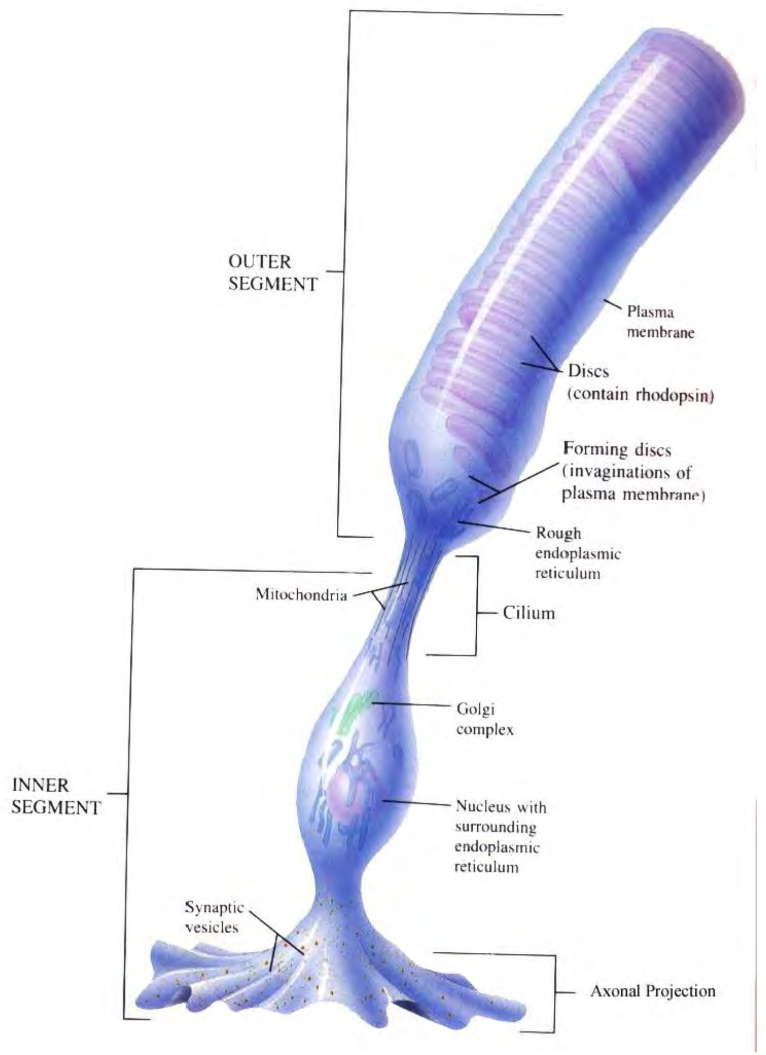
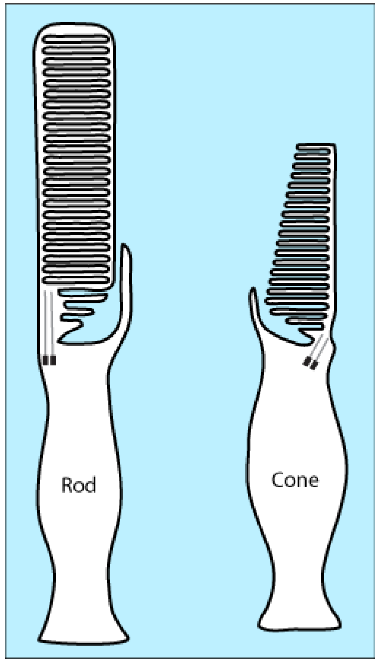
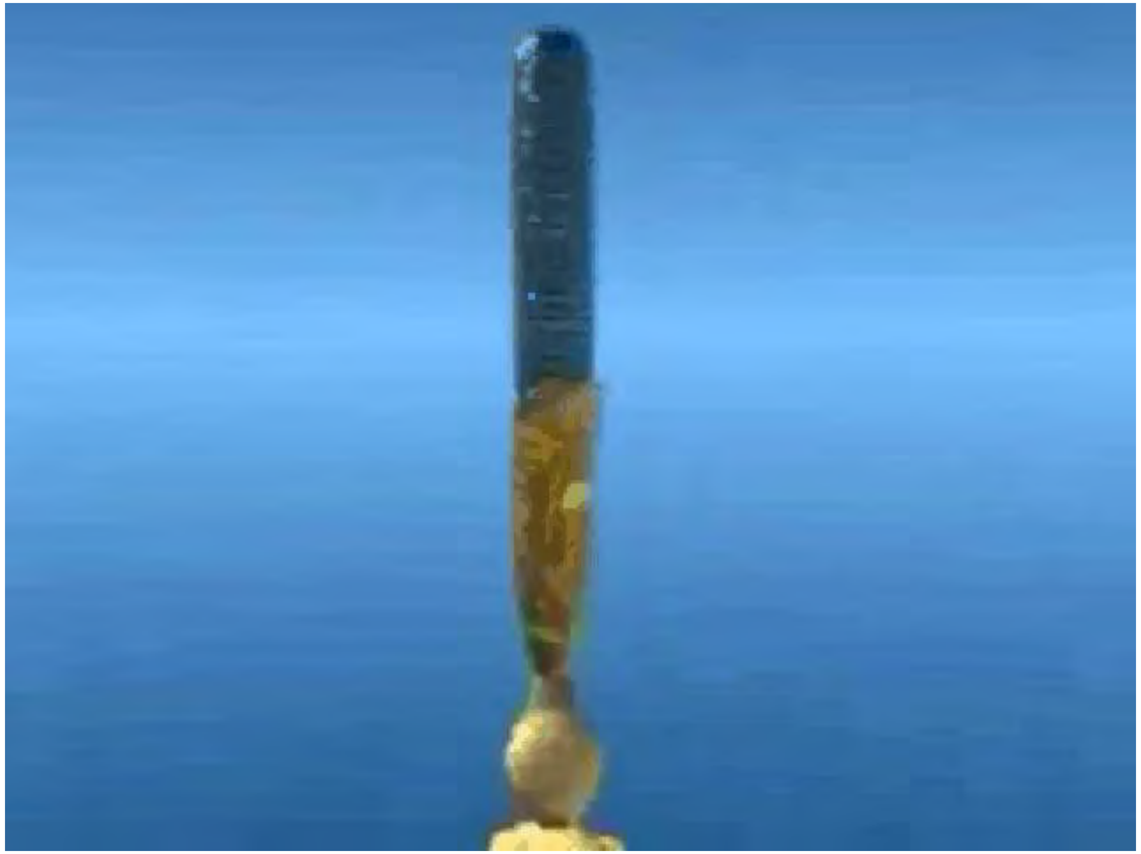
The Human Visual System

Jack Fein and Leathem Mehaffey

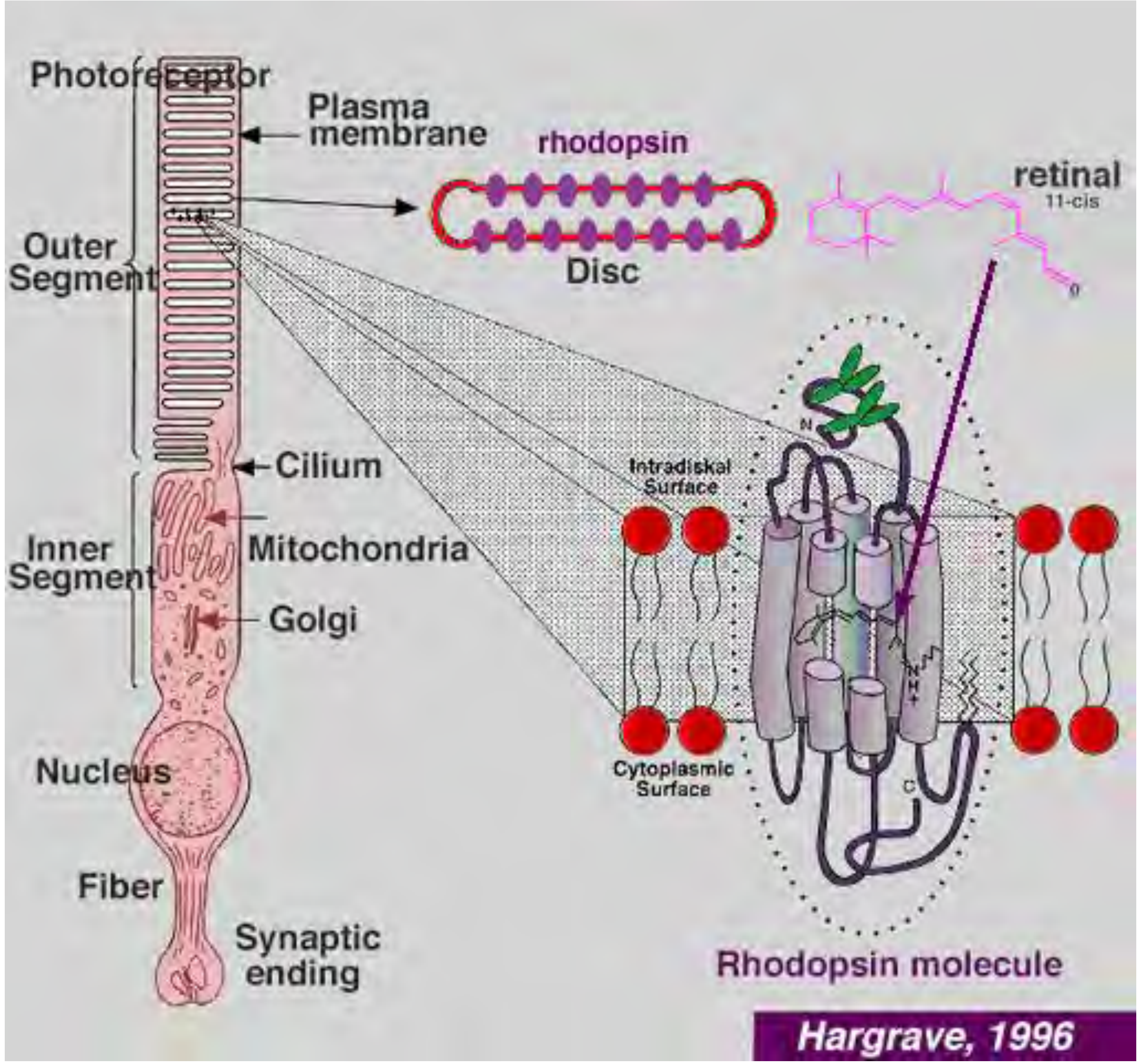
Anatomy of photoreceptors







How Do Photoreceptors Work?



Photoreceptors must turn light energy into chemical energy and eventually into the vocabulary of the nervous system, electrical energy.

They do this using a protein called opsin along with an auxiliary molecule called a chromophore that does the actual capture of light (photons).

The chromophore is called retinal, a form of vitamin A, or carotene.

Molecular basis of vision: chromophores and opsins

- The visual pigment consists of a protein (opsin) and a chromophore.
- One can find, in vertebrates, four different opsins and two chromophores.
  - Three of the opsins are associated with color vision (*photopsins* or *iodopsins*, found in cones) and one with night vision (*rhodopsin*, found in rods).
  - The two vertebrate chromophores are retinal (found in terrestrial animals and ocean fish) and dehydroretinal (found in tadpoles and freshwater fish; forms *porphyropsin*).
- The combinations of chromophore and opsin result in markedly different sensitivity to different wavelengths (colors) of light.

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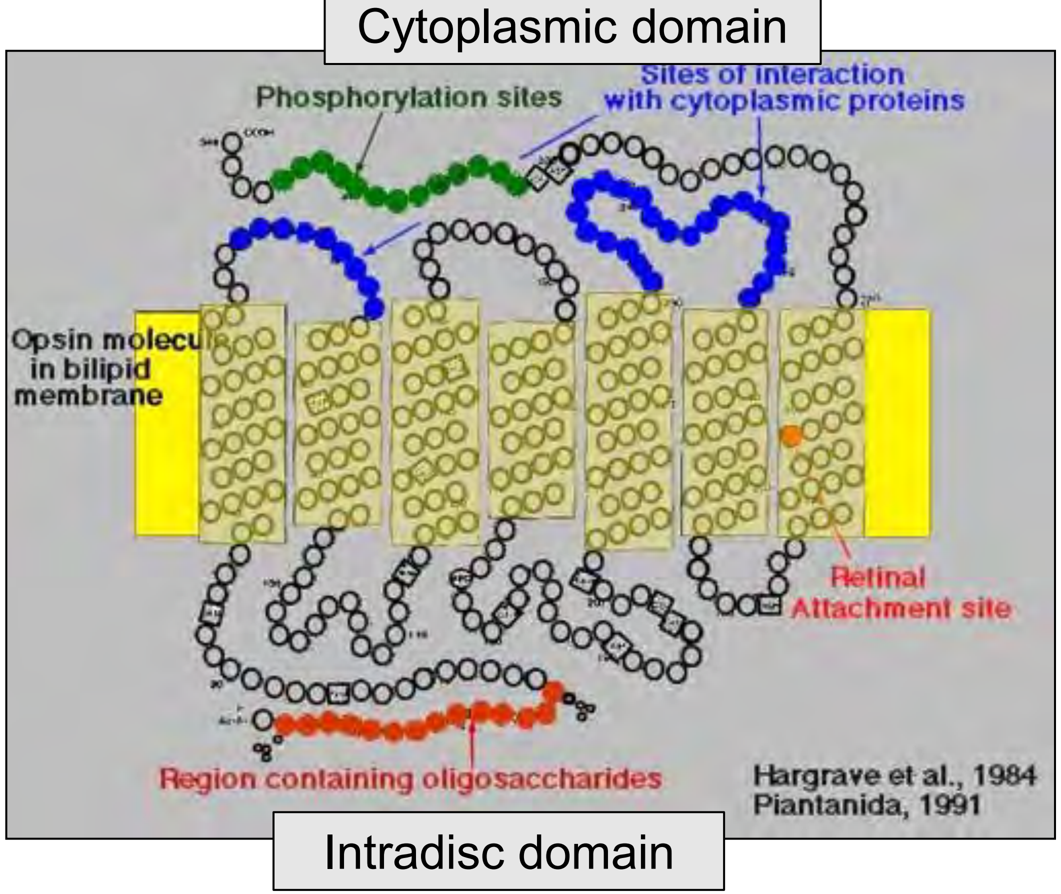
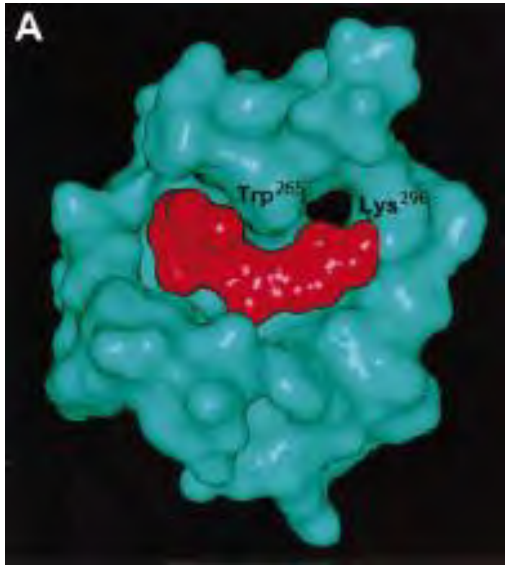
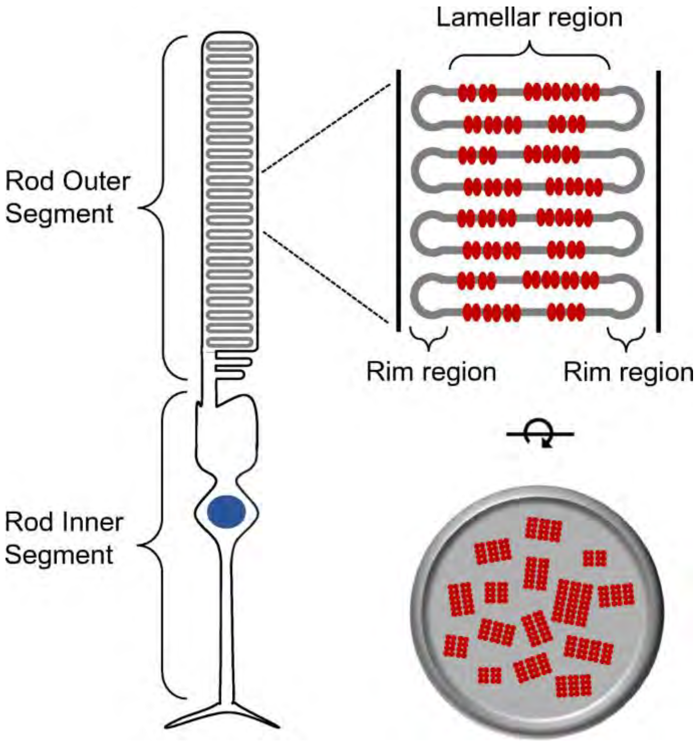
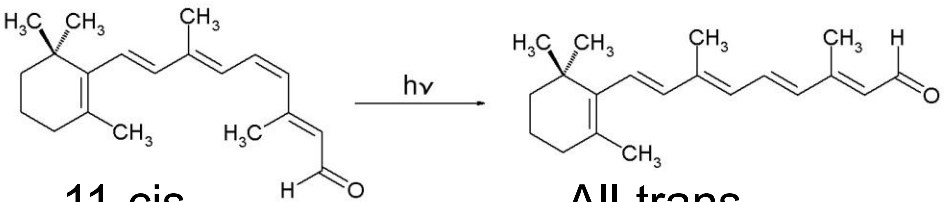


Rhodopsin



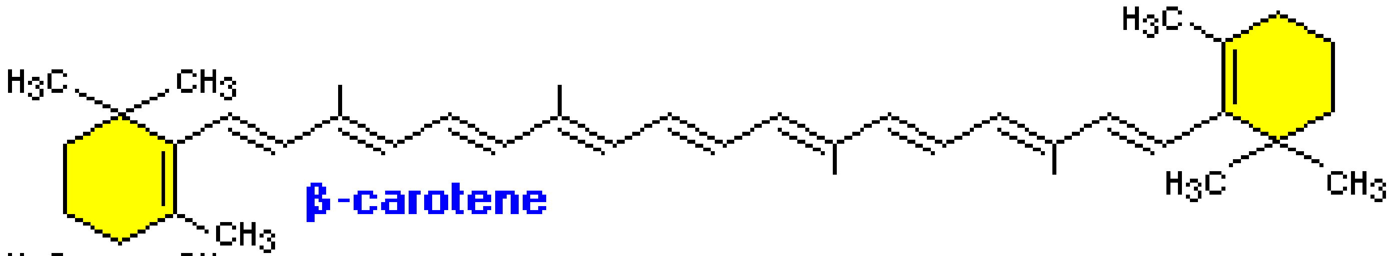




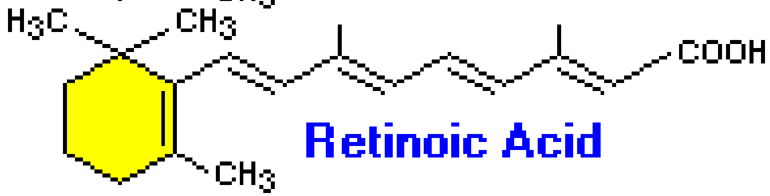
11-cis
retinal

All-trans
retinal

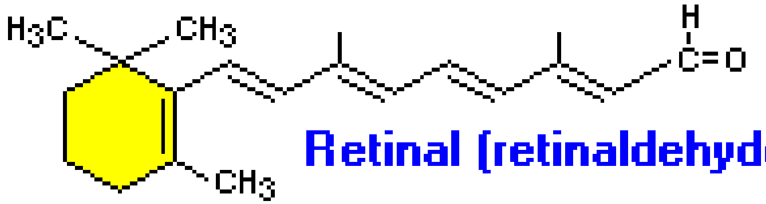
Vitamin A and Vision



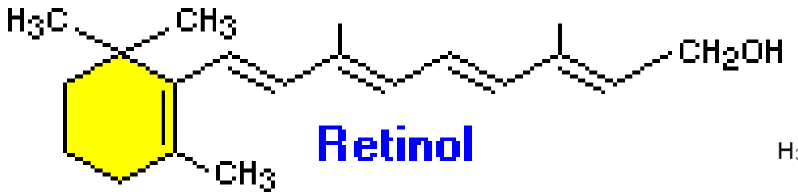
β-carotene



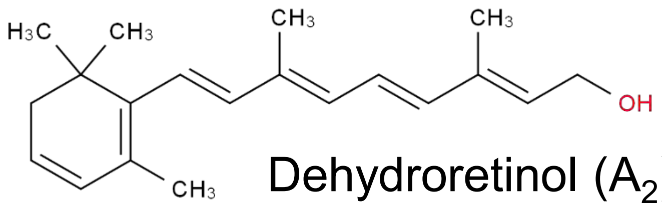
Retinoic Acid



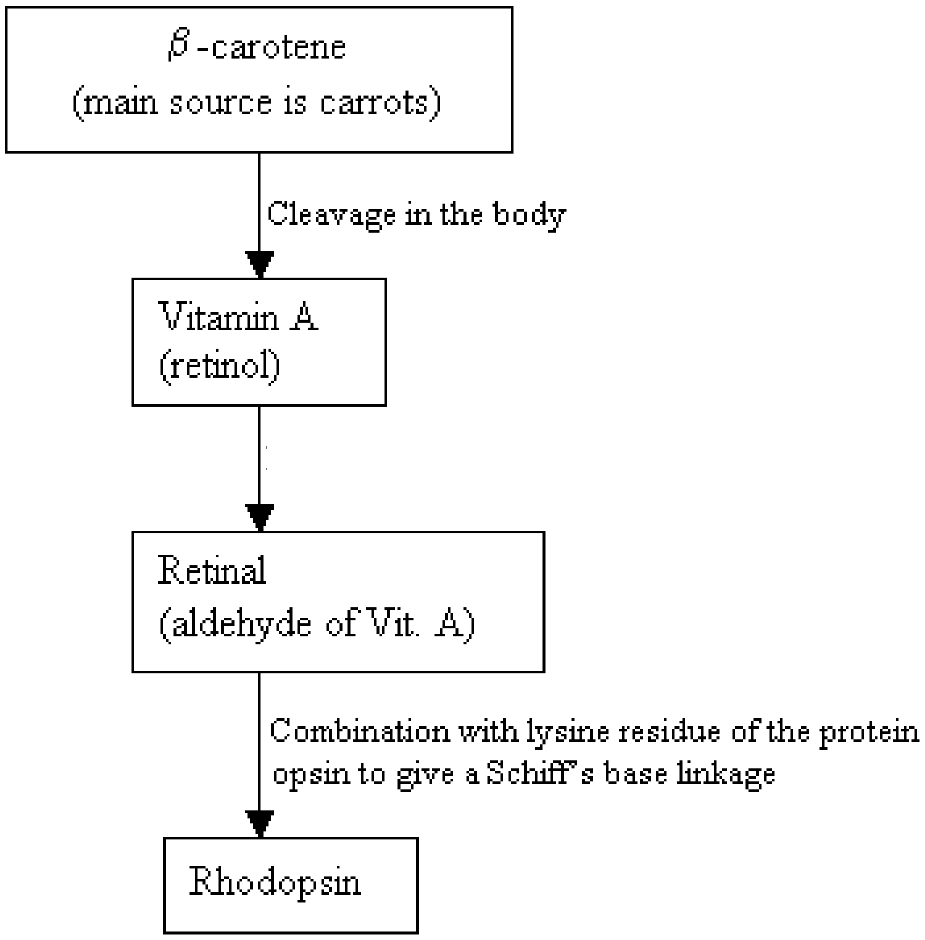
Retinal (retinaldehyde)

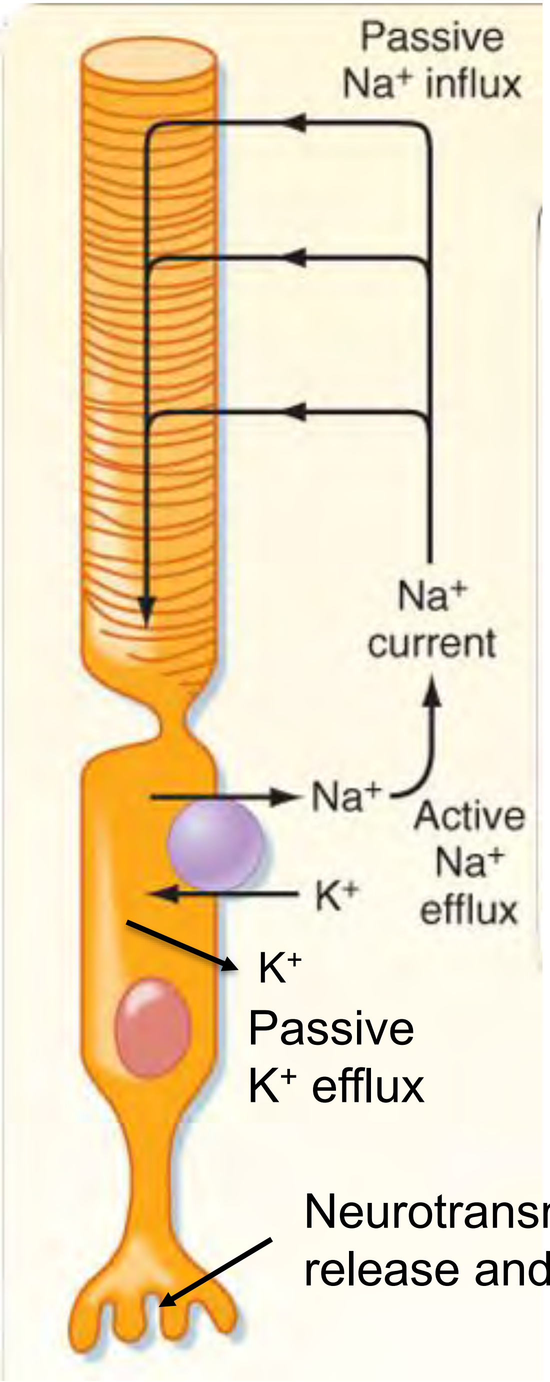


Retinol



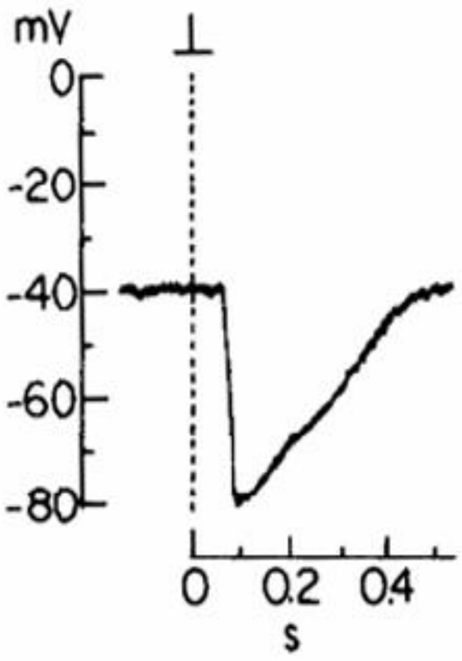
Dehydroretinol (A_2)





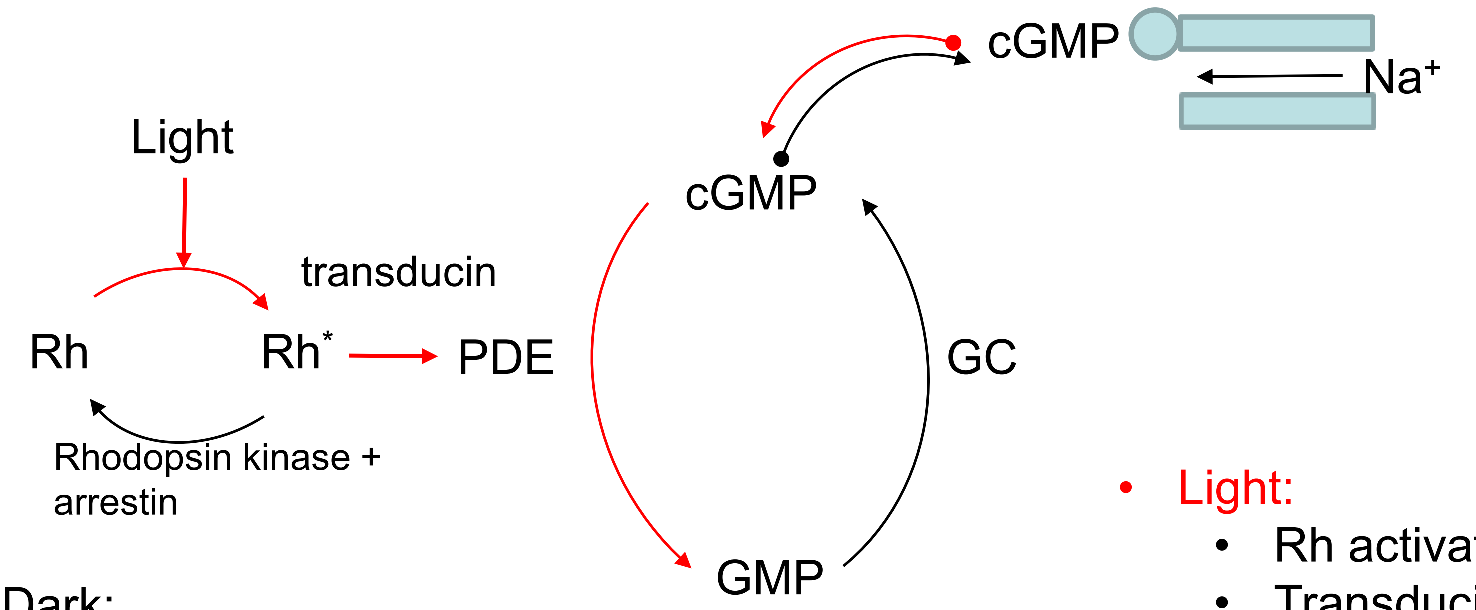
How Photoreceptors Work: The Dark Current

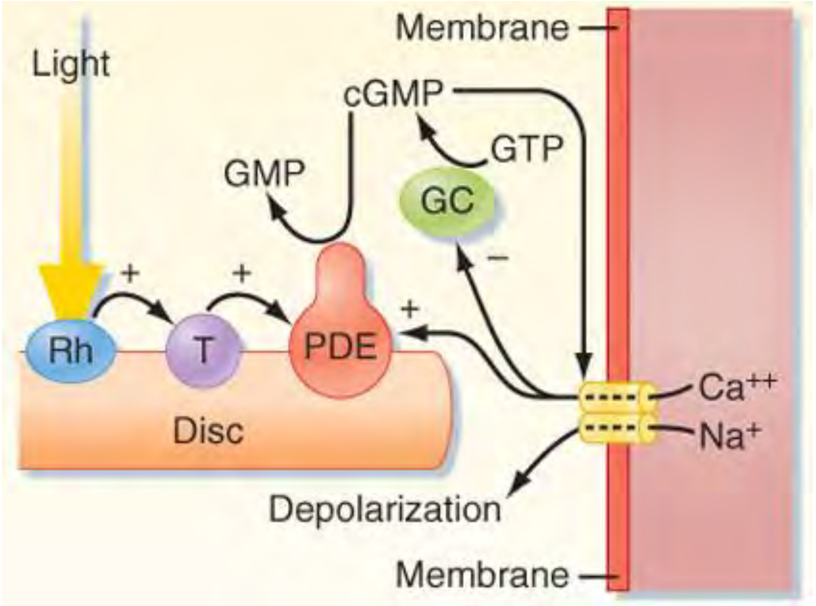
- In the dark, channels in the membrane of the outer segment are open and allow sodium to flow down a concentration gradient into the cell. This depolarizes* the cell.
    - The sodium flows down to the inner segment where it is actively pumped out (uses ATP energy) in exchange for potassium.
- The depolarization causes neurotransmitter (glutamate) to be released at the synaptic end.
- In response to light the channels close, the photoreceptor repolarizes and the release of neurotransmitter slows or stops.
- Thus, photoreceptors are most active in the dark.



*makes the inside of the cell less negative.

How Photoreceptors Work: The Visual Cascade



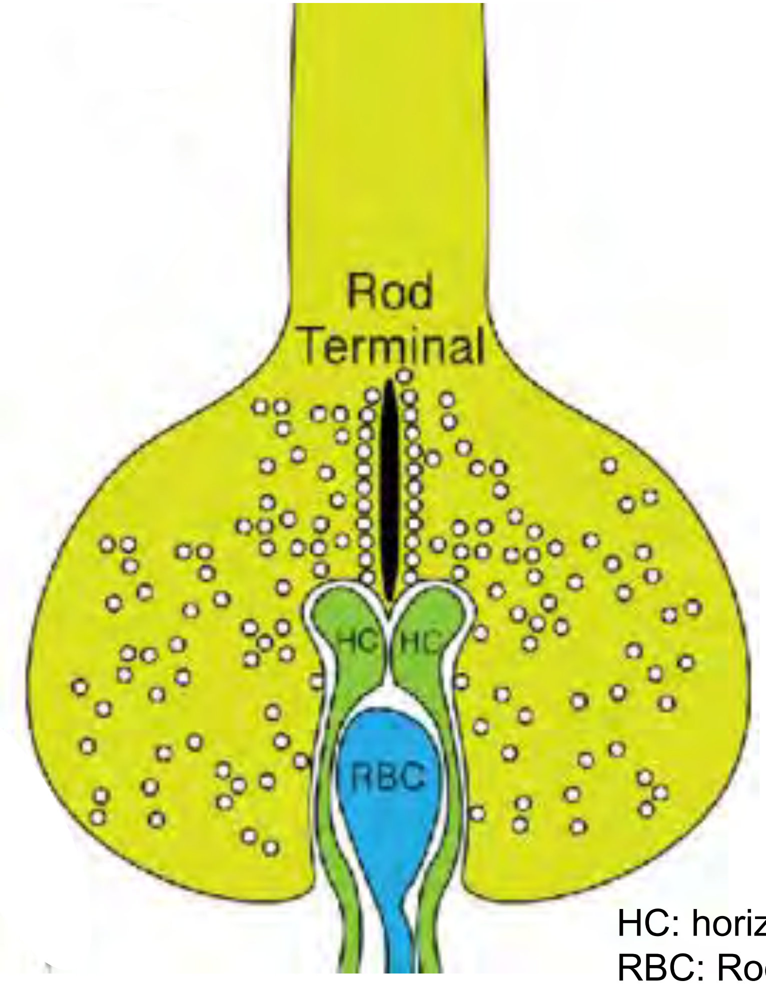


- Dark:
  - GC converts GMP to cGMP
  - cGMP binds to channels, opens them
  - Na^+ flows in, depolarizes cell

- Light:
  - Rh activated, releases transducin
  - Transducin activates PDE
  - PDE converts cGMP to GMP
  - GMP lost from channels, channels close
  - Na^+ flow stops, cell hyperpolarizes

Key: Rh: rhodopsin; PDE: phosphodiesterase; GC: guanadyl cyclase; cGMP: cyclic guanadyl monophosphate; T: transducin (Rh*)

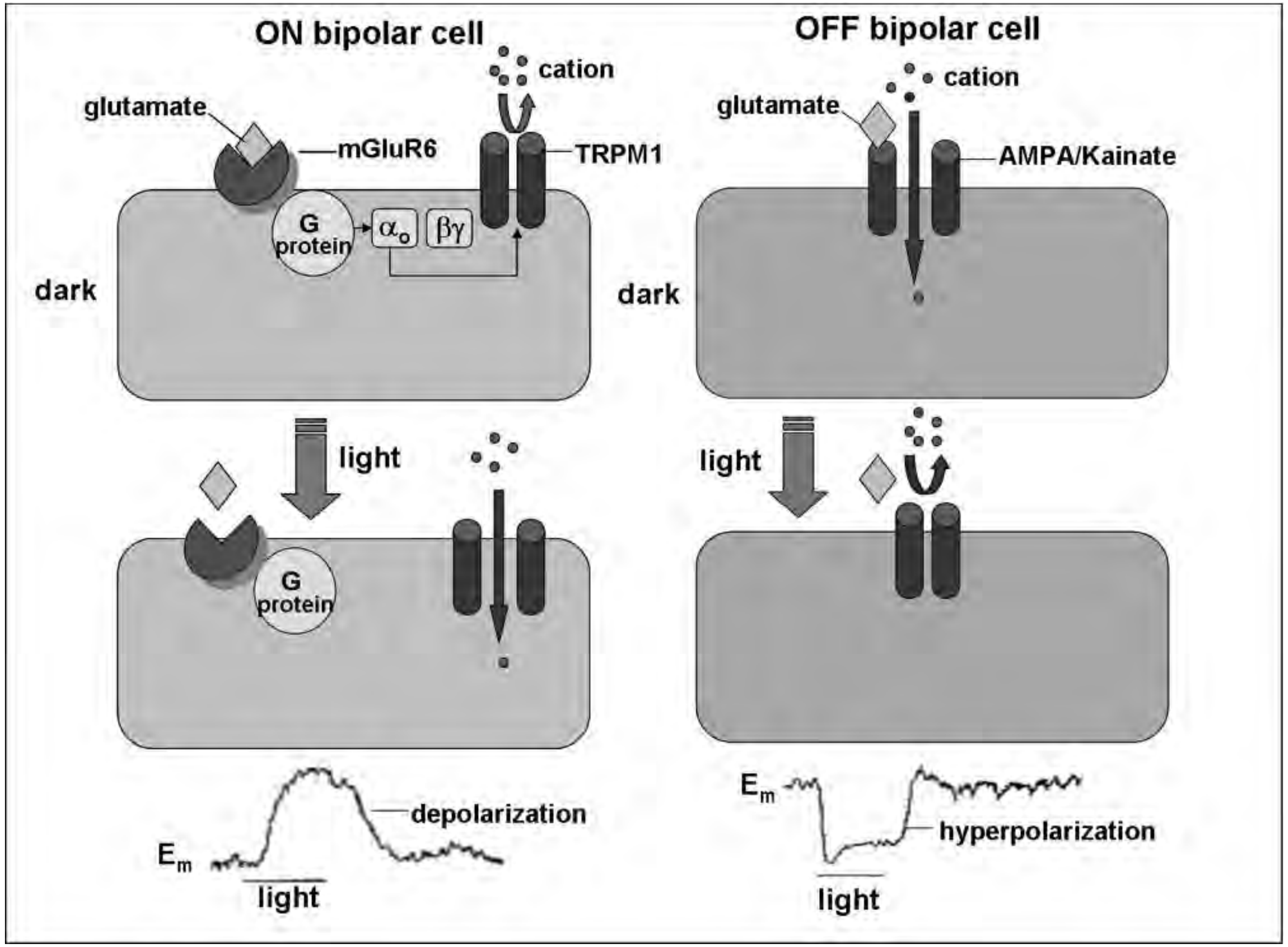
Photoreceptor Ribbon Synapse



The ribbon synapse acts like a conveyer belt to deliver synaptic vesicles in a graded manner to the presynaptic membrane. Found in photoreceptors and hair cells.

HC: horizontal cell (presynaptic)
RBC: Rod Bipolar Cell (postsynaptic)

“On” and “Off” bipolar cells

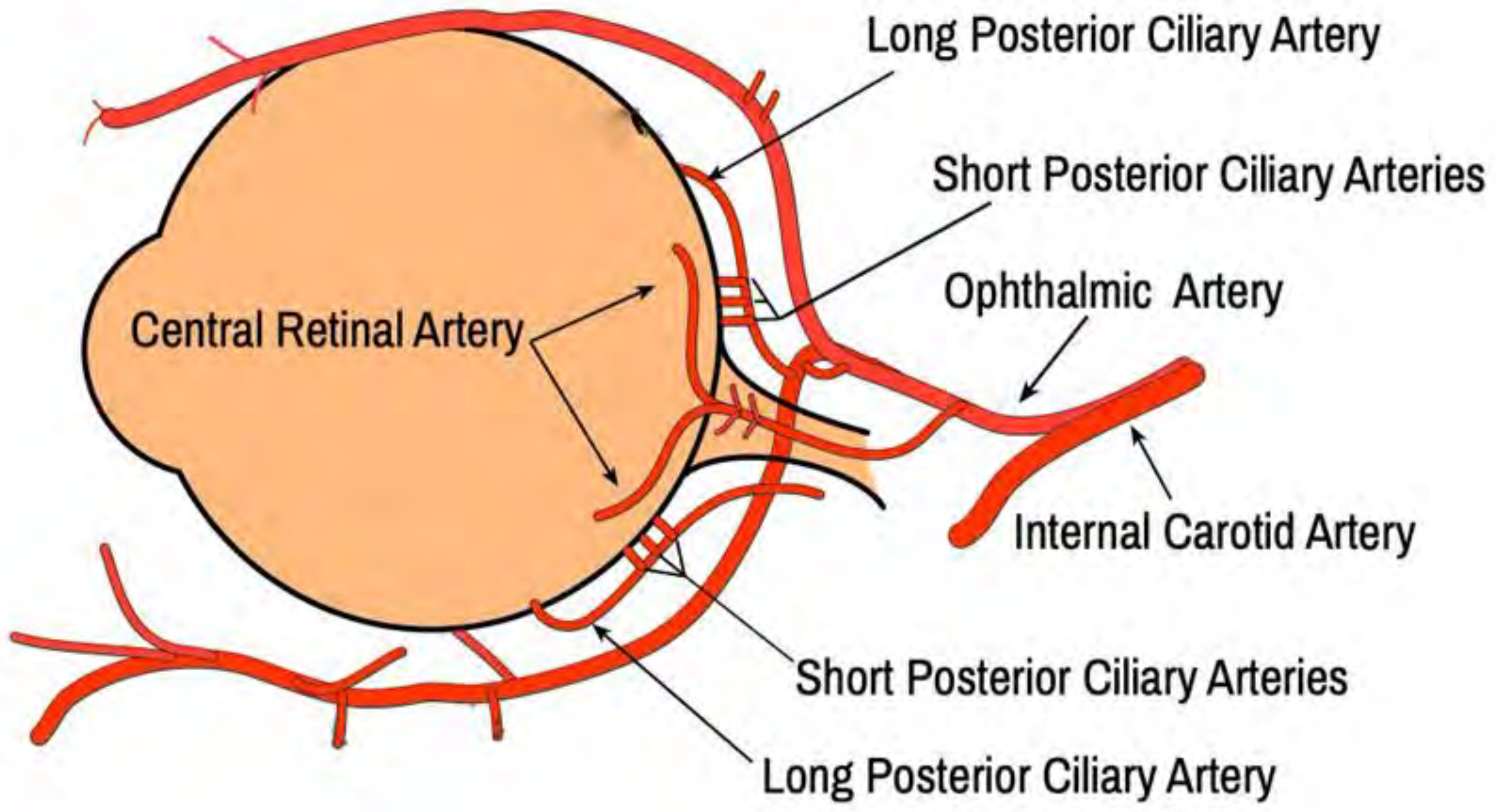


Photoreceptors release glutamate while in the dark.
When stimulated by light, they cease releasing glutamate.

- “Off” bipolar cells respond to glutamate by depolarizing.
  - In the dark they are depolarized (stimulated)
- “On” bipolar cells respond to glutamate by hyperpolarizing.
  - In the dark they are hyperpolarized (inhibited).

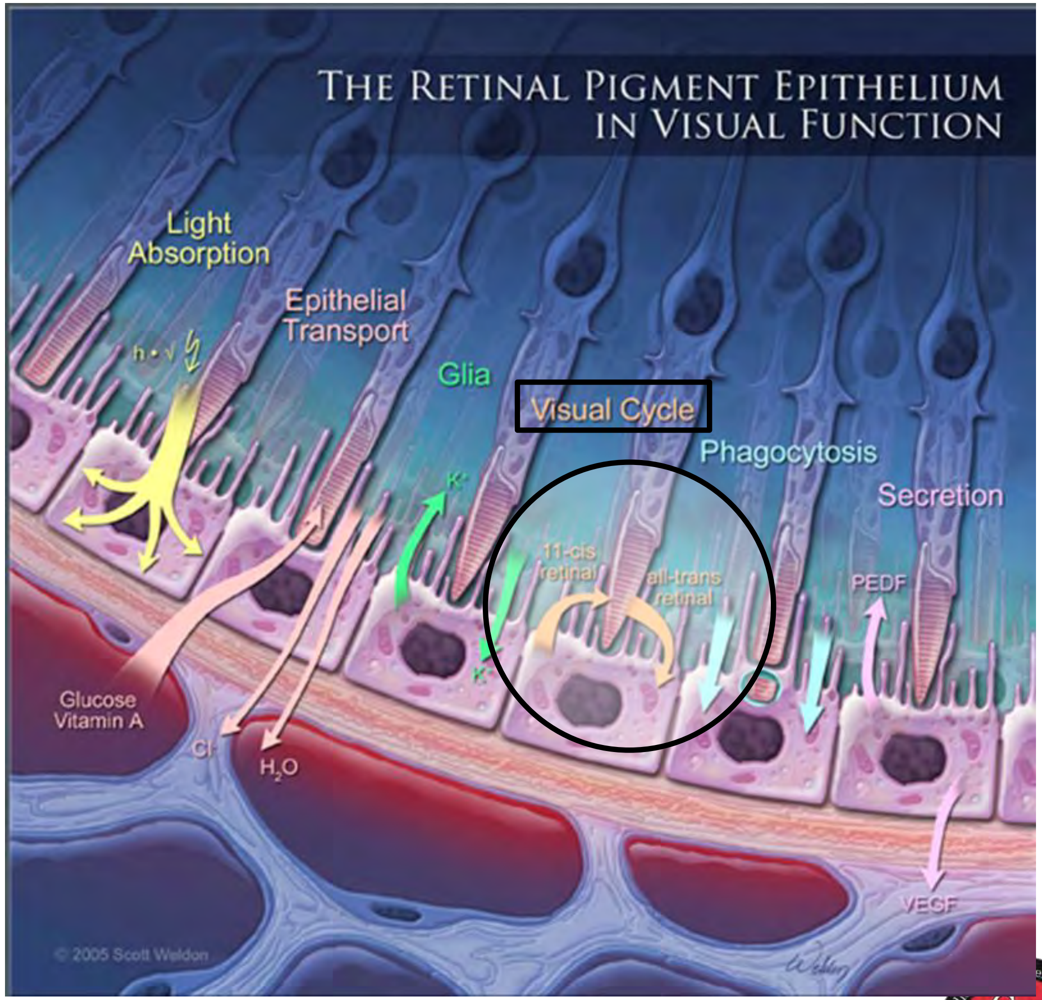
Thus:
Light *decreases* glutamate release and
Hyperpolarizes (inhibits) “off” bipolars
and
Depolarizes (stimulates) “on” bipolars

Dual Circulation serves a very active tissue

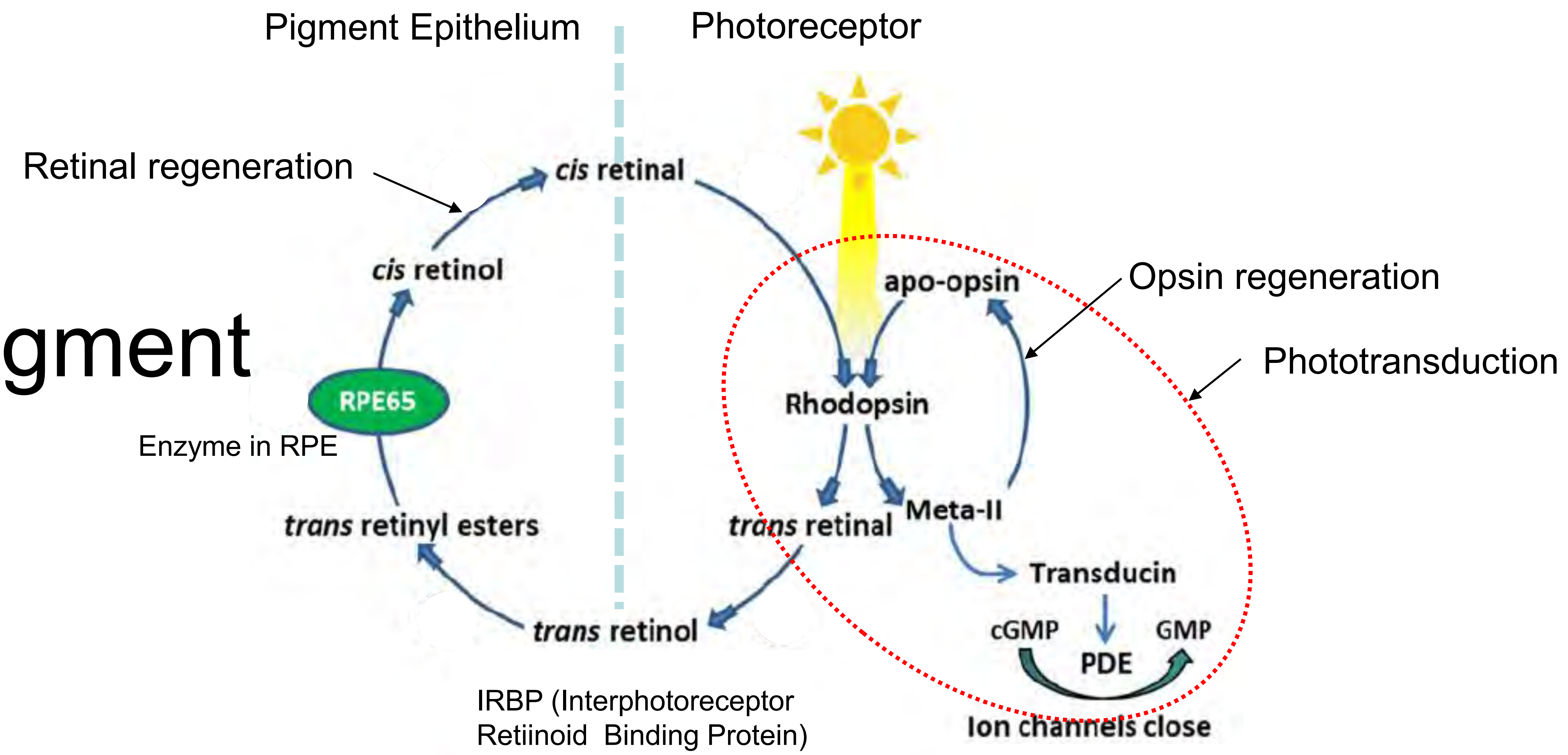


The Visual Cycle: recovery

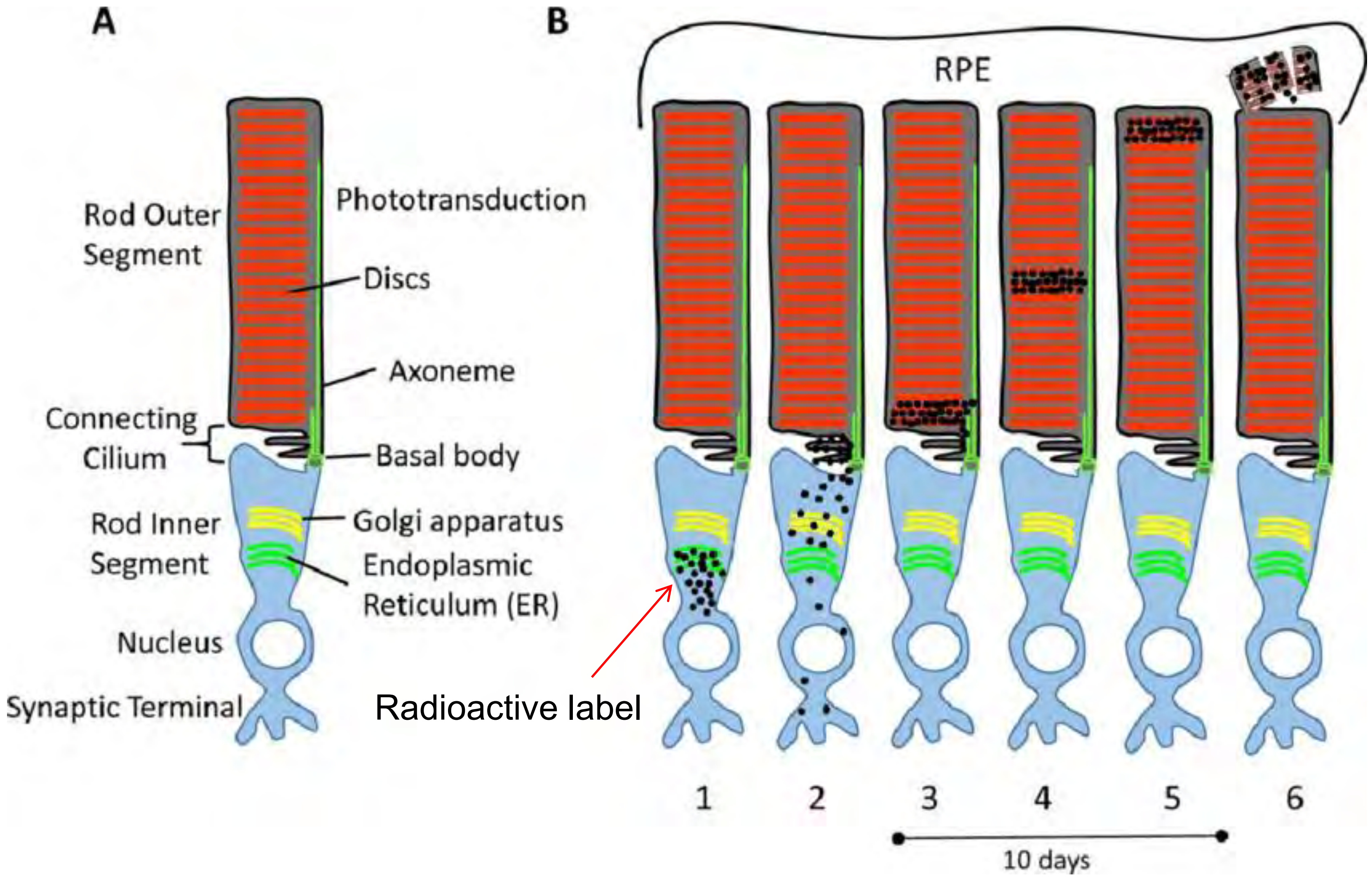
- The actual mechanism of light stimulation is that native 11-cis retinal is isomerized by light to all-trans retinal.
- This sets off the cascade.
- Eventually the all-trans retinal pops off the opsin.
- It must travel from the receptor to the pigment epithelium in order to be regenerated to the 11-cis form.
- This is the major limiting factor in dark adaptation (non-neural).



The photopigment cycle



Photoreceptor turnover



Membrane protein transport in photoreceptors: the function of PDEd: The Proctor lecture. Invest Ophthalmol Vis Sci.**55**:8653-8666, 2014

Recycling of Photoreceptors

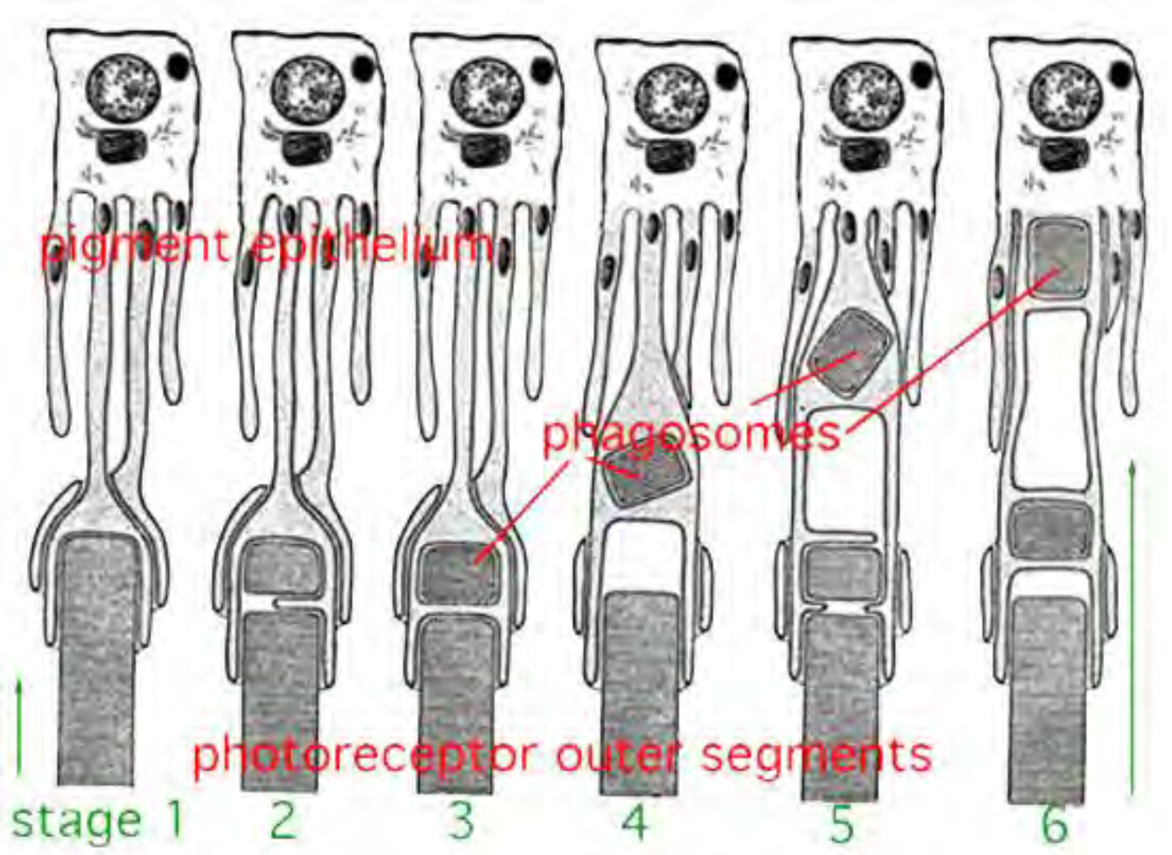
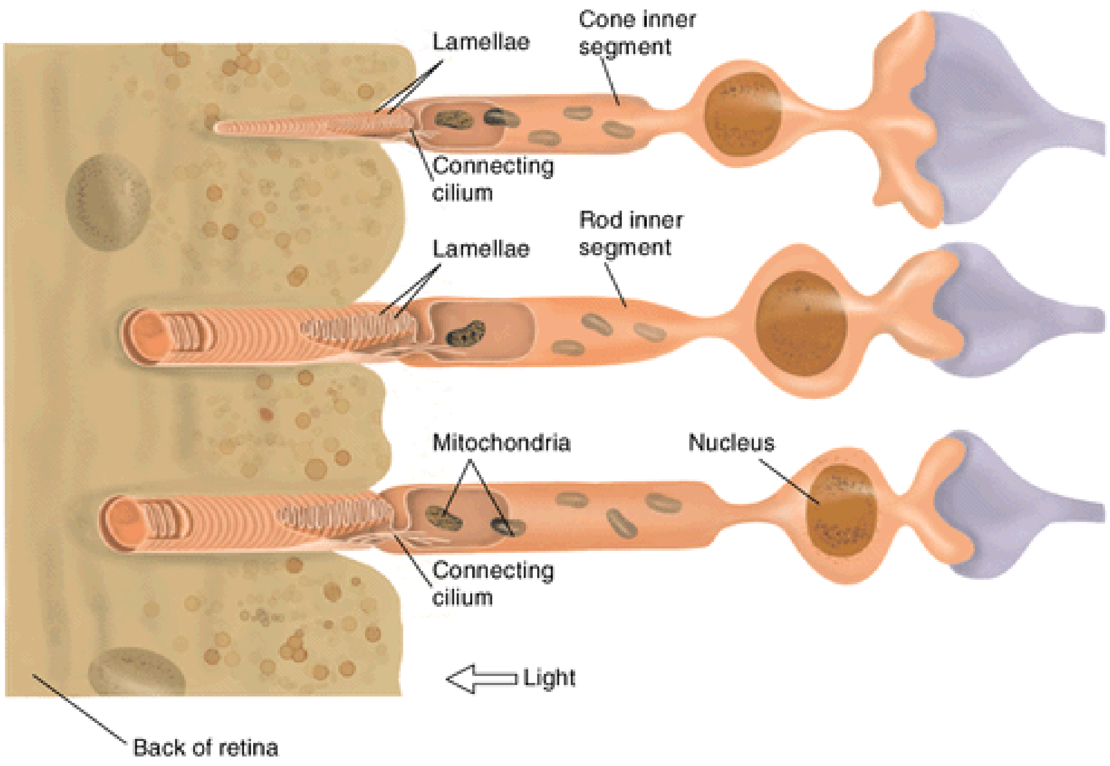
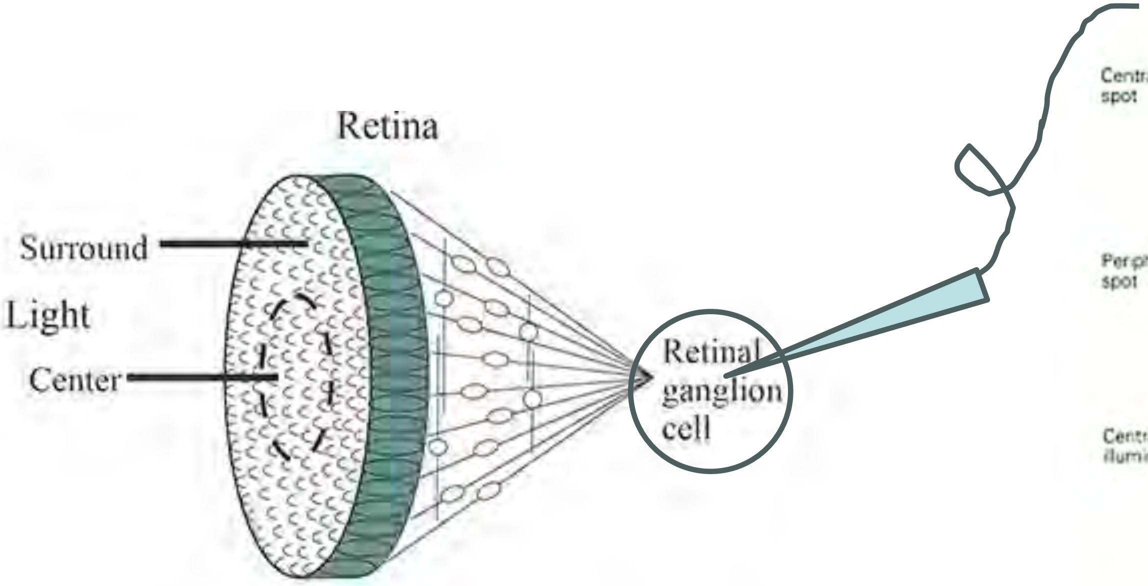


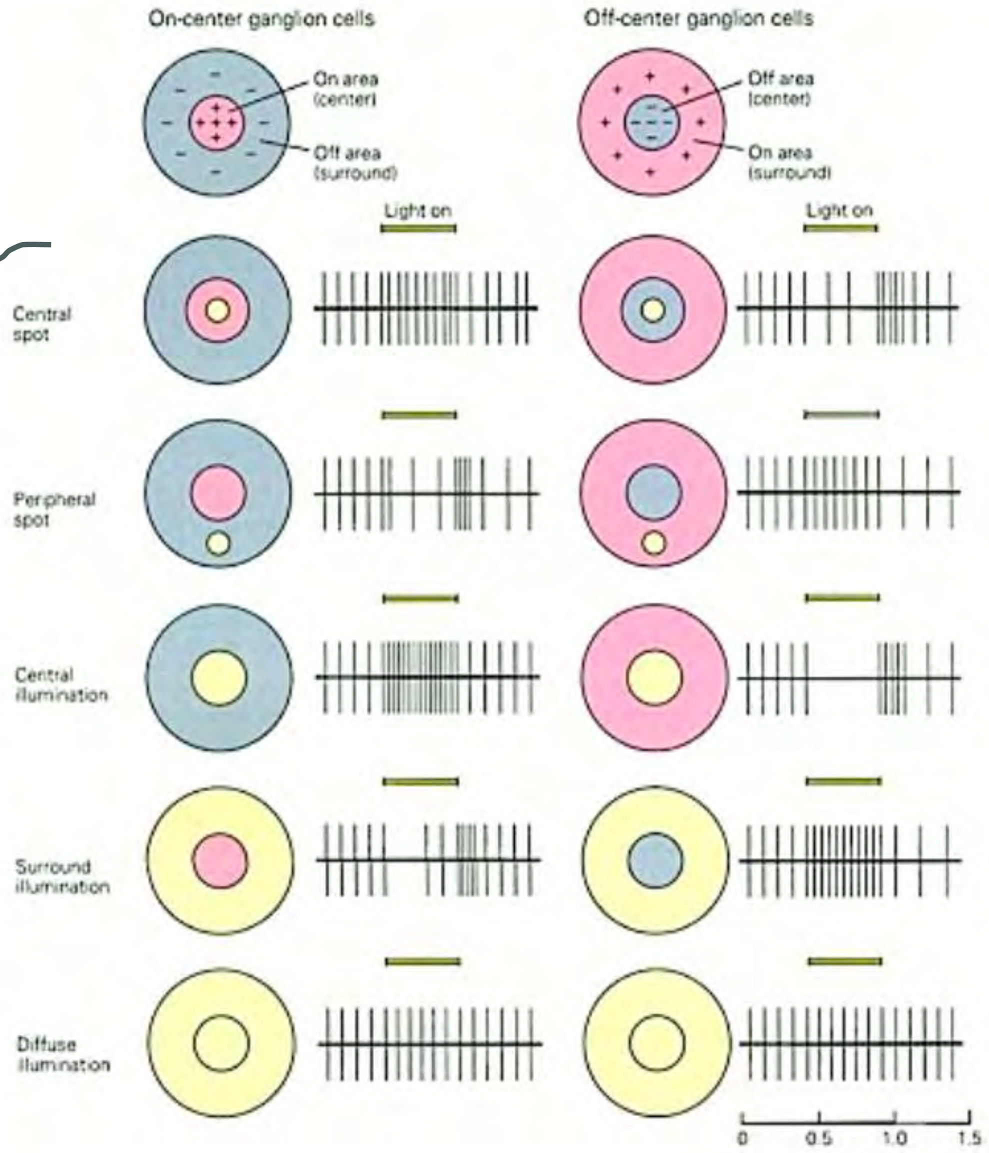
Fig. 12. Diagrammatic representation of disc shedding and phagosome retrieval into the pigment epithelial cell.



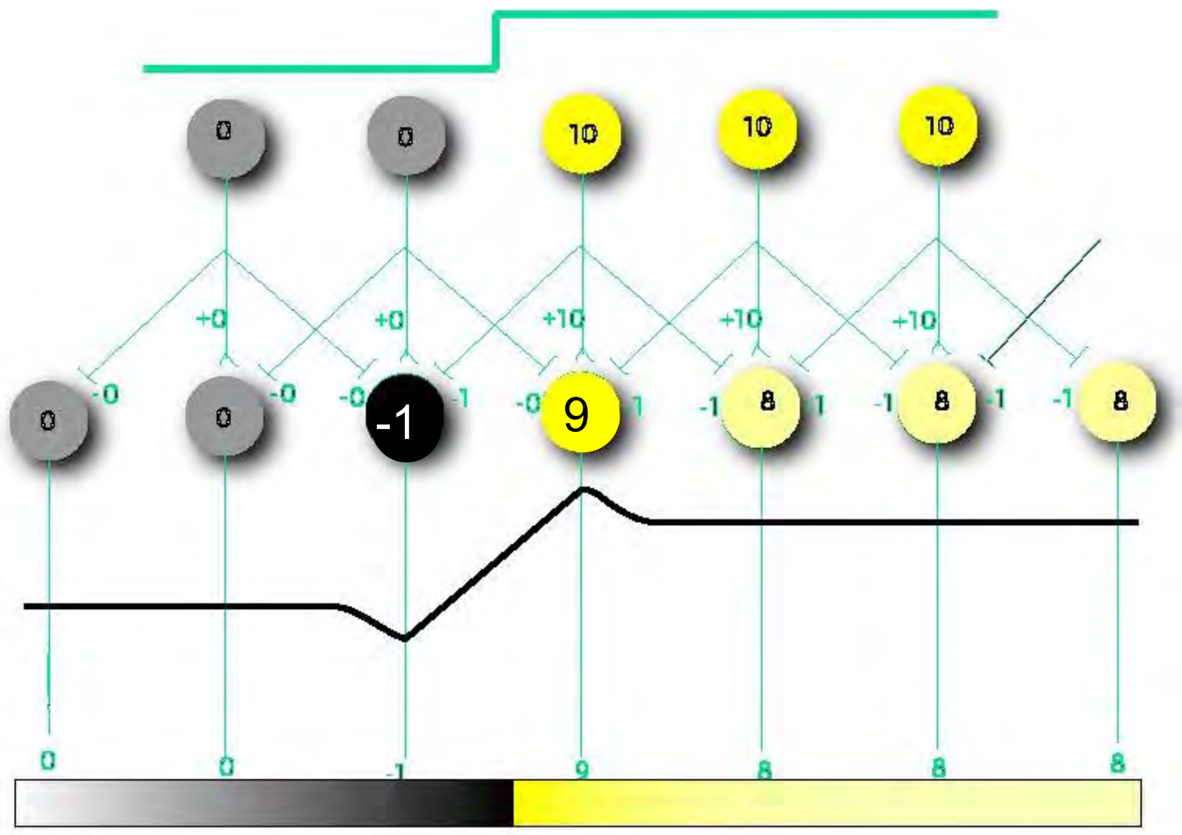
Visual Processing in the Retina

Simple Receptive Fields: Center/Surround

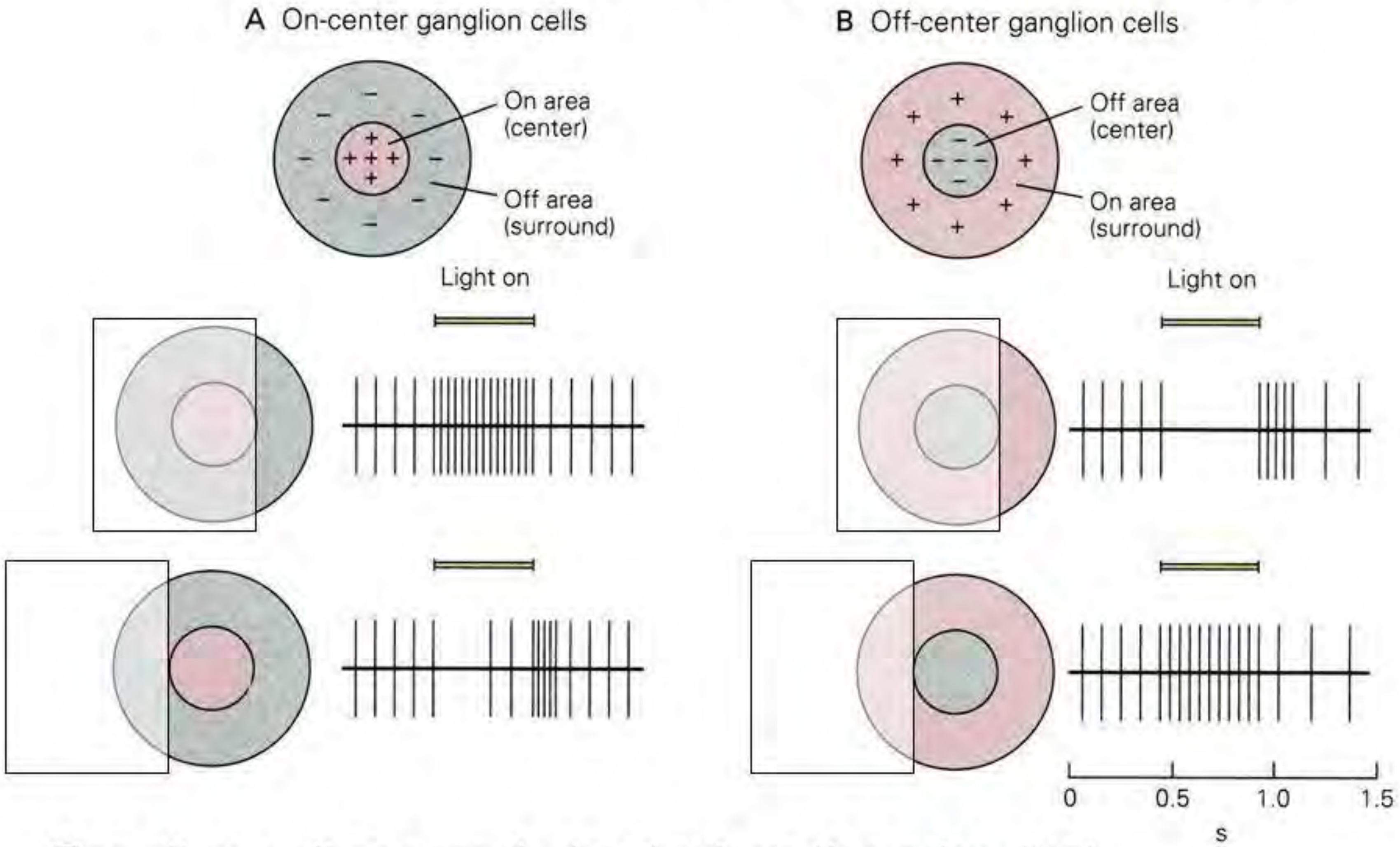




Lateral Inhibition and Edge Enhancement



Edge detection begins in the retina

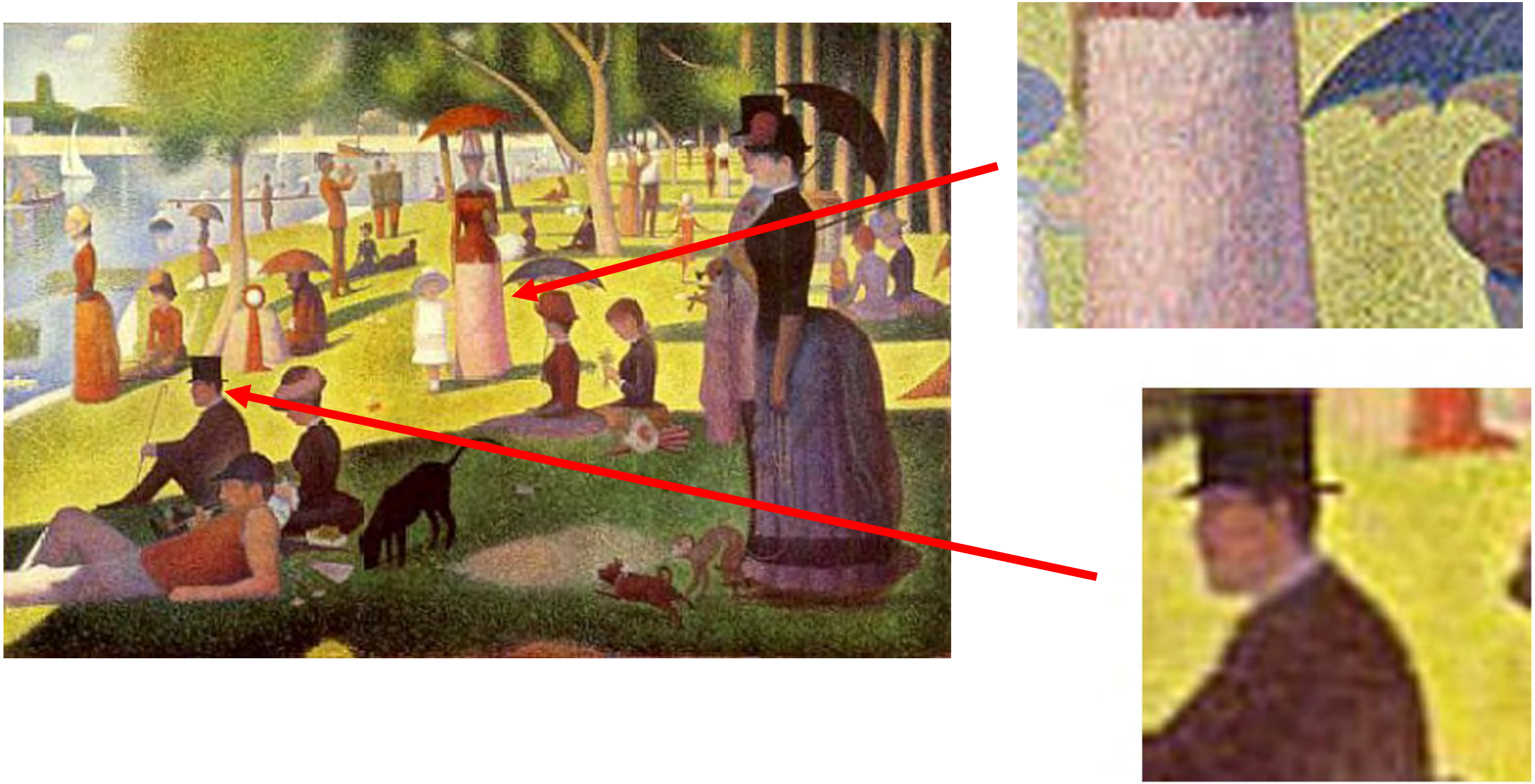


- Ganglion cell responds best when the edge just touches the central region of the receptive field

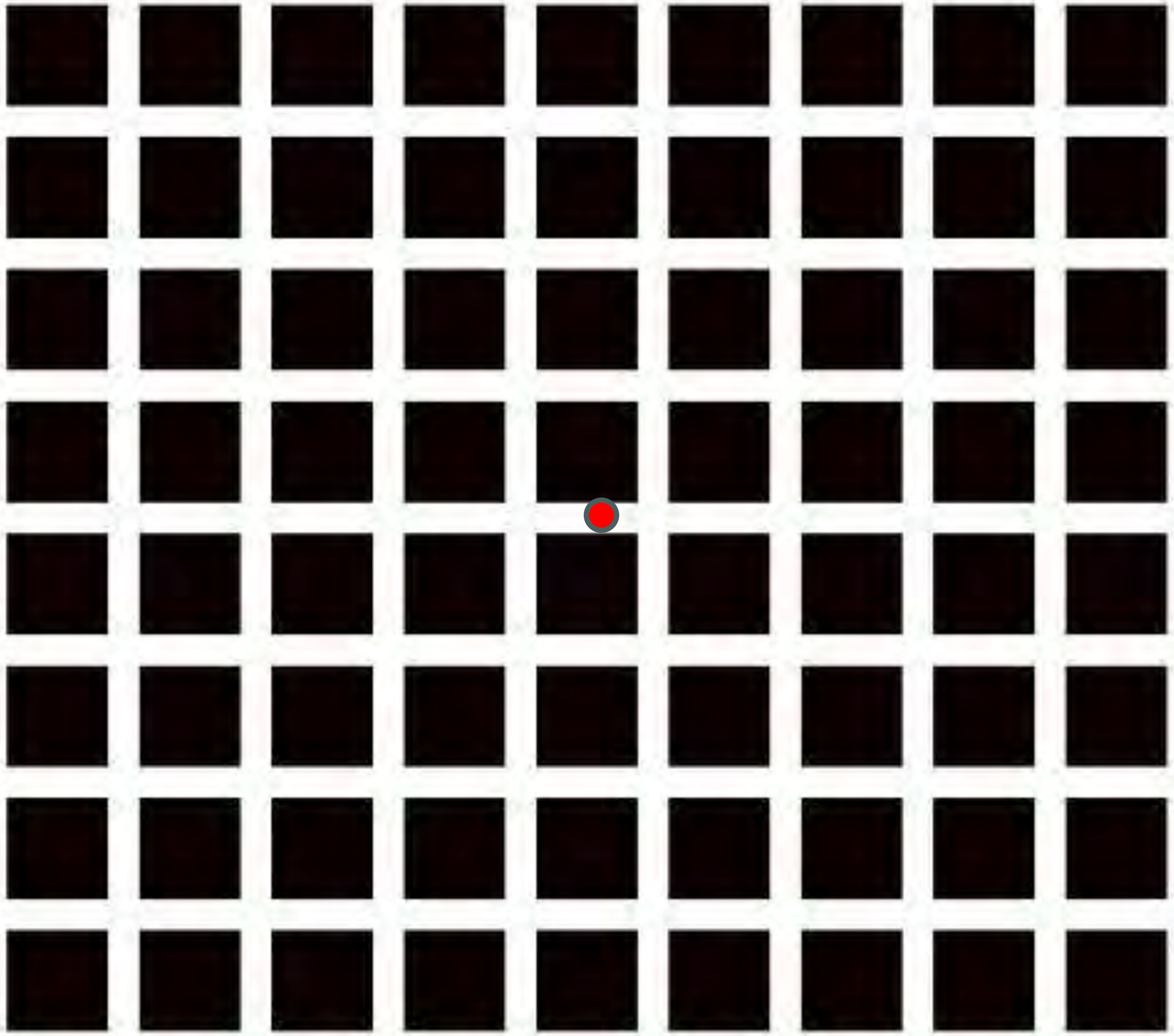
(Kandel et al)

Mach Bands

Mach Bands and Art

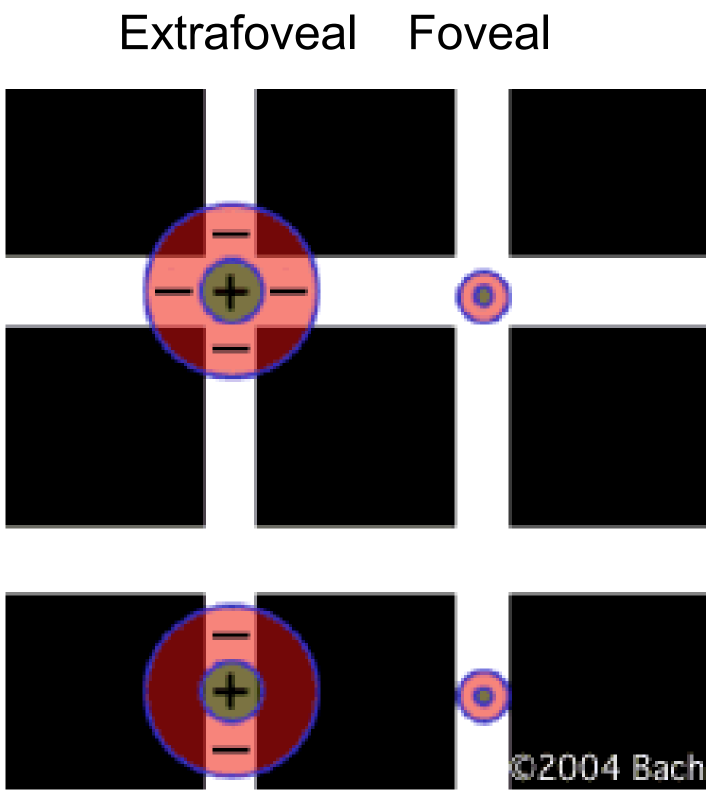


Center-Surround in Action: Hermann's Grid



Focus your eyes on the red spot.
Where do you see the dark spots??

Hermann's Grid and Center/Surround Fields

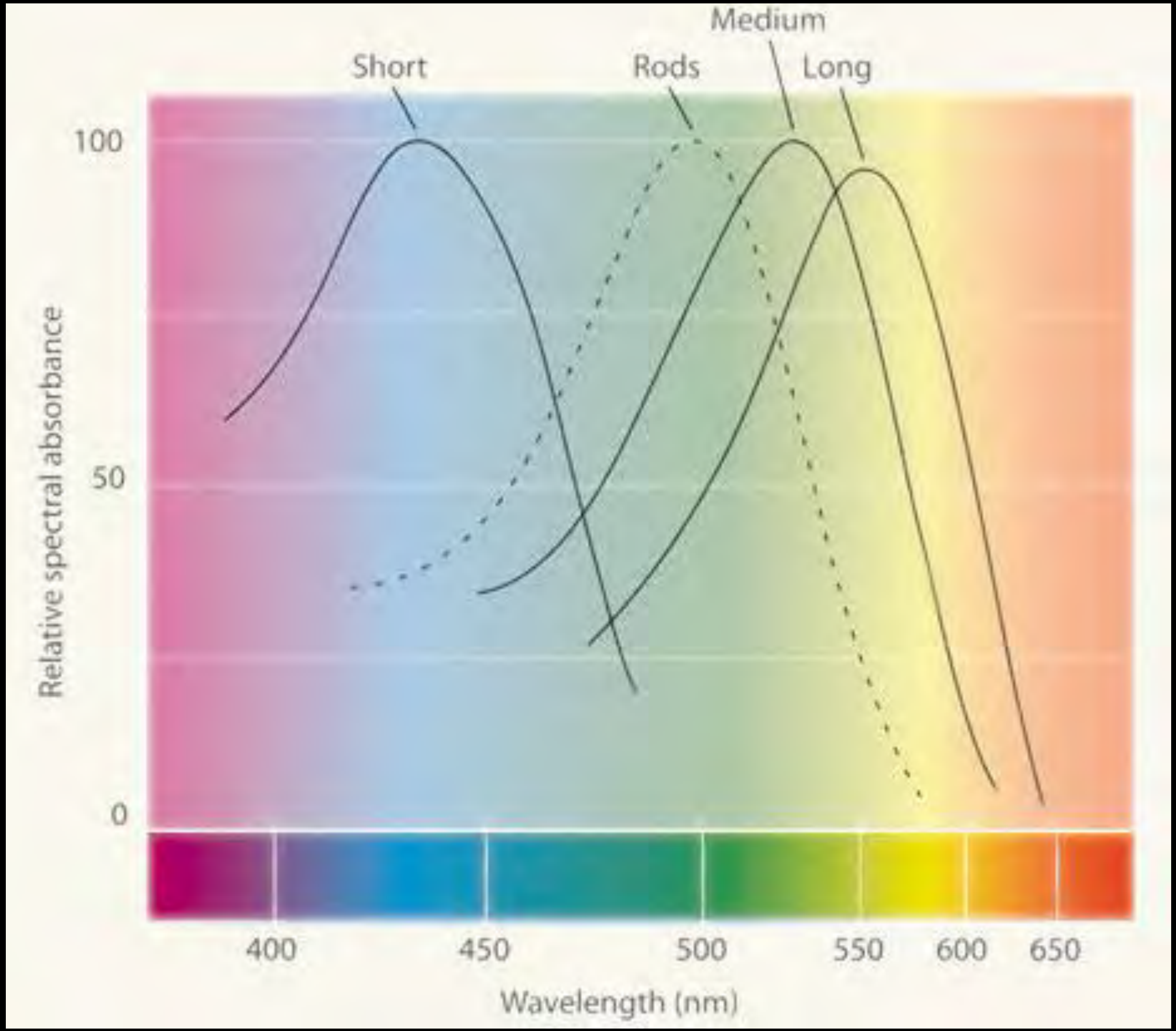


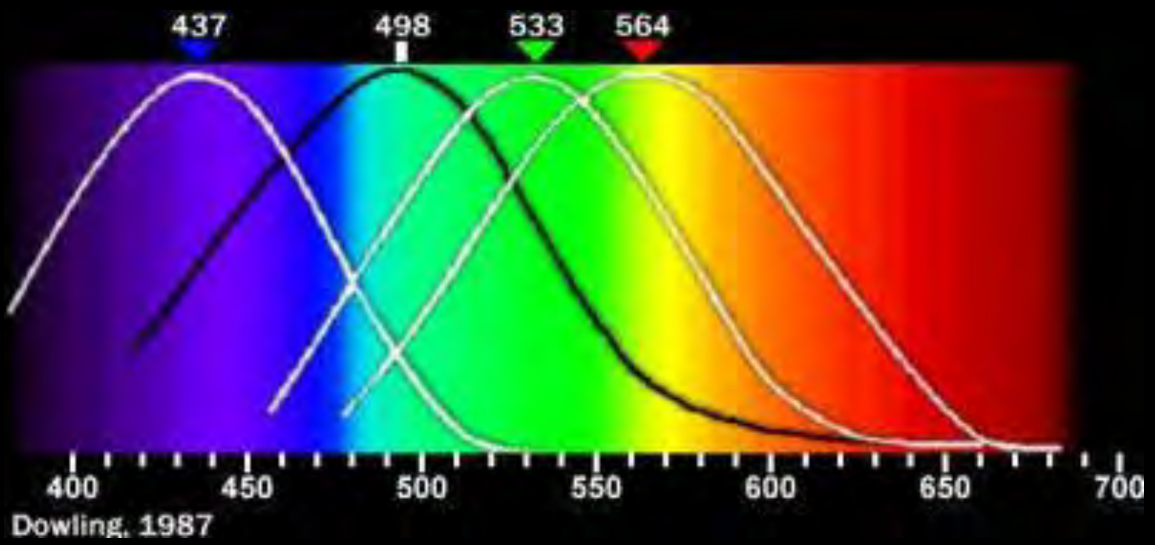
Extrafoveal	Intersection	On center stimulated; Off surround strongly stimulated	Dark spot
	Non-intersection	On center stimulated; Off surround weakly stimulated	No spot
Foveal	Intersection	On and Off centers equally stimulated	No spot
	Non-intersection	On and Off centers equally stimulated	No Spot

•Color Vision

" . . . And please let Mom, Dad, Rex, Ginger, Tucker, me and all of the rest of the family see color."

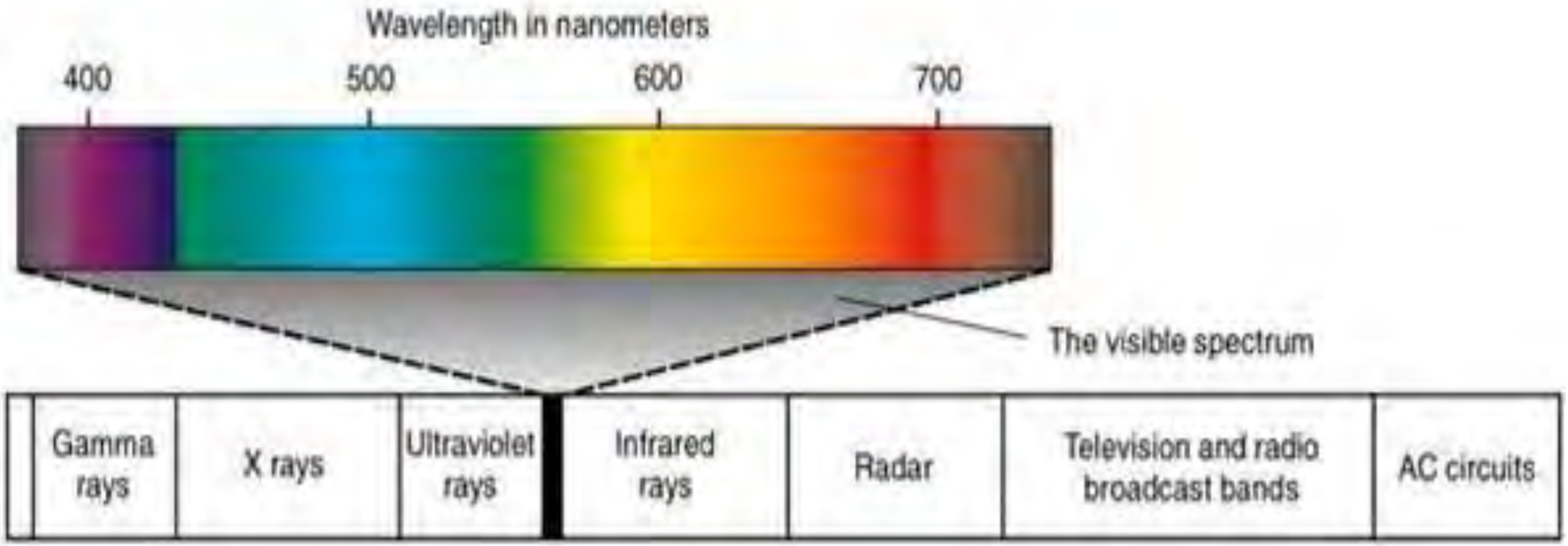
Spectral sensitivity of rods and cones





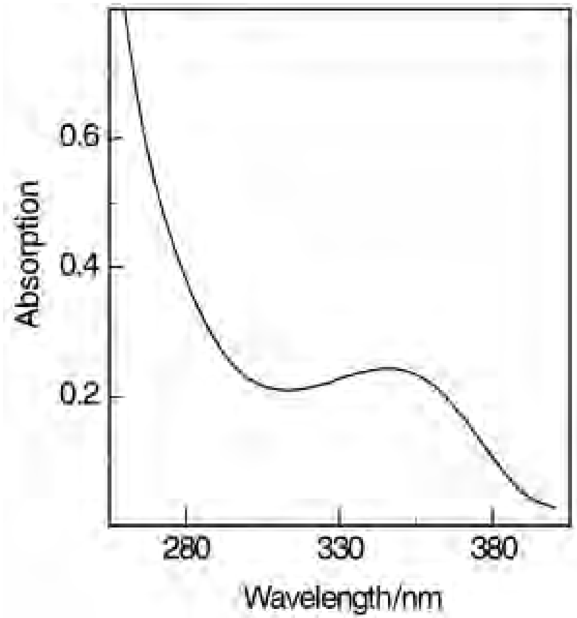
In all four cases the chromophore is retinal. It is the associated protein (opsin) that alters the wavelength sensitivity.

The Electromagnetic Spectrum

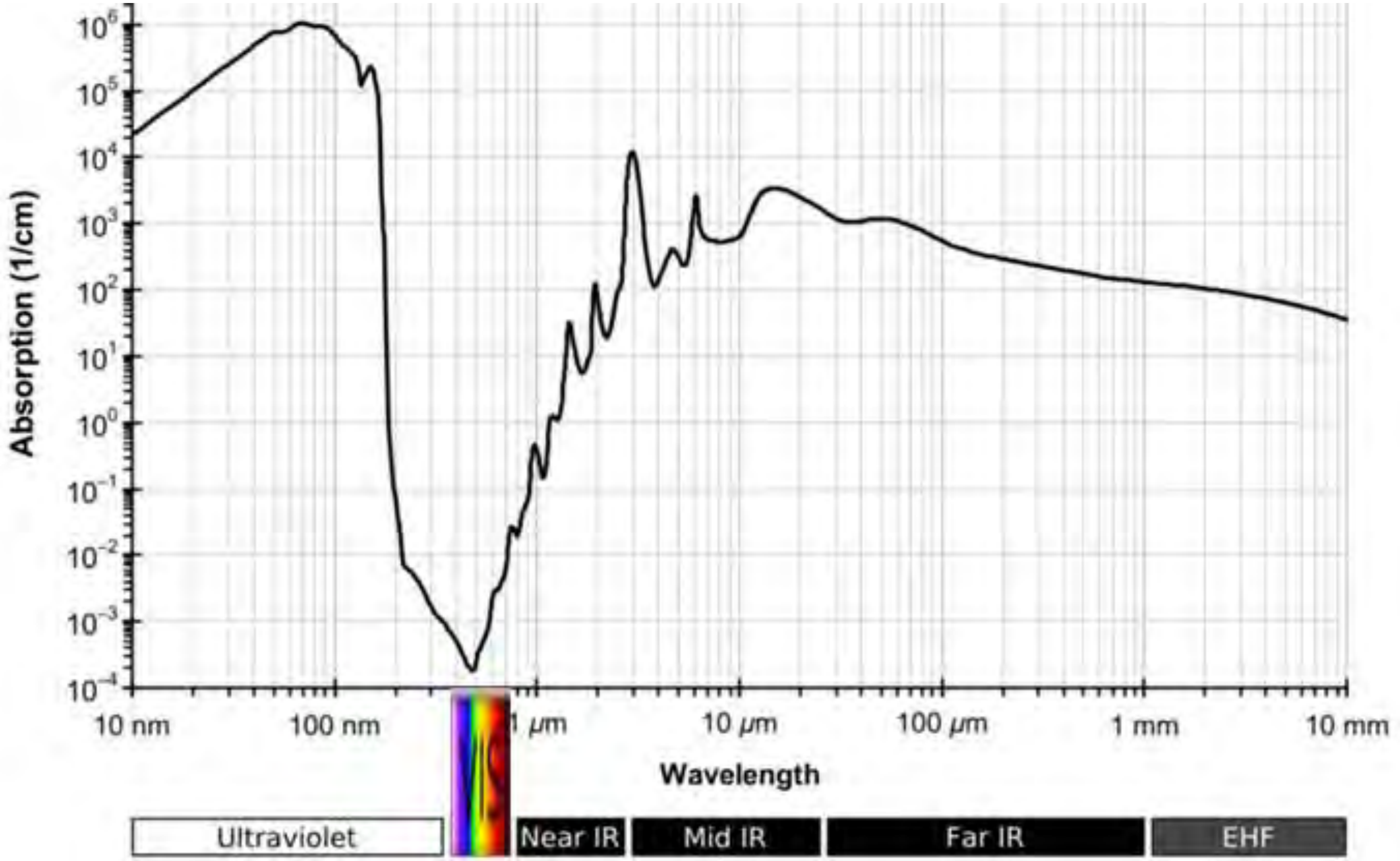


Atmospheric absorption

Ozone

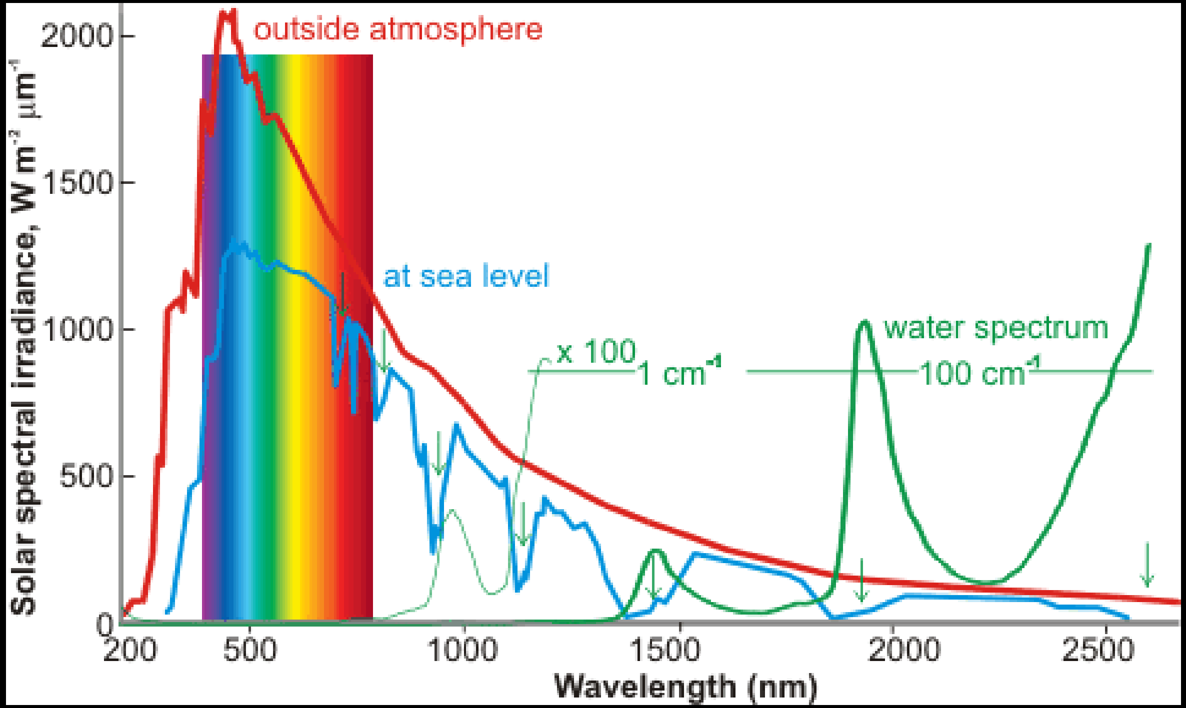


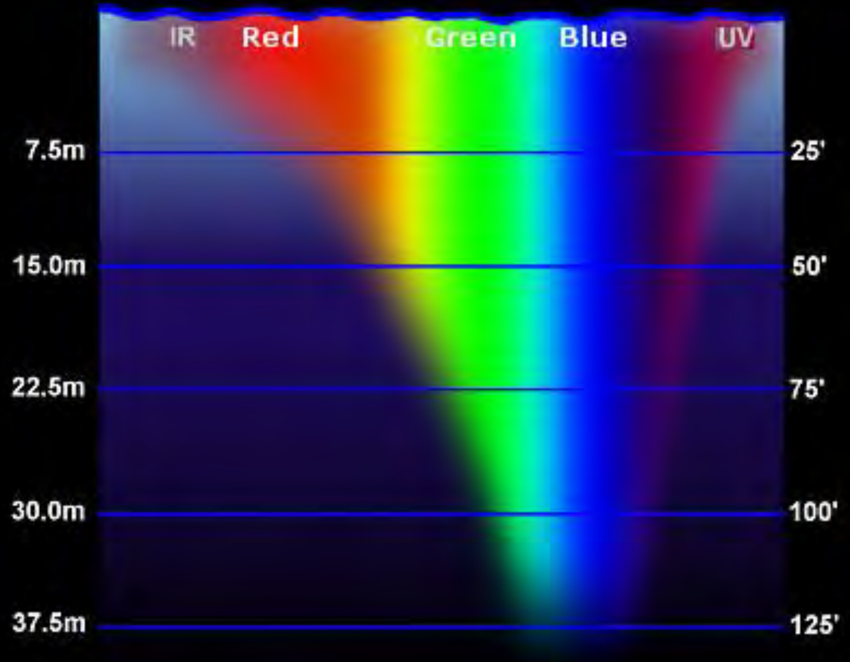
Water Vapor



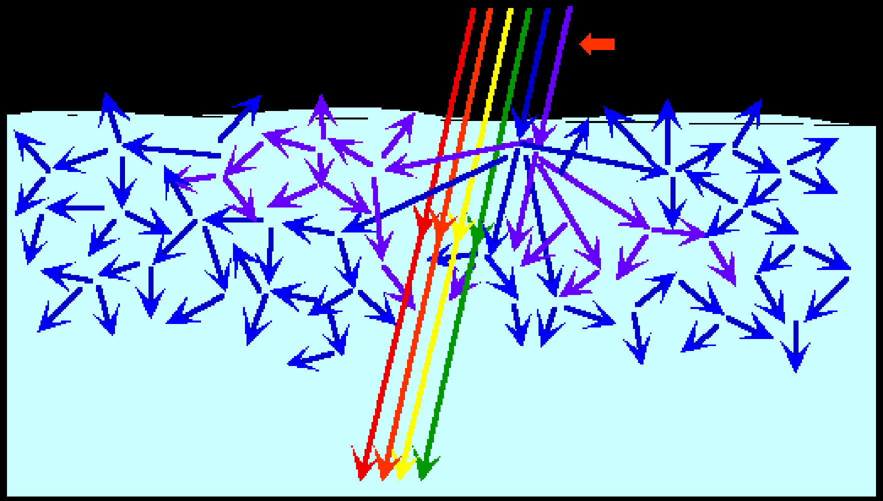
Specific spectral sensitivity of receptors is no coincidence.

Atmospheric absorption



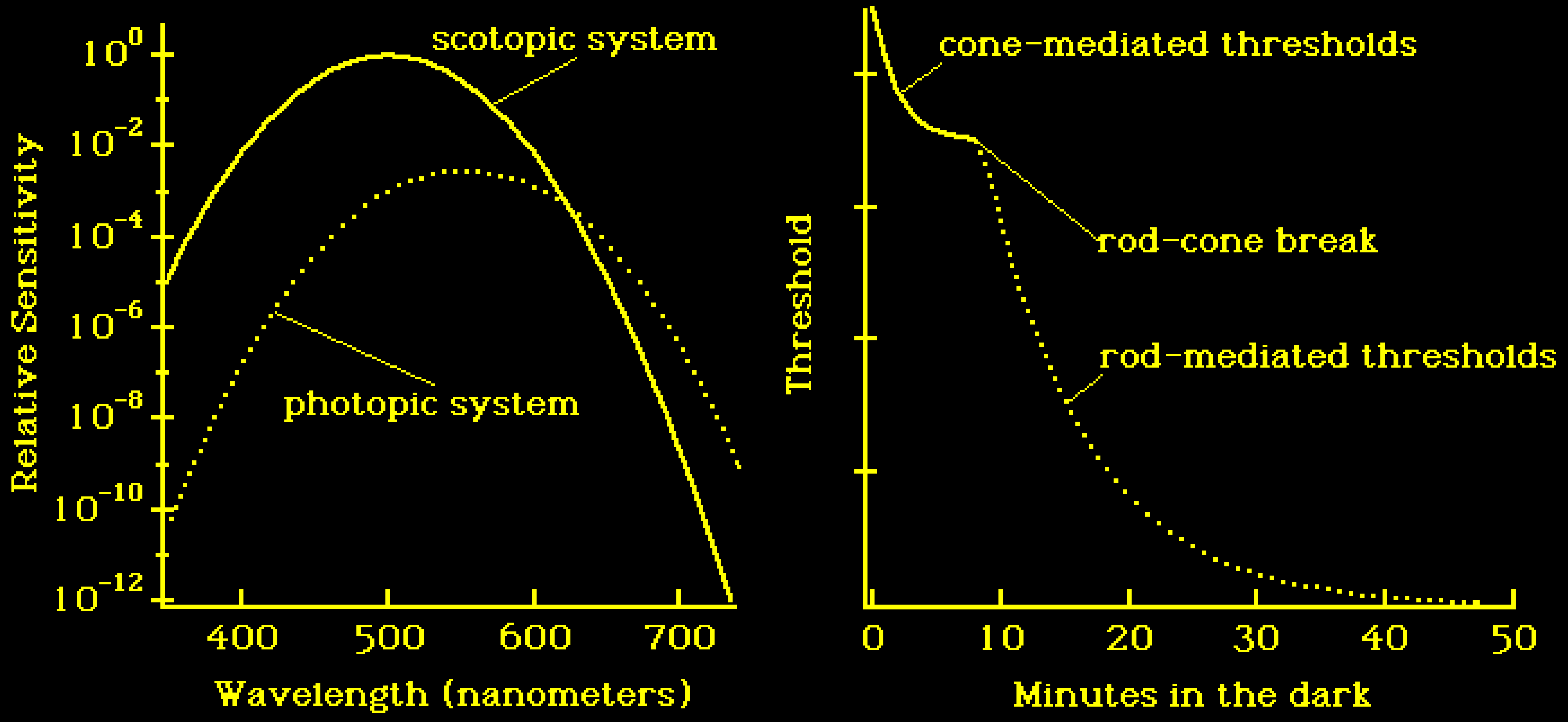


Sea water

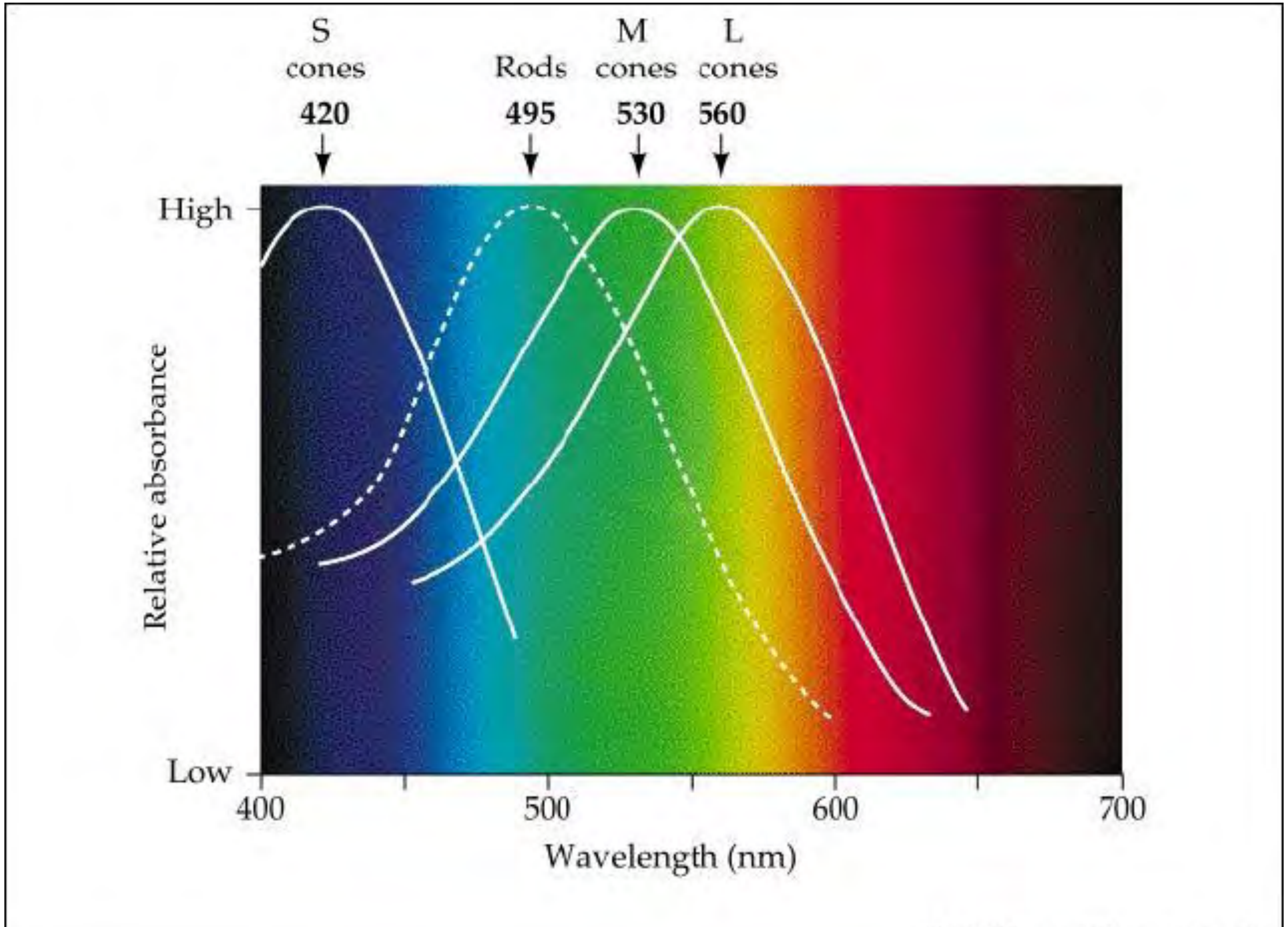


Fresh Water (turbid)

Two kinds of vision: scotopic and photopic



Human Trichromacy



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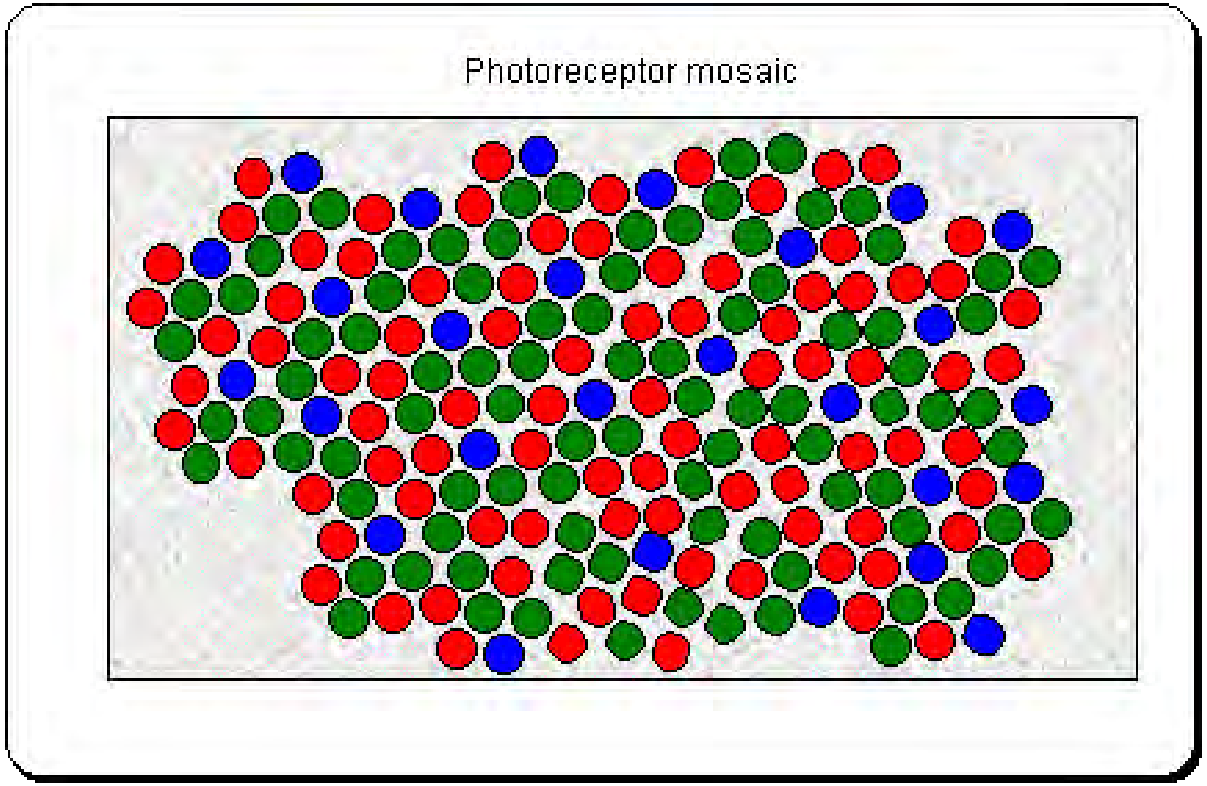
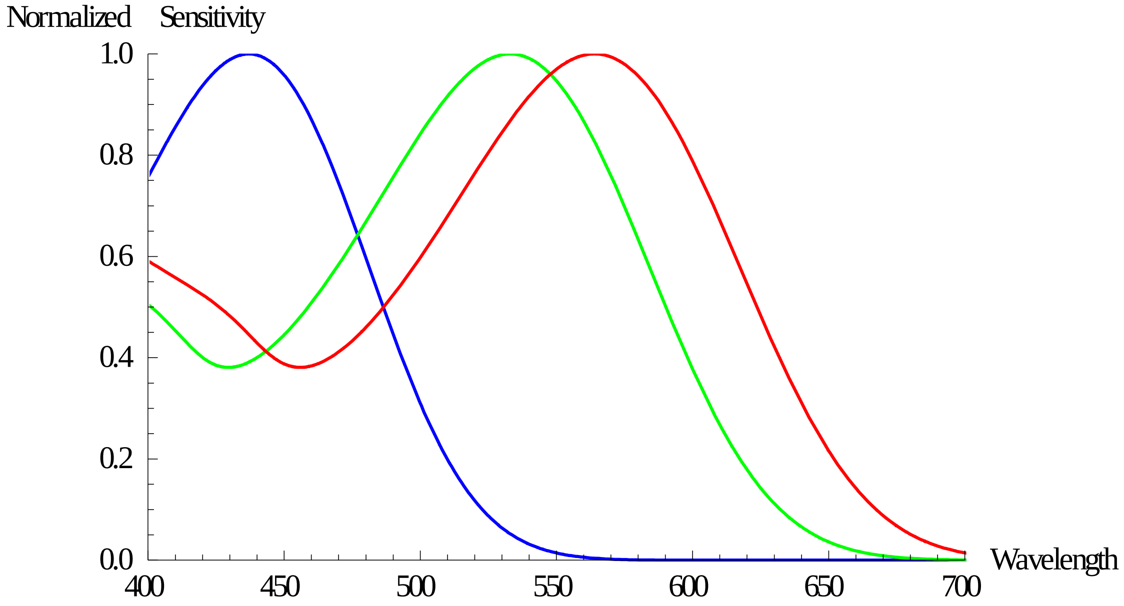
Distribution of cones

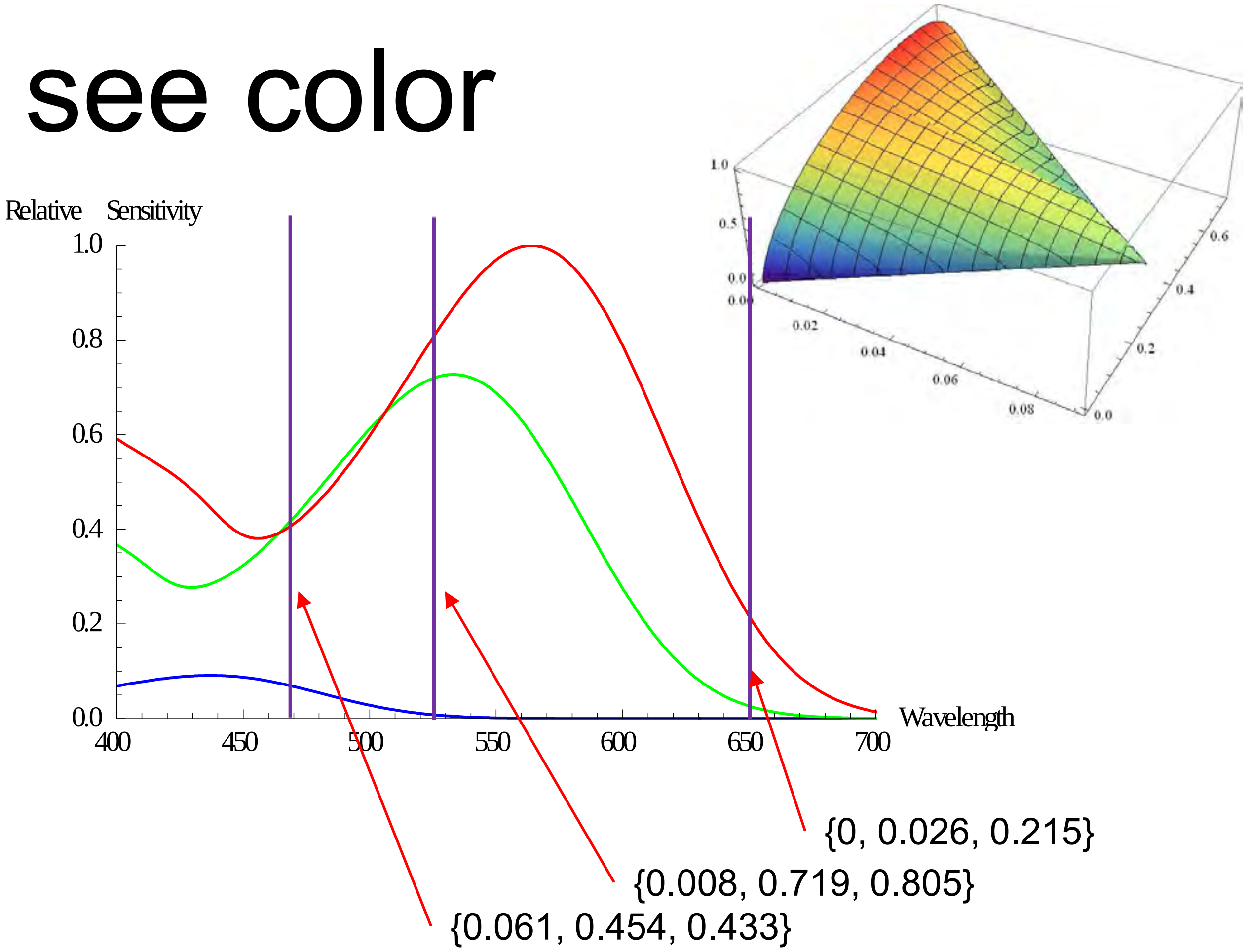


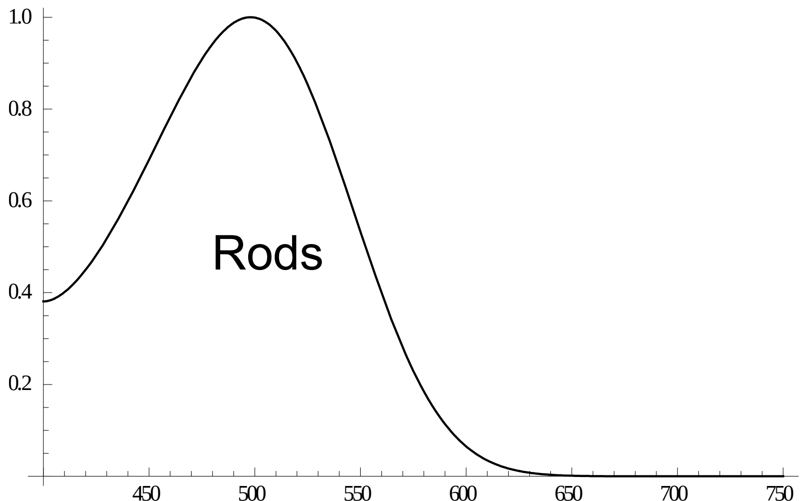
About 64% of all cones in the human retina are “red” cones; 32% are “green” and 2% are “blue”.

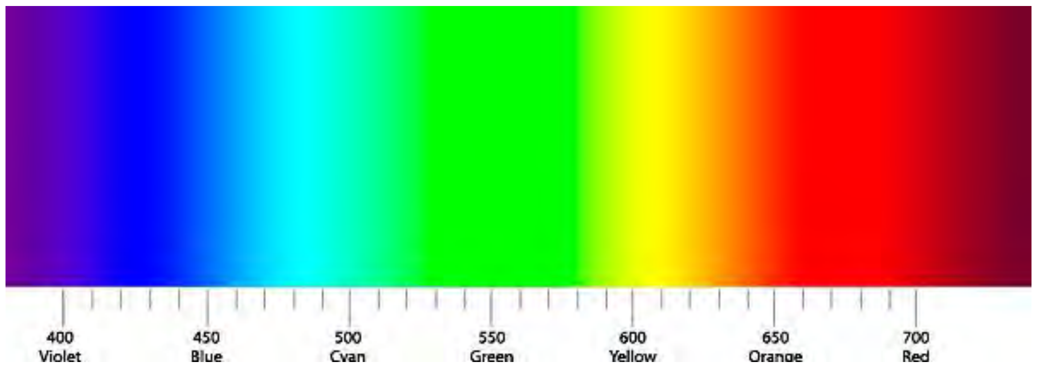
Most blue cones are located outside the fovea, leading to some unequal perceptions of color depending upon locus.

How we see color

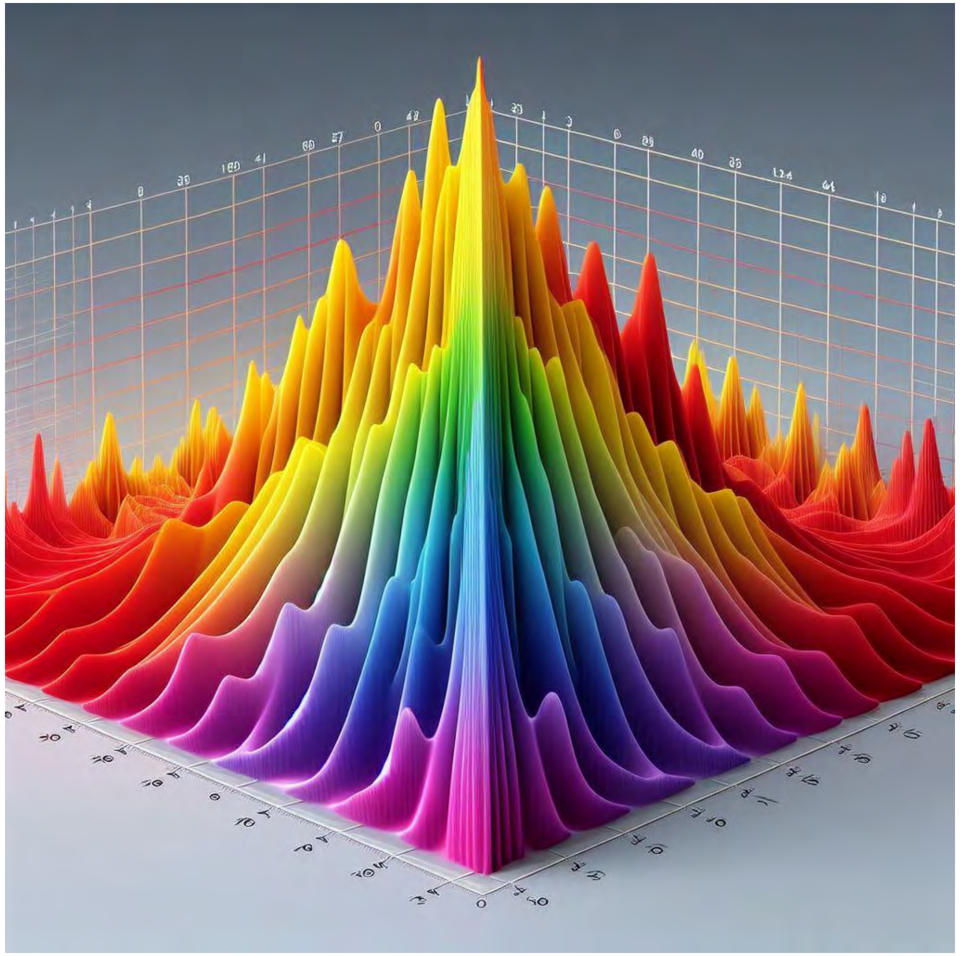








Color Space

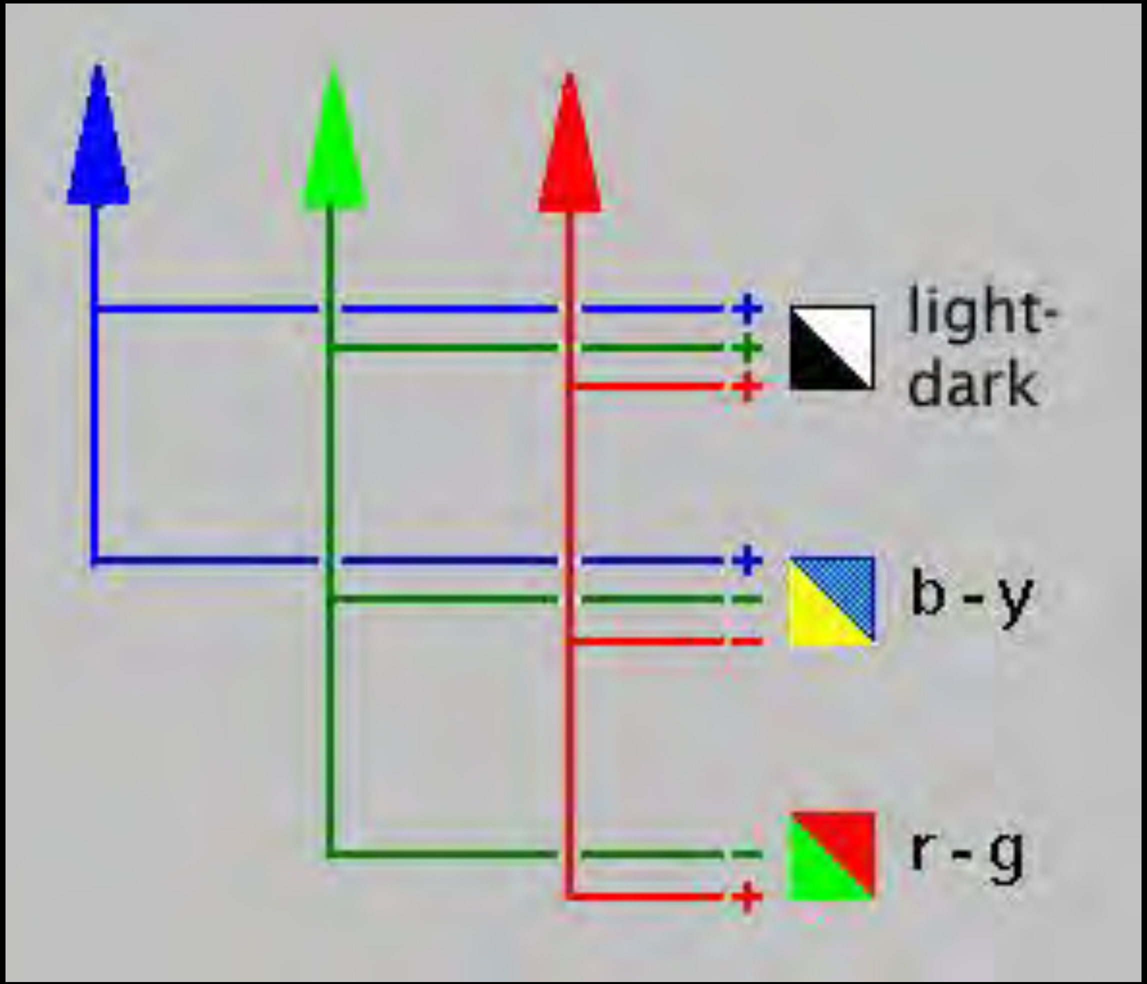


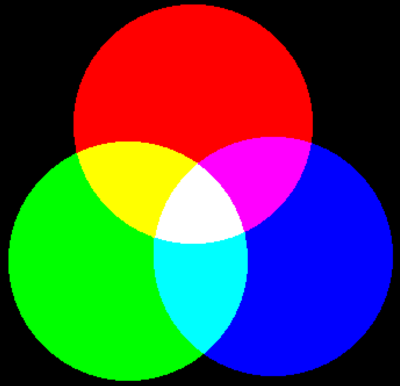
What you see here is a three-dimensional space in which each wavelength in the visual spectrum is mapped onto each of the three axes which are the spectral sensitivity of the three cone photoreceptors.

Note that some colors, particularly in the far red and far blue, will have similar coordinates and hence be confused.

Note also that the highest sensitivities are in the green and yellow areas of the spectrum.

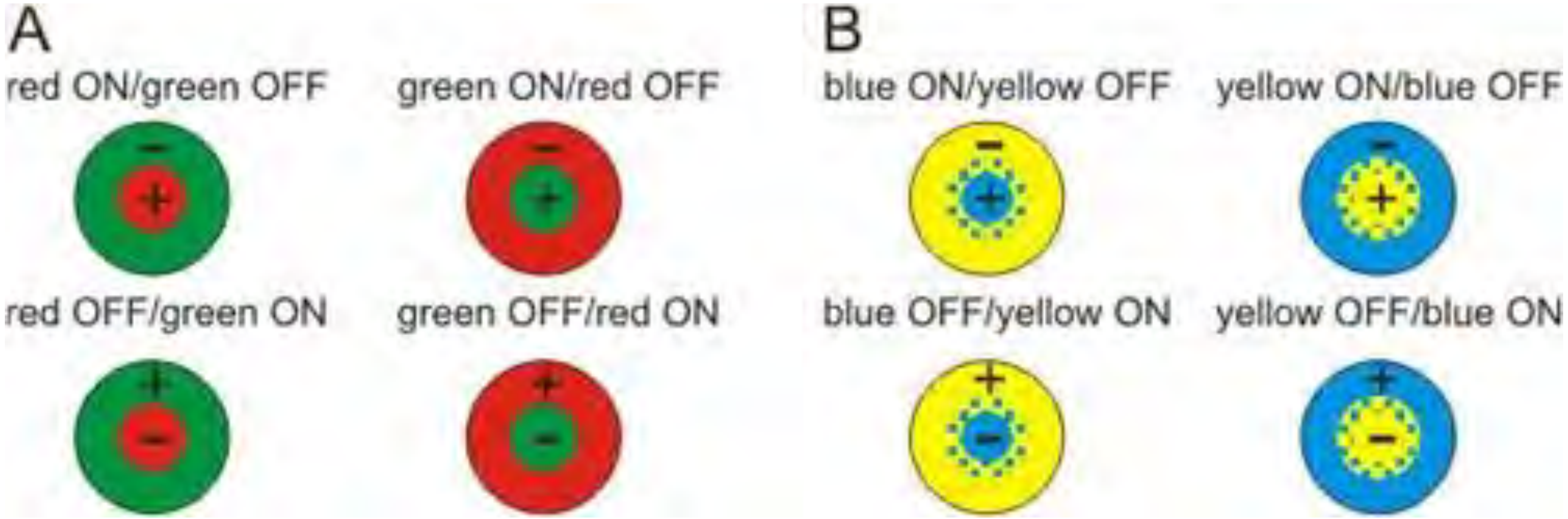
Color opponency system



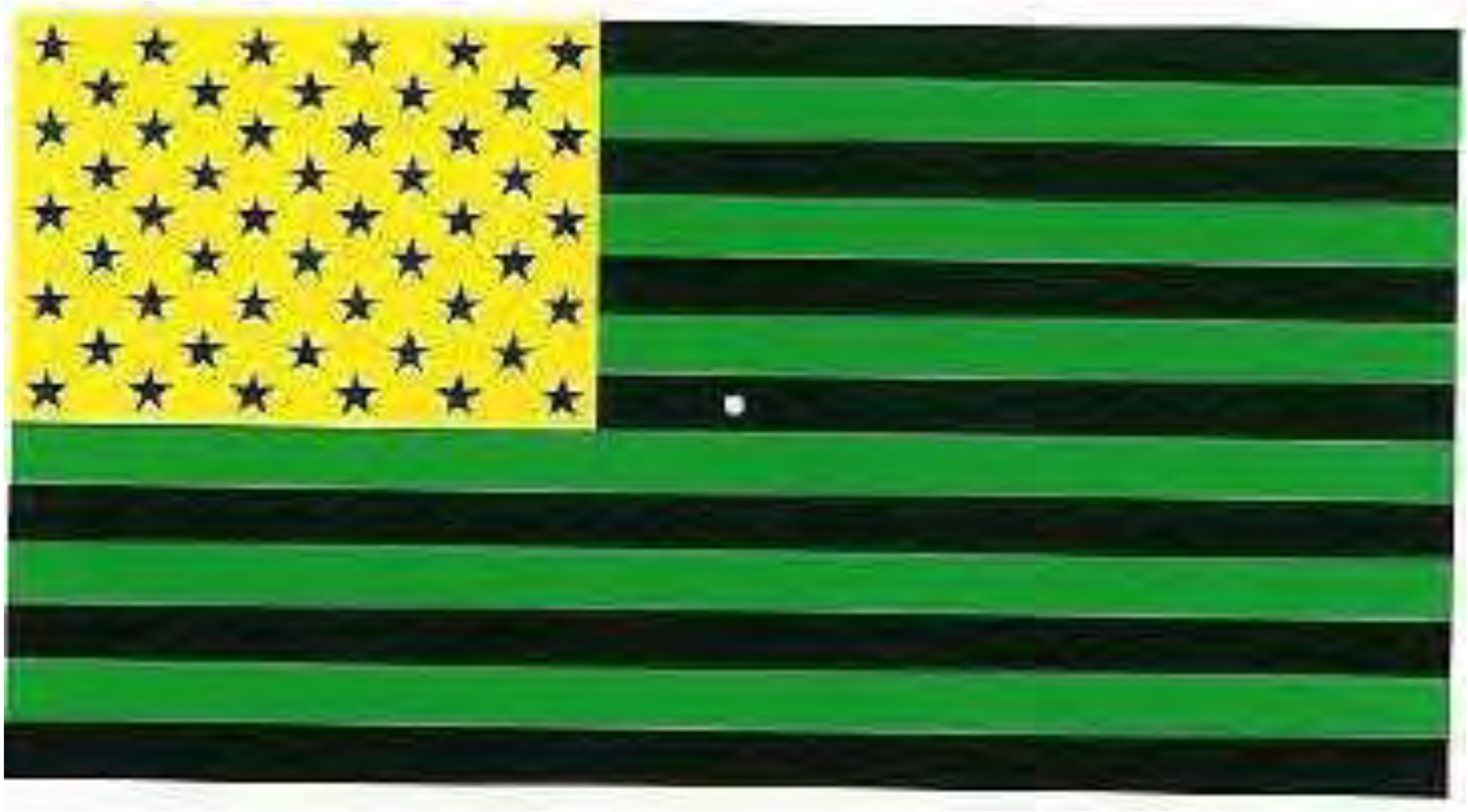


Additive colors

Color-opponent fields



Color opponency illustrated



Color opponency illustrated