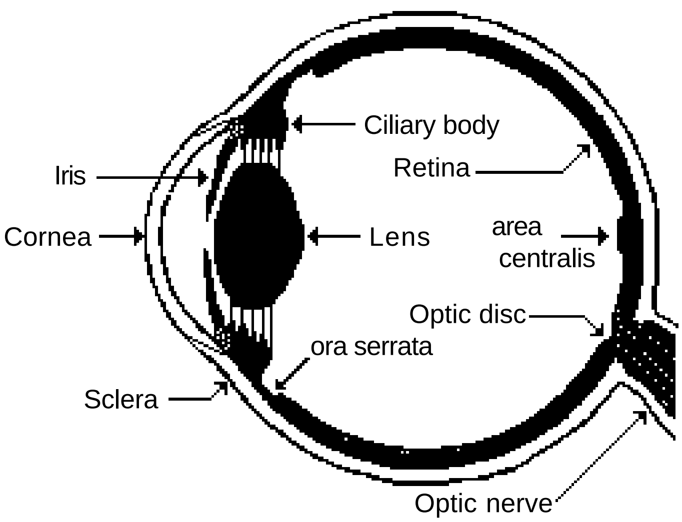
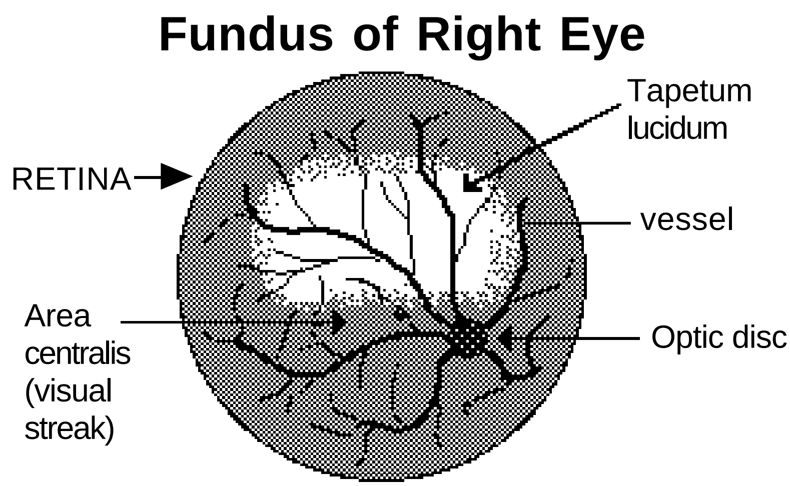
Visual System

EYEBALL — composed of three concentric layers:

1] SCLERA (white) and CORNEA (transparent) = outer, fibrous layer.
2] IRIS, CILIARY BODY and CHOROID = middle, vascular layer (uvea).
The choroid contains a tapetum lucidum in most domestic animals (absent in the pig).
3] RETINA = inner layer of the eyeball (develops embryologically from an optic cup).
The pigmented epithelium of the retina lines the iris, ciliary body & choroid.
The functional optic part of retina lines the fundus to the level of the ora serrata.



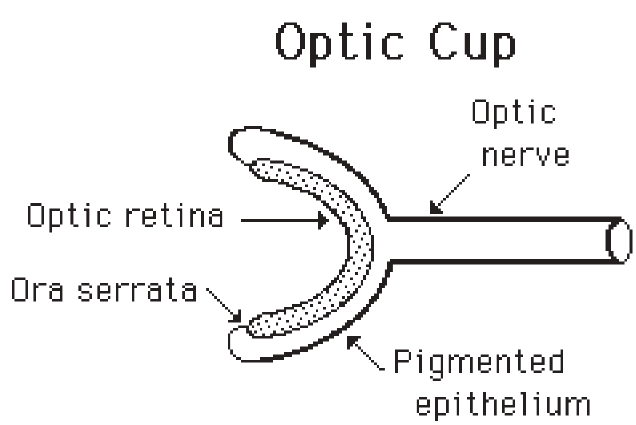


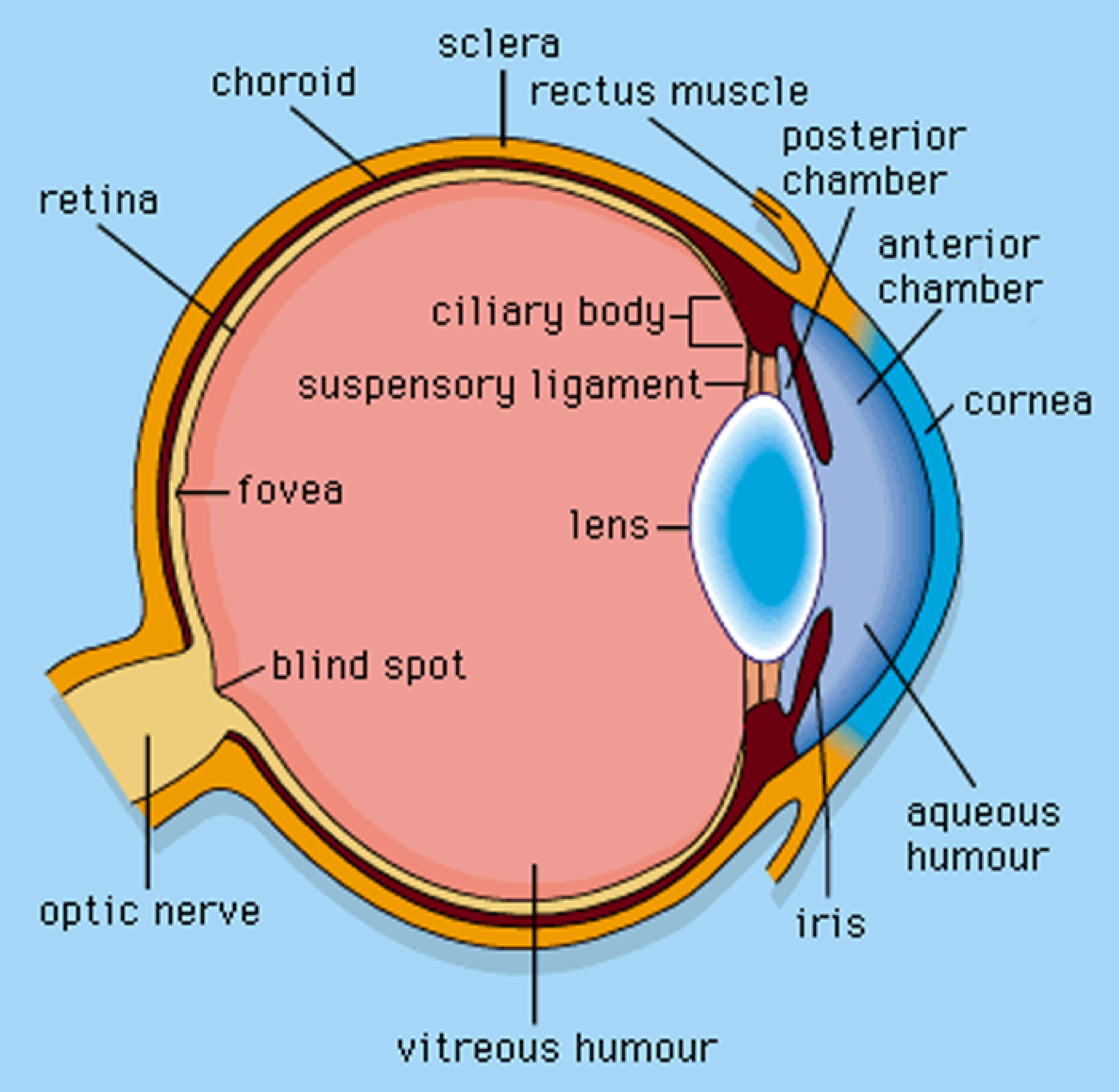
RETINA

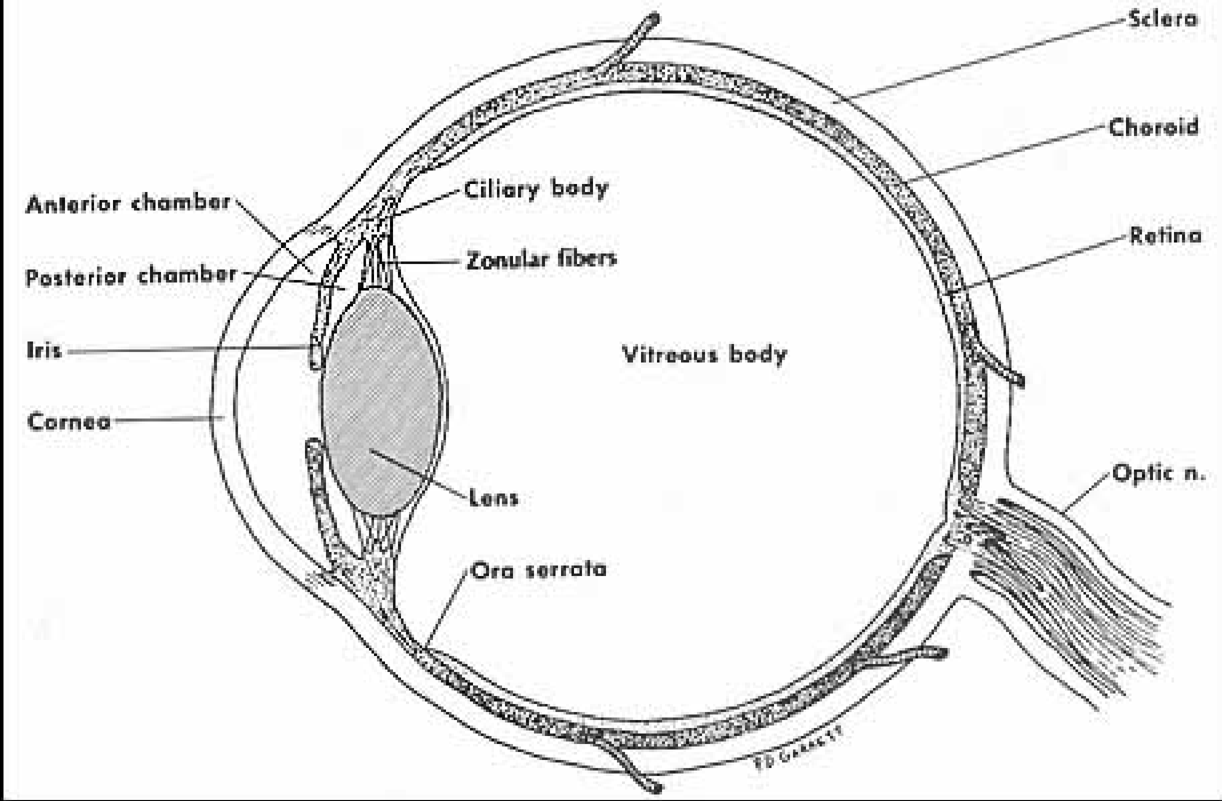
Overview. The retina develops from the optic cup of the diencephalon, and the optic nerve is histologically a CNS tract. Ten histological layers are recognized in the optic part of the retina. Light must penetrate eight of the layers to reach outer segments of rods and cones where photons are absorbed. Processes of pigmented epithelial cells surround the outer segments of rods and cones. Pigmented epithelial cells are a source of Vitamin A that rods and cones convert to retinal, the photon absorbing molecule.

Circuitry. Photoreceptor cells (rods and cones) synapse on bipolar cells which, in turn, synapse on ganglion cells. Photoreceptor cells also synapse on horizontal cells which provide lateral inhibition to sharpen the visual image, as do amacrine cells.

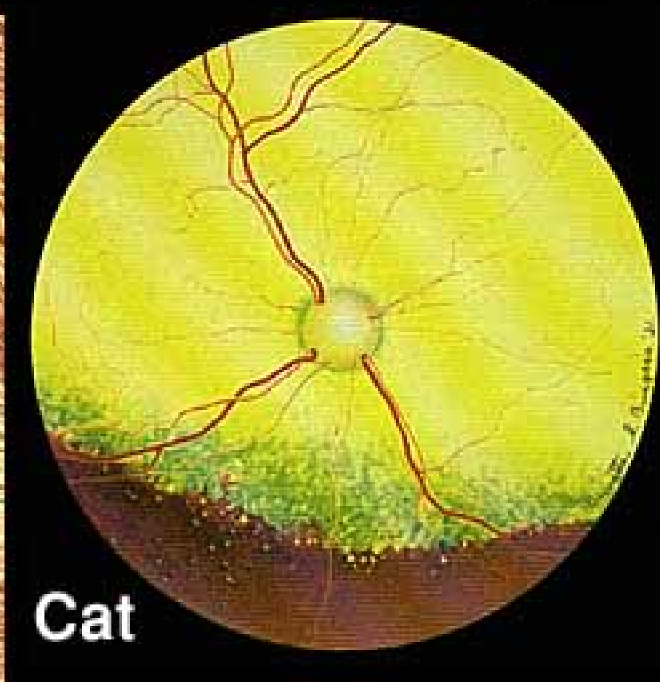
Nonmyelinated axons of ganglion cells run to the optic disk and then exit the eyeball as myelinated axons that comprise the optic nerve. Photoreceptor cells are absent at the optic disc (blind spot). Retinal vessels enter at the disc and course along the retinal surface.



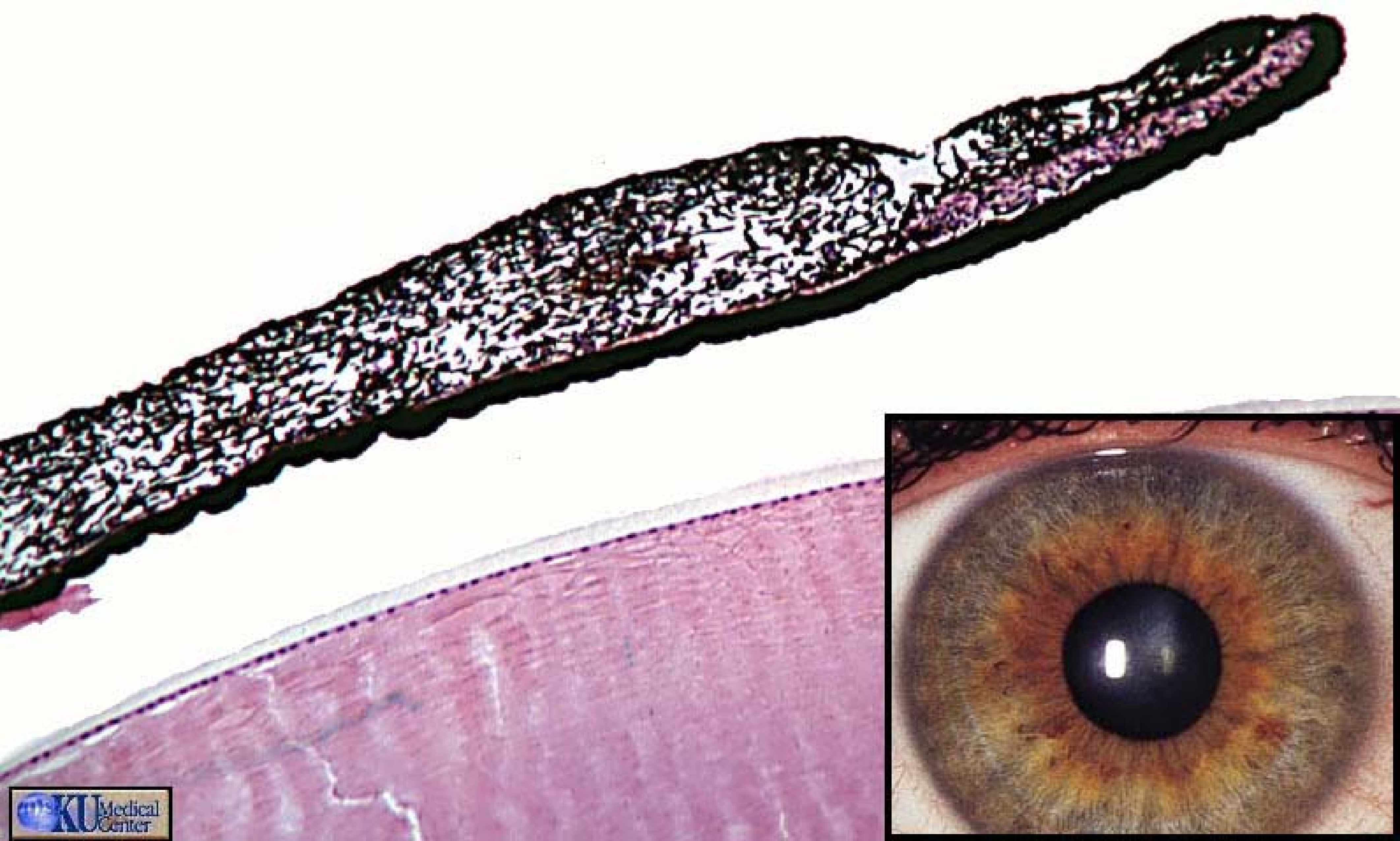

sclera
choroid
rectus muscle
posterior chamber
retina
anterior chamber
ciliary body
suspensory ligament
cornea
fovea
lens
blind spot
aqueous humour
optic nerve
iris
vitreous humour

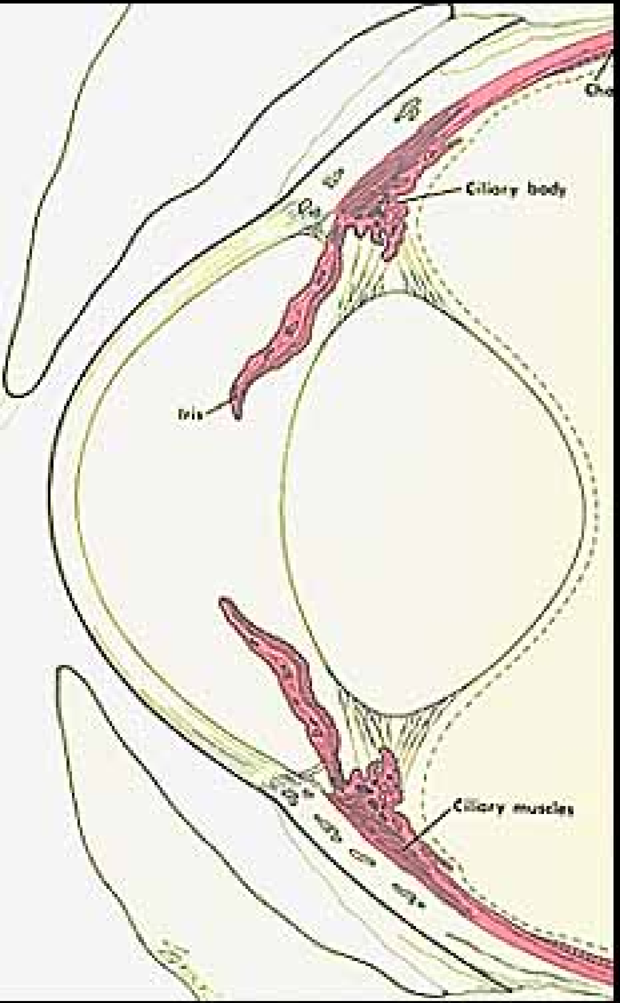

Sclera
Choroid
Ciliary body
Anterior chamber
Zonular fibers
Retina
Posterior chamber
Iris
Vitreous body
Cornea
Optic n.
Lens
Ora serrata

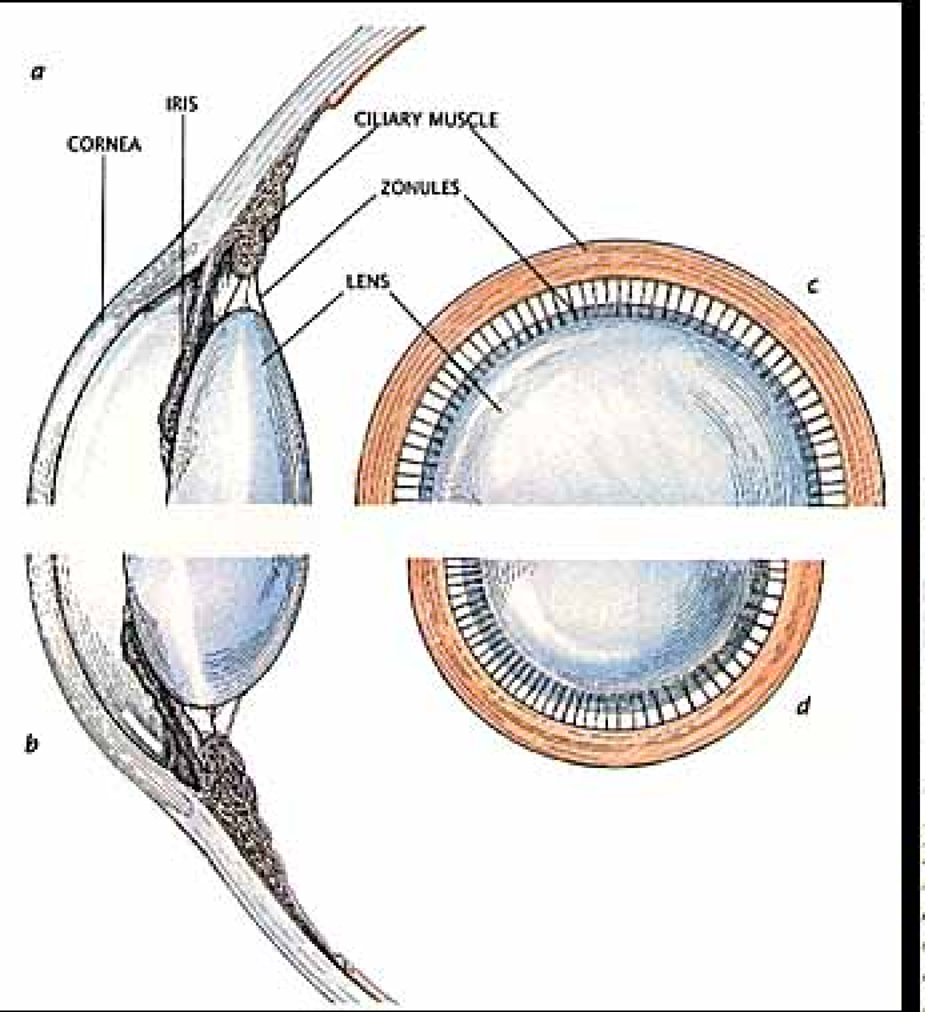

Dog

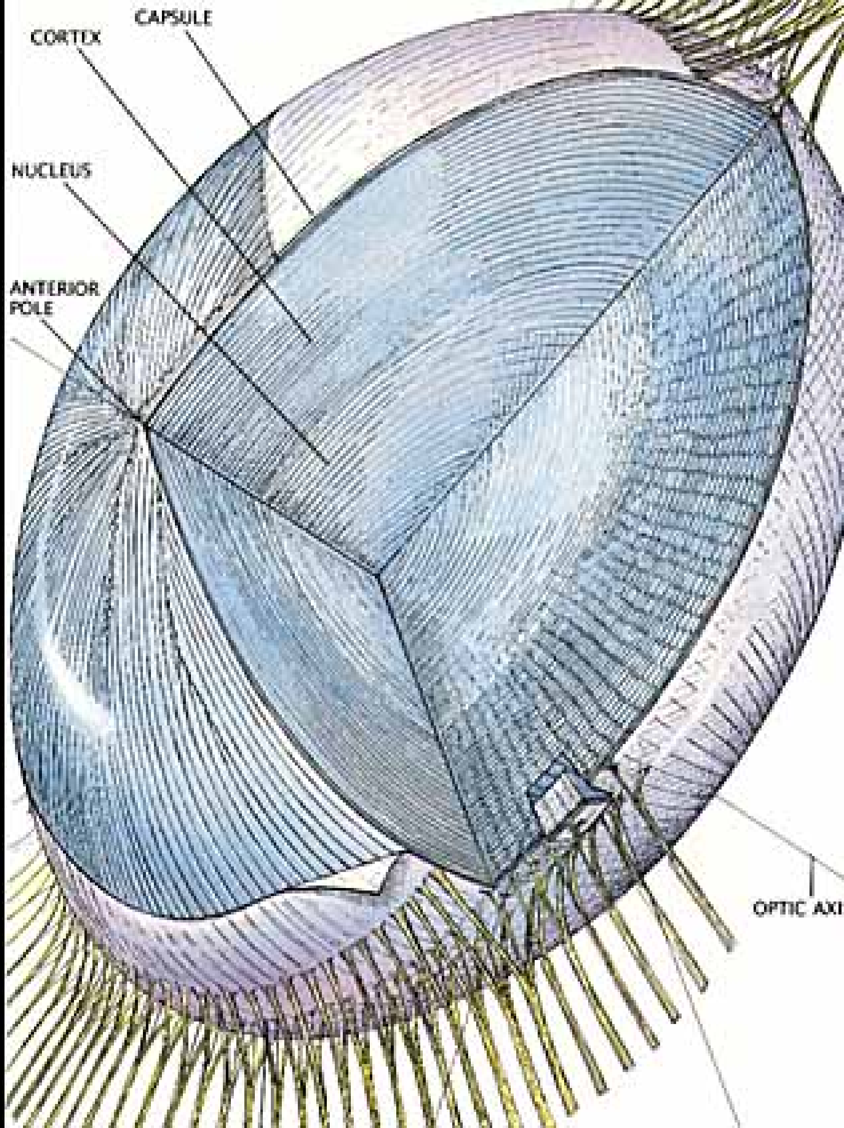

Cat

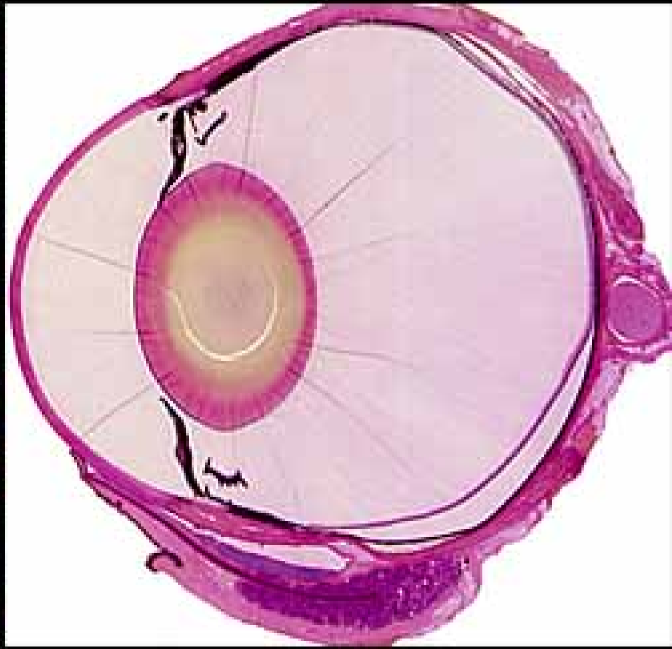

KU Medical Center

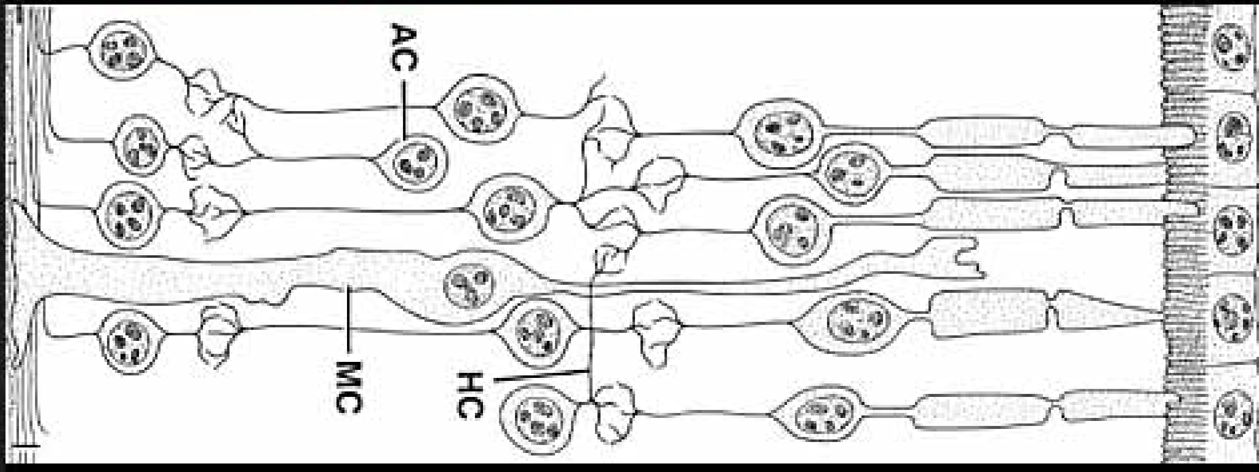

KU Medical Center

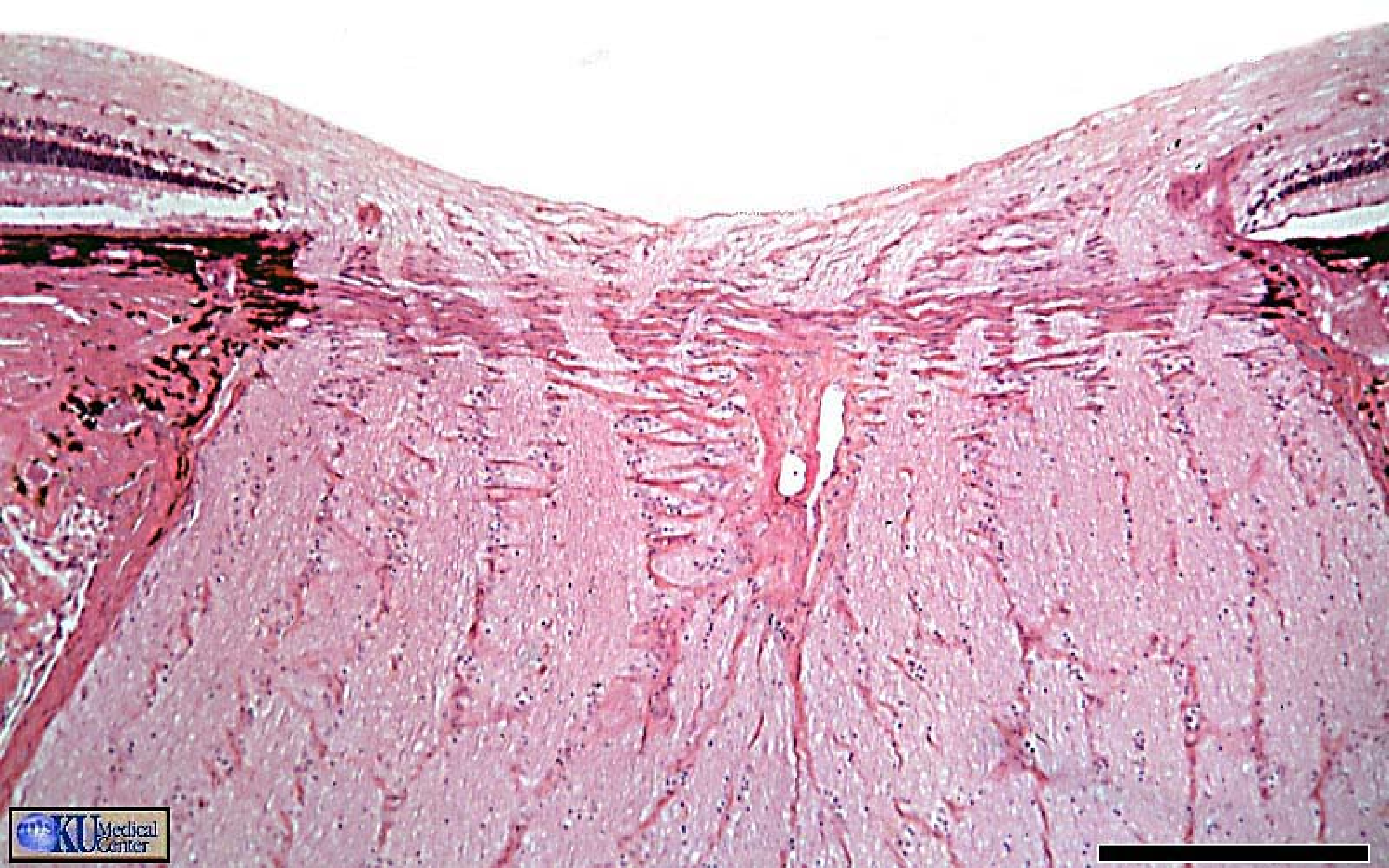

Ciliary body
Iris
Ciliary muscles

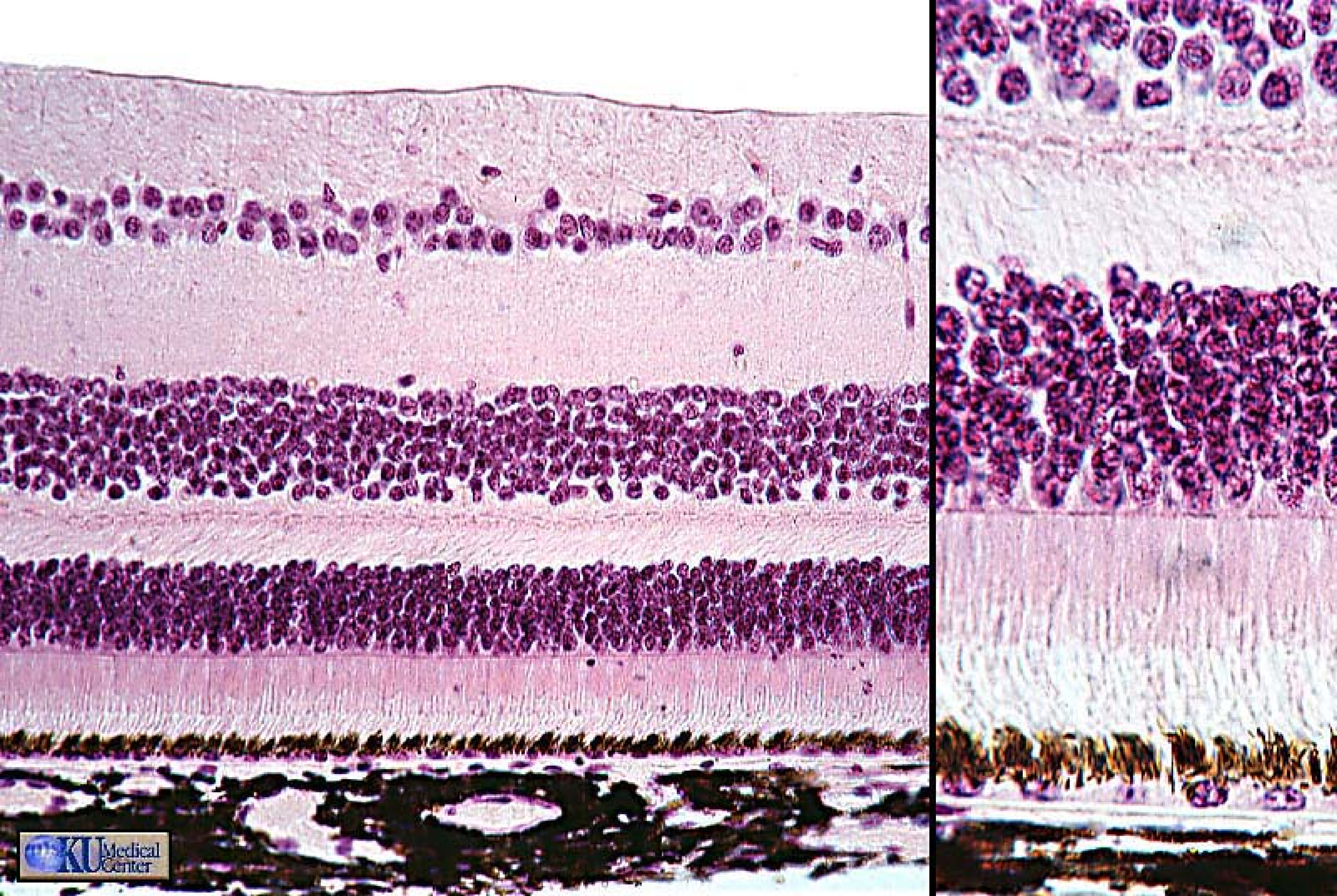

a
IRIS
CORNEA
CILIARY MUSCLE
ZONULES
LENS
c
b
d


CAPSULE
CORTEX
NUCLEUS
ANTERIOR
POLE




AC
MC
HC


KU Medical Center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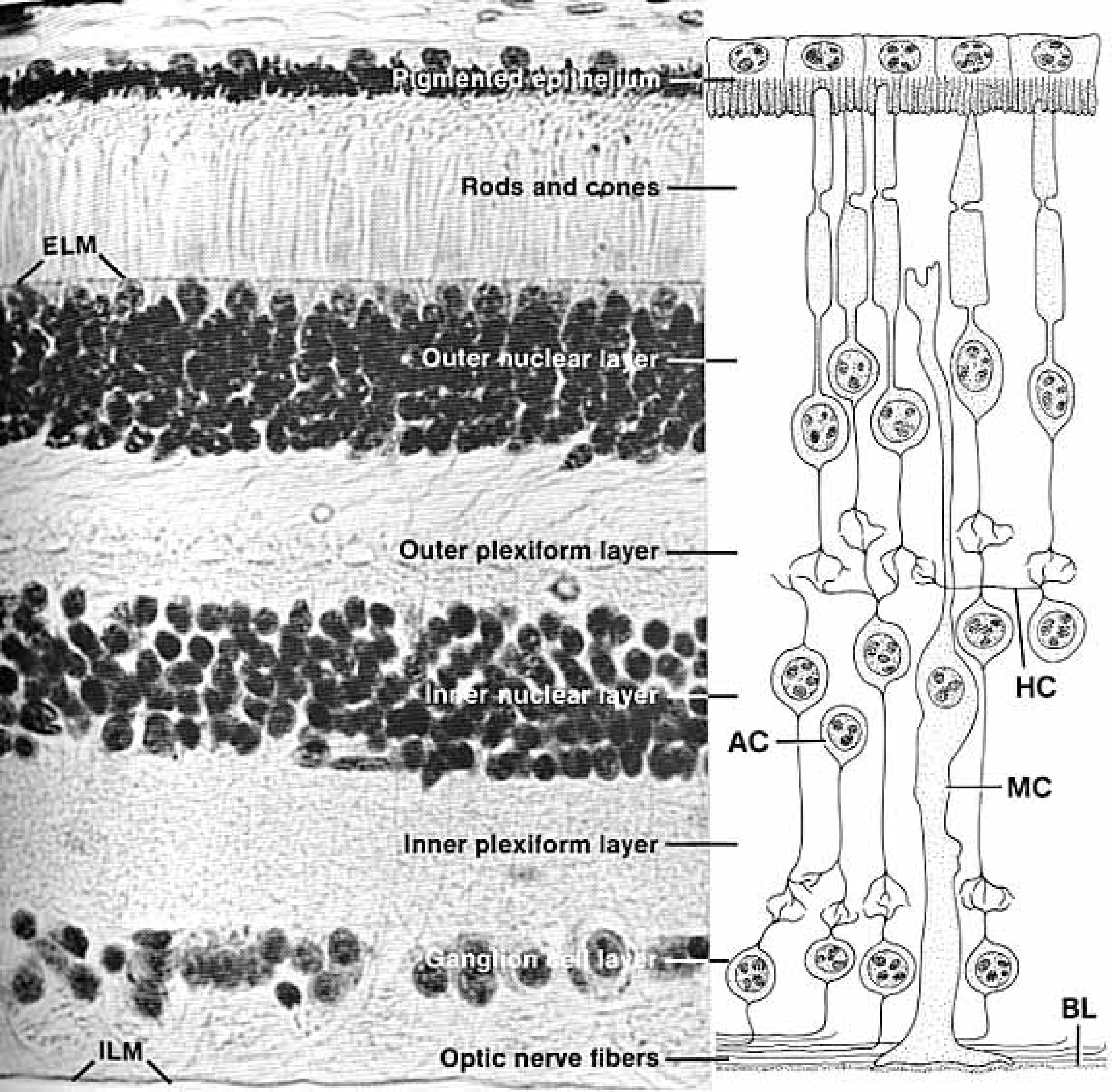
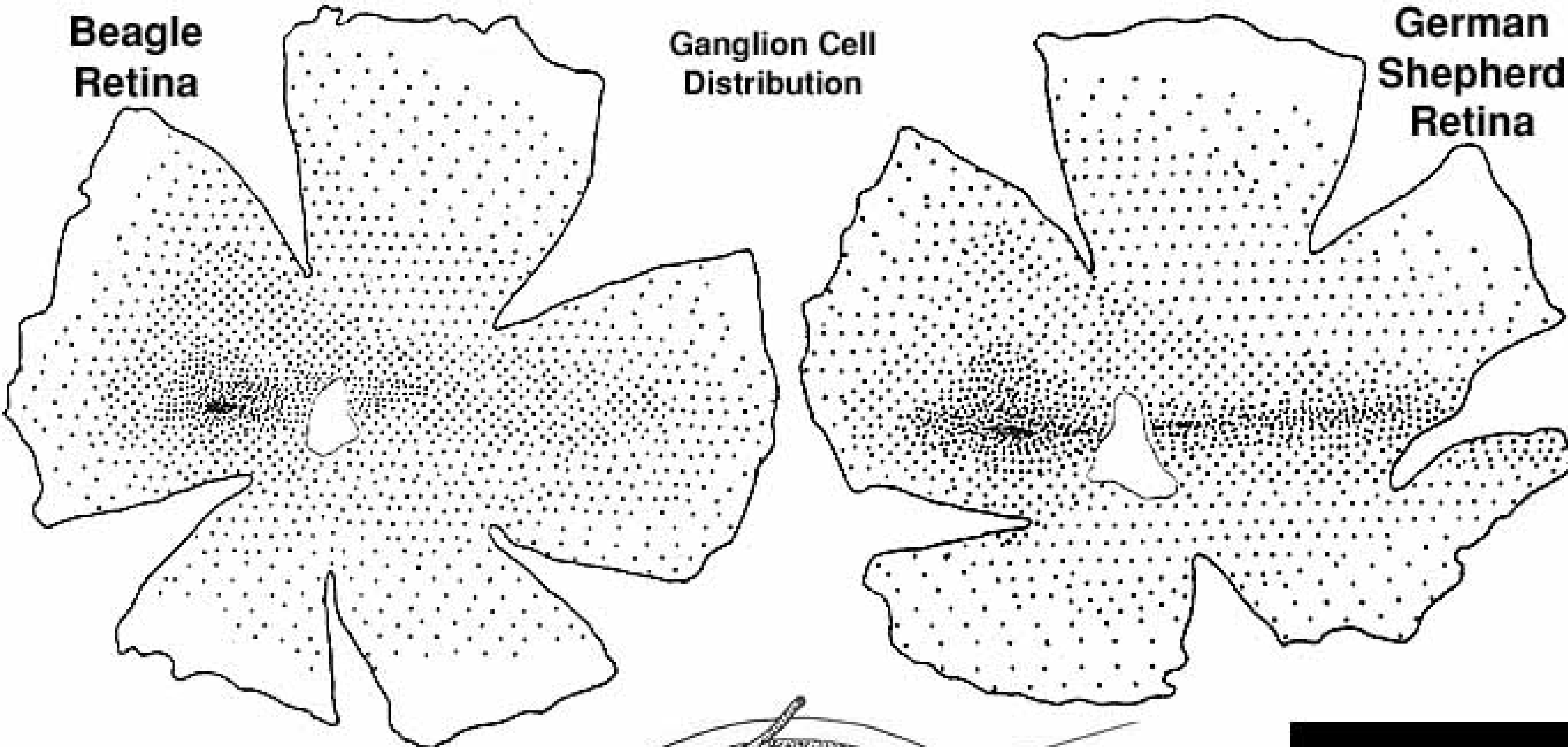
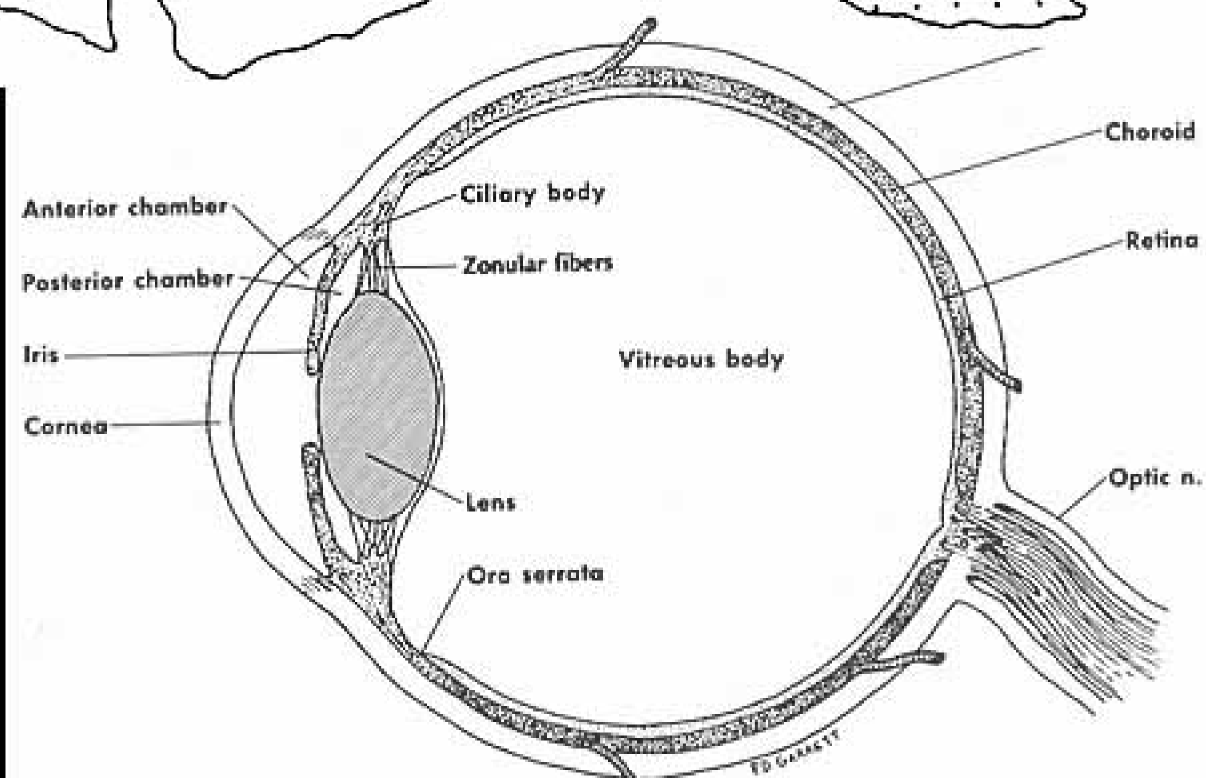
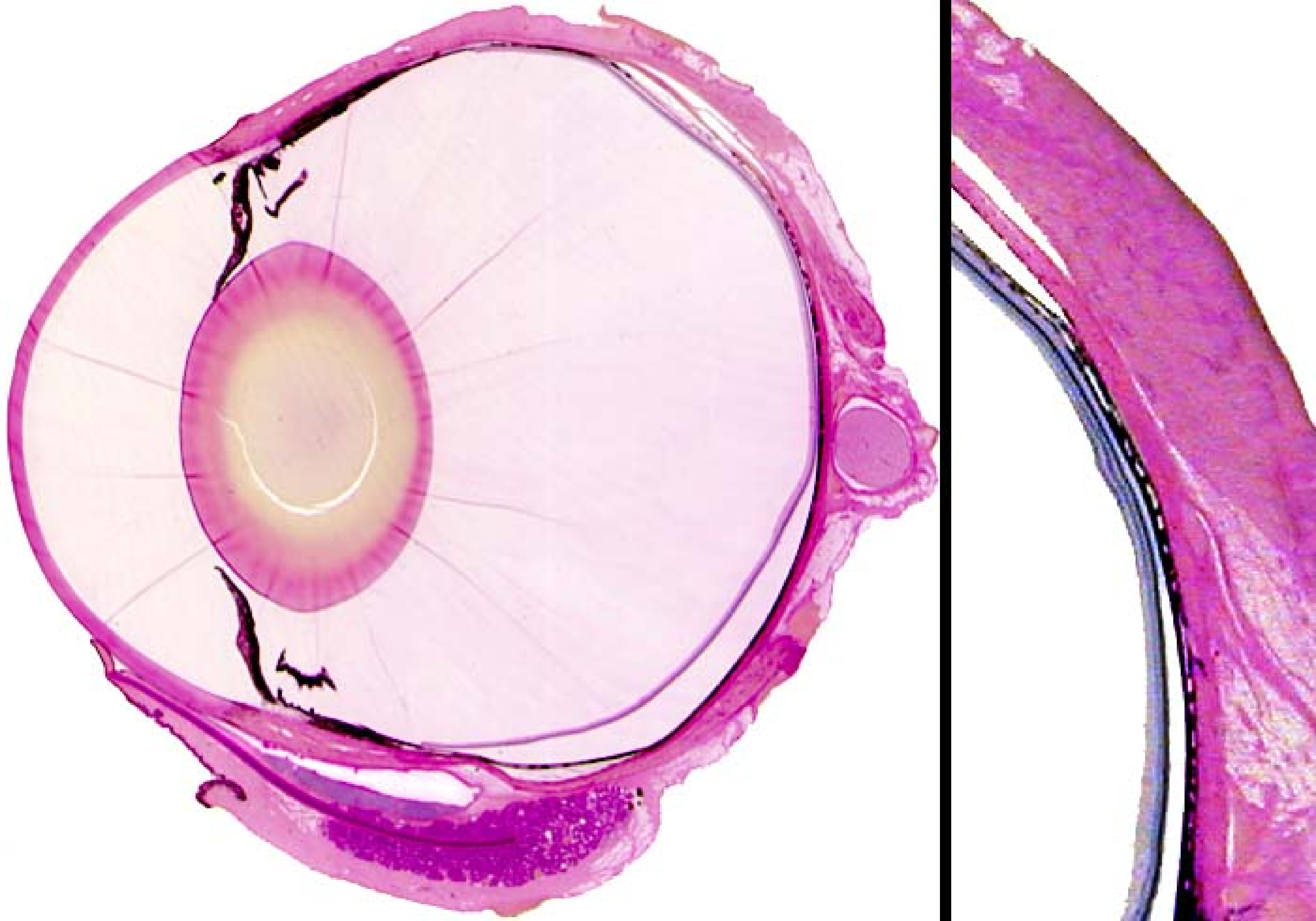
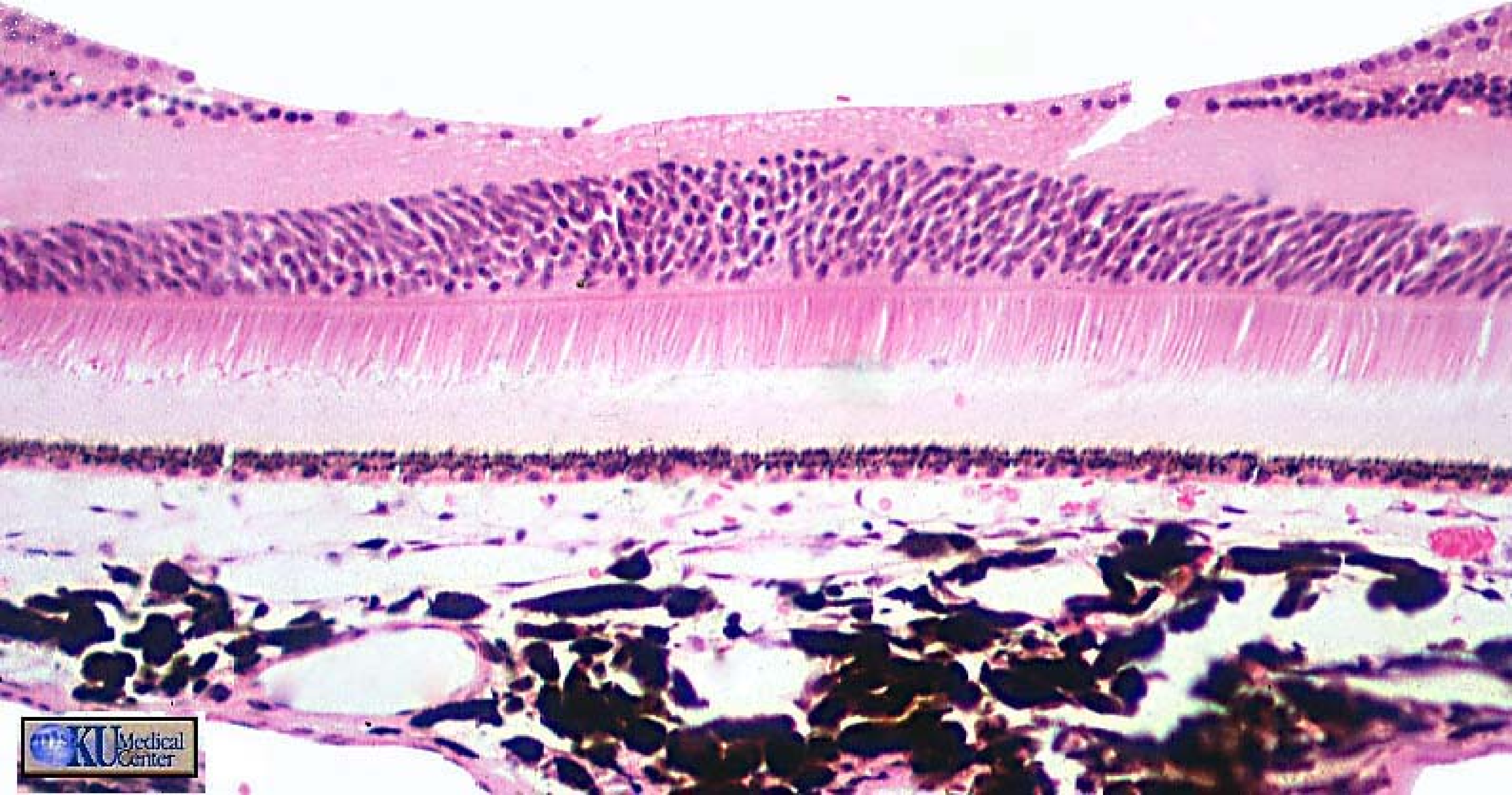


Pigmented epithelium
Rods and cones
ELM
Outer nuclear layer
Outer plexiform layer
Inner nuclear layer
HC
AC
MC
Inner plexiform layer
Ganglion cell layer
BL
ILM
Optic nerve fibers


Beagle Retina
Ganglion Cell Distribution
German Shepherd Retina


Choroid
Ciliary body
Anterior chamber
Retina
Zonular fibers
Posterior chamber
Iris
Vitreous body
Cornea
Optic n.
Lens
Ora serrata

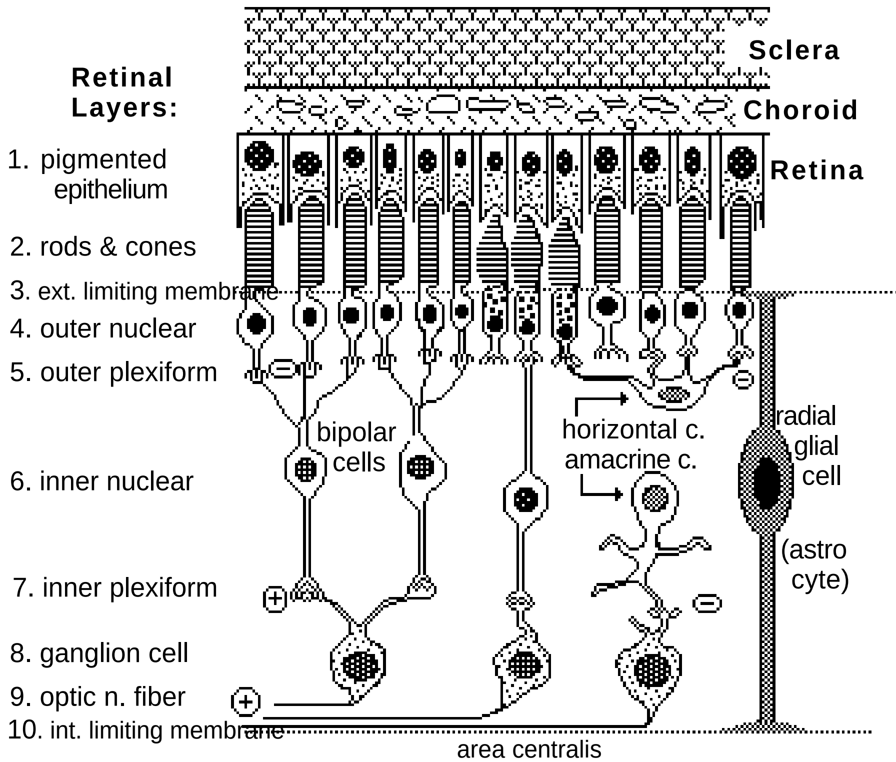




Photoreceptor cells:

There are two populations of photoreceptor cells: rods & cones. The outer segments of rods & cones contain stacked membranous discs that are continually produced, sloughed, and phagocytized by pigmented epithelium. The discs contain the photosensitive pigment (retinal) that intercepts photons.

Photoreceptor cells are excited (depolarized) in the dark and inhibited (repolarized) by light (photons). Excitation (depolarization) spreads electrotonically and triggers proportional release of glutamate neurotransmitter which either excites or inhibits the bipolar cells they synapse on.



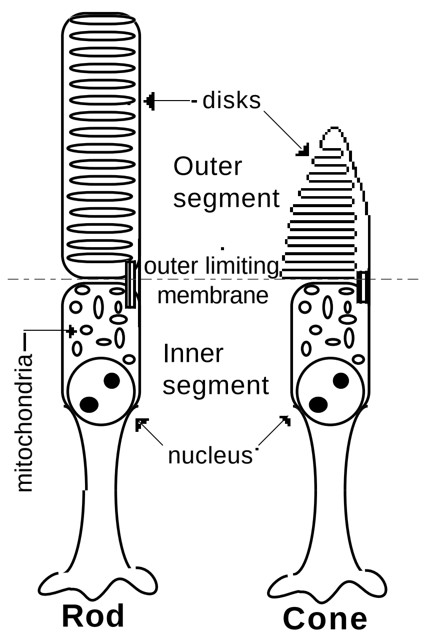
Bipolar cells:

In general, bipolar cells are spontaneously active, and they are either hyperpolarized (inhibited) or depolarized (excited) by photoreceptor cells. Bipolar cells generate electrotonic potentials and they synapse on ganglion cells (as well as some amacrine cells).

Bipolar cells associated with rods form convergent circuits (spatial summation), which improves vision in dim light but at the expense of image resolution. Bipolar cells associated with cones form relay circuits (temporal summation) which provides good visual detail but requires bright light.

RODS

- 95% of photoreceptor cells (in human retina)
- widely disributed throughtout the retina
- single population all containing rhodopsin (protein + retinal) and the same wavelength (color) sensitivity
- functional in dim light
- participate in highly convergent circuits (>1,000 rods converge on one ganglion cell)
- exhibit spatial summation



CONES

- 5% of photoreceptor cells (in human retina)
- concentrated in the Area Centralis of the retina
- multiple populations, based on different wavelength (color) sensitivities due to protein differences (protein + retinal)
- operate under bright light conditions
- participate in relay circuits (few cones per ganglion cell)
- exhibit temporal summation

Transduction: Photon to Neural Signal

Transduction = converion of energy from one type to another = converting photon energy into neural signals.

Dark condition in rods . . .

• Rhodopsin builds up in the rod outer segment.

Rhodopsin = protein (scotopsin) bound to retinal (11-*cis* Vitamin A aldehyde)

• cGMP is abundant and acts to keep cation channels open.

• Na^{+} and Ca^{++} influx depolarizes the rod cell in a graded electrotonic manner (-40 mV).

• The depolarized rod cell releases glutamate at its synapse with bipolar and horizontal cells.

Photon effect in rods . . .

• Photon energy converts *cis*-retinal to all *trans*-retinal, destabilizing rhodopsin which becomes enzymatically active as it dissociates.

• Activated rhodopsin triggers a G protein (transducin) to activated many phosphodiesterase molecules which enzymatically convert cGMP to GMP.

• Cation channels close in the absence of cGMP and the rod cell becomes polarized (-70 mV).

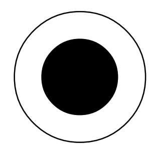
(One photon activates one rhodopsin molecule which triggers closure of hundreds of cation channels.)

• The rod cell releases less glutamate at its synapse.

Note: Transduction is the same in cones, except that the protein is different (not scotopsin).

Ganglion cells

Ganglion cell axons leave the retina and form the optic nerve. Unlike all other retinal cells, ganglion cells generate action potentials. They fire continuosly, and the presence/absence of light merely changes their firing rates.



Ganglion cells respond to a spot of light with a center "ON/surround-OFF" pattern (or an "OFF/ON" pattern), i.e., the spot causes stimulated ganglion cells to increase their firing rates and lateral inhibition (by horizontal cells) causes surrounding ganglion cells to decrease their firing rates.

Three functionally different populations of ganglion cells have been discovered:

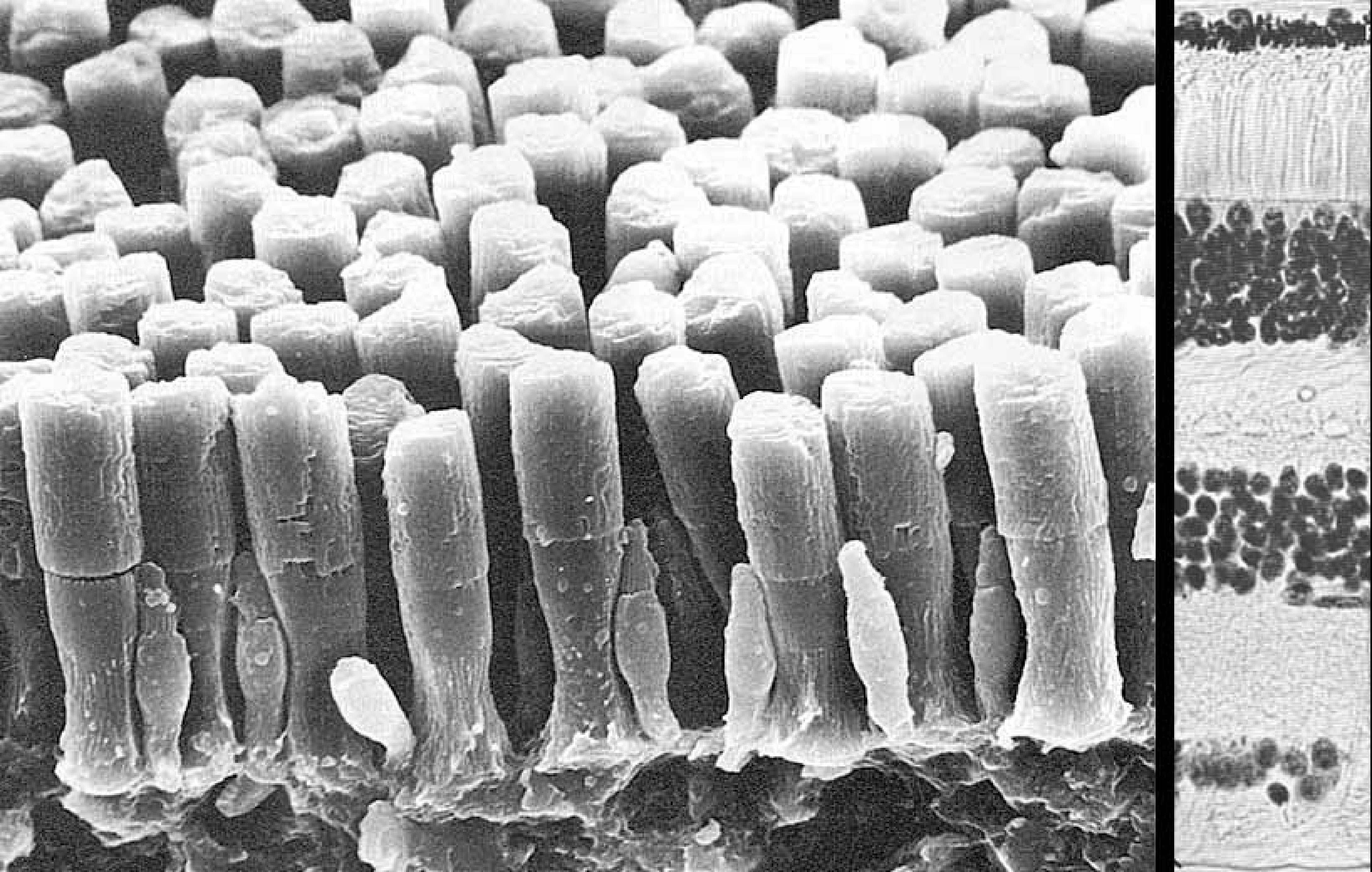
1] Large cells that receive rod input from a broad area and signal motion, position, and depth;
2] Small cells with small receptive fields that are unaffected by color differences; and
3] Small cells that are color sensitive, i.e., excited by one color and inhibited by another.

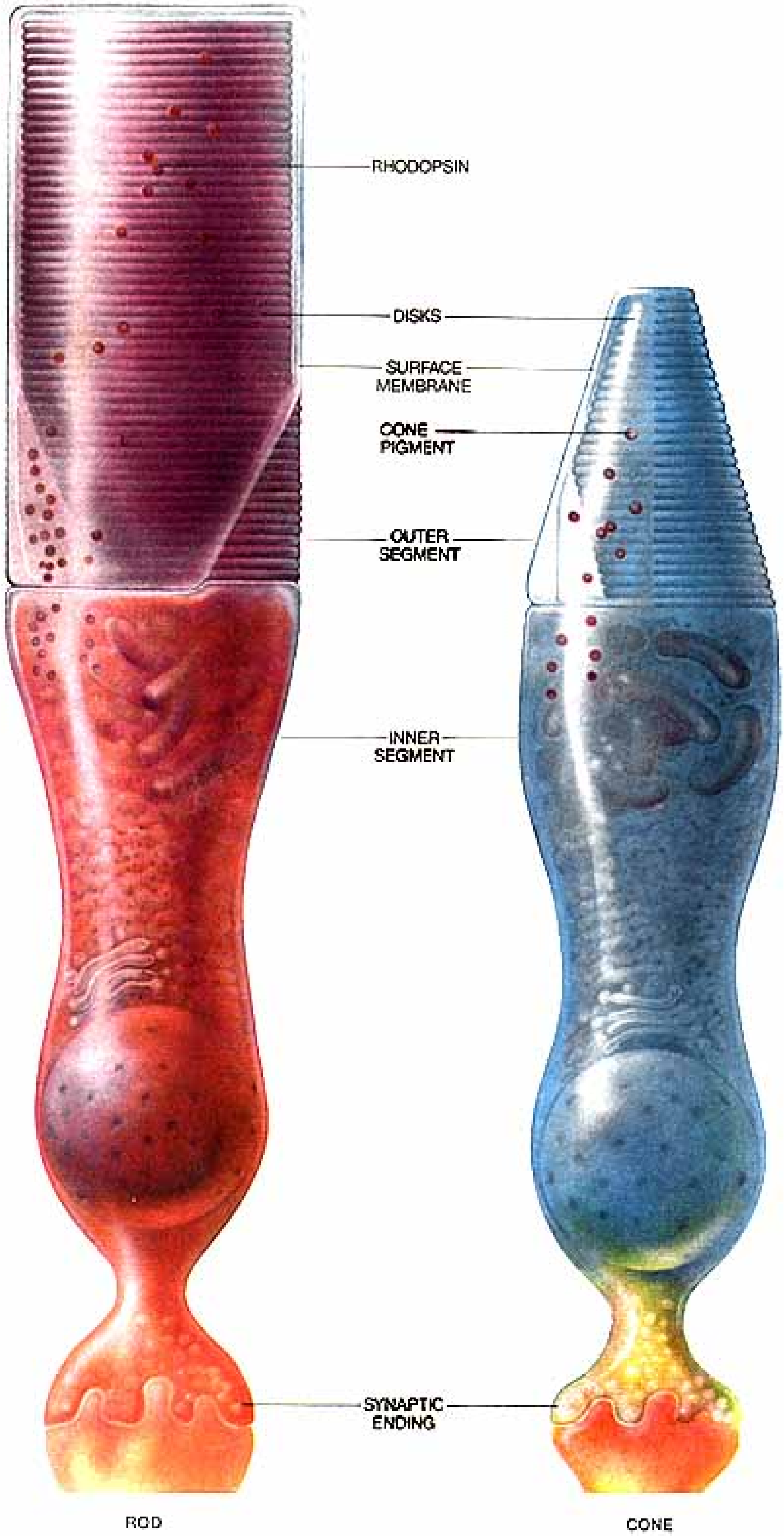
Other retinal cells

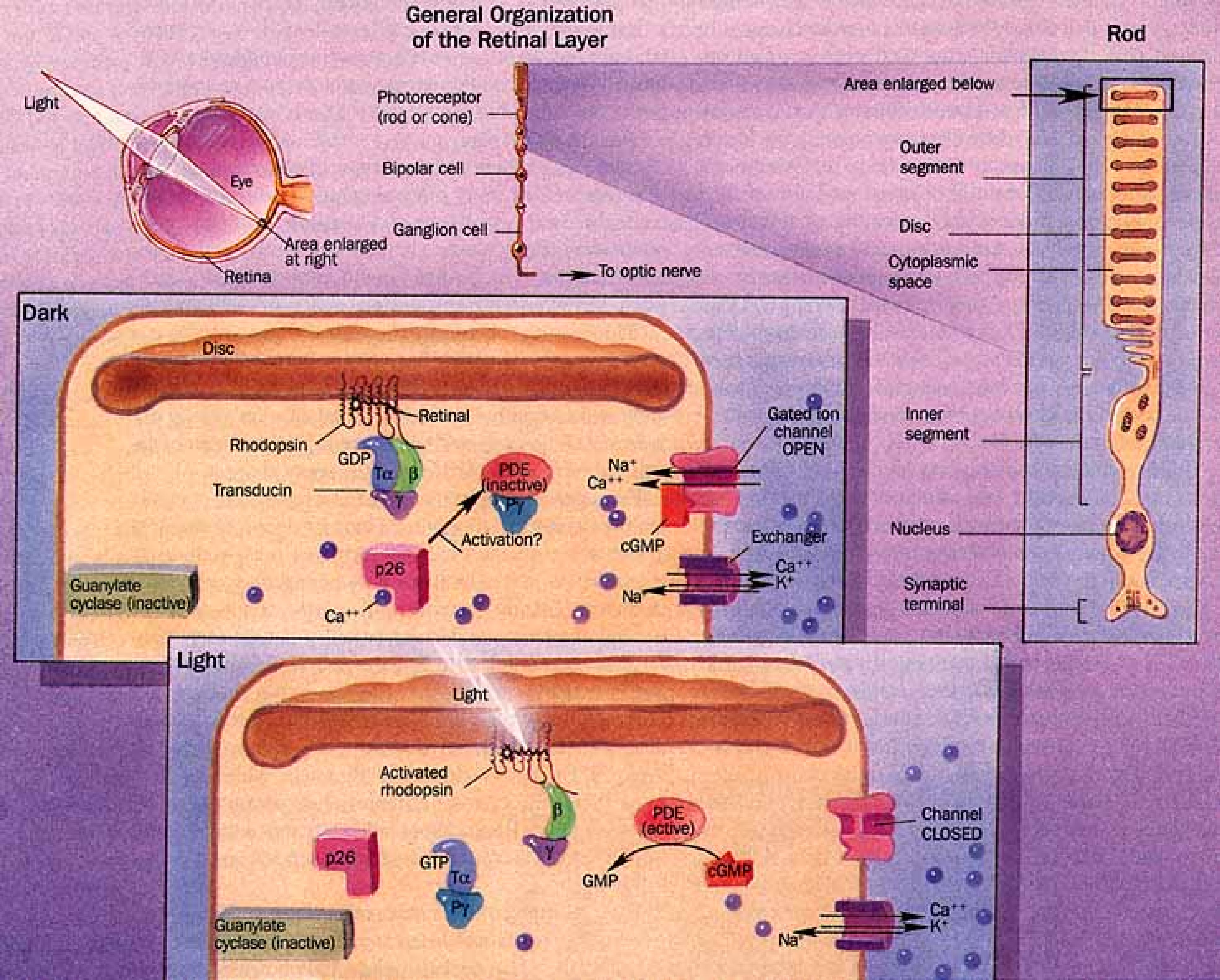
Horizontal cells are always inhibitory. They are primarily responsible for lateral inhibition, i.e., the inhibition that surrounds the excitation generated by a spot of light.

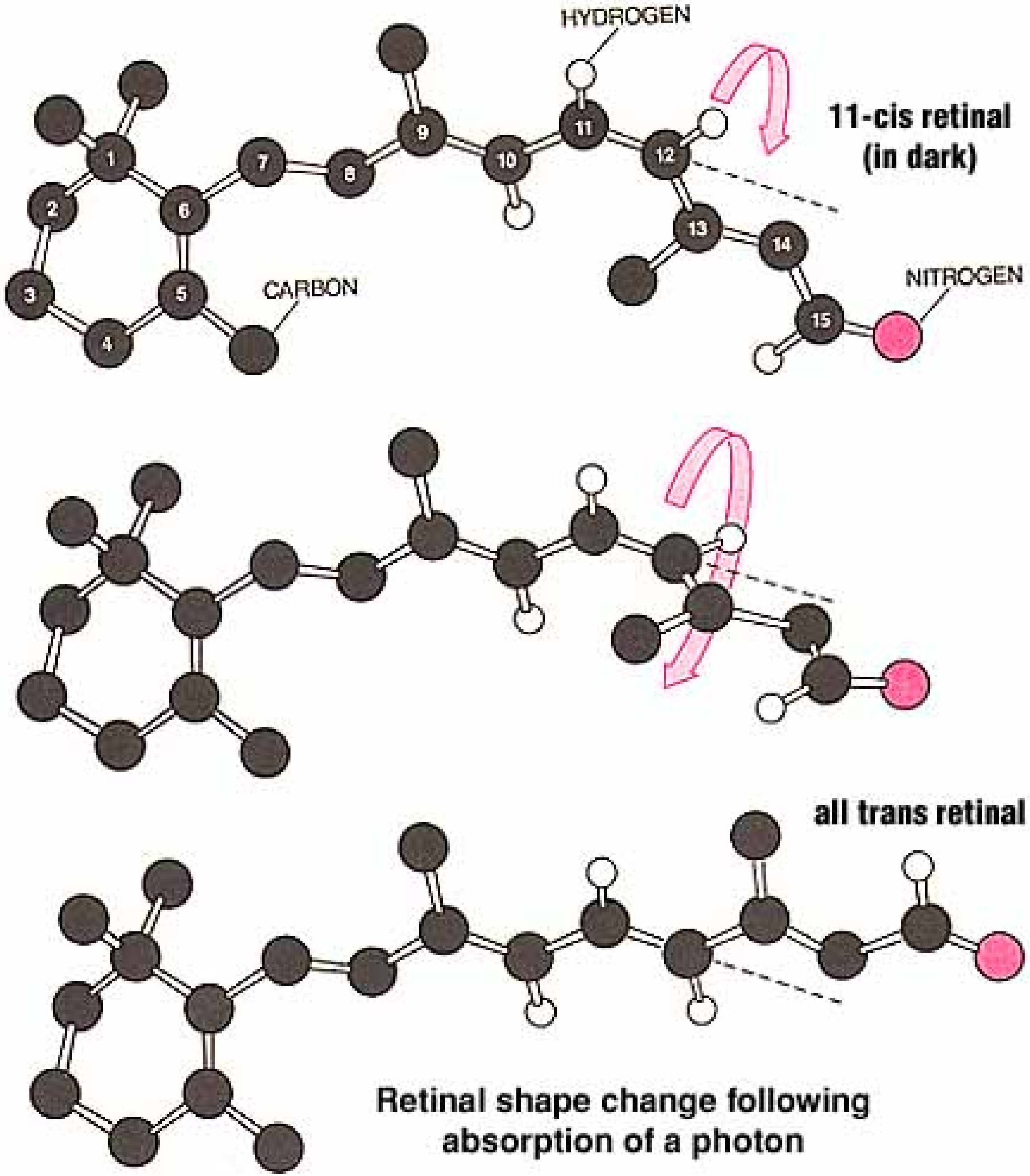
Amacrine cells are often inhibitory neurons that make synaptic contact with bipolar & ganglion cells. Some respond to the onset/offset of light, others are responsive to direction of light movement. The optic nerve contains efferent axons which synapse on amacrine cells to provide brain control of retinal activity. There are 30 different populations of amacrine cells with respect to morphology and neurotransmitters released.

Radial glial cells (Mueller cells): modified astrocytes which provide structural and metabolic support. Like astrocytes they take up excess ions and neurotransmitter molecules to maintain homeostasis. Processes of these cells form the internal and external limiting membranes.

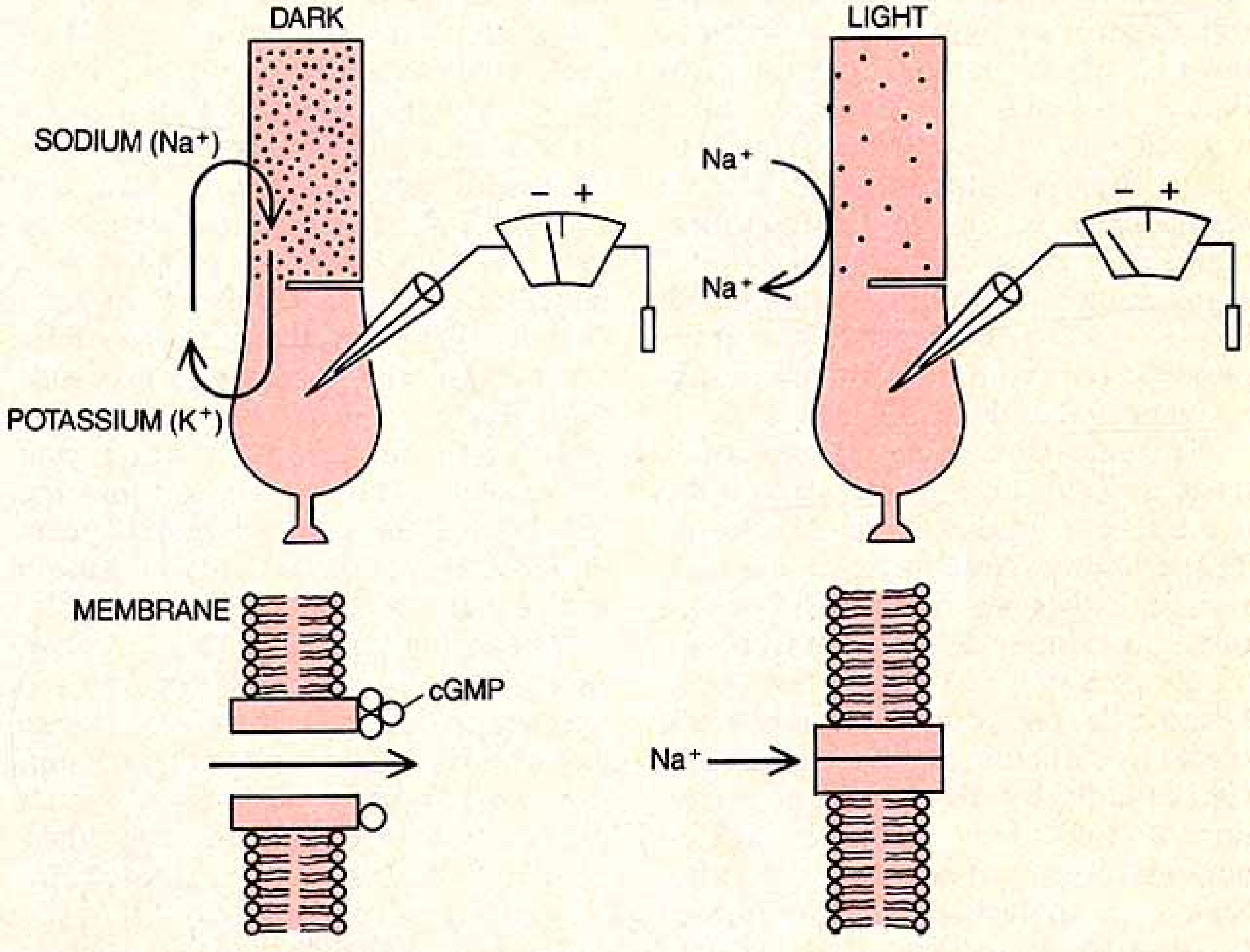



RHODOPSIN
DISKS
SURFACE MEMBRANE
CONE PIGMENT
OUTER SEGMENT
INNER SEGMENT
SYNAPTIC ENDING
ROD
CONE


General Organization
of the Retinal Layer
Rod
Light
Eye
Area enlarged
at right
Retina
Photoreceptor
(rod or cone)
Bipolar cell
Ganglion cell
To optic nerve
Area enlarged below
Outer
segment
Disc
Cytoplasmic
space
Inner
segment
Nucleus
Synaptic
terminal
Dark
Disc
Retinal
Rhodopsin
GDP
Tα
β
γ
Transducin
PDE
(inactive)
Pγ
Activation?
p26
Ca++
Guanylate
cyclase (inactive)
Gated ion
channel
OPEN
Na+
Ca++
cGMP
Exchanger
Ca++
K+
Na+
Light
Light
Activated
rhodopsin
β
γ
PDE
(active)
GMP
cGMP
p26
GTP
Tα
Pγ
Guanylate
cyclase (inactive)
Channel
CLOSED
Ca++
K+
Na+



Retinal shape change following absorption of a photon


DARK
LIGHT
SODIUM (Na+)
POTASSIUM (K+)
Na+
Na+
– +
– +
MEMBRANE
cGMP
Na+

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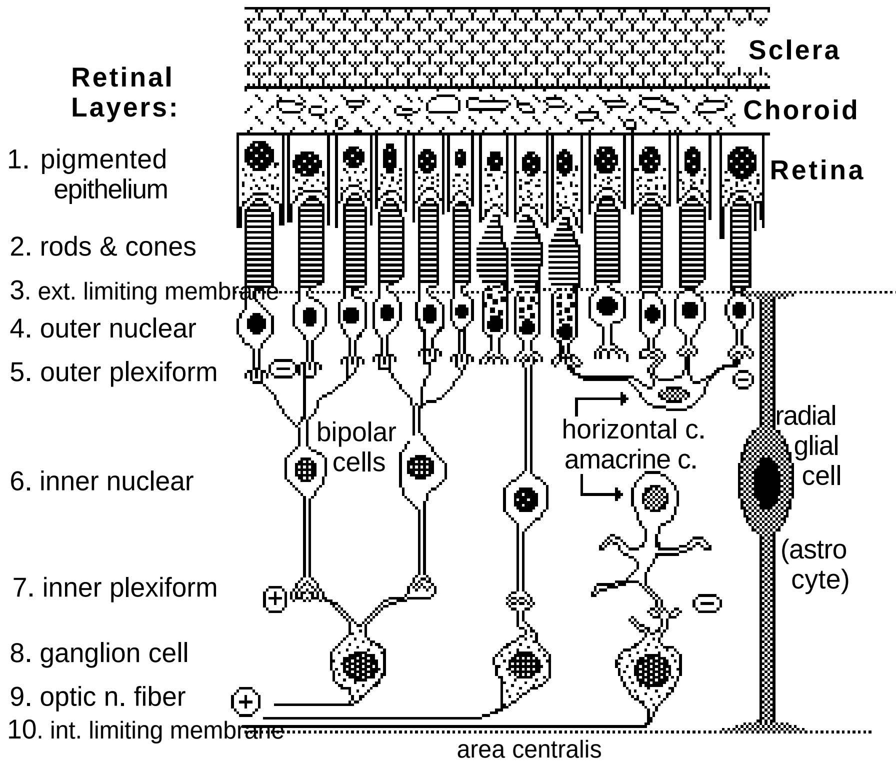

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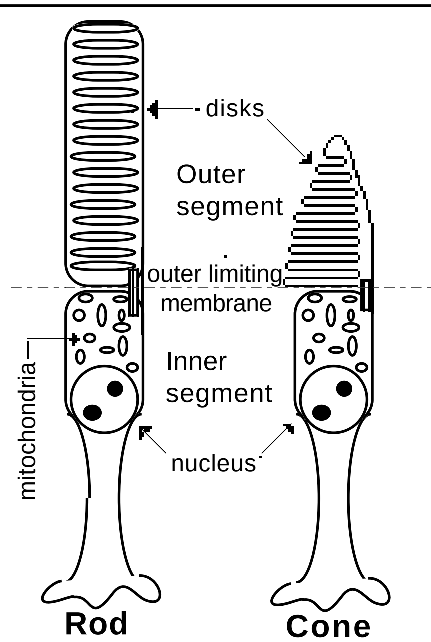

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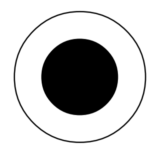

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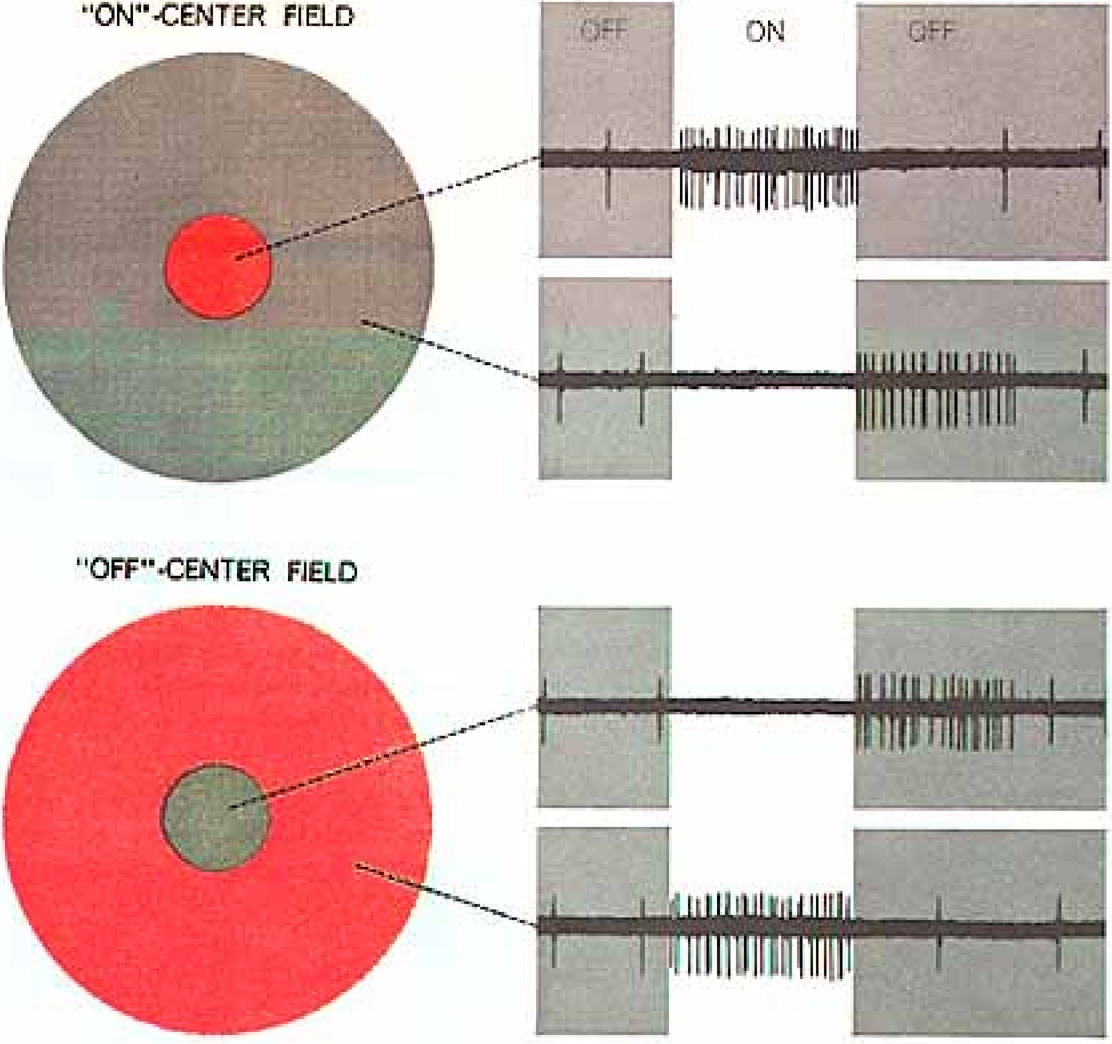
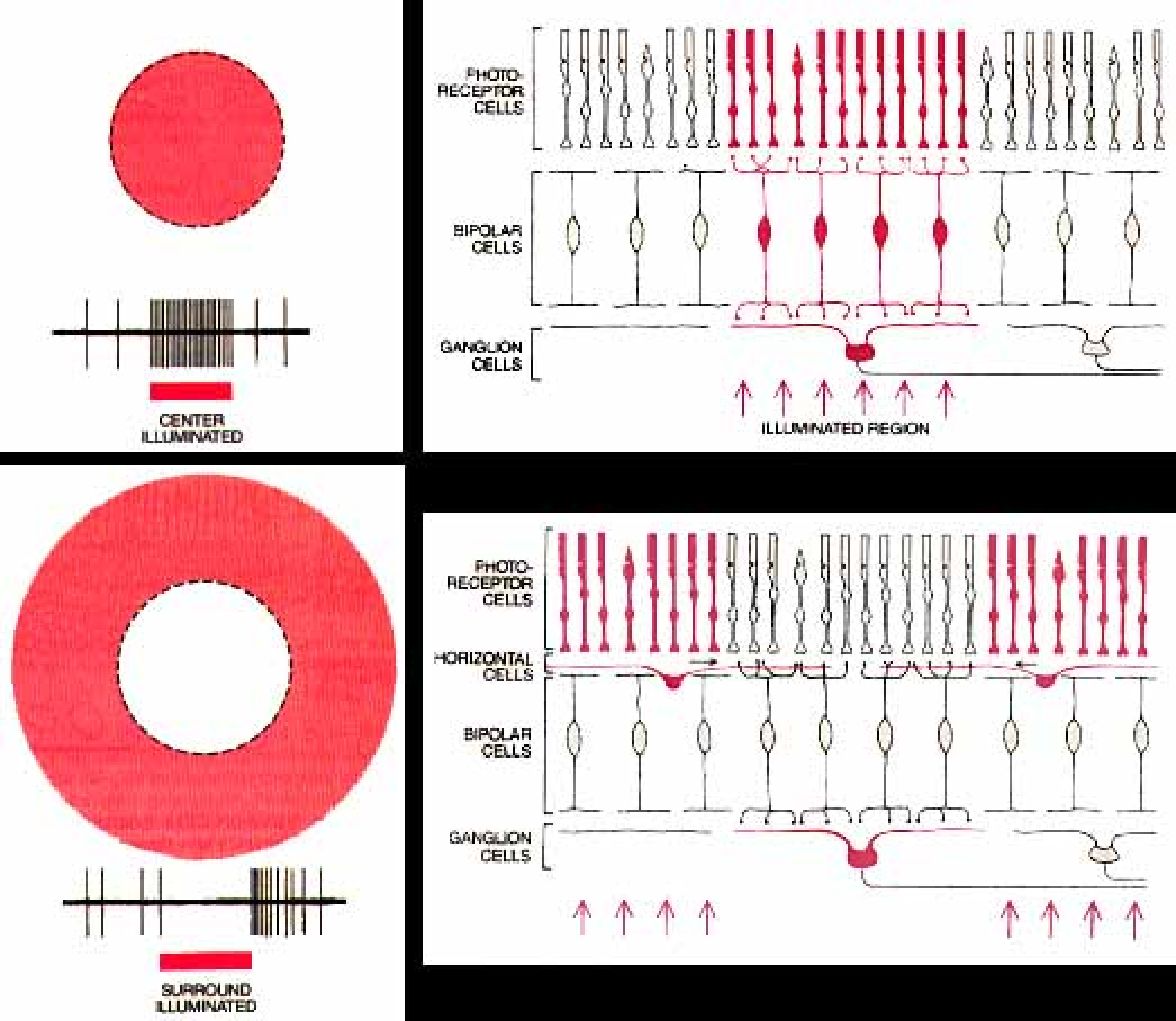

"ON"-CENTER FIELD
OFF
ON
OFF
"OFF"-CENTER FIELD


CENTER ILLUMINATED
PHOTO-RECEPTOR CELLS
BIPOLAR CELLS
GANGLION CELLS
ILLUMINATED REGION
SURROUND ILLUMINATED
PHOTO-RECEPTOR CELLS
HORIZONTAL CELLS
BIPOLAR CELLS
GANGLION CELLS

VISUAL PATHWAY

<u>Optic nerve</u> — axons from ganglion cells of the retina (1.5 million axons in human; 0.2 million in dog)

<u>Optic chiasm</u> (chiasma) — optic nerve axons decussate, except that a percentage of axons from the lateral side of each retina do not cross, depending on species:
— in submammalian vertebrates, e.g., fish, 100% of optic fibers cross in the chiasm
— in domestic animals: horse 90%; sheep 88%; pig 72%; dog 75%; cat 63% cross
— in human: 50% of optic nerve fibers cross in the optic chiasma.
(NOTE: % crossing is related to eye position in the head and visual field overlap)

<u>Optic tract</u> —axons from both eyes. The optic tract conveys contralateral visual field information (i.e., axons from the lateral part of the retina of the ipsilateral eye & the medial & central parts of the retina of the contralateral eye).

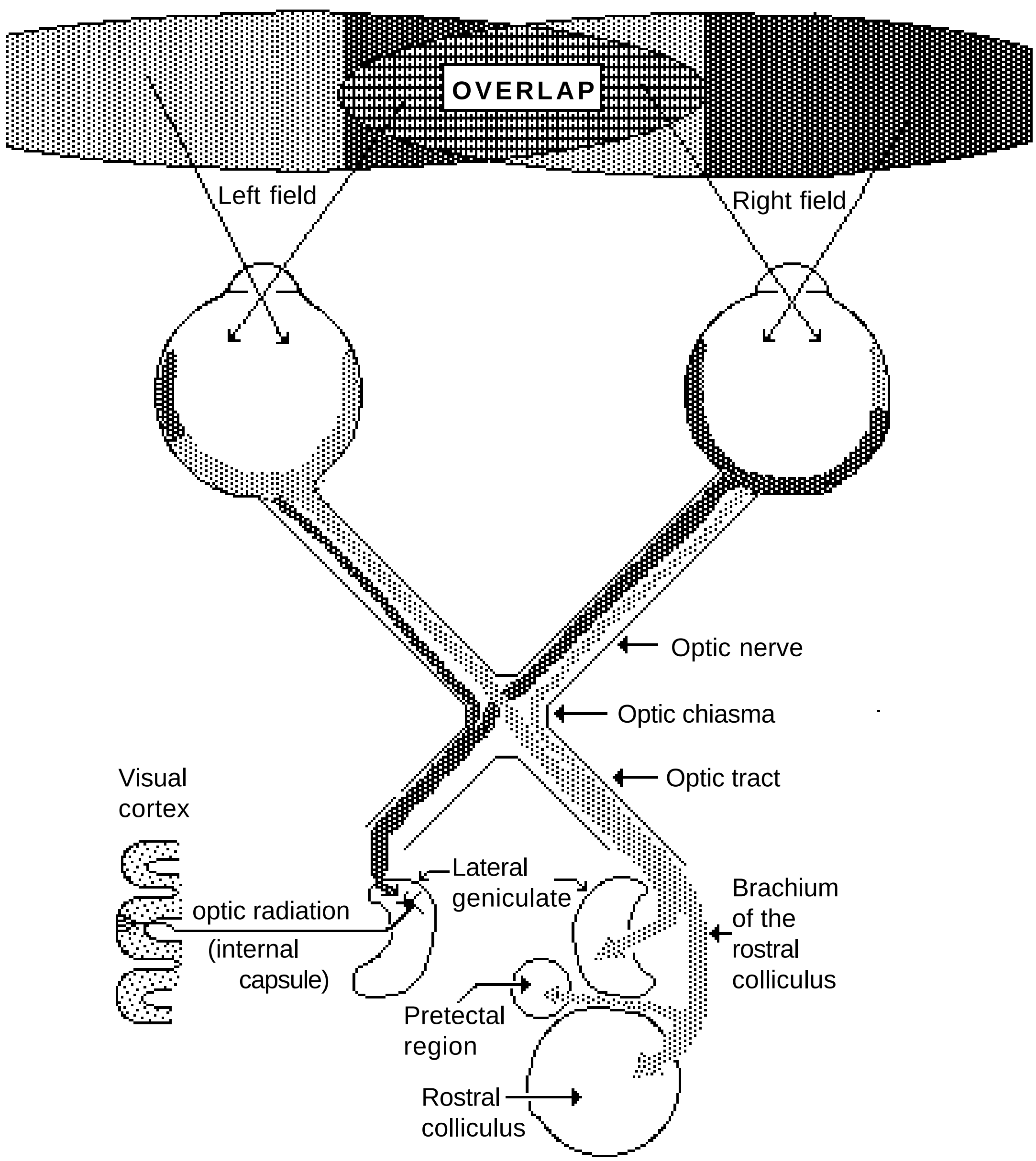
Visual Fields

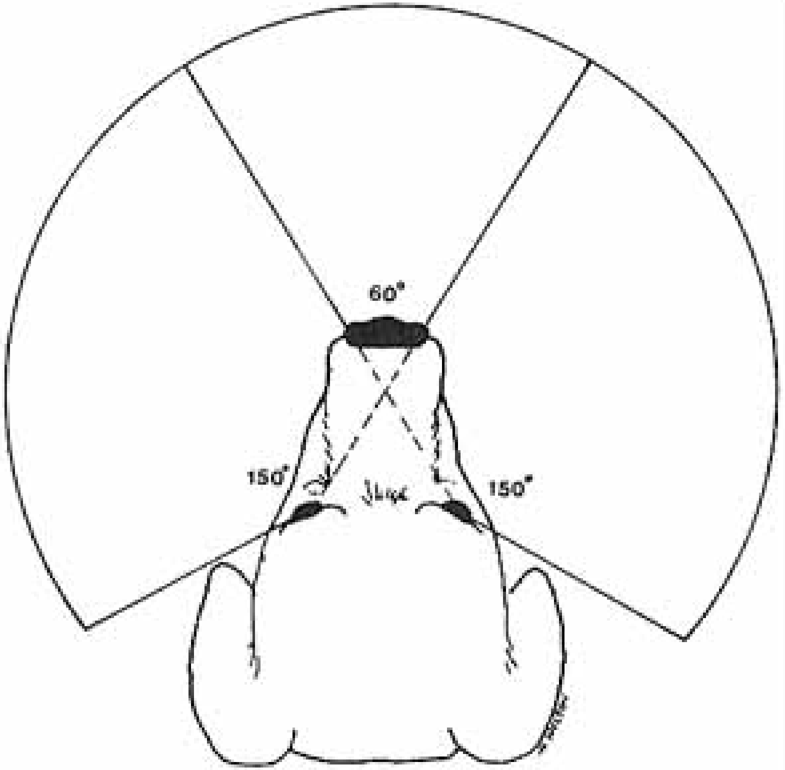
Binocular vision, which is important for depth perception, requires visual field overlap so that individual objects can be viewed simultaneously by both eyes.

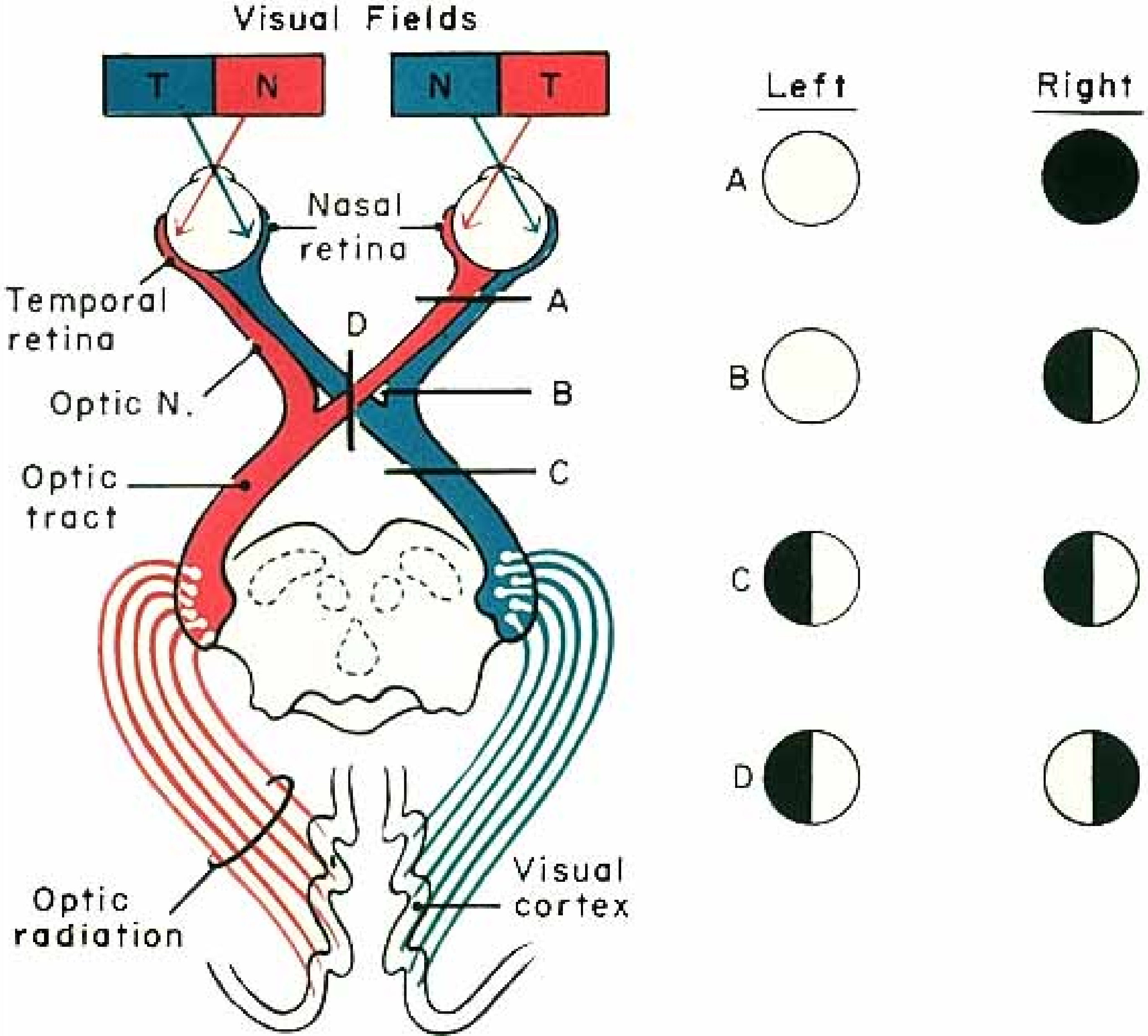
For binocular vision to occur, the visual cortex in one cerebral hemisphere must receive information about an object from both eyes.

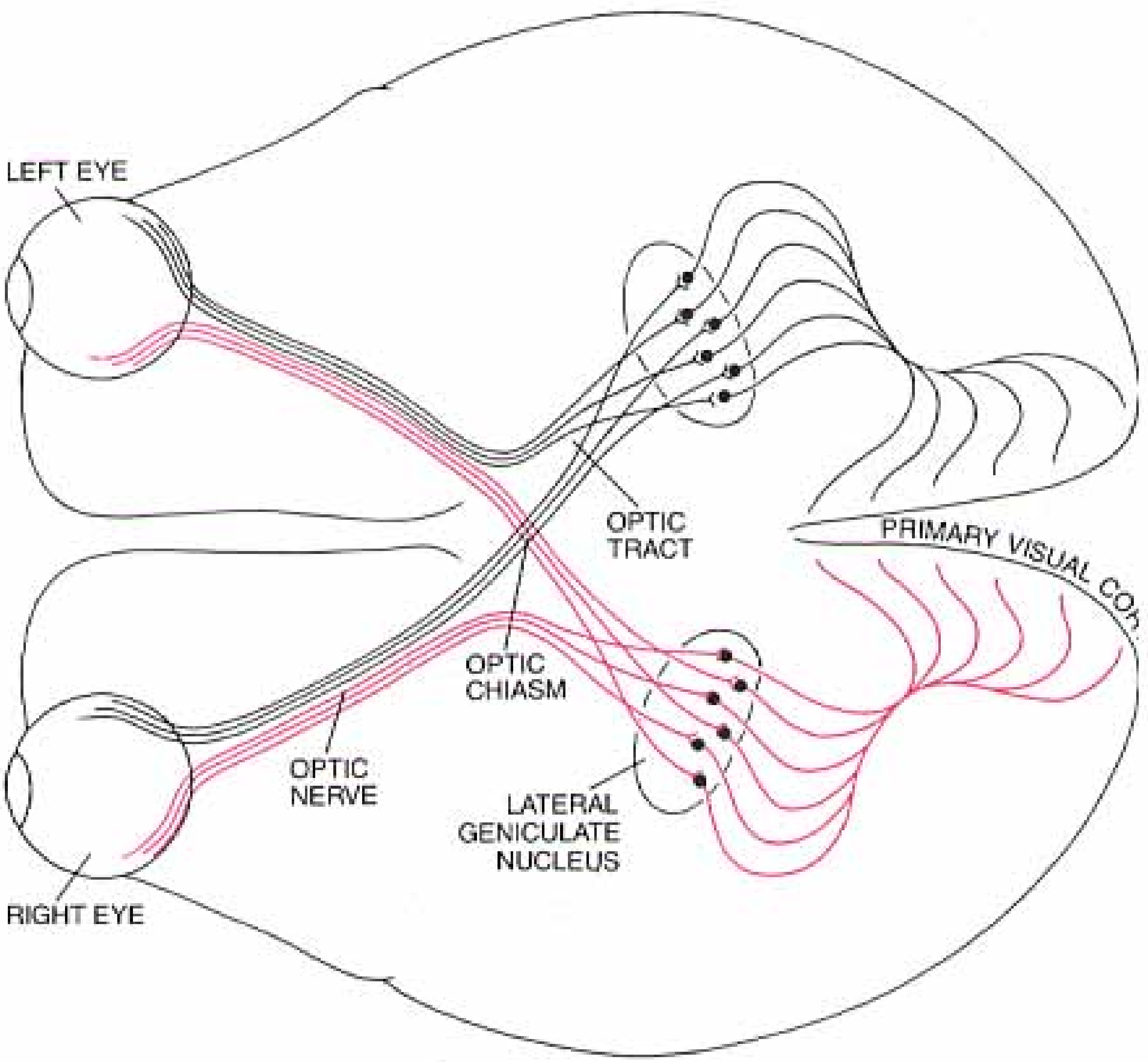
This requires that "corresponding" ganglion cells in each eye send their axons through the same optic tract. In visual cortex, some columns monitor stimulation in corresponding loci of the two eyes.

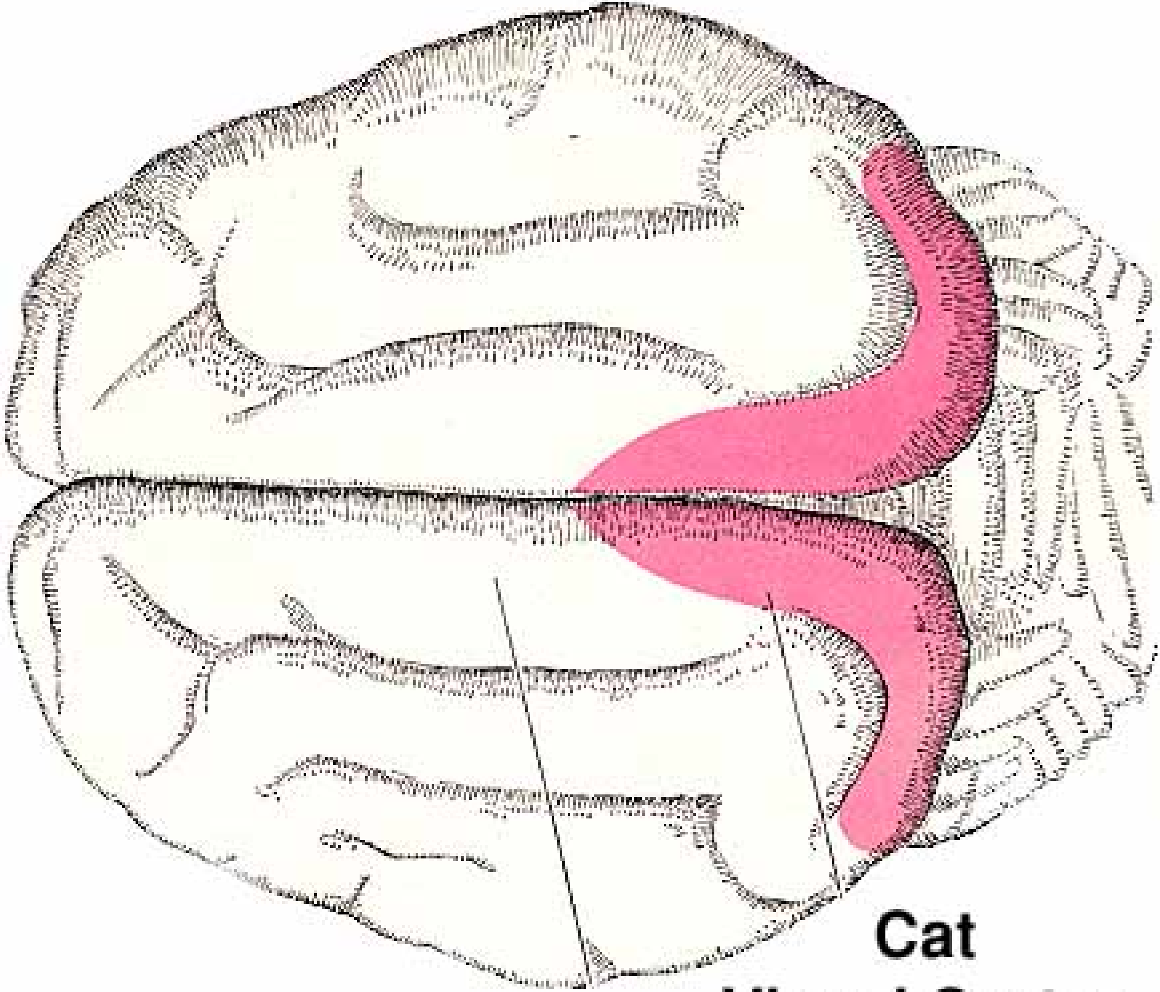
The cerebral cortex controls extraocular eye muscles so that corresponding points in each retina view the same object (otherwise double vision ensues).



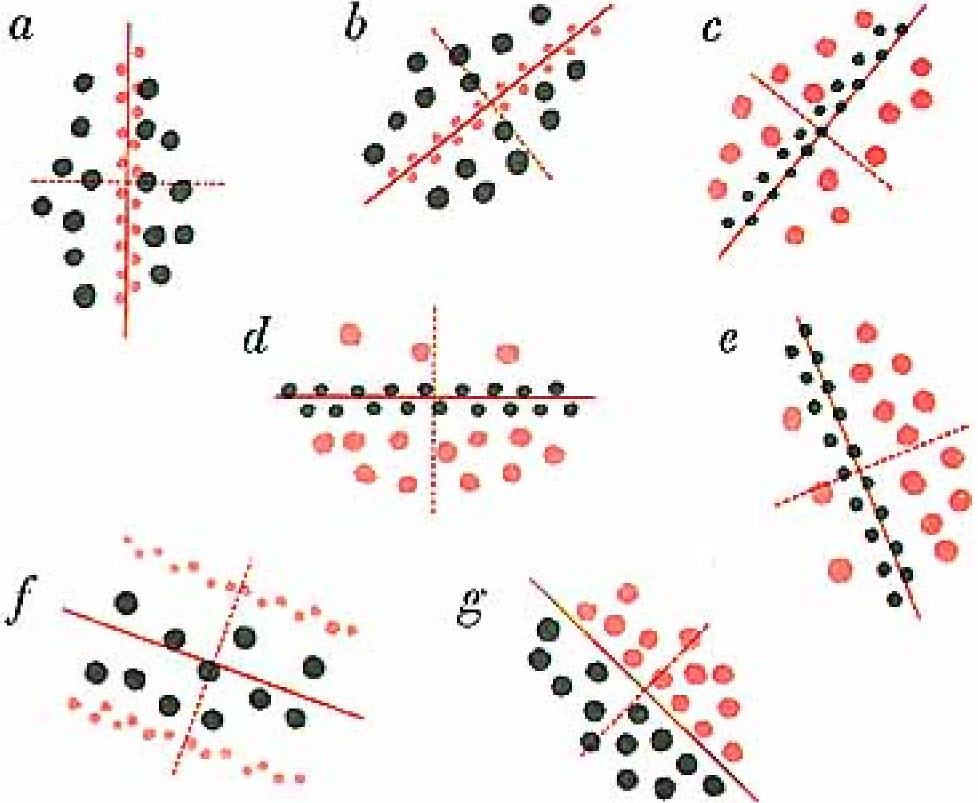

60°
150°
150°

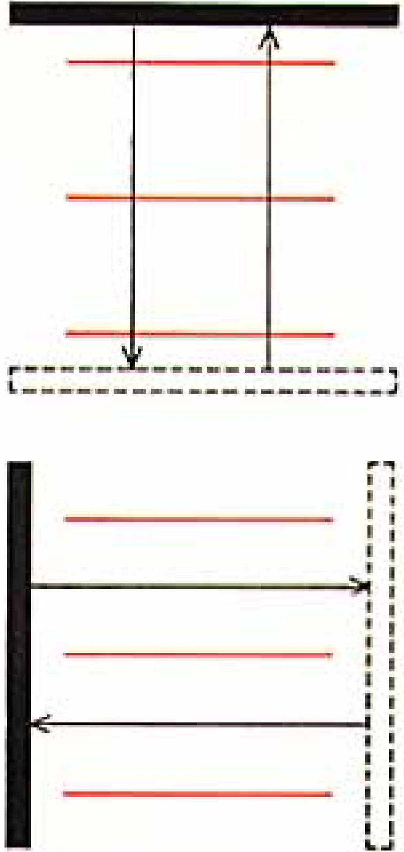

Visual Fields
T
N
N
T
Left
Right
Nasal retina
Temporal retina
Optic N.
Optic tract
Optic radiation
Visual cortex
A
B
C
D

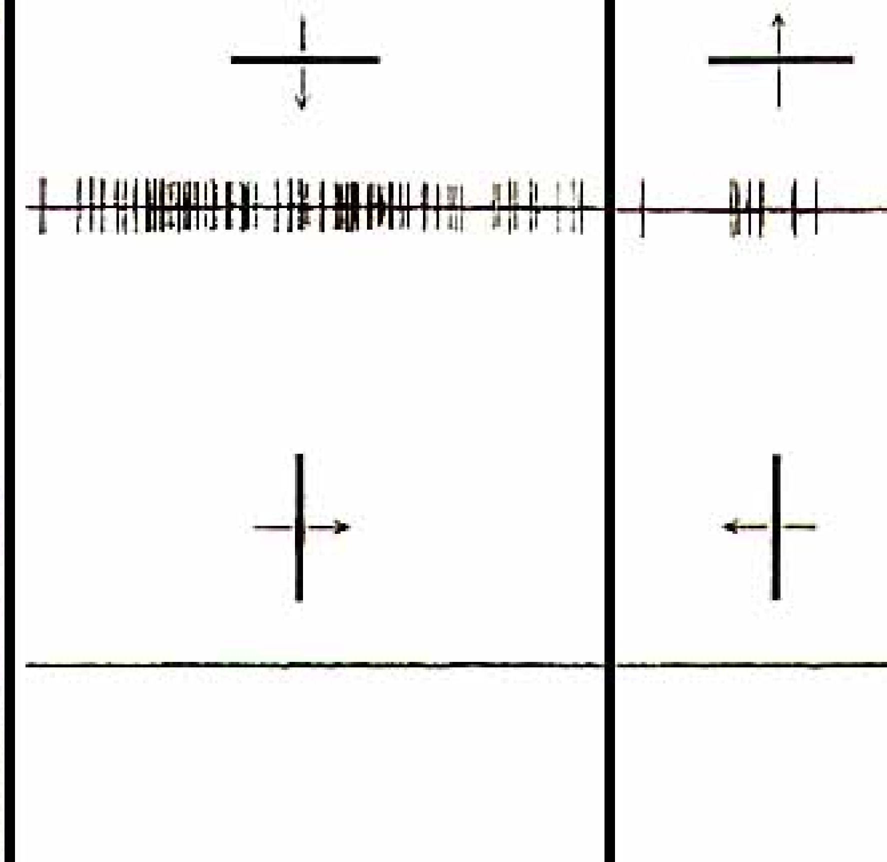




Cat Visual Cortex


a
b
c
d
e
f
g





Conscious Visual Pathway

Optic tract fibers synapse in the **lateral geniculate nucleus**, which exhibits a retinotopic organization and "ON/surround-OFF" receptor fields. Neurons of the lateral geniculate nucleus send their axons into the optic radiation of the internal capsule and then to the visual cortex. Actually, the lateral geniculate nucleus is stratified, with input from each eye and large/small ganglion cell input entering different layers.

The **visual cortex** is retinotopically organized. Representation of the area centralis is greatly enlarged compared to cortical surface area devoted to the rest of the retina.

The visual cortex exhibits the typical columnar organization of neocortex. Columns respond to the geometric & dynamic elements of an image. A cell column within visual cortex becomes excited in response to light–dark boundaries oriented at a certain angle, moving in a certain direction, affecting either or both eyes, etc. Some cell columns are activated by particular colors.

Association cortex, surrounding the primary visual cortex, is required to associate meaning and significance to the elements of the primary image. There are two separate visual integrations:

1] A phylogenetically older "where" system that analyzes motion and depth. Damage produces:
- — failed ocular pursuit of a moving target, i.e., inaccurate eye saccades (tiny movements);
- — poor depth perception (astereopsis);
- — deficient visually guided movements, e.g., reaching (optic ataxia); and
- — deficits in visual attention.

2] A phylogenetically newer "what" system that analyzes form and color. Damage produces:
- — loss of color vision;
- — impaired pattern recognition, including face/object recognition (visual agnosia).

Three principles of conscious visual transmission are:
- • Retinotopic mapping — eventually lost at level of association cortex
- • Parallel processing — color/form/motion remain separate from retina to cortex
- • Hierarchial processing — receptive fields become larger and more complex at each level.

Color Vision

Humans have three populations of color senstive cones. We are trichomatic and can distinguish the range of colors with which you are familiar.

Color vision in dogs is said to be comparable to people who are red-green color blind. Dogs are dichromatic and seem to see blue and yellow but not green or orange-red.

All of several horses tested could distinguish red and blue from gray. Some but not all of the horses could also distinguish yellow and green from gray.

Two populations of color senstive cones are found in other species, e.g., cat and pig. Nocturnal animals are completely color blind (rat, hampster, etc.).

Reflex Visual Pathways

Axons participating in subconscious visual reflexes leave the optic tract and travel in the **brachium of the rostral colliculus** to reach two visual reflex centers, the rostral colliculus and the pretectal region. (Axons also leave the optic tract to reach the hypothalamus.)

Two important visual reflexes are:

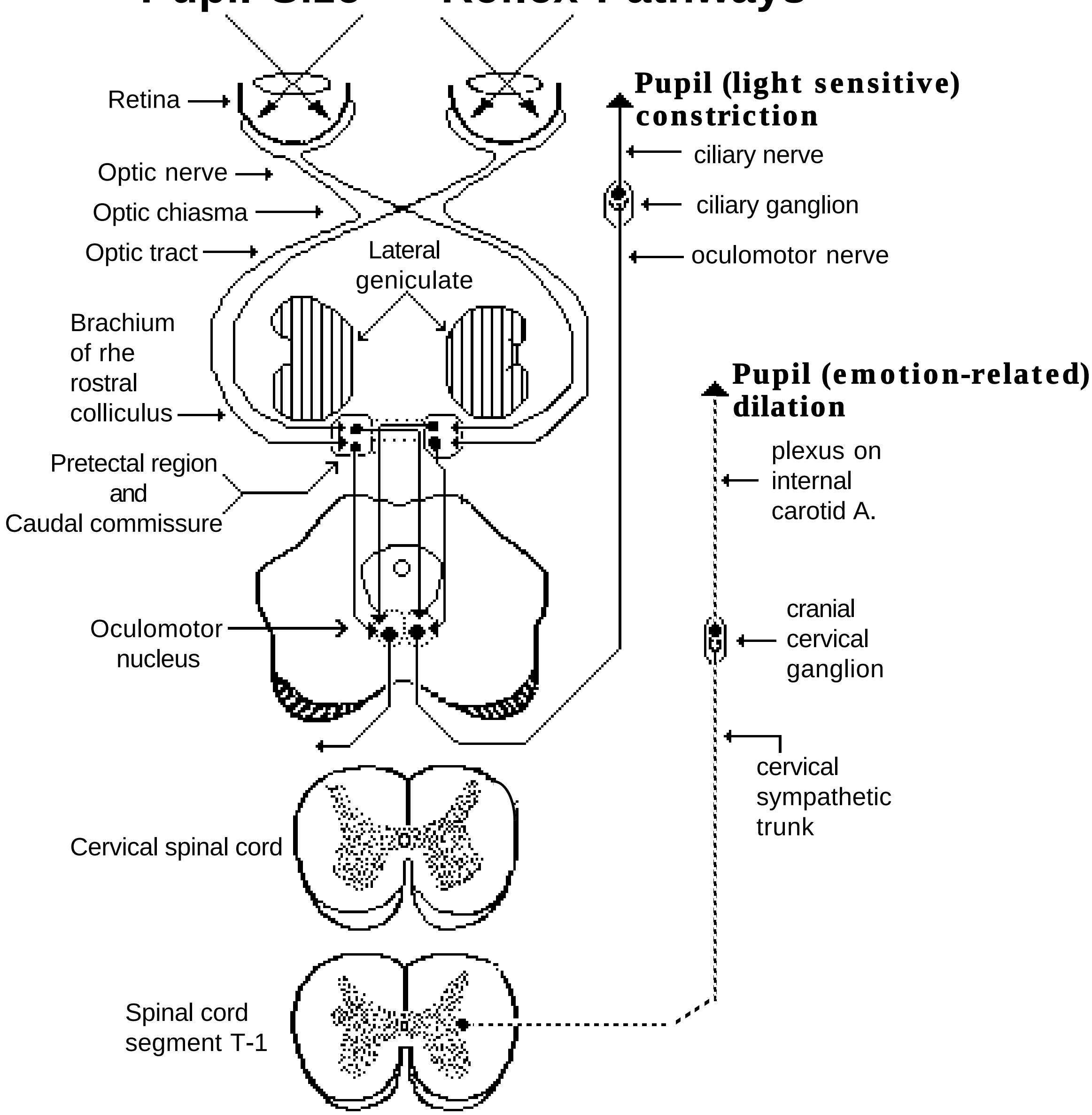
1] *Eye, ear and head turning to orient to a sudden, prominent visual stimulus* involves the **rostral colliculus**. Neurons of the rostral colliculus send their axons to appropriate motor nuclei via tectobulbar and tectospinal tracts. (The rostral colliculus is used by visual cortex for subconsious eye movements.)

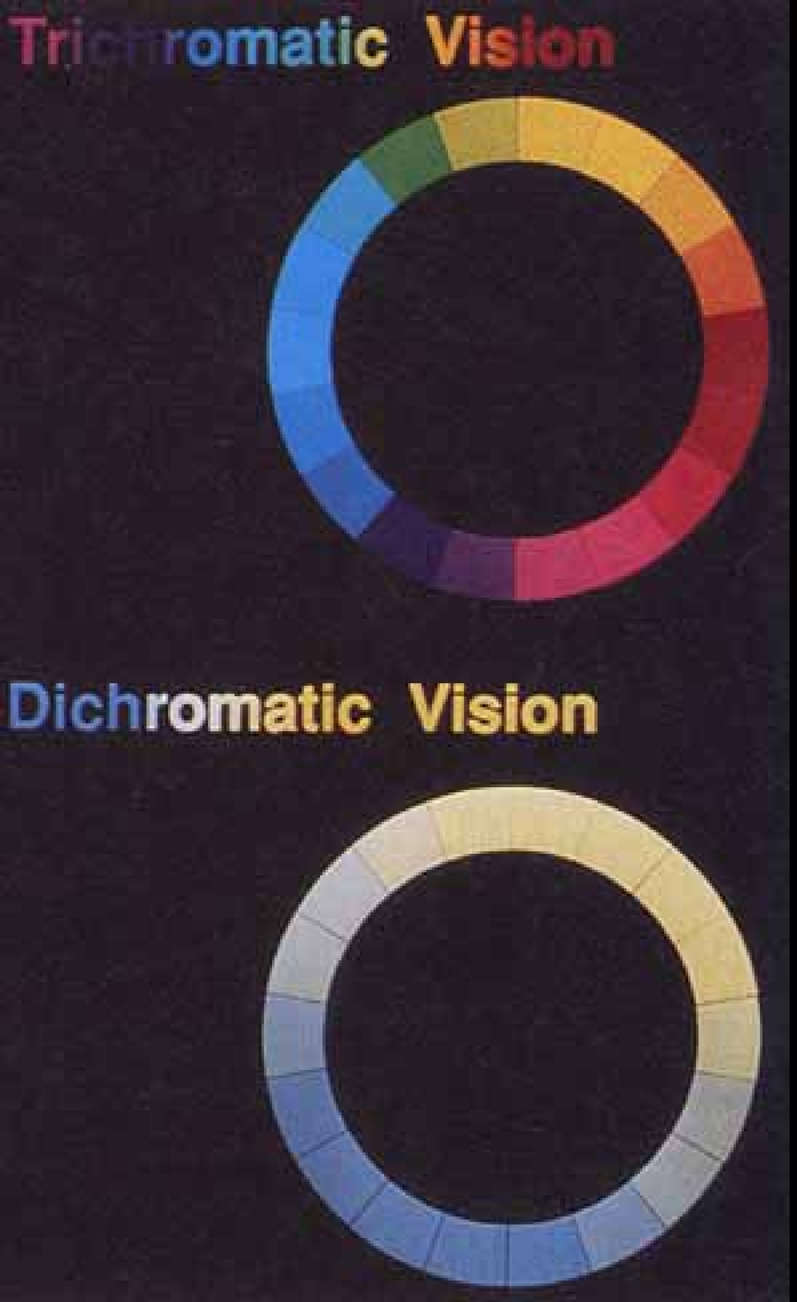
In higher mammals, the rostral colliculus depends on input from the cerebral cortex to function and cortical damage produces apparent total blindness. In birds, the rostral colliculus equivalent (optic lobe) provides all visual function.

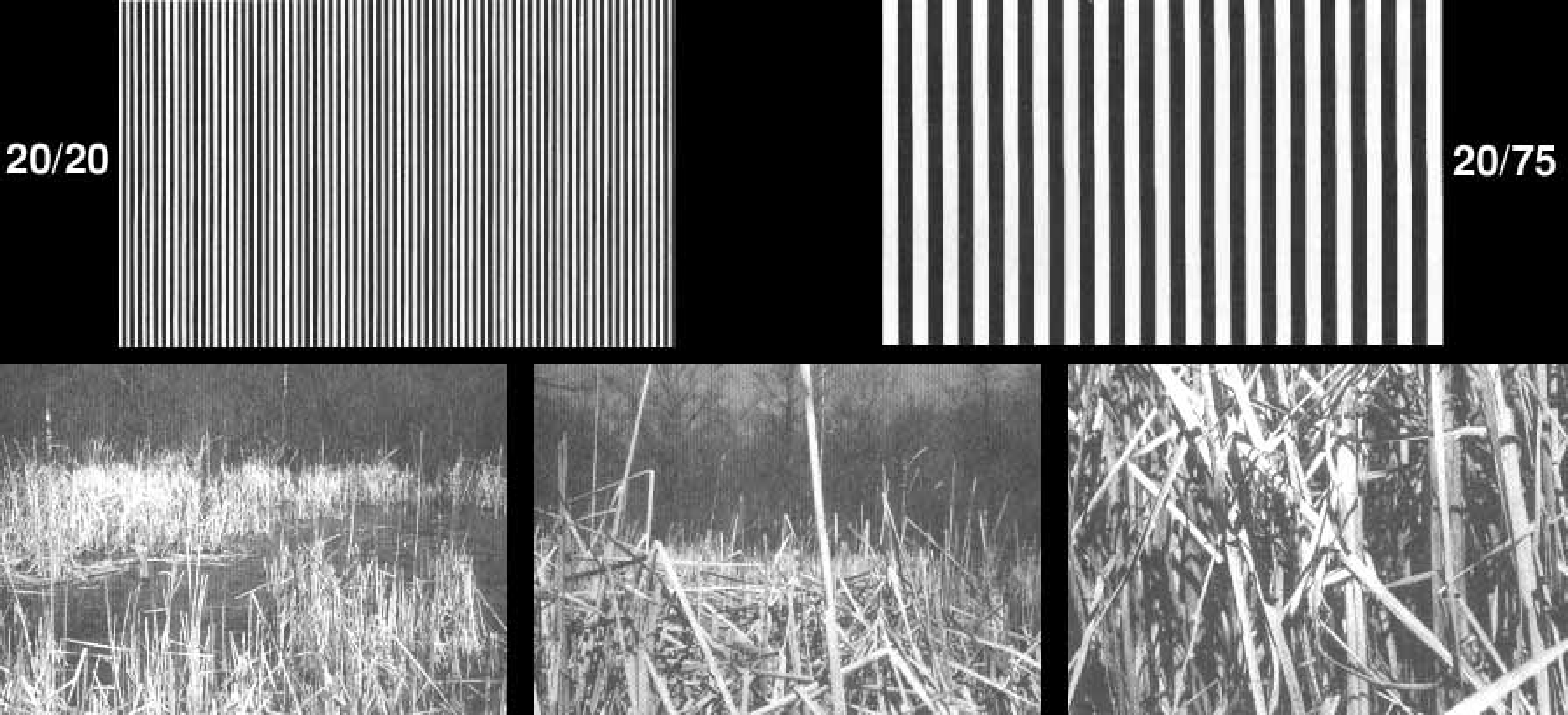
2] *Pupil size regulation to compensate for light intensity* involves the **pretectal region**, with fiber decussation in the caudal commissure. Axons go to the **parasympathetic nucleus of the oculomotor nerve** for pupillary constriction (dilation is achieved by less constriction).

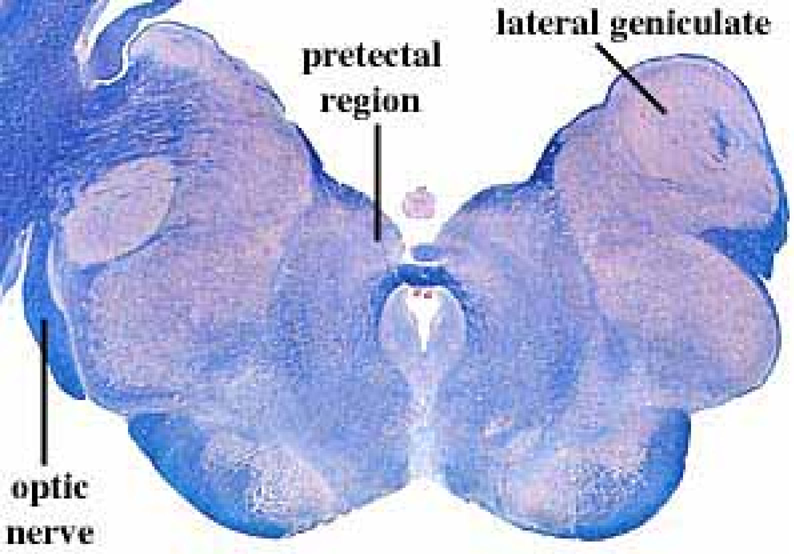
Pupil dilation in response to emotional situations (fight/flight) involves sympathetic preganglionic neurons in the cranial thoracic spinal cord. Pupil constriction in response to accommodation for near vision is controlled by the cerebral cortex.

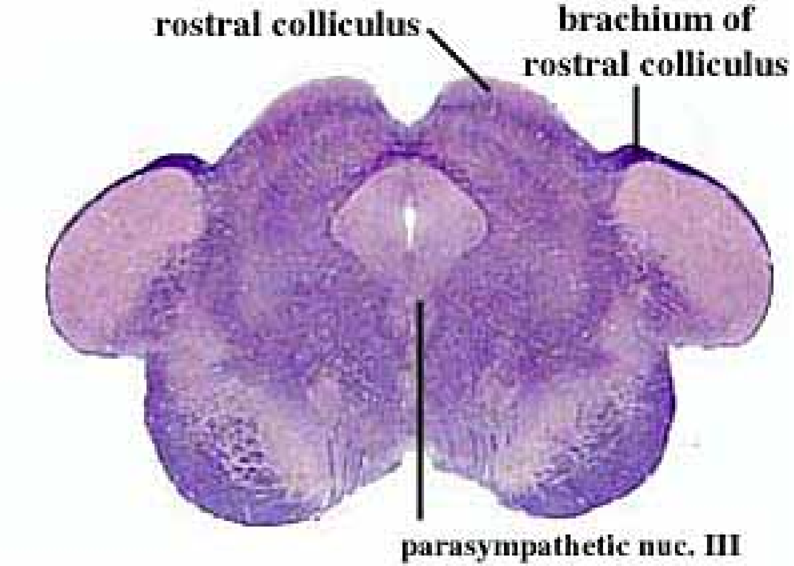
Pupil Size — Reflex Pathways

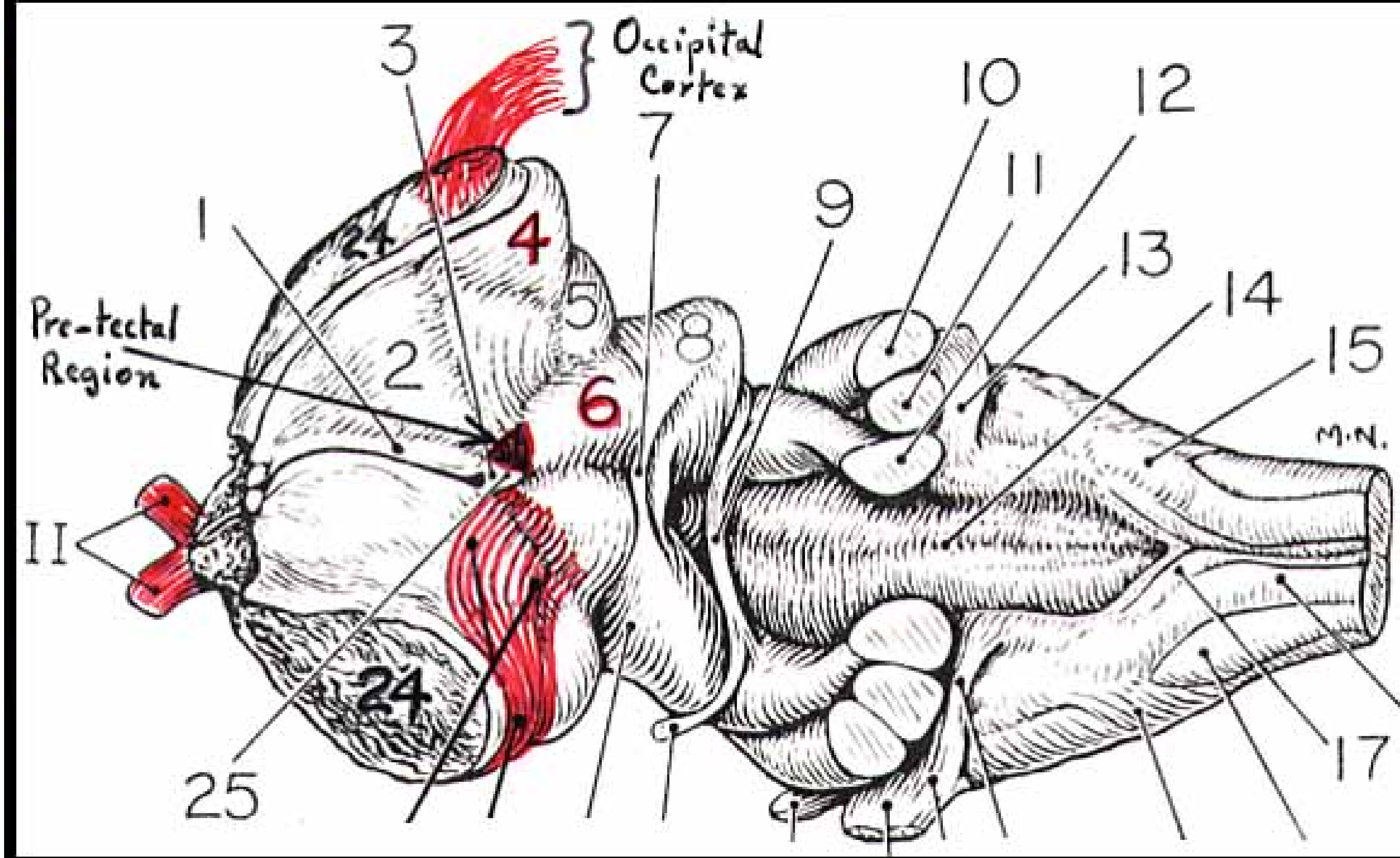



Trichromatic Vision
Dichromatic Vision


20/20
20/75


lateral geniculate
pretectal region
optic nerve


rostral colliculus
brachium of rostral colliculus
parasympathetic nuc. III


3
Occipital Cortex
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Pre-tectal Region
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M.N.
II
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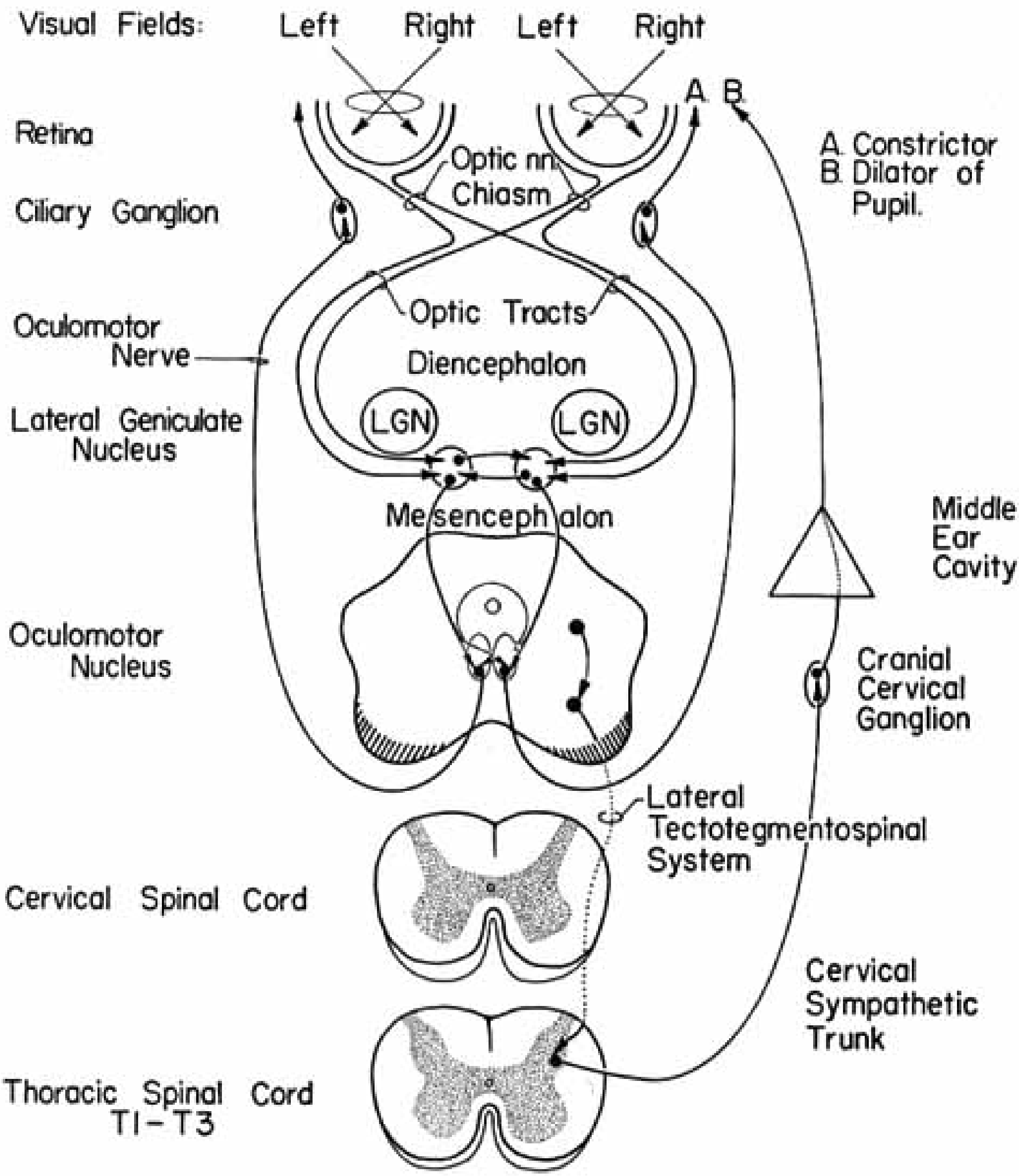
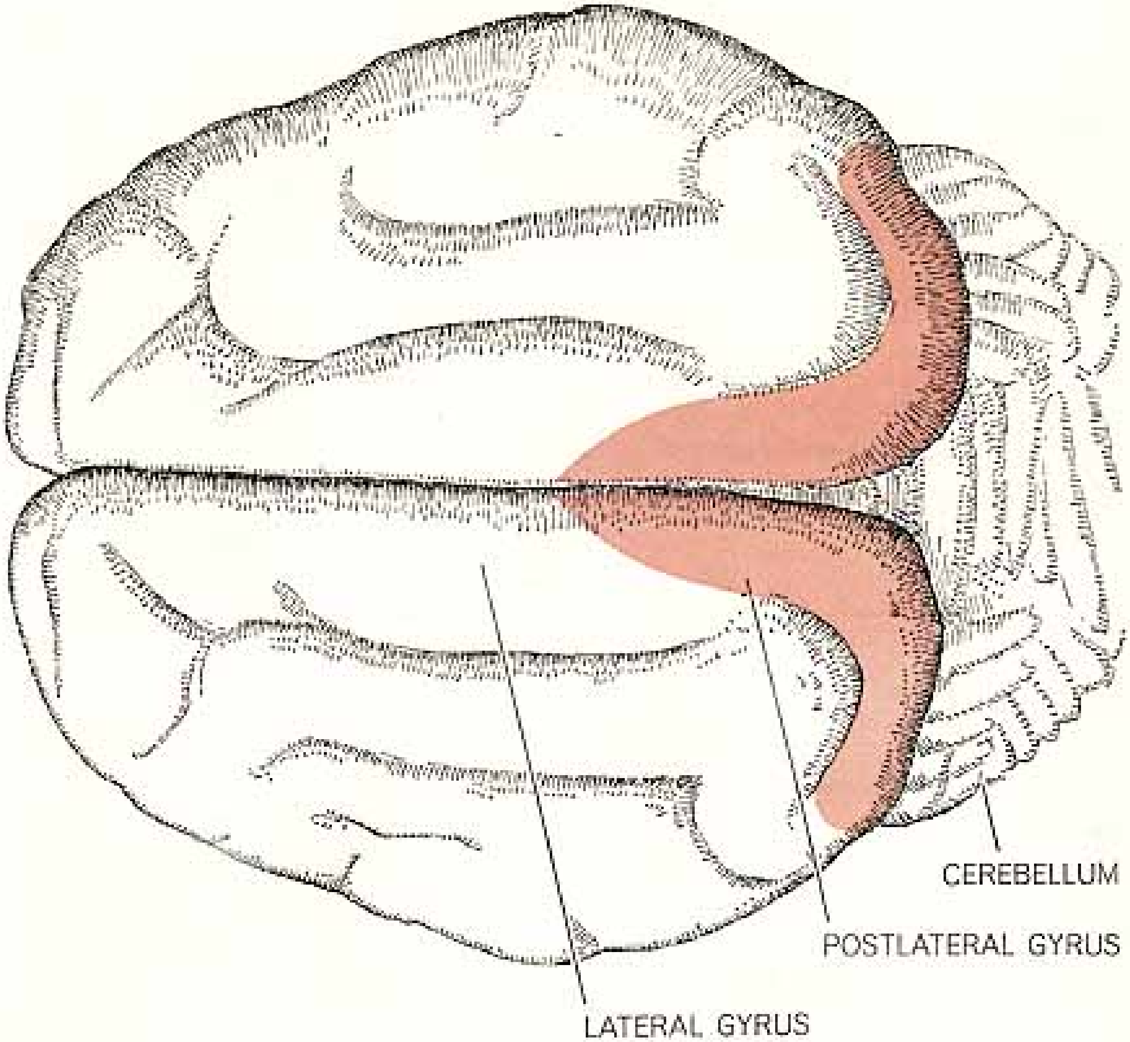
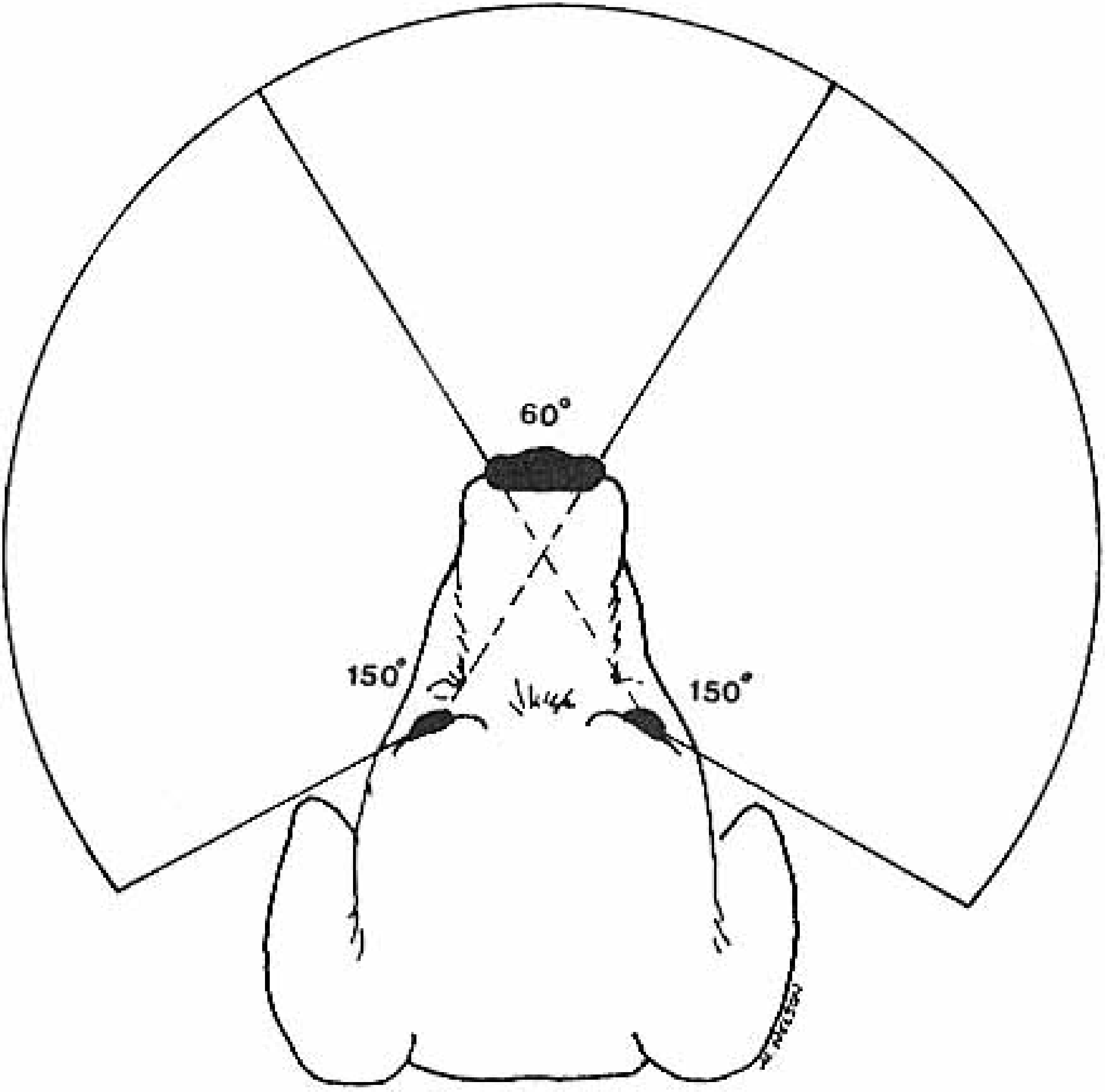
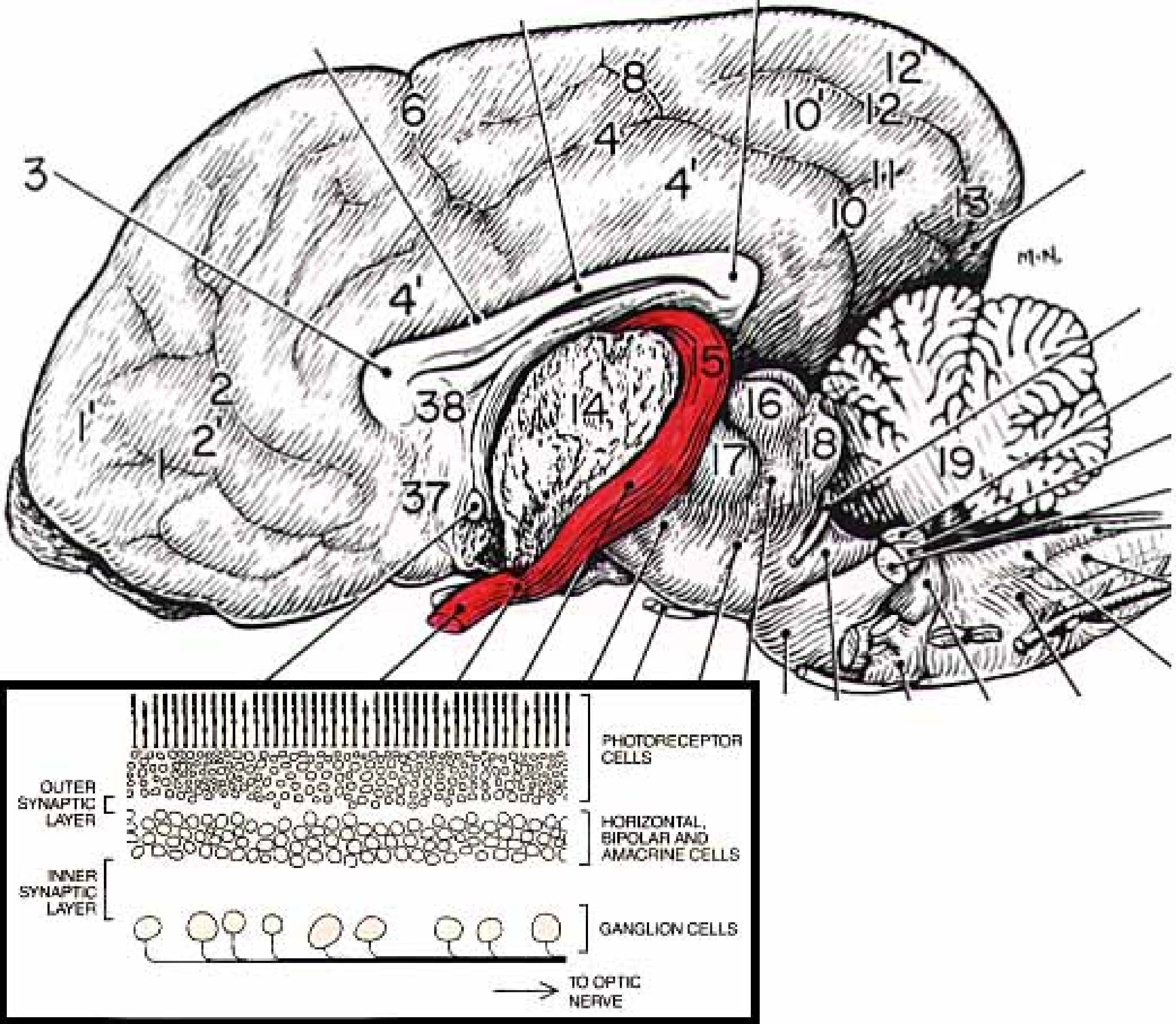
25

Pathway for Pupillary Control




CEREBELLUM
POSTLATERAL GYRUS
LATERAL GYRUS


60°
150°
150°



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4'
4'
12'
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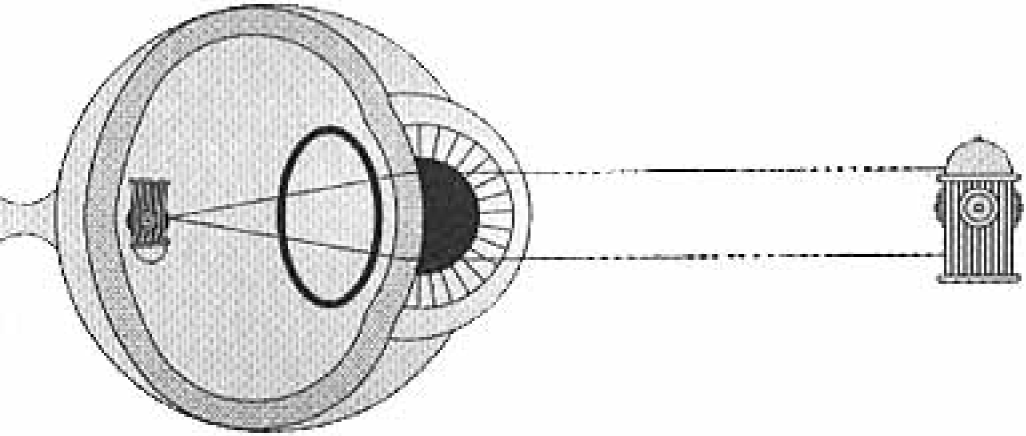
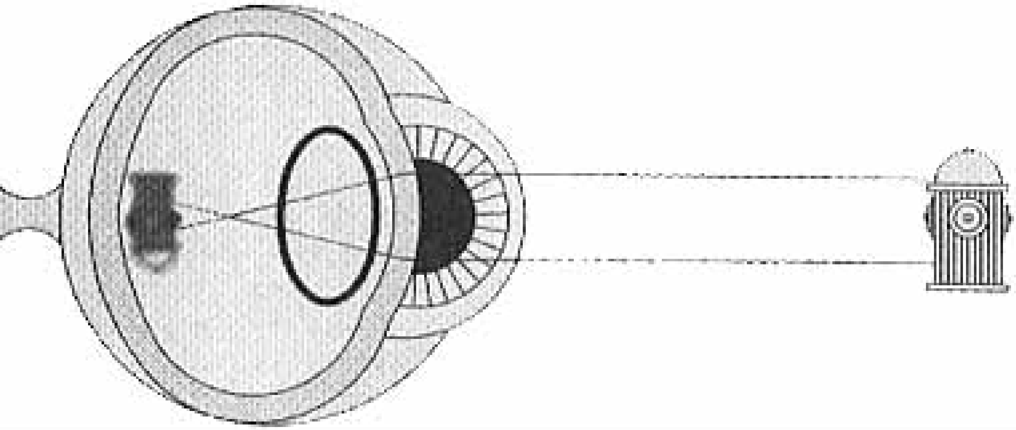
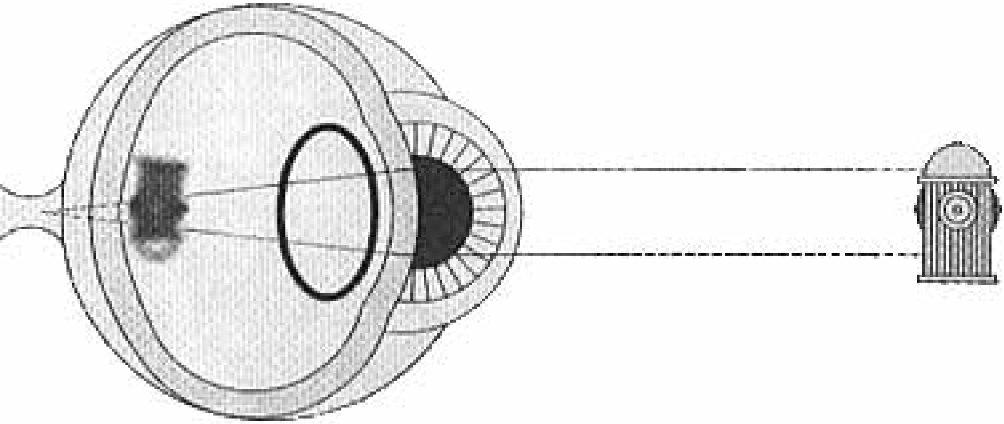
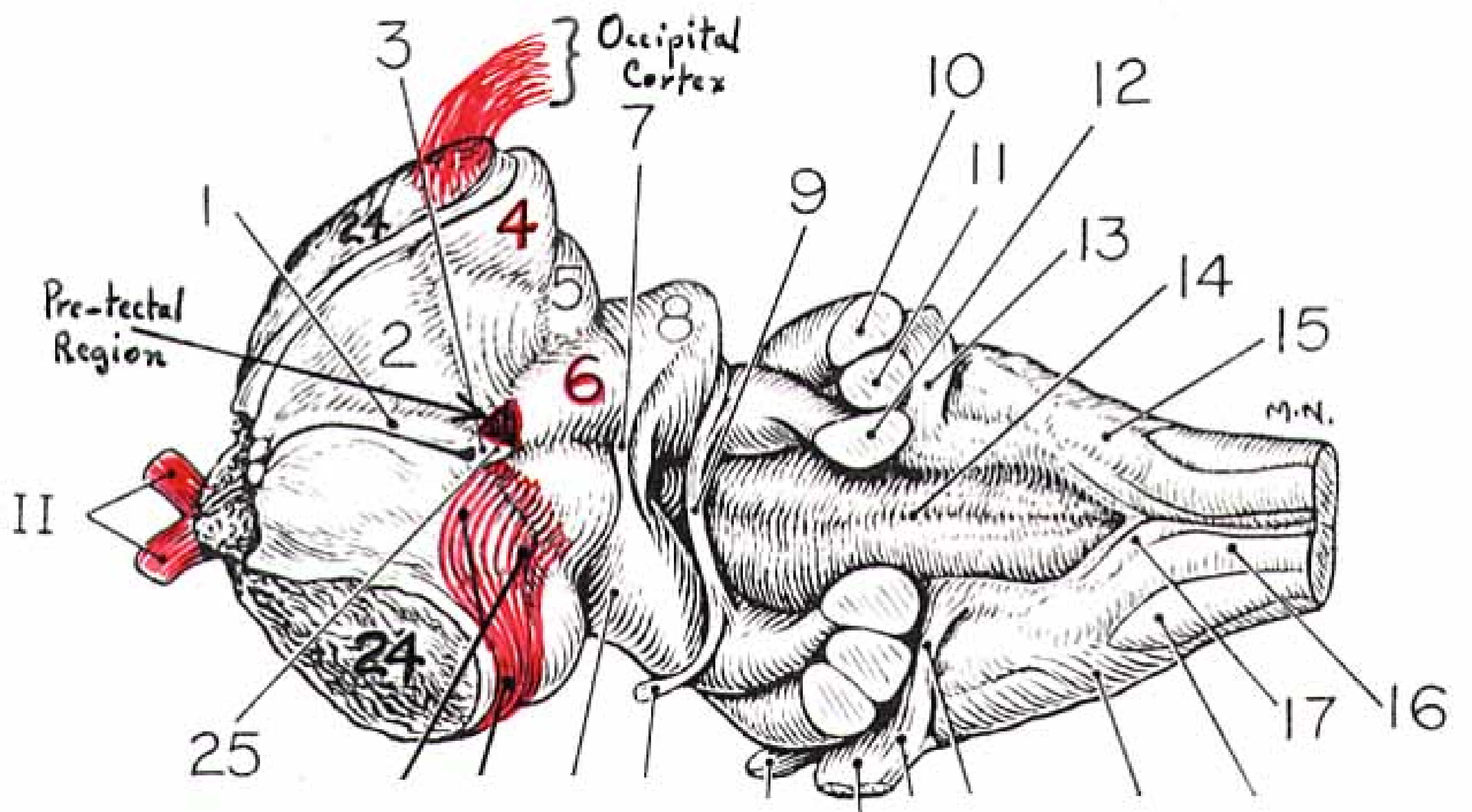
37
OUTER SYNAPTIC LAYER
PHOTORECEPTOR CELLS
HORIZONTAL, BIPOLAR AND AMACRINE CELLS
INNER SYNAPTIC LAYER
GANGLION CELLS
TO OPTIC NERVE









Occipital Cortex
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Pre-tectal Region
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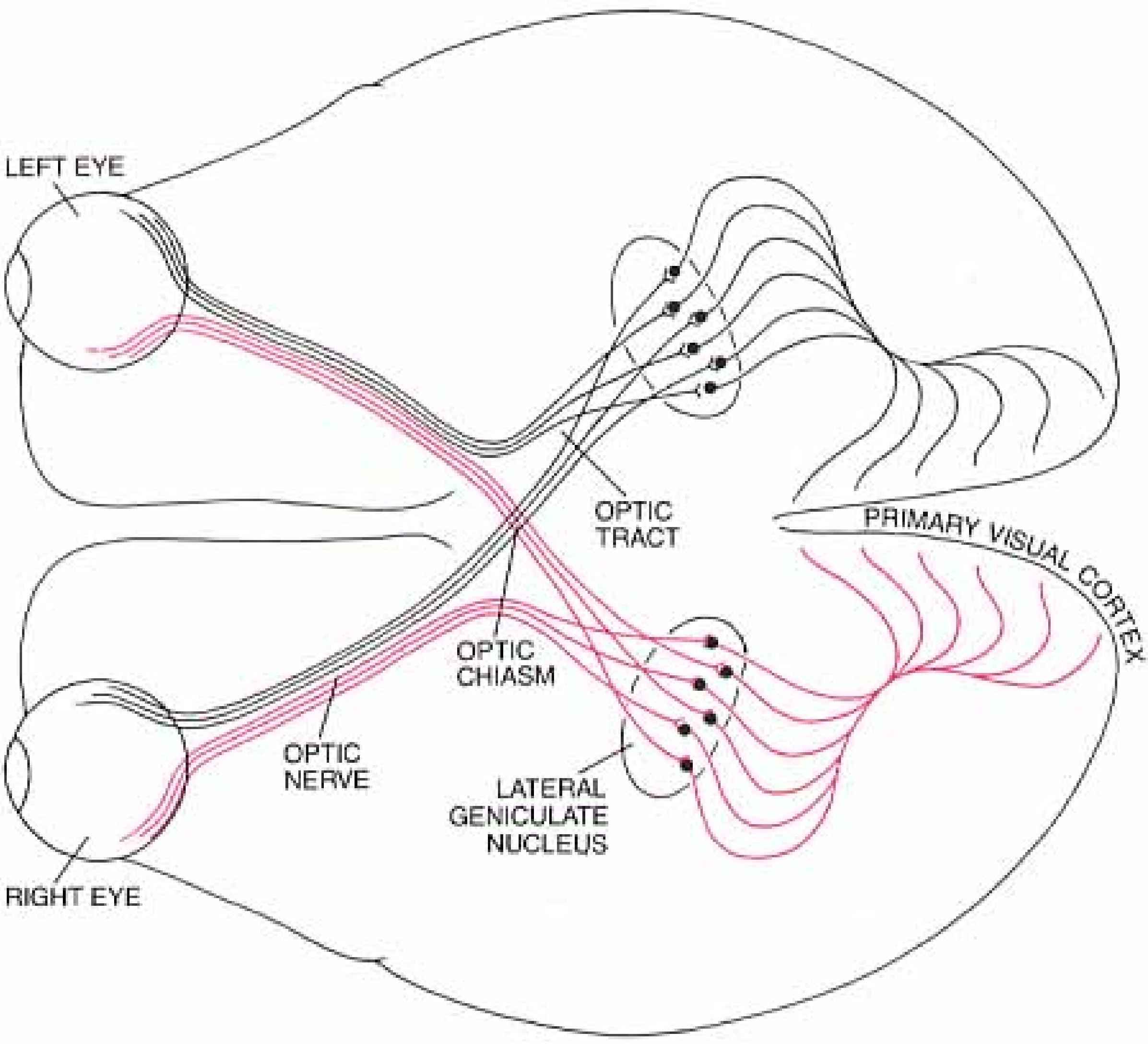
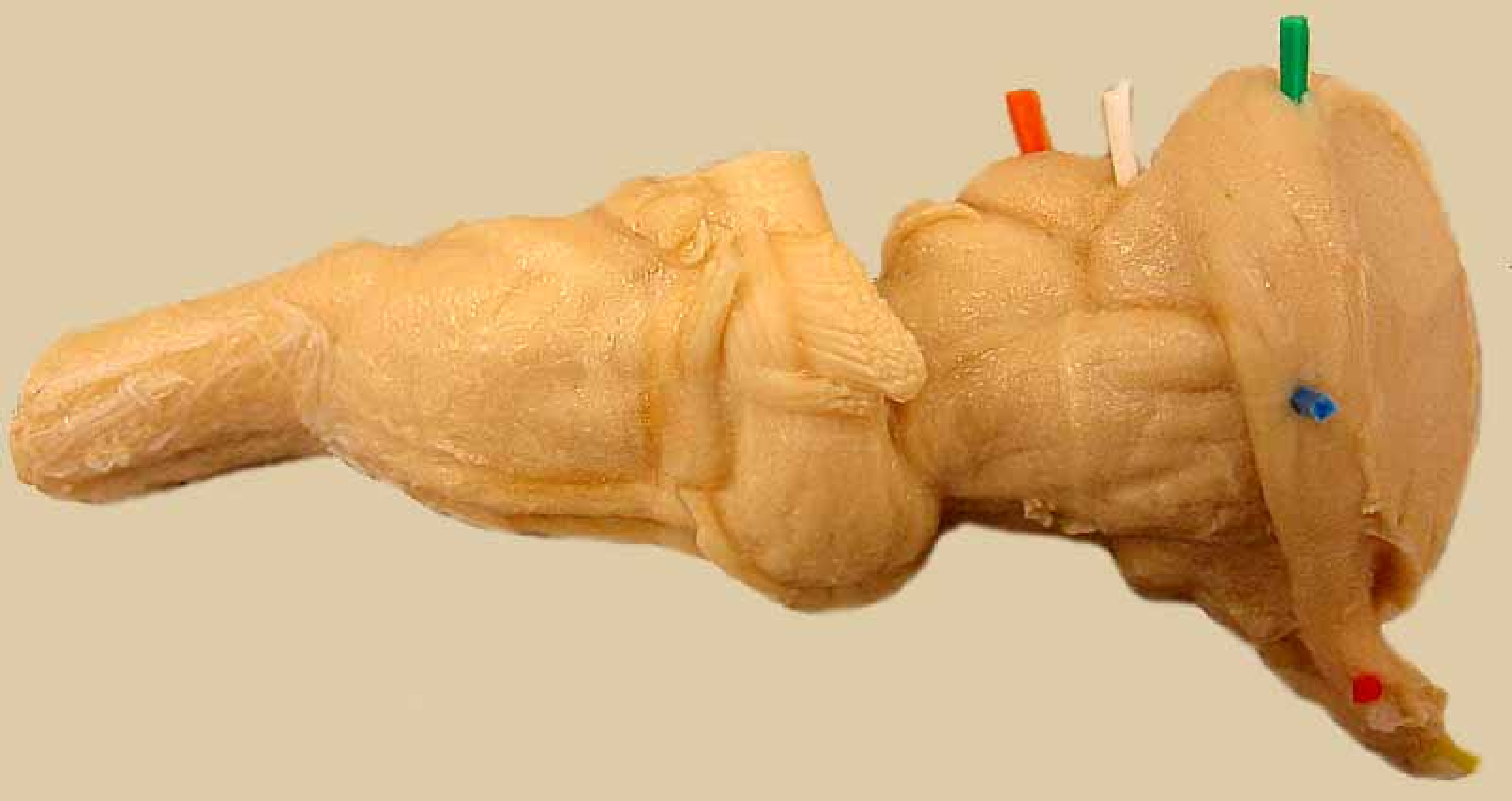
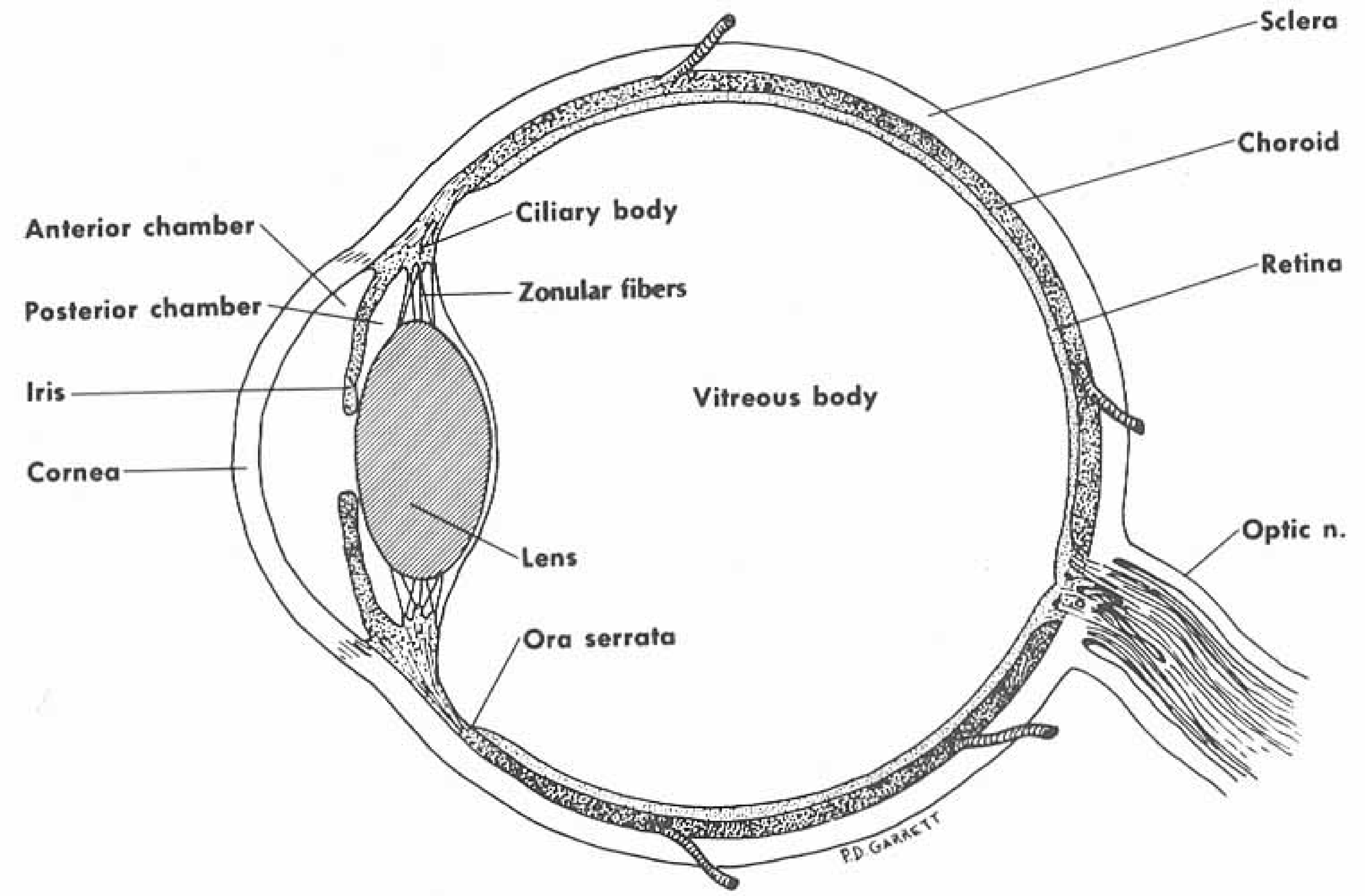

LEFT EYE
OPTIC TRACT
PRIMARY VISUAL CORTEX
OPTIC CHIASM
OPTIC NERVE
LATERAL GENICULATE NUCLEUS
RIGHT EYE




Sclera
Choroid
Ciliary body
Anterior chamber
Retina
Zonular fibers
Posterior chamber
Iris
Vitreous body
Cornea
Optic n.
Lens
Ora serrata
P.D. GARRETT