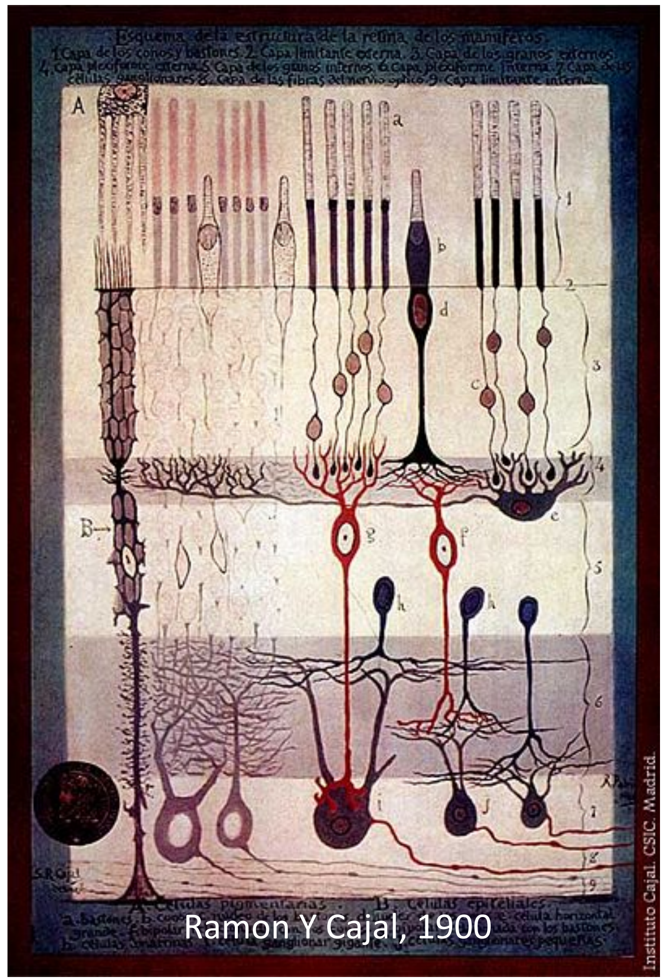
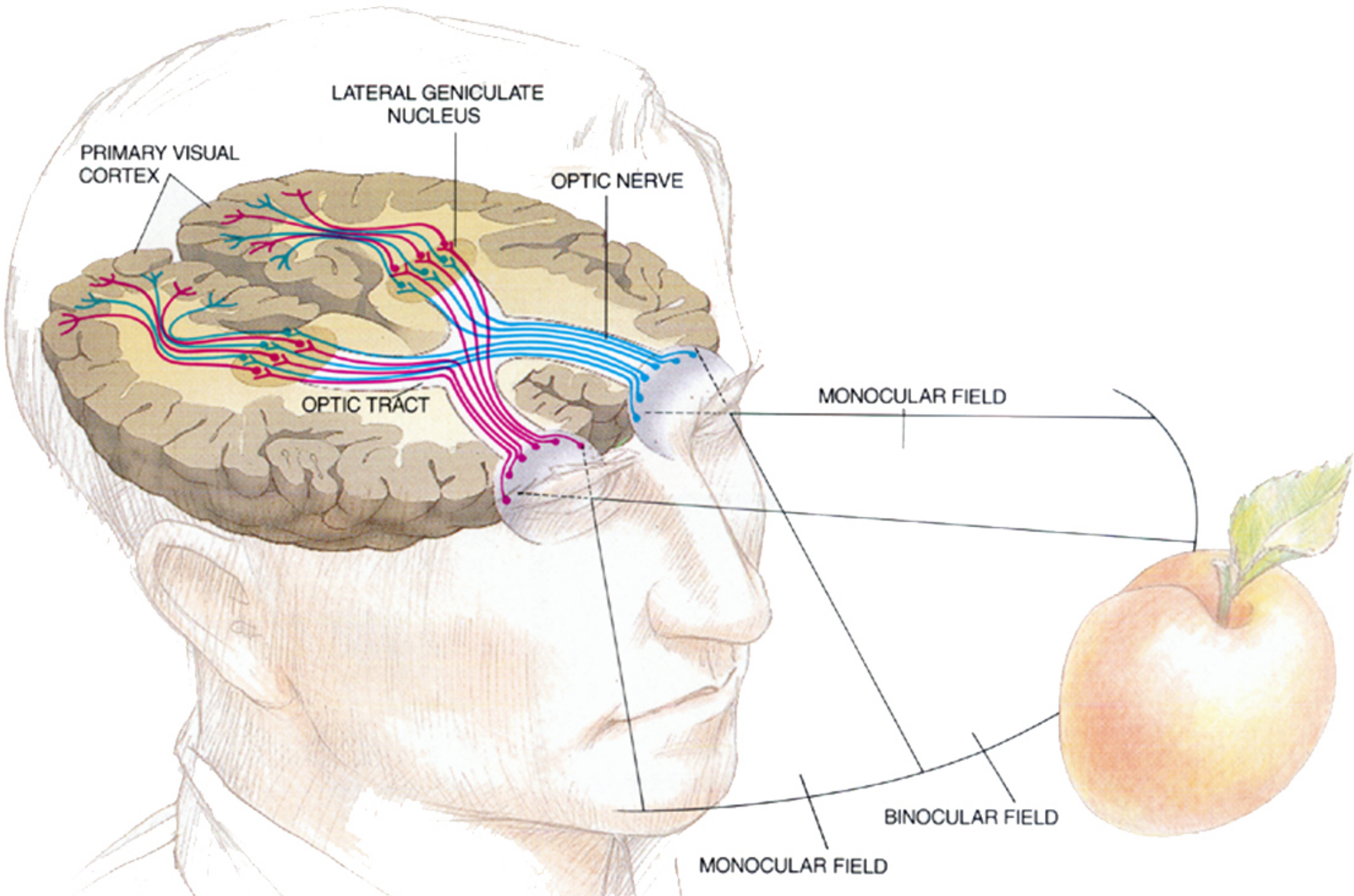
Introduction to Neuroscience: Visual Processing by the Retina

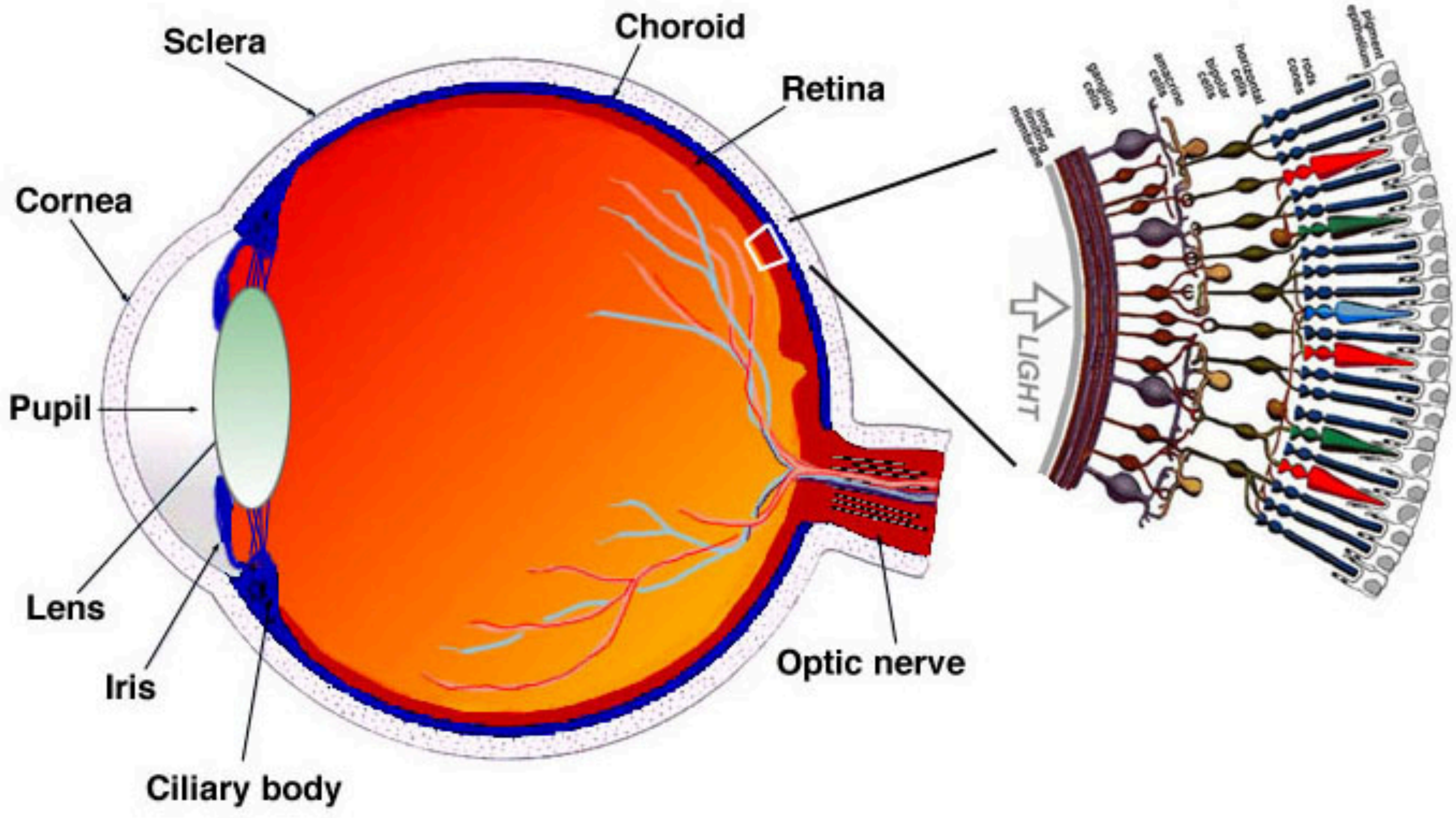


Ramon Y Cajal, 1900

Visual processing starts in the retina, and travels through the optic nerve to the brain

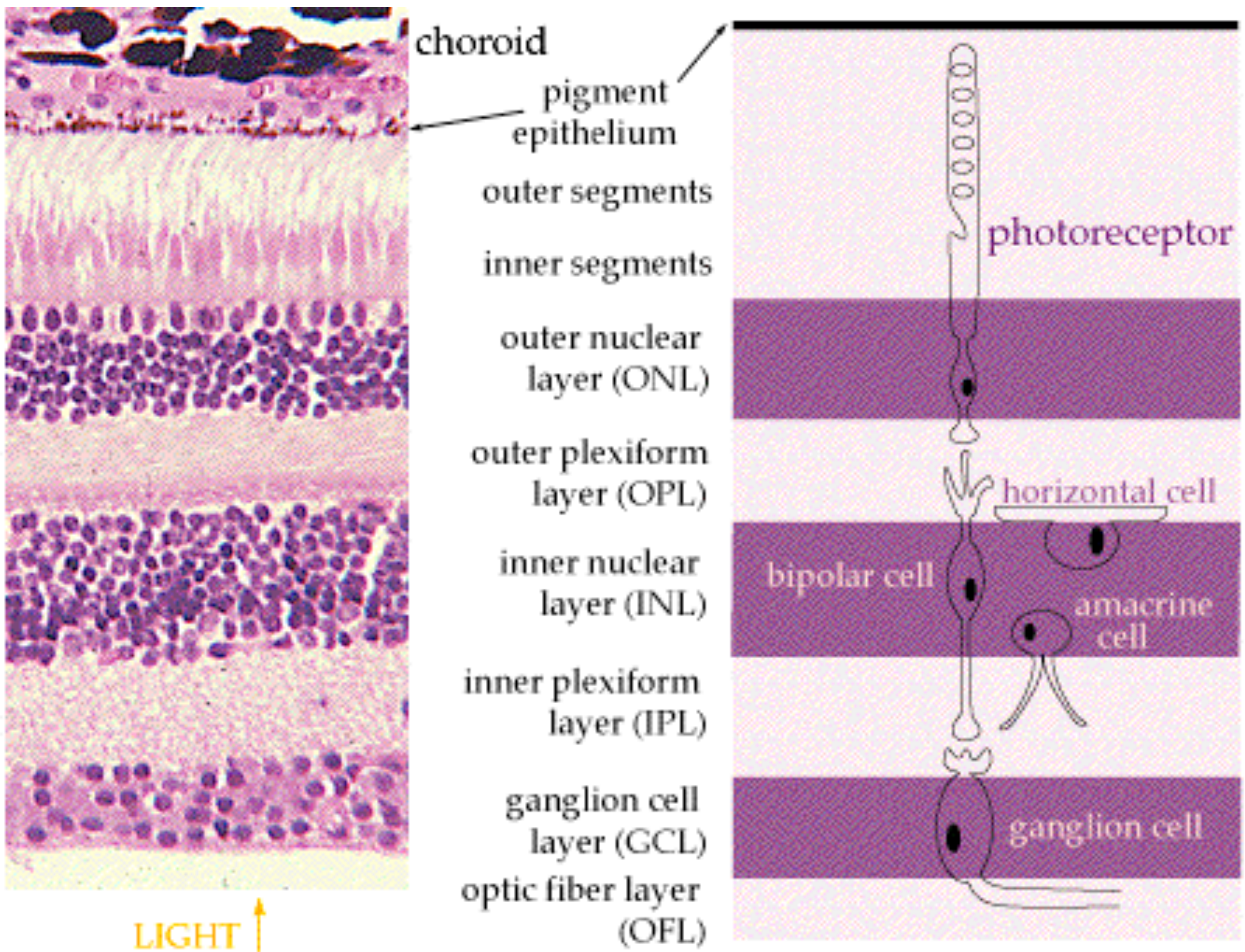


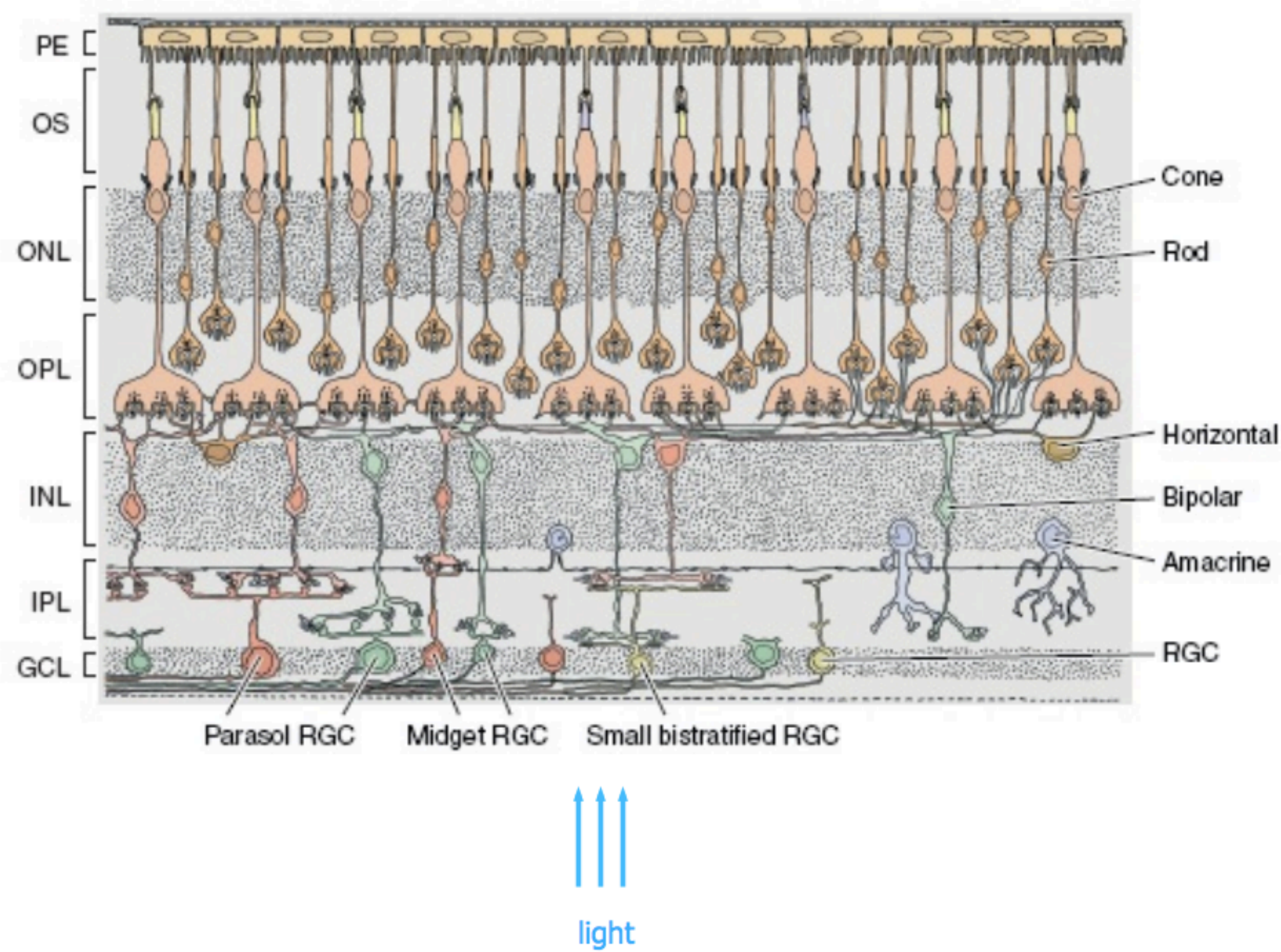
The human Eye



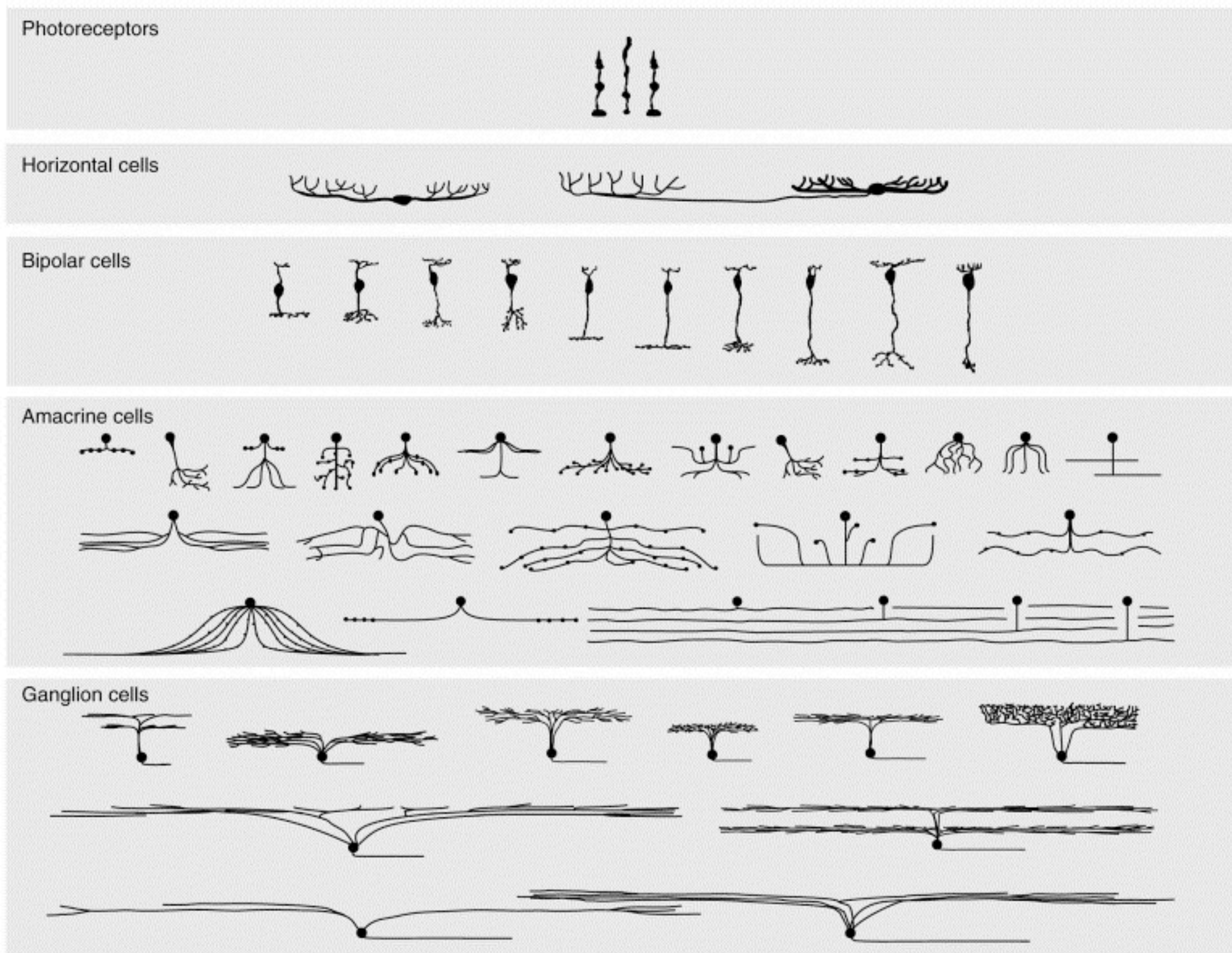
http://webvision.med.utah.edu/

An introduction to the cell types of the retina



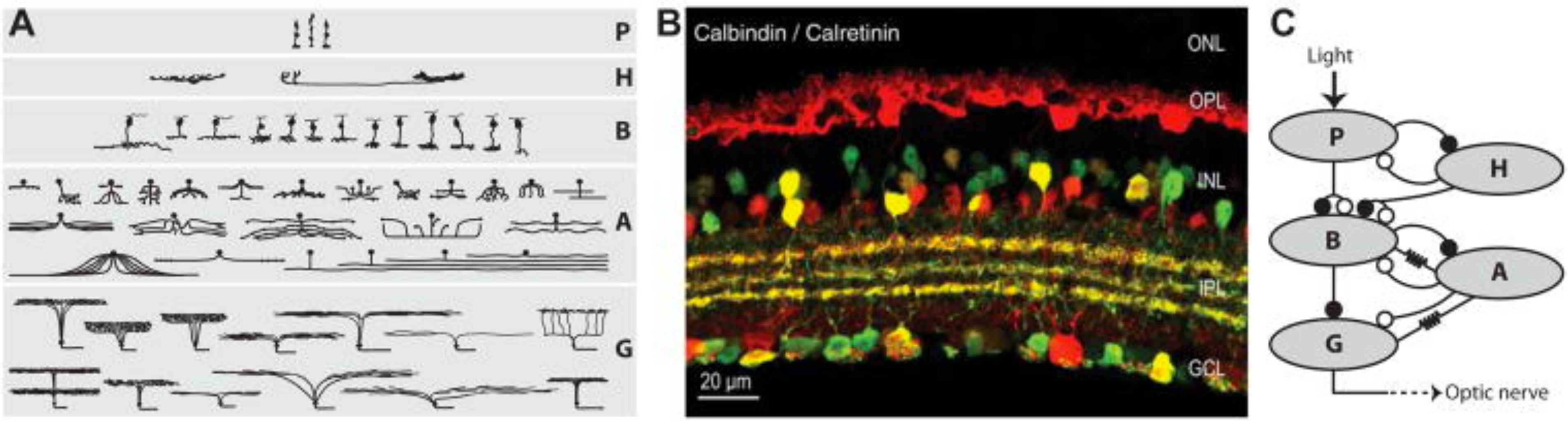

PE
OS
ONL
OPL
INL
IPL
GCL
Cone
Rod
Horizontal
Bipolar
Amacrine
RGC
Parasol RGC
Midget RGC
Small bistratified RGC
light

Each class is composed of multiple subtypes

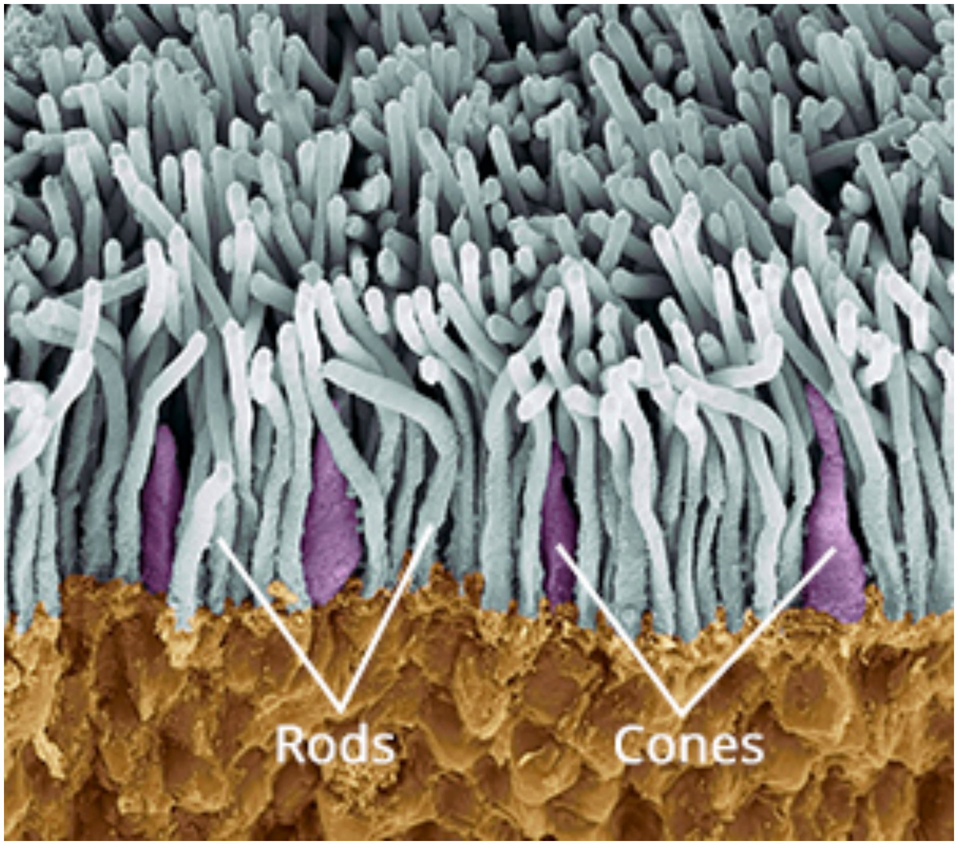


Current Opinion in Neurobiology

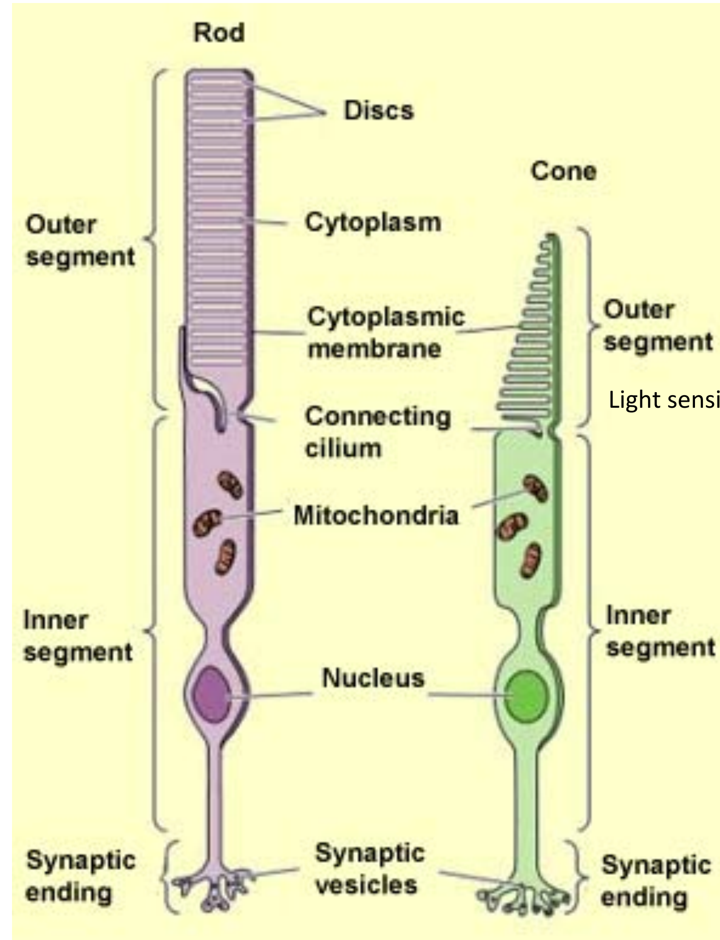
Retinal neurons stratify in specific laminas of the plexiform layers



Photoreceptors: Rods and Cones

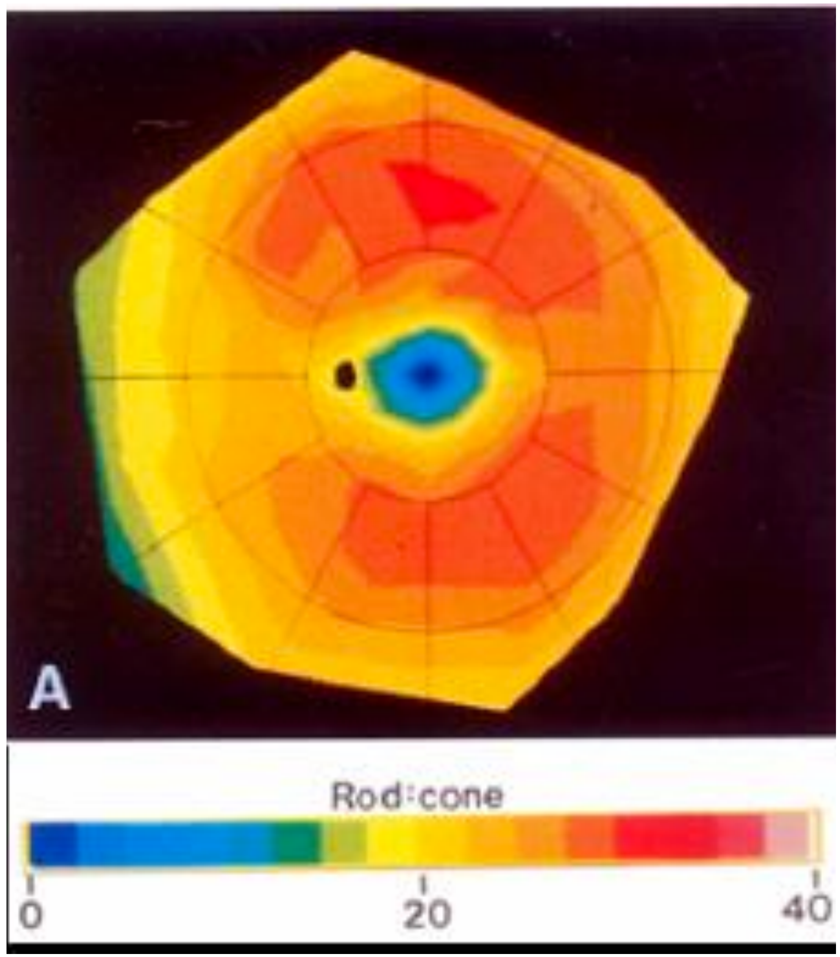


Rods: dim night vision.
Cones: bright day light vision & color vision



Light sensitive pigment

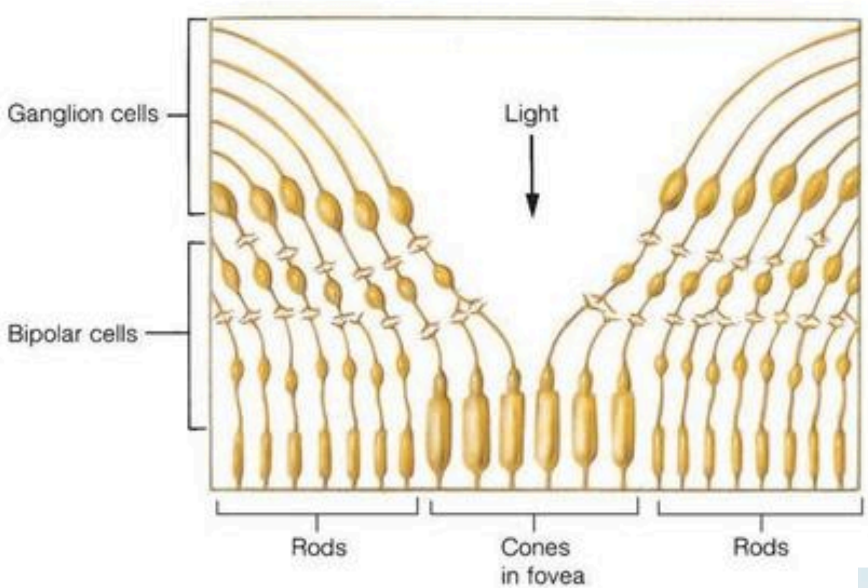
Distribution of Rods and Cones in human retina

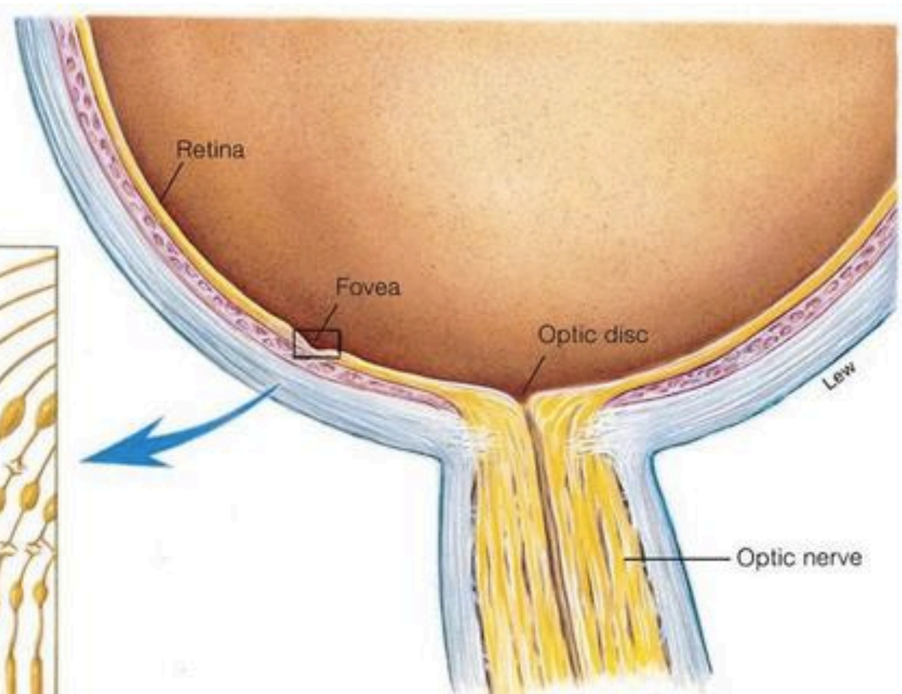


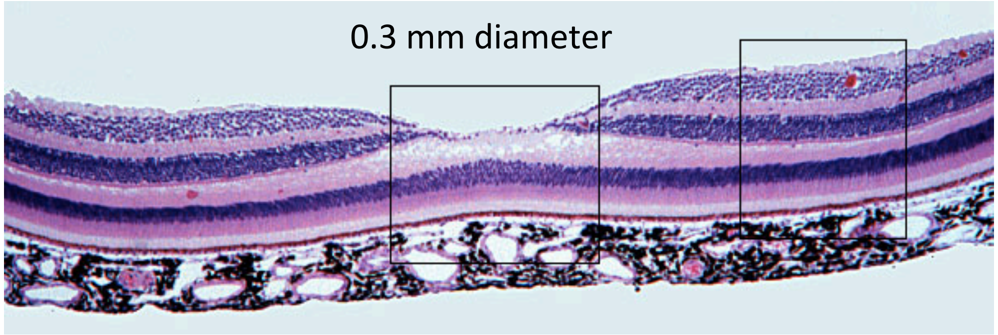
Curcio et al., 1990

Fovea

Note: not all retinas have a fovea!
Primates do.
Some species have area centralis.







The Blind Spot

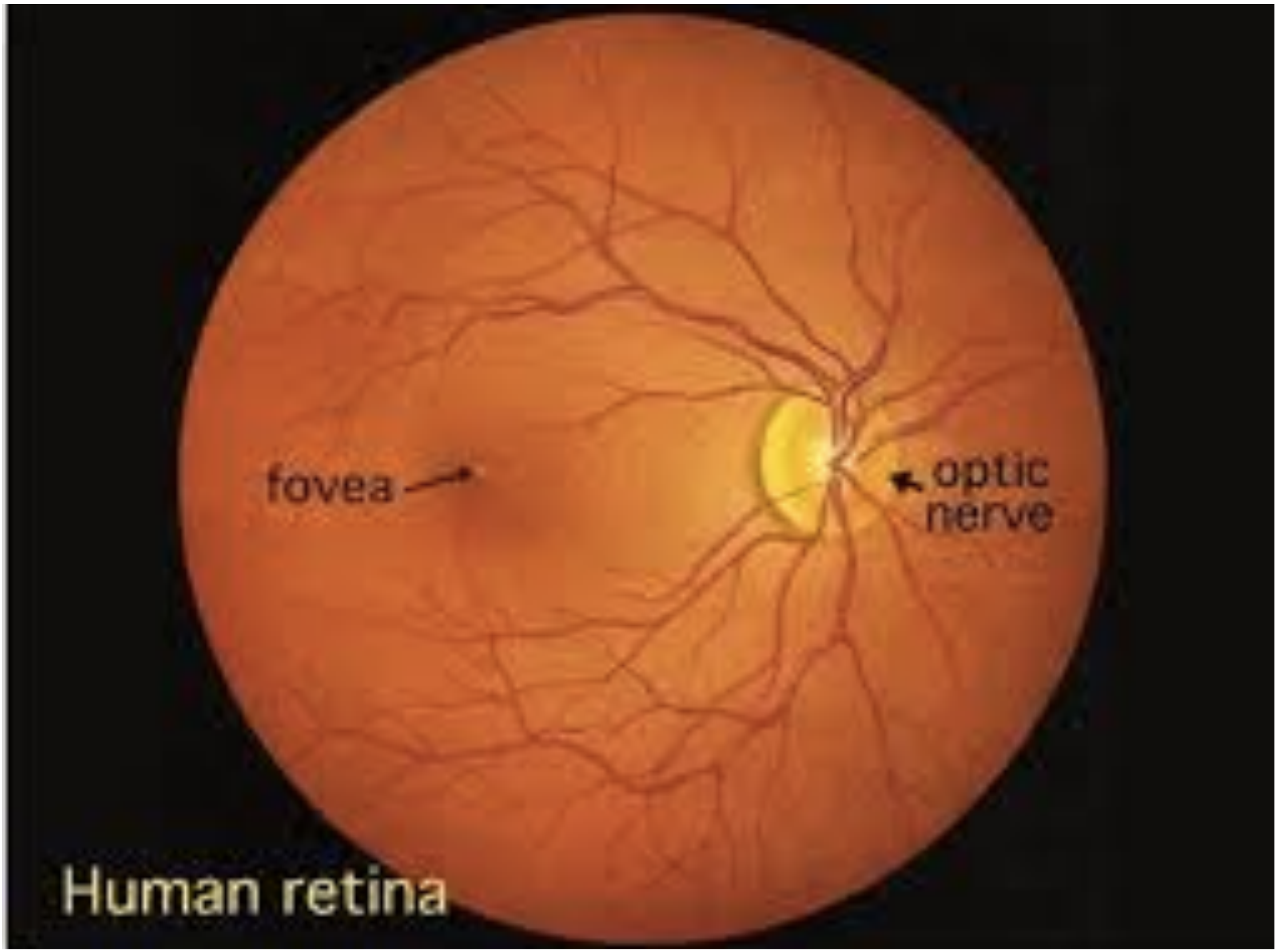
(located at the optic disc)

Close your right eye

Fixate on the spot with your left eye

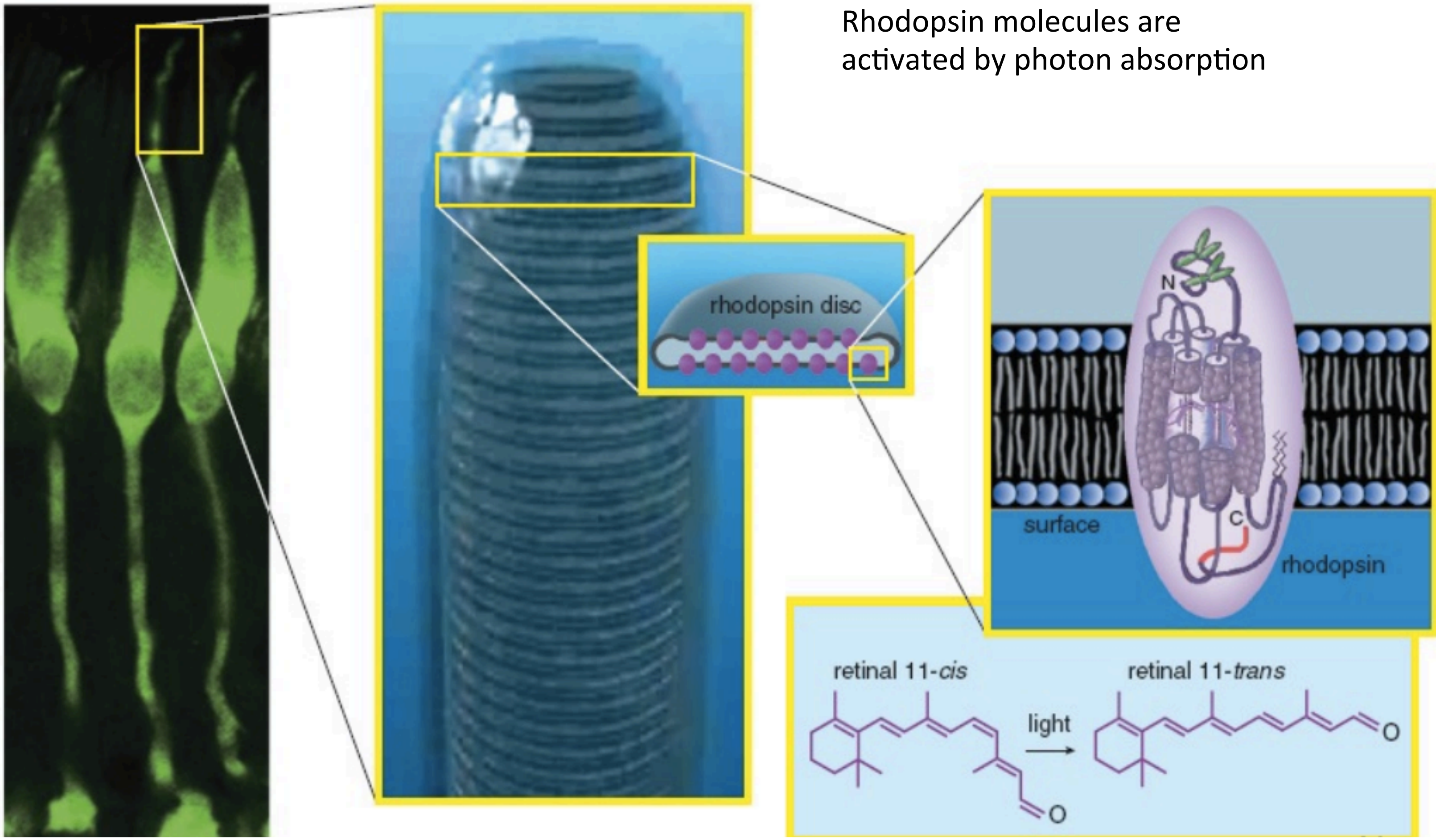
Move paper until cross disappears

Ophthalmic view of the retina

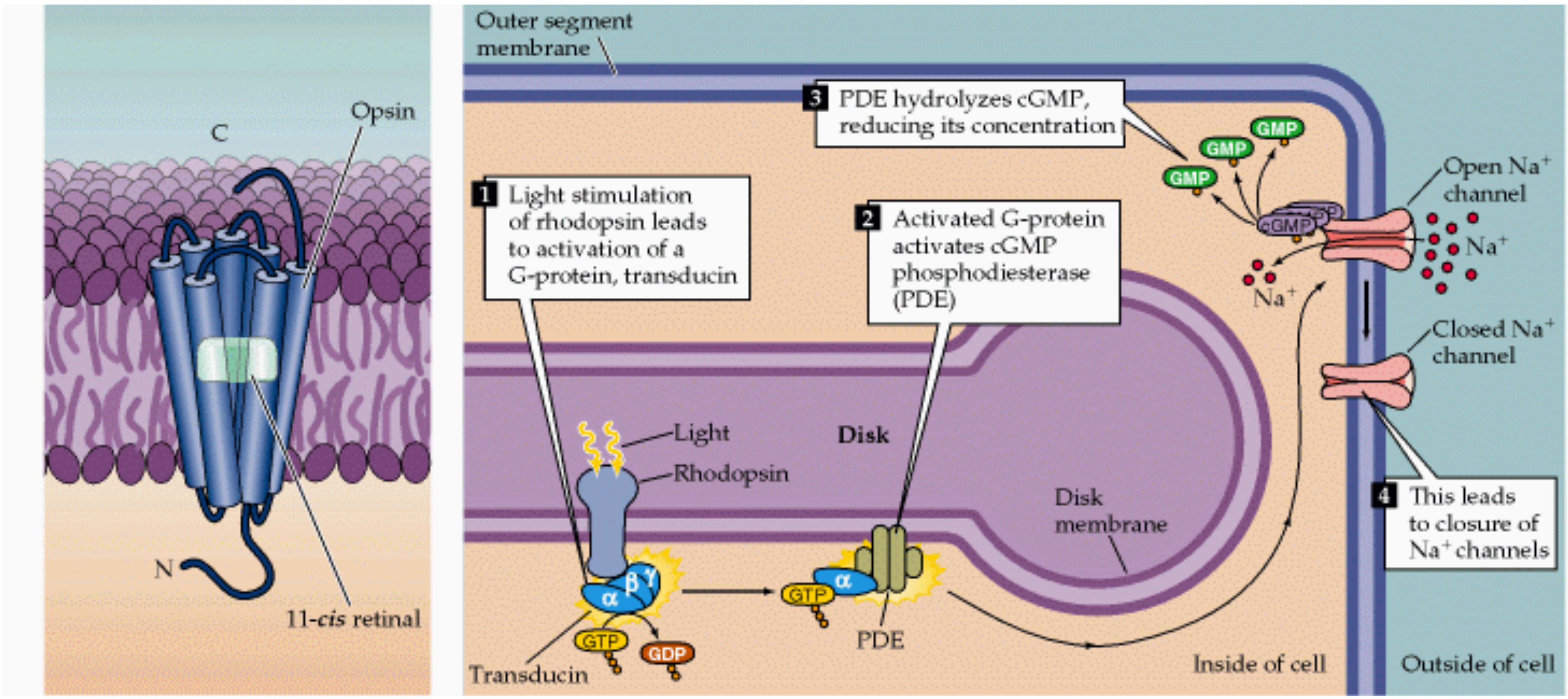


How photoreceptors work?

Rhodopsin molecules are
activated by photon absorption

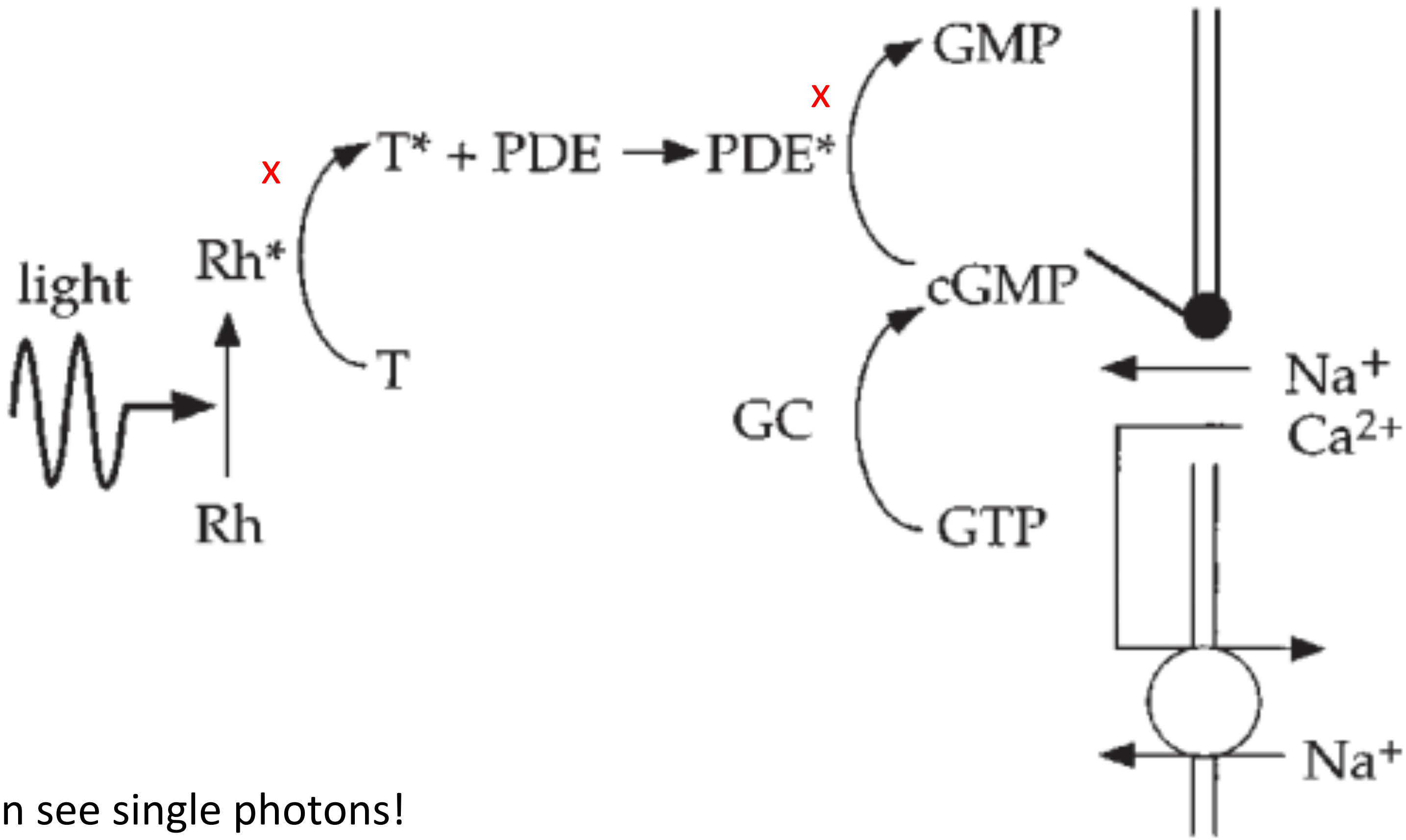


Phototransduction



Rhodopsin+light -> activates the G protein transducin.
The alpha subunit of transducin releases GDP, binds GTP, and diffuses to activate PDE.
The activated PDE (phosphodiesterase) reduces cGMP levels.
Sodium channels close
Photoreceptor hyperpolarizes

Amplifying the visual signal

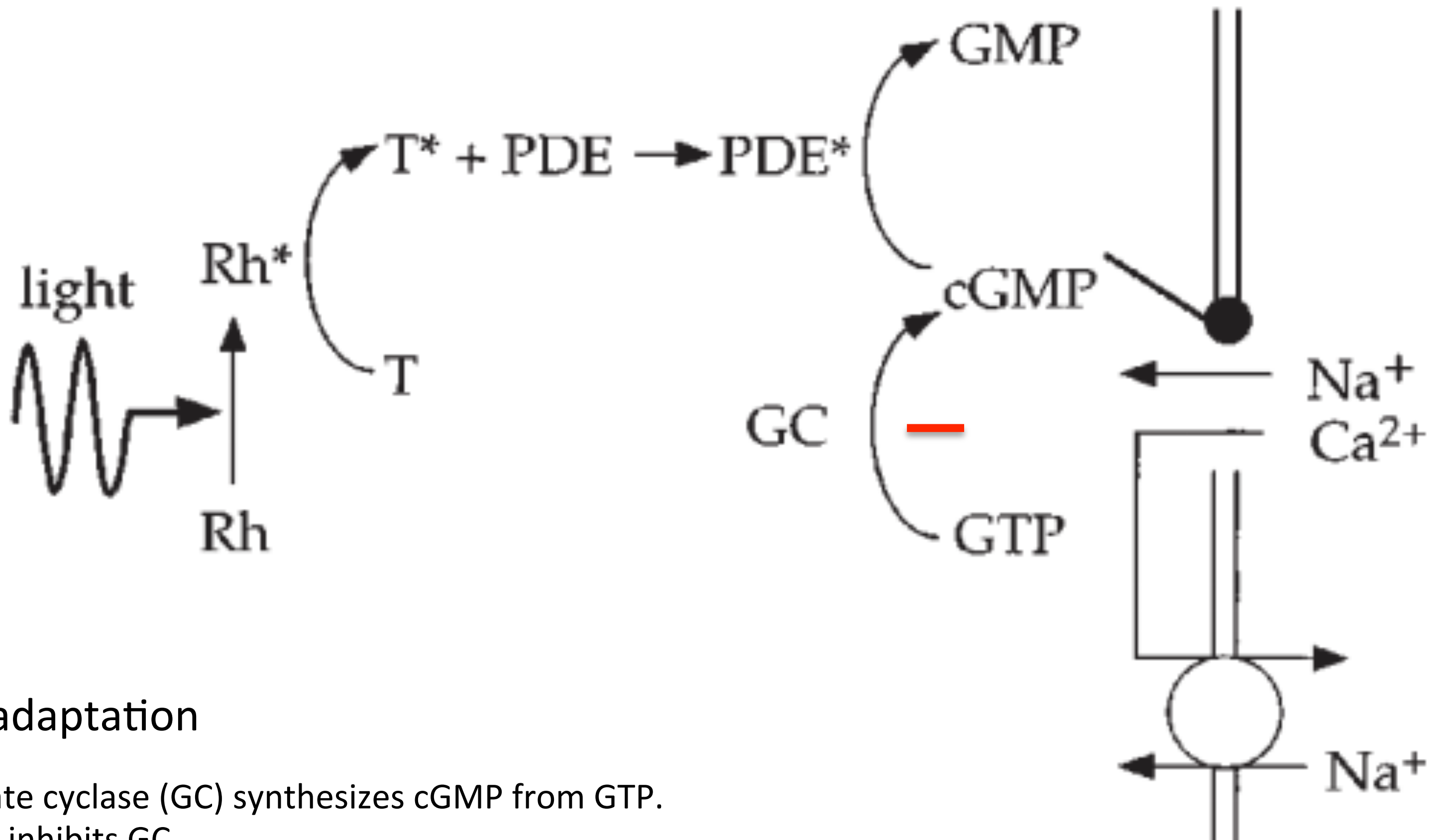


We can see single photons!

A single photoactivated rhodopsin activates ~30 transducin & PDE molecules, each PDE can break down thousands of cGMP molecules.

Rieke & Baylor, 1998

Recovery

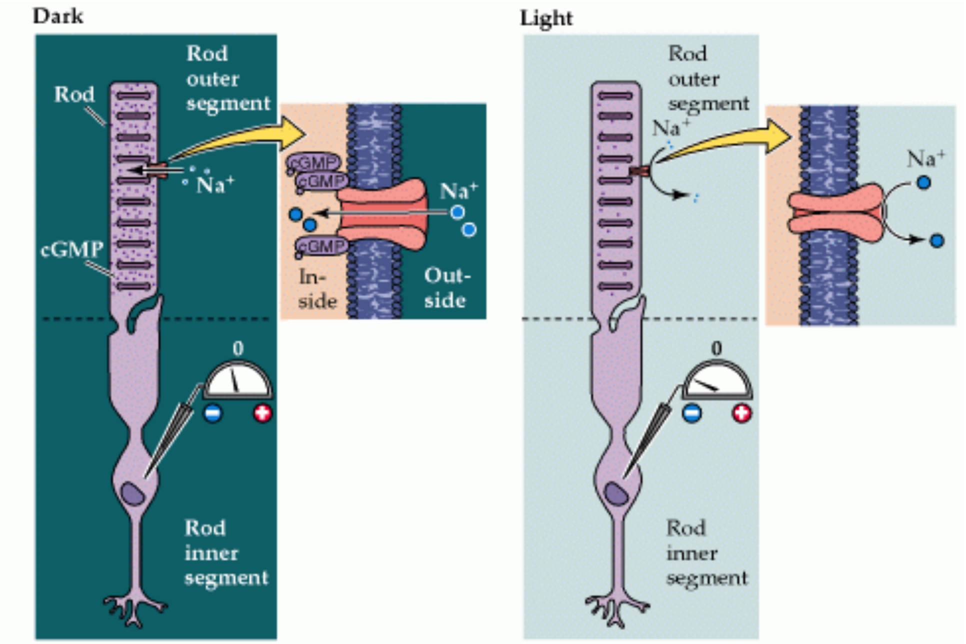


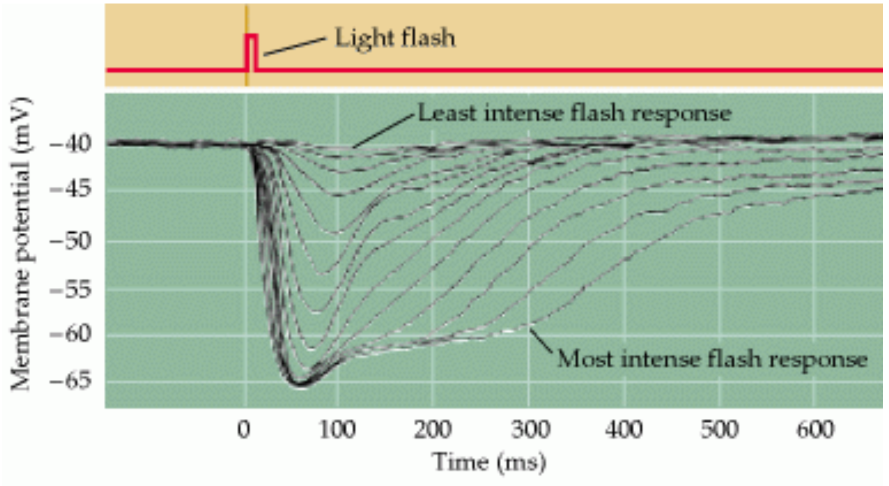
Light adaptation

Guanylate cyclase (GC) synthesizes cGMP from GTP.
Calcium inhibits GC.
Upon closure of channels (light), Ca concentration decreases -> cGMP level increases.

Rieke & Baylor, 1998

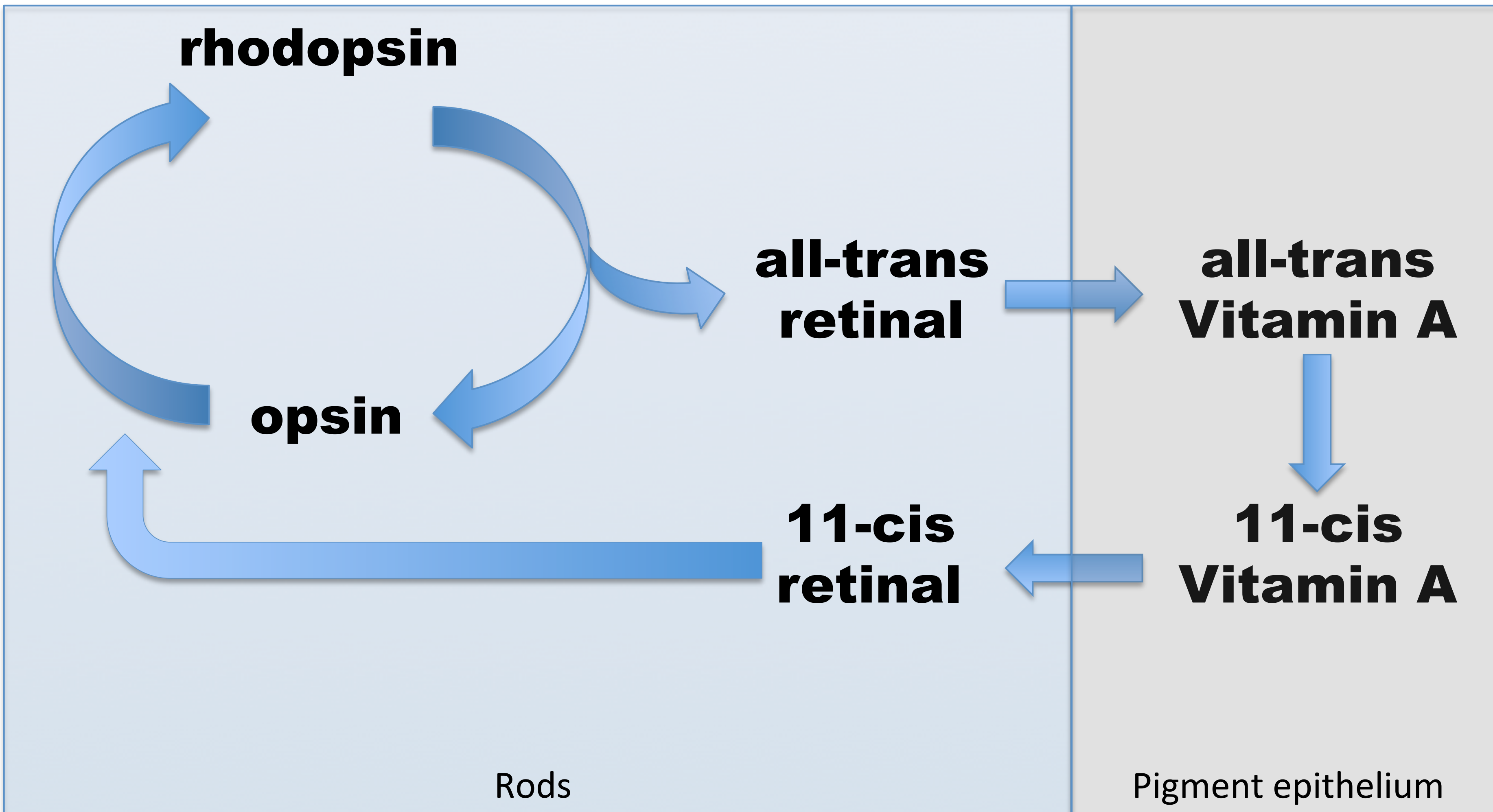
The dark current





Purves et al., 2001

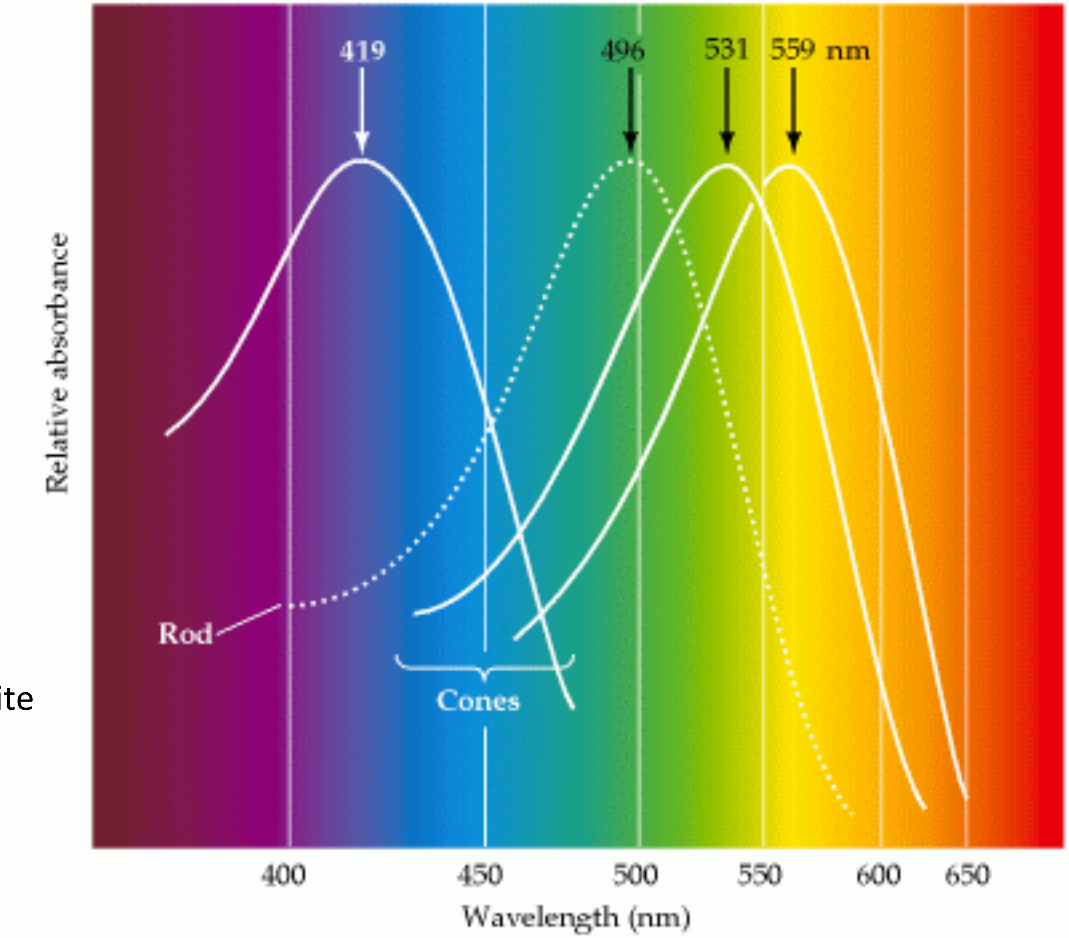
The rhodopsin cycle



Cones mediate color vision

Color vision is based on two or more photoreceptors that bare different photopigments

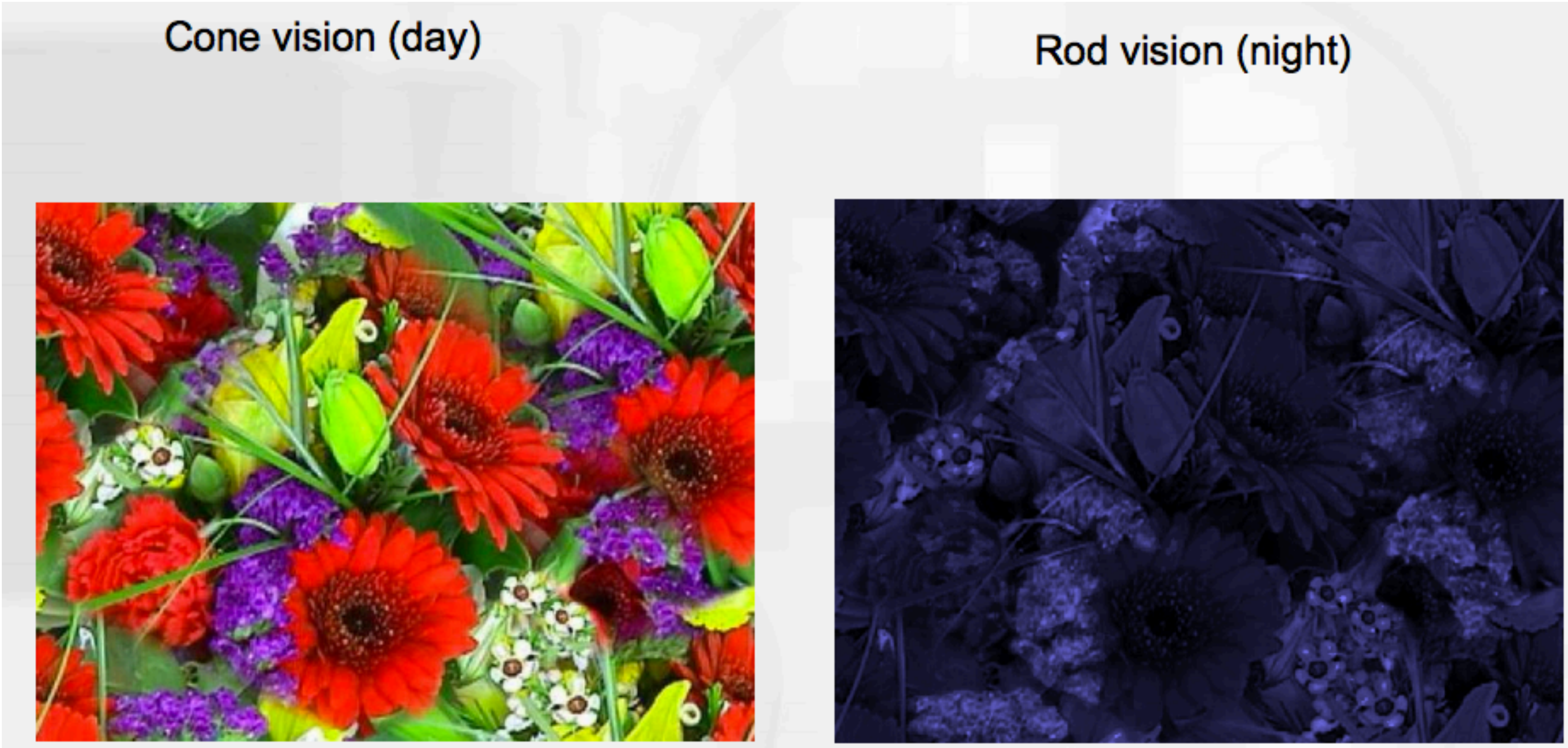
- Red (L)
- Green (M)
- Blue (S)



"As it is almost impossible to conceive each sensitive point of the retina to contain an infinite number of particles…, it becomes necessary to suppose the number limited, for instance to the three principal colors."
Thomas Young, 1802

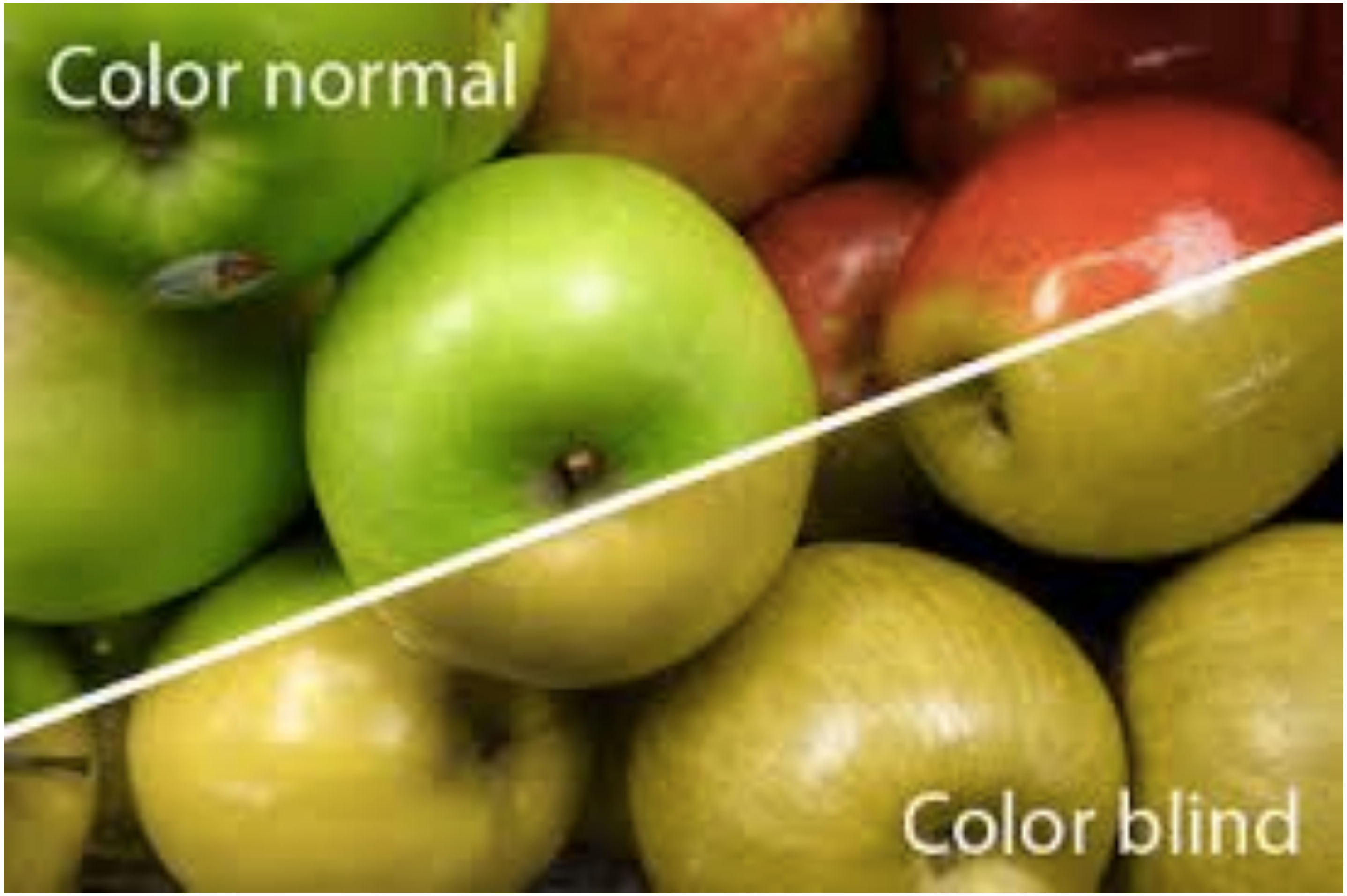
Purves 2001

Monochromatic vision at night



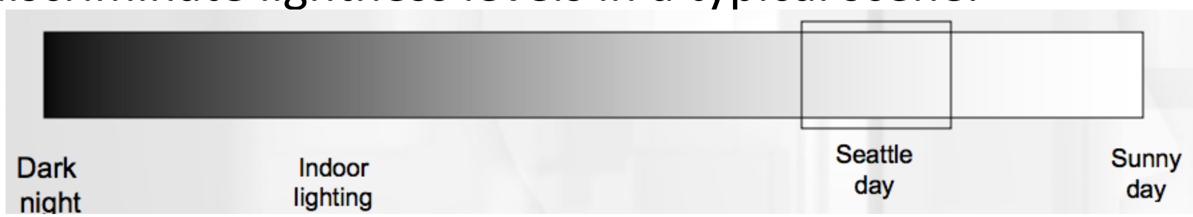
Some animals normally have monochromatic vision:

Color blindness

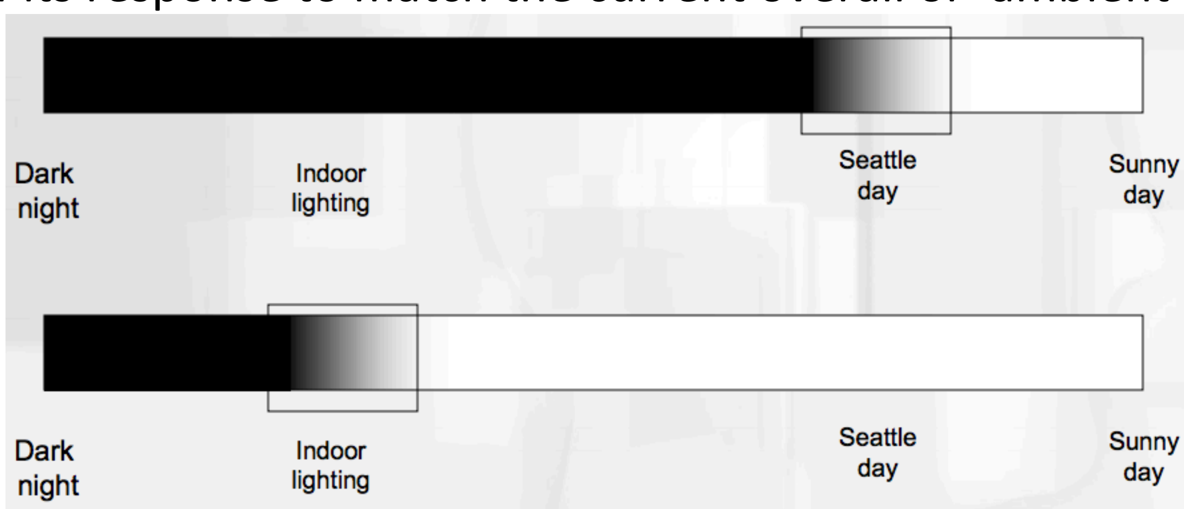


Visual adaptation

- Light intensities range across ~9 orders of magnitude.
  - A piece of white paper can be 1,000,000,000 times brighter in outdoor sunlight than in a moonless night.
  - If we were sensitive to this whole range all the time, we wouldn't be able to discriminate lightness levels in a typical scene.



  - The visual system solves this problem by restricting the 'dynamic range' of its response to match the current overall or 'ambient' light level.

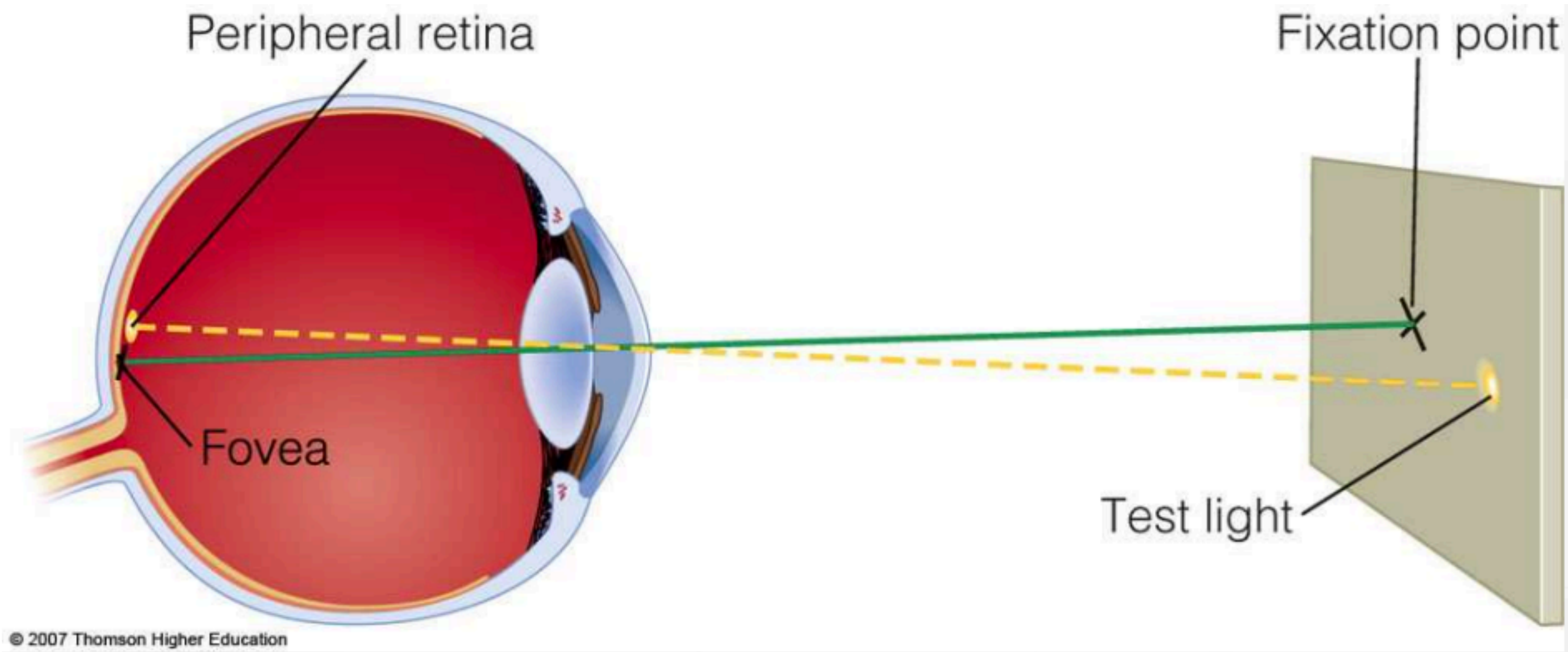


Visual adaptation

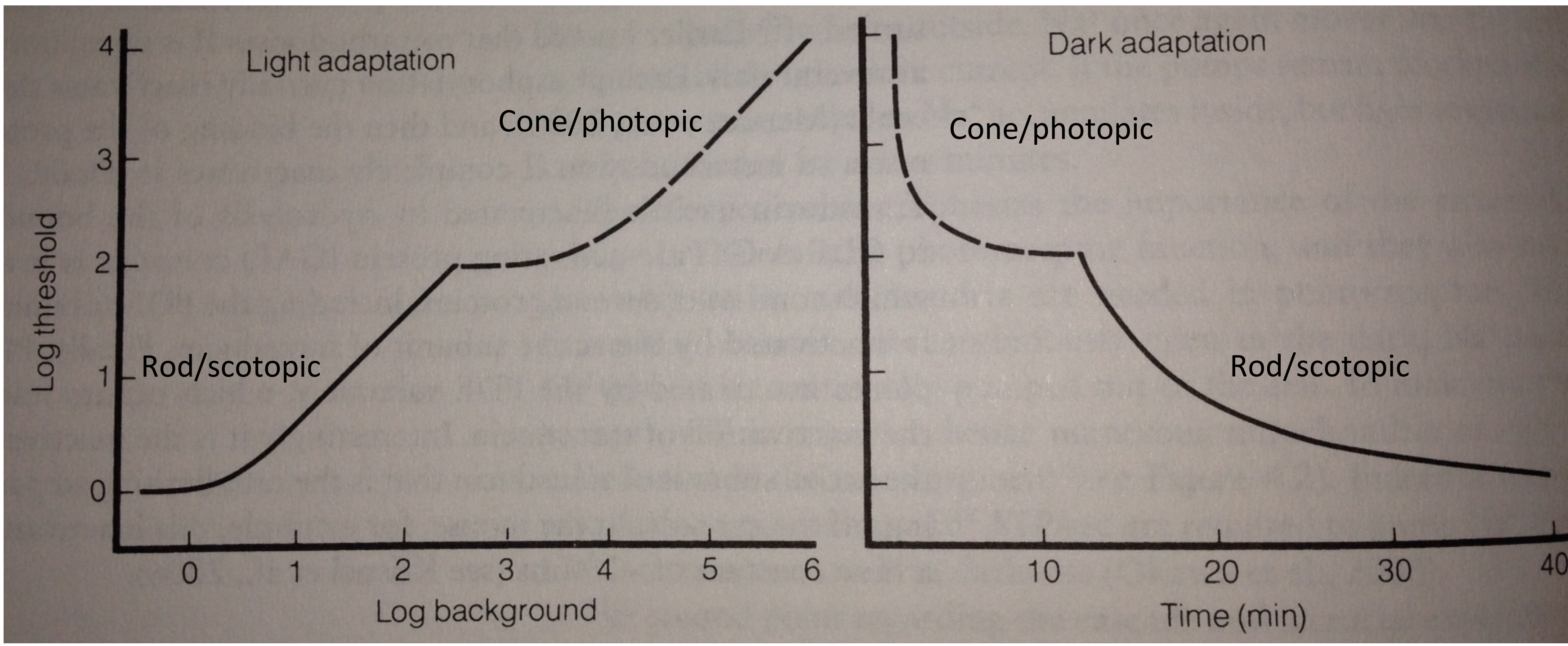
- Already at the retina!
  - Pupil’s diameter: 2-8 mm.
  - Rods and cones – two visual systems.
  - Both rods and cones adapt – becomes less sensitive as light levels increase.

Craik & Vernon, 1941:
Pressure blind experiments.

Psychophysical Measurement of Light/Dark Adaptation

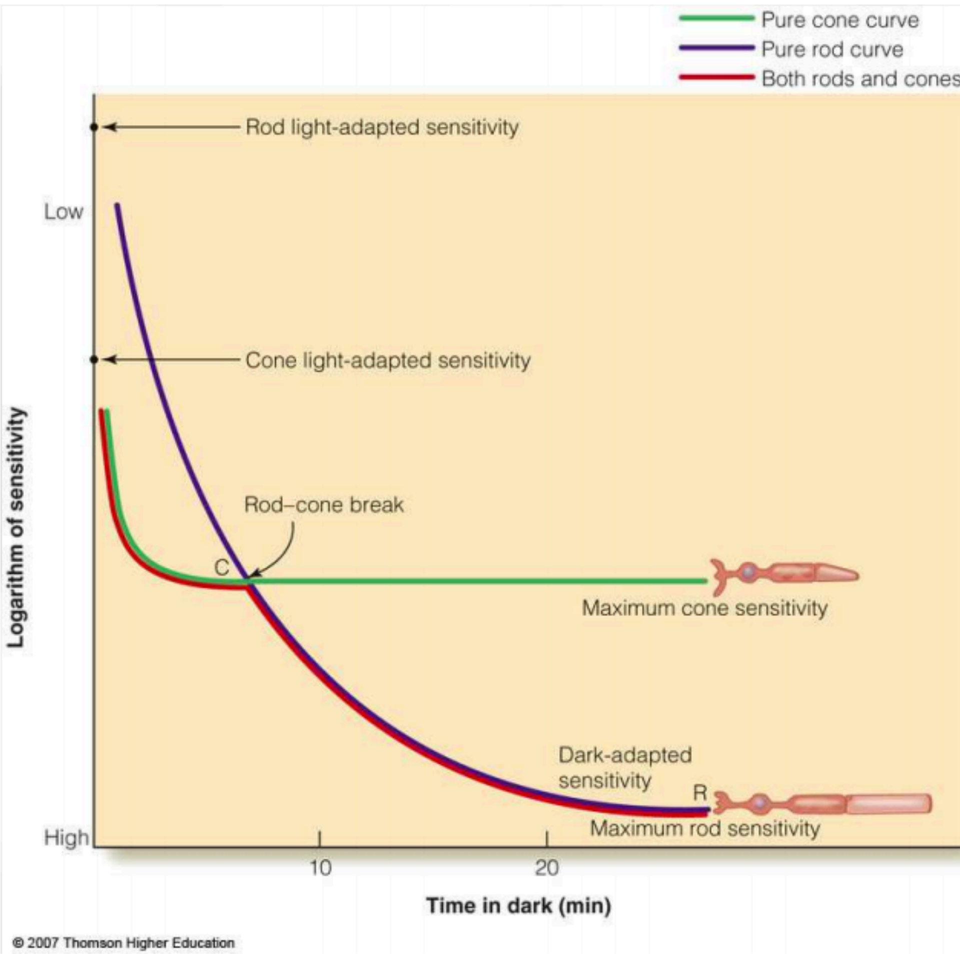


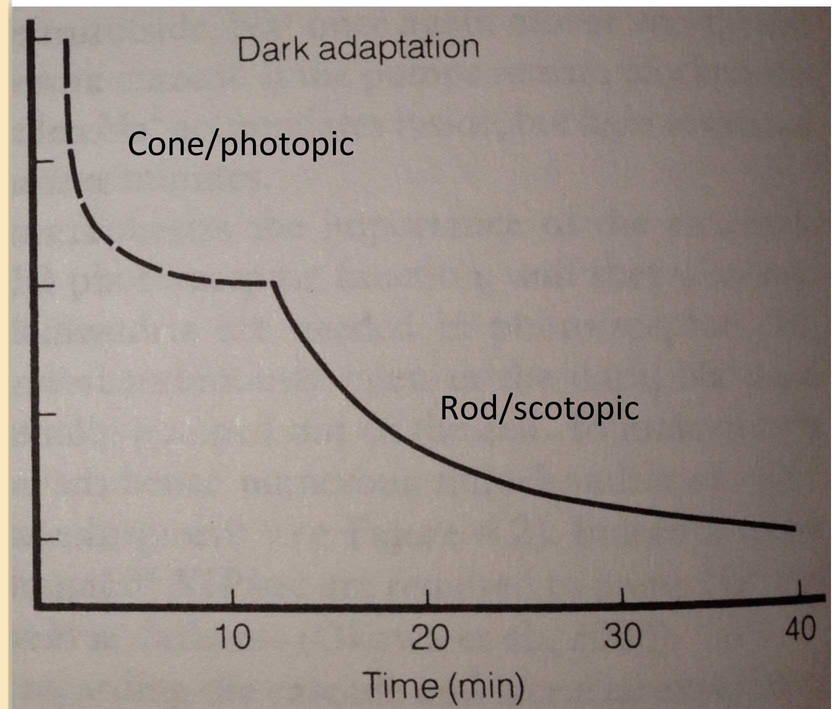
Light and dark adaptation



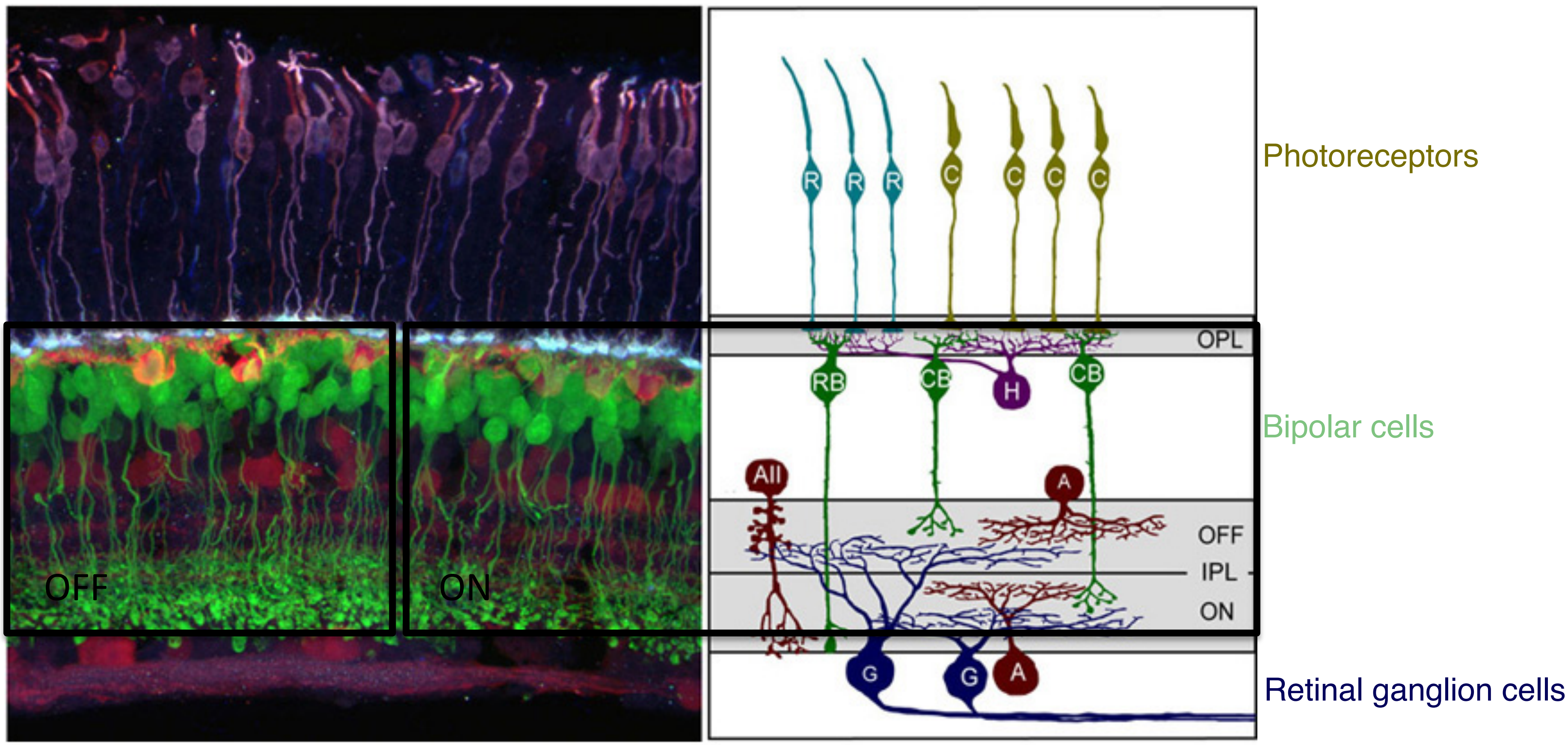
Weber law: $C = \frac{\Delta I}{I}$ $\quad \frac{11-10}{10} = \frac{110-100}{100}$

Light and dark adaptation



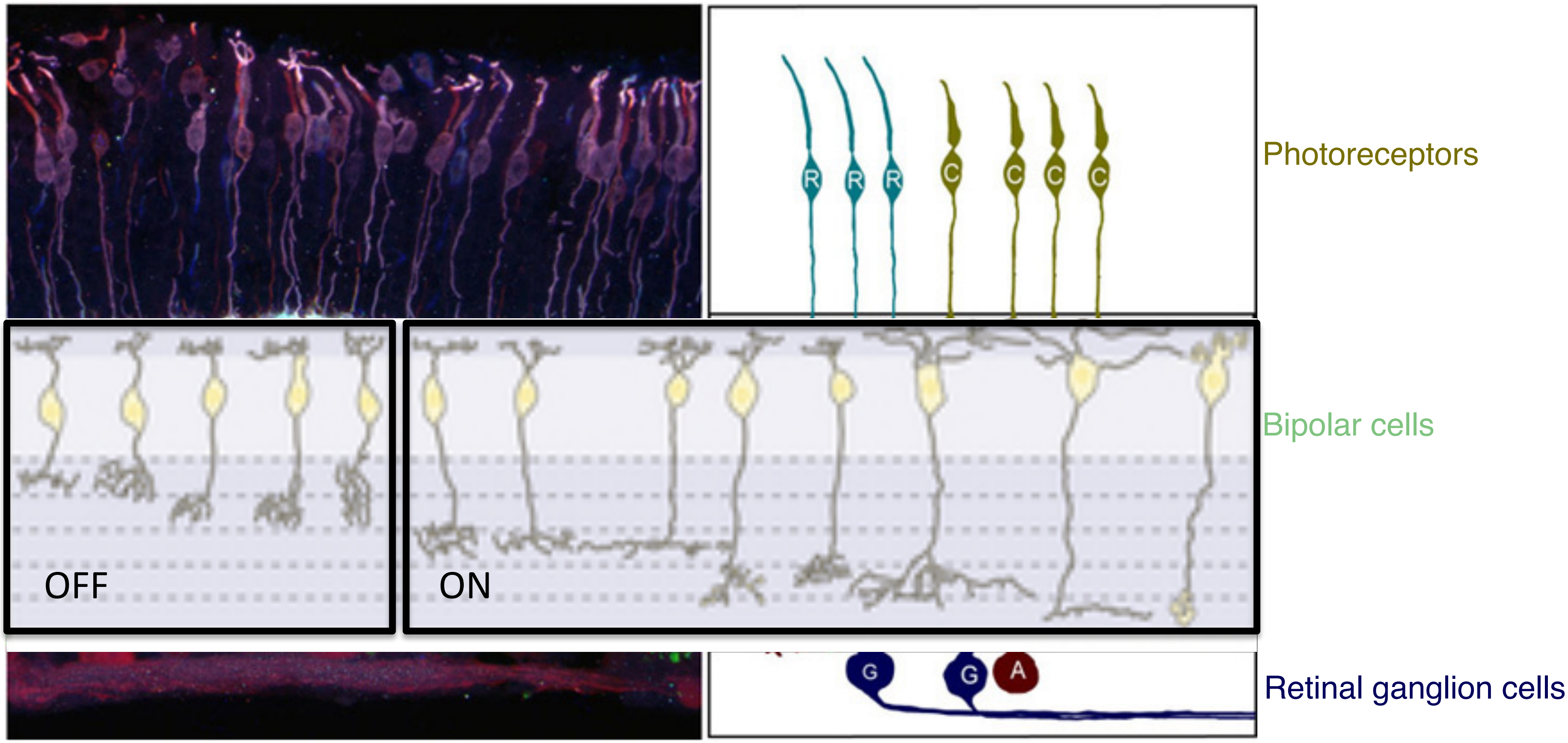


Bipolar Cells



Adapted from Morgan and Wong http://webvision.med.utah.edu
And from Euler et al. 2014 Nature reviews Neuroscience

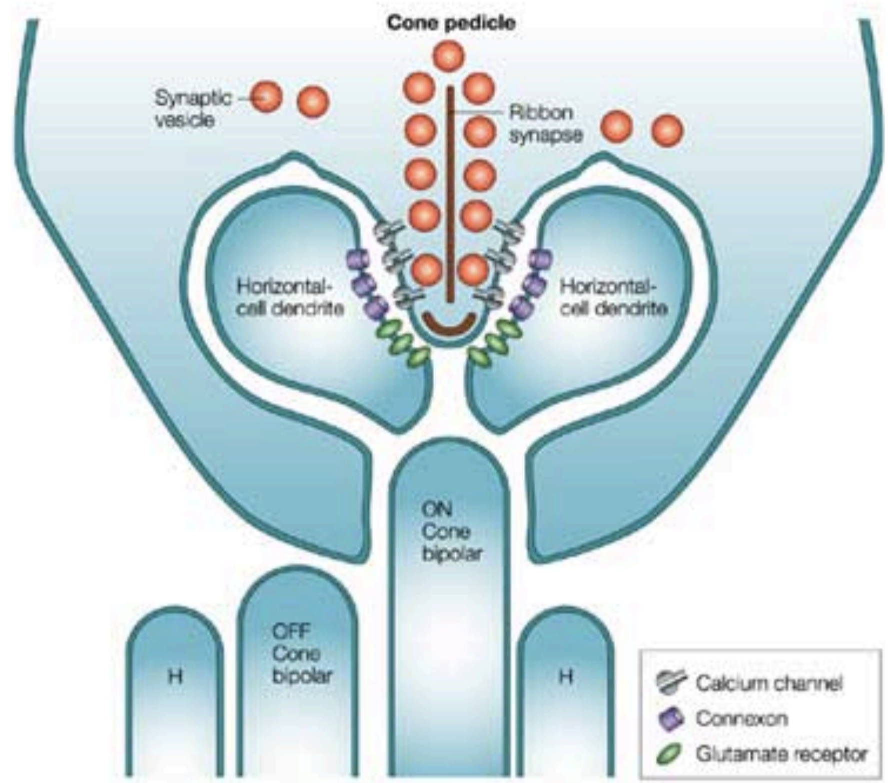
Bipolar Cells



Adapted from Morgan and Wong http://webvision.med.utah.edu
And from Euler et al. 2014 Nature reviews Neuroscience

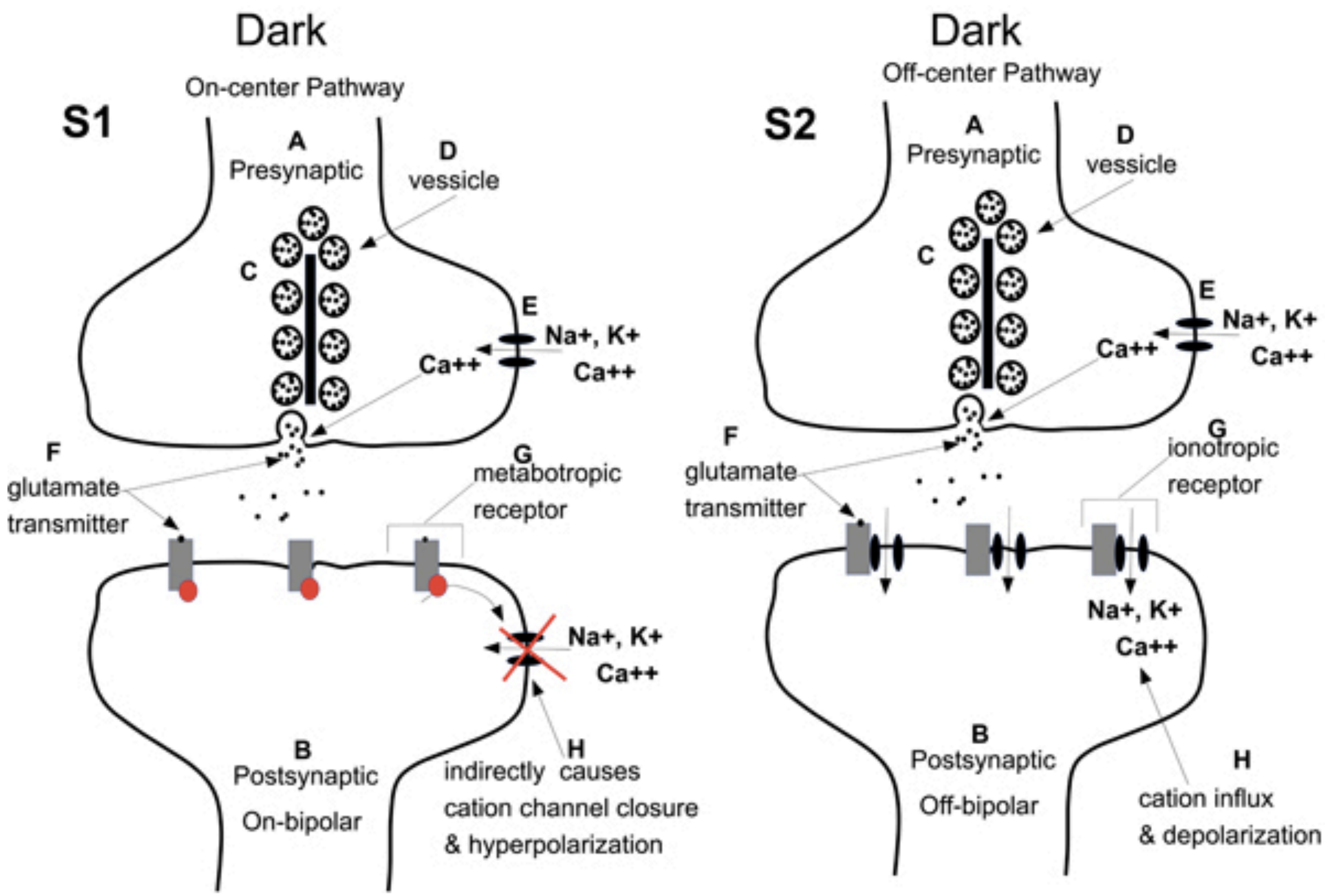
Ribbon synapse

- Graded neurotransmitter release. Precise, sustained, and rapid.
- The synaptic ribbon releases 100s-1000s vesicles per second.
- Each pre-synaptic cell has 10-100 ribbons.
- Requires a large pool of readily releasable vesicles.

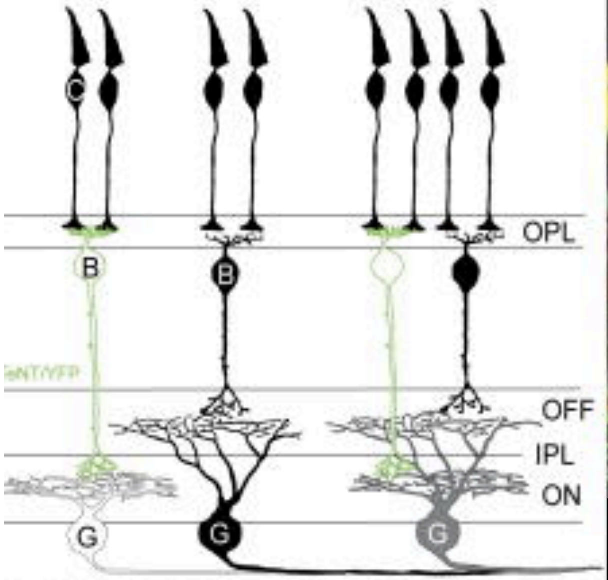


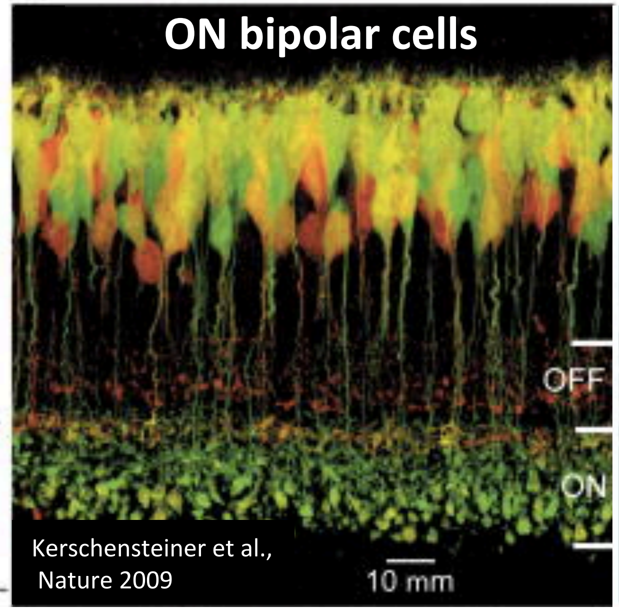
Nature Reviews | Molecular Cell Biology

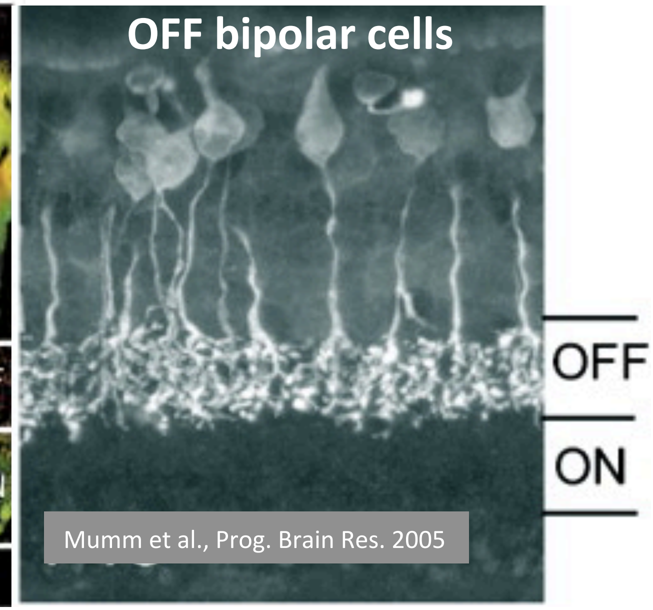
On- and Off-bipolar cells



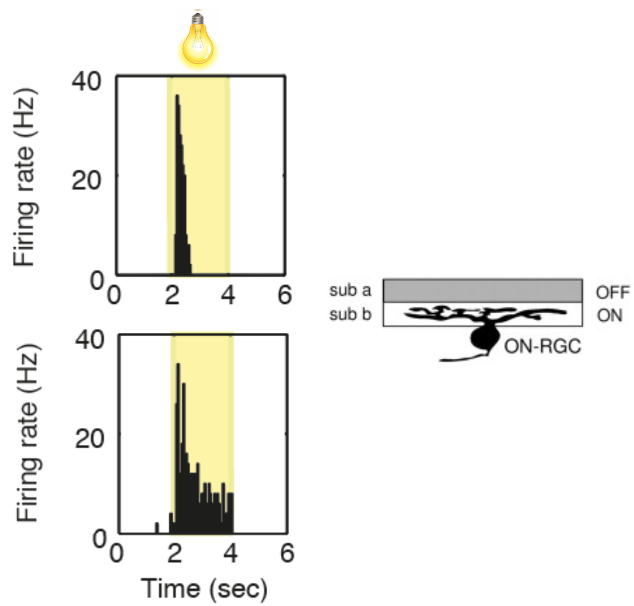
On and Off retinal pathways

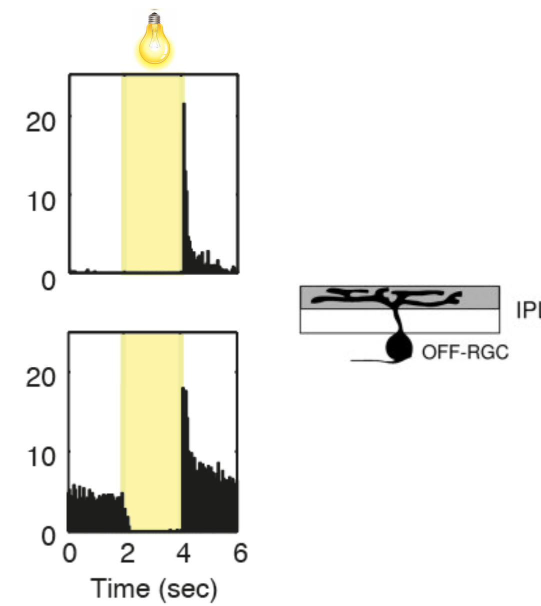




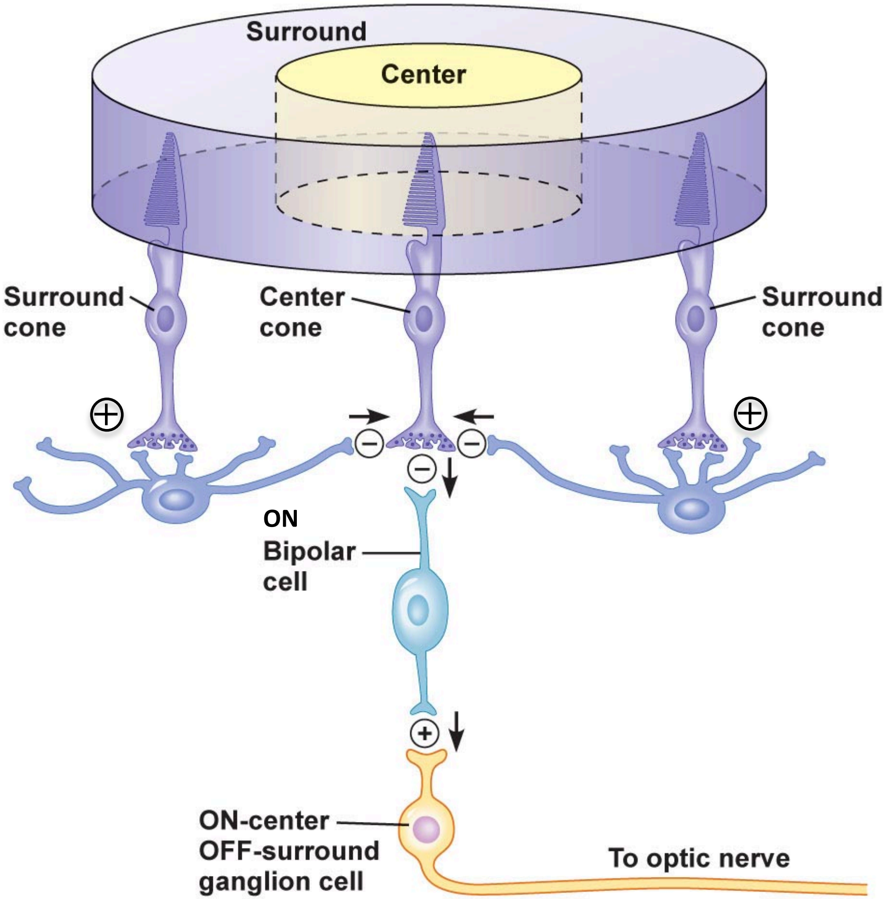


Retinal ganglion cells (RGC):





Horizontal Cells



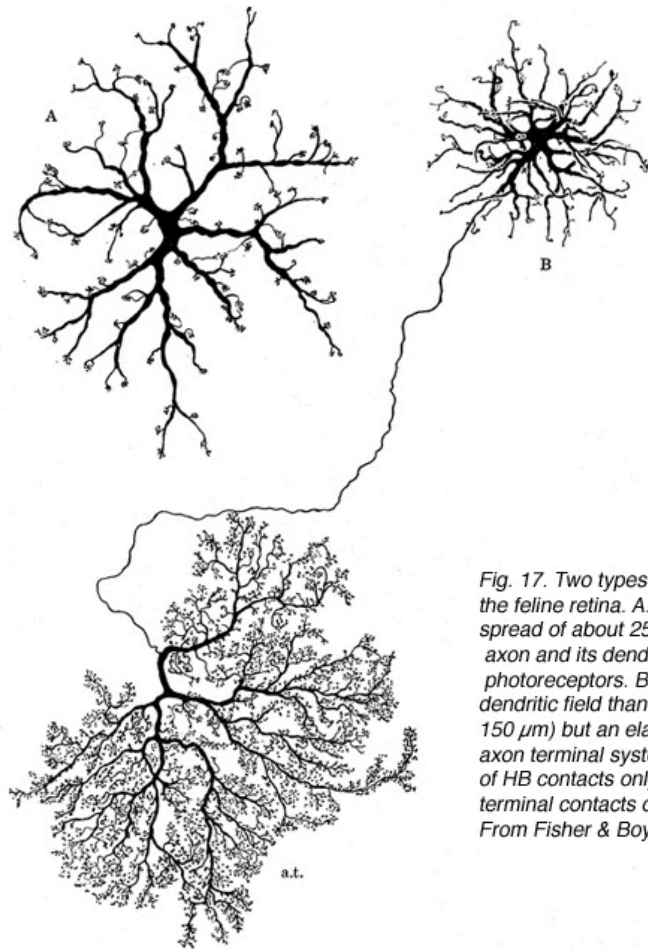
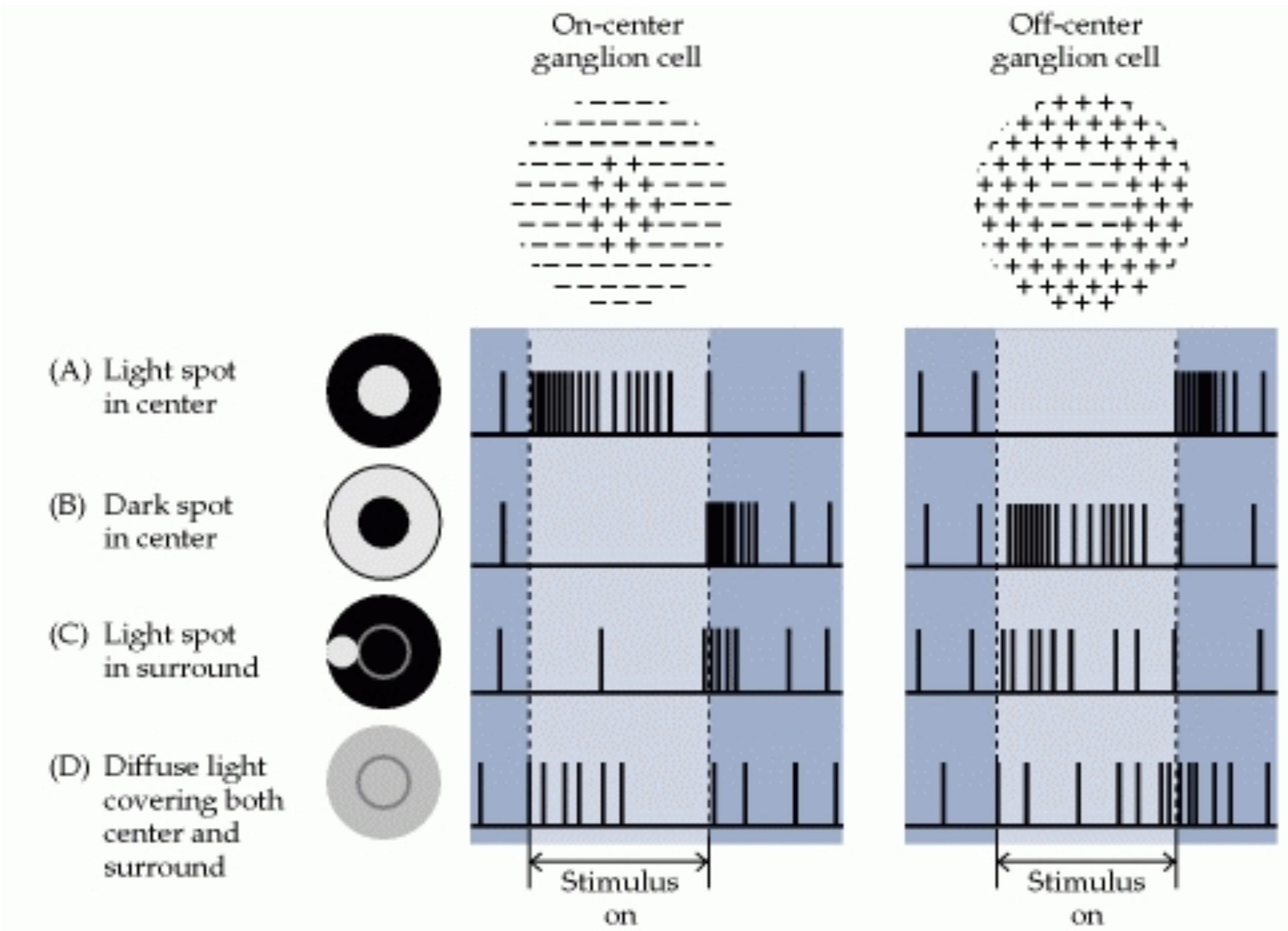


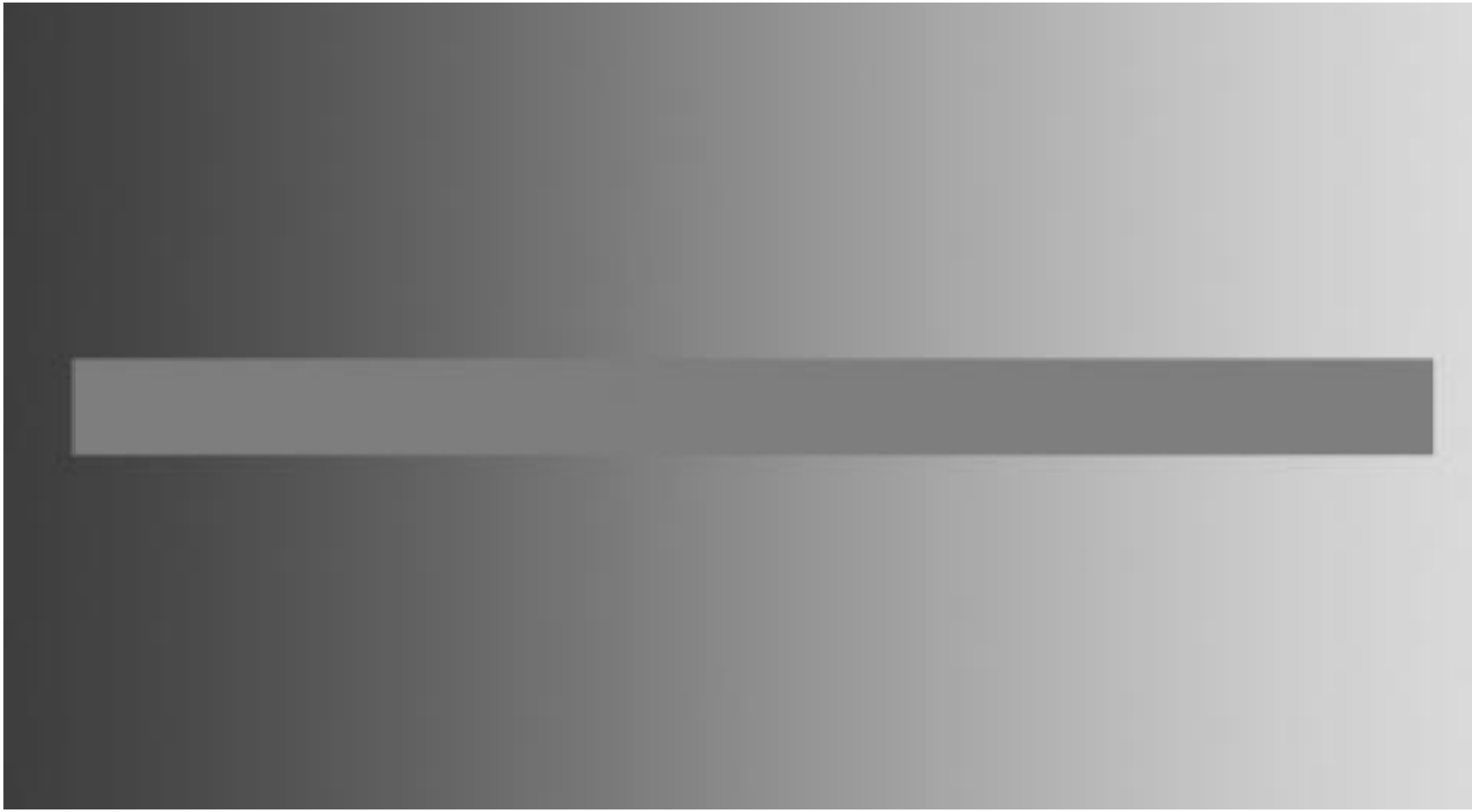
Fig. 17. Two types of horizontal cells in the feline retina. A. HA with a dendritic spread of about 250 μm x 250 μm has no axon and its dendrites contact only cone photoreceptors. B. HB has a smaller dendritic field than HA (about 150 μm x 150 μm) but an elaborately branched axon terminal system (a.t.). The dendrites of HB contacts only cones, while the axon terminal contacts only rods. From Fisher & Boycott, 1974.

Center-surround organization of receptive fields

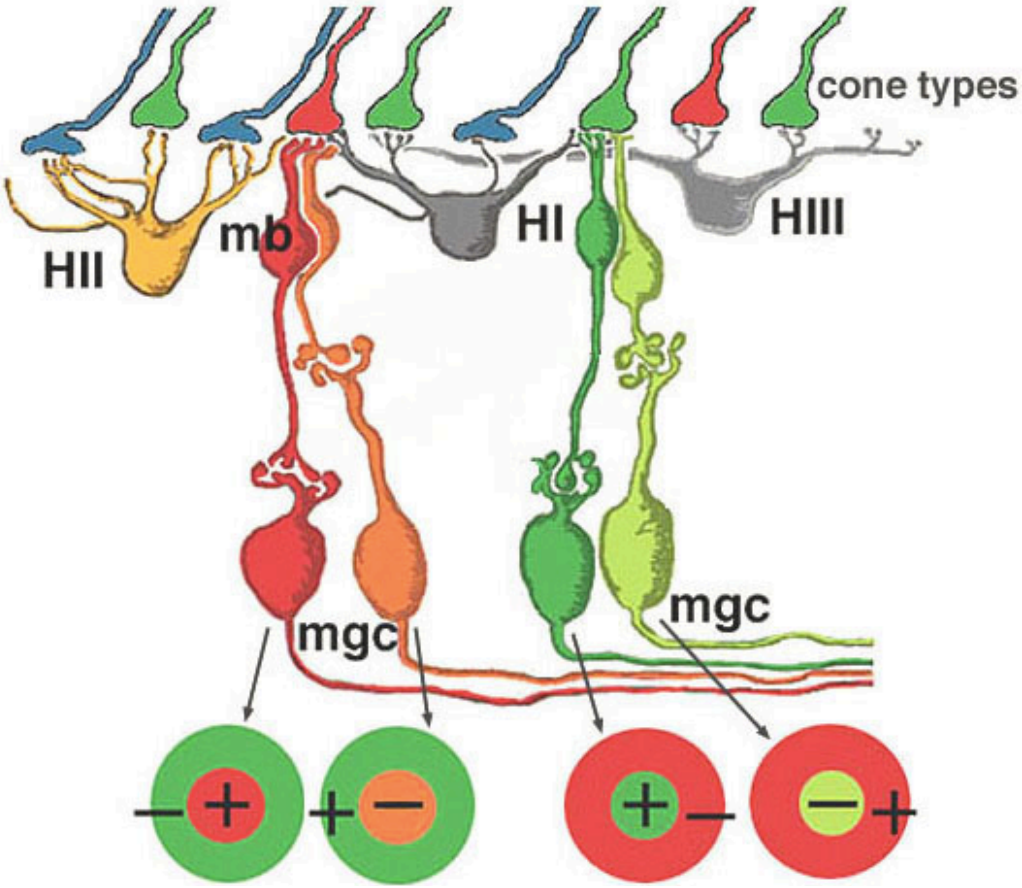


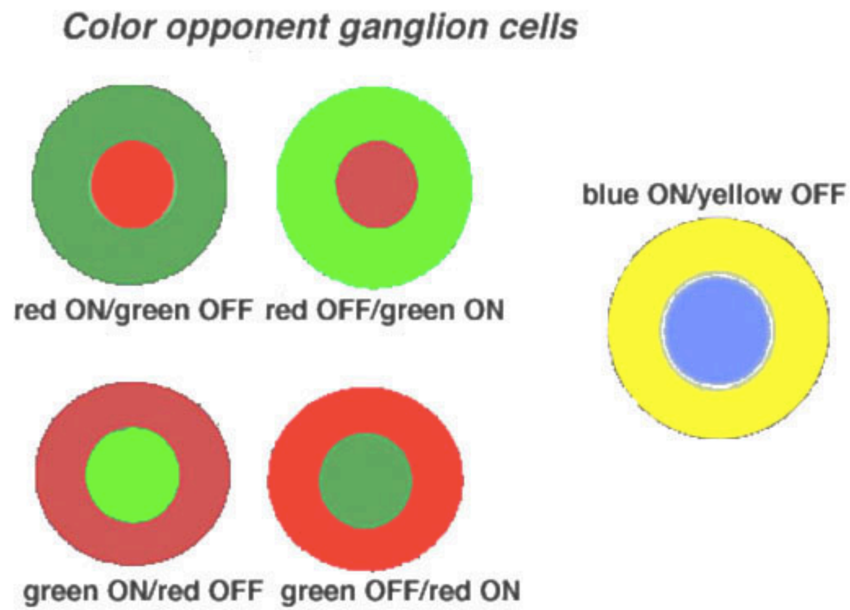
Hartline (1938) & Granit (1947) – On, Off; Barlow & Kuffler (1950) – antagonistic center-surround.

Retinal neurons signal relative intensity of stimulation

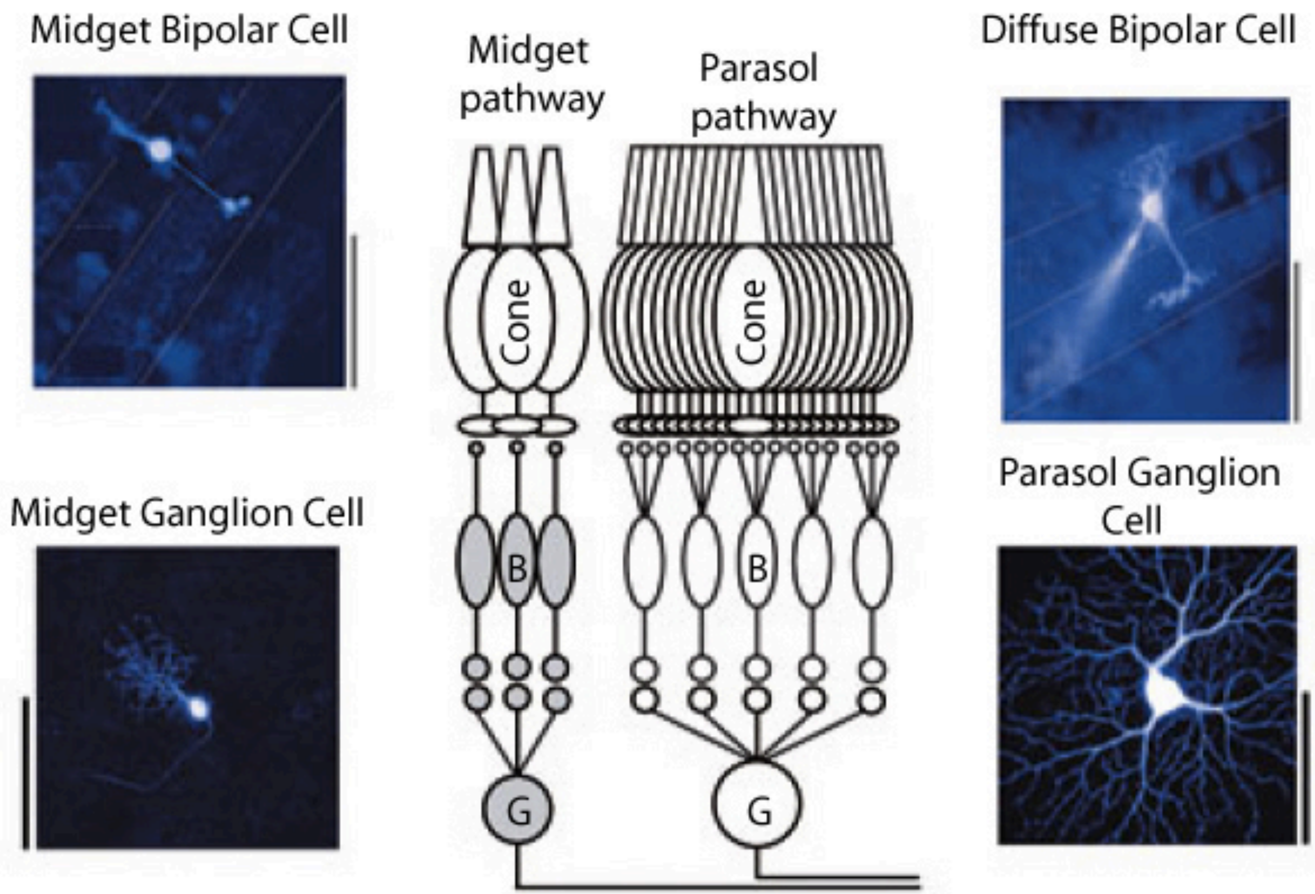


Midget ganglion cells





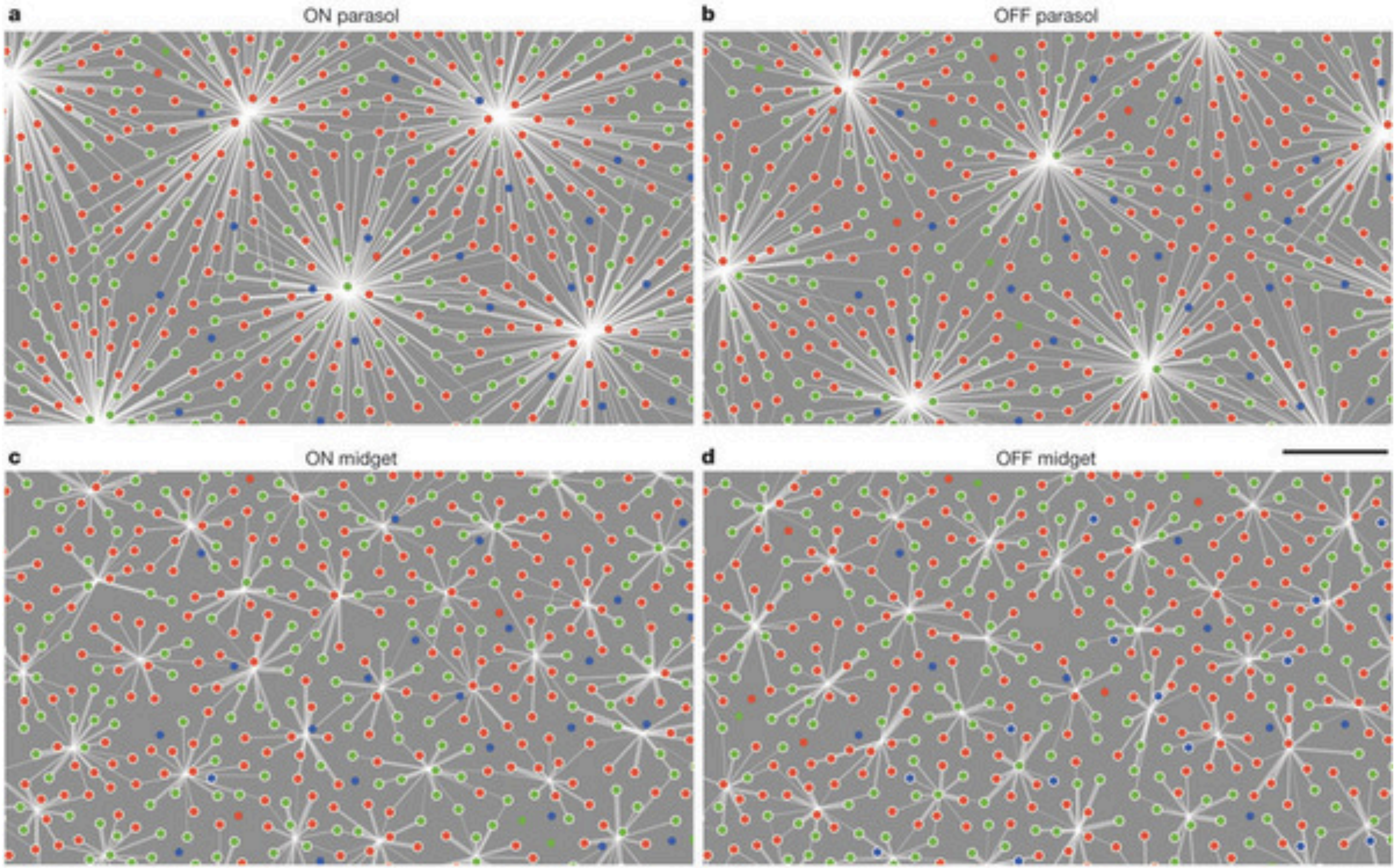
Convergence and acuity



= not selective for color

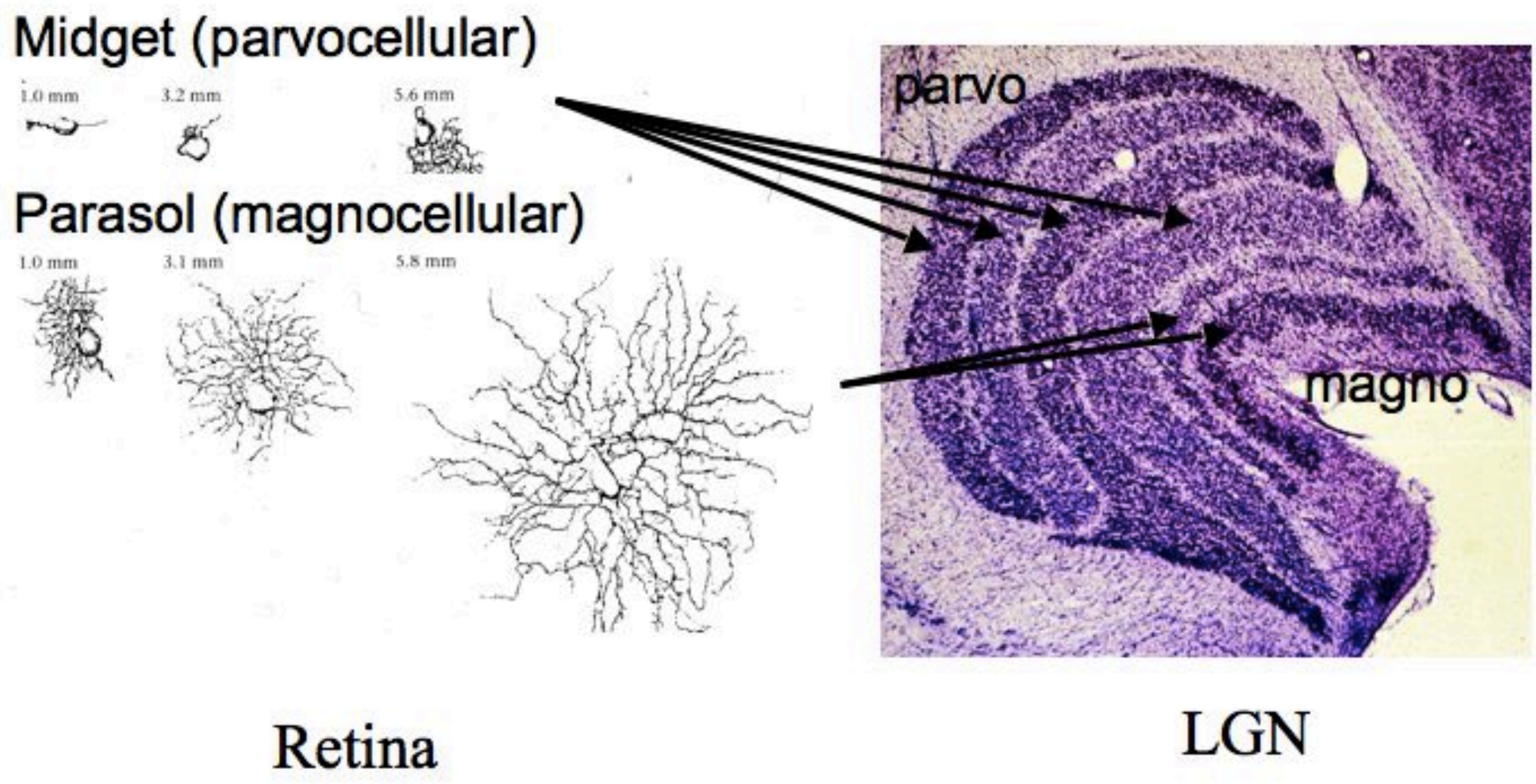
- Small dendritic arbors
- Small receptive fields
- ~80% of ganglion cell
- chromatic
- Form and color
- Fine details

- Large dendritic arbors
- Large receptive fields
- ~10% of ganglion cells
- Non-chromatic
- Gross features of stimulus
- movement



Field et al., 2010

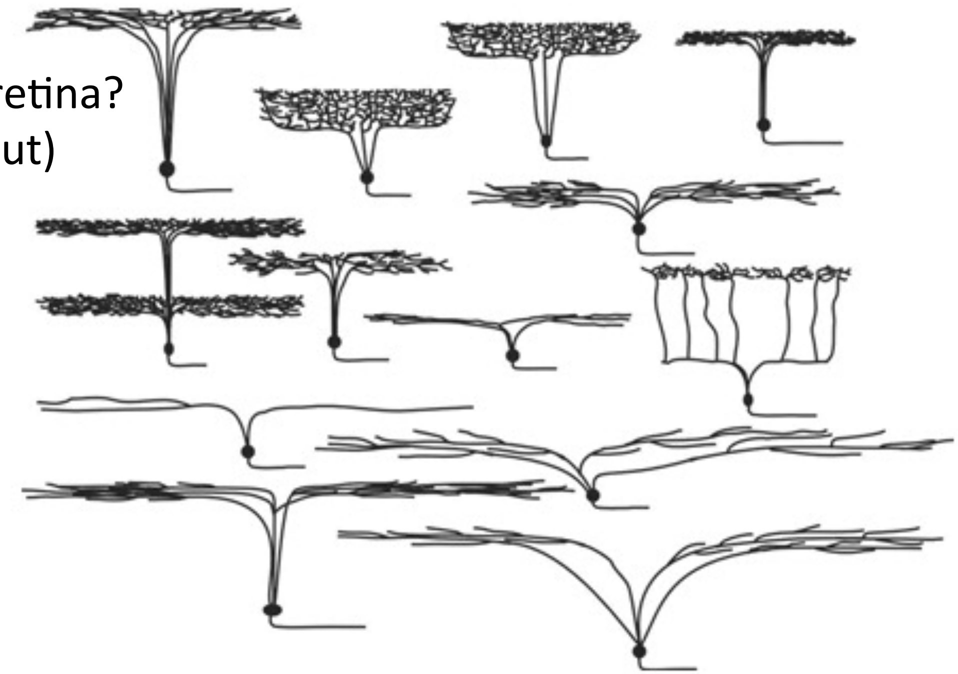
Magno and Parvo pathways

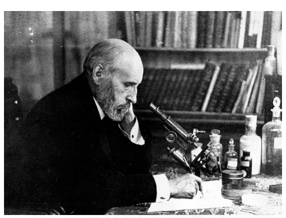


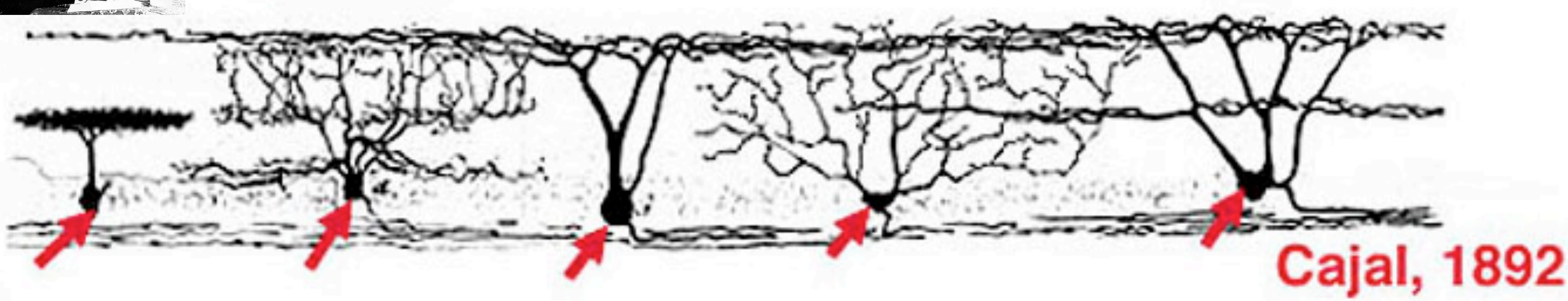
Retinal ganglion cells

What defines a neuron subtype in the retina?

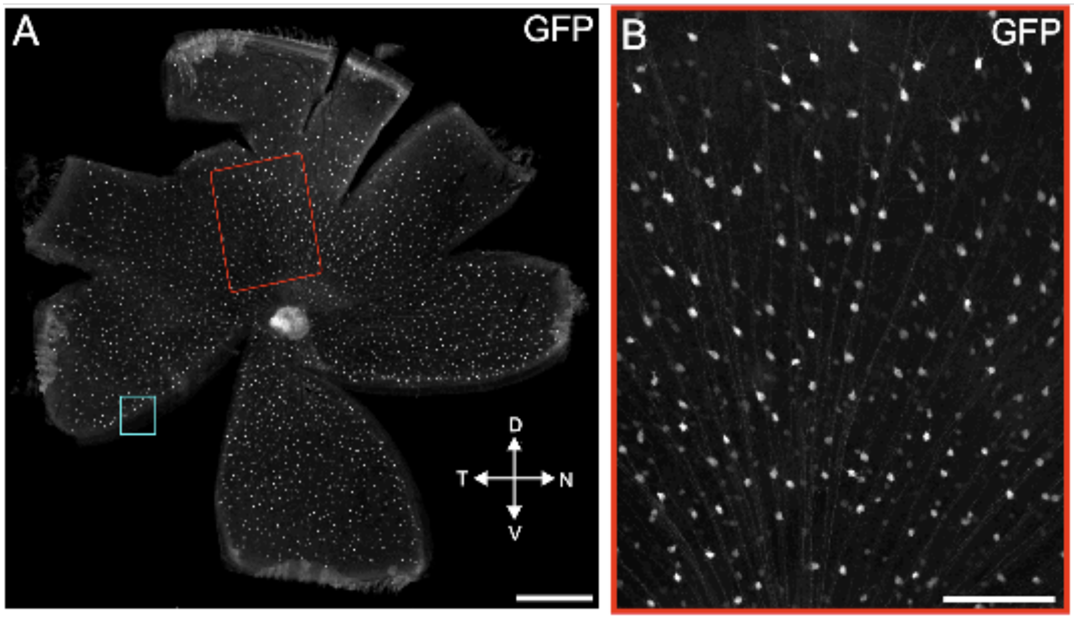
- Morphology (including input & output)
- Physiology (=light responses)
- Form mosaic/tile the retina



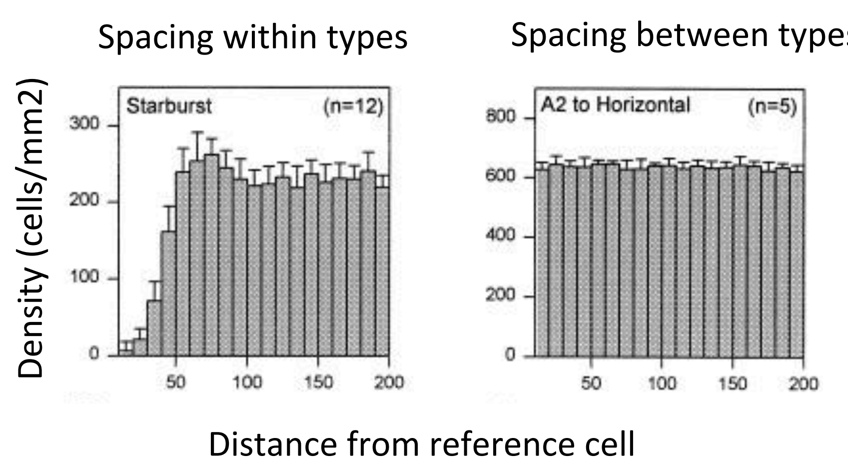




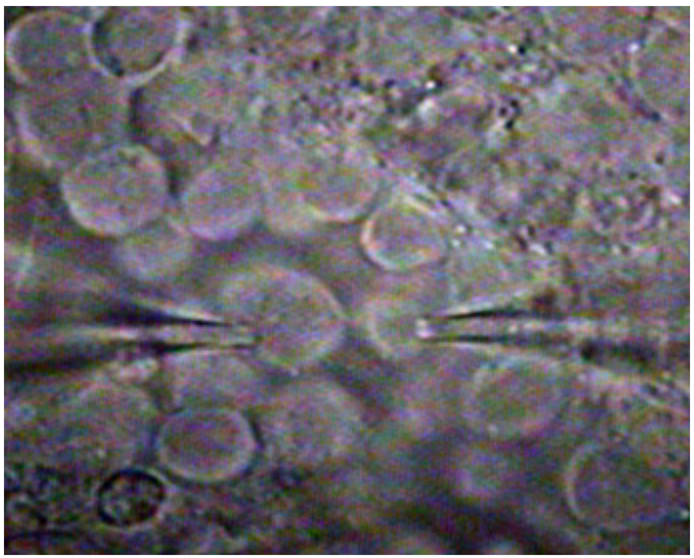
Mosaic organization

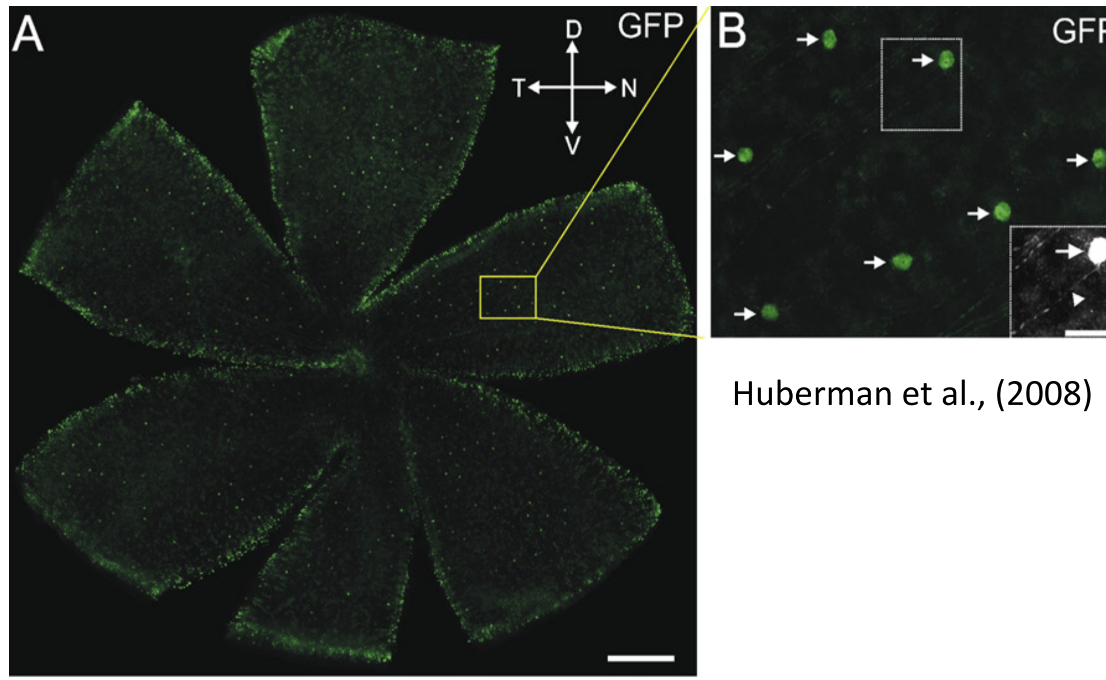


- Cover the entire visual field
- Exclusion zone for same cell type



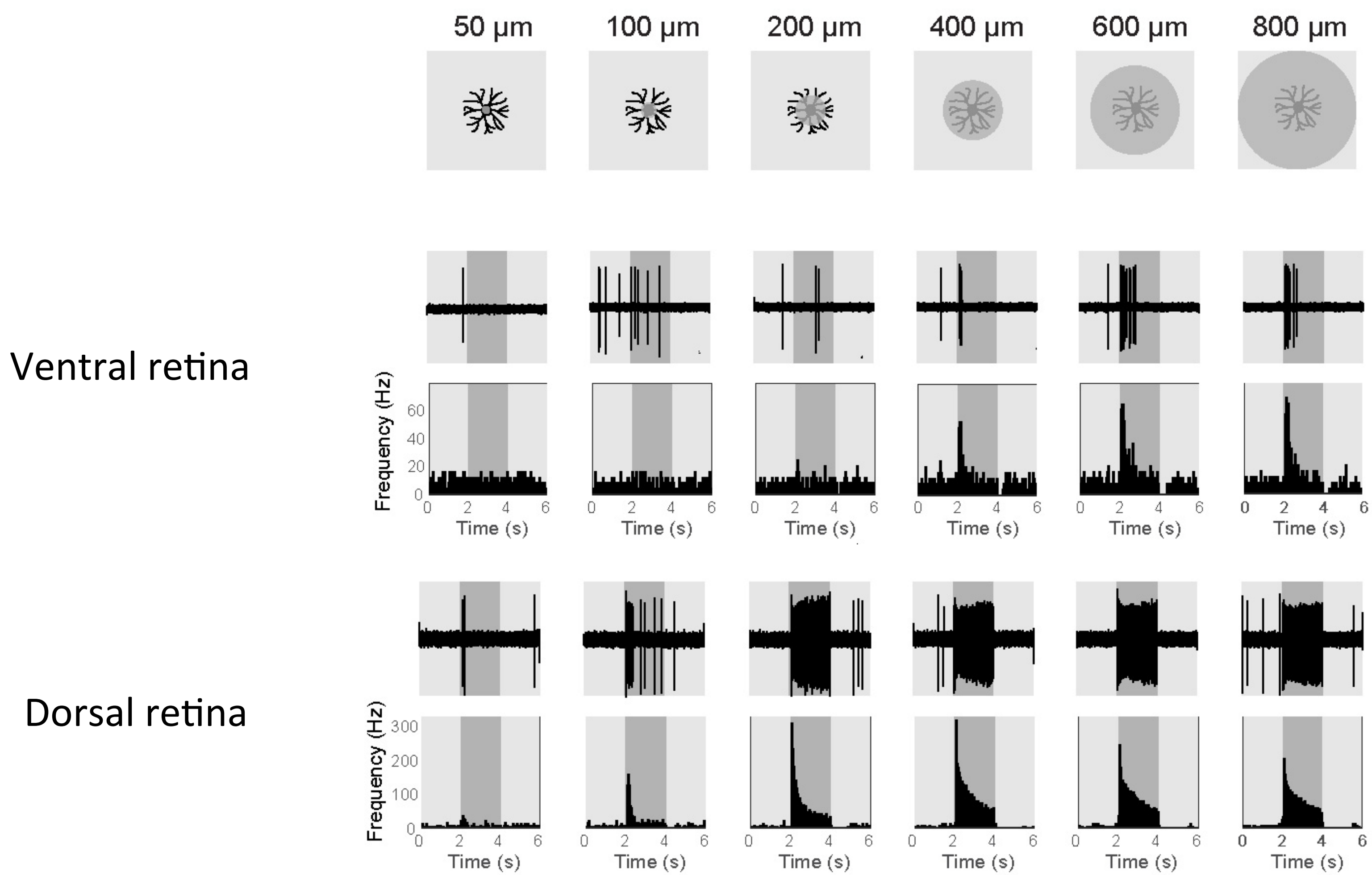
Two-photon targeted recordings from transgenic mouse lines





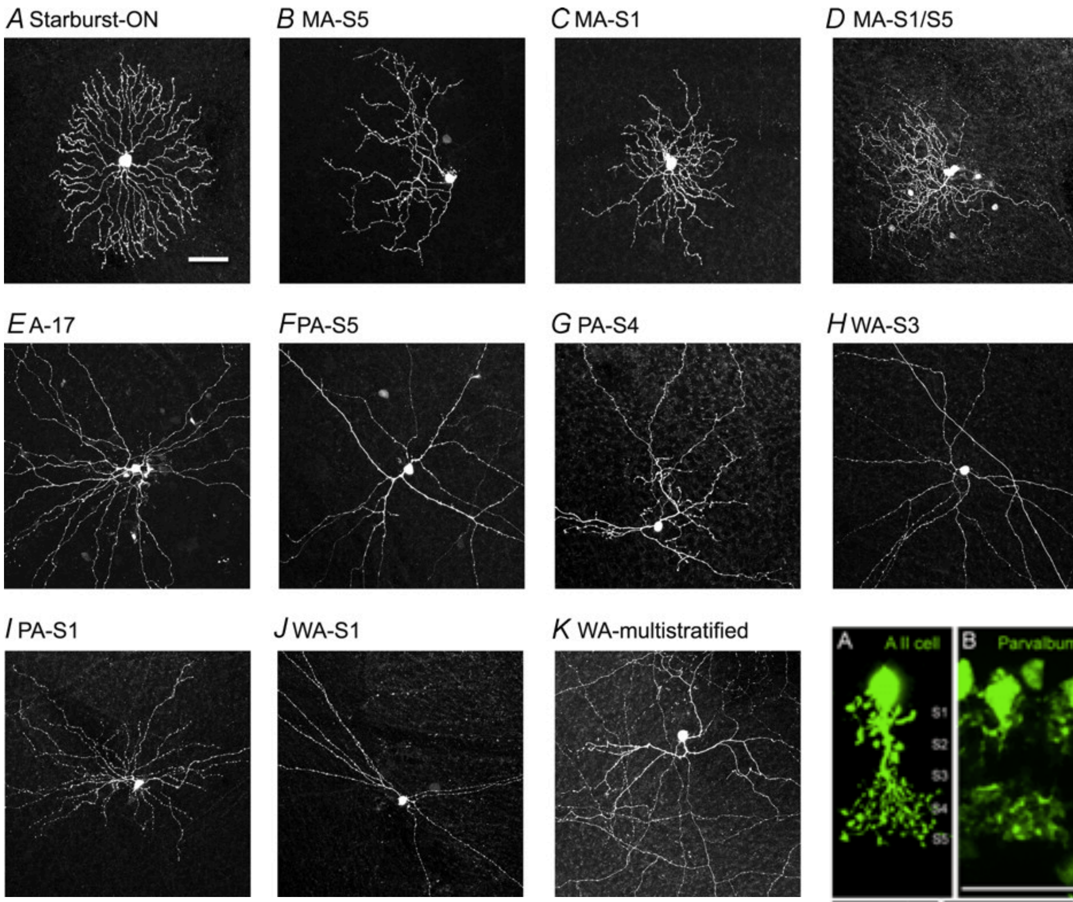
Huberman et al., (2008)

Transient-OFF-α-retinal ganglion cells display different response properties at different retinal locations

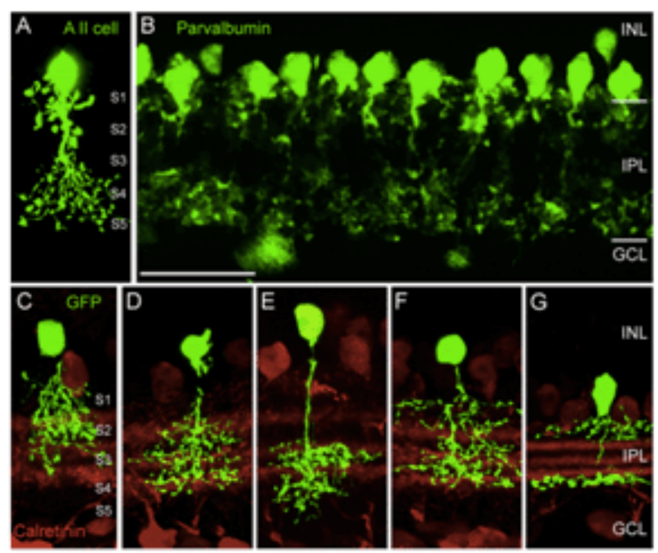


Recent evidence from mouse retina reveal some of the accepted concepts may be overruled.
For example, transient-Off-alpha RGCs show different response properties in different retinal locations

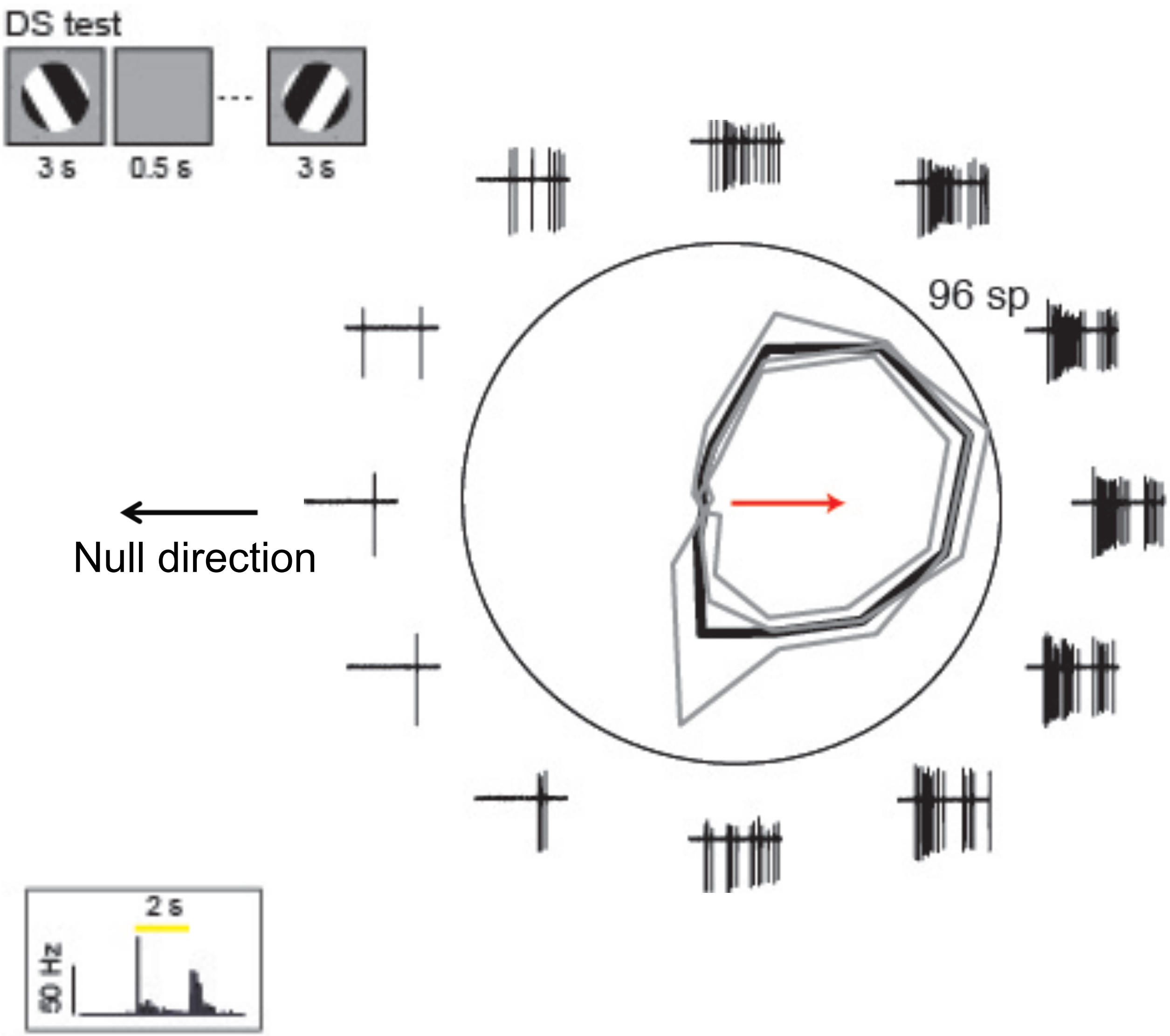
Amacrine Cells



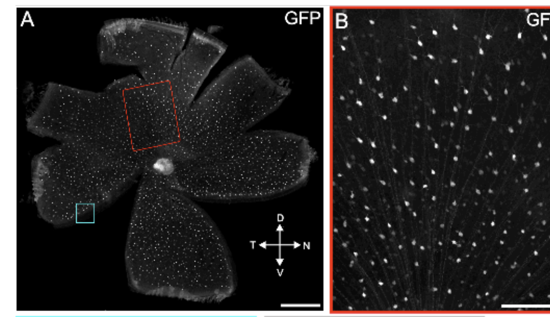
- GABA
- Glycine
- Dopamine
- acetylecholine



Direction selective retinal ganglion cell has preferred and null directions

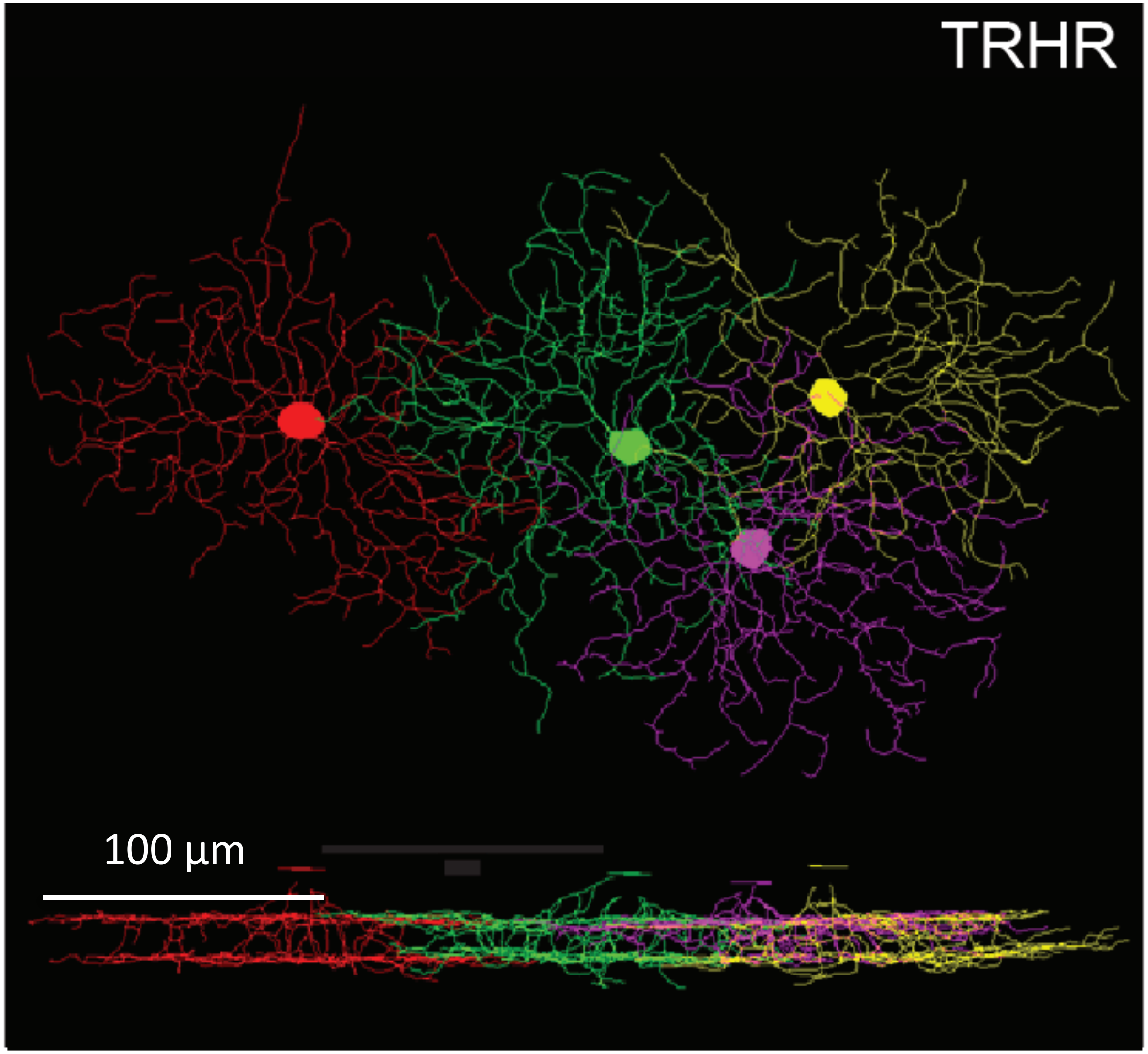


Preferred direction



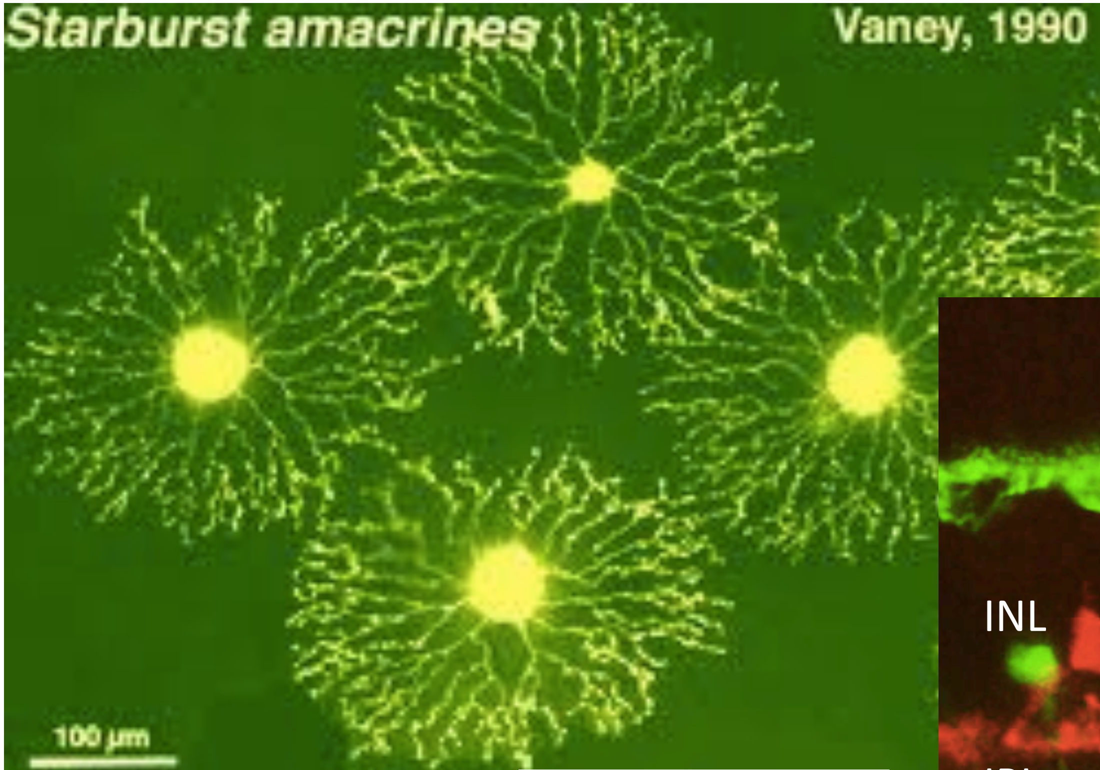
Rivlin-Etzion et al.,
J Neurosci, 2011

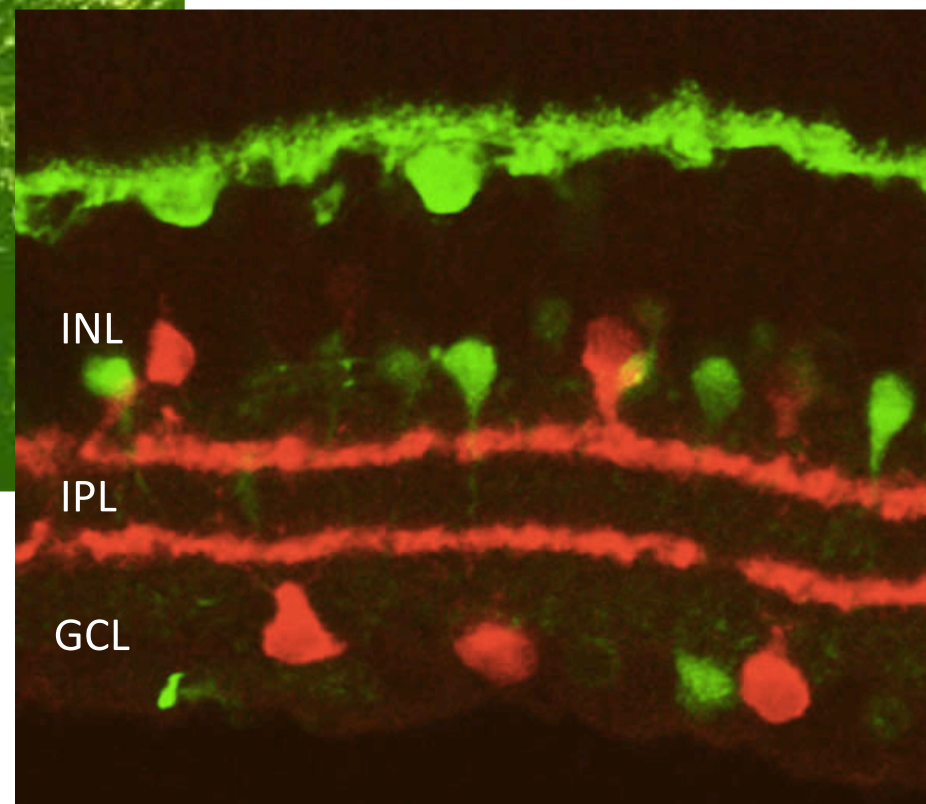
On-Off Direction Selective Ganglion Cells

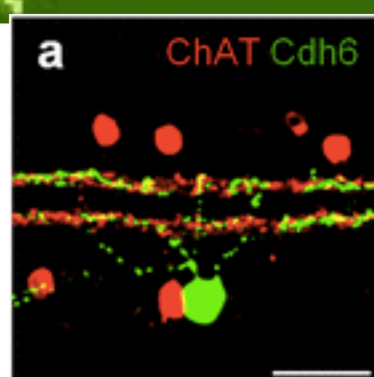


Rivlin-Etzion et al.,
J Neurosci, 2011

Starburst amacrine cells

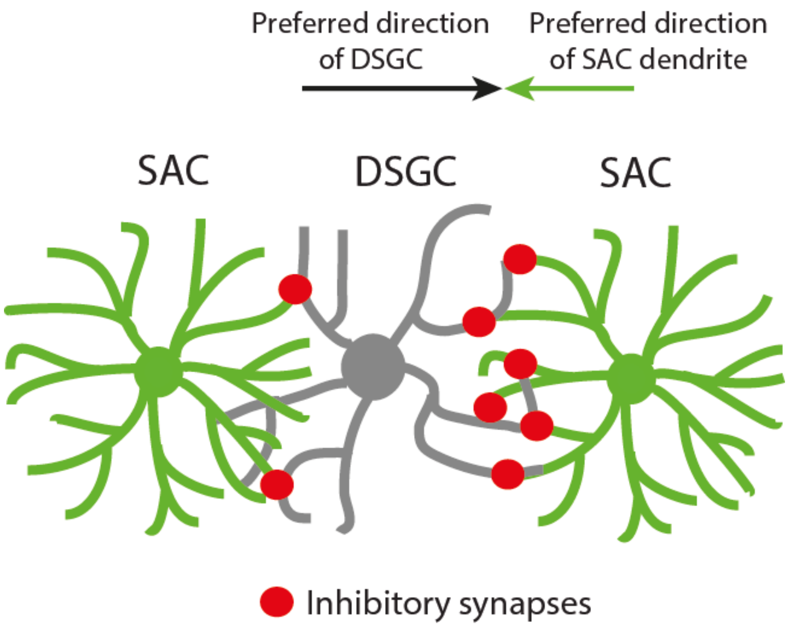


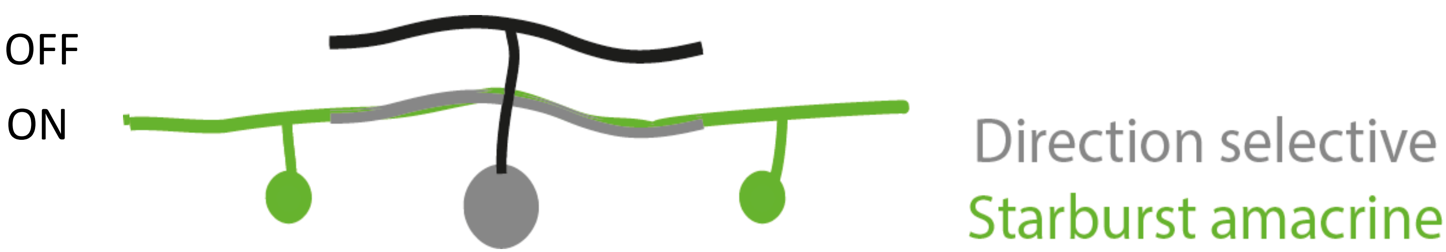




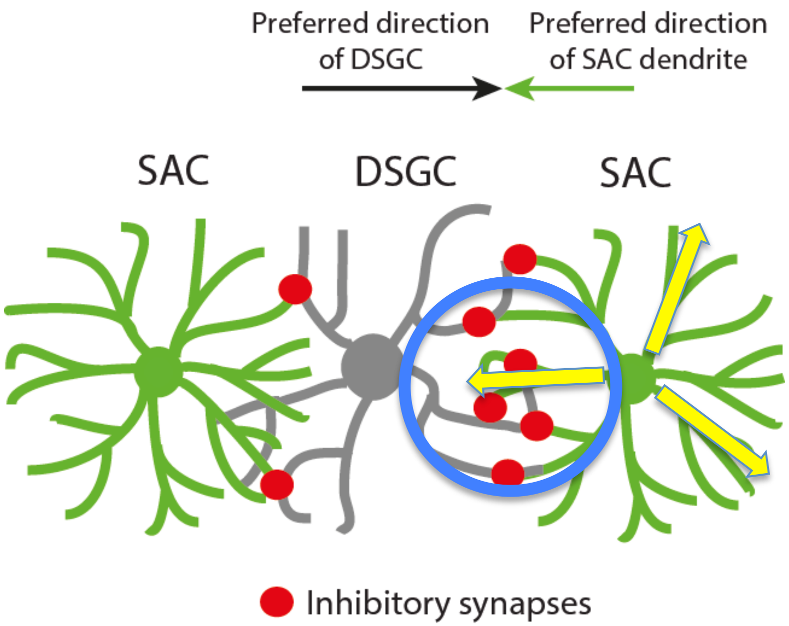
Starburst amacrine cells costratify with direction selective ganglion cells

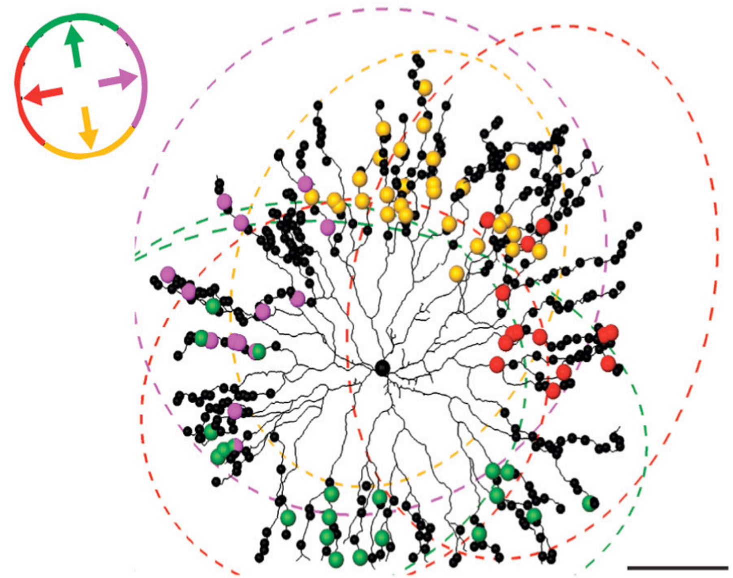
Directional responses are mediated by asymmetric inhibition from starburst amacrine cells



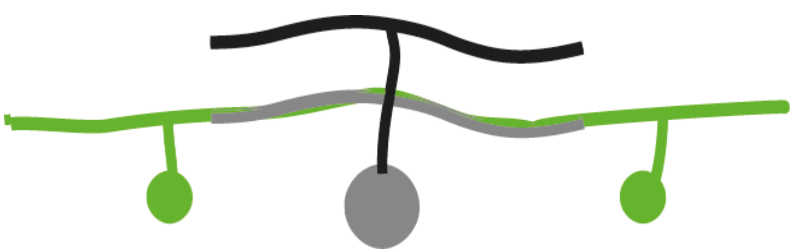


Directional responses are mediated by asymmetric inhibition from starburst amacrine cells



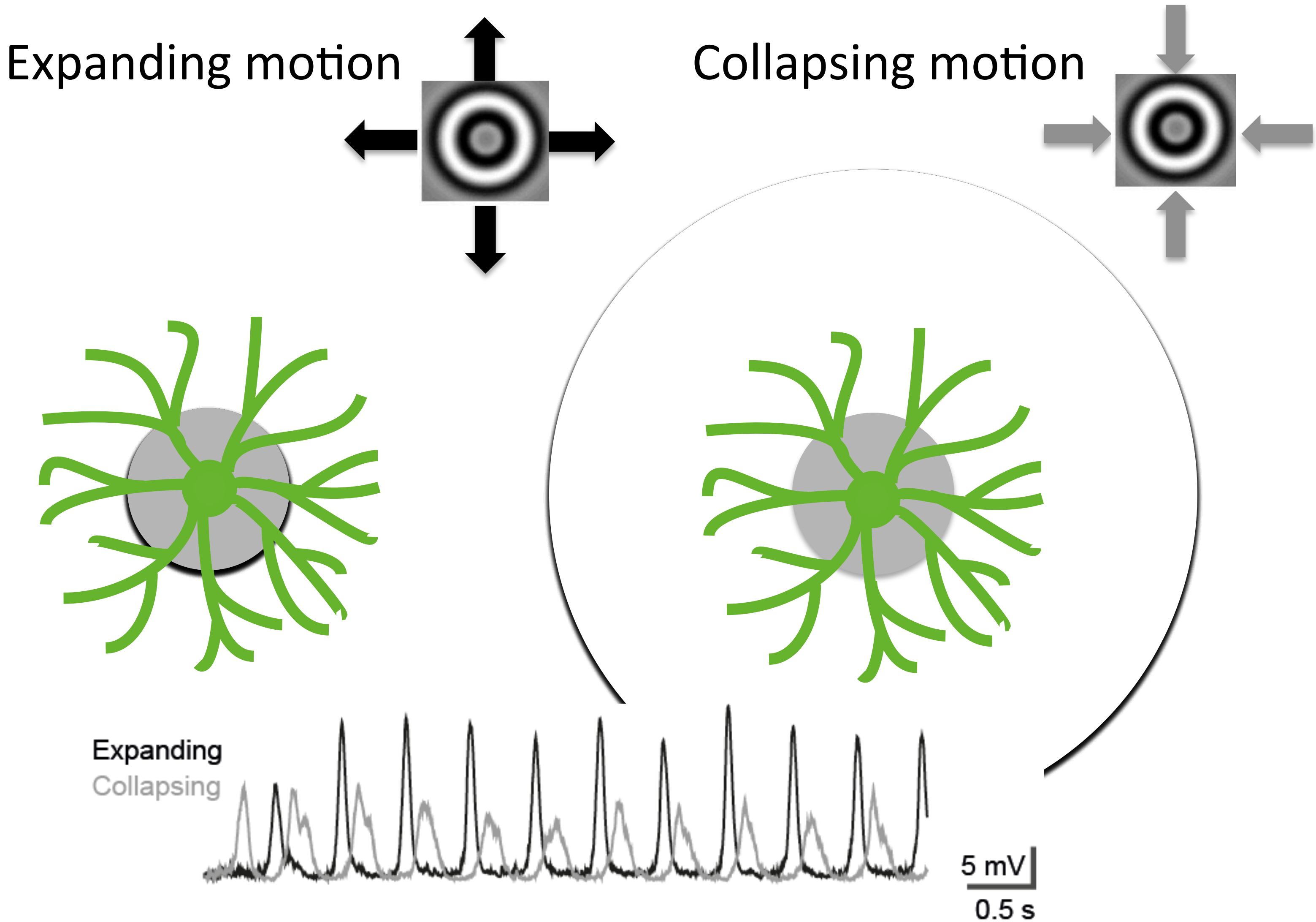


Brigmann & Denk 2011

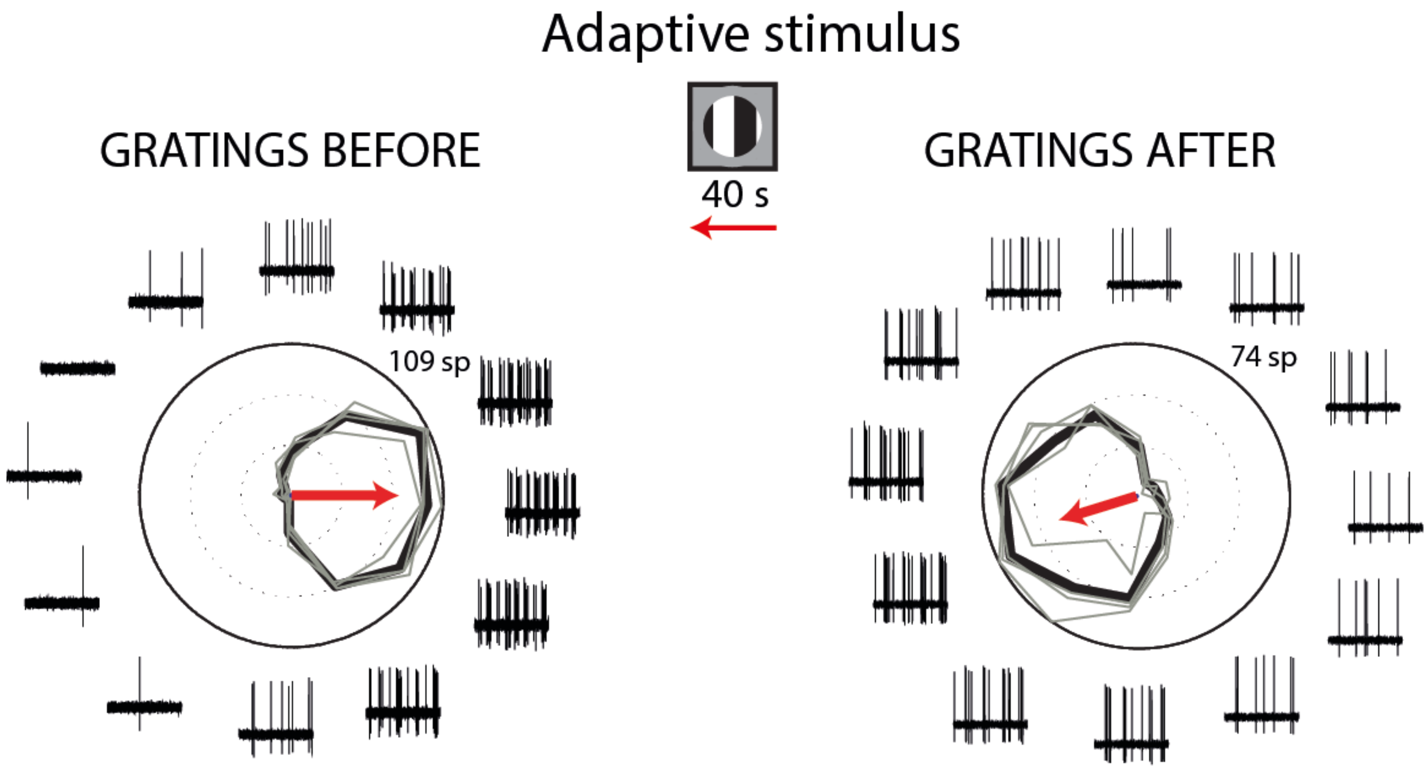


Direction selective
Starburst amacrine

SAC processes prefer centrifugal (=expanding) motion

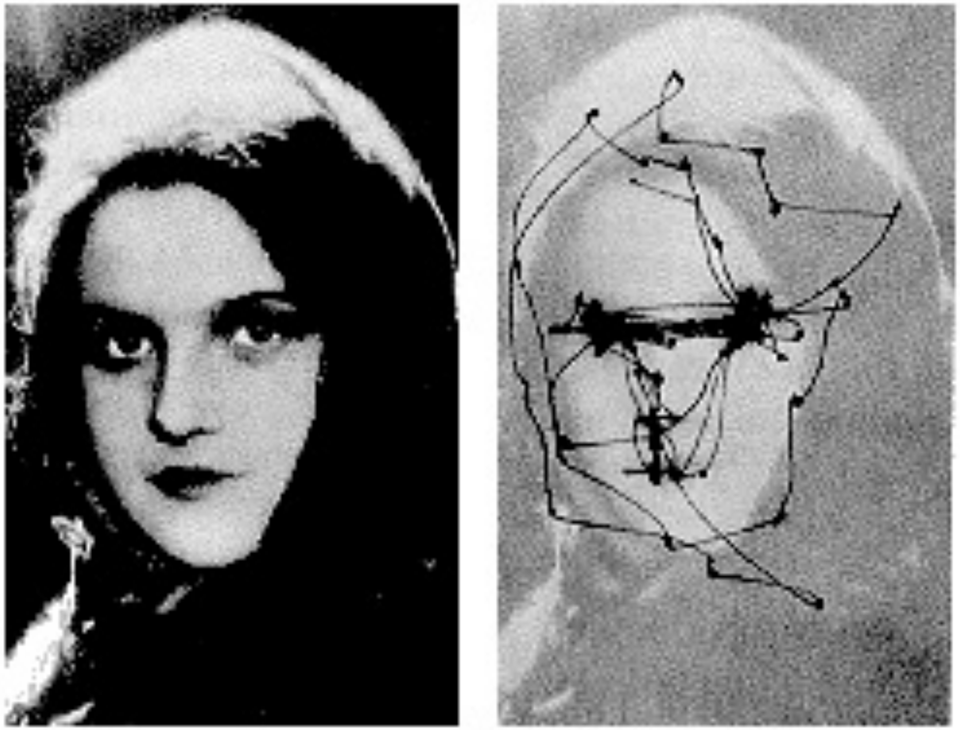


On-Off DSGCs reverse their directional preference upon visual stimulation



Recent evidence from mouse retina reveal some of the accepted concepts may be overruled.
For example, following a specific adaptation protocol, DSGC overcome the anatomy of the circuit and reverse their directional preference.

The visual image is not stable on the retina



saccades

Some computations performed by RGCs

- Texture motion: RGCs that respond to high spatial frequencies moving in all directions.
- Object motion-sensitive (OMS) ganglion cells fire only when a local patch on the receptive field center moves with a trajectory different from the background.
- Approaching motion.
- Prediction of location of a moving object.
- Omitted stimulus response: after exposure to a periodic stimulus, if one stimulus is omitted, some neurons generate a pulse of activity at the time corresponding to the missing stimulus.
- Saccadic suppression.

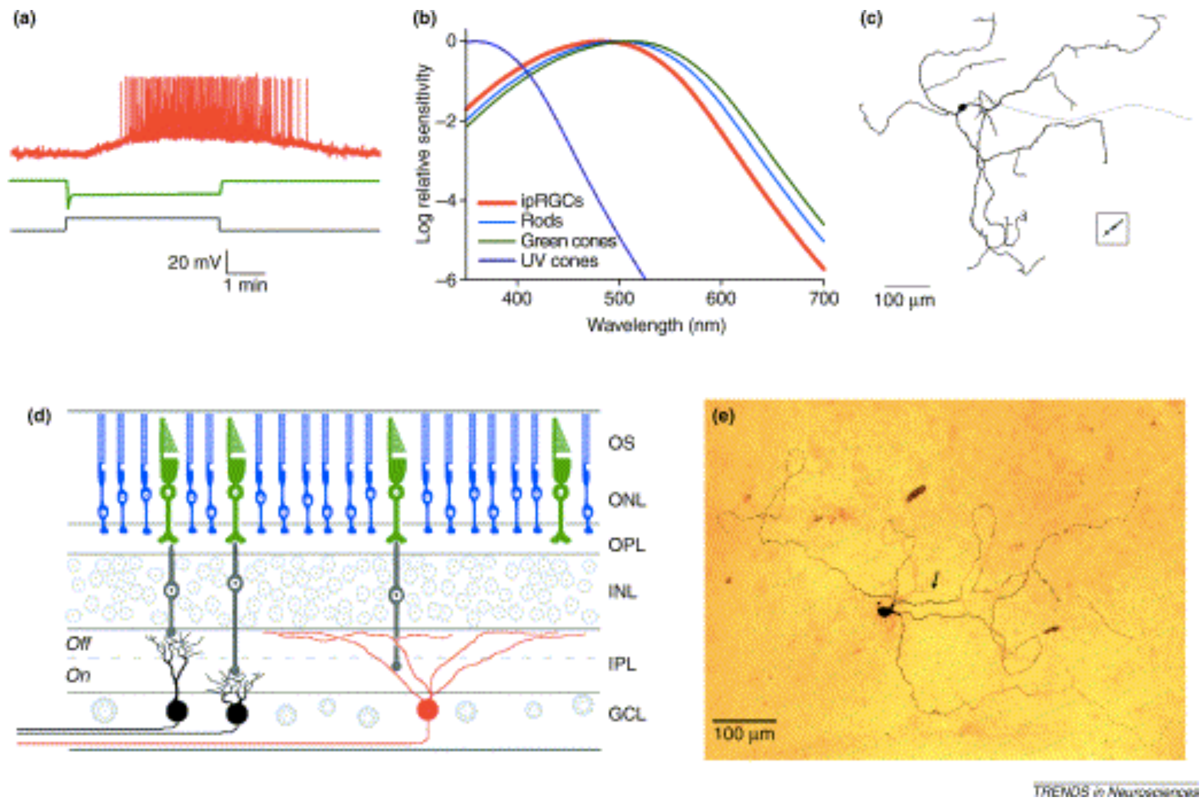
Review: Gollisch & Meister 2010

Retina: advantages

- Simple system, but performs complex computations.
- Organized structure.
- Full control on its input.
- Approachable for recordings/imaging.
- Similar anatomical arrangement in all mammals.

Intrinsic photosensitive RGCs (ipRGCs)

- Express the visual pigment melanopsin
- Mice, rats, cats, monkeys, human
- Light responses develop slowly
- Sustained depolarization to light
- Slow recovery
- Project to the suprachiasmatic nucleus – controls the circadian clock
- Projects to the pretectal nucleus, which controls the pupillary light reflex



Berson, 2002

Visual acuity

- The human visual system is capable of acuity of 1 min of arc or 60 cycles/degree of visual angle.
- One degree of visual angle is thought to cover approximately 280-300 μm of retinal distance.

One factor that determines visual acuity is the size of the eye:
The larger the eye, the bigger the area that covers
a given object in the visual field.
The bigger the area, the more neurons are involved
in encoding of the object…