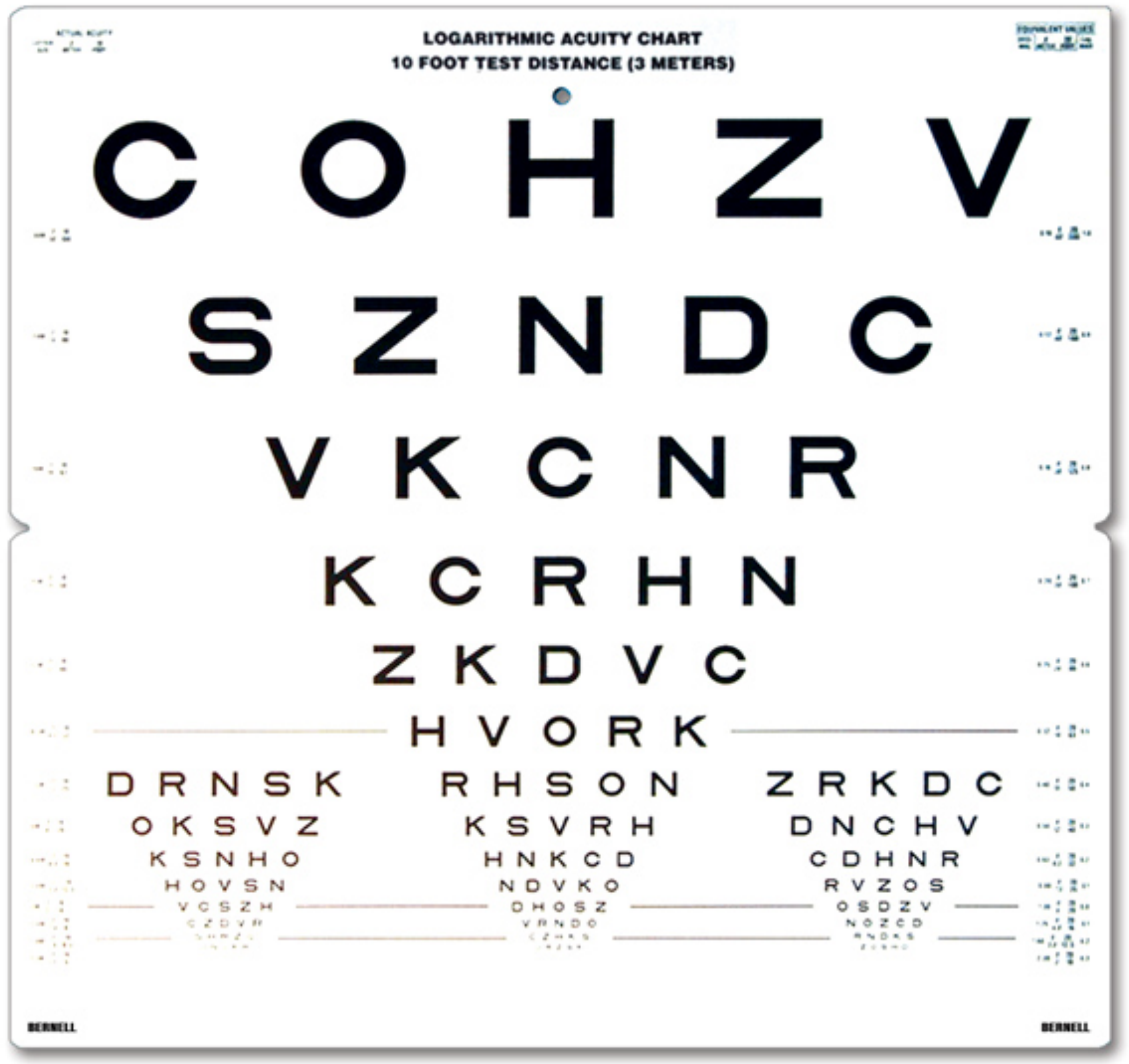




Result: The viewing angle of the smallest period is about 1 angular minute under optimal conditions.

The distance between two cones in the retina is about half an angular minute (30 arcsec). A lighter and a darker stripe must therefore fall on different receptors to see the lattice (or the gap)

Visual acuity: logMAR



Most common letter chart used today is logMAR:

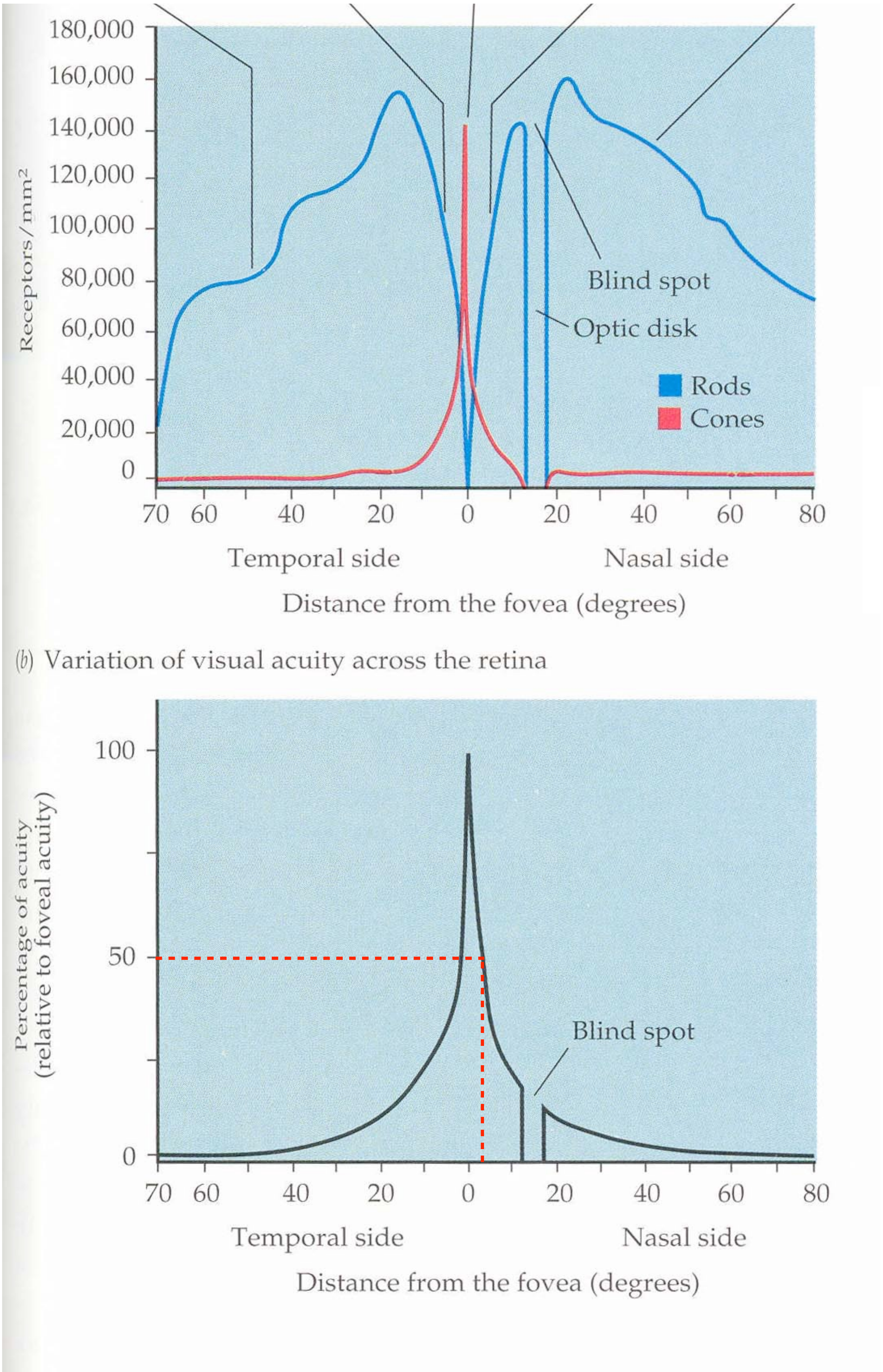
Logarithm of the Minimum Angle of Resolution (logMAR)

Resolving detail at 1 arcmin = $\log_{10}(1) = 0$ logMAR

Category	Snellen acuity	logMAR	Minimum angle (arcmin)
“Normal” acuity	6/6	0	1
Mild or no visual impairment	> 6/18	0,47	3
Moderate - Severe visual impairment	3/60 < x < 6/18	1.3 < x < 0.47	3 < x < 20
Blindness	< 3 / 60	< 1.3	> 20

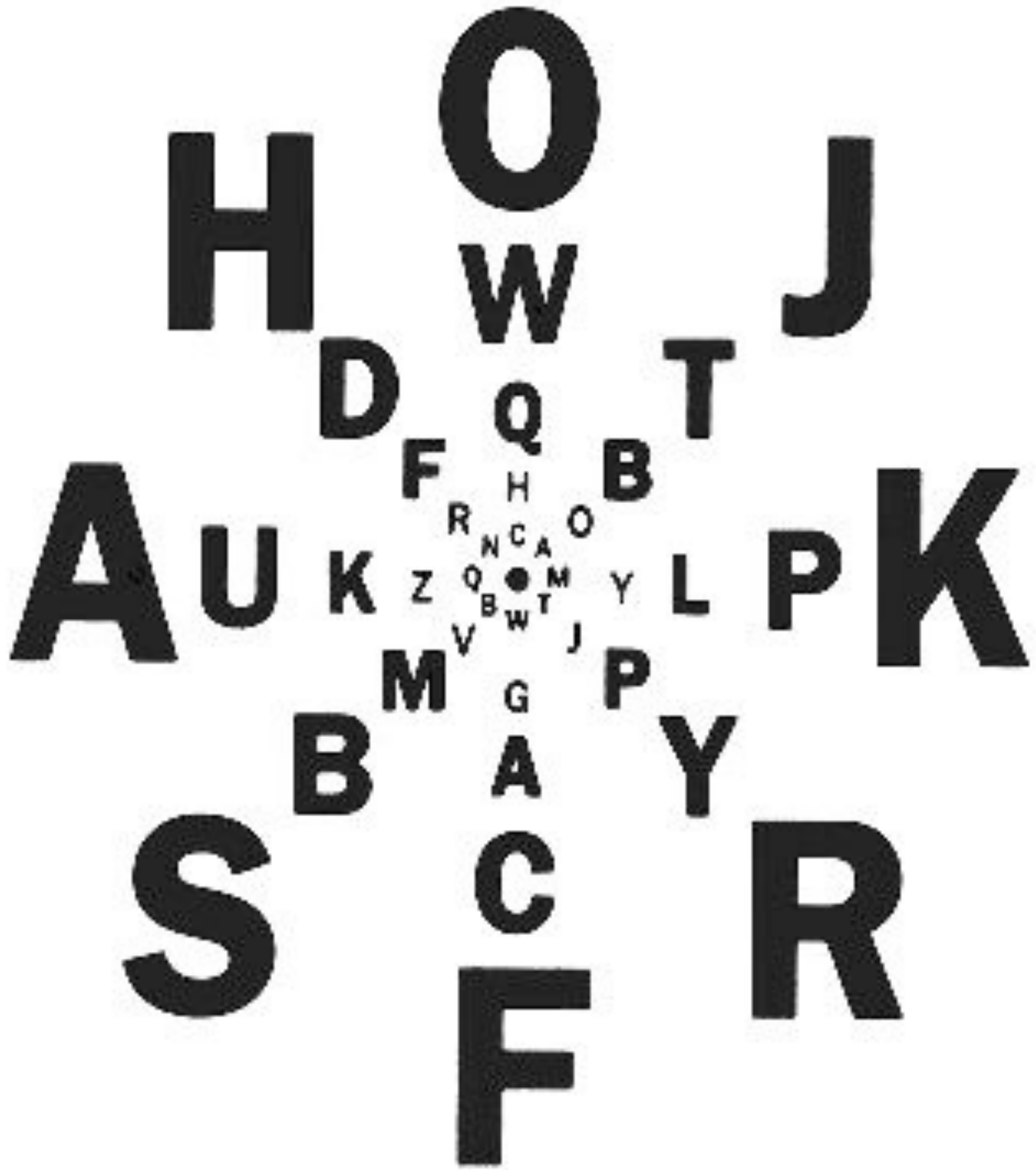
From the International Classification of Diseases: http://apps.who.int/classifications/icd10/browse/2016/en#/H54.2

Visual acuity across the visual field

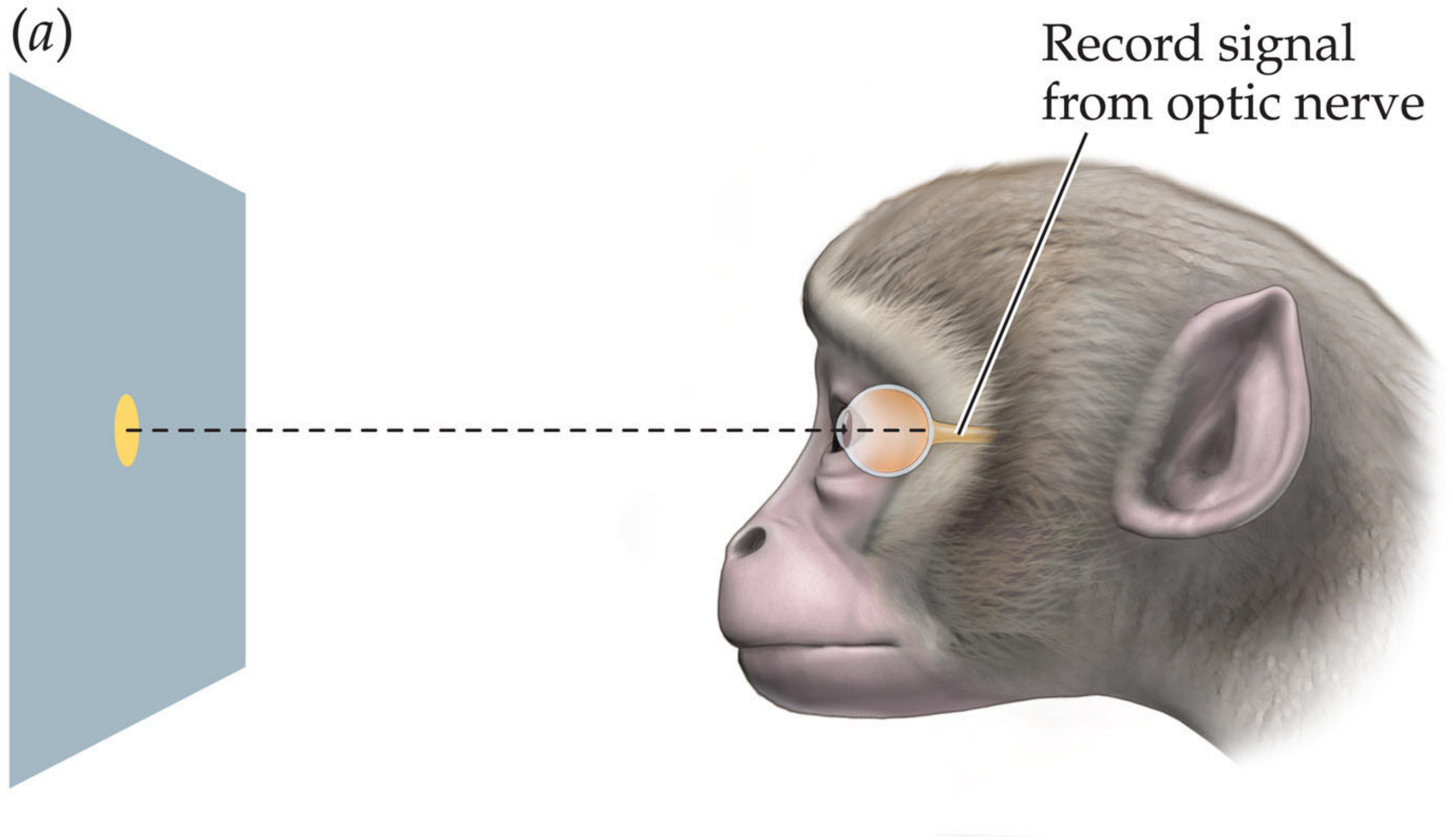


Visual acuity depends primarily on the density of cones – and thus decays with retinal eccentricity

The rod system has a relatively constant visual acuity of about 25 arcmin across the field of view

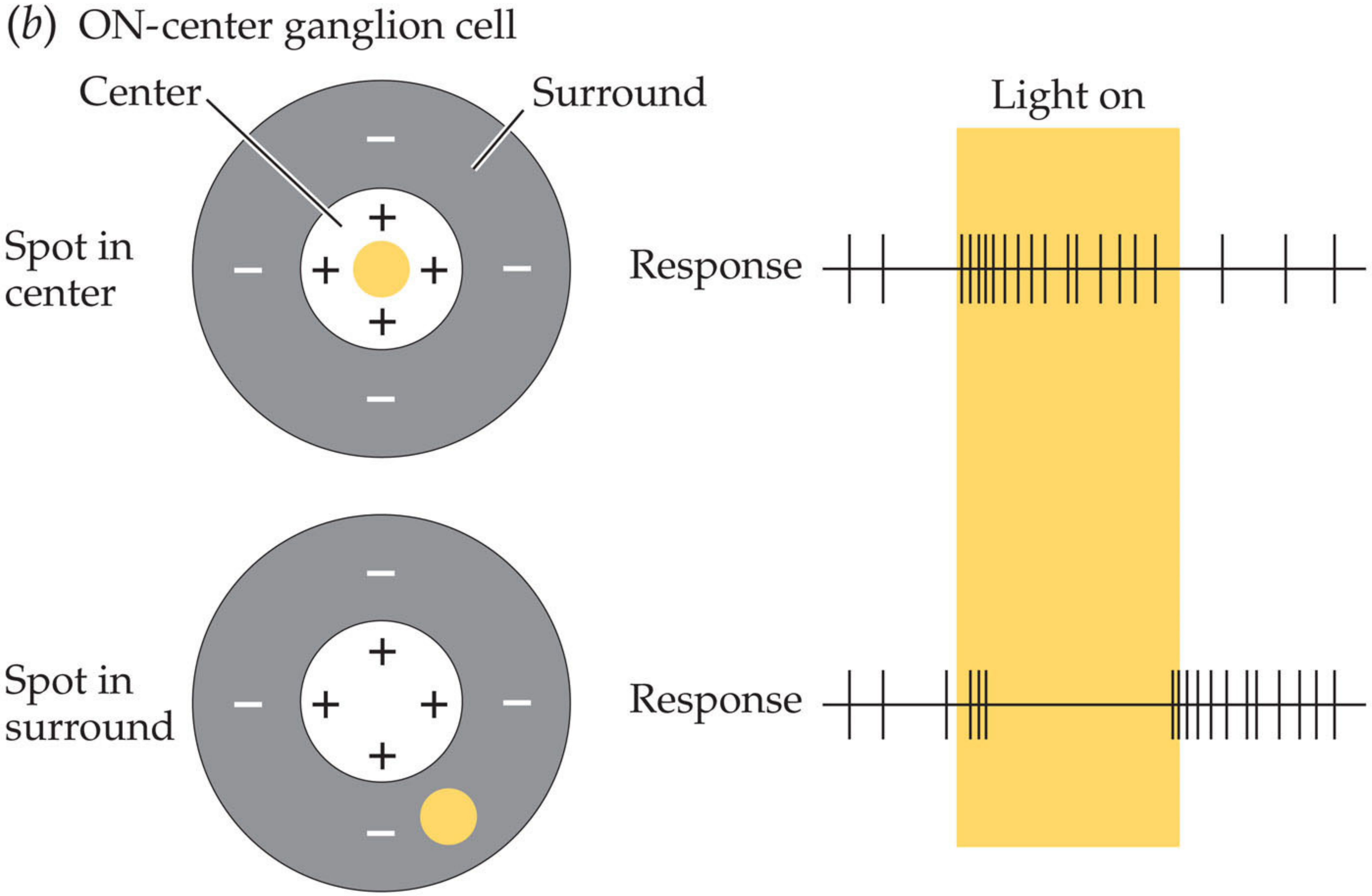

O
H W J
D T
Q
F B
H
R O
C
N A
A U K Z Q M Y L P K
B T
W
V J
M P
G
B Y
A
S R
C
F

Retinal ganglion cell receptive fields (Part 1)



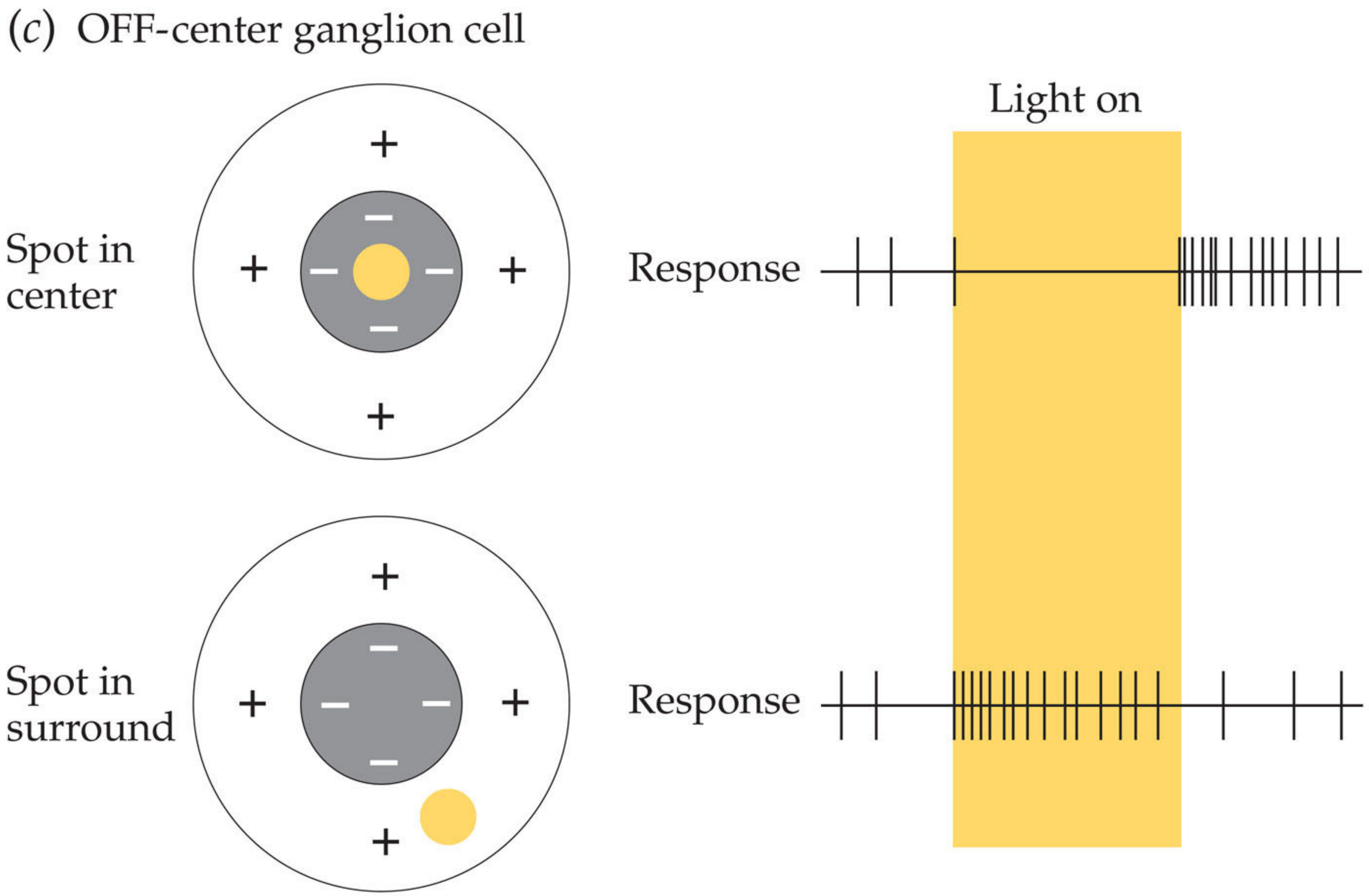
SENSATION & PERCEPTION 4e, Figure 2.14 (Part 1)

Retinal ganglion cell receptive fields (Part 2)



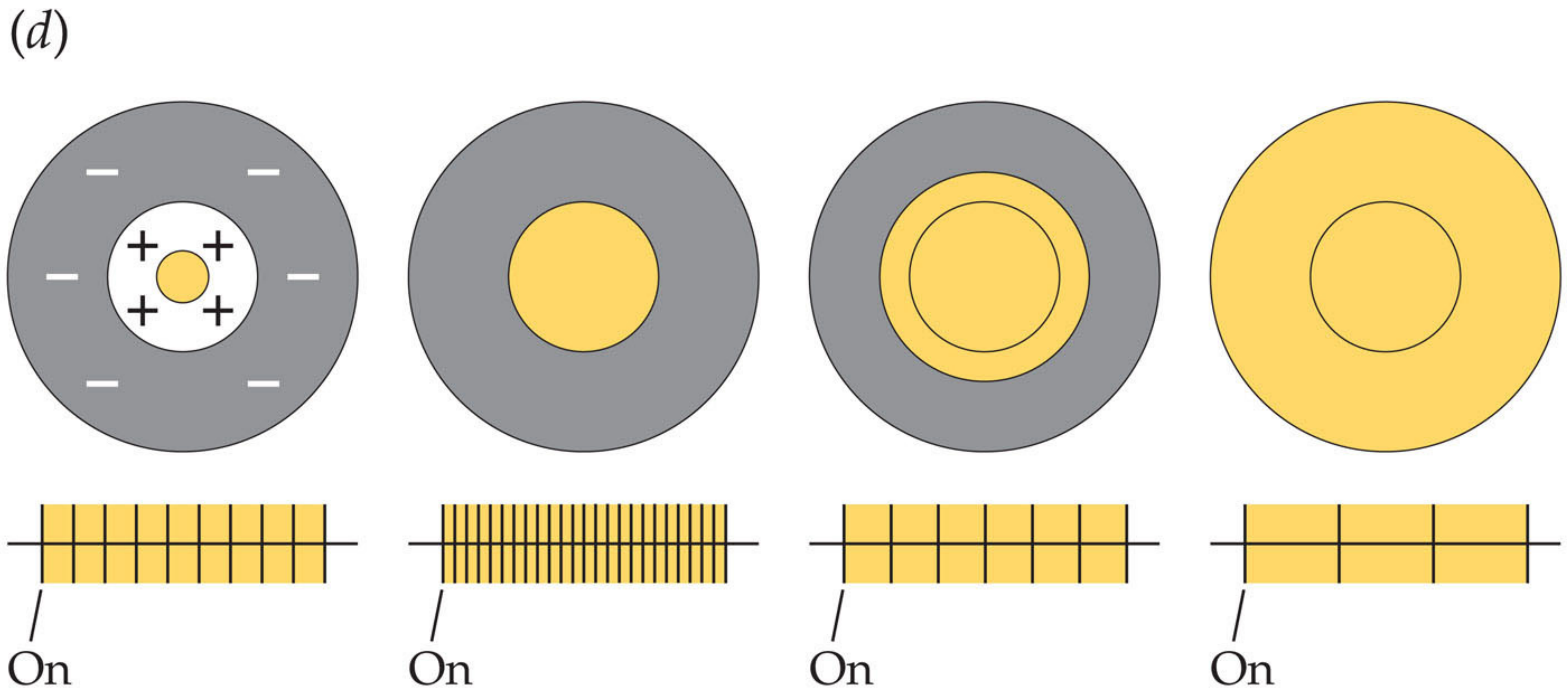
SENSATION & PERCEPTION 4e, **Figure 2.14 (Part 2)**

Retinal ganglion cell receptive fields (Part 3)



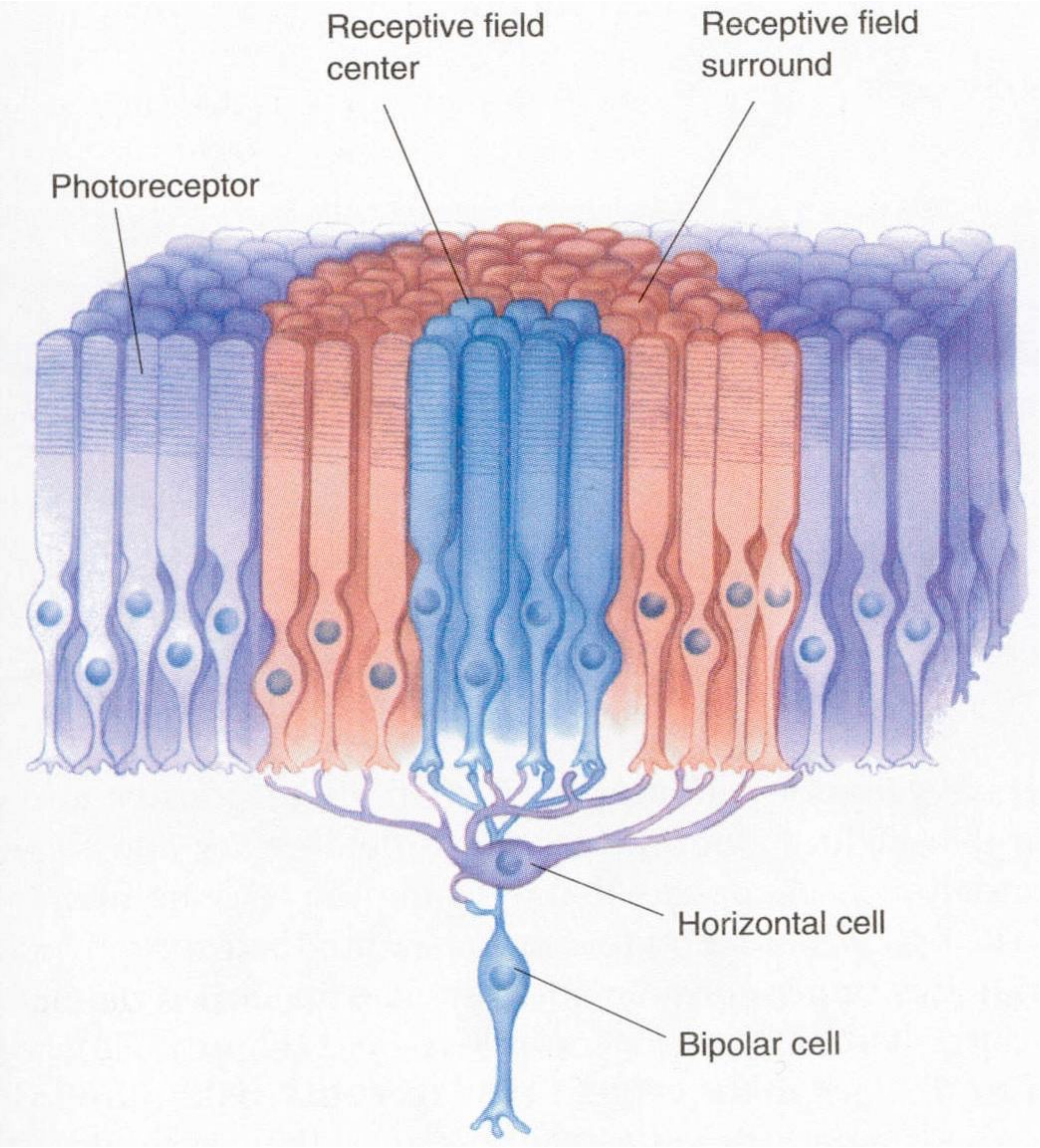
SENSATION & PERCEPTION 4e, **Figure 2.14 (Part 3)**

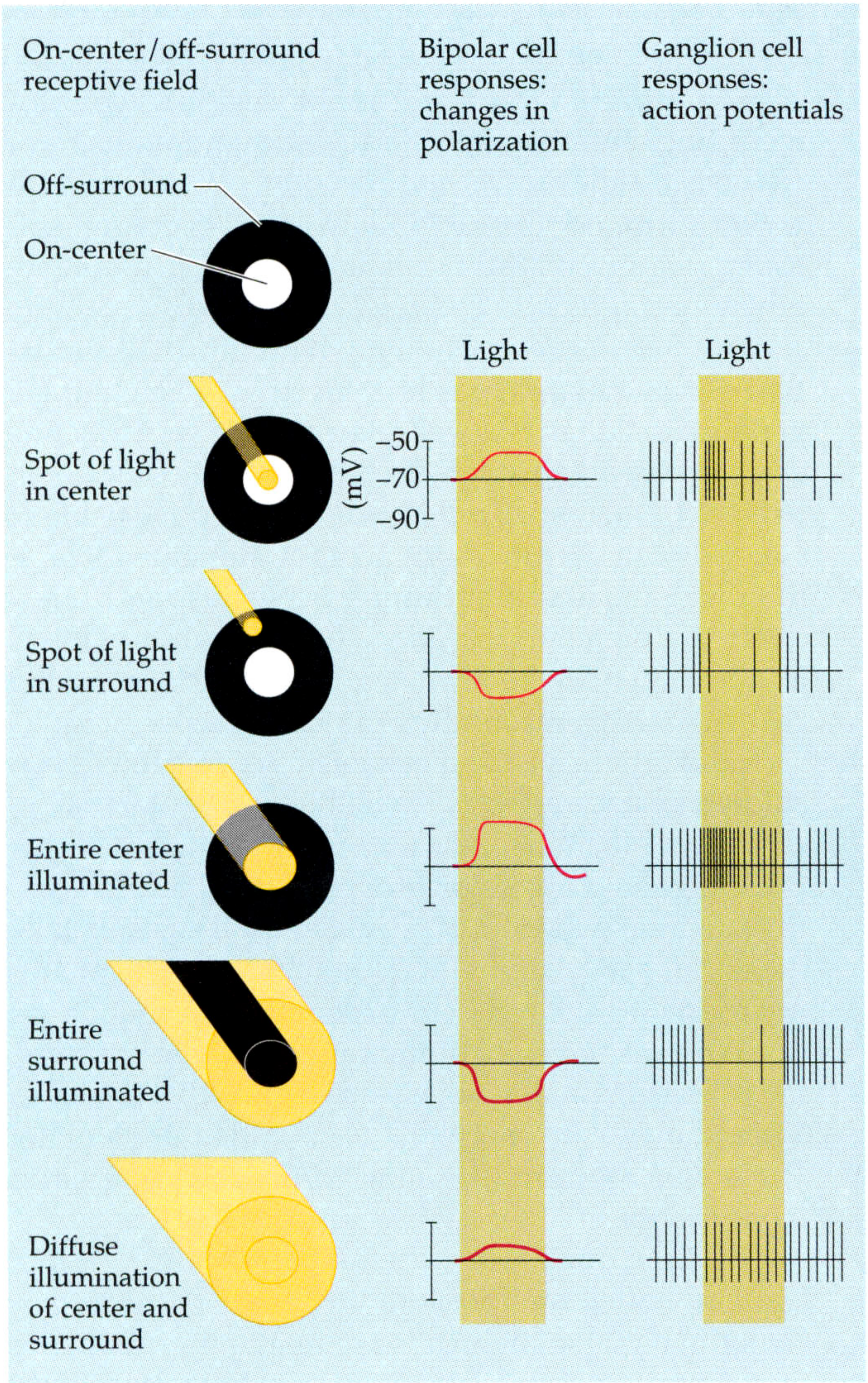
Retinal ganglion cell receptive fields (Part 4)



SENSATION & PERCEPTION 4e, Figure 2.14 (Part 4)

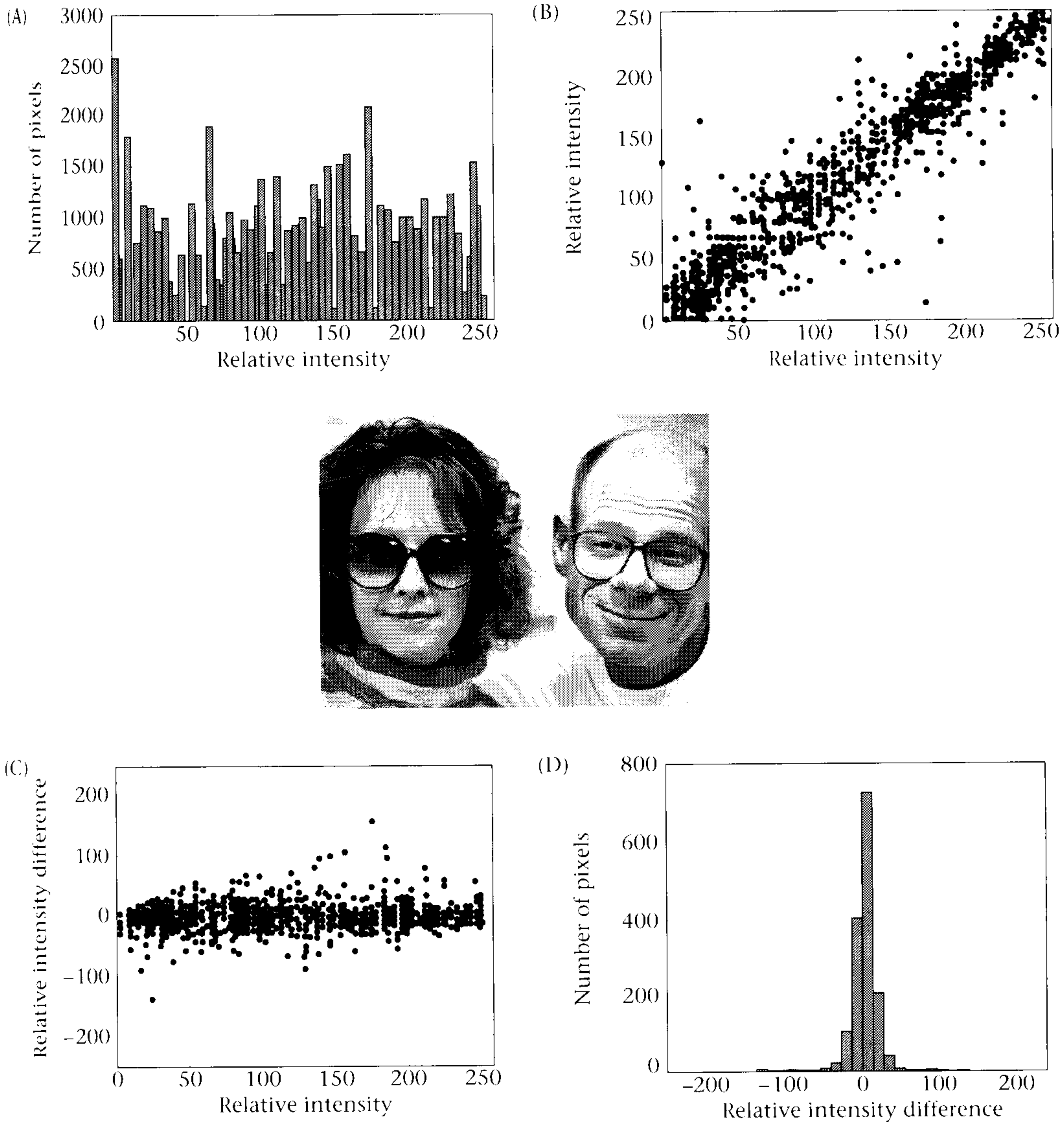
Lateral Inhibition





Why lateral inhibition?

Redundancy of natural scenes



Neighbouring pixels in natural scenes usually have the same intensity

This leads to a high correlation of signals from adjacent cones

Difference formation (lateral inhibition) prevents this

A grossly-simplified overview

This lecture aimed to give you the biggest picture of retinal processing, but this is an active and exciting area of research.

Textbooks in vision will tell you:

- There are two functional types of ganglion cells that send projections to the cortex …
  But: maybe more than 20 in most mammals, more than 30 in mouse!
- There are four light sensitive cells (rods and three types of cones) …
  But there is in addition a fifth one, a light sensitive ganglion cell that express melanopsin; seems play role in pupil response and circadian rhythm. Furthermore, some women have up to five cones types (genetic mutation variation in M/L)

Supplementary Literature

Baden, T., Euler, T., & Berens, P. (2020). Understanding the retinal basis of vision across species. *Nature Reviews Neuroscience*, 21(1), 5–20.

Masland, R. H. (2012). The Neuronal Organization of the Retina. *Neuron*, 76(2), 266–280.

Baden, T., Berens, P., Franke, K., Román Rosón, M., Bethge, M., & Euler, T. (2016). The functional diversity of retinal ganglion cells in the mouse. *Nature*, 529(7586), 345–350.

The End

Felix Wichmann

Neural Information Processing Group
Eberhard Karls Universität Tübingen