Vision

1. Basic structure of Eye.

Lenses, Retina.

2. Making an image

Cornea vs. lense.

Why we can't see well underwater.

When we need glasses.

3. Sensitivity of vision

a. Can you see single photons?

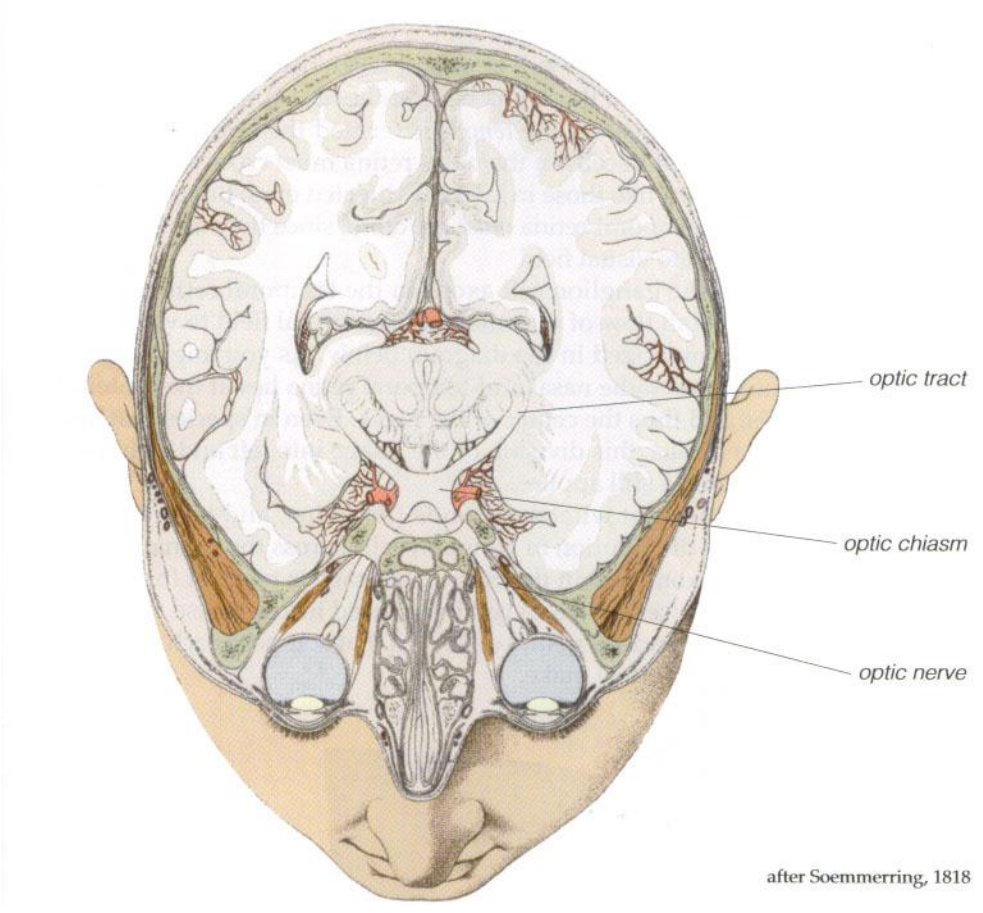
b. Why we can't see stars during the day:
Signal/noise.

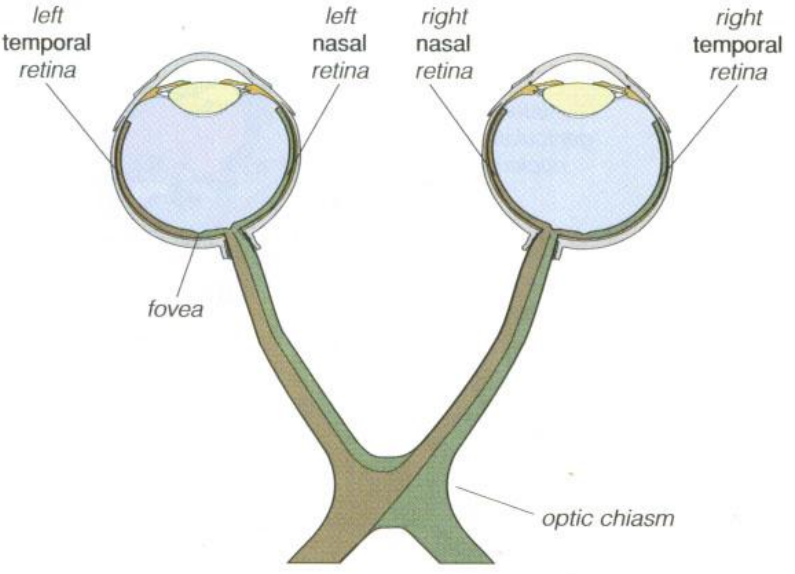
4. How light energy is converted into electrical (nerve) impulses. (This time or Next time ?)

Ion channels.

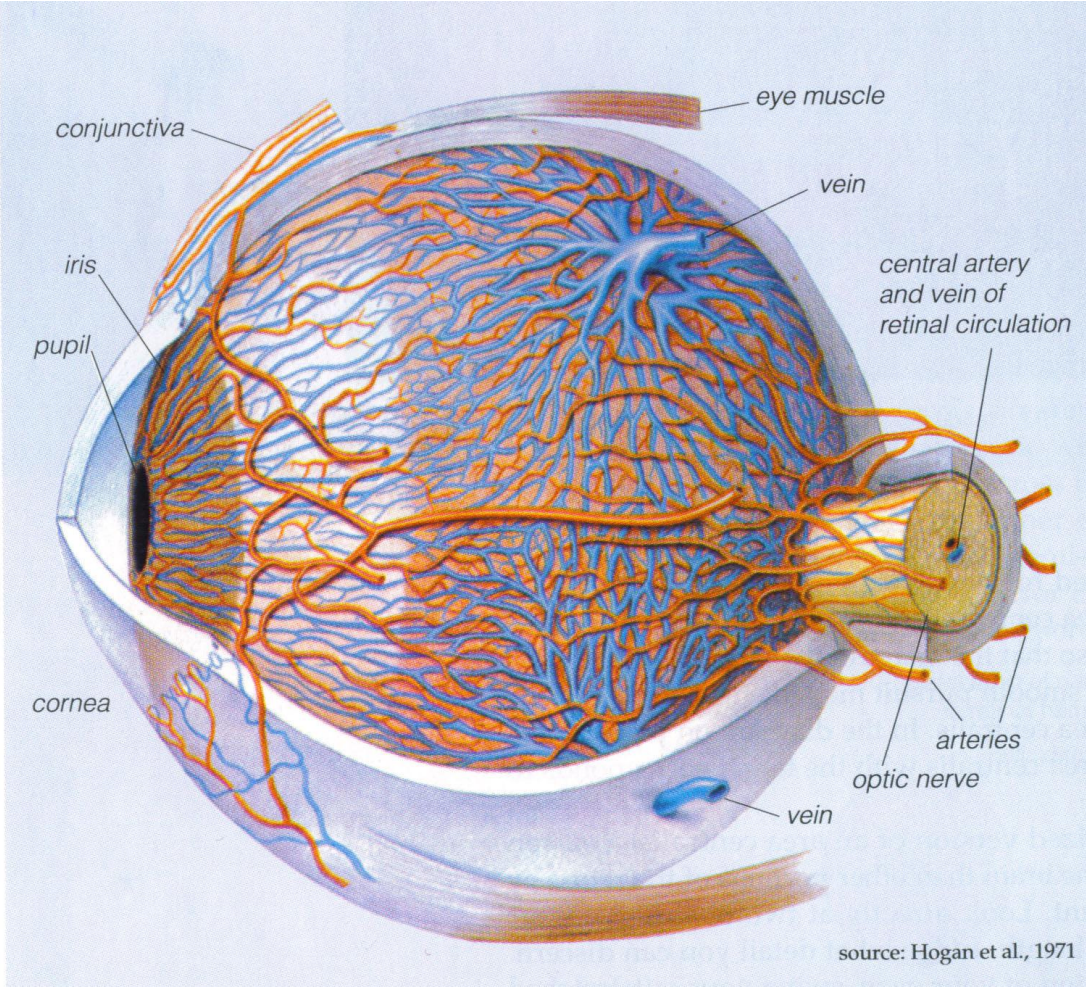
Visual System

Optic tract– right side of both sides goes into right side of optic tract



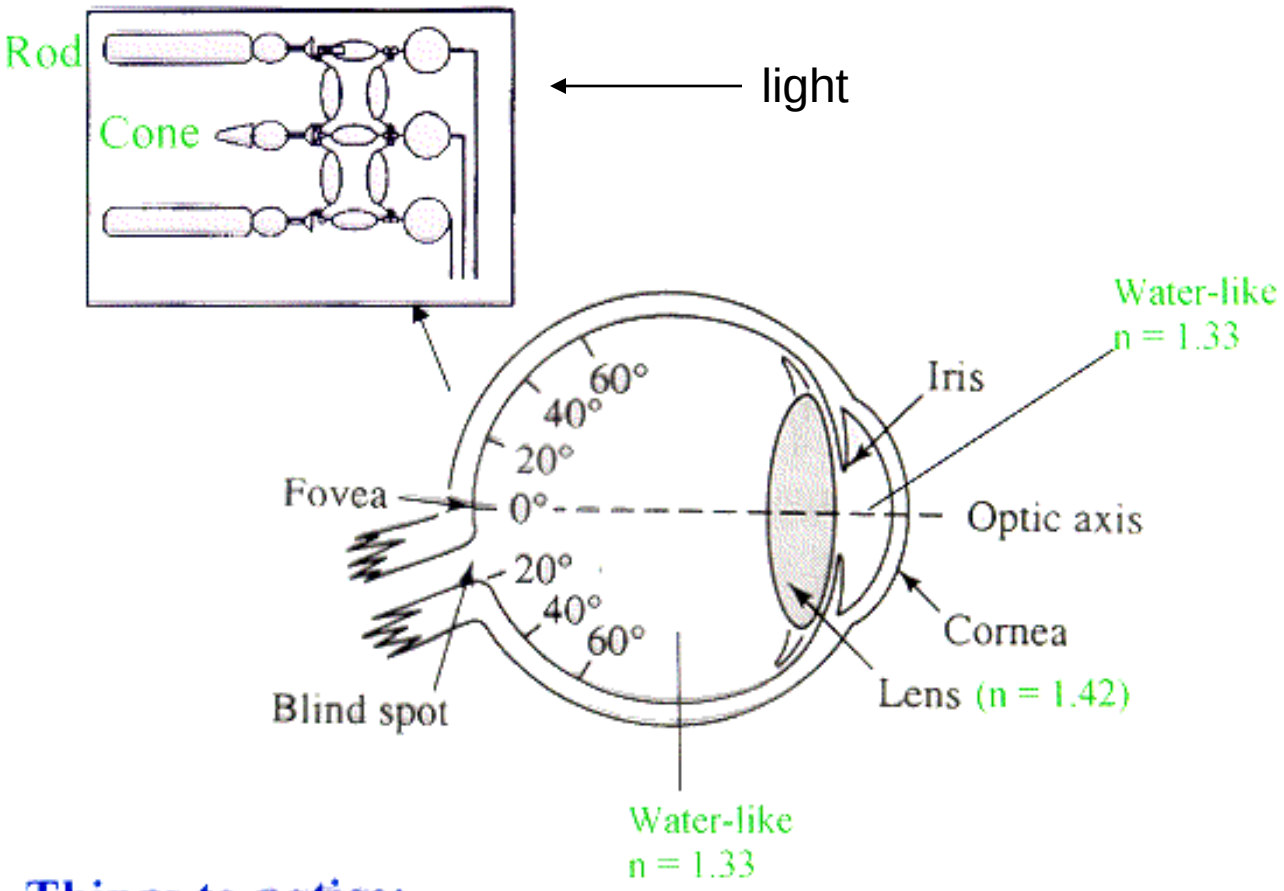


The Eye



Tons of blood vessels cause lots of Oxygen use.

Basic Structure of the Eye



Things to notice:

Image formation:

1. Two lenses, not one! **One fixed, one variable**
   Big index mismatch at cornea/air; some at lens.
2. **Image distance is fixed.**
3. **Normal eye: object at ∞, focussed on retina with lense relaxed.**

Light (and color) detection:

4. **Sensitivity of retina = function position**

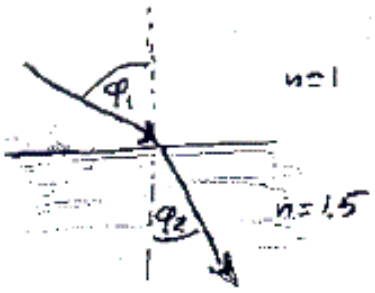
5. **Rods and Cone Backwards!**

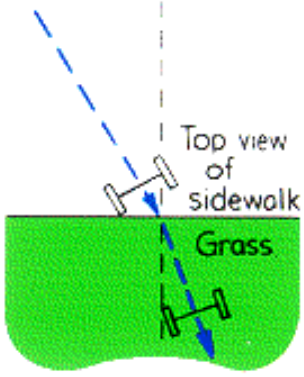
Forming an image…

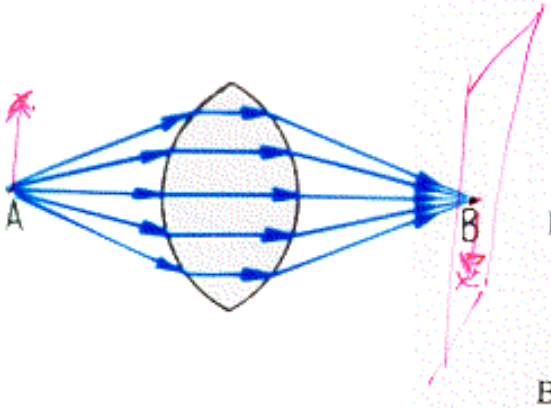
Light going from one media (index of refraction)to another.

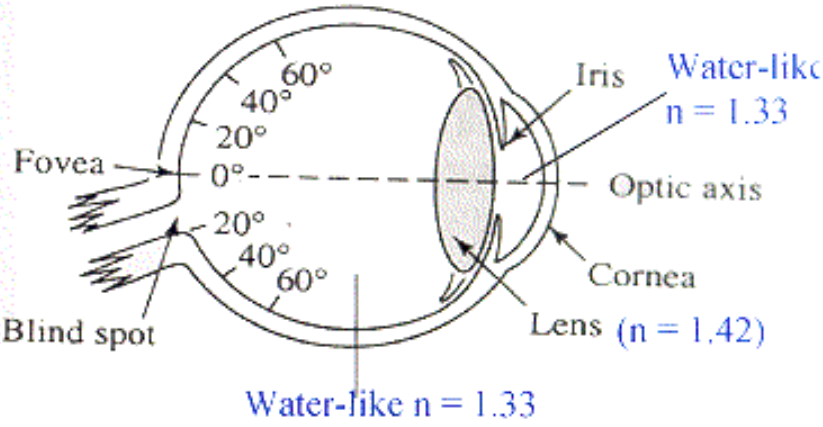
(Snell's Law)

$n_1 \sin\theta_1 = n_2 \sin\theta_2$









Amount of bending depends on index mismatch and angle of incidence.

Cornea is responsible for 2/3 → ¾ of light bending.

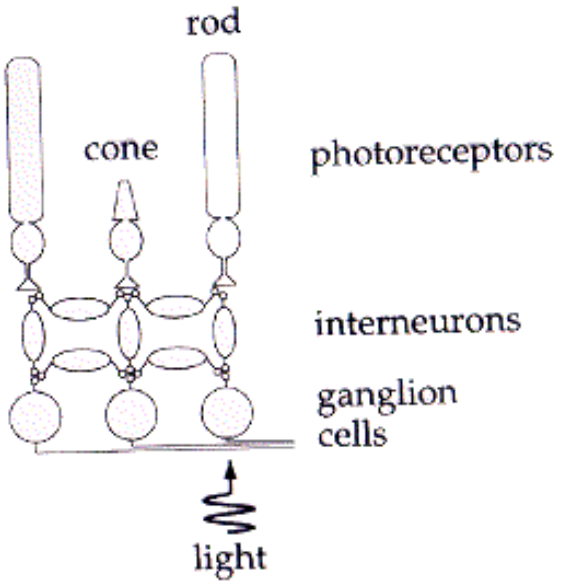
Why can't you focus well under water?

Why is image formed upside-down, but not left-to-right?

Retina

Two types of photoreceptors:

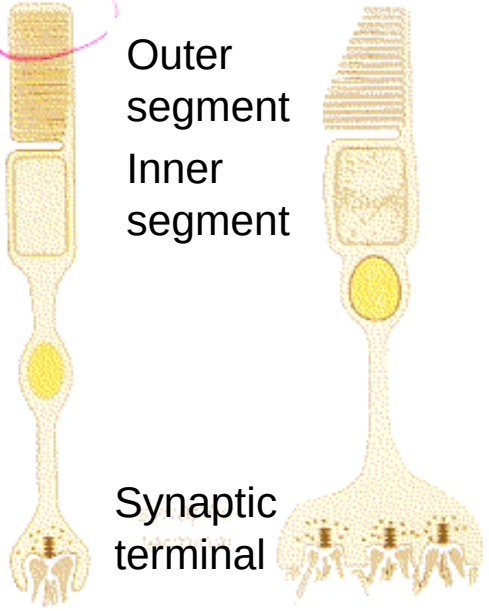
- **Rods:** dark-level sensitivity
- **Cones:** color, most of day-vision



Mammalian rod contains ~ 10^8 rhodopsin molecules

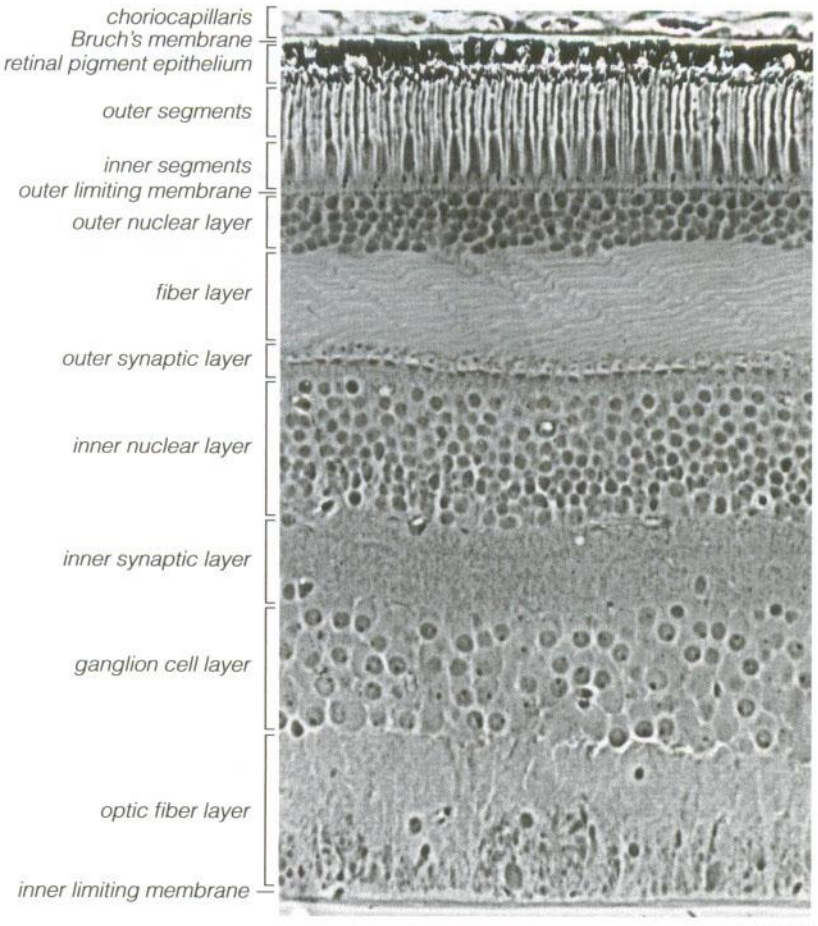
Rod ~3 μm

Cone

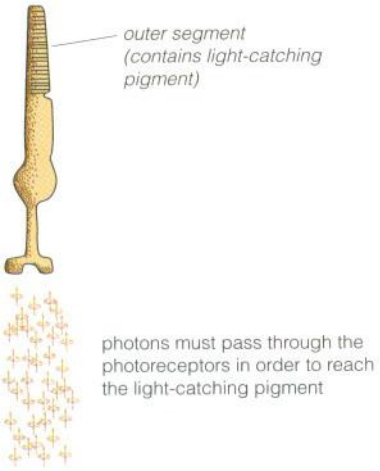


Rhodopsin– pigment that absorbs light→ changes shape: bent → straight that ultimately leads to signal, i.e. ion channel opening, nerve firing.

Your receptors face "backwards"



source: Boycott and Dowling, 1969



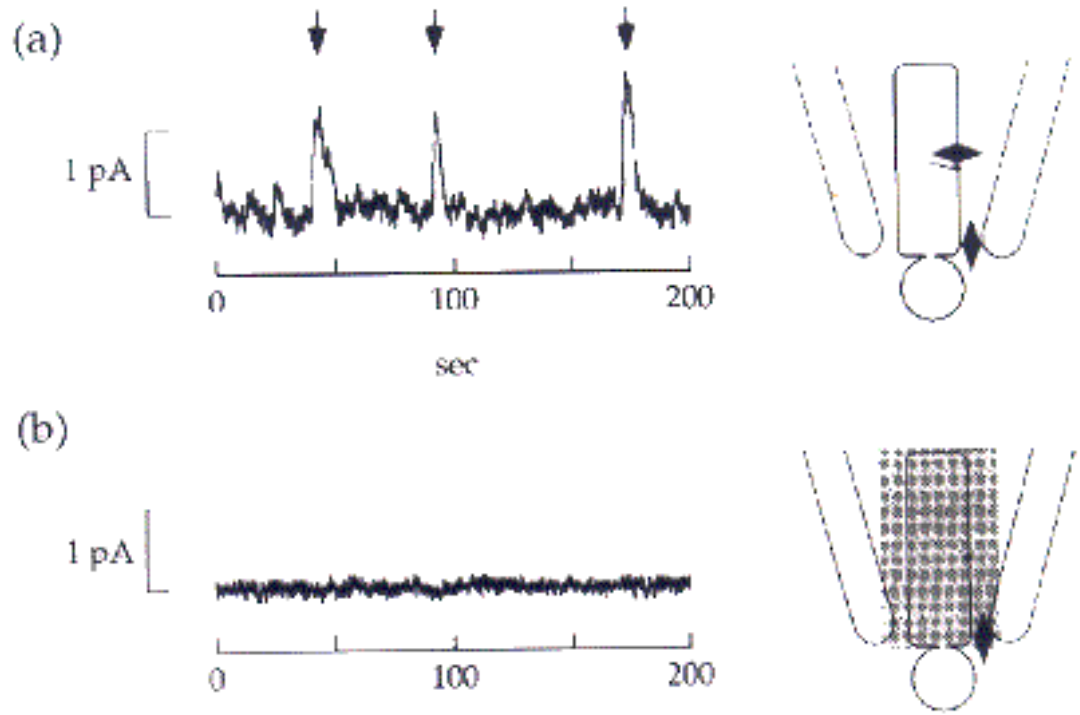
1.25 mm from Fovea, Roieck, pg38

Why?

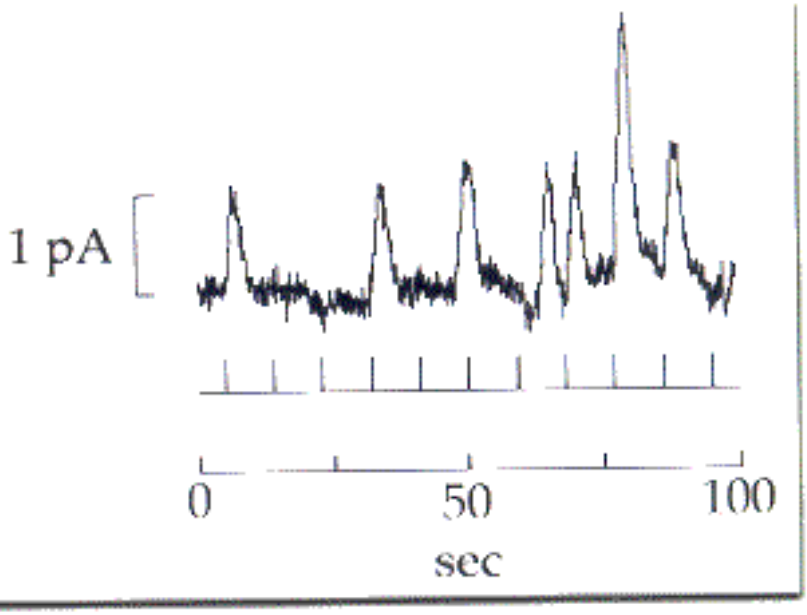
1. May be consequence of neural tissue development.
2. Outer portion of photoreceptors, which are very metabolically active, are near epithelium which supplies oxygen and nutrients. (Rodieck, pg 39.)

Rods

Isolated rod can "see" single photon!



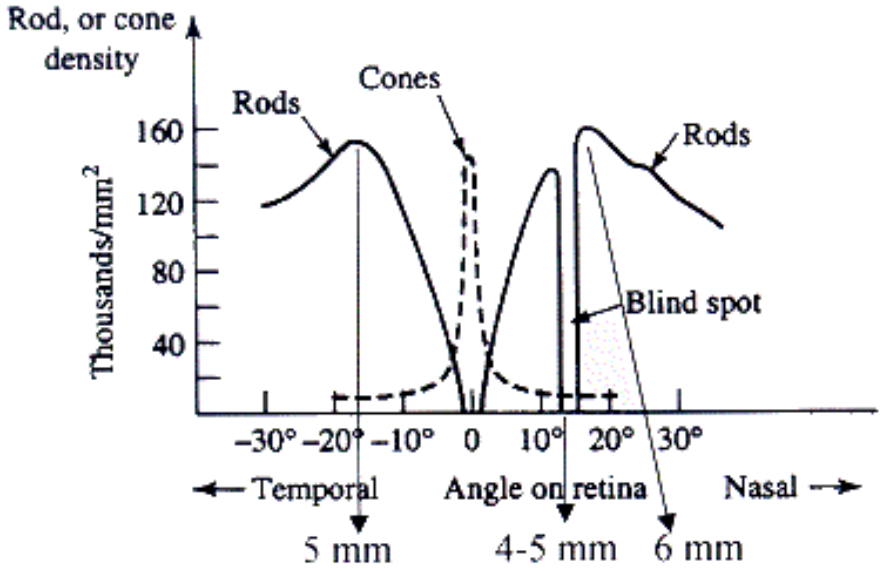
Rieke, Rev. Mod. Phys Fig. 6

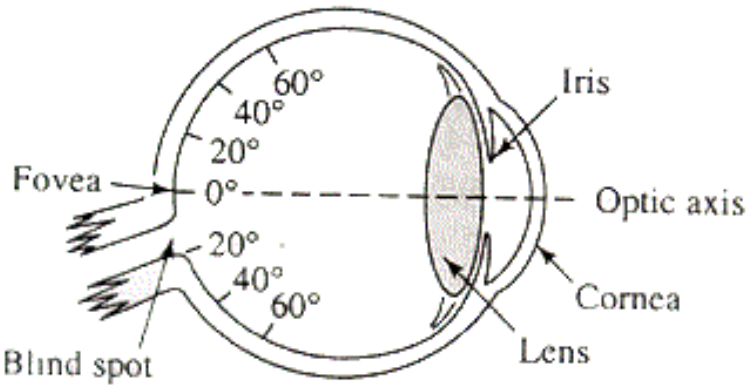


From Fred Rieke (UWash.) home page: http://depts.washington.edu/pbiopage/rieke/

Distribution of Rods and Cones are *not* uniform on retina.

Density of rods and cone in left eye [Benedek 3.10]



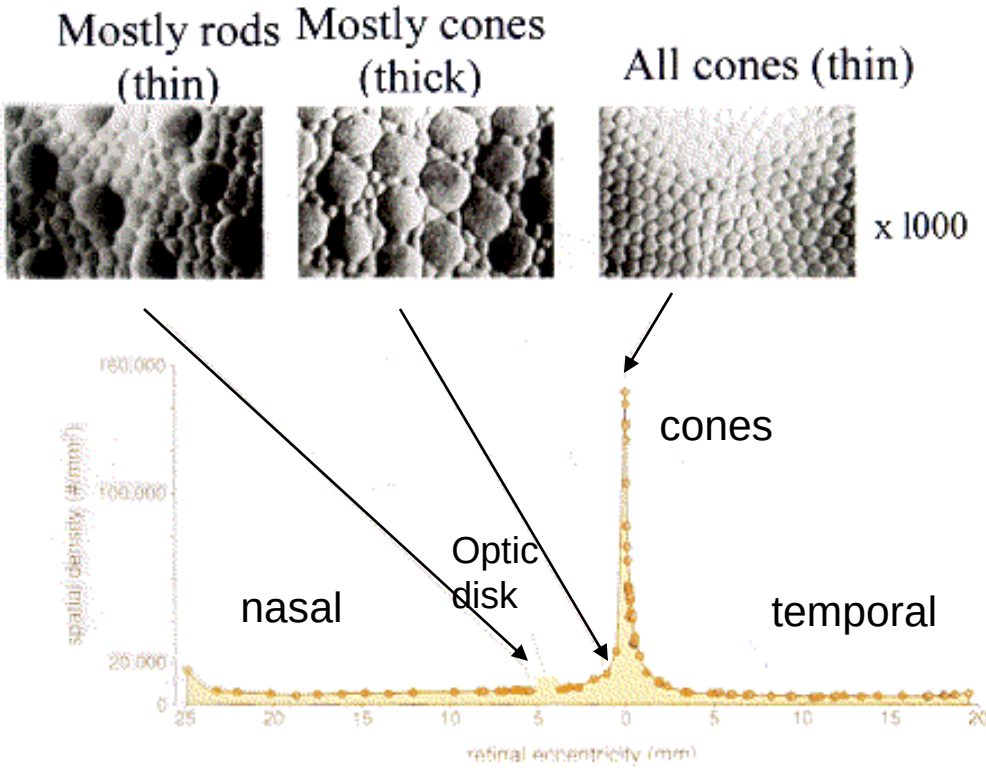


Each peak density @ > 100,000 receptors/mm^2

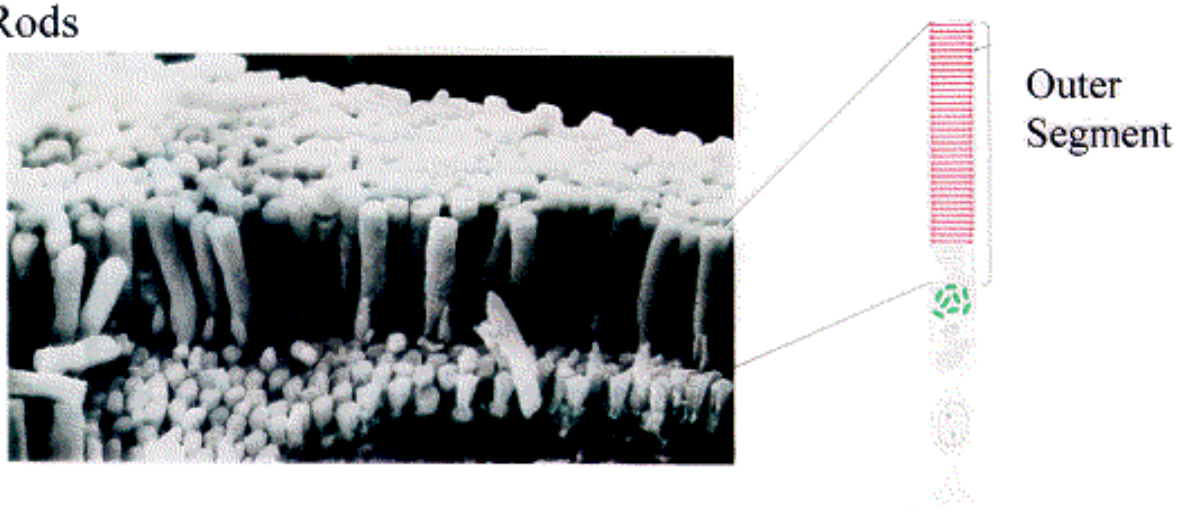
For max. sensitivity in low light, where should you look?

Distribution/pictures con't

Cones



Rods

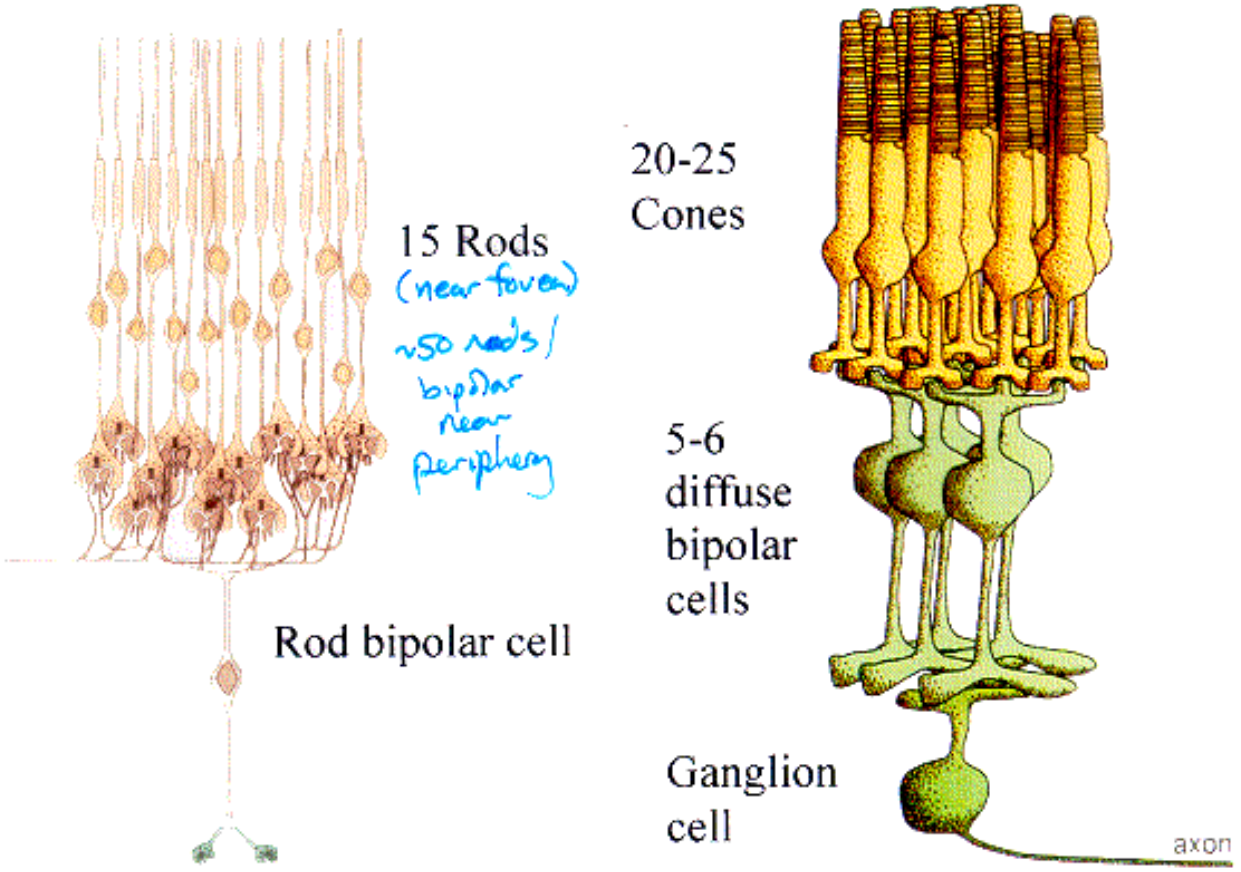


Rods & Cones are organized in groups

Order of magnitude…**Retina has**
$\approx 10^8$ photoreceptors,
$\approx 10^7$ intermediate cells (e.g. bipolar cells)
$\approx 10^6$ ganglion cells, which ultimately form optic nerve.

20 rods contact a second order cell. Between 25 and several hundred bipolars provide input to a ganglion cell (depending on where in the retina you are). [source: Prof. Fred Rieke, UWashington]

Rods (Cones) connected to a single ganglion cell act as a functional unit.

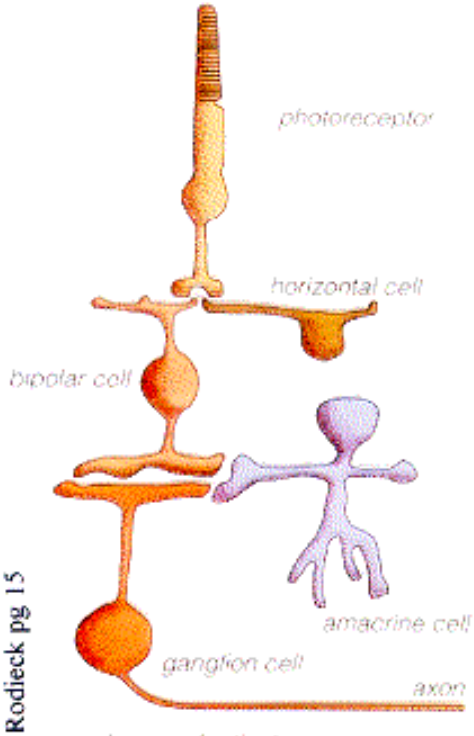


Signal processing begins in retina.

Output of rods can be modulated by horizontal cells

Important in dynamic range; Seeing differences in light.

[Rodieck. pg 144. 185]



Rodieck pg 15

classes of retinal neurons

1. **Dynamic range:** can see over range of intensities of $10^{\wedge 10}$.
(Uses both rods and cones.)
Rod vision: 10^6 dynamic range

Any one cell can't respond over this range.
Rod output can change by 100x.
Bipolar cell output can change by 100x.

- **If light level low, rod output → bipolar input.**
- **If light level high, horizontal cell attenuates rod output.**

Your eye responds logarithmically to light
Allows you to see over huge range of intensities.

2. Horizontal cells & other processing makes visual response more sensitive to differences in light intensity in image, than absolute light levels.

Absolutely uniform illumination into eye – see nothing!

Light (Intensity) levels

Definition of intensity? Power/area = (Energy/time)/area: Watts/m^2

Units? Photons/area/time x energy/photon

Energy/photon= $h\nu$/photon

You can see over enormous range: 10 orders of mag.!

Entering your eye:
$< 10^{-2}$ photons/μm^2/sec (starlight) to
$> 10^{8}$ photons/μm^2/sec in bright sunlight. (Ricke, rev. mod. Phys)

You can see very little light!
At retina: $4x10^{-4}$ photons/μm^2/sec.
Some sense of light and dark.
Can navigate a bit. [Rieke, UW]

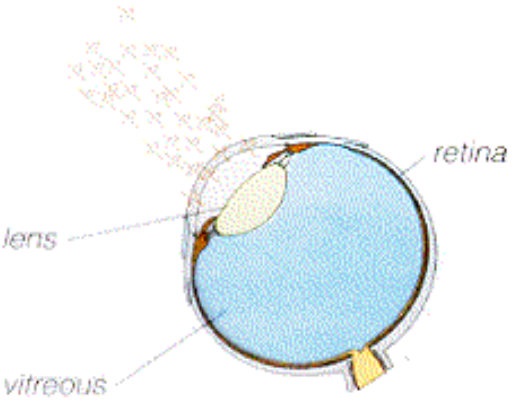
If photoreceptor (rod) is about 3 μm diameter, this corresponds to 0.004 photons/rod/sec or 1 photon per 250 rods / sec!

Relevant integration time: 0.1 sec.

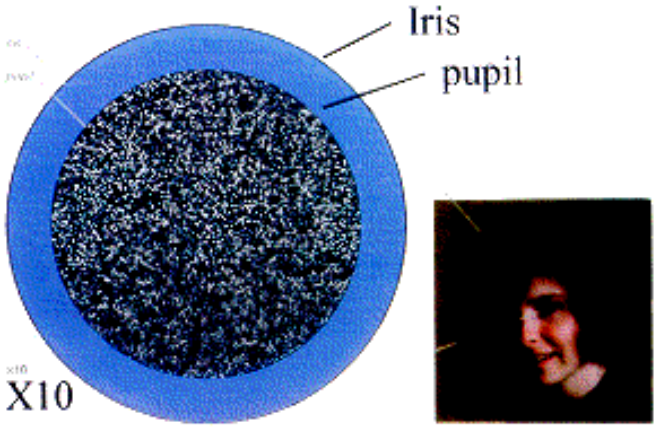
Can see at 1 photon per 2500 rods per 0.1 sec!

Starlight: ≈100,000 photons/sec

Quick calculations…



photons from Polaris ×1



10,000 photons/0.1 sec at pupil
[Low I – photon nature of light.]

Starlight: About 2,800 visible photons/s/mm^2 hit surface of earth/eye from North star (Polaris).

Pupil (in dark) ≈ 40mm^2, 6 mm diam. = 112,000 photons/sec

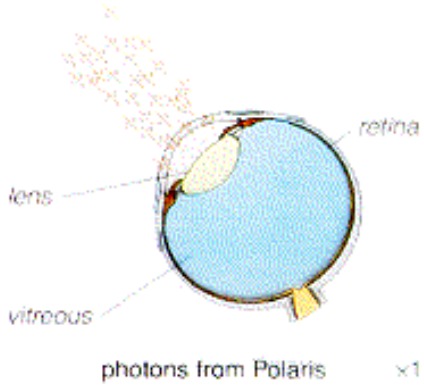
Eye has a memory/shutter time of about 0.1sec
= 11,200 photons/shutter time.

rod cell keeps ~~earth~~ producing current

Memory time determined by length of time of ~~action potential~~ induced by photon in photoreceptor.

(lack of current)

Losses of light going through eye.



Only ≈ 10% of the photons that hit front of your cornea actually get absorbed by photoreceptor (rod/cone) and only 2 out of 3 of these photons lead to a chemical reaction (photoisometerization of rhodopsin from bent to straight form).

Losses… going through parts of eye …

Start with 11,200 photons/0.1 sec

Loss: Eye part (for cones, but total very similar for rods)

10%: Cornea (2.5% front reflection, 9% absorbed/scattered inside)
9,400 photons ledt.

42%: lense, vitreous humor, pigment in retina < photoreceptors
5,500 photons left.

46%: Hit inner segment (front) of photoreceptor but don't hit outer receptor (back) where photopigments (rhodopsin) are.
2,900 photons left.

64%: 1 out of 3 photons entering outer-segment get absorbed.
1,044 photons absorbed.

33%: 2 out of 3 absorbed photons leads to isomerization of rhodopsin (bent → straight)

700 photoisomerizations/0.1 sec

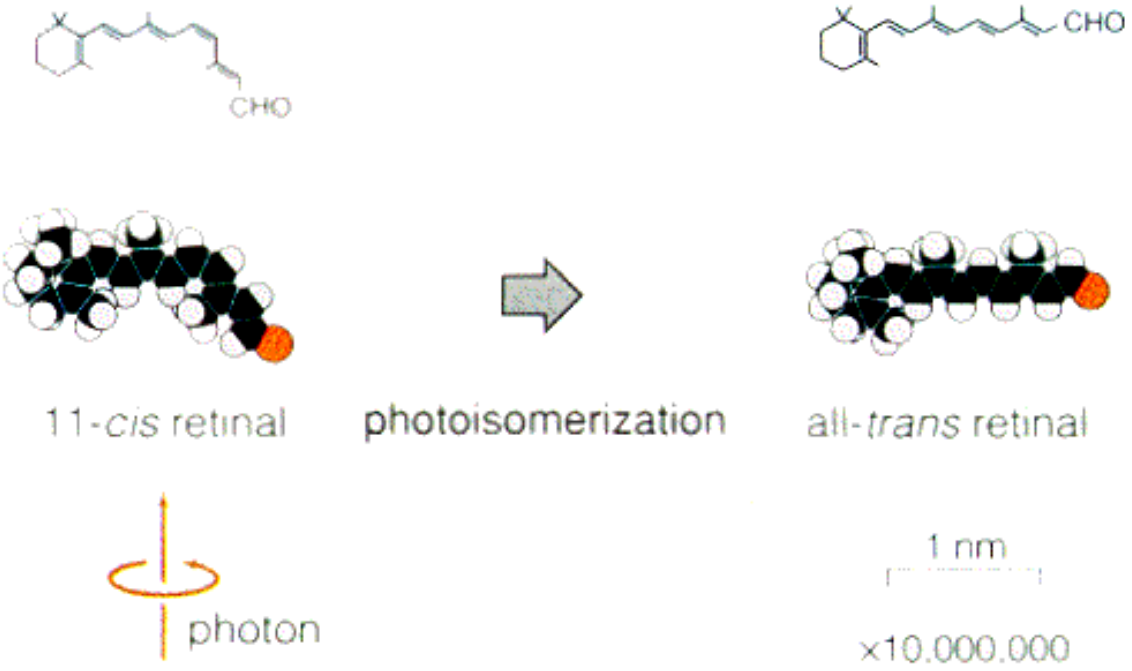
6% of photons entering your eye actually create signal.

Rhodopsin Protein
Contains visual pigment: retinal.
Colored: Responsible for light absorption

Photon absorbed, straightens out molecule, leads to biochemical cascade… ultimate changes concentration of cyclic nucleotide, change in # ion cNucleotide-gated ion channels open, change in # action potentials/sec. …

How you detect photons.

Mammalian rod contains 10^8 rhodopsin proteins.



Light causes isomerization of retinal

Can you see a single photon?

Classic experiment: Hecht et al., 1942.
(Followed by Sakitt, 1972).

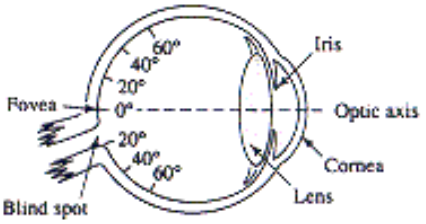
Experimental Arrangements:

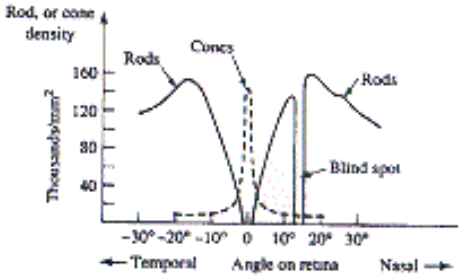
Short, dim light flash into eye of average N photons.
Ask patient: "yes" saw it, "no" didn't.
Keep reducing light level until can't see it.

Light flash:

Measure ave. # photons at cornea by thermopile.

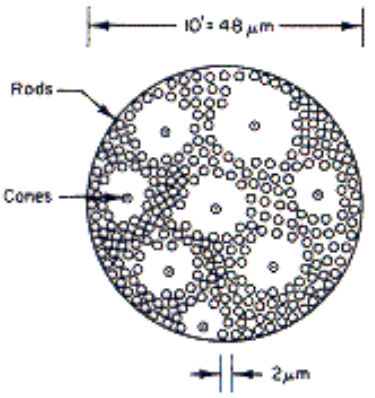
Thermopile: detector that heats up when photon absorbed; know heat capacity very well.





To maximize sensitivity:

1. Position: Shine 20° off-center.
2. Flash time < 0.1 sec: actual 1 msec.
3. Flash color: 510 nm (blue-green)
4. Spot size? If light < 10 minutes of arc, "receptive field": maximum sensitivity. [If shine light bigger than field, lower response/light intensity.]
5. Dark Adaptation. Sensitivity of eye > 30 min. in dark. Hecht waited 40 min. (2000x more sensitive > 30 min. in dark compared to bright room.)



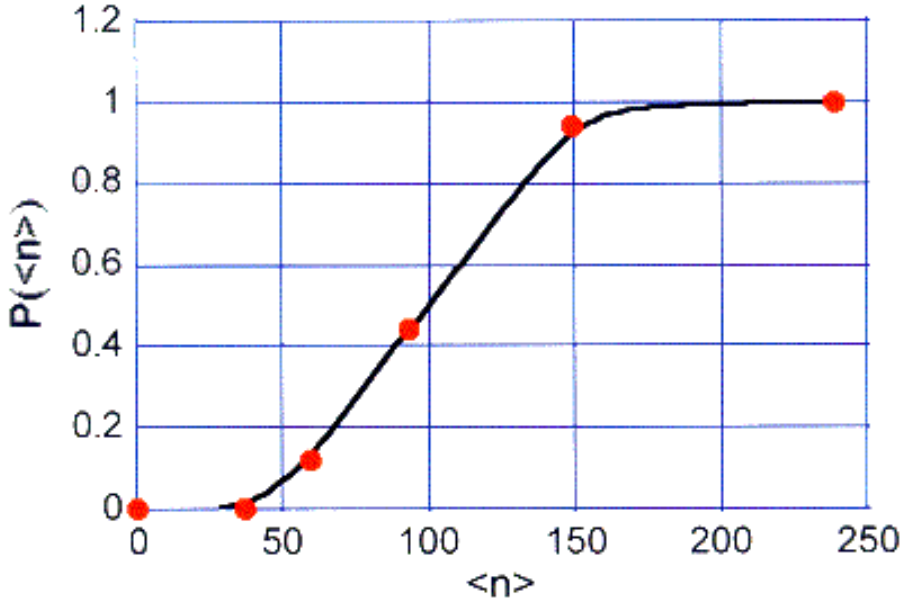
Data of Hecht et al. (1942)

Present series of flashes of <n> photons/flash entering eye (at cornea).

P(<n>) =Probability of seeing flash with <n> photons.
("yes/no" decision)

Table 3.1. Frequency of Seeing ($P(\bar{n})$) Versus $\bar{n}$, the Number of Photons at the Cornea (from Hecht et al. [6]).

$P(\bar{n})$	$\bar{n}$
0	37
.12	59
.44	93
.94	149
1.0	239



Simple Data Analysis

If P(<n>) = 0.5 defined as threshold of seeing

You can see ≈100 photons entering cornea.
(50-140 photons needed, depending on person)

10% of incident photons are absorbed.

You can see 5-14 absorbed photons

2/3 of molecules absorbed get excited.

3-10 excited molecules in retina lead to signal.

Over area of 500 rods.

Probability that two photons arrived at same rod very small.

"We may therefore conclude that in order for us to see, it is necessary for only 1 quantum of light [photon] to be absorbed by each of 5 to 14 retinal rods." Hecht, 1942.

Why can't we see a single excitation?

Answer: photopigment spontaneously isomerize even in absence of external light.

5 spontaneous excitations per receptor field per 0.1 seconds.

This creates a "dark noise".

External Signal must be one this order or greater to see it.

Mammalian rod: 10^8 rhodopsins.

A rhodopsin spontaneously isomerizes 1/300 years!

[Remember: normally 2 eV photon to cause transition: = 80kT! Think ΔG!]

In each rod, 1 rhodopsin isomerizes every 90 sec.

One isomerization leads to rod firing. If 500 rods in visual field, 0.5 isomerization/0.1sec/ receptor field. Each isomerization leads to a nerve firing.

rod