Early Visual Processing: Receptive Fields & Retinal Processing (Chapter 2, part 2)

Lecture 5

Jonathan Pillow
Sensation & Perception
(PSY 345 / NEU 325)
Princeton University, Spring 2019

What does the retina do?

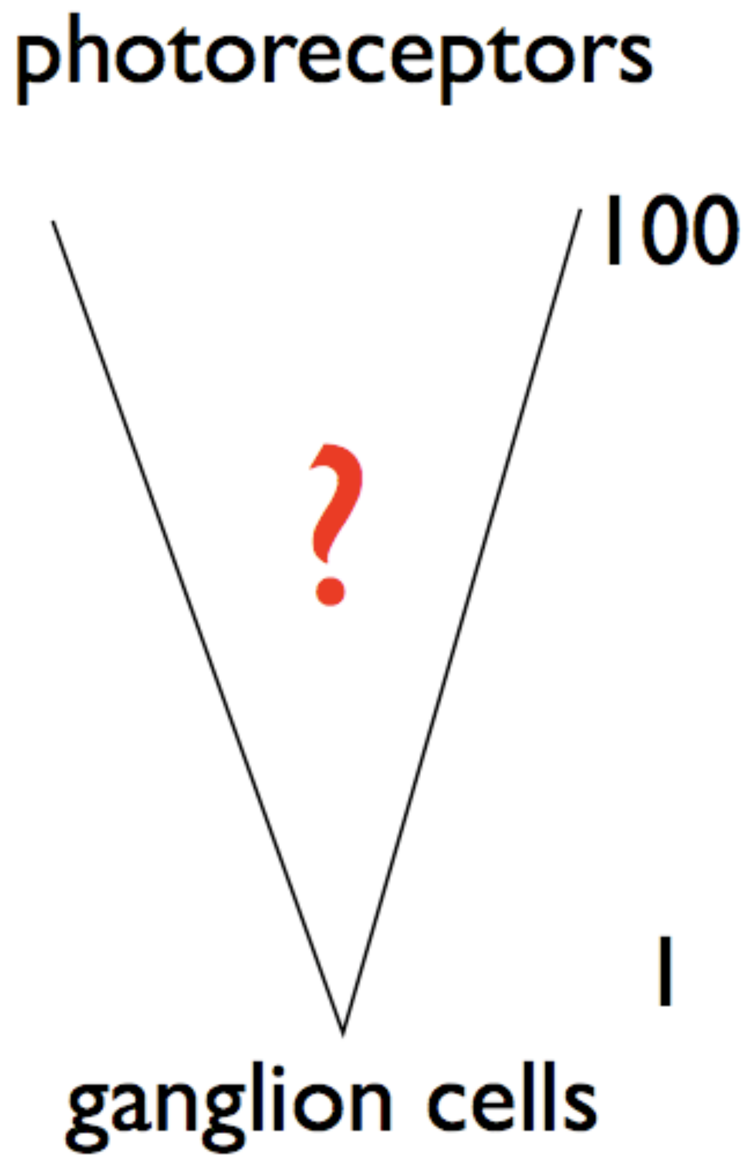
1. Transduction

• Conversion of energy from one form to another (i.e., "light" into "electrical energy")

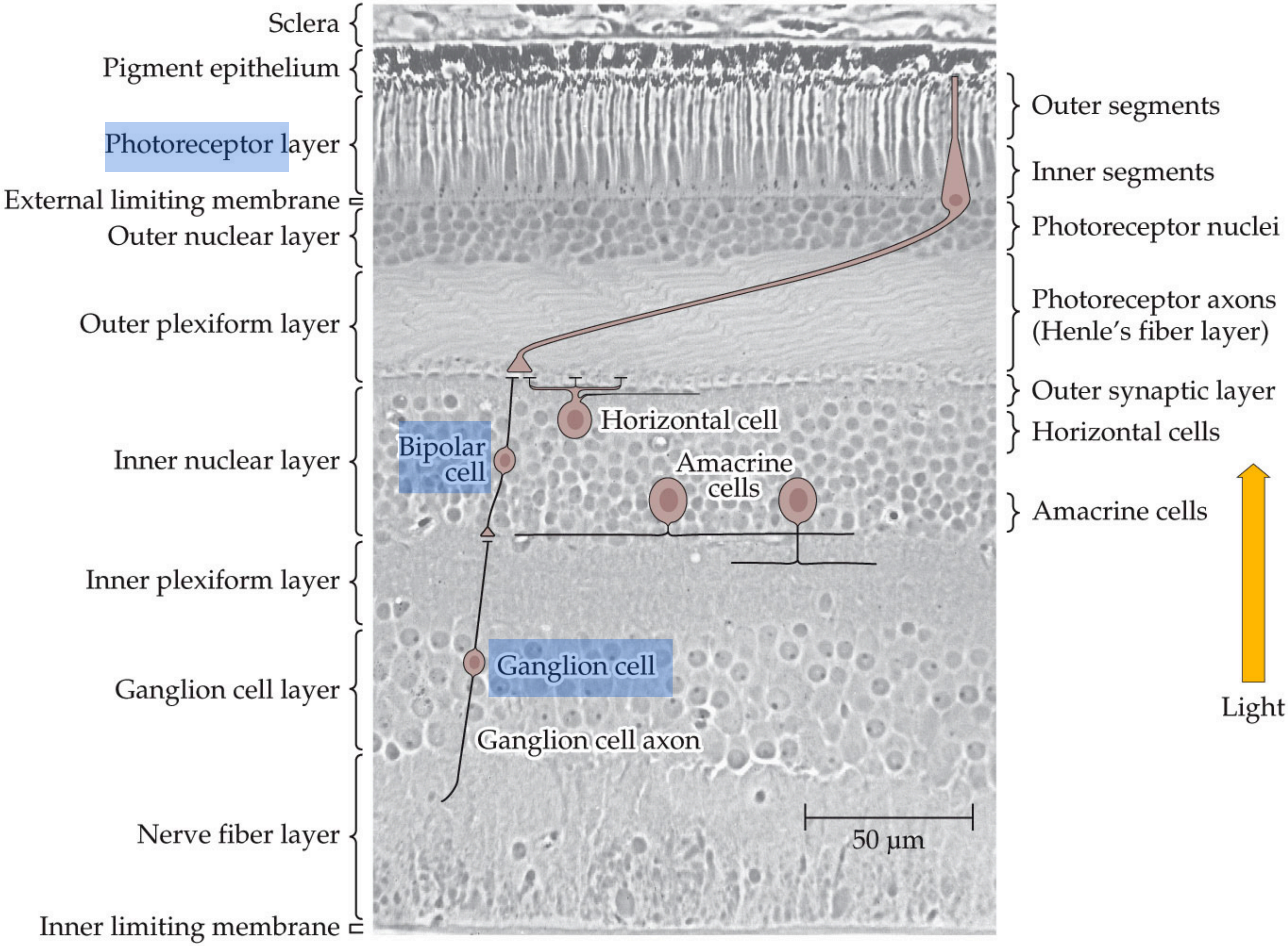
this is a major, important concept

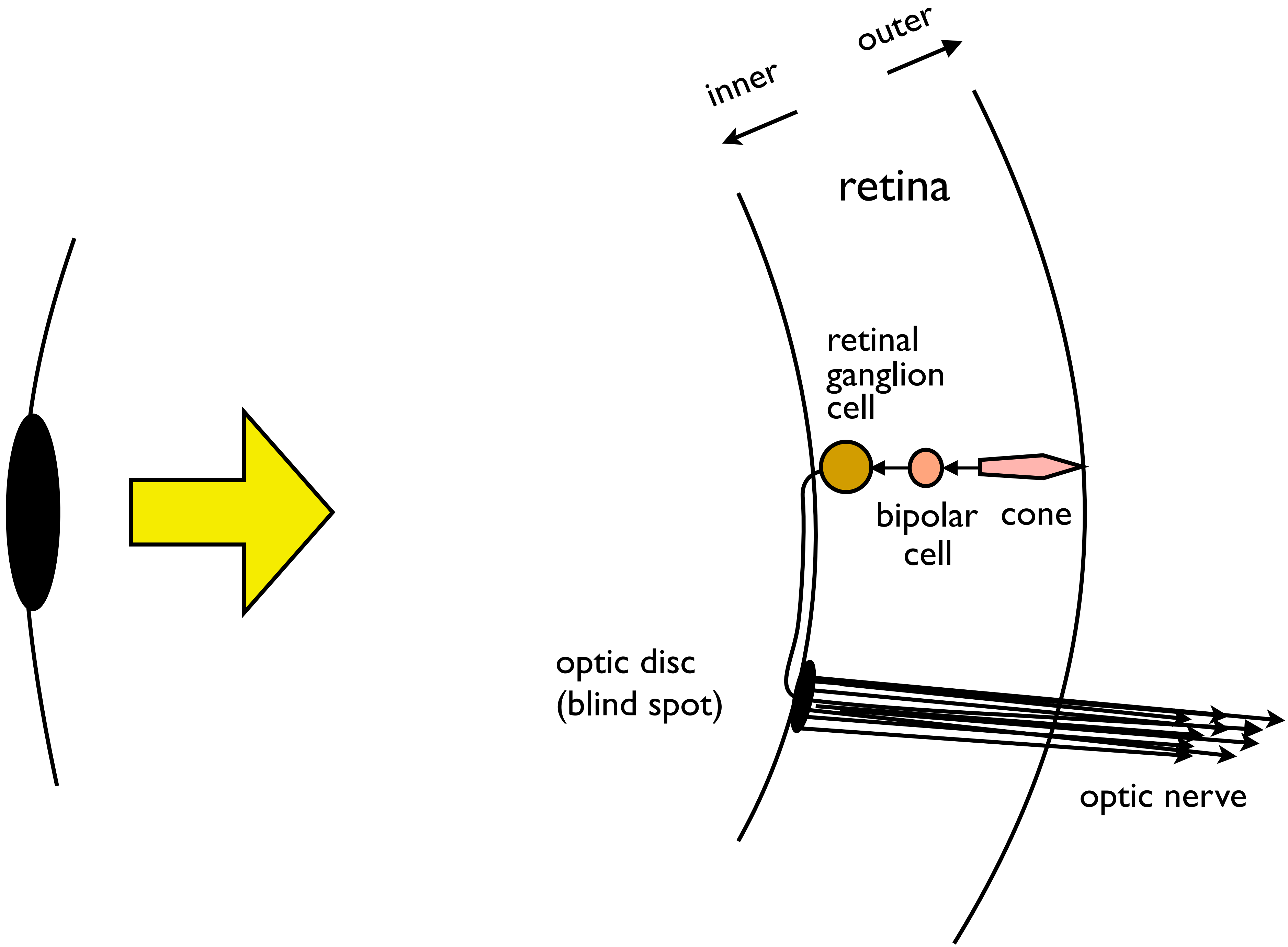
2. Processing

• **Amplification** of very weak signals
(1-2 photons can be detected!)
• **Compression** of image into more compact form so that information can be efficiently sent to the brain
optic nerve = "bottleneck"
analogy: jpeg compression of images


photoreceptors
100
?
1
ganglion cells

Basic anatomy: photomicrograph of the retina





outer
inner
retina
retinal ganglion cell
bipolar cell
cone
optic disc (blind spot)
optic nerve

What's crazy about this is that the light has to pass through all the other junk in our eye before getting to photoreceptors!

Cephalopods (squid, octopus): did it right.

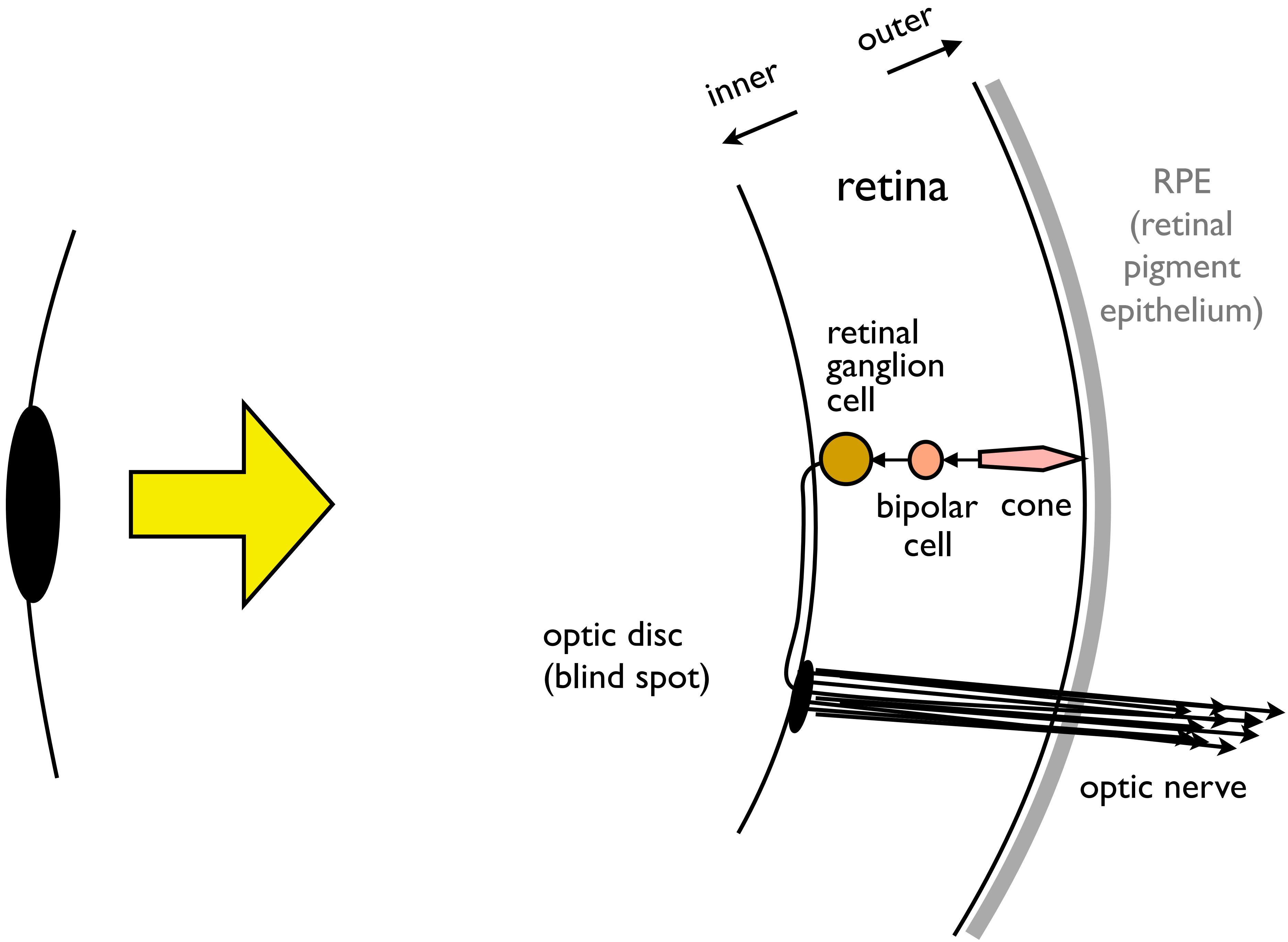
- photoreceptors in innermost layer, no blind spot!

<u>Debate</u>:

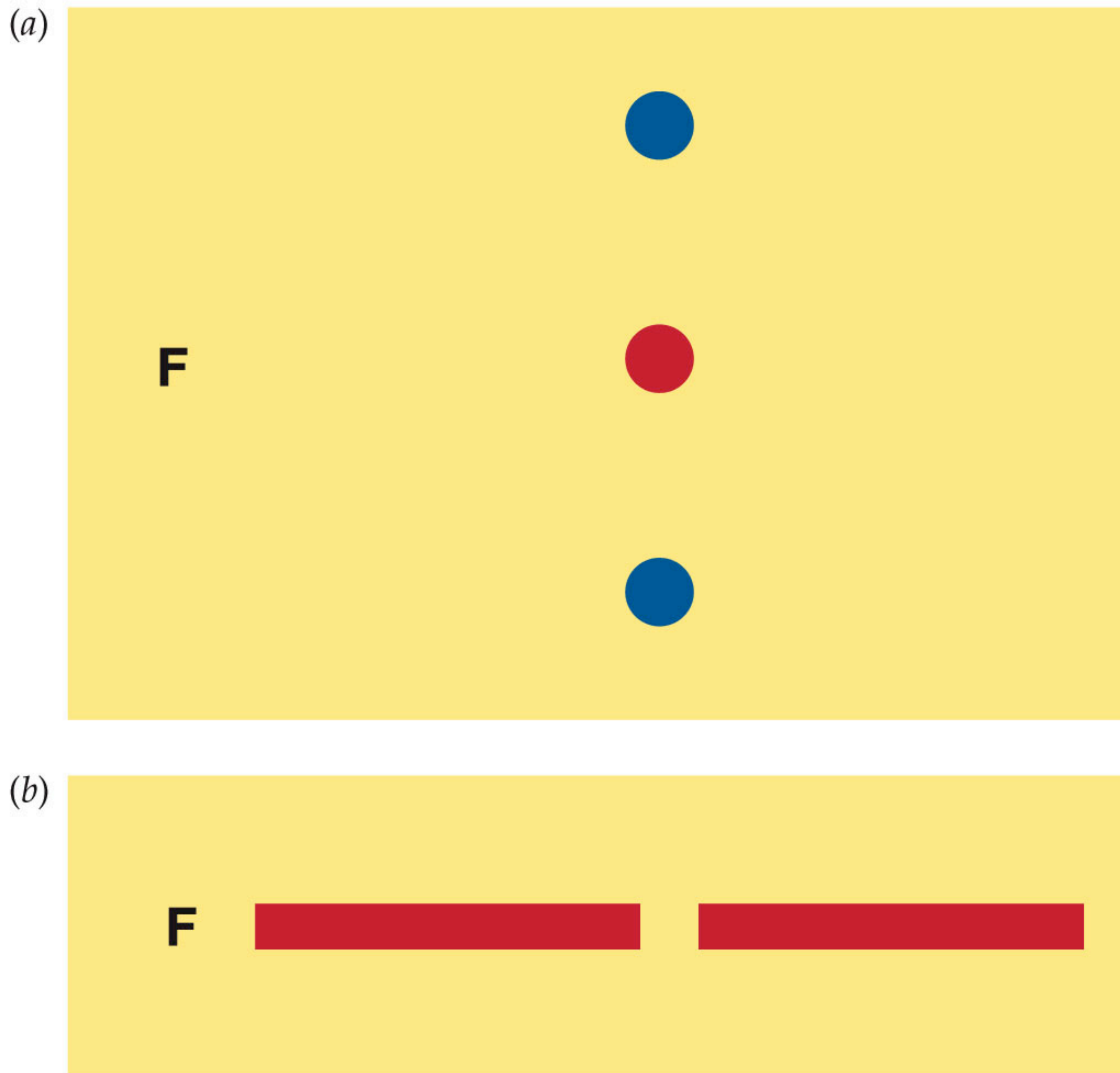
1. accident of evolution?

   OR

2. better to have photoreceptors near blood supply?


outer
inner
retina
RPE
(retinal
pigment
epithelium)
retinal
ganglion
cell
bipolar
cell
cone
optic disc
(blind spot)
optic nerve

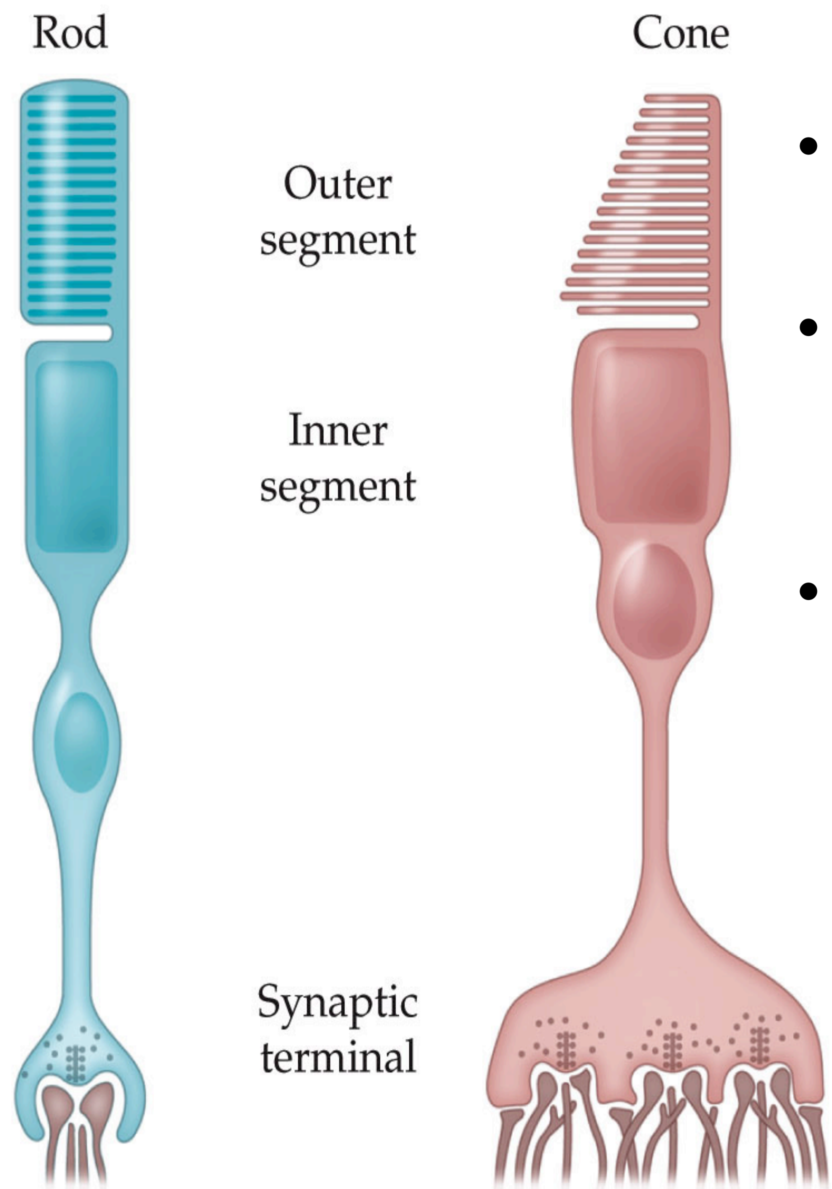
blind spot demo



phototransduction: converting light to electrical signals

rods

- respond in low light ("scotopic")
- only one kind: don't process color
- 90M in humans



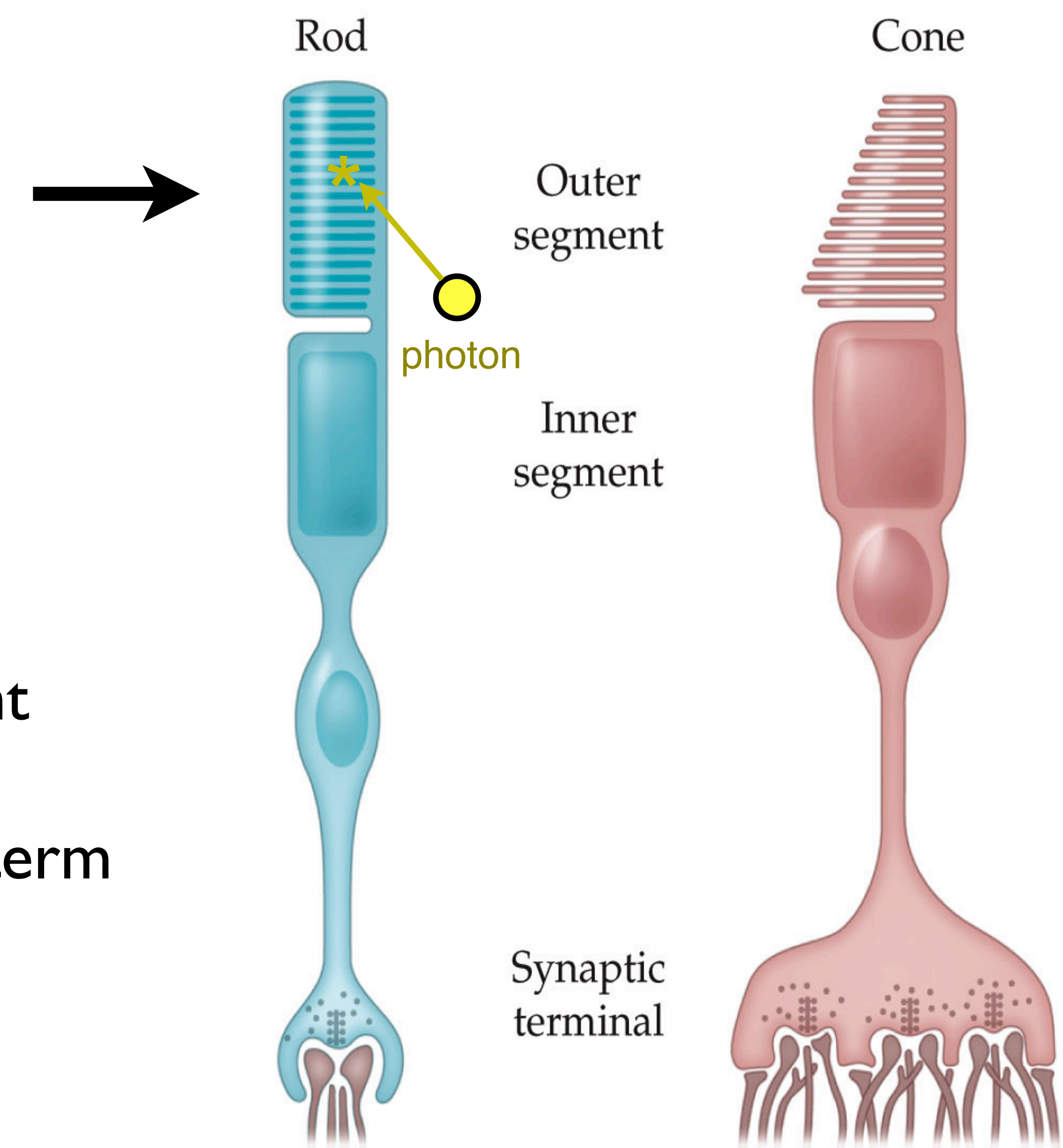
cones

- respond in daylight ("photopic")
- 3 different kinds: responsible for color processing
- 4-5M in humans

phototransduction: converting light to electrical signals

<u>outer segments</u>

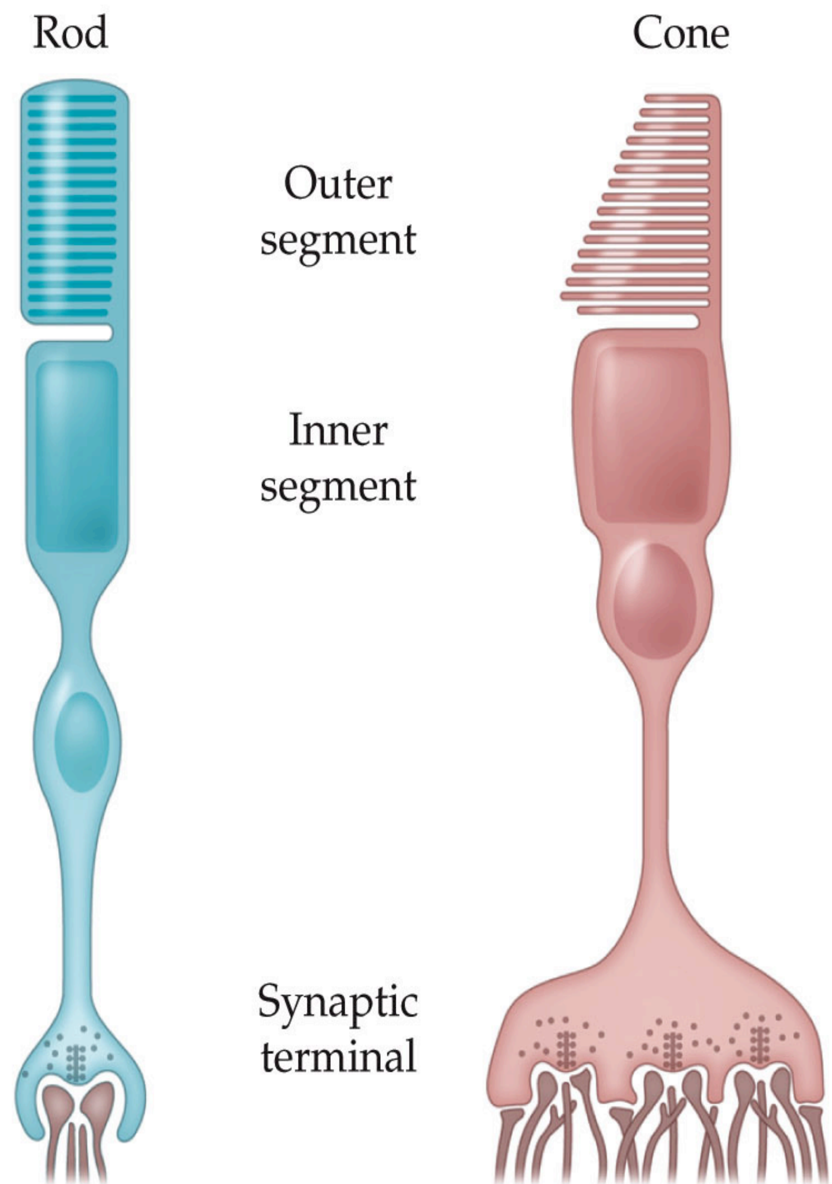
- packed with discs
- discs have **opsins** (proteins that change shape when they absorb a photon - amazing!)



- different opsins sensitive to different wavelengths of light
- **rhodopsin**: opsin in rods
- **photopigment**: general term for molecules that are photosensitive (like opsins)

dark current

- In the dark, membrane channels in rods and cones are open by default (unusual!)
- current flows in continuously
- membrane is *depolarized* (less negative)



- neurotransmitter is released at a high rate

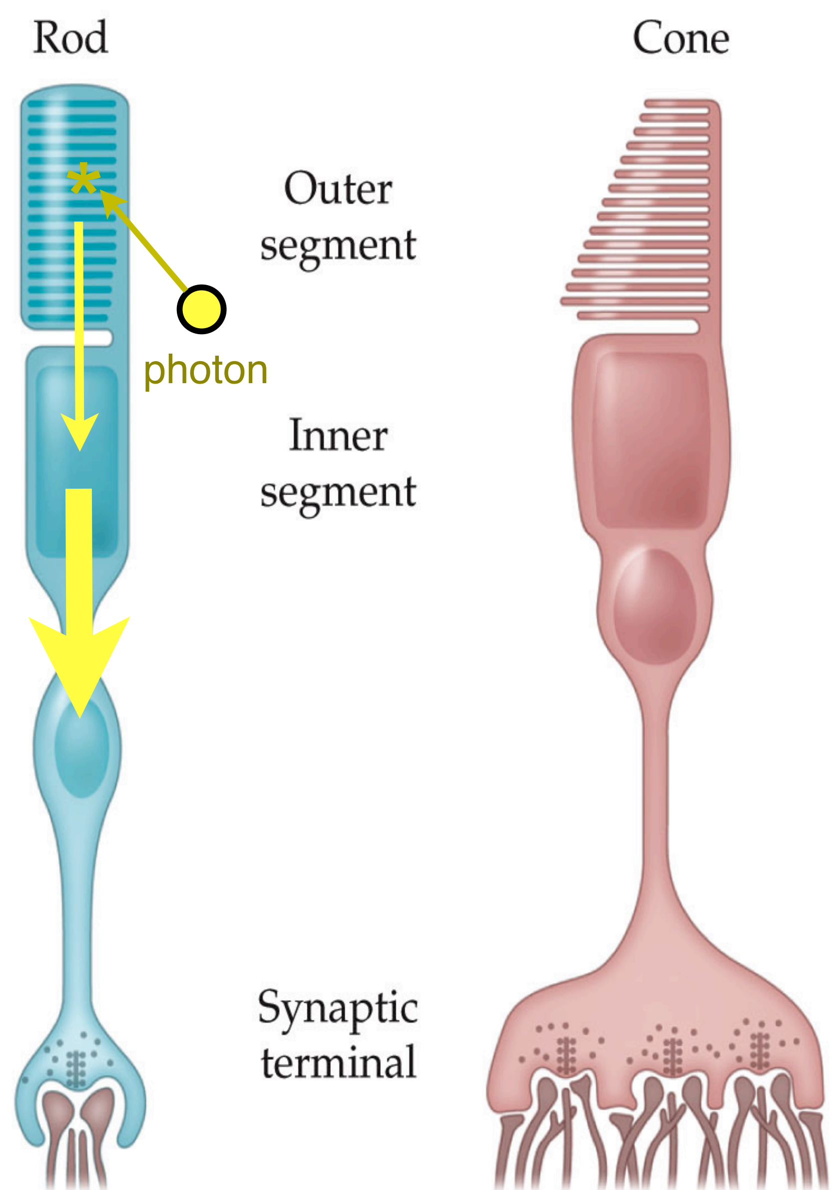
↓ to bipolar cells

transduction & signal amplification

- photon is absorbed by an opsin

- channels close (dark current turns off)

- membrane becomes *more* polarized (more negative)



- neurotransmitter is released at a lower rate

↓ to bipolar cells

transduction & signal amplification

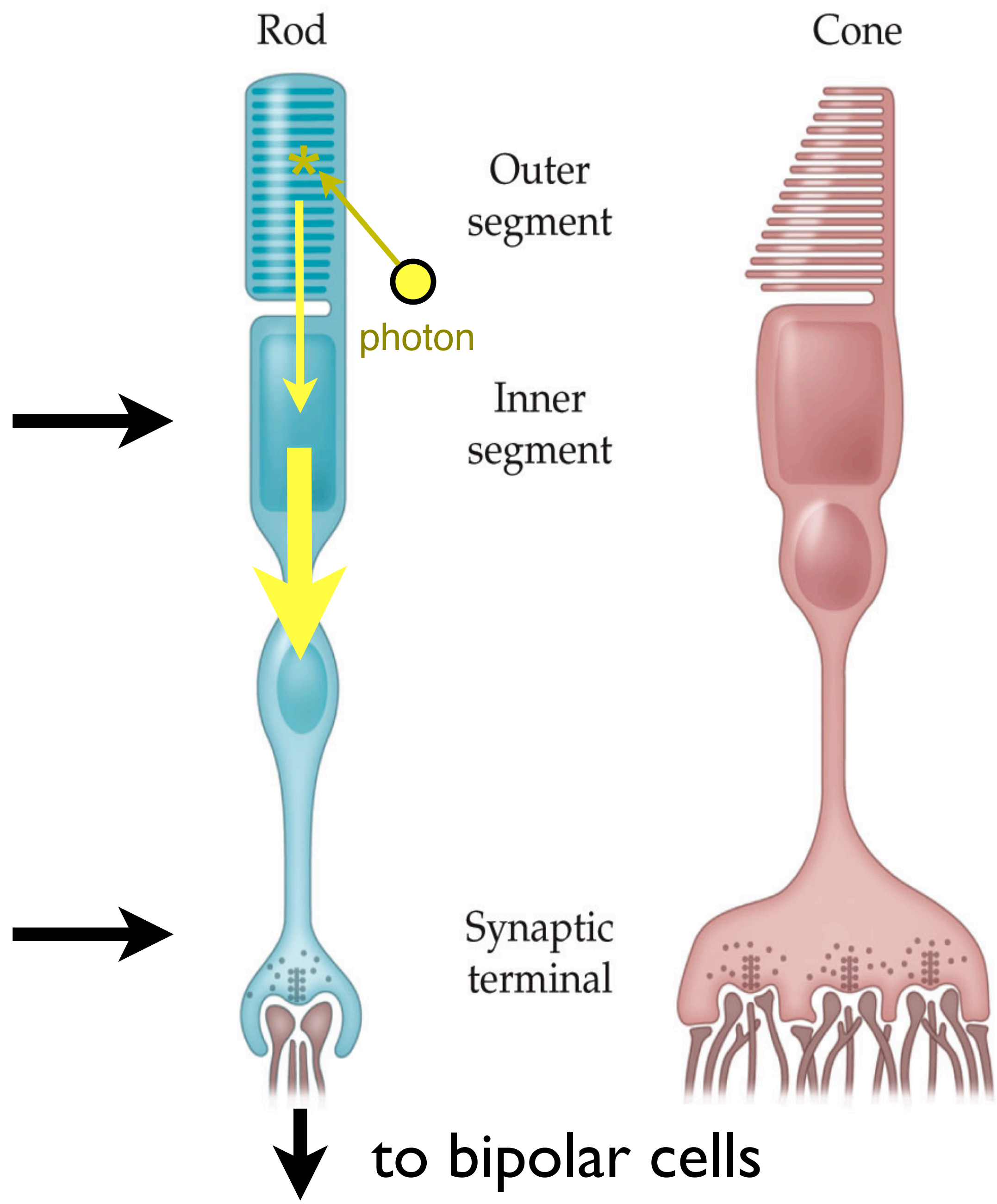
<u>inner segments</u>

machinery for amplifying signals from outer segment

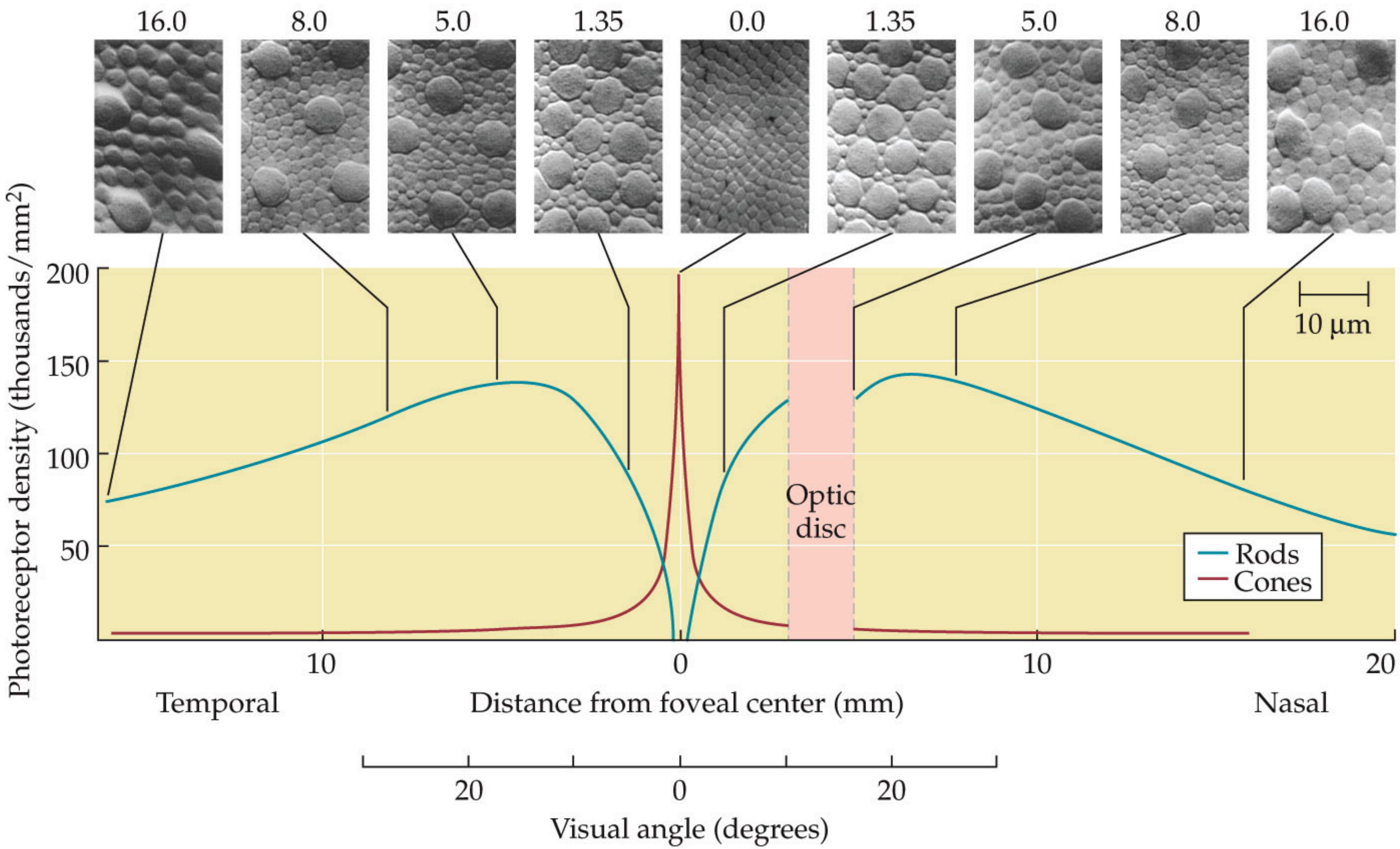
<u>neurotransmitter release</u>

graded potential

(*not* spikes!)



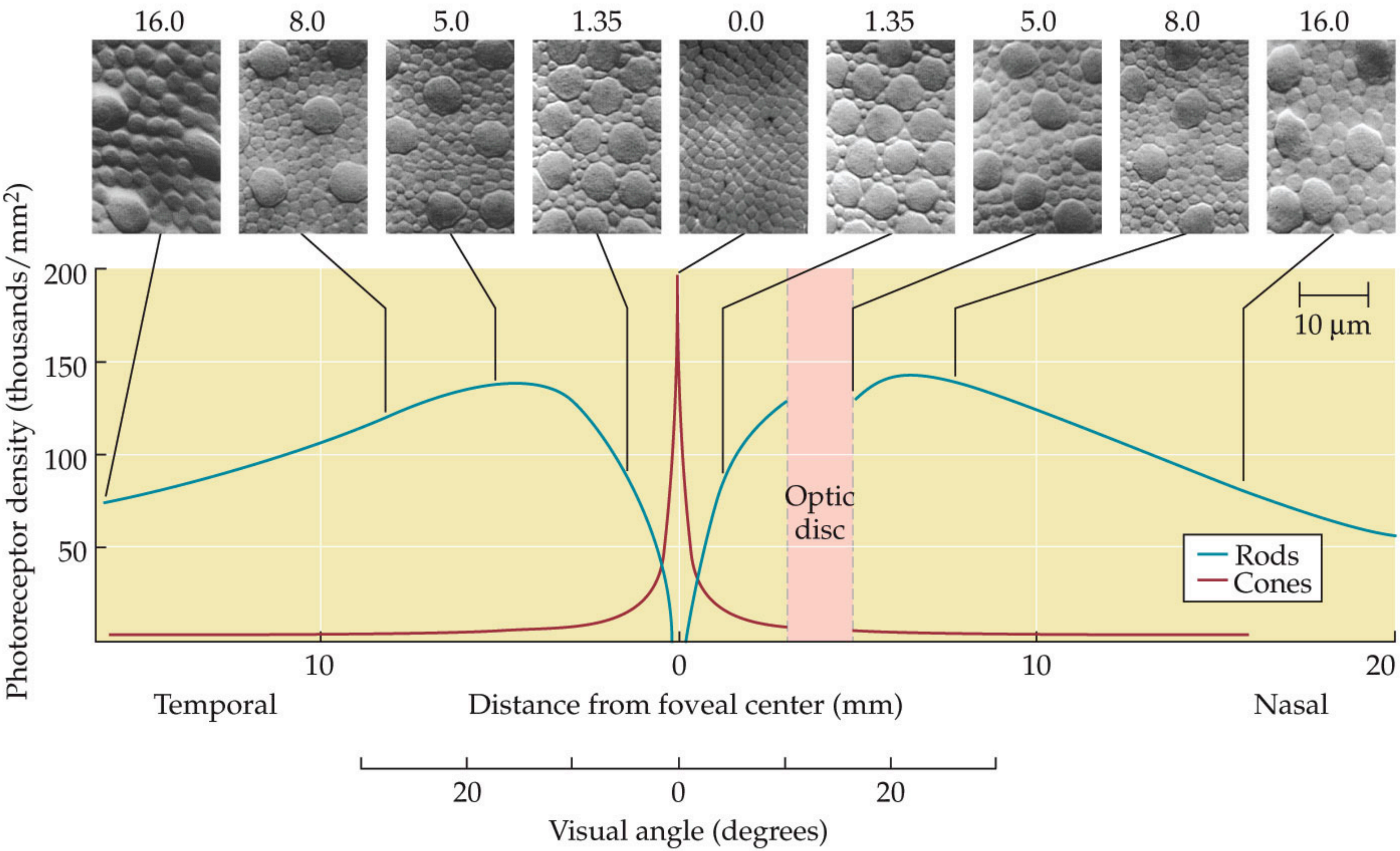
Photoreceptors: not evenly distributed across the retina



- fovea: mostly cones
- periphery: mostly rods

Q: what are the implications of this?

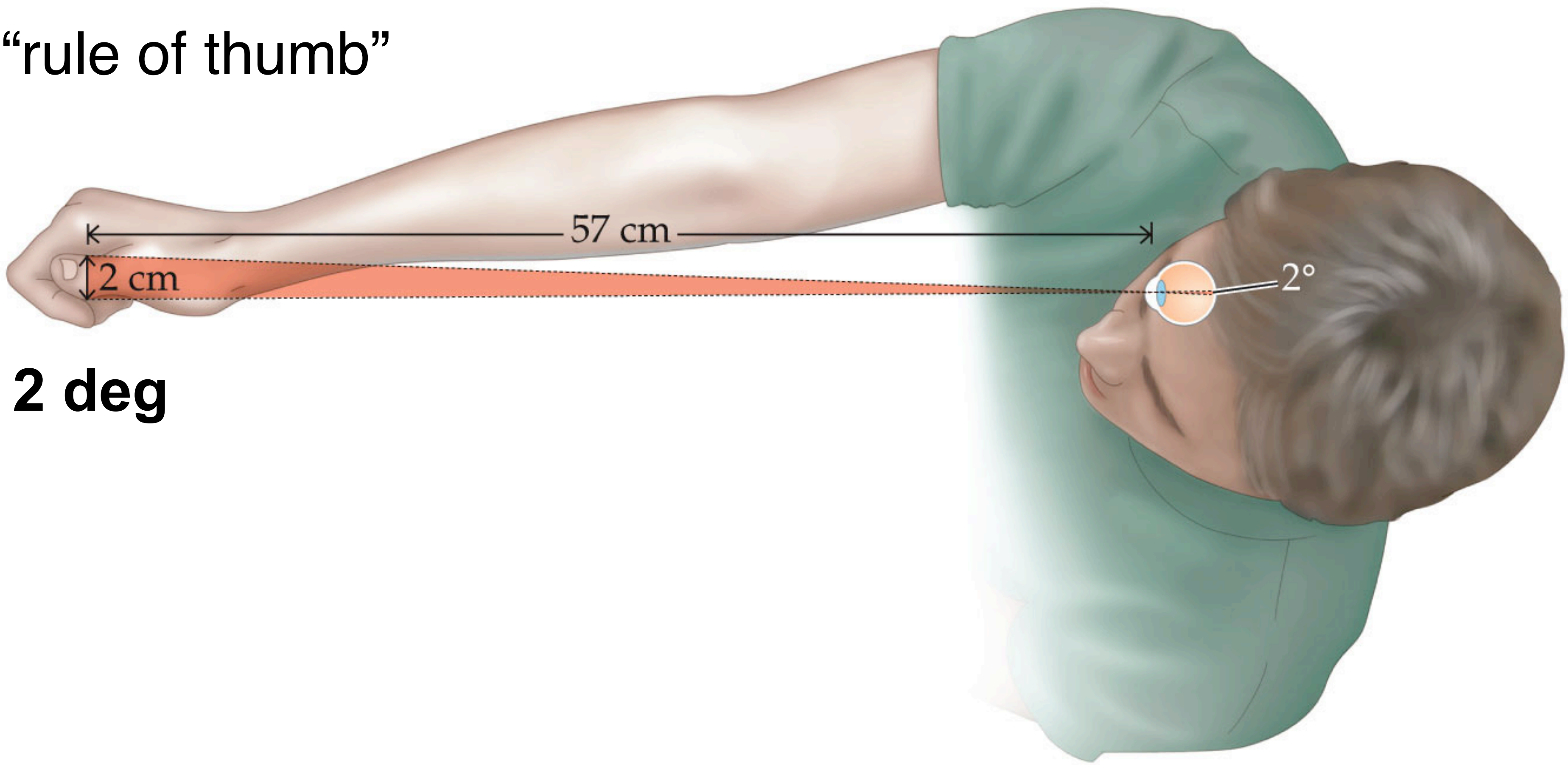
Photoreceptors: not evenly distributed across the retina



- not much color vision in the periphery
- highest sensitivity to dim lights: 5° eccentricity

visual angle: size an object takes up on your retina (in degrees)

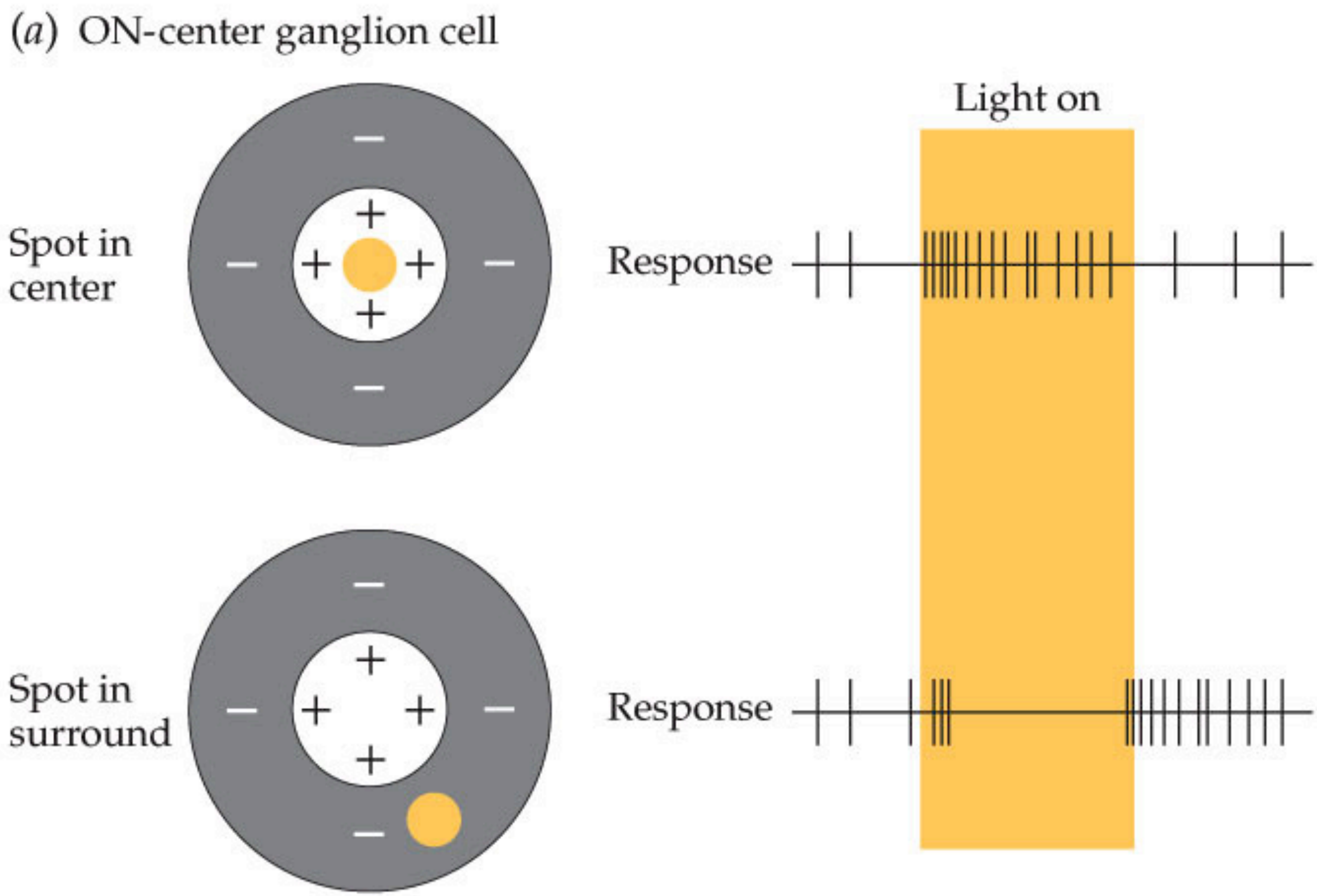
"rule of thumb"



2 deg

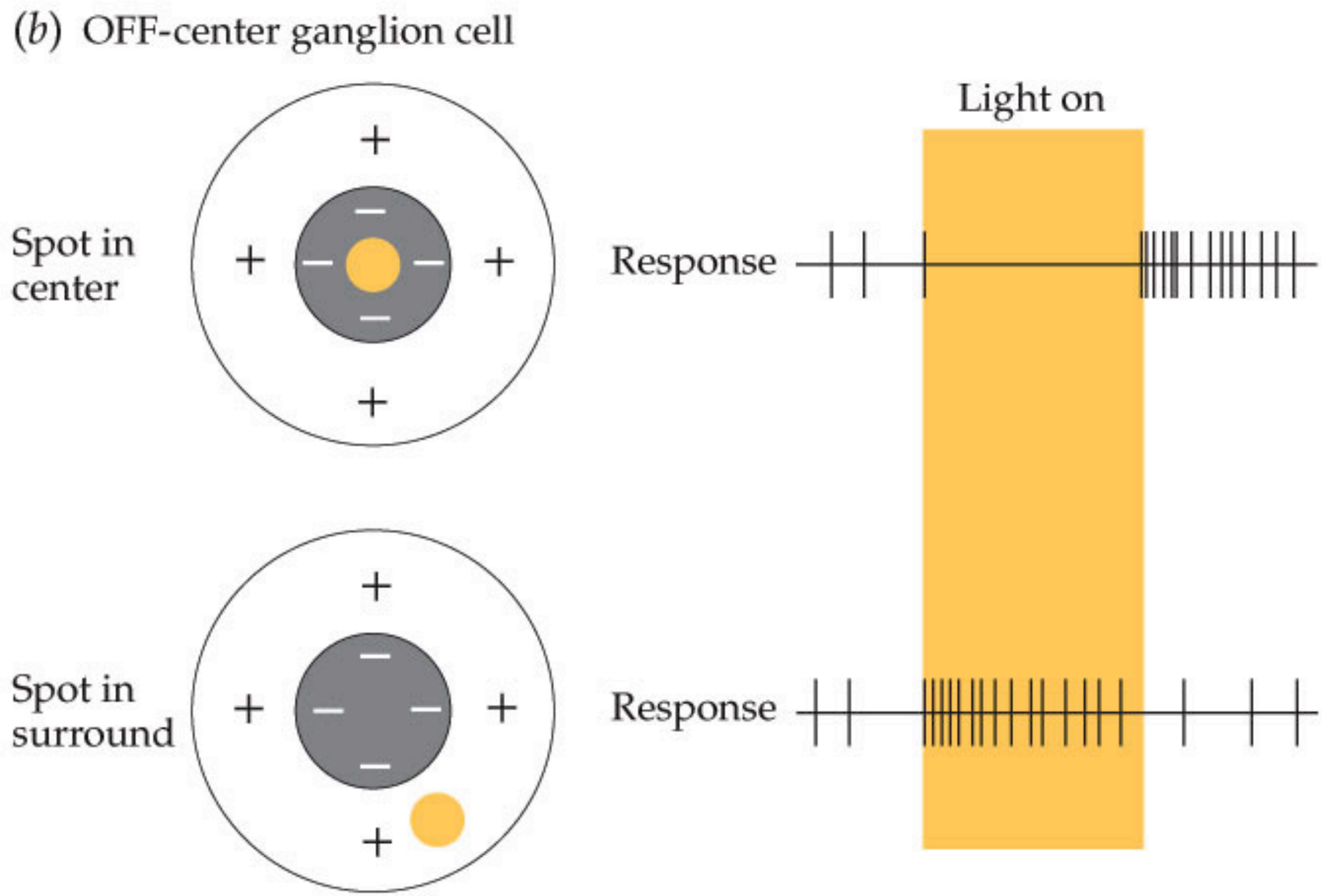
Vision scientists measure the size of visual stimuli by **how large an image appears on the retina** rather than by **how large the object is**

"ON" Cell


(a) ON-center ganglion cell
Light on
Spot in center
Response
Spot in surround
Response

Retinal Information Processing: Kuffler's experiments

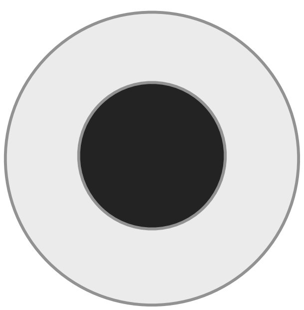
"OFF" Cell



Retinal Information Processing

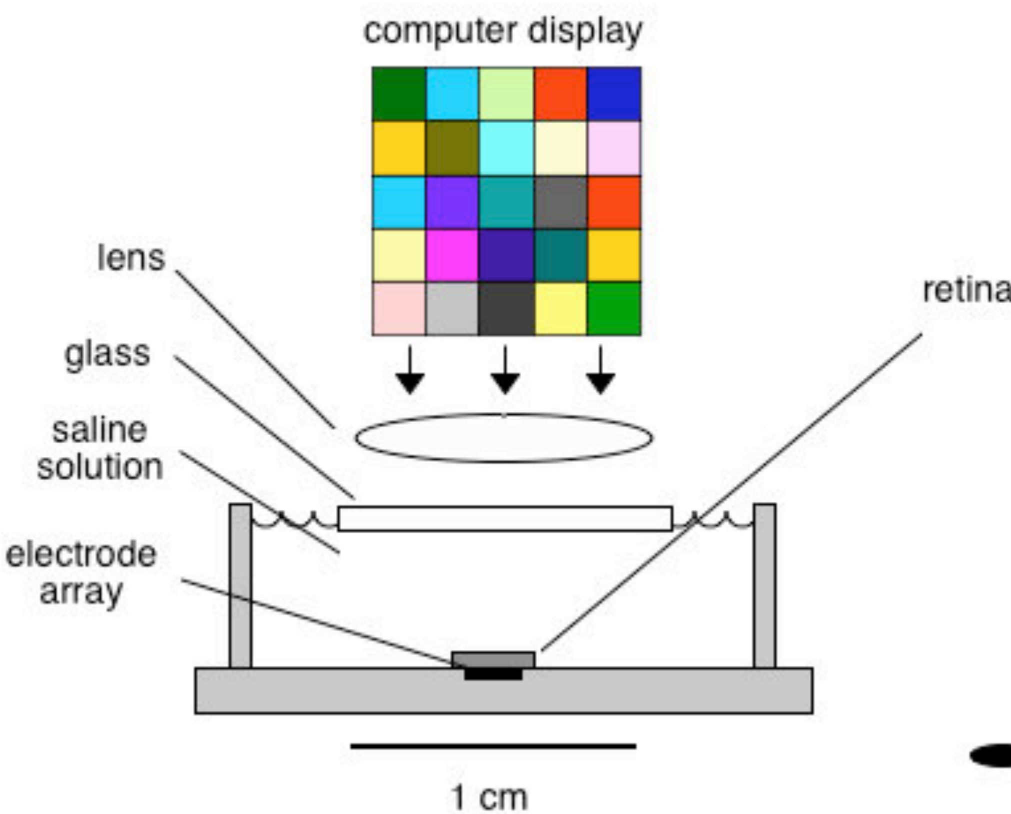
Kuffler: mapped out the **receptive fields** of individual retinal ganglion cells in the cat

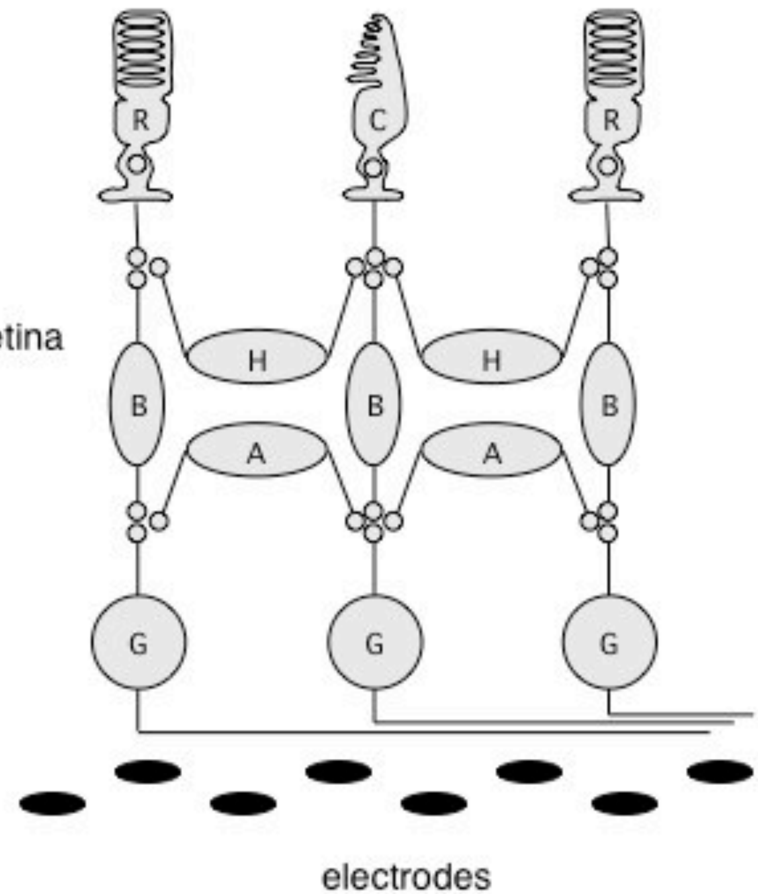
- ON-center ganglion cells
  – excited by light that falls on their center and inhibited by light that falls in their surround



- OFF-center ganglion cells
  - inhibited when light falls in their center and excited when light falls in their surround

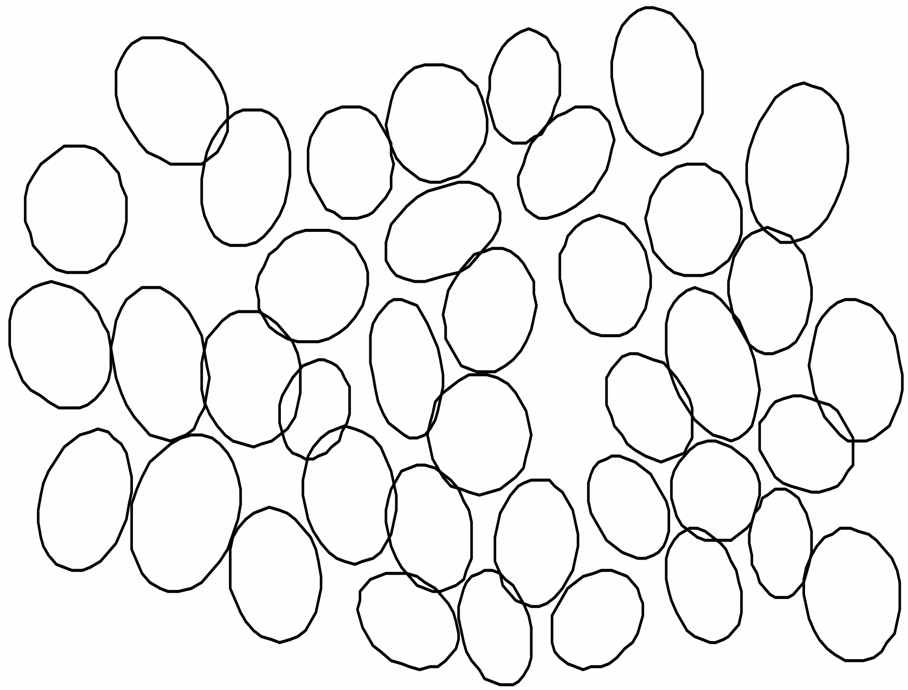
Recording from retina in a dish!





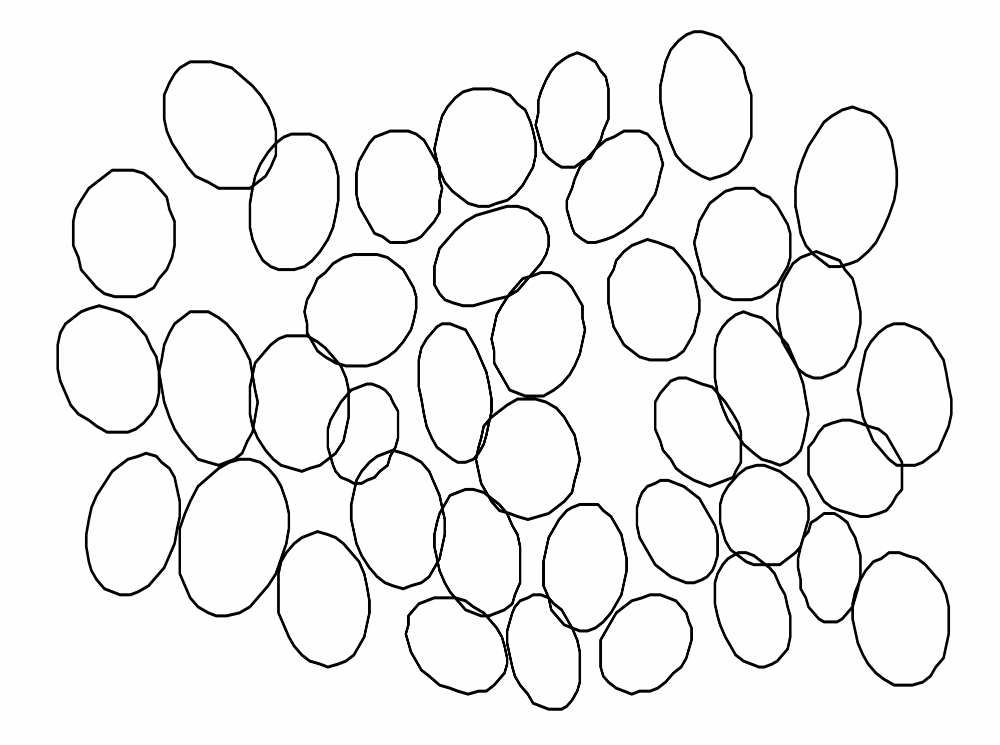
Data: Chichilnisky Lab, The Salk Institute

Responses to Moving Bar: #1



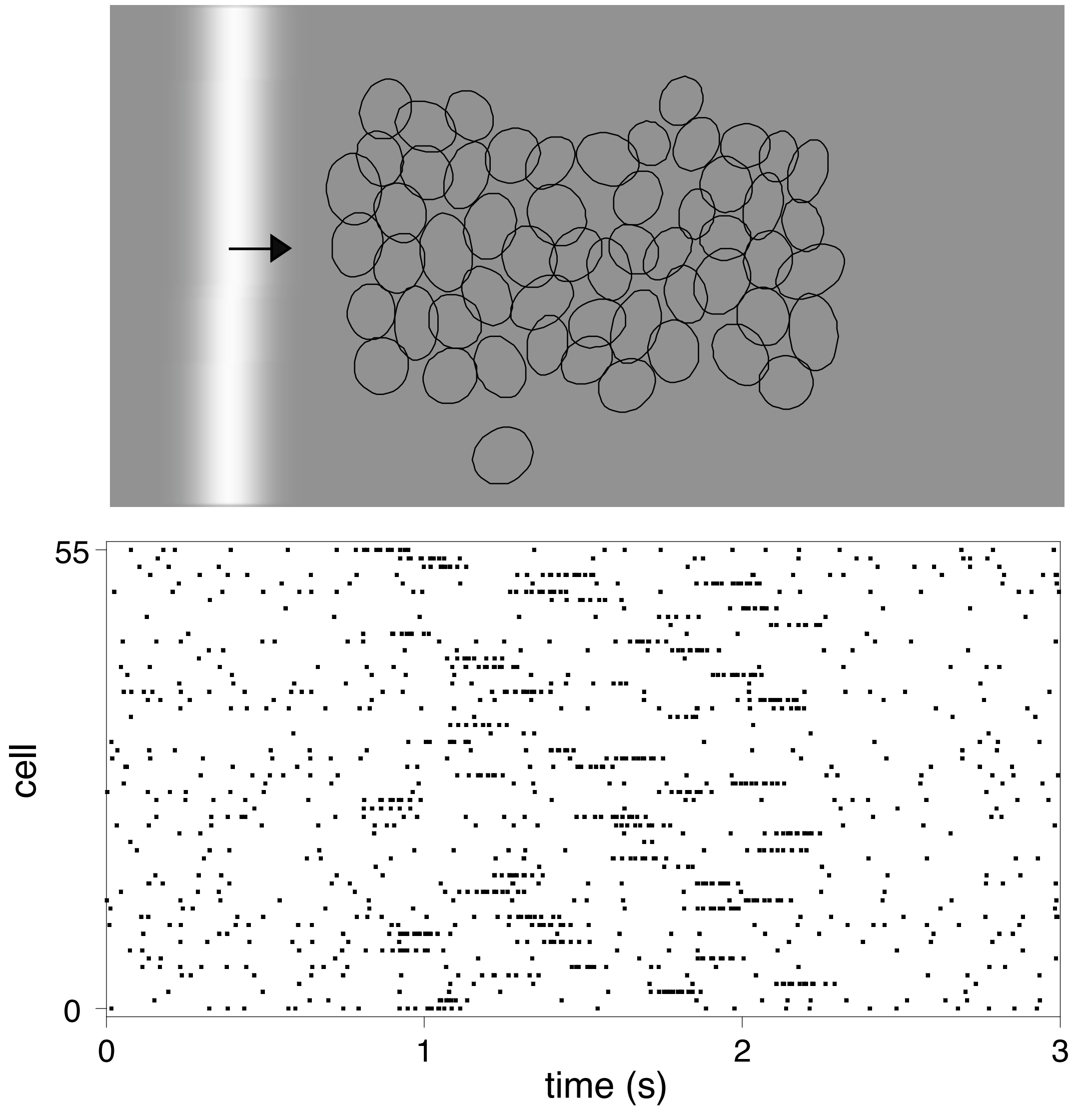
Frechette et al, 2005

Responses to Moving Bar #2



Frechette et al, 2005

Responses to Moving Bar



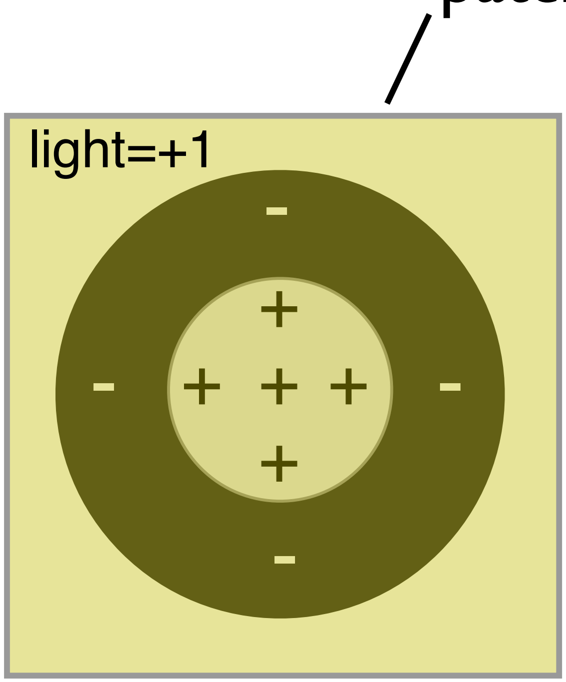
Frechette et al, 2005

Receptive field: "what makes a neuron fire"

- weighting function that the neuron uses to add up its inputs

Response to a dim light

patch of light



light level

1×(+5) + 1×(-4) = +1 spikes

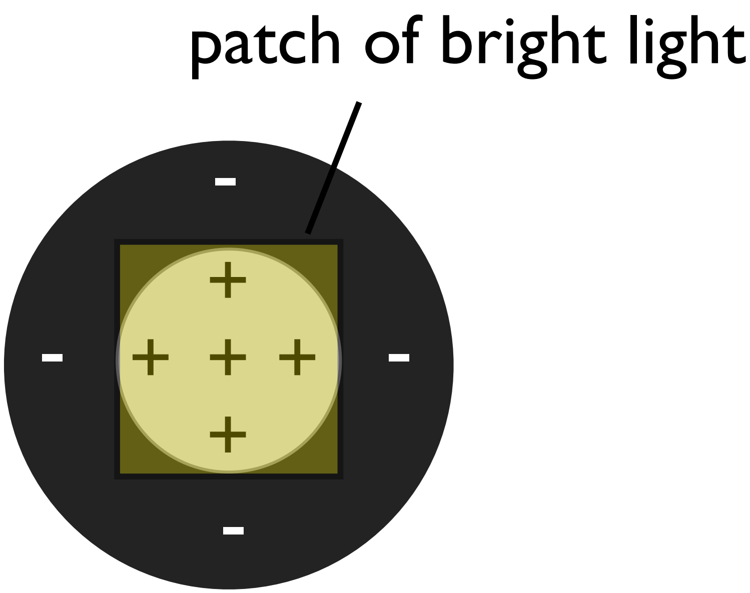
"center" weight

"surround" weight

Receptive field: “what makes a neuron fire”

- weighting function that the neuron uses to add up its inputs

Response to a spot of light



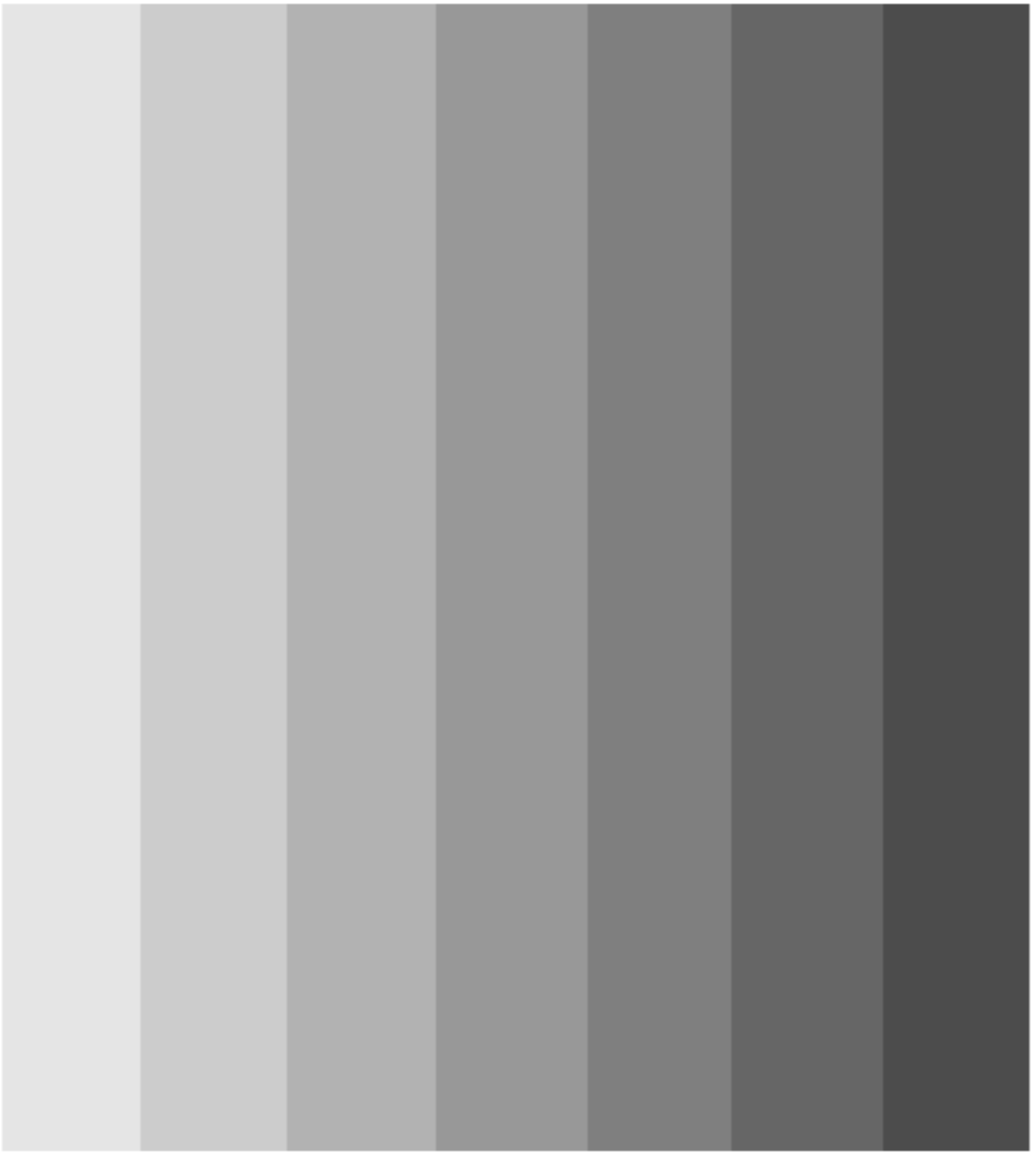
light level

$1 \times (+5) \;+\; 0 \times (-4) \;=\; +5$ spikes

“center” weight

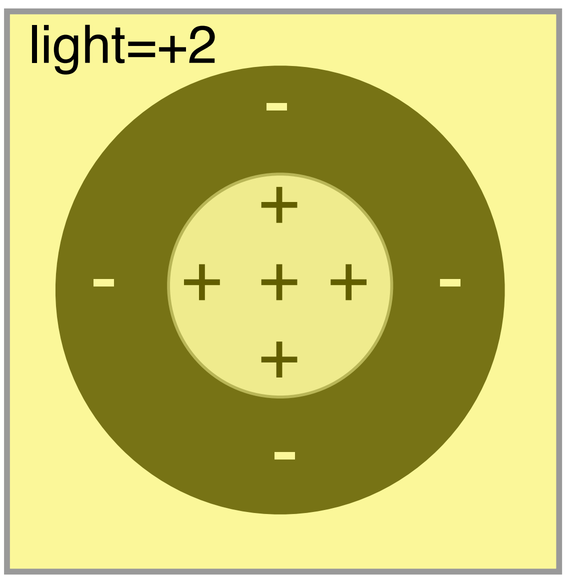
“surround” weight

Mach Bands



Each stripe has constant luminance ("light level")

Response to a bright light



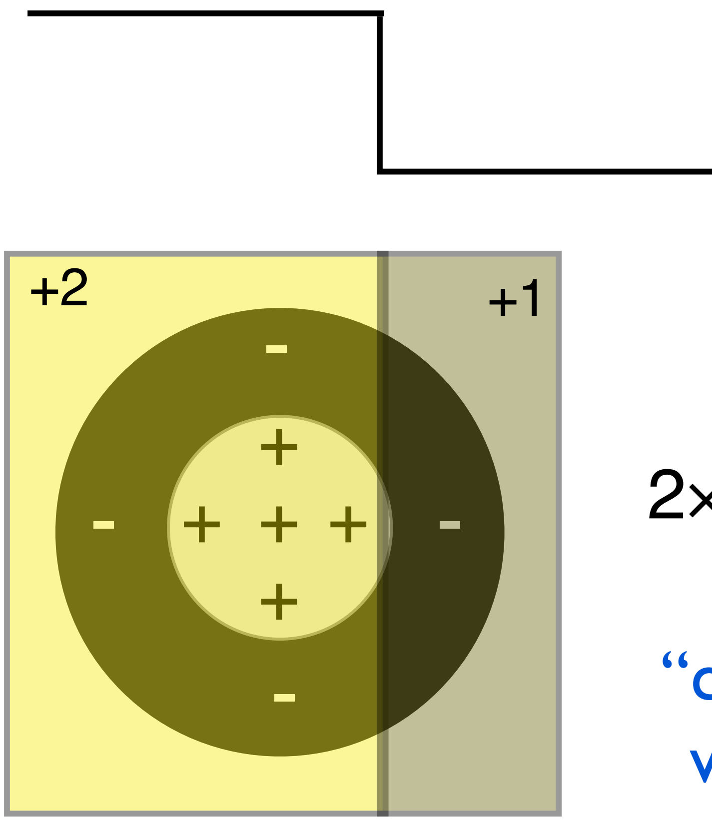
higher light level

2×(+5) + 2×(-4) = +2 spikes

"center" weight

"surround" weight

Response to an edge

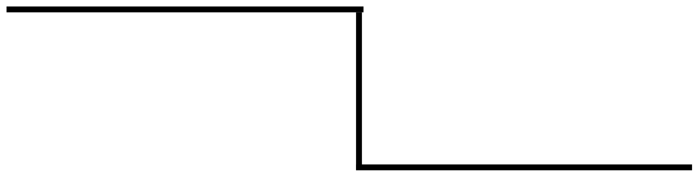


$$2\times(+5) \quad + \quad 2\times(-3) + 1\times(-1) \quad = \quad +3 \text{ spikes}$$

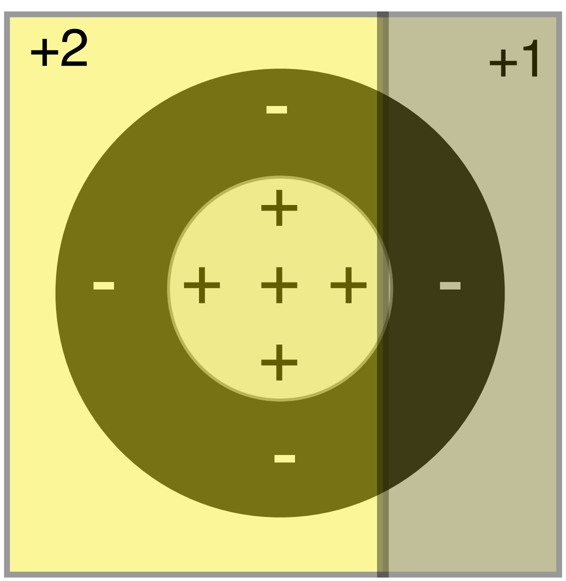
"center" weight

"surround" weight

Mach Band response



+2	+2	+2	+3	0	+1	+1	+1
+2	+2	+2	+3	0	+1	+1	+1
+2	+2	+2	+3	0	+1	+1	+1
+2	+2	+2	+3	0	+1	+1	+1
+2	+2	+2	+3	0	+1	+1	+1
+2	+2	+2	+3	0	+1	+1	+1

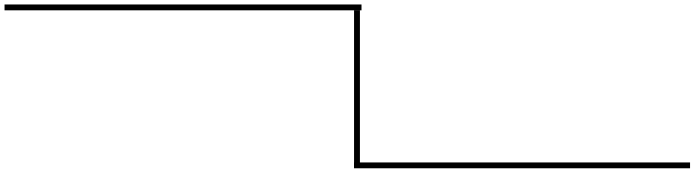


$$2\times(+5) \quad + \quad 2\times(-3) + 1\times(-1) \;=\; +3 \text{ spikes}$$

"center" weight

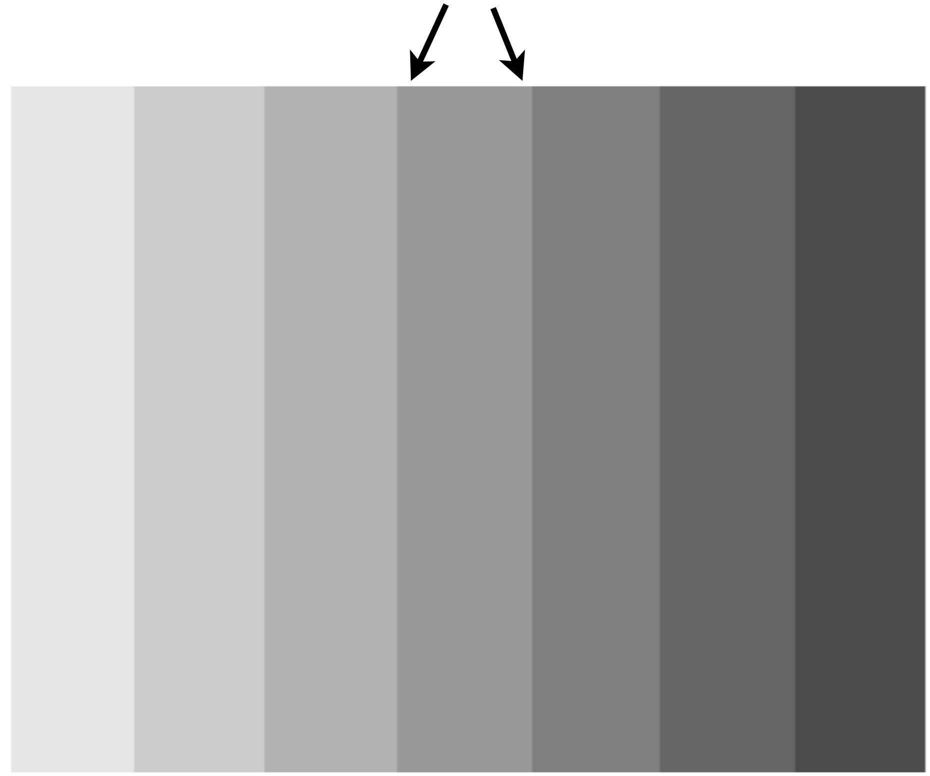
"surround" weight

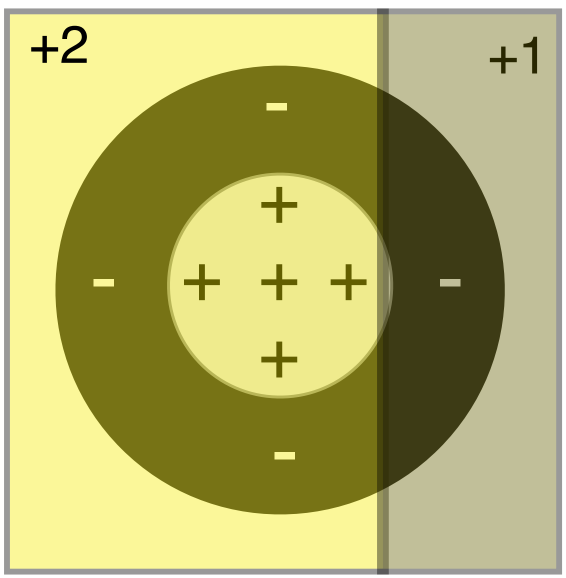
Mach Band response



+2	+2	+2	+3	0	+1	+1	+1
+2	+2	+2	+3	0	+1	+1	+1
+2	+2	+2	+3	0	+1	+1	+1
+2	+2	+2	+3	0	+1	+1	+1
+2	+2	+2	+3	0	+1	+1	+1
+2	+2	+2	+3	0	+1	+1	+1

edges are where light difference is greatest





$$2\times(+5) + 2\times(-3) + 1\times(-1) = +3 \text{ spikes}$$

"center" weight

"surround" weight

Also explains:

Lightness illusion

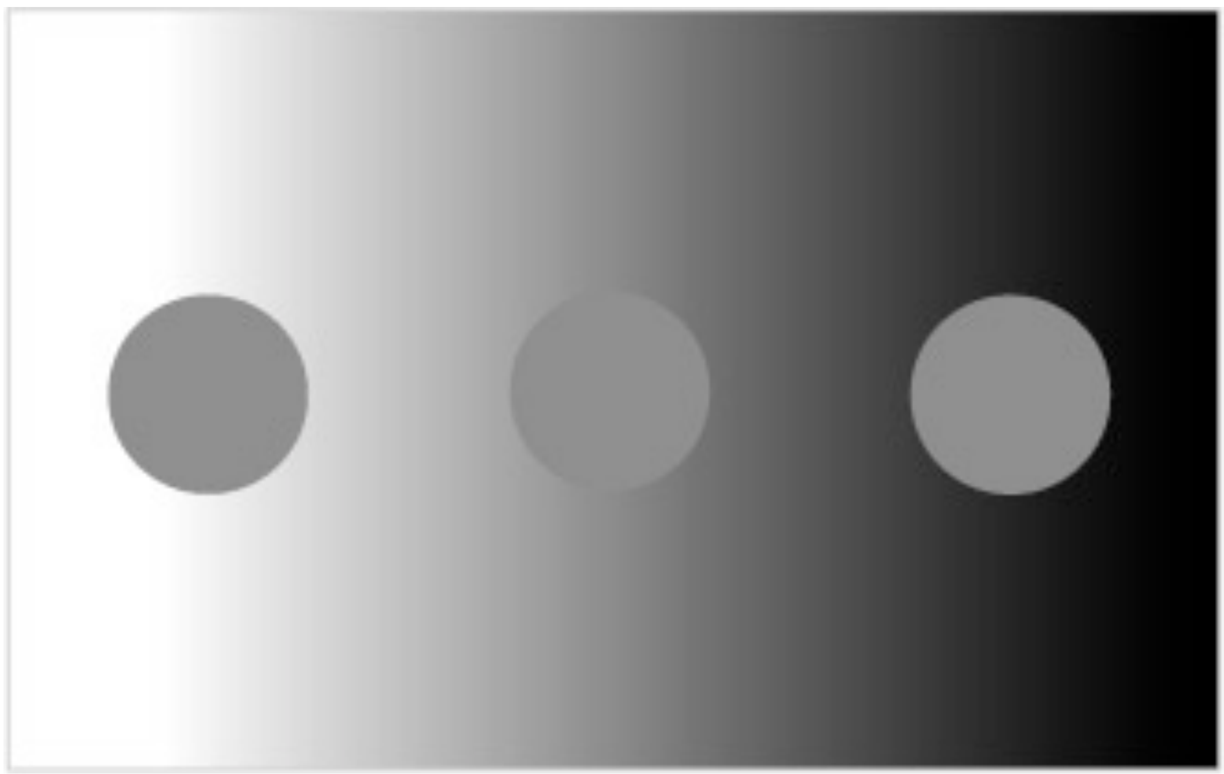
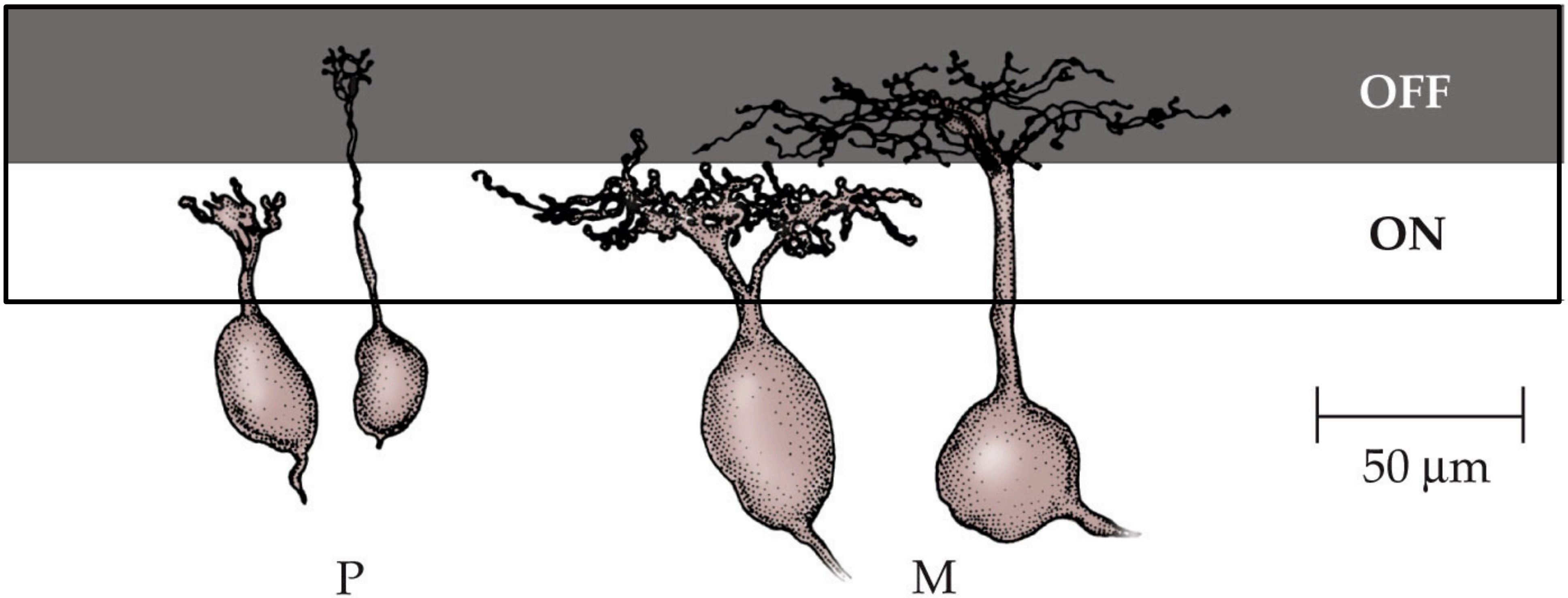


Figure 2.12 Different types of retinal ganglion cells

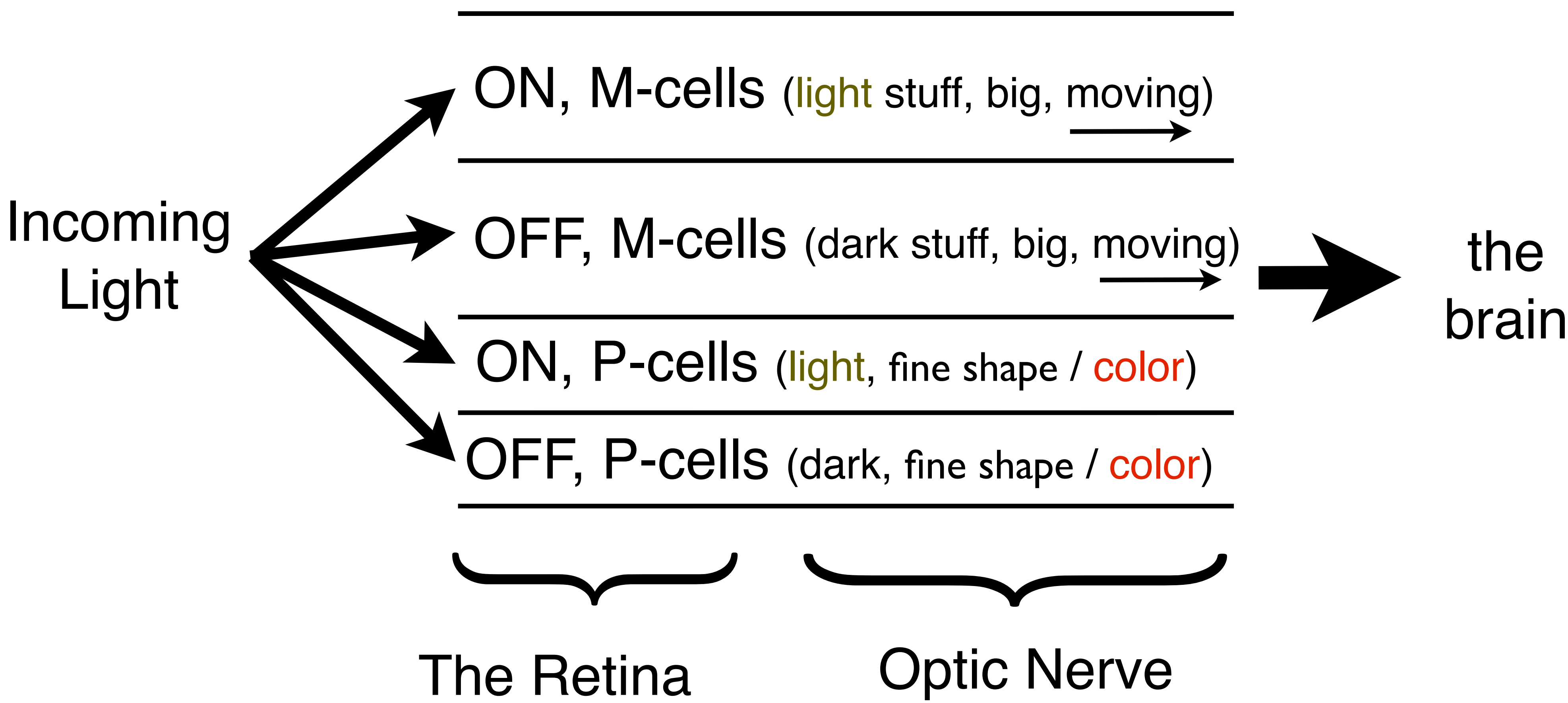
ON and OFF retinal ganglion cells' dendrites arborize ("extend") in different layers:



Parvocellular
("small", feed pathway processing shape, color)

Magnocellular
("big", feed pathway processing motion)

"Channels" in visual processing



Luminance adaptation

remarkable things about the human visual system:

- incredible range of luminance levels to which we can adapt
  (six orders of magnitude, or 1million times difference)

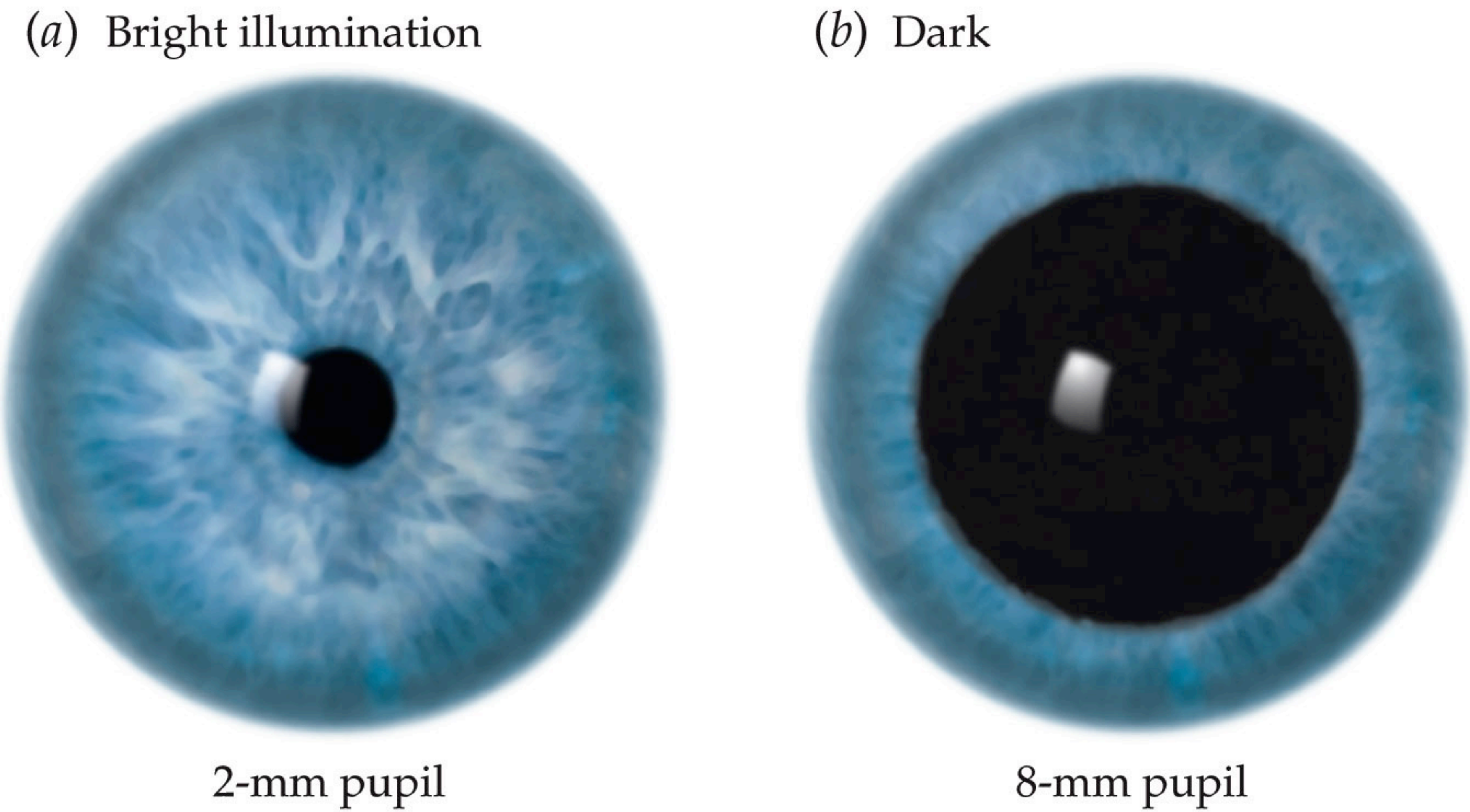
Two mechanisms for **luminance adaptation**
(adaptation to levels of dark and light):

(1) Pupil dilation

(2) Photoreceptors and their photopigment levels

the more light, the more photopigment gets "used up",
→ less available photopigment,
→ retina becomes less sensitive

The possible range of pupil sizes in bright illumination versus dark



- 16 times more light entering the eye

Luminance adaptation
- adaptation to light and dark

- It turns out: we're pretty bad at estimating the overall light level.
- All we really need (from an evolutionary standpoint), is to be able to recognize objects *regardless* of the light level
- This can be done using light differences, also known as "contrast".

Contrast = difference in light level, divided by overall light level

$$C = \frac{\Delta I}{I}$$

(Think back to Weber's law!)

Luminance adaptation

“center-surround” receptive field

Contast is (roughly) what retinal neurons compute, taking the difference between light in the center and surround!

$$\Delta I = (5 \cdot I_{ctr}) \; - \; (4 \cdot I_{surround})$$

Contrast = difference in light level, divided by overall light level

$$C = \frac{\Delta I}{I}$$

(Think back to Weber’s law!)

• from an “image compression” standpoint, it’s better to just send information about local differences in light

summary

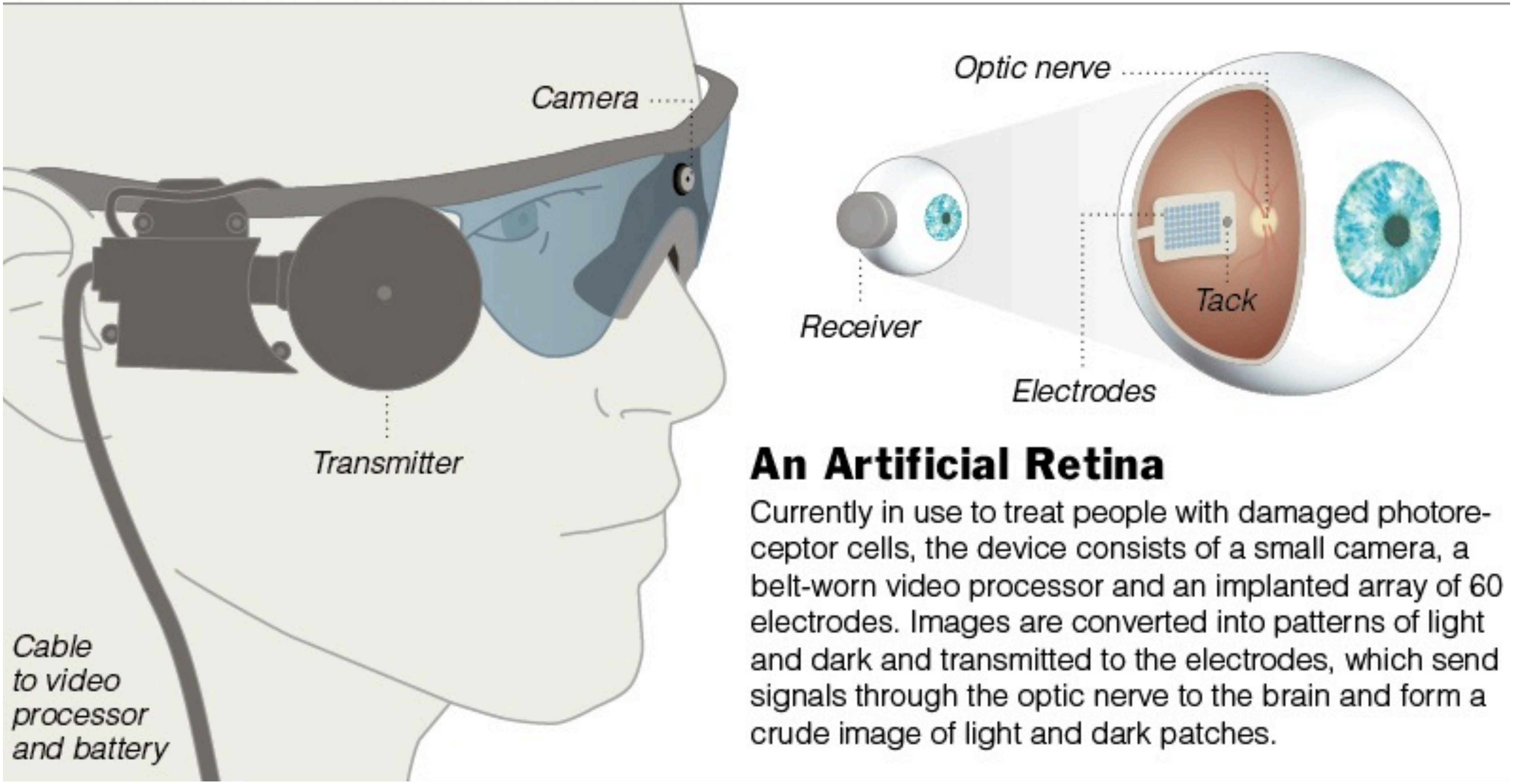
- transduction: changing energy from one state to another
- Retina: photoreceptors, opsins, chromophores, dark current, bipolar cells, retinal ganglion cells.
- "backward" design of the retina
- rods, cones; their relative concentrations in the eye
- Blind spot & "filling in"
- Receptive field
- ON / OFF,   M / P channels in retina
- contrast, Mach band illusion
- Light adaptation: pupil dilation and photopigment cycling

Now that you know how the retina works....

a cool technological application:

"Burst of Technology Helps Blind to See" (NYT, June 2009)

http://www.nytimes.com/2009/09/27/health/research/27eye.html?emc=rss&partner=rss



- shows patterns of light and dark, like the "pixelized image we see on a stadium scoreboard,"

- 60 electrodes
- future versions to have 200, 1000 electrodes