BioNB2220 Spring 2019
Cornell University Nilay Yapici, PhD

Lecture 32: Vison, the Eye

Professor Nilay Yapici

Pre-lecture preparation – : Posted on the course website before the lecture

Reading – Chapter 9- Pages 293-329

Optional Readings- : Posted on the course website before the lecture

Lecture Objectives

- Be able to describe the process of phototransduction in the photoreceptor cells of the retina.
- Be able to describe the major cell types in the retina, and how they communicate with
- each other.
- Be able to understand how receptive fields for photoreceptors, bipolar and ganglion cells in
- the retina are formed.
- Be able to discuss the contribution of horizontal cells in the process of lateral inhibition in the retina.

Lecture outline

1) Photoreceptors transduce electromagnetic radiation in our visual range. These specialized cells have a resting membrane potential which is more depolarized than normal neurons. The reason for this is the presence of a cGMP-activated sodium channels in the membrane. There are two types of photoreceptors. Rods are more sensitive to light so that they are more active during dimmer light but are overwhelmed by bright light. Cones are less sensitive to light and contain one of three opsins. The relative activation of these opsins is how we perceive color.
2) The outer segment of photoreceptors houses multiple disks which each contain an opsin protein (rhodopsin in rods, and s, m, or l cone opsins in cones). These photopigments contain the chemical retinal. Light activates retinal, which in turn activates the opsin. The activated opsin than activates a G-protein called transducin. Transducin then activates phosphodiesterase, which converts cGMP into GMP. This leads to a closure of the cGMP-activated sodium channels and a subsequent hyperpolarization of the cell.
3) Photoreceptors can release glutamate, but through graded potentials, as all cells in the retina except the ganglion cells do. Since these are small cells, they do not require an action potential to release transmitter. All they need is sufficient depolarization to activate voltage-gated calcium channels. <u>Photoreceptors release *MORE* transmitter at rest (in the dark) than they do in the light!! So when a light comes on, they release *LESS* transmitter</u>.
4) Photoreceptors are most densely packed at the **fovea**. At the fovea, there are many cones, but few rods. The largest density of rods is just around the fovea. This means that color vision has the highest resolution when you fixate on an image (look directly at it), whereas night vision is more acute in the periphery.
5) <u>Vertical pathway</u>: Photoreceptors form a synapse with bipolar cells. There are small interneurons which communicate through graded potentials. There are ON-center (off surround) as well as

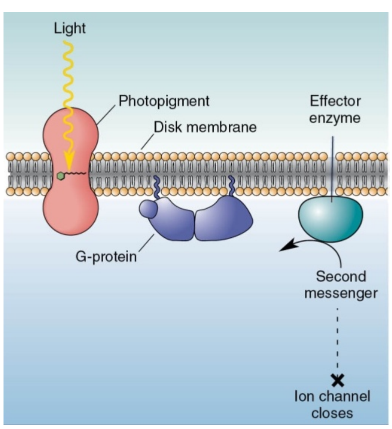
OFF-center (on surround) bipolar cells. Bipolar cells than make contact with ganglion cells. These cells DO have action potentials, as well as long axons which make up the optic nerve that leave the eye.

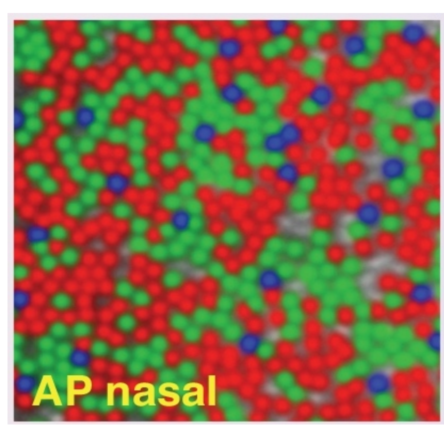
6) Horizontal pathway: Horizontal cells also communicate through graded potentials. They form connections with several photoreceptors across a small area of the retina. They act to invert the response of photoreceptors onto other photoreceptors to which they are connect via an inhibitory connection. This is called lateral inhibition, and contributes to contrast enhancement (below). These are the cells that make retinal cells have a center surround receptive field rather than just a center.

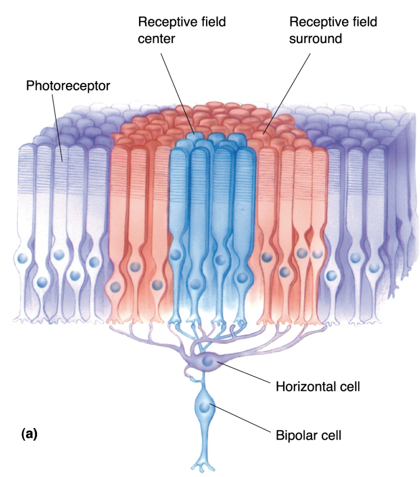
7) Lateral inhibition and contrast enhancement: Horizontal cells act to enhance contrast along visual edges. They do so by exaggerating responses in photoreceptors and the subsequent cells along the vertical pathway. To understand this, you need to map out responses along these visual edges.

Study questions:

1) How does the eye convert electromagnetic radiation to a visual image?
2) What is the advantage of inside out laminar structure in the retina?
3) How does the same membrane potential change in the photoreceptor cell causes different patterns of activation in ON and OFF bipolar cells?
4) What is the main difference between retinal ganglion cells and the rest of the cell types in retina?







Lecture 32: Visual System I-The Eye

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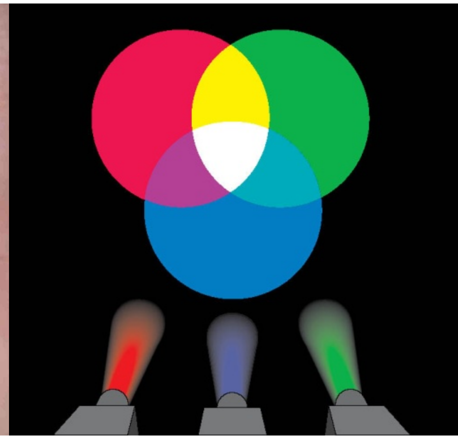
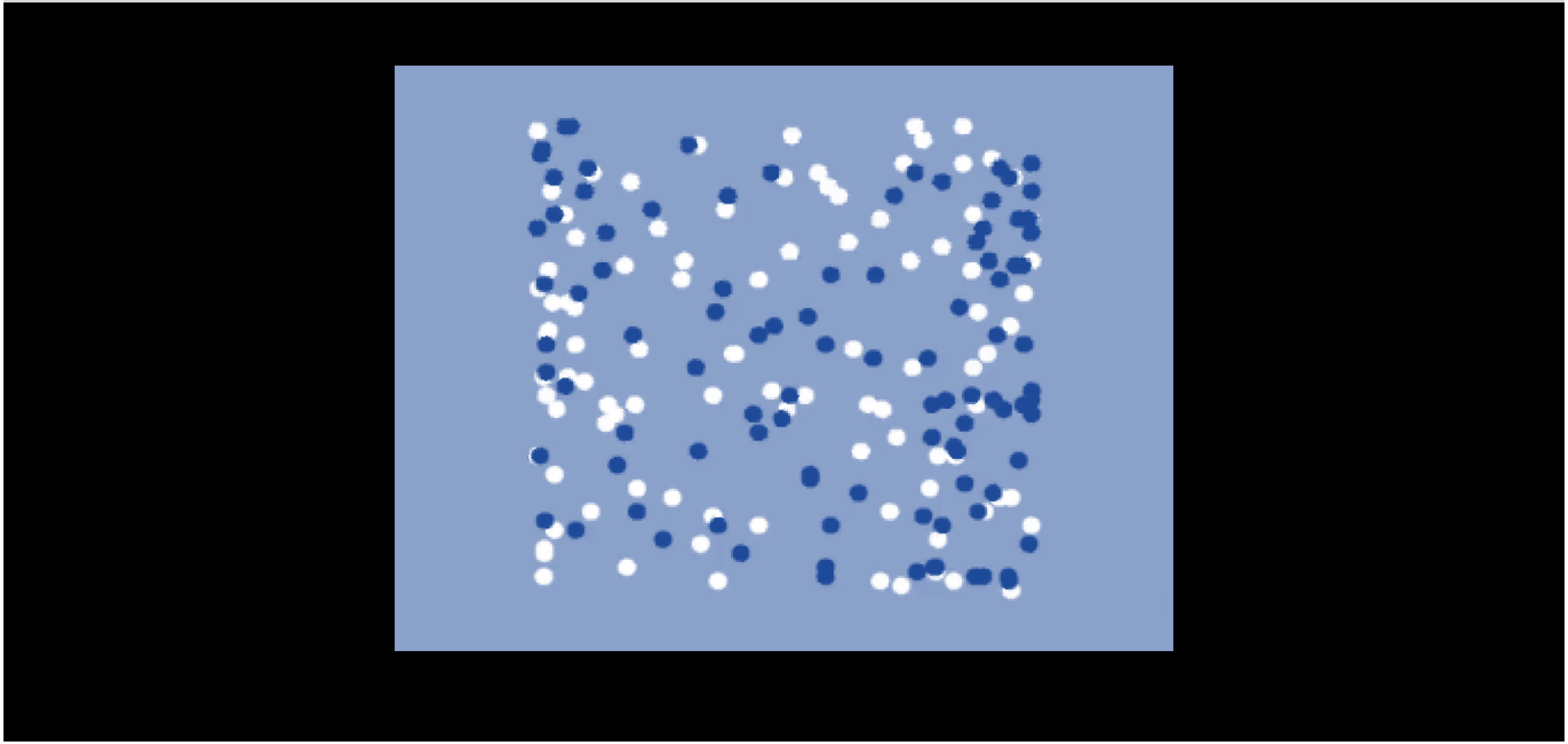
Office Hours: Wednesdays 2PM-5PM

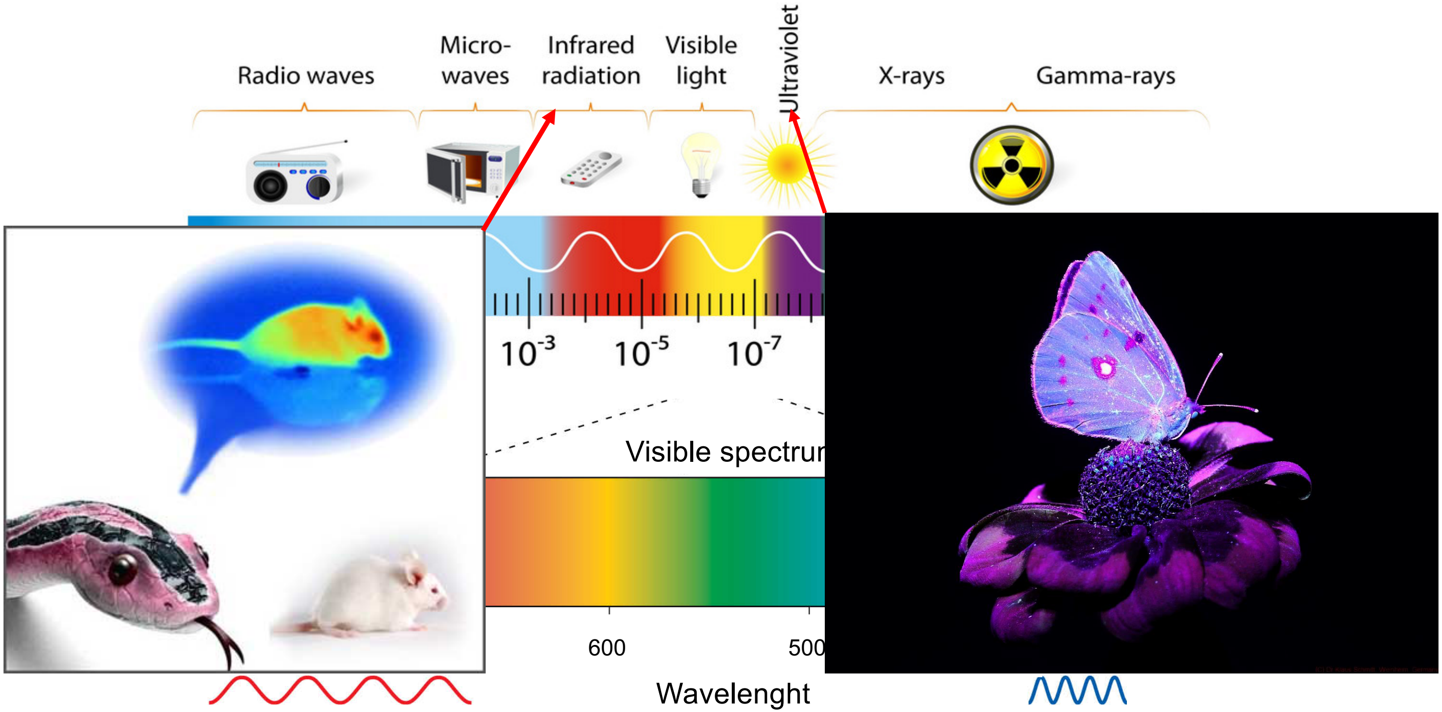

Learning objectives

- Be able to describe what is phototransduction in the photoreceptor cells of the retina.
- Be able to describe the major cell types in the retina, and how they communicate with each other.
- Be able to understand how receptive fields for photoreceptors, bipolar and ganglion cells in the retina are formed.
- Be able to discuss the contribution of horizontal cells in the process of lateral inhibition in the retina.

Our visual system detects motion, color and contrast to generate a visual percept

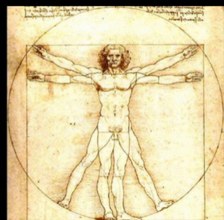


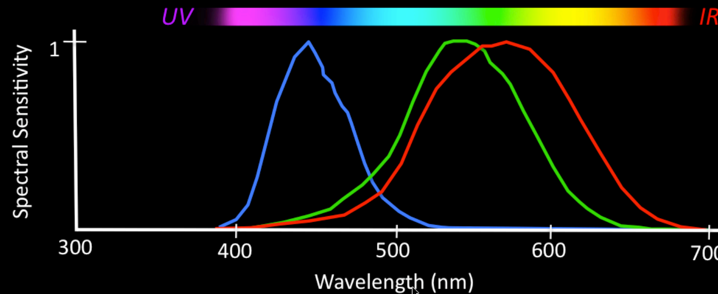
Our eyes convert electromagnetic radiation to visual percepts



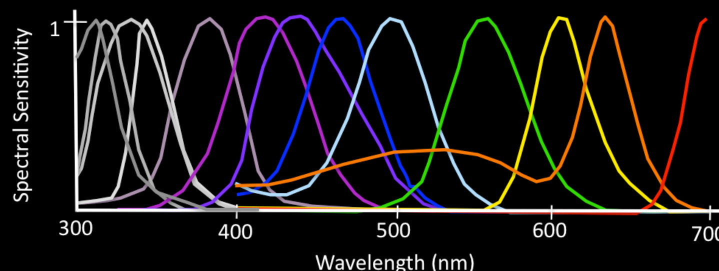
Mantis Shrimp: Extraordinary Eyes

Homo sapiens





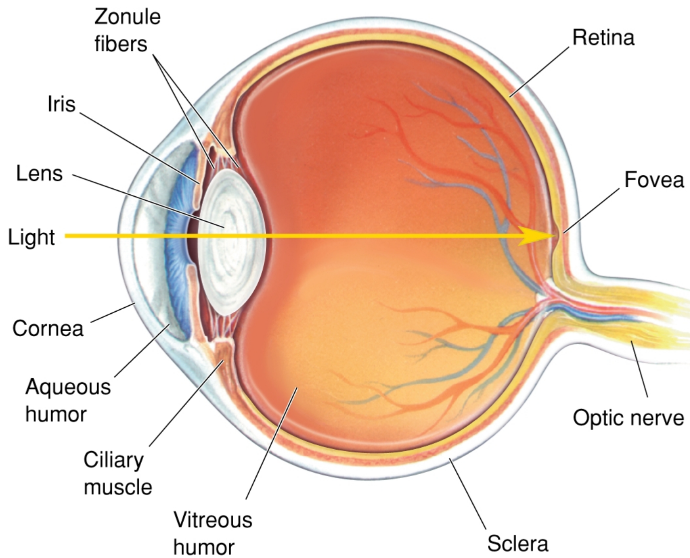
Neogonodactylus oestedii



Marshall *et al.,* 2007; Marshall and Oberwinkler, 1999

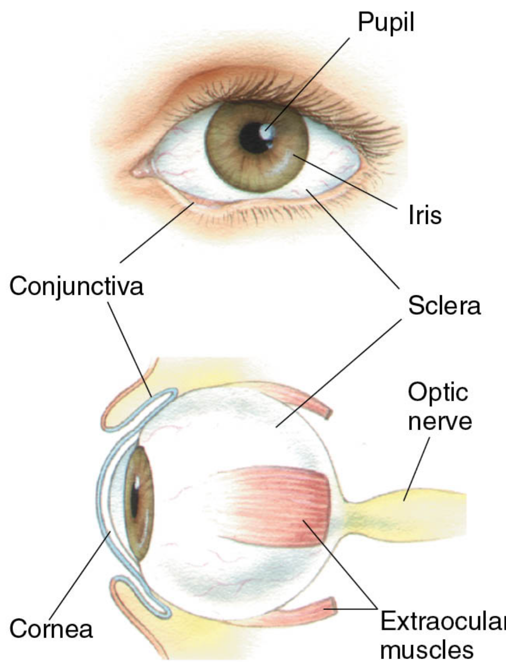
Evolution of the visual system

Light is detected by the eye

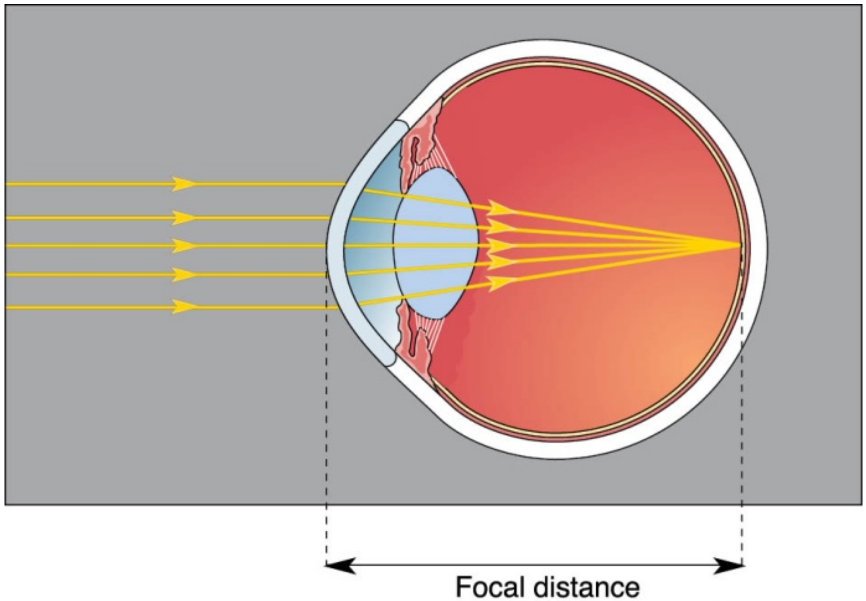


Anatomy of the eye

- Pupil: opening where light enters the eye
- Sclera: white of the eye
- Iris: gives color to eyes
- Cornea: glassy transparent external surface of the eye
- Optic nerve: bundle of axons from the retina



Eye collects light, focuses on retina, and forms an image.

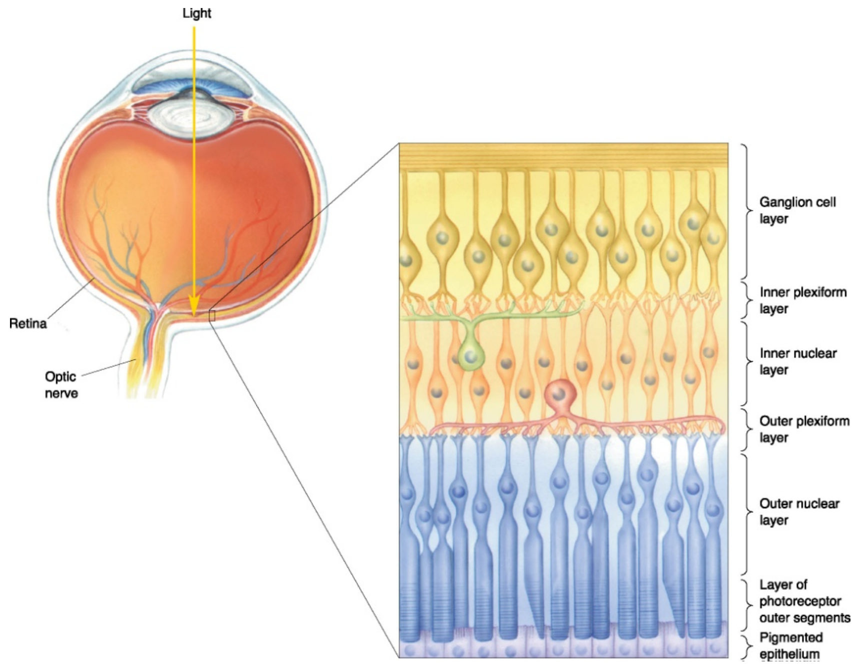


$$\text{Refractive power (diopters)} = \frac{1}{\text{focal distance (m)}}$$

Laminar organization of the retina

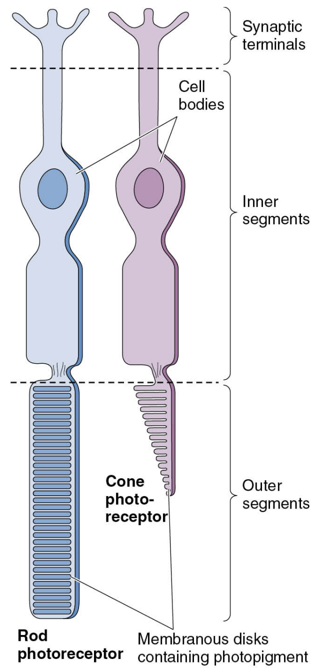
- The retina is organized as inside-out layers; light sensitive photoreceptor neurons are located at the last layer.

- Light passes through ganglion cells and bipolar cells before reaching photoreceptor cells.



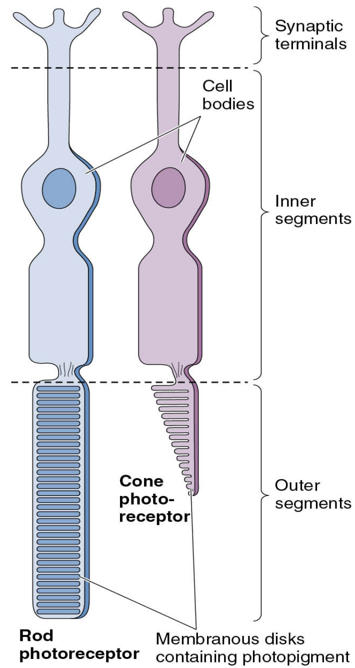
Photoreceptor cells transform light stimulus to a neural response

- Types of photoreceptor cells
  - Rods
  - Cones
- Four main regions
  - Outer segment
  - Inner segment
  - Cell body
  - Synaptic terminal



Photoreceptors transform light stimulus to a neural response

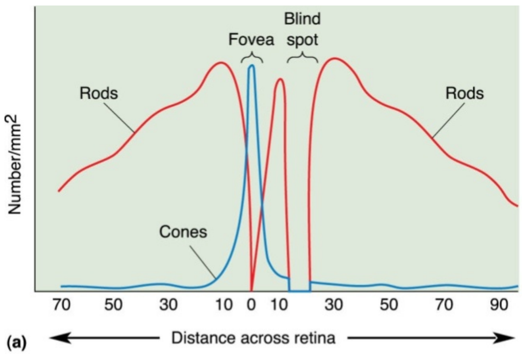
- Rods are long, cylindrical outer segment with many disks
- Cones are shorter, tapering outer segment with fewer disks
- Rods are over 1000 times more sensitive to light than cones

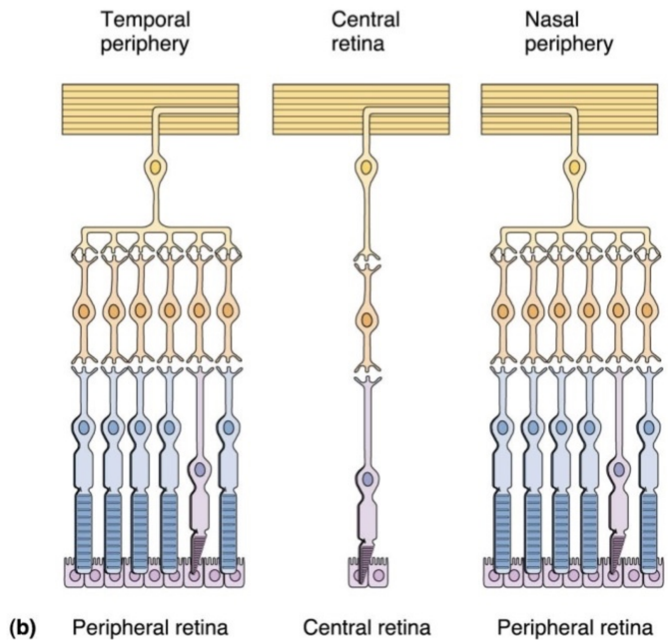


Rod and con distribution across the retina is different

Peripheral retina

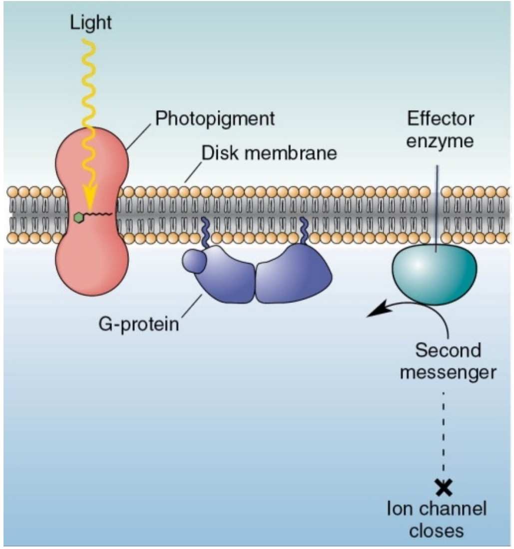
- has higher ratio of rods to cones
- has higher ratio of photoreceptor cells to ganglion cells
- is more sensitive to low light





Photoreceptor cells carry light sensitive receptors

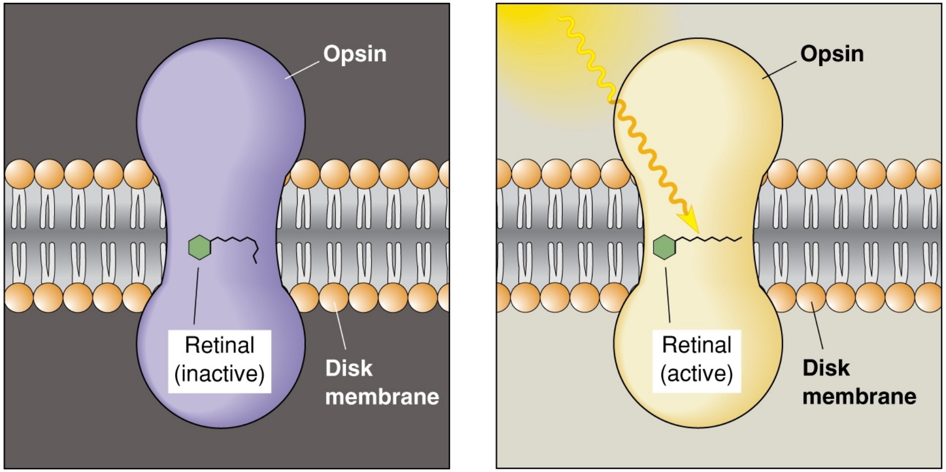
- The photoreceptors convert light energy into changes in membrane potential!
- Photoreceptors are GPCRs (similar to olfactory receptors and T1Rs and T2Rs)



Each rod or con cell contains a specific opsin

Retinal changes structure with light

Each photoreceptor is composed of a light absorbing molecule called retinal and a protein called opsin.



Each rod or con cell contains one type of opsin

Rod photoreceptors

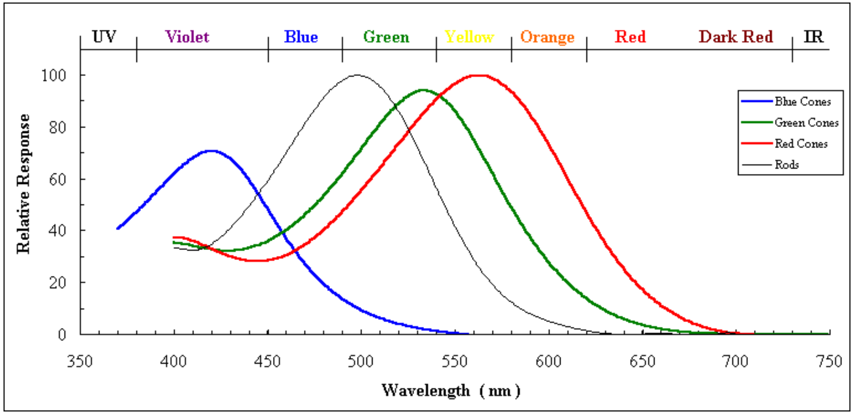
Rhodopsin

Con photoreceptors

Blue ------Short wavelength

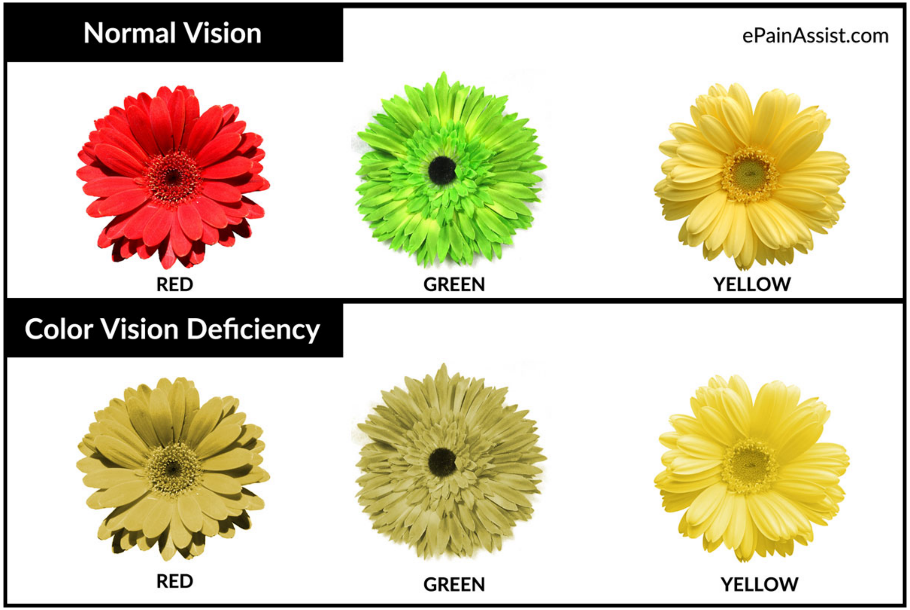
Red -------Long wavelength

Green ------Medium wavelength

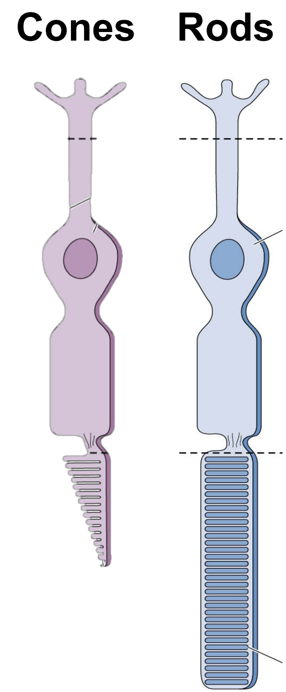


Color Blindness

Defects in cone photoreceptors can cause different types of color blindness



Summary of Rod and Cone Photoreceptors



Rods are responsible for vision at low light levels. They do not mediate color vision, and have a low spatial acuity.

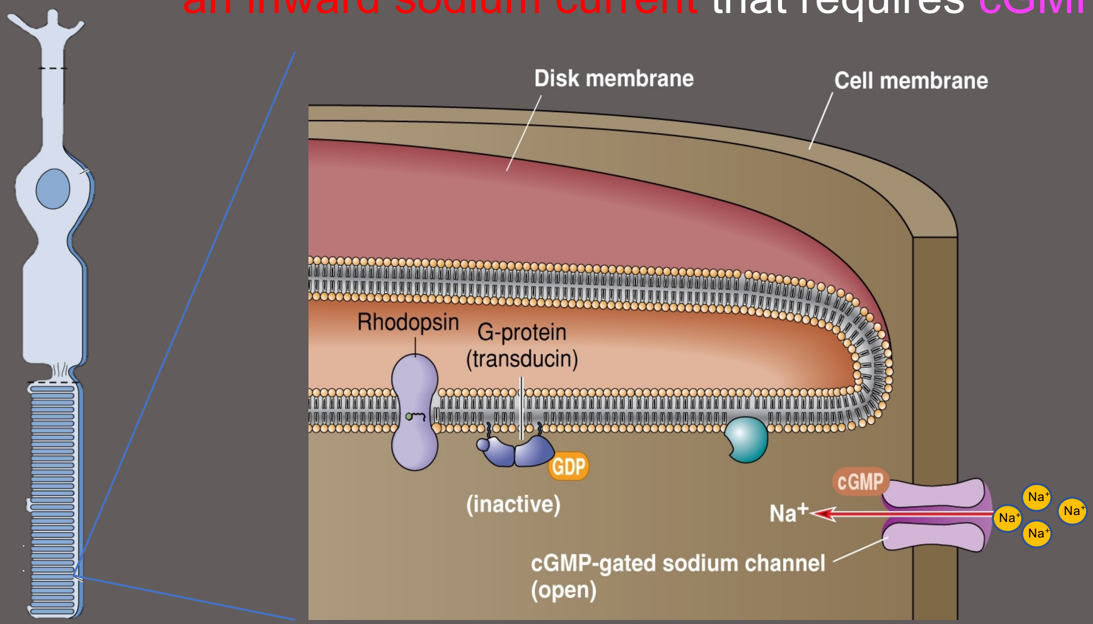
Rods contain **rhodopsin**.

Cones are active at higher light levels, are capable of color vision and are responsible for high spatial acuity.

Cones contain 1 of three kinds of opsins; Blue, Red and Green

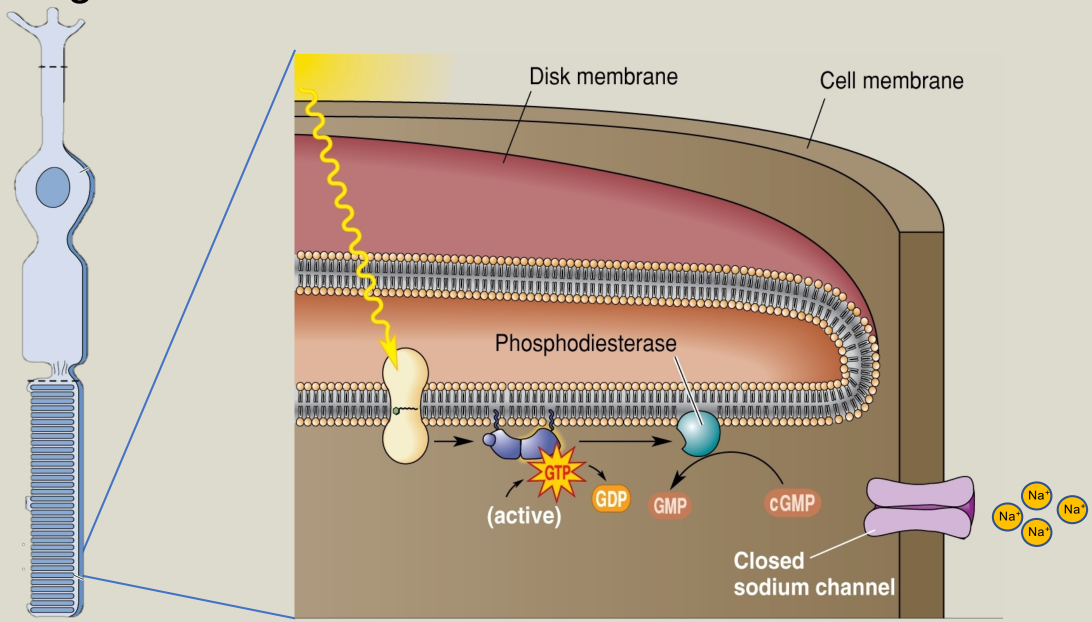
How does light converted to action potentials

Photoreceptors are continuously depolarized in the dark because of an inward sodium current that requires cGMP

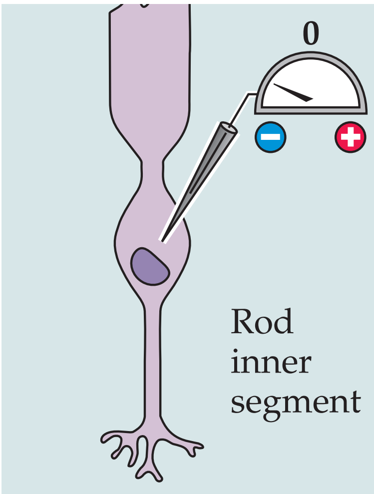


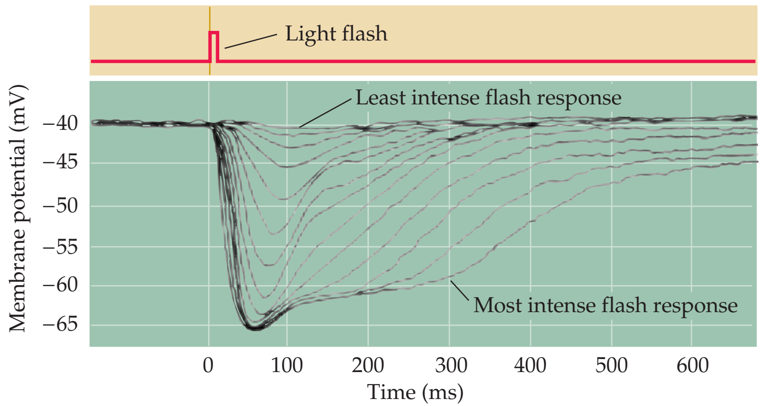
How does light converted to action potentials

Activation of the rhodopsin by light energy causes G-protein to change GDP to GTP which activates PDE and breaks down cGMP



Light pulse causes hyperpolarization in photoreceptor cells



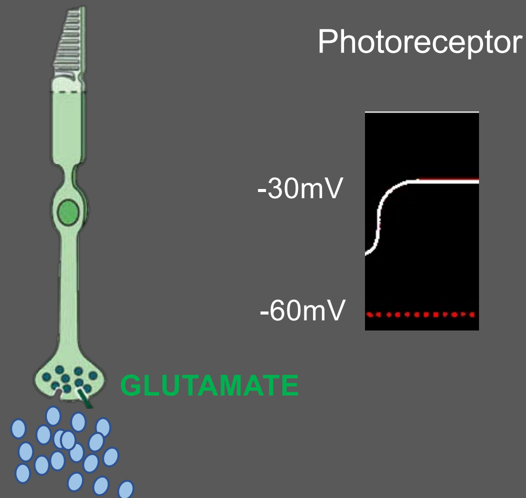


The neurotransmitter released by photoreceptors is glutamate

DARK

Photoreceptors are depolarized.

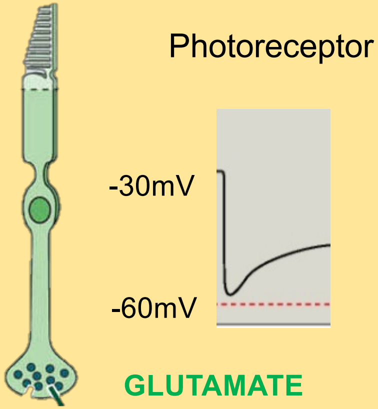
Glutamate is released.



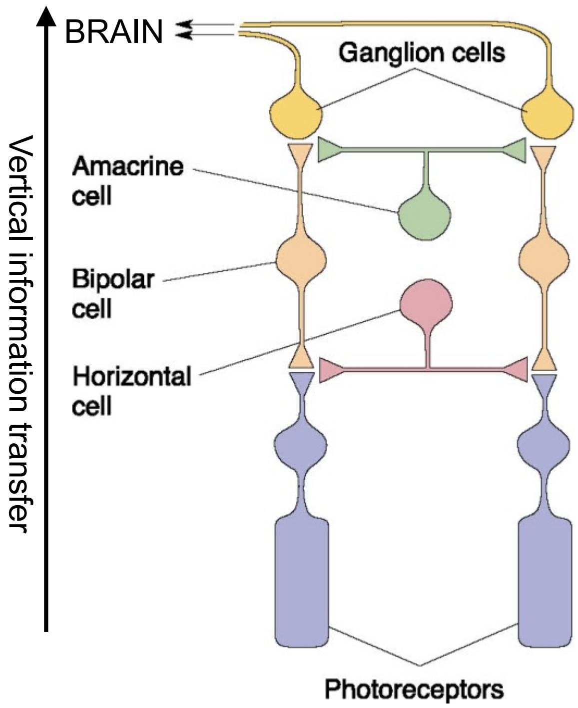
LIGHT

Photoreceptors are hyperpolarized.

Glutamate release is inhibited.



Retinal Processing and Output

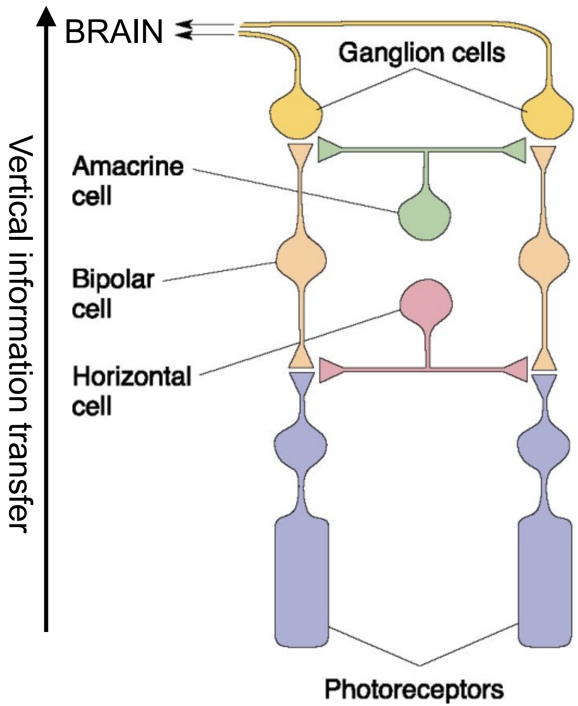


Ganglion cells----- Transmit light induced action potentials to the brain

Bipolar Cells--------Receive input from photoreceptors and transmit light information to ganglion cells

Photoreceptors----Light detection

Retinal Processing and Output



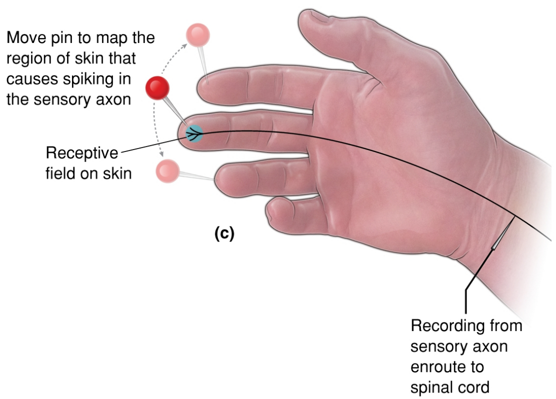
Ganglion cells — ACTION POTENTIAL

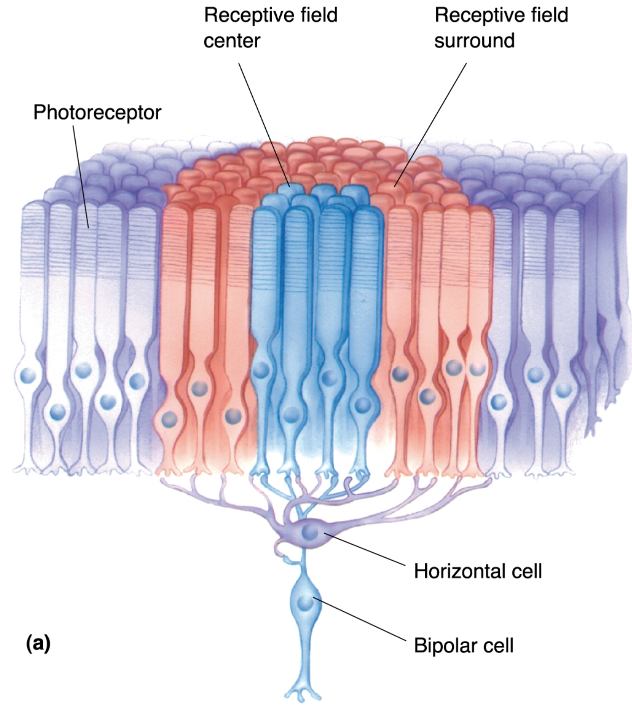
Bipolar Cells — GRADED CHANGES IN MEMBRANE POTENTIAL

Photoreceptors — GRADED CHANGES IN MEMBRANE POTENTIAL

Retinal Ganglion cells have receptive fields

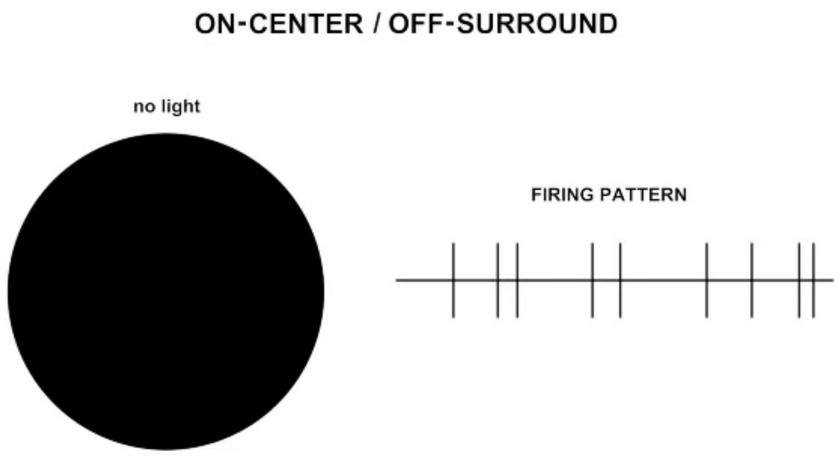
Receptive field of retinal cells are similar to the receptive field of mechanosensitive receptors in the skin





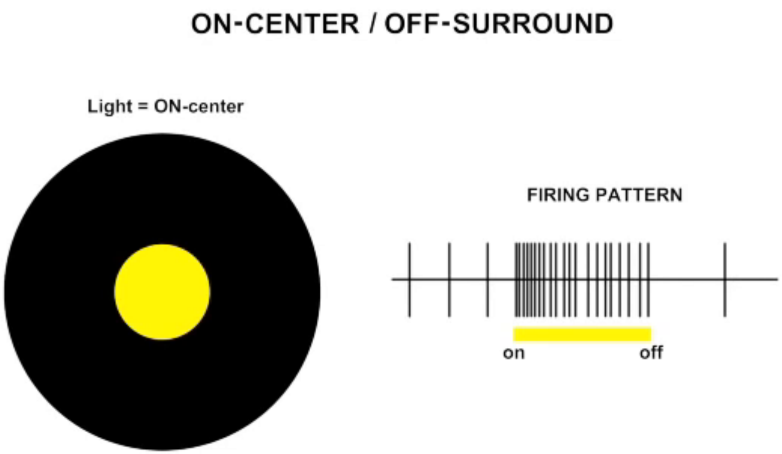
Retinal Ganglion cells have receptive fields

On-Center/Off surround ganglion cell have spontaneous firing in the absence of light



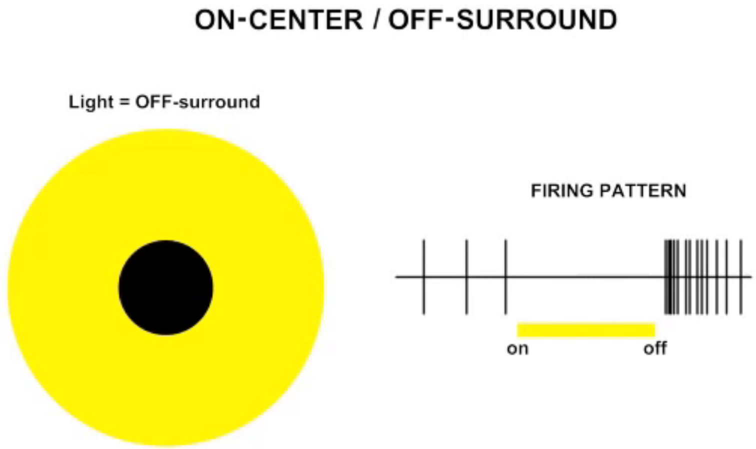
Retinal Ganglion cells have receptive fields

In the presence of light on the center, this ganglion cell increases firing rate



Retinal Ganglion cells have receptive fields

If the light hits the surround, this ganglion cell decreases firing rate



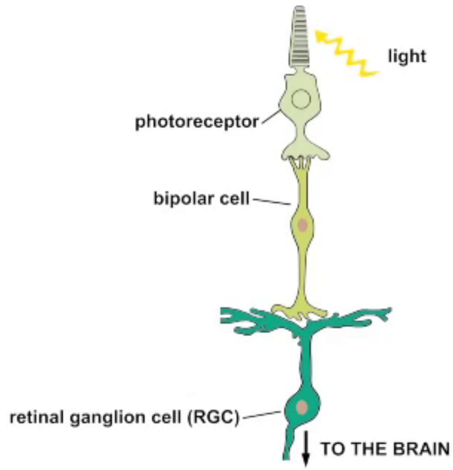
How are retinal ganglion cell receptive fields generated?

Watch also Pre-lecture video

Step by step phototransduction:

1. Light stimulation hyperpolarizes the photoreceptor cell
2. Photoreceptor cell stops releasing glutamate
3. Bipolar cells express glutamate receptors and respond to changes in glutamate levels differently.

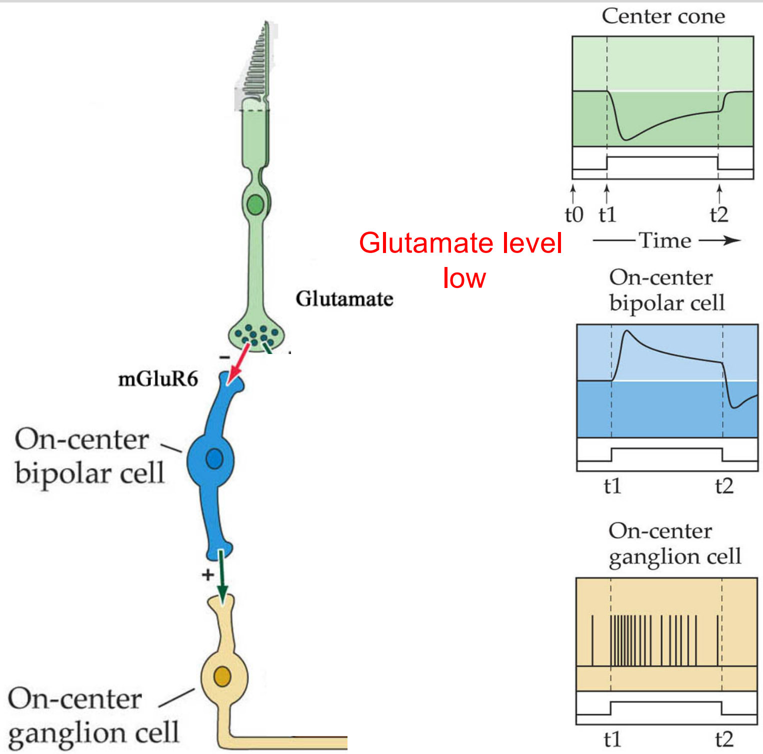
❖ There are two types of bipolar cells on and off.



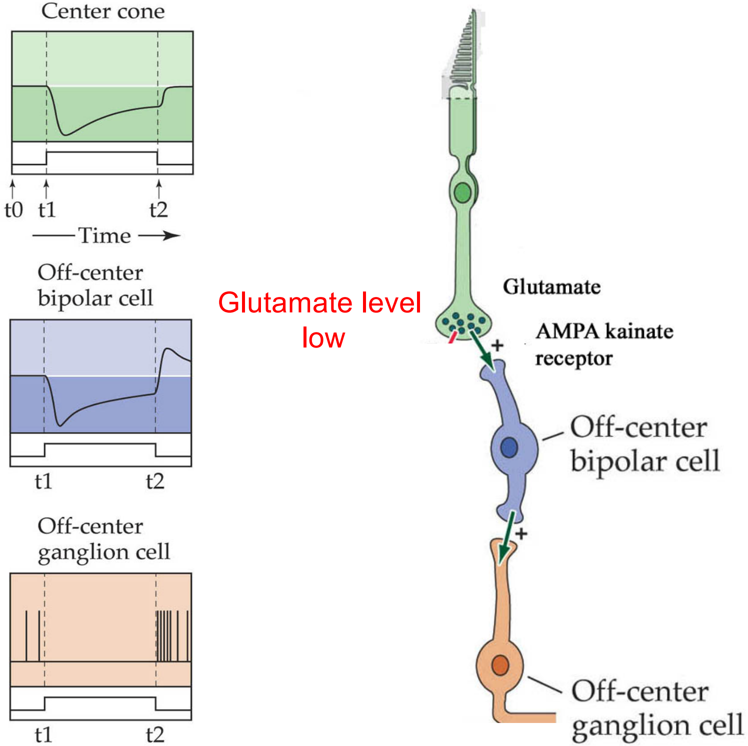
On-center-bipolar cells

ON-Center-Bipolar Cells

- ON-center-bipolar cells carry metabotropic glutamate receptors (mGluR), that inhibit them in the presence of glutamate.
- Light decreases glutamate release from the photoreceptor.
- In the absence of glutamate mGluR is inhibited, and ON-center-bipolar cell gets activated.
- Depolarized ON-bipolar cell increases transmitter release which activates ON-Ganglion cell.



Off-bipolar cells

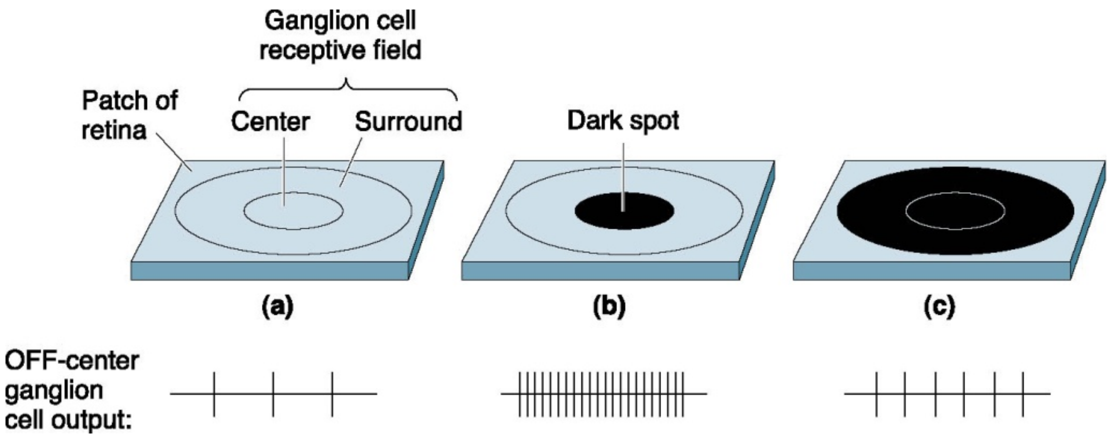


<u>OFF-Bipolar Cells</u>

- OFF-bipolar cells carry ionotropic glutamate receptors (AMPA kainite receptor).
- In the presence of glutamate these receptors activate the bipolar cells.
- Light decreases glutamate release from the photoreceptor which deactivates the AMPA receptors and inhibits the OFF-bipolar cell.
- Inactive OFF-bipolar cell decreases transmitter release which inhibit OFF-Ganglion cell.

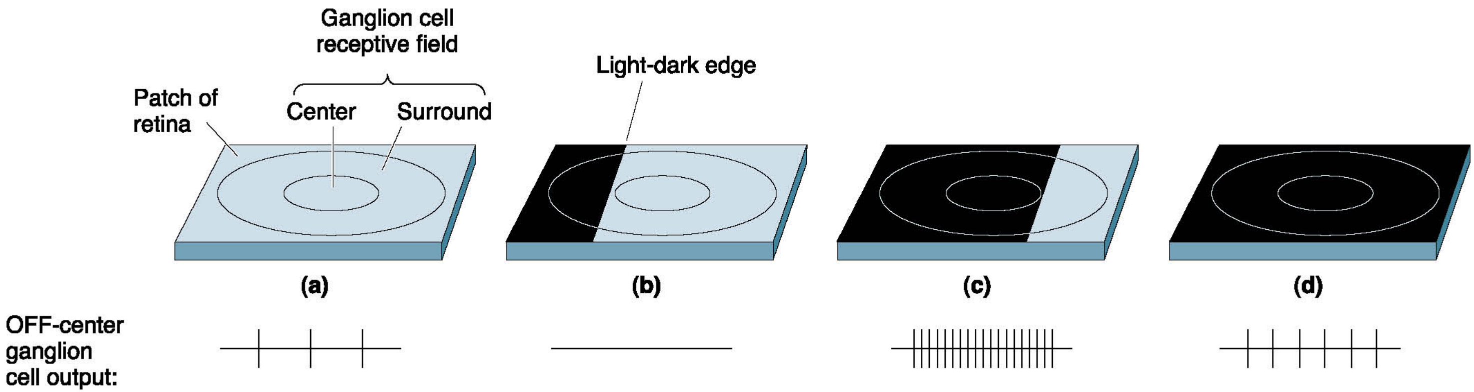
Ganglion cell receptive fields

Ganglion cells differ in firing action potentials.



Ganglion cell receptive fields

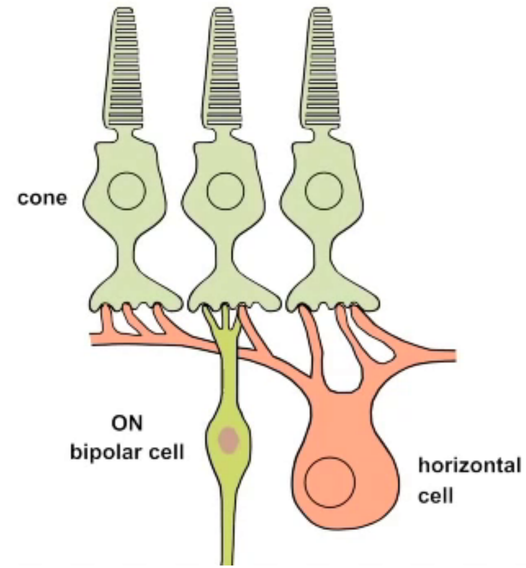
Responses of an OFF-center ganglion cell is determined by the fraction of the center and surround that are filled by light and dark



How are retinal ganglion cell receptive fields generated?

Horizontal Pathway

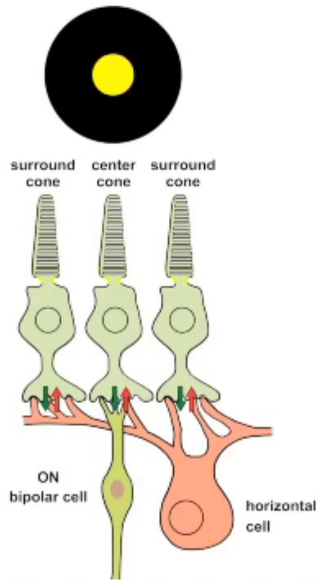
- Photoreceptor cells are also connected to horizontal cells in the retina.
- Horizontal cells receive excitatory input from the photoreceptors and send inhibitory feedback in return.



How are retinal ganglion cell receptive fields generated?

Horizontal Pathway

- When center is illuminated by light, center photoreceptor is hyperpolarized and decrease releasing glutamate.
- Surround photoreceptors are depolarized and increase releasing glutamate
- Horizontal cell is excited by glutamate and send inhibitory feedback to the photoreceptors.
- This inhibitory feedback makes the receptive fields of retinal ganglion cells sharper

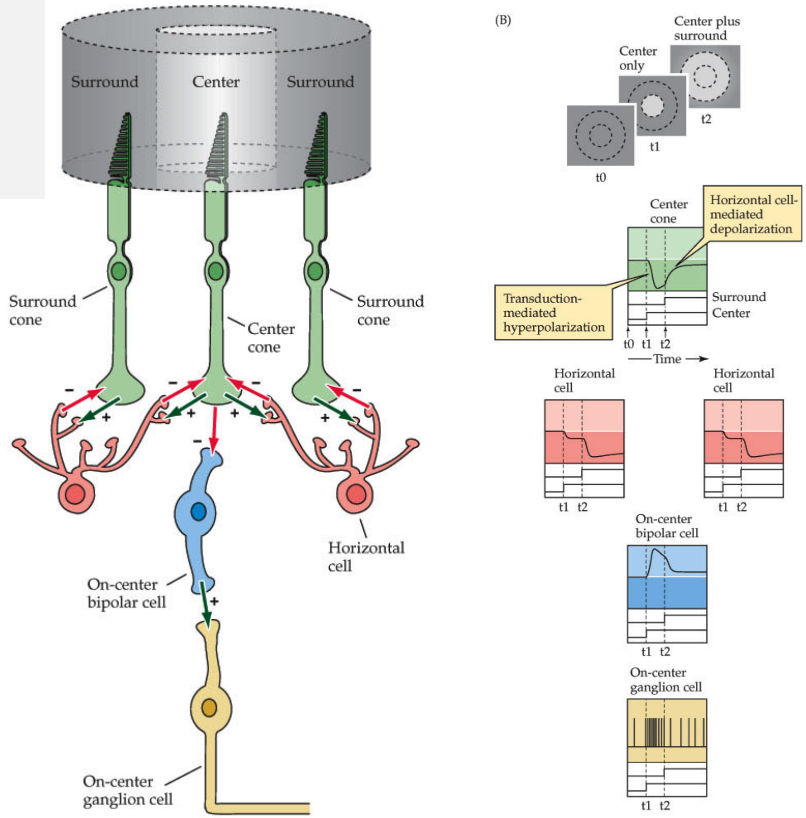


Take home messages

- Light emitted by or reflected off objects in space is imaged onto the retina and stimulates the photoreceptor cells
- Phototransduction is light energy converted into membrane potential changes through light activated membrane proteins called opsins.
- Mapping of visual space onto retina cells is not uniform.
- Based on their activity when light hits on or surround, bipolar cells and ganglion cells of the retina can be classified as ON or OFF center or surround cells ---Learn this well!

FOR STUDYING PURPOSES
(not included in the lecture)
On center, Off surround cone cell

- What happens to the voltage in each cell type when you
    A. shine light on the center only
    B. shine light on the surround only
    C. shine light on the center + surround



Bipolar pathways have two output pathways: on/off

- Rules: ① receptor cells release neurotransmitter when **DE**polarizes

  ② light **HYPER**polarizes receptor cell

Two types of glutamate receptors

① AMPA (excitatory)

② mGluR6 (inhibitory)

When bipolar cells stop releasing Glutamate, the **OFF** cell gets less active and stops releasing in turn (and vice-versa)