

Lecture 5: Human Visual System: An Overview

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Computer Imaging & Graphics

The Roadmap

Theoretical Preliminaries

Human Visual Systems

Display and Camera

Modeling and Rendering

Overview

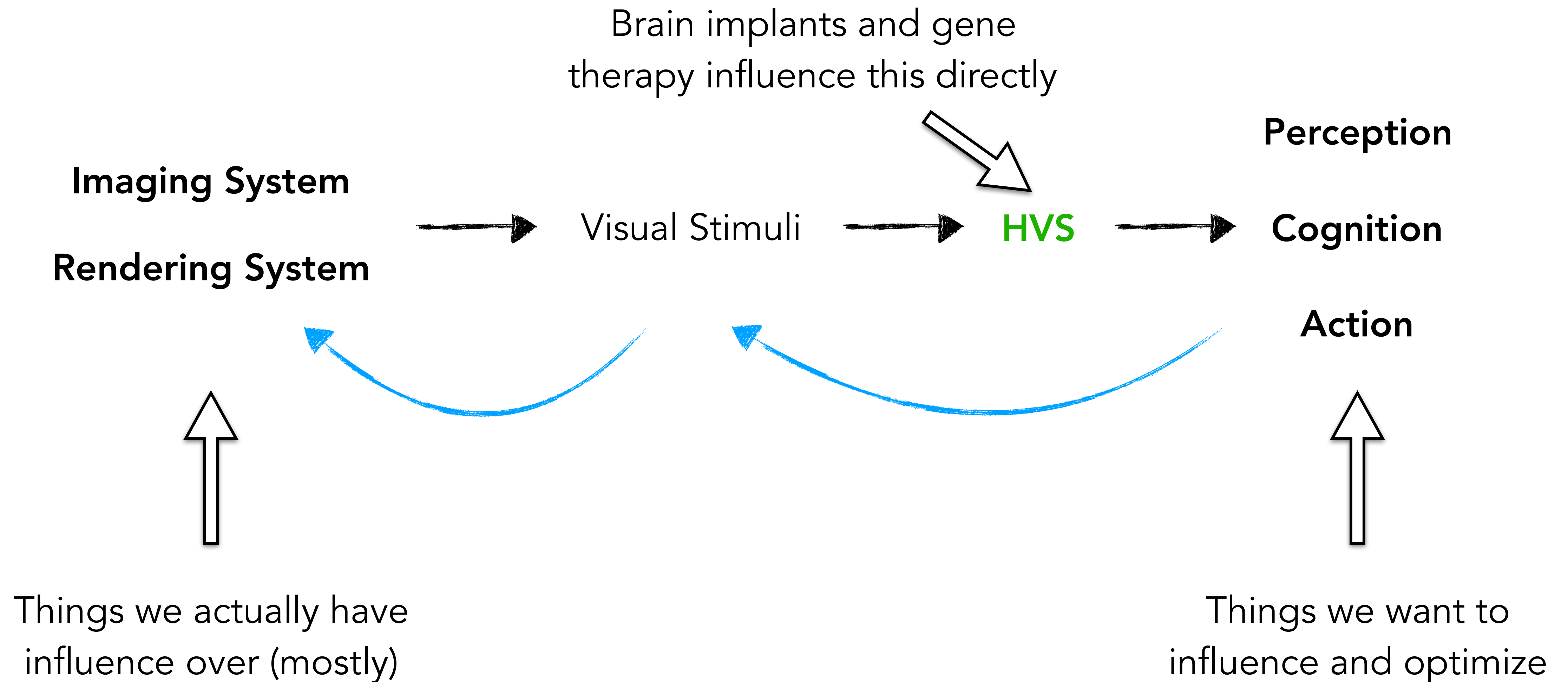
Color Vision

Colorimetry

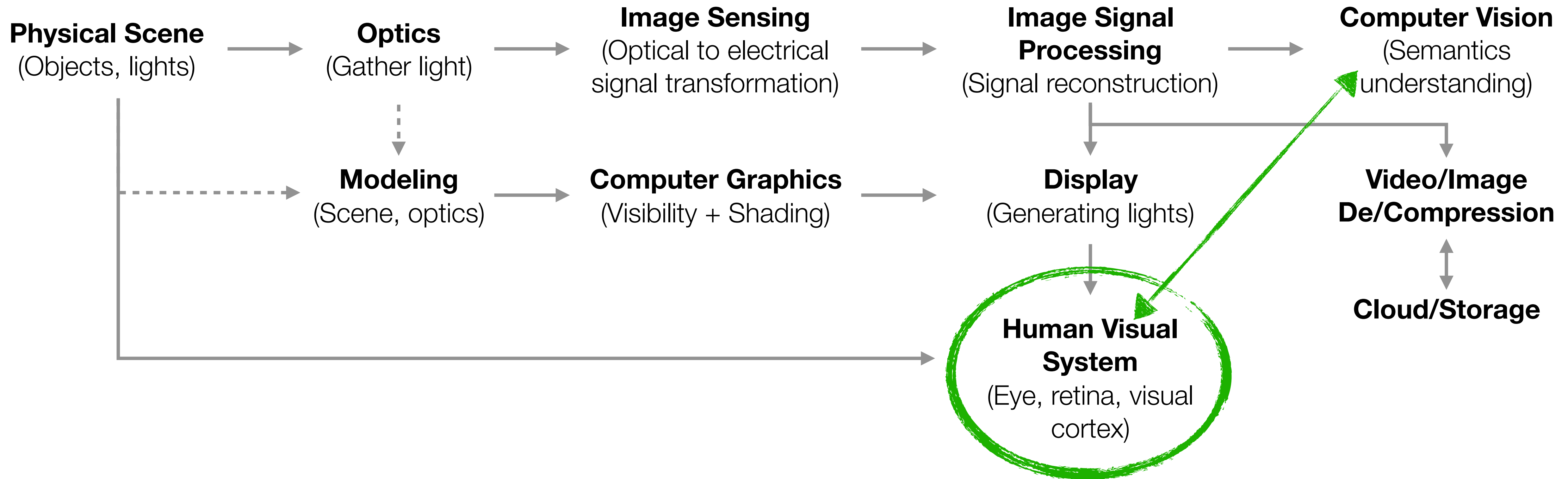
Visual Adaptation



Why Study Human Vision (Other Than For Science Itself)?

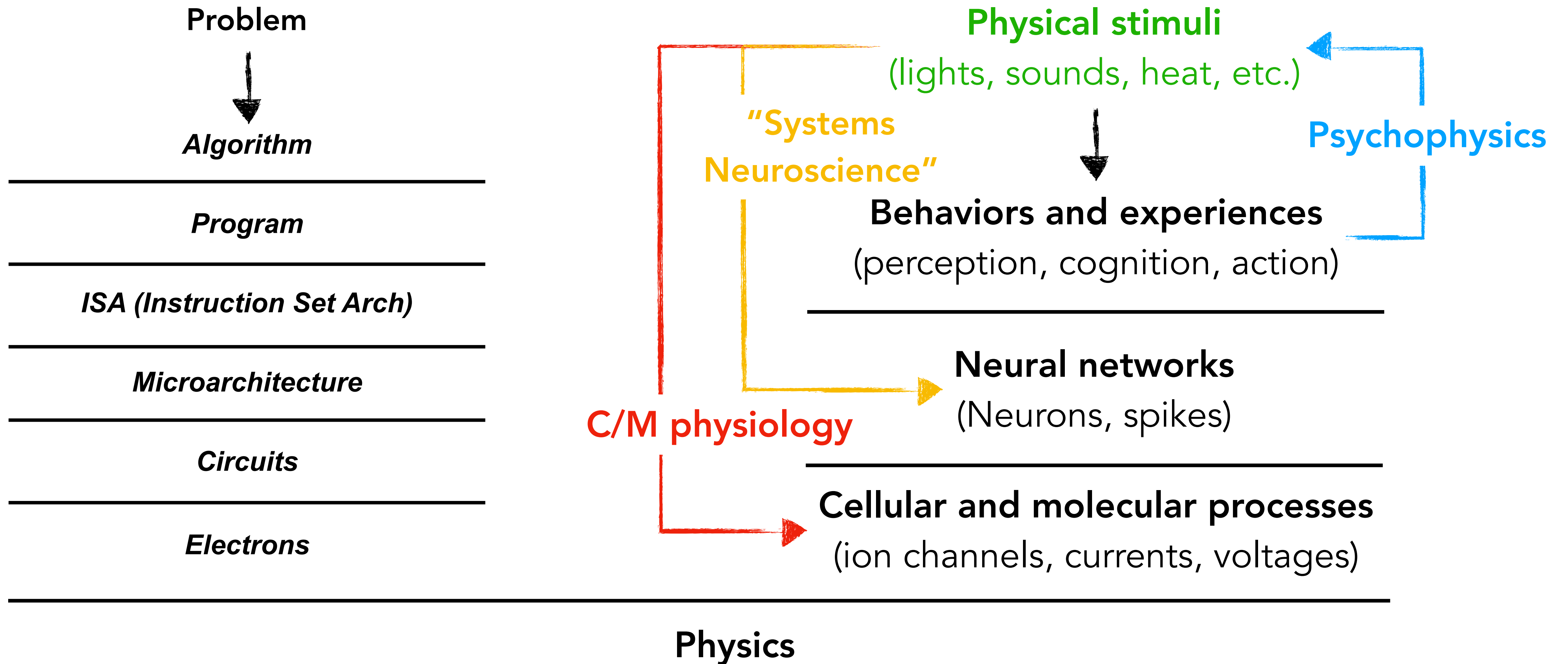


Why Study Human Vision (Other Than For Science Itself)?

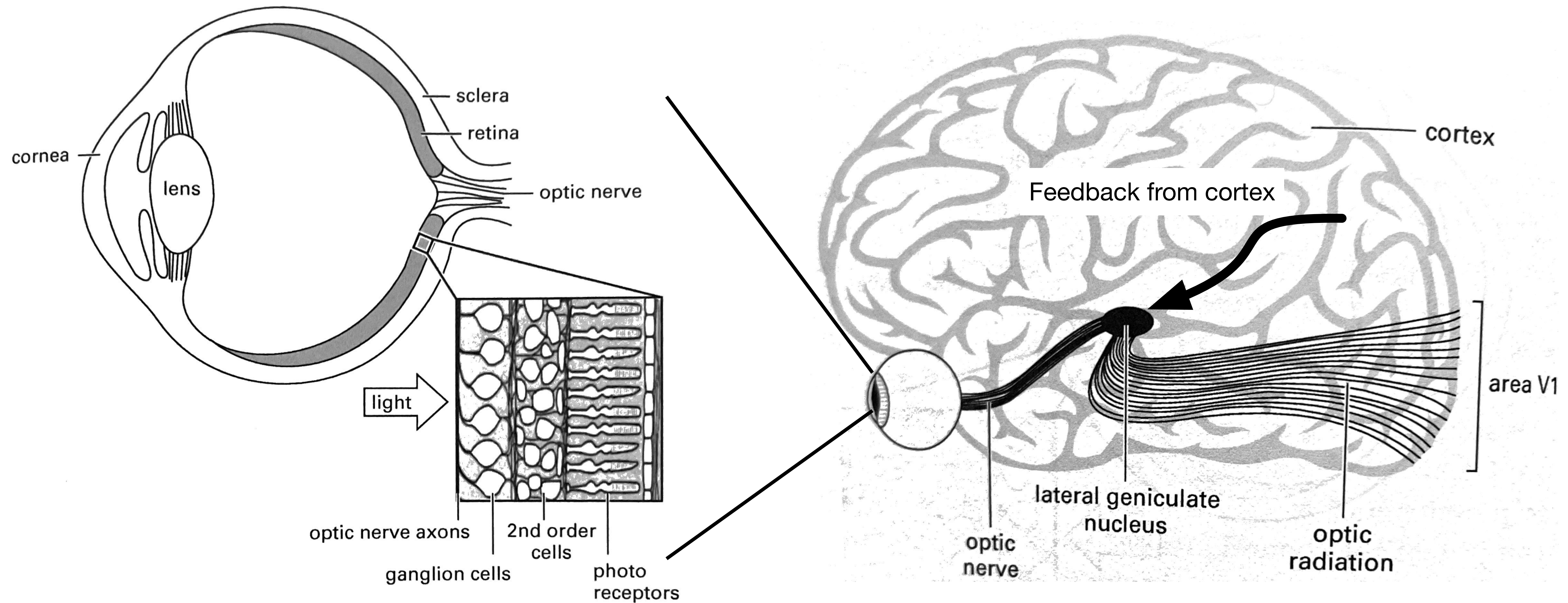


The Big Picture

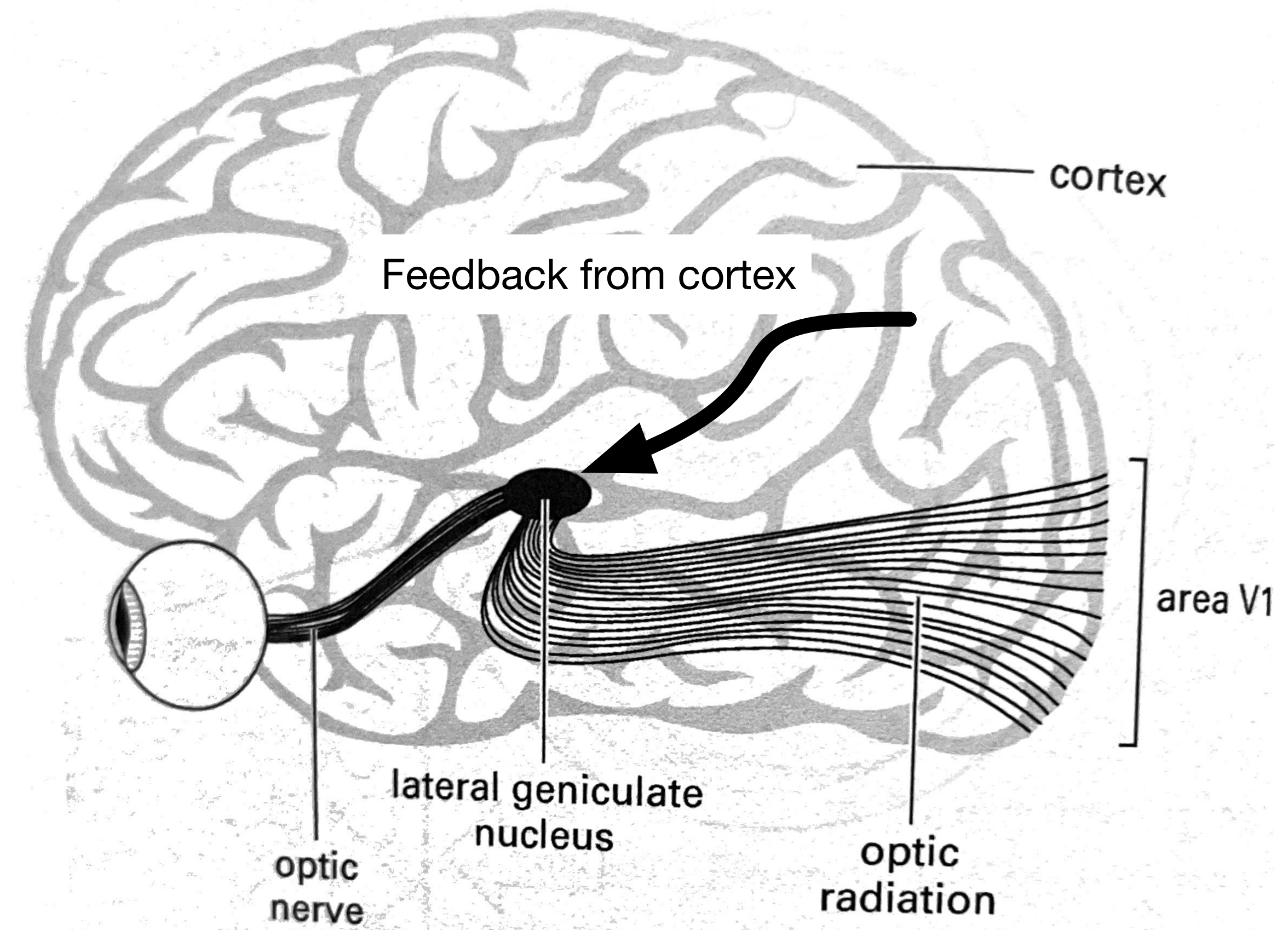
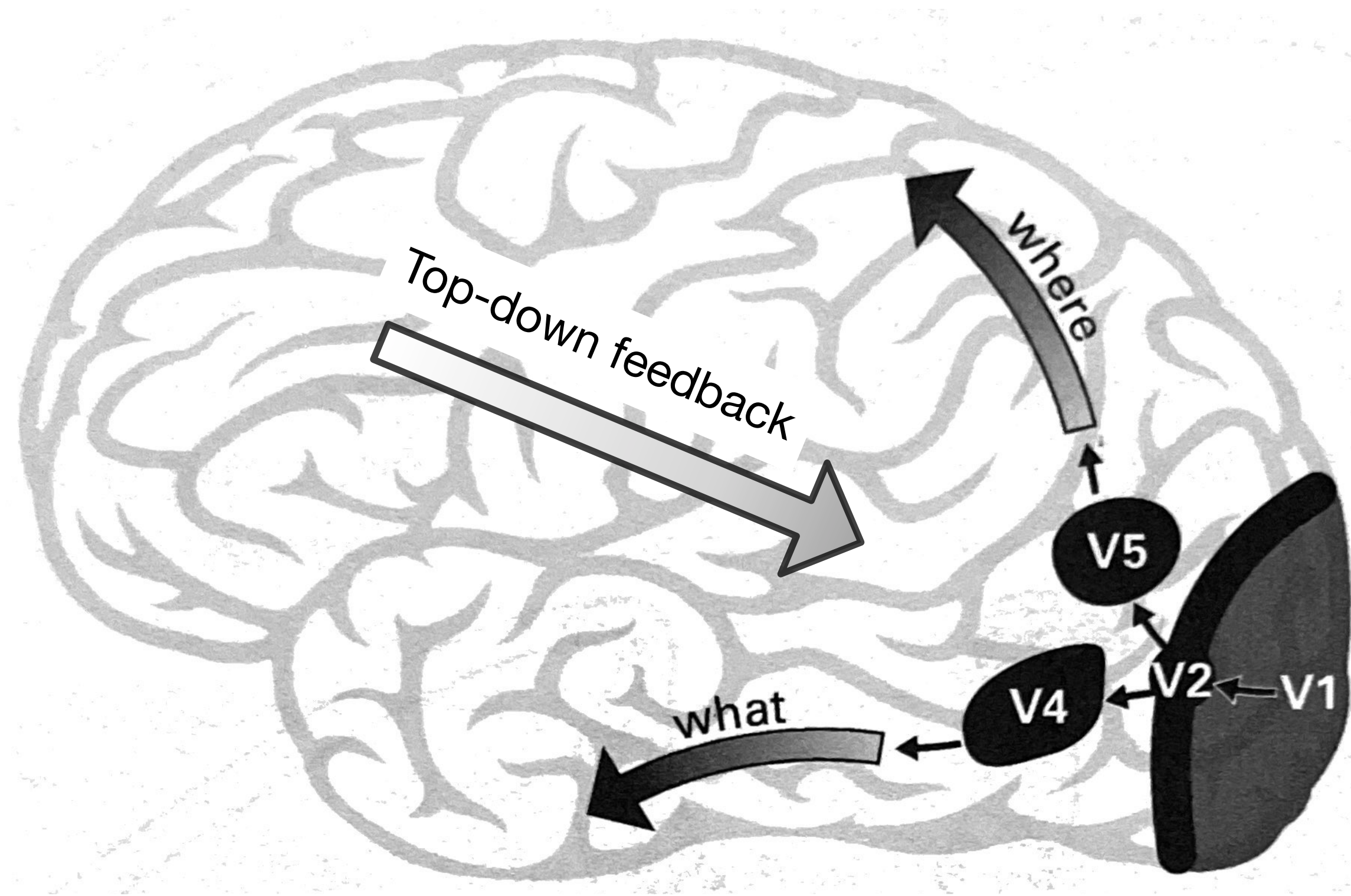
Levels of Abstraction



Retino-Geniculo-Cortical Pathway



Once in the Cortex



Modeling Lights

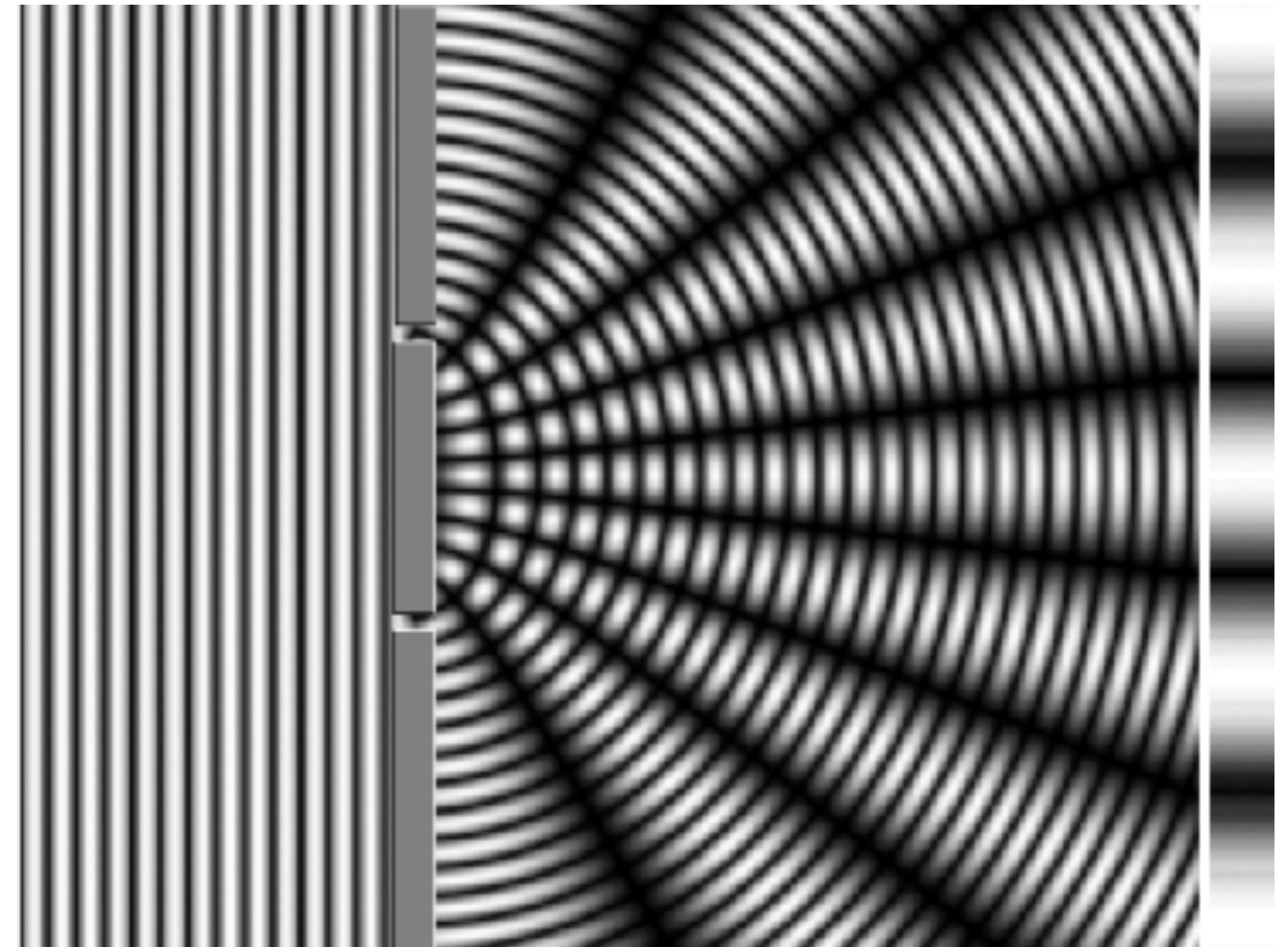
What is Light?

Geometrical optics

- Radiometry: modeling lights as packets of photons traveling along rays.
- Our focus today unless otherwise noted.

Wave optics

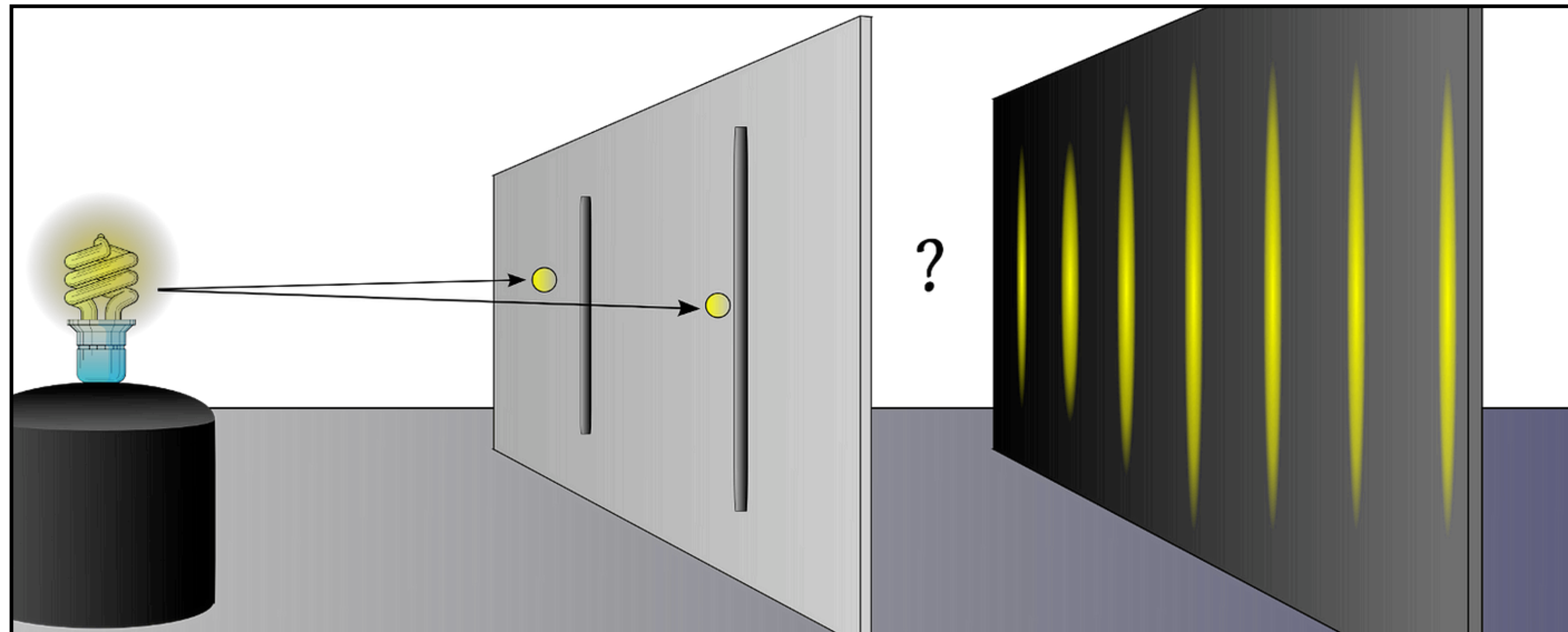
- Electromagnetic waves
- What are some of the phenomena that can't be explained by geometrical optics?



What is Light?

What are some of the phenomena that can't be explained by lights as waves?

- The sequential version of the double-slit experiment.



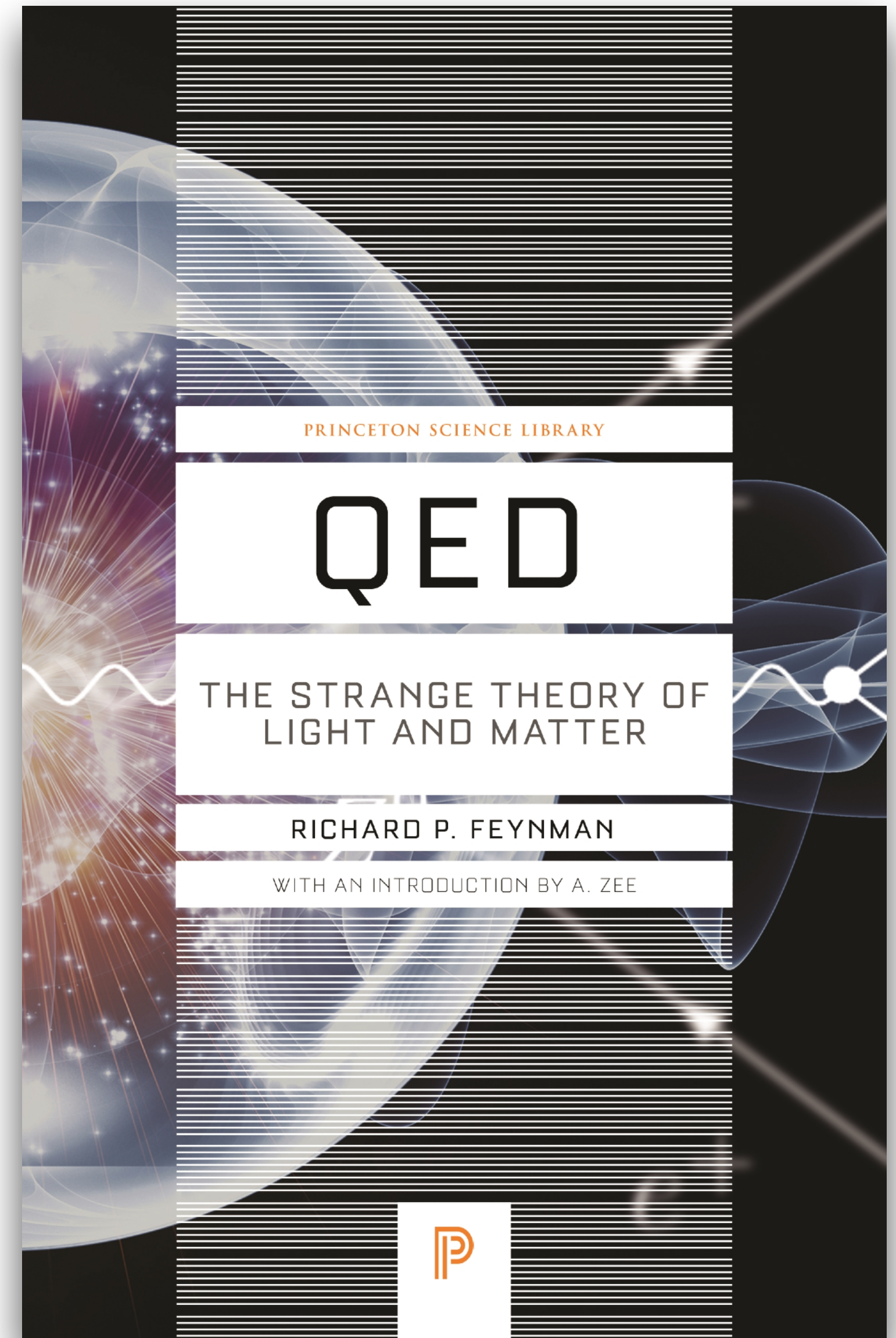
What is Light?

What are some of the phenomena that can't be explained by lights as waves?

- The sequential version of the double-slit experiment.

Quantum electrodynamics (QED)

- *"I want to emphasize that light comes in this form—particles. It is very important to know that light behaves like particles, especially for those of you who have gone to school, where you were probably told something about light behaving like waves. I'm telling you the way it does behave—like particles."*



Photon Energy

In this lecture we consider light as photons in the geometrical optics regime.

Light sources emit photons. Materials emit, absorb, and/or scatter photons.

Each photon has an energy level, dictated by its frequency/wavelength.

Energy of a $\lambda = 500$ nm
photon: $\sim 4 \times 10^{-34}$ J

Energy of a $\lambda = 750$ nm
photon: $\sim 2.7 \times 10^{-34}$ J

Energy of a photon — $E = hf = \frac{hc}{\lambda}$

Planck constant.
 $\sim 6.63 \times 10^{-34} \text{ J} \cdot \text{s}$

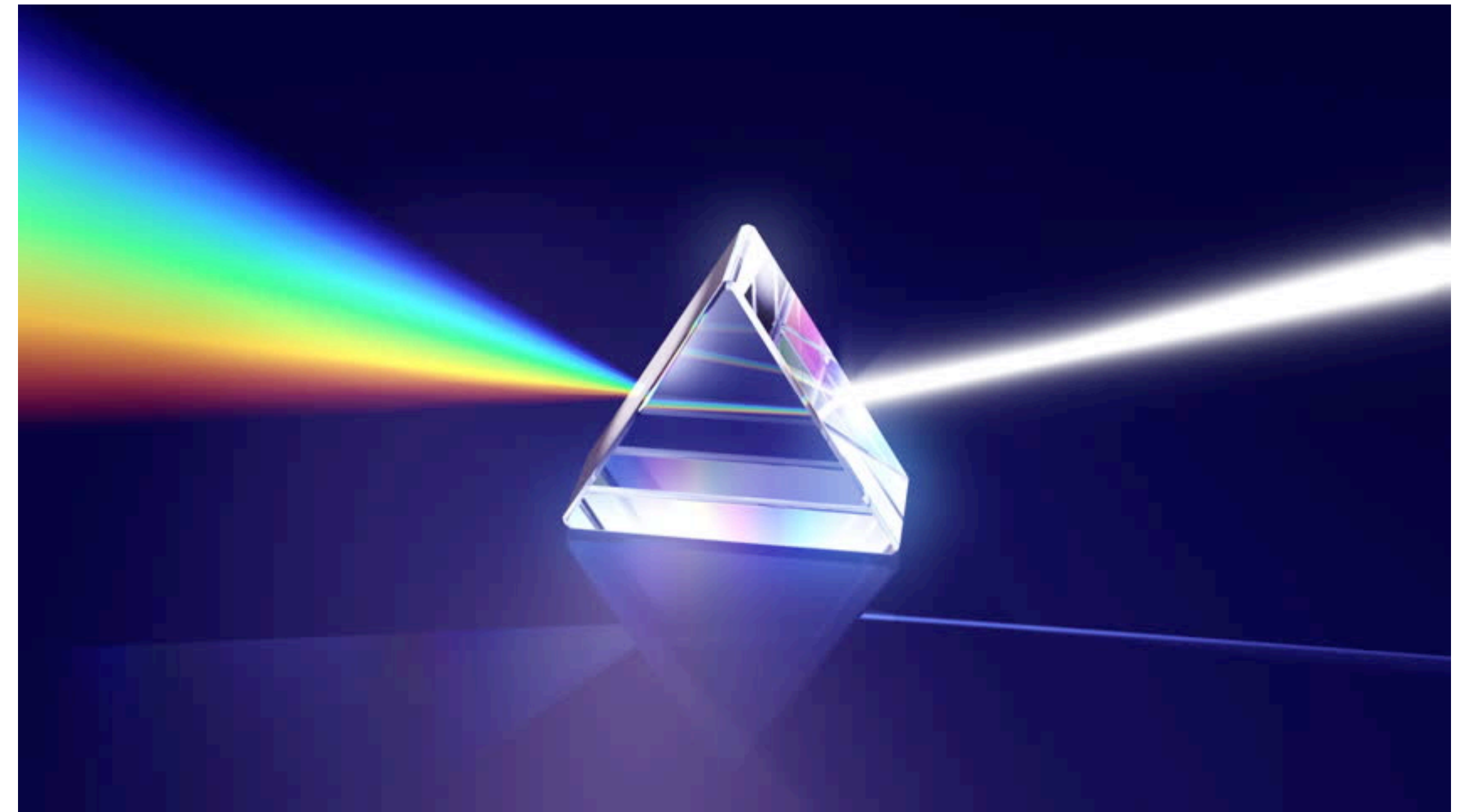
Light frequency

Speed of light (m/s)

Light wavelength

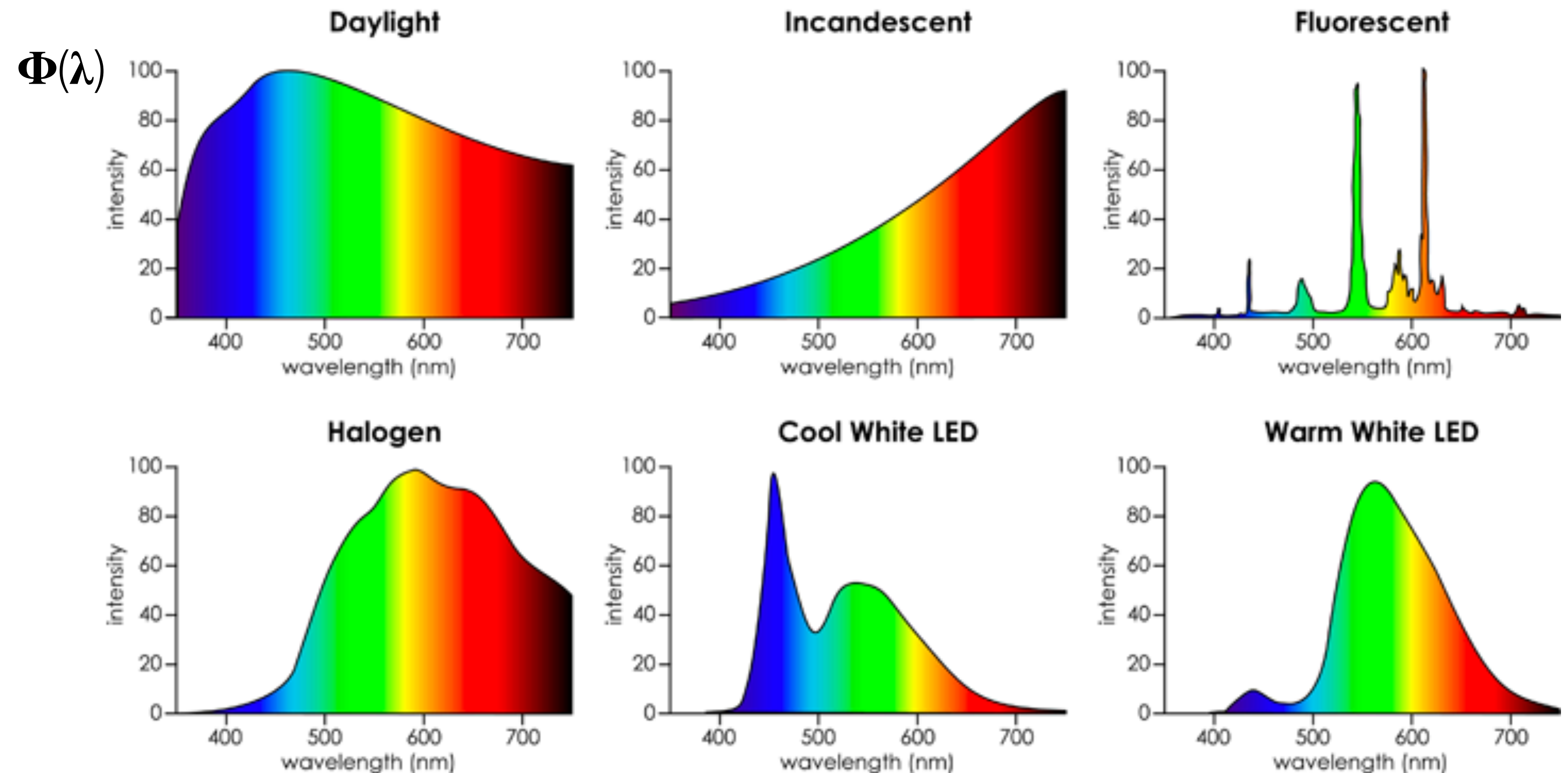
Light Spectrum

Most light sources mix photons of different wavelengths.



Spectral Power Distribution

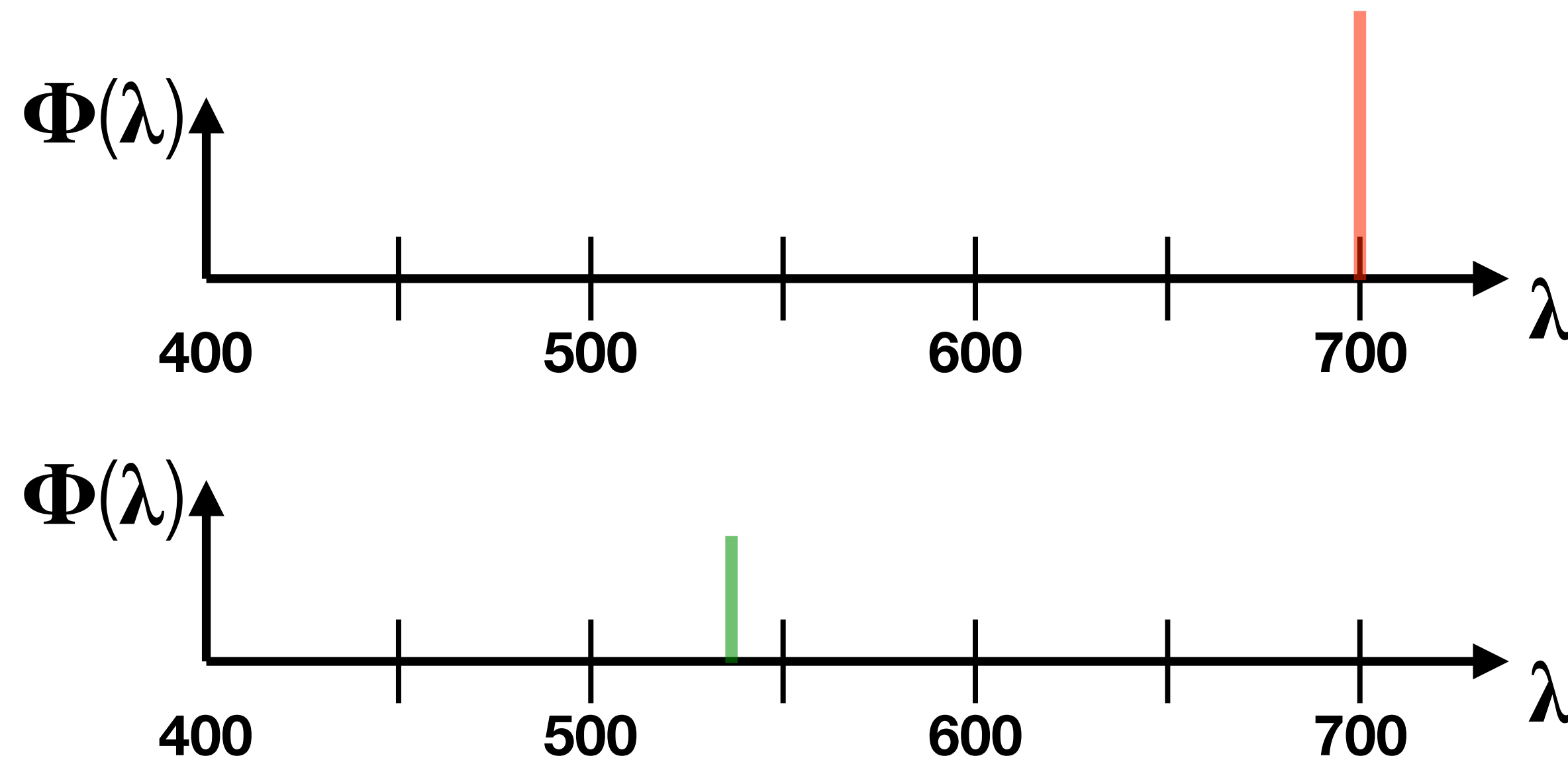
SPD $\Phi(\lambda)$: the power distribution by wavelength.
Unit is W/nm.



Spectral Light

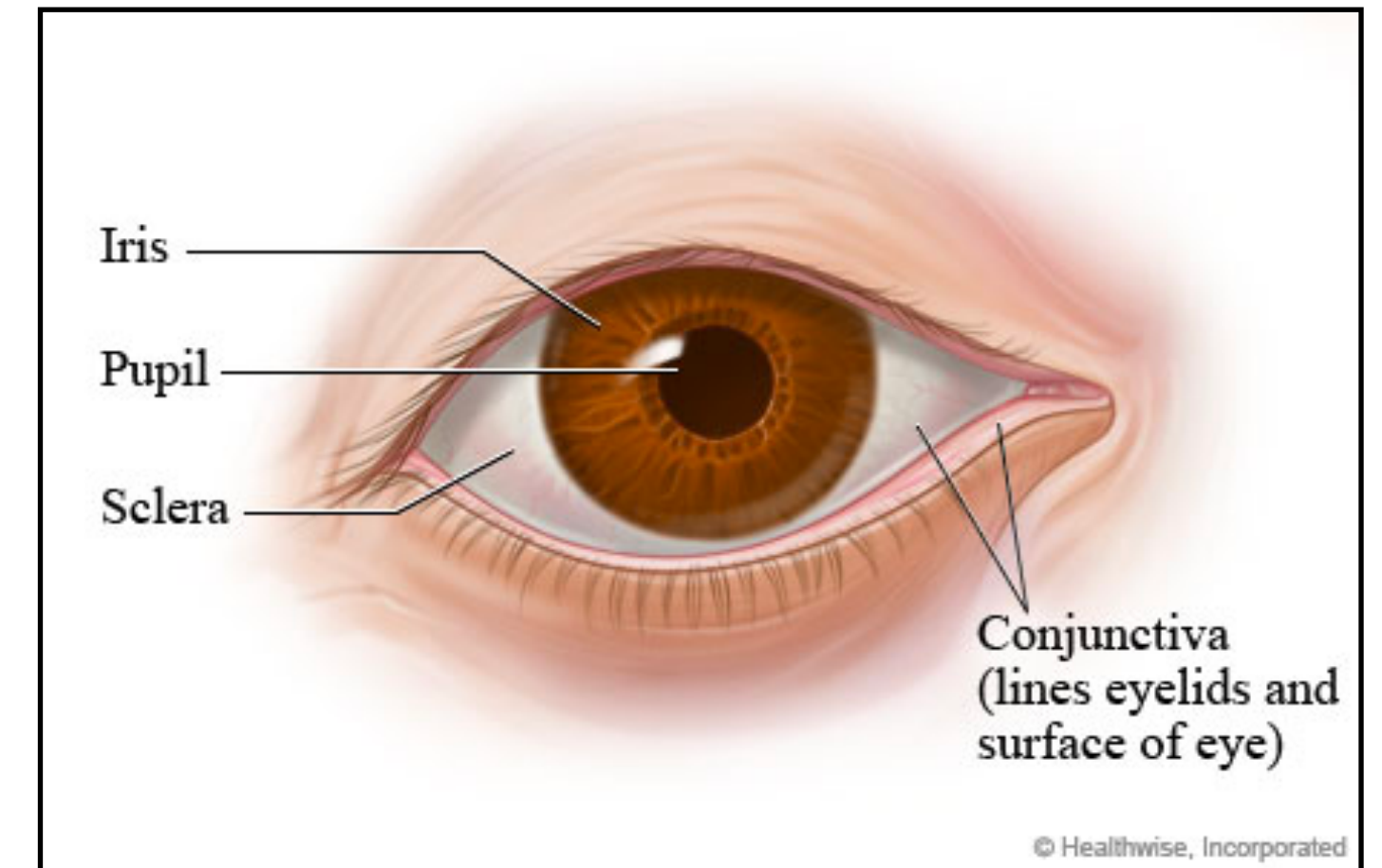
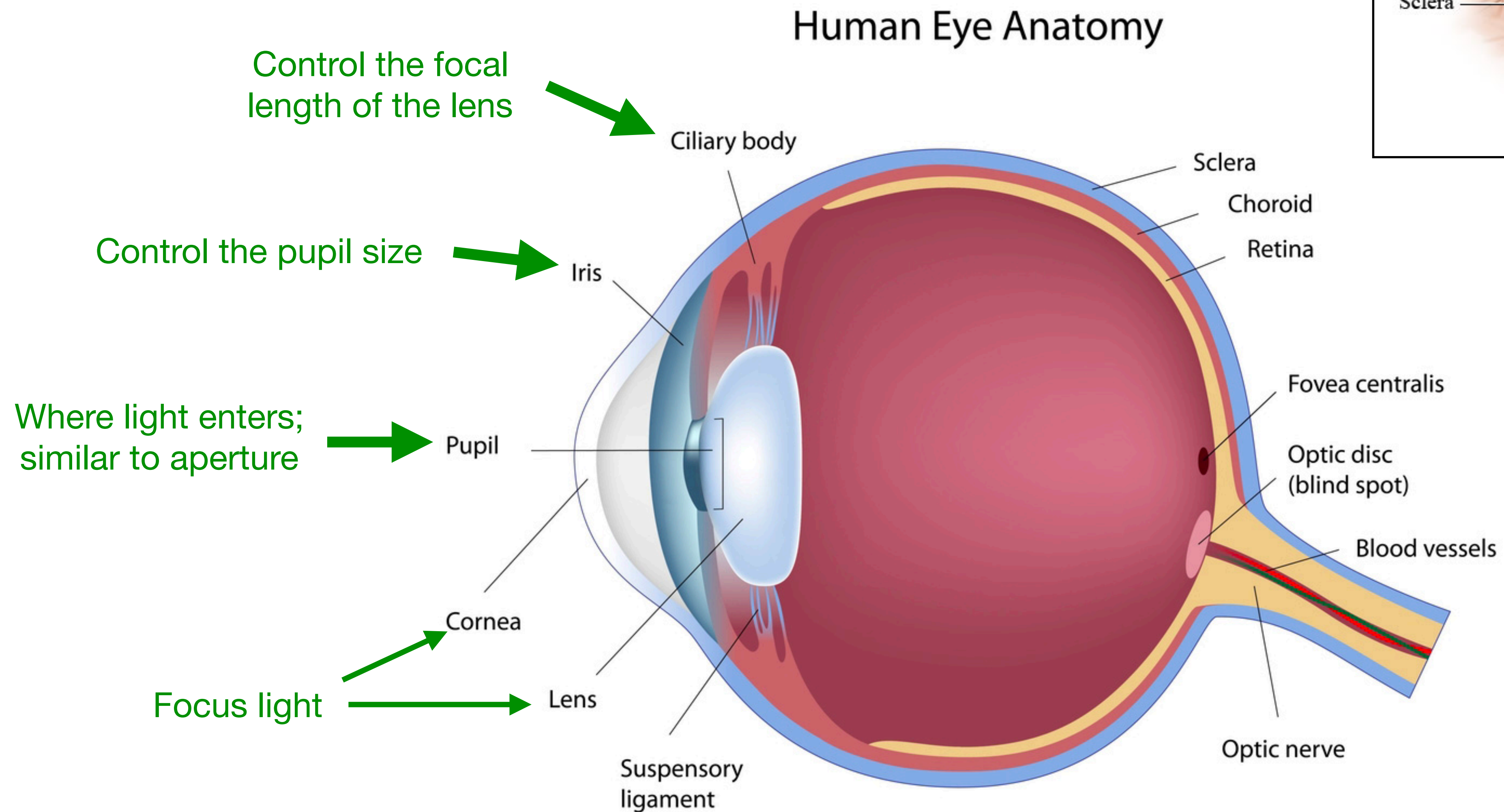
Single-wavelength (monochromatic) light are called **spectral light**.

- SPDs of spectral lights are very narrow spikes.
- Few natural lights are spectral lights. Lasers can generate spectral lights.
- Mixing spectral lights to produce arbitrary lights



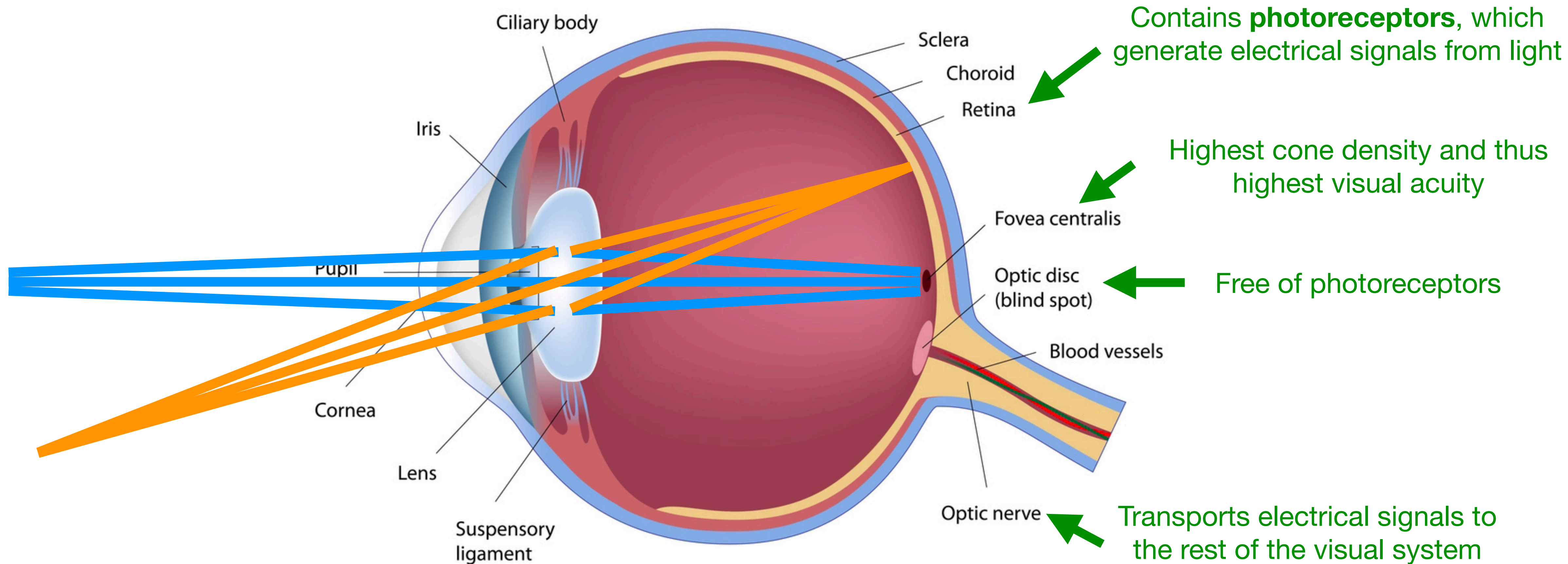
The Eye

Human Eye Anatomy



Human Eye Anatomy

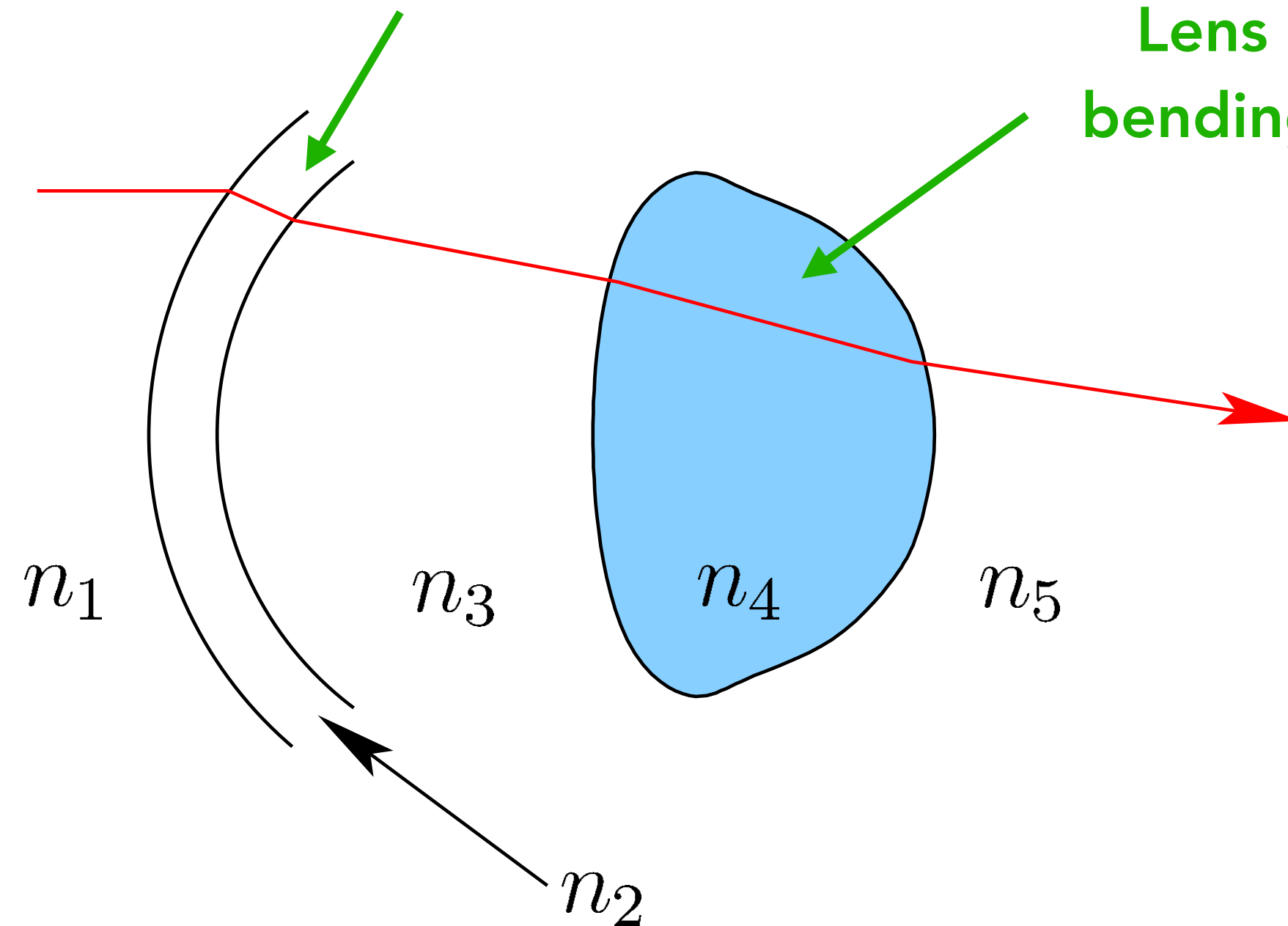
Human Eye Anatomy



Eye Optics Focuses Lights

Most of the light bending (2/3) is due to the cornea, which is rigid in its shape

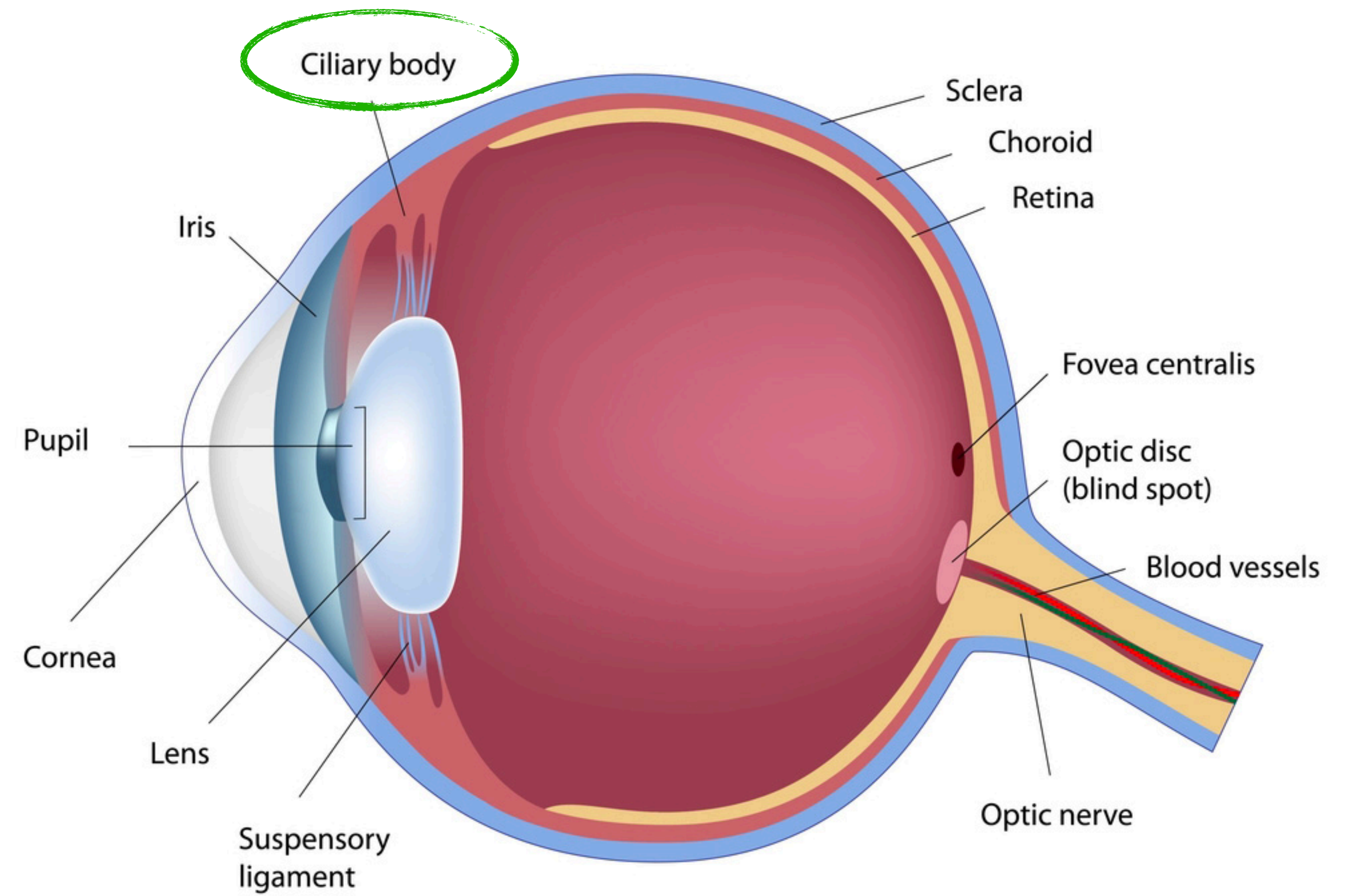
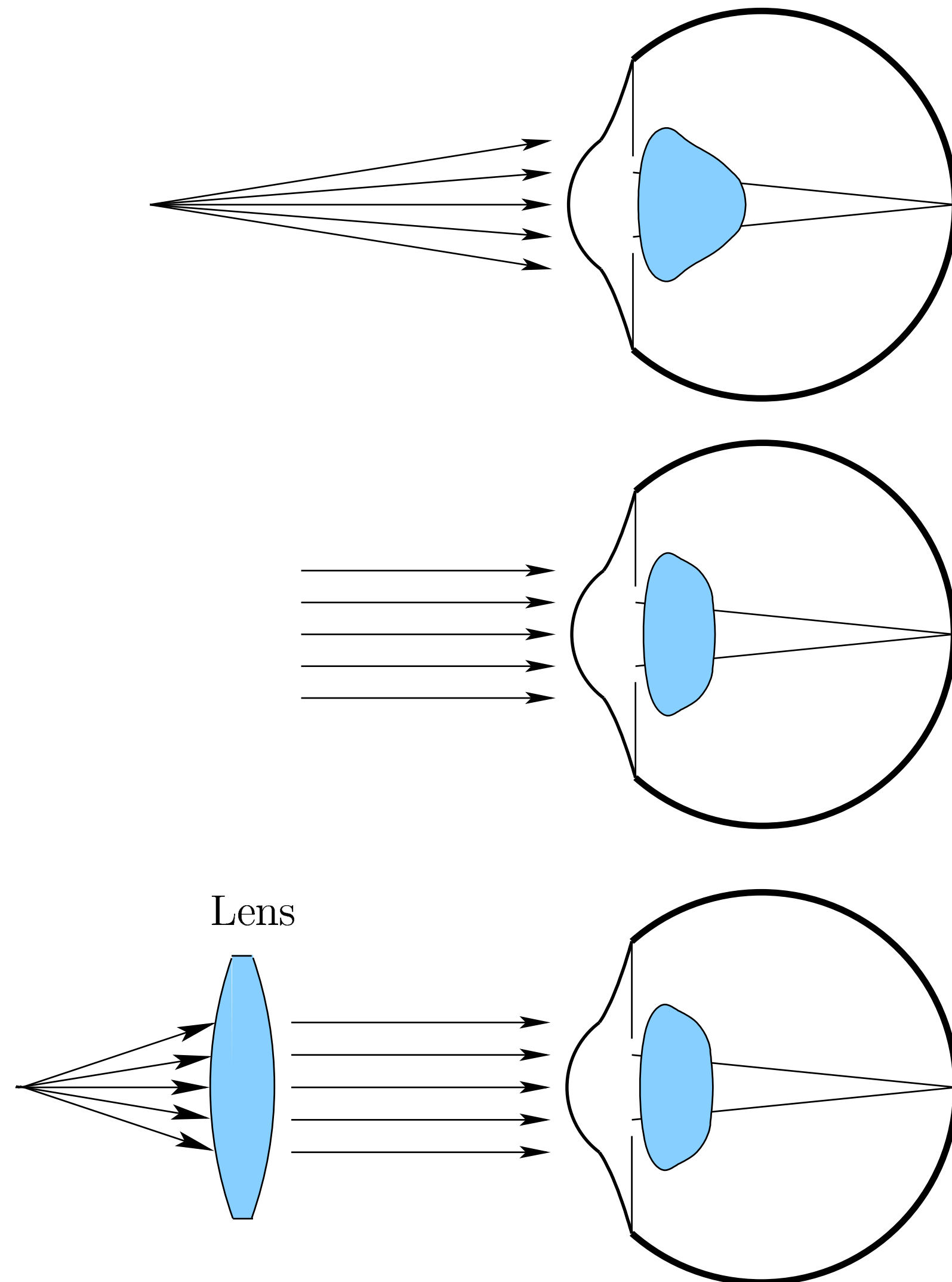
Lens provides the remaining bending power and is malleable



1. $n_1 = 1.009$ (air)
2. $n_2 = 1.376$ (cornea)
3. $n_3 = 1.336$ (aqueous fluid)
4. $n_4 = 1.413$ (lens)
5. $n_5 = 1.337$ (vitreous fluid)

Figure 4.25: A ray of light travels through five media before hitting the retina. The indices of refraction are indicated. Considering Snell's law, the greatest bending occurs due to the transition from air to the cornea. Note that once the ray enters the eye, it passes through only liquid or solid materials.

Lens Accommodates



Ocular Media Absorb Lights Selectively

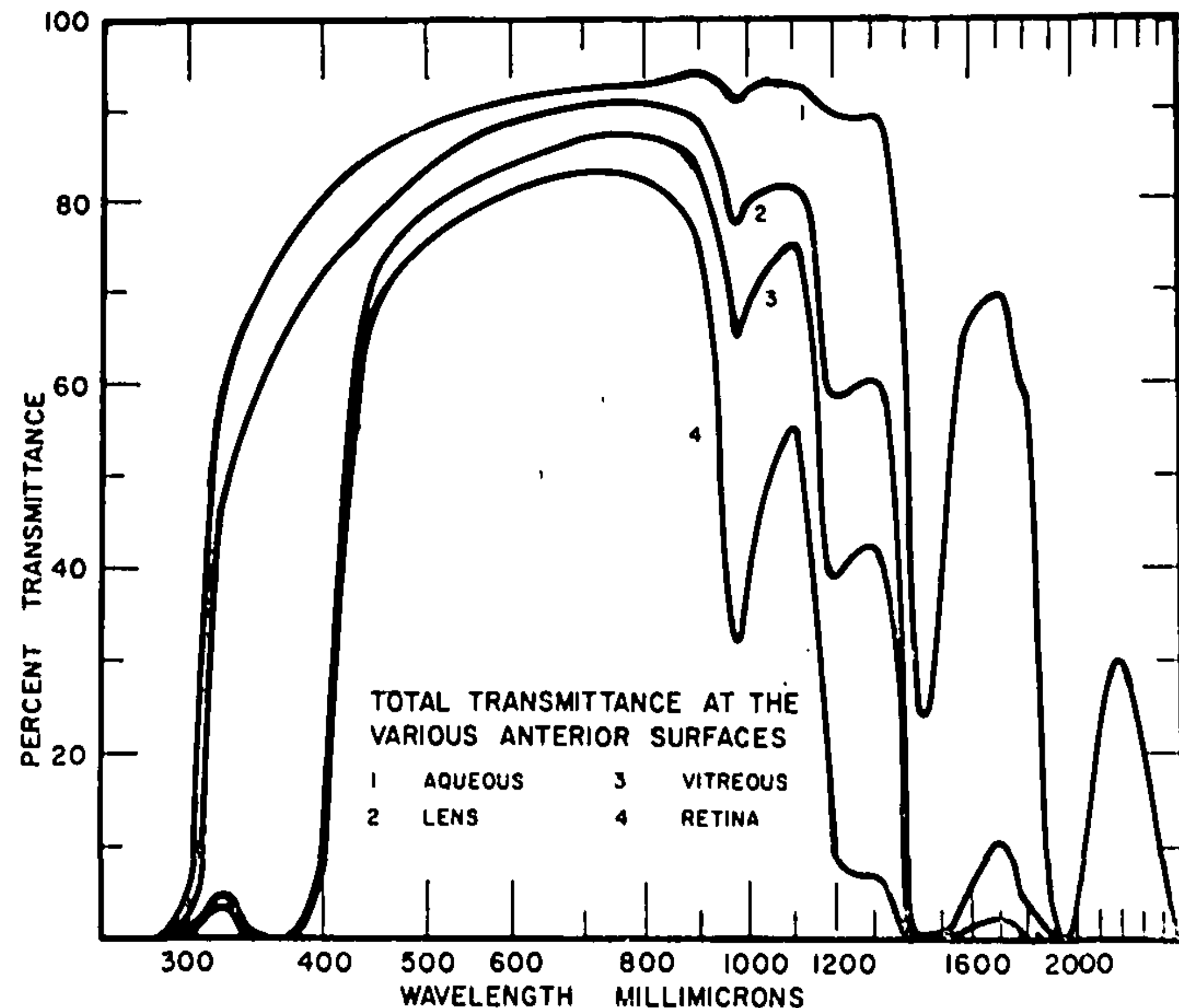


Fig. 7. Total transmittance through entire eye.

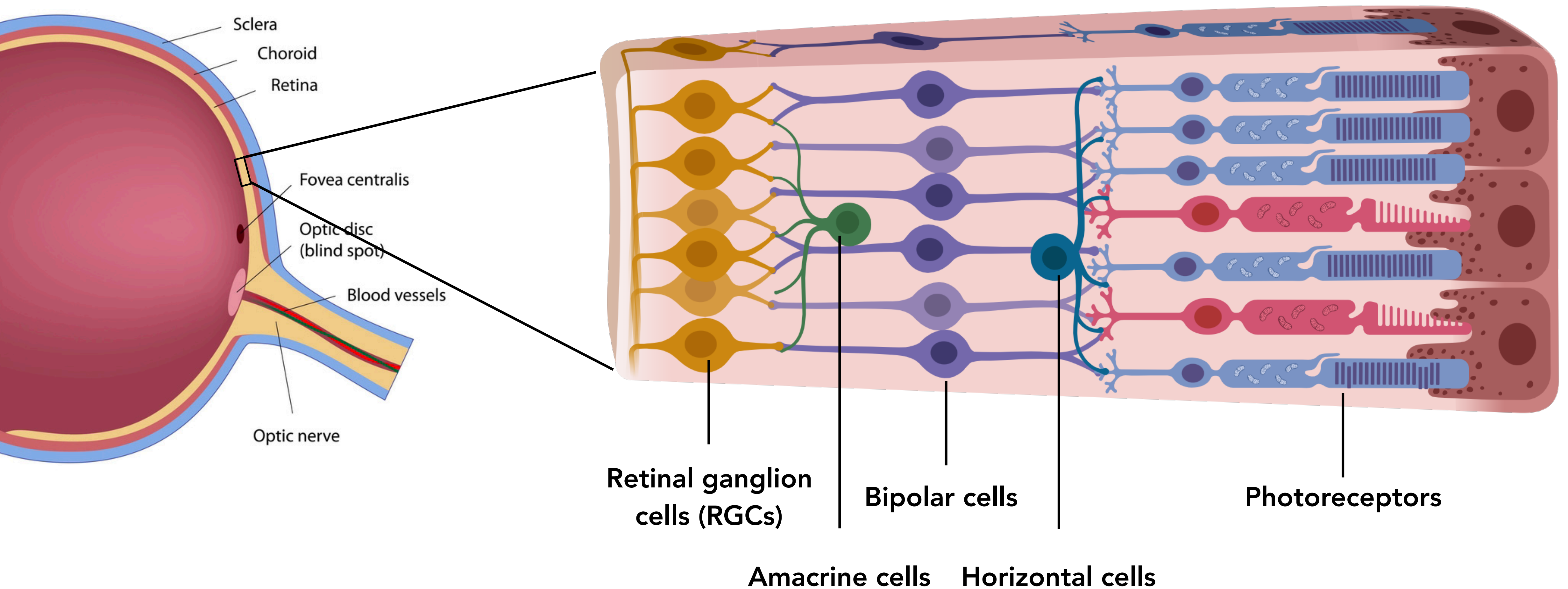
Data is the remaining/transmitted lights at each ocular surface.

- Results at the retina show the total amount of lights left after ocular absorption.
- This includes both direct transmission and forward scattering.
- 380 nm — 780 nm is "visible range".

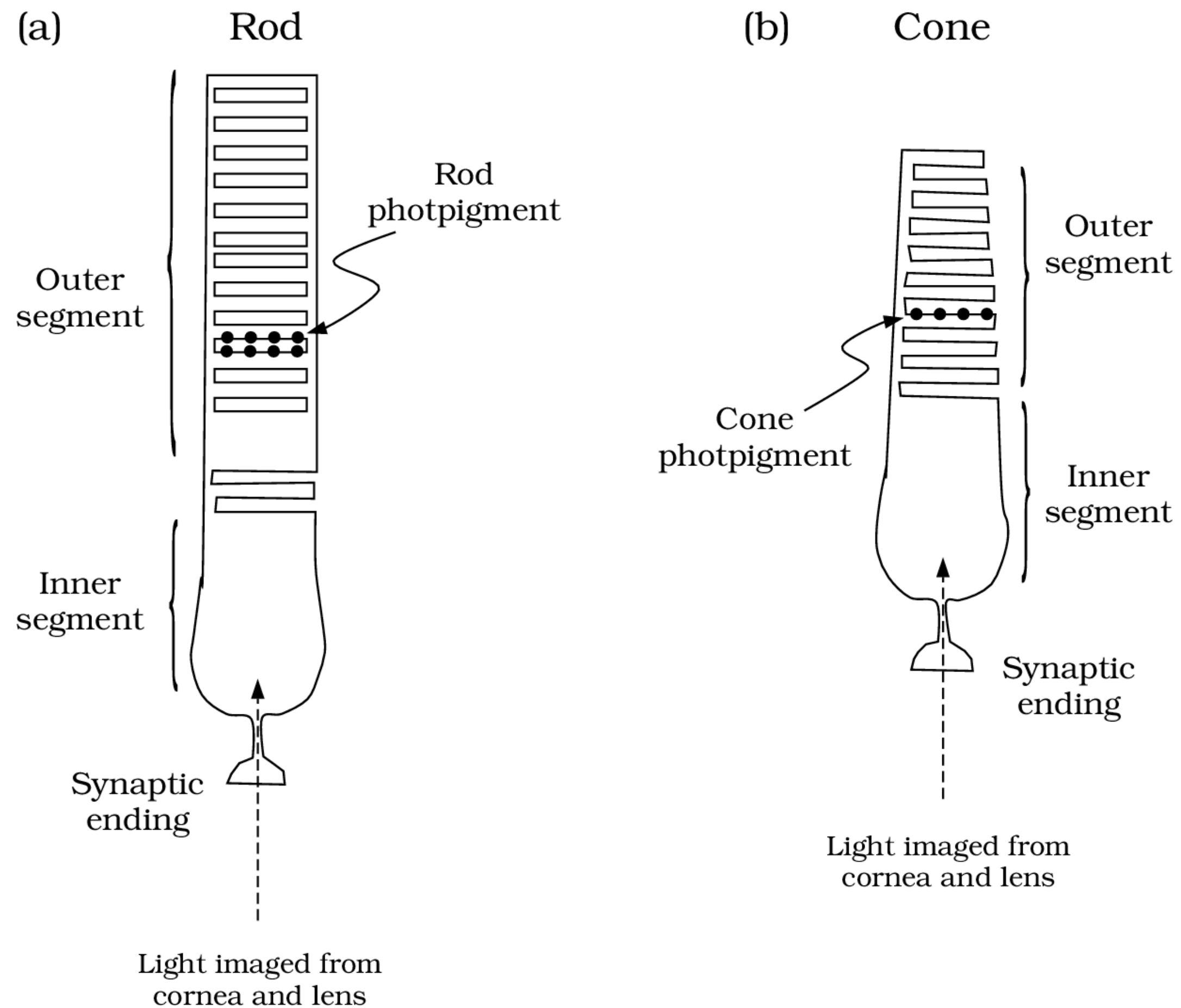
Color vision comes from wavelengths, so selective spectral absorption shapes our color vision. More later.

The Retina

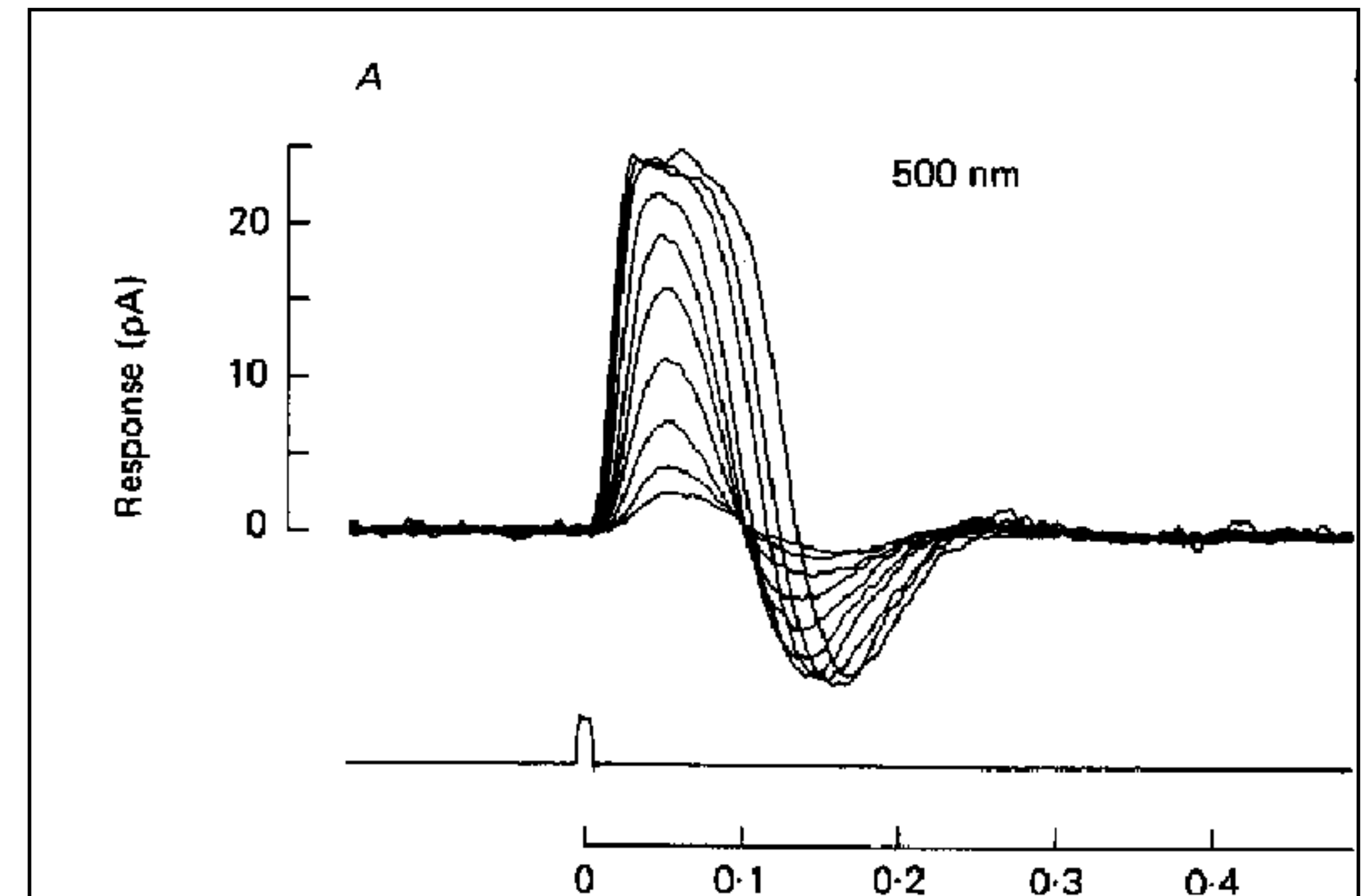
Neurons on the Retina



Photoreceptors: Optical Signals → Electrical Signals



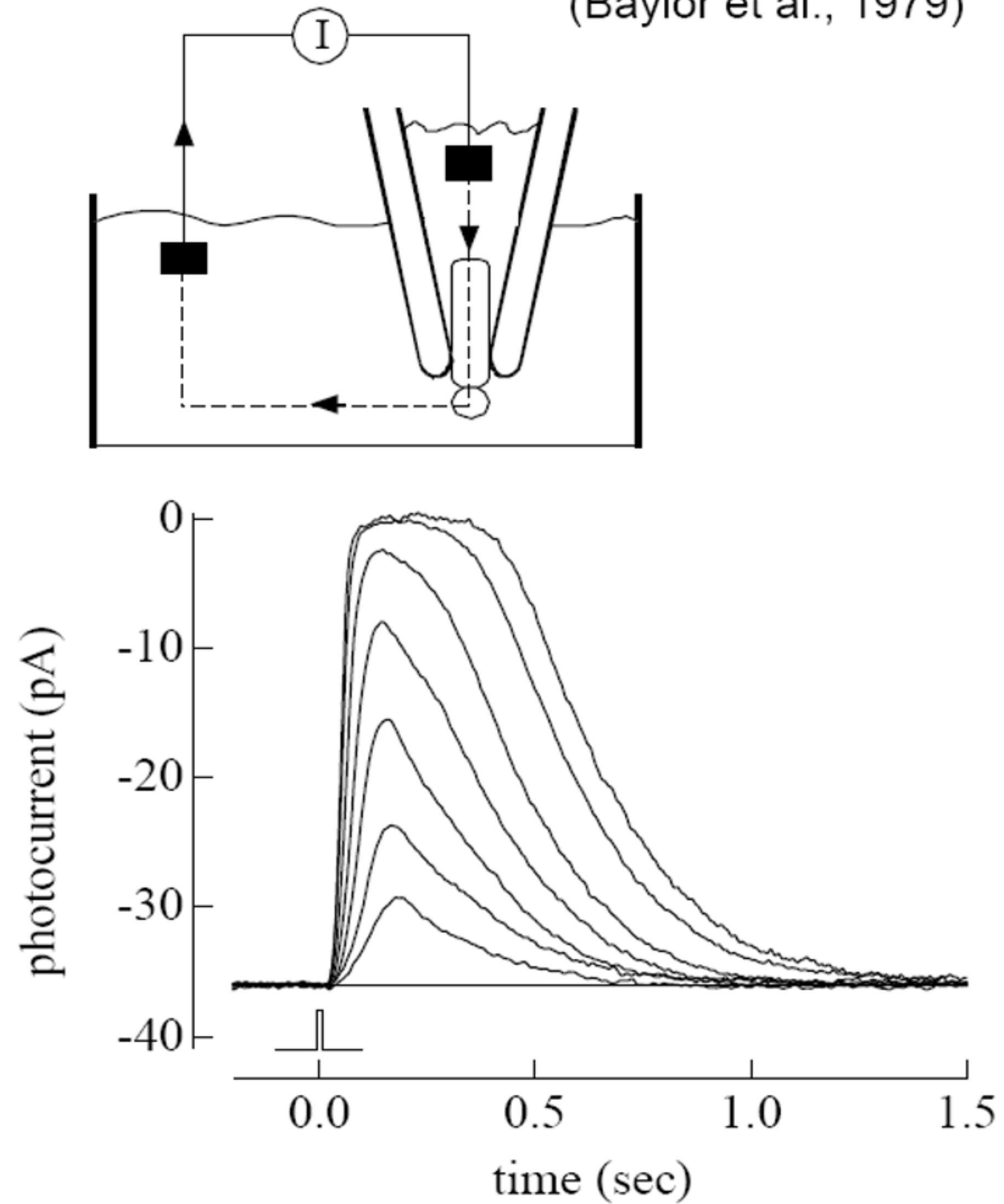
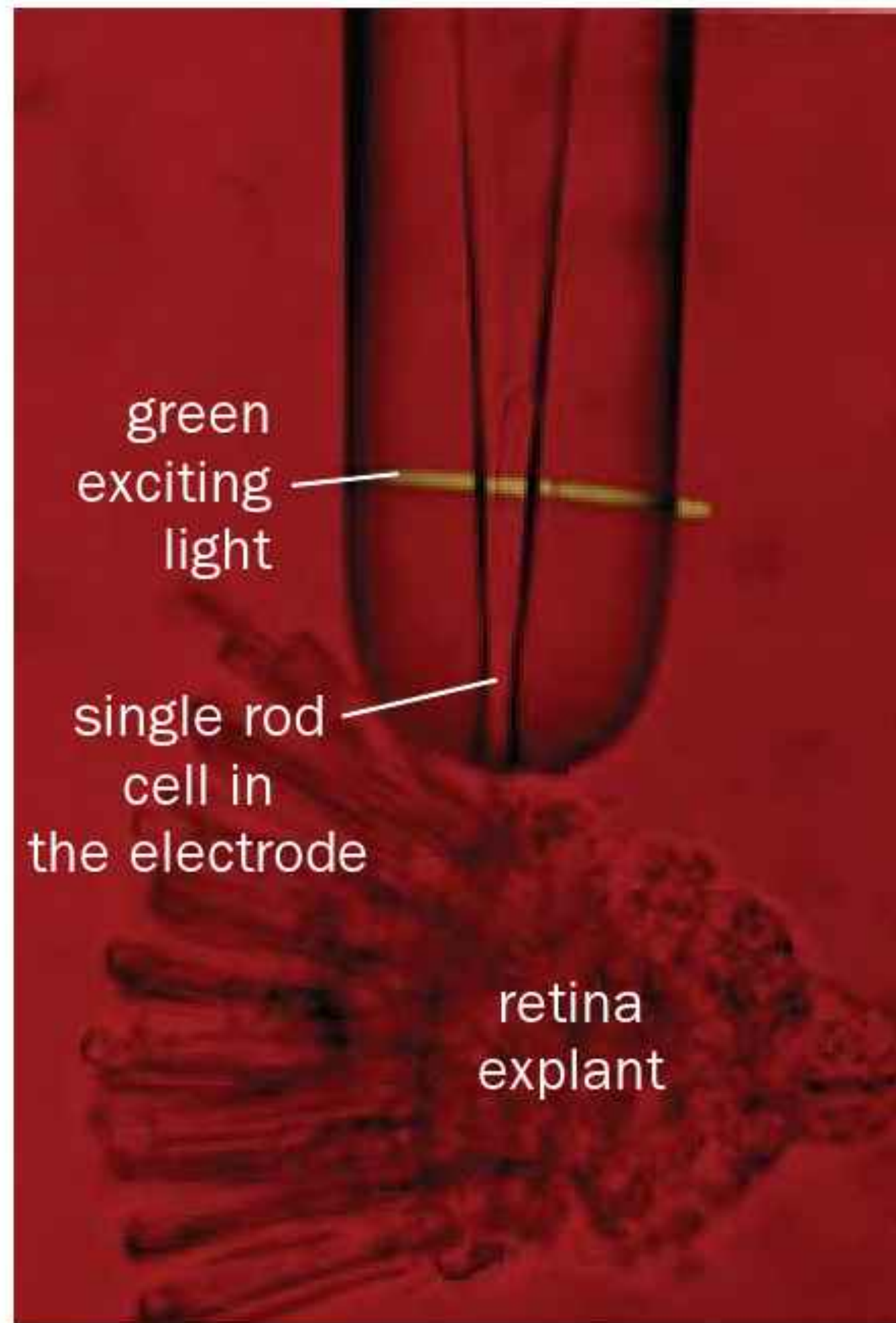
Photocurrents in response to photon absorption



SUCTION ELECTRODE RECORDING

(Baylor et al., 1979)

(A)

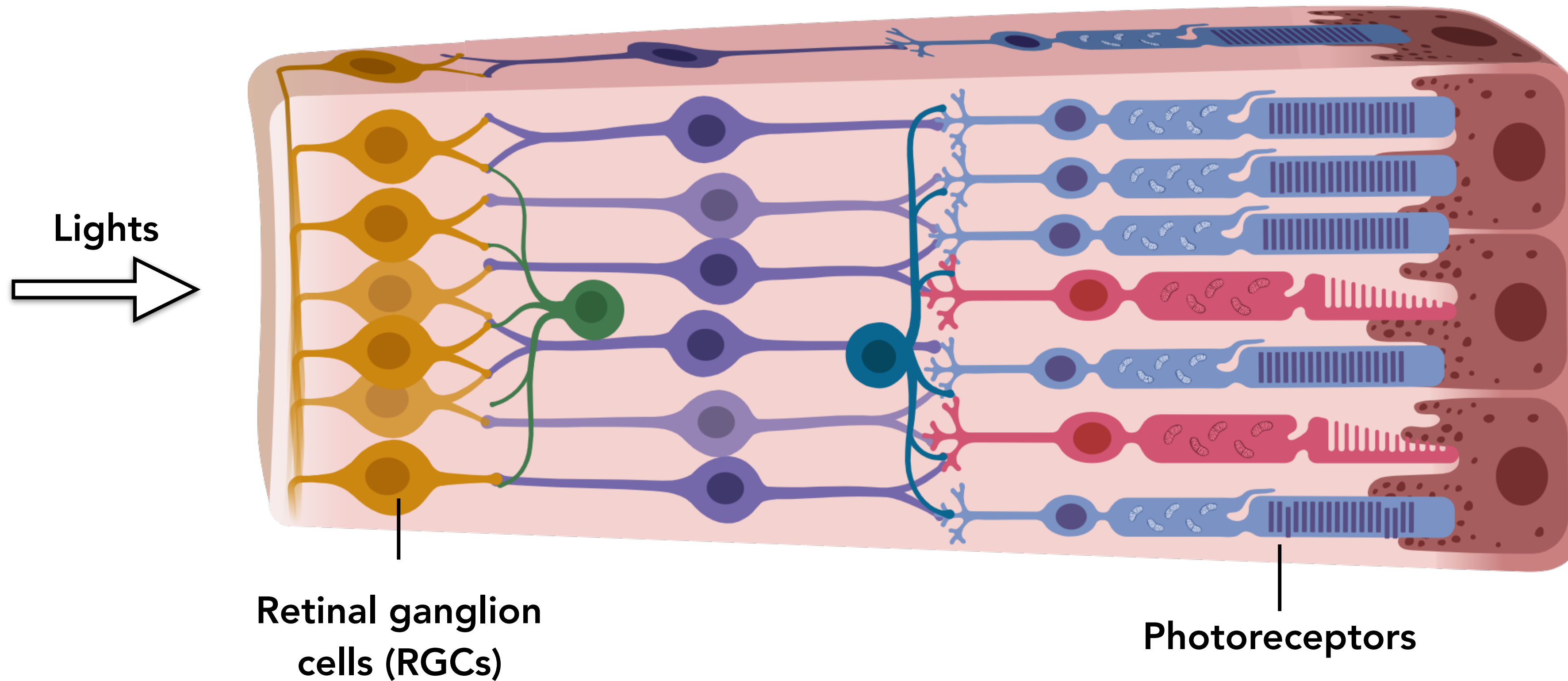


Opposite Functional and Anatomical Organizations

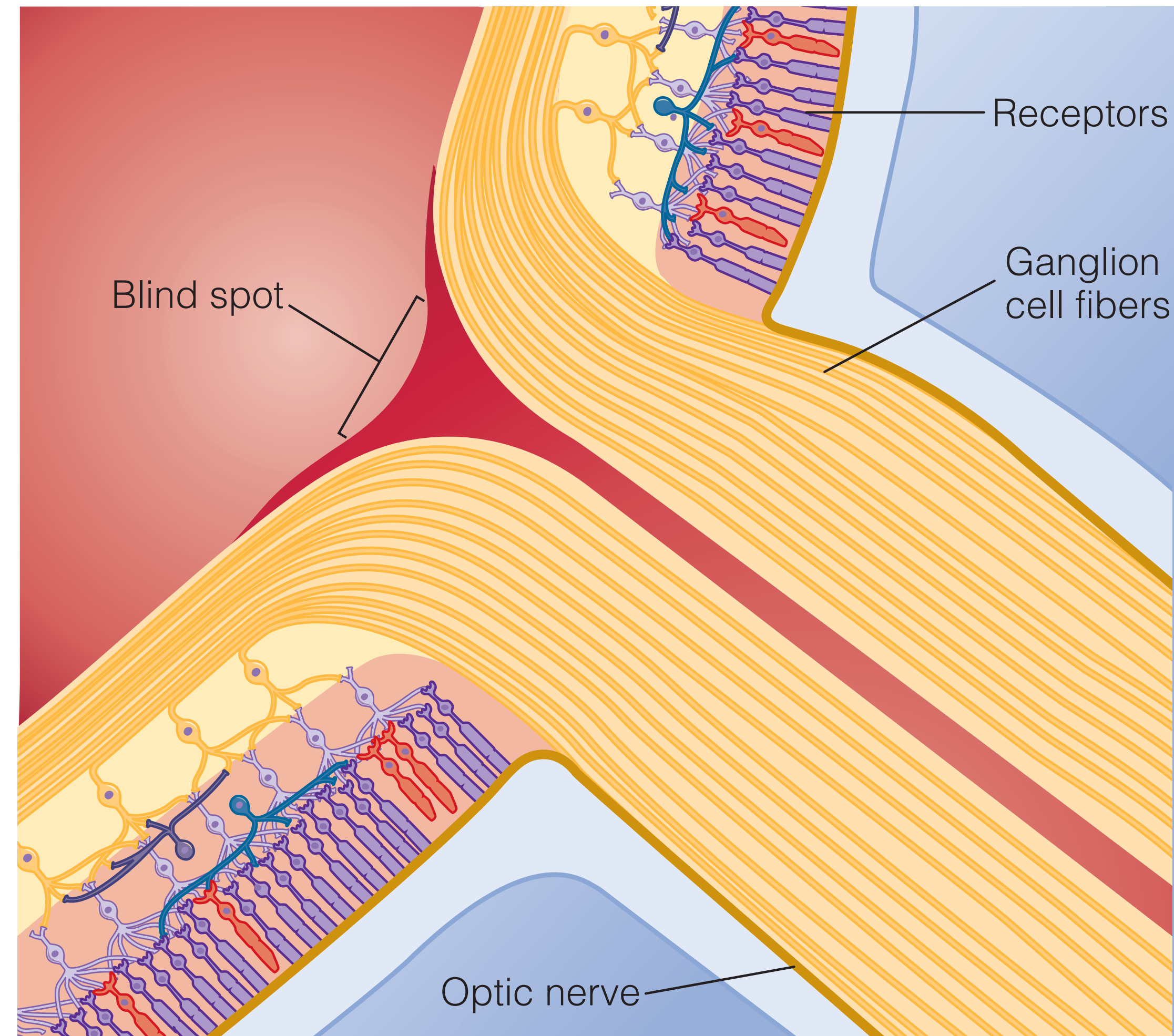
Electrical information flow



Optical information flow

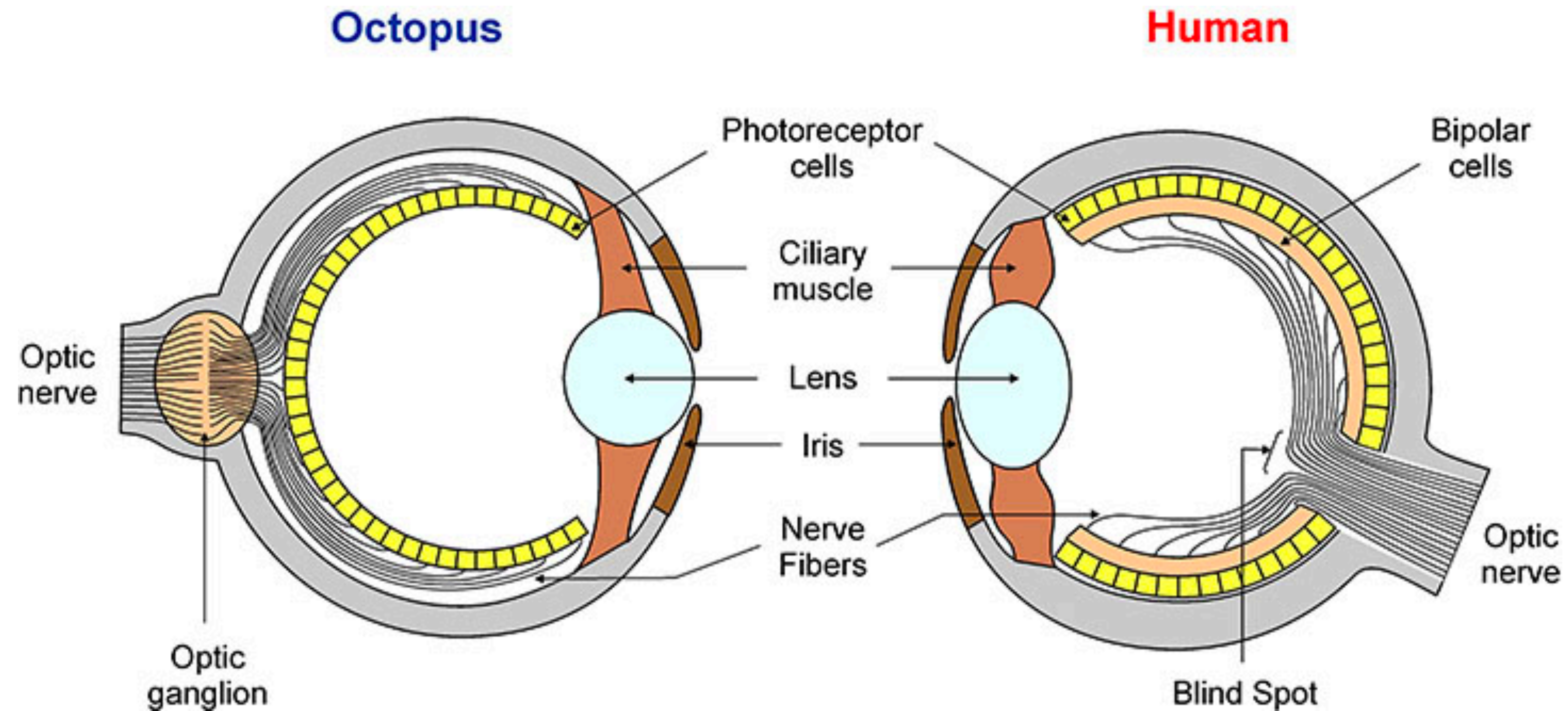


Blind Spot



Blind Spot

Optic nerves route *before* the retina in human eyes



Blind Spot: "See" It For Yourself

Test:

- Cover your LEFT eye and stare at the cross with your RIGHT eye.
- Slowly move towards the computer screen while still staring at the cross with your RIGHT eye.
- At some point the black circle will disappear.

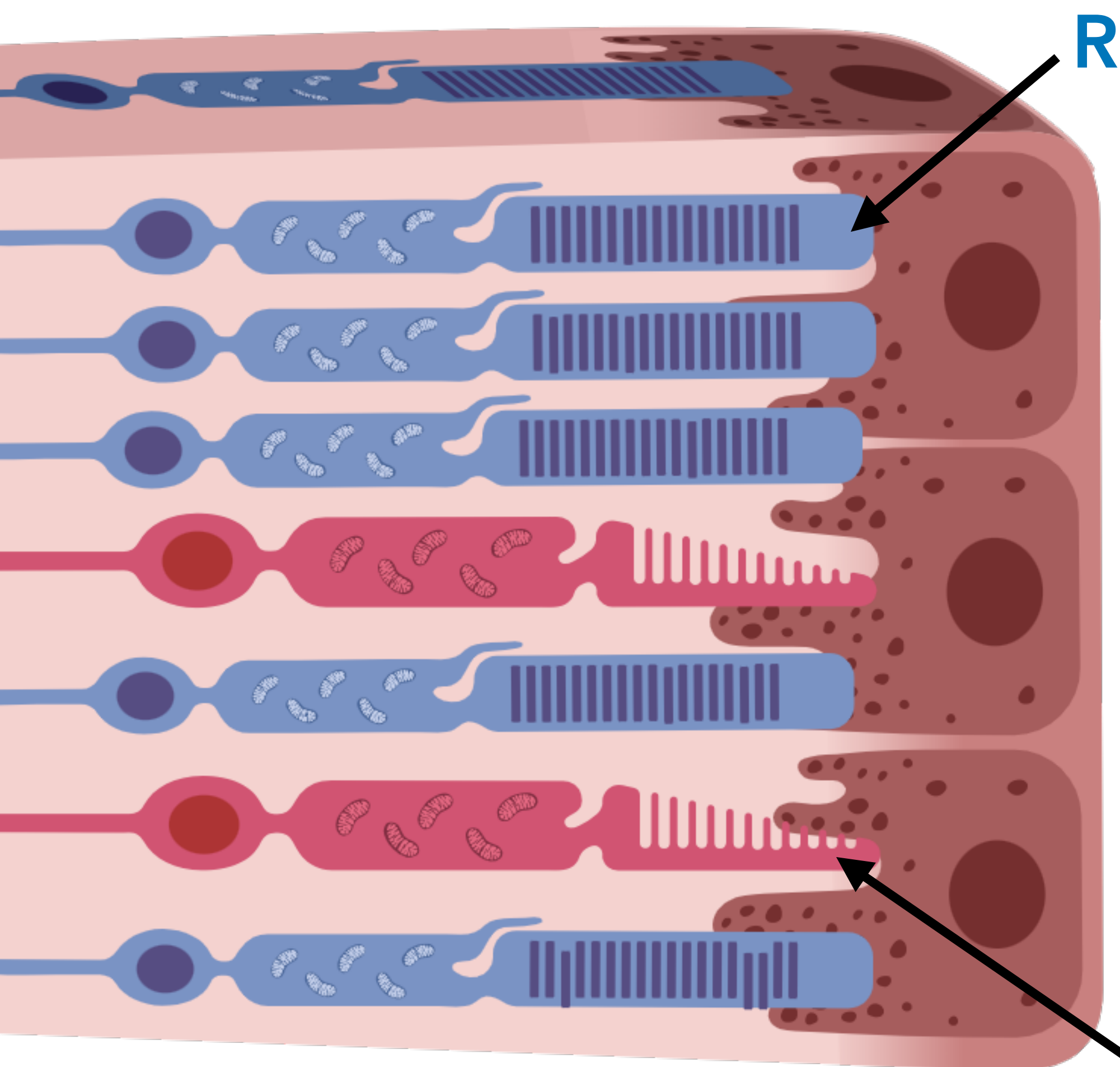
Blind spot doesn't appear dark because your brain "makes stuff up"



Retina Functions and Specializations

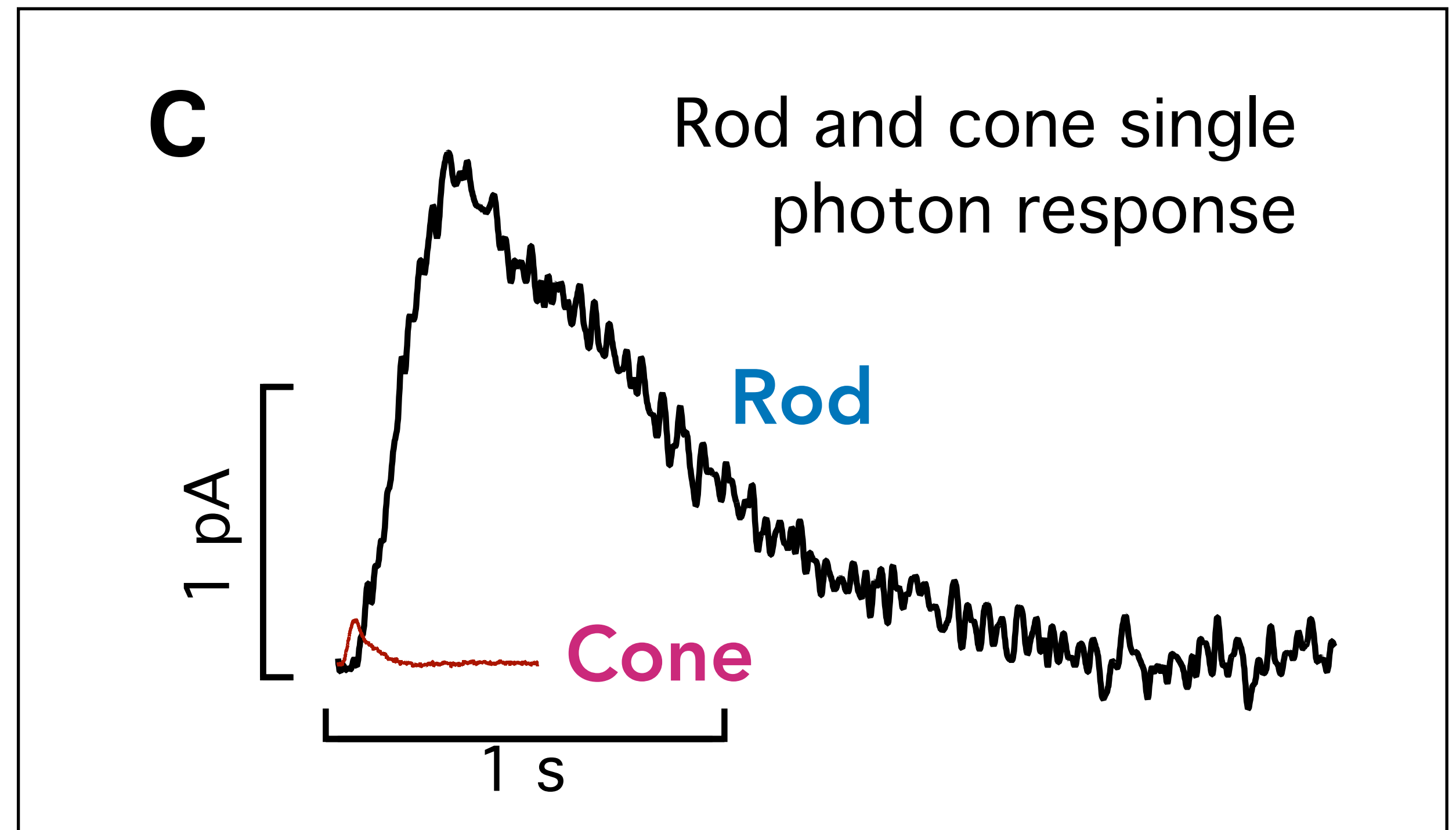
- Rods vs. Cones
- Contrast Detection
- Adaptation

Cones vs. Rods: Sensitivity



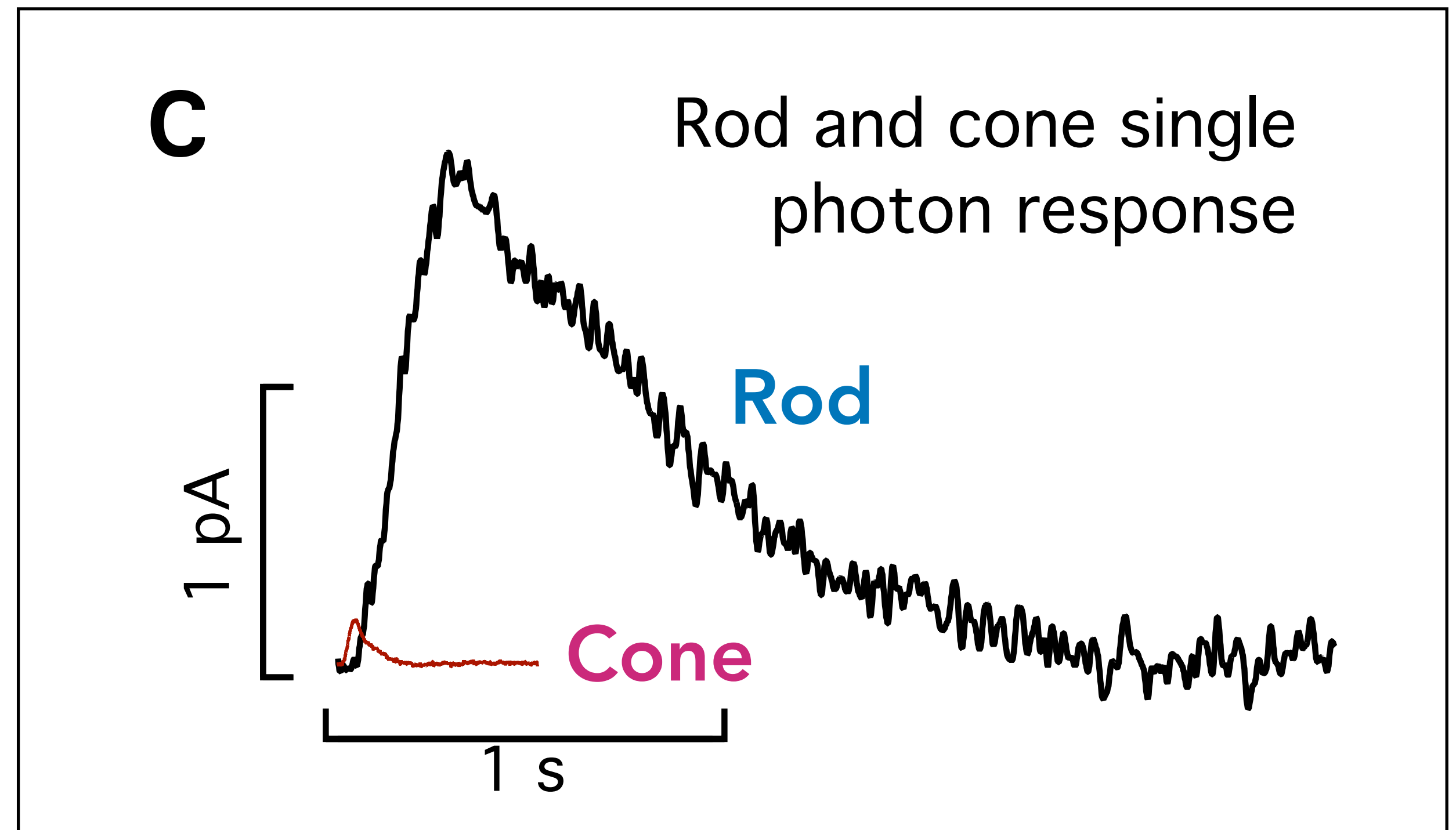
Rod (~120 million in total)

Cone (~6 million in total)



Cones vs. Rods: Sensitivity

- Rod vision is much more sensitive than cone vision.
 - Single photon response is just one reason; we will see others later.
- Rods are responsible for night vision (scotopic vision) and cones are responsible for daylight vision (photopic vision).
- Cones have faster kinetics
 - Better encode motion



Cones vs. Rods: Sensitivity

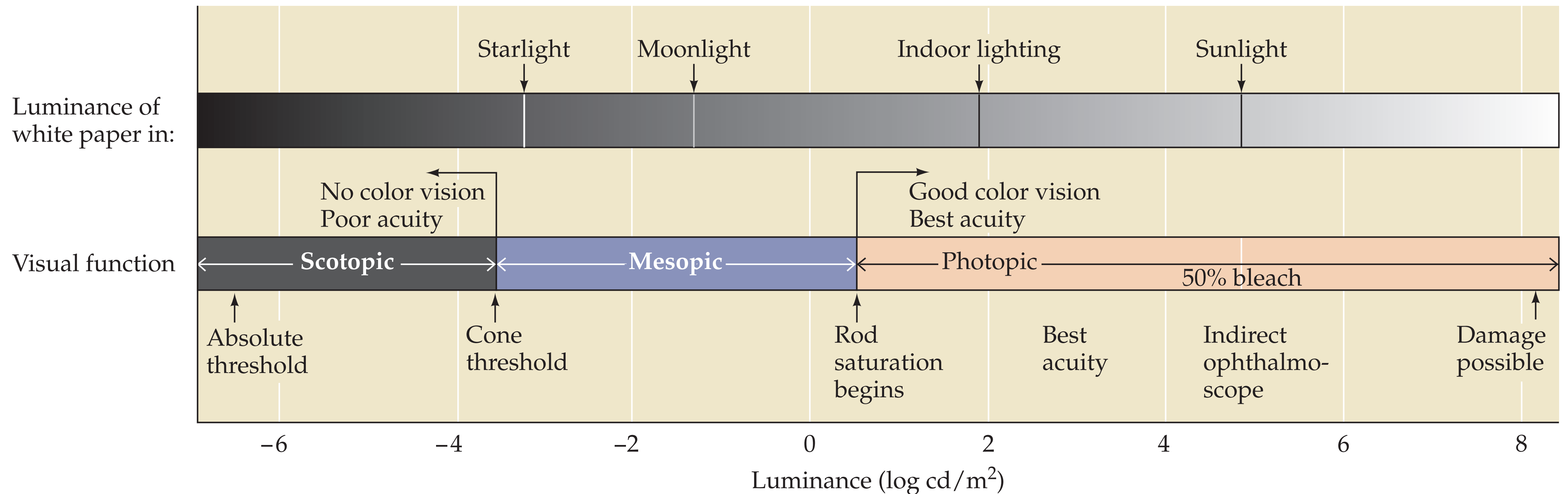
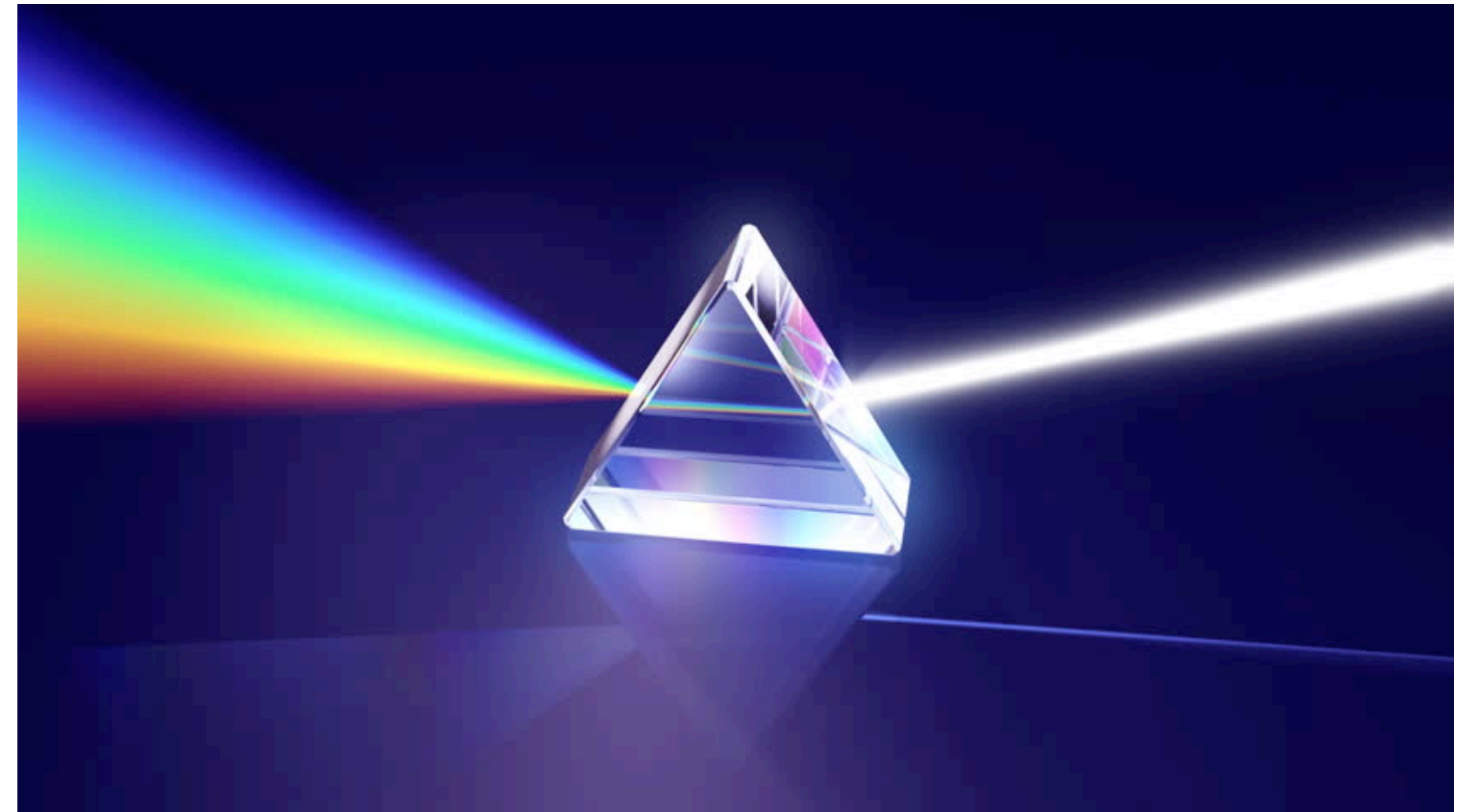


FIGURE 11.11 The range of luminance values over which the visual system operates. At the lowest levels of illumination, only rods are activated. Cones begin to contrib-

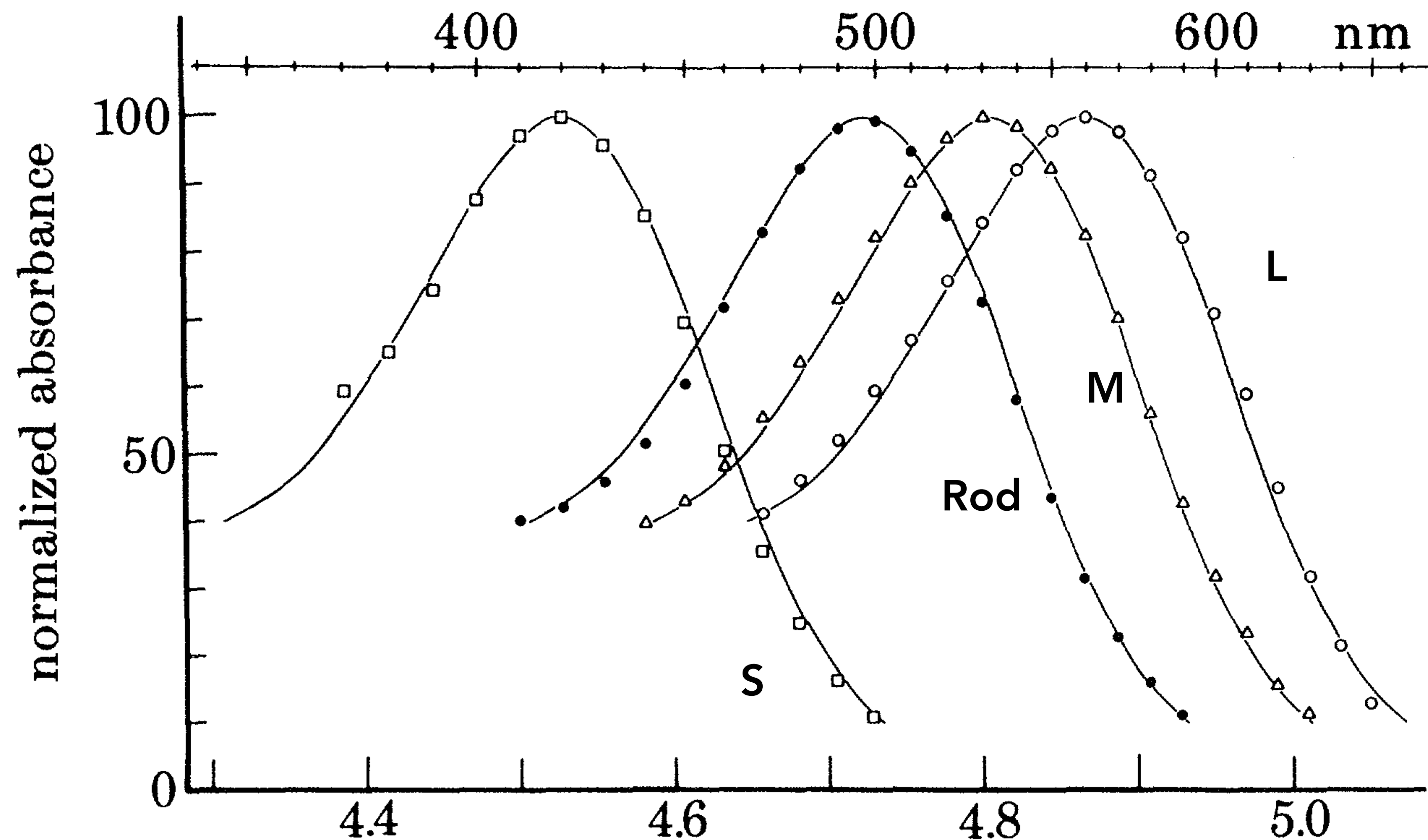
ute to perception at about the level of starlight and are the only receptors that function under relatively bright conditions.

Spectral Sensitivity and Color

- Color vision fundamentally comes from how photoreceptors encode wavelengths.
- There are three cone types but only one rod type, so no color vision in rods (just light intensity).
 - Don't see color at night

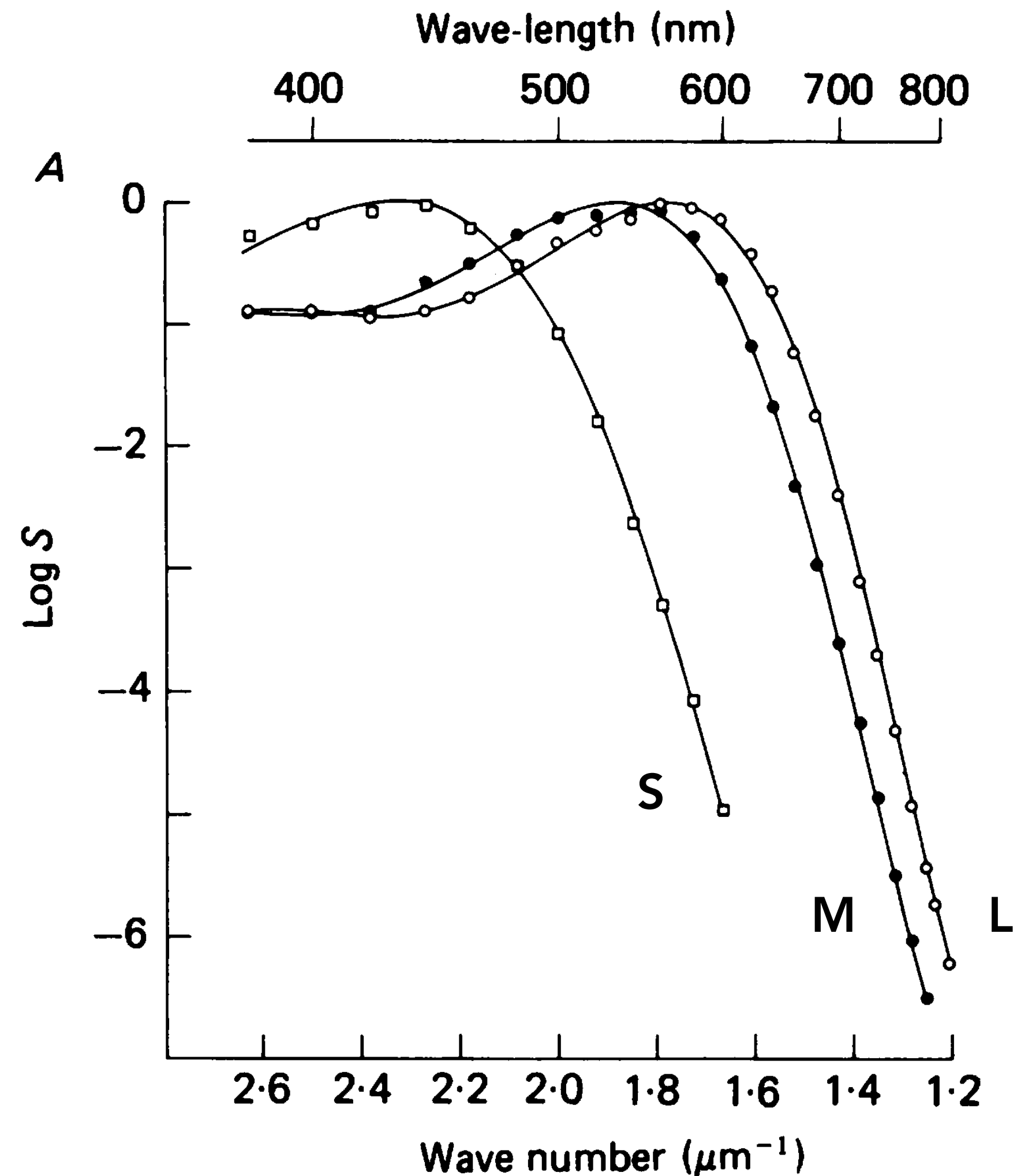


Spectral Sensitivity and Color



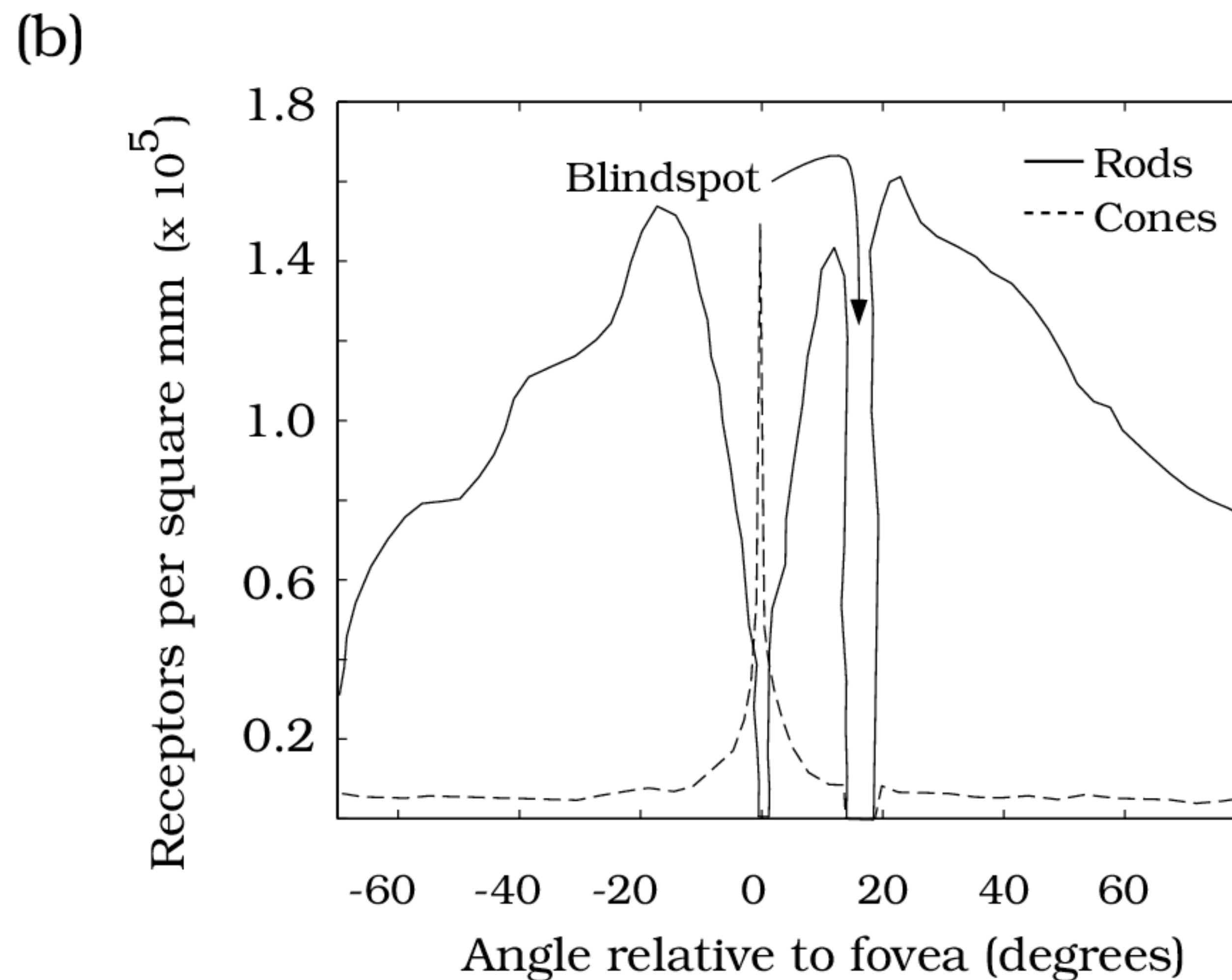
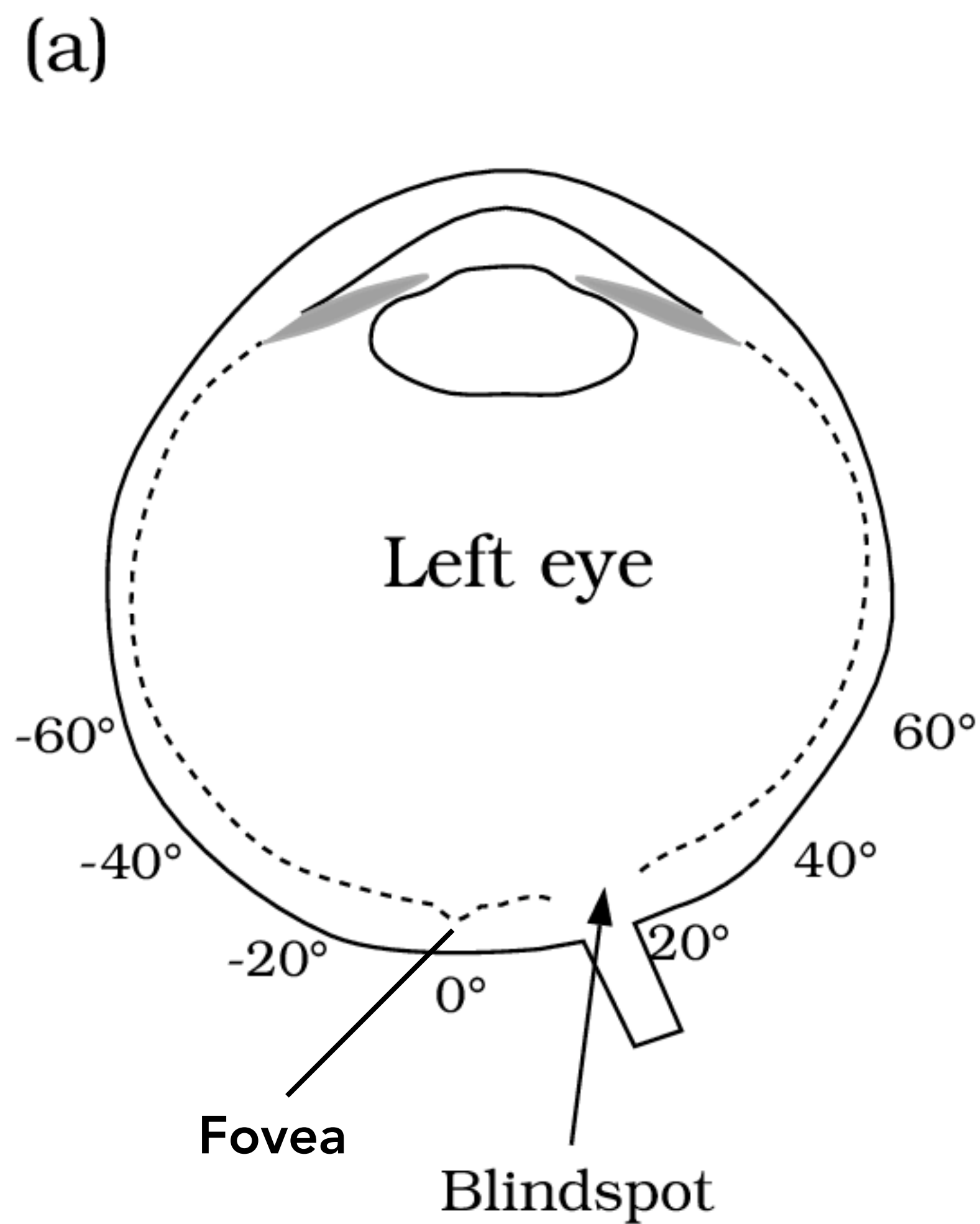
- Absorbance spectra from microspectrophotometry
- Absorbance is proportional to fraction absorbed under certain simplifications
- Data from humans
- **Three cone types**
- Long, Medium, Short

Spectral Sensitivity and Color

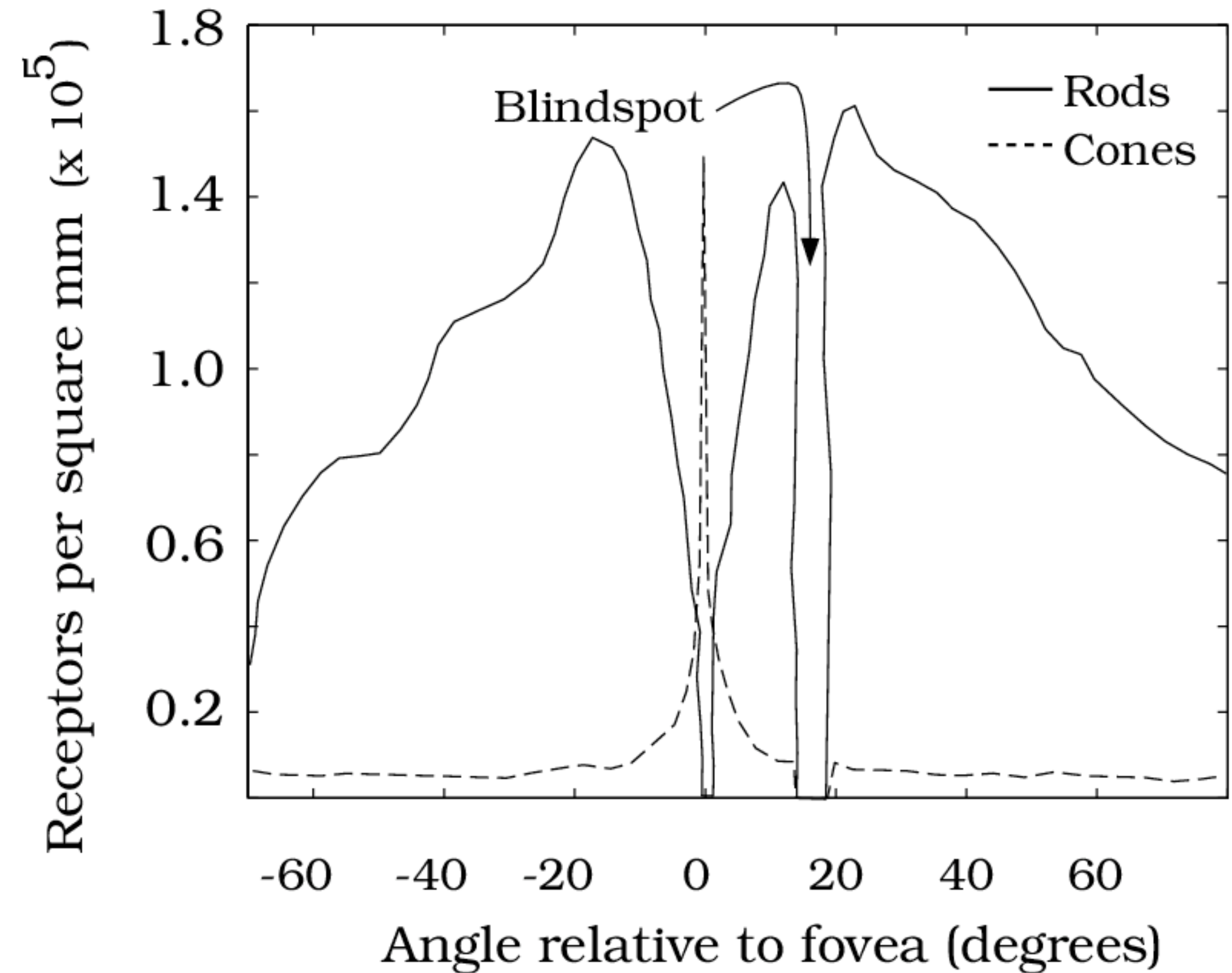
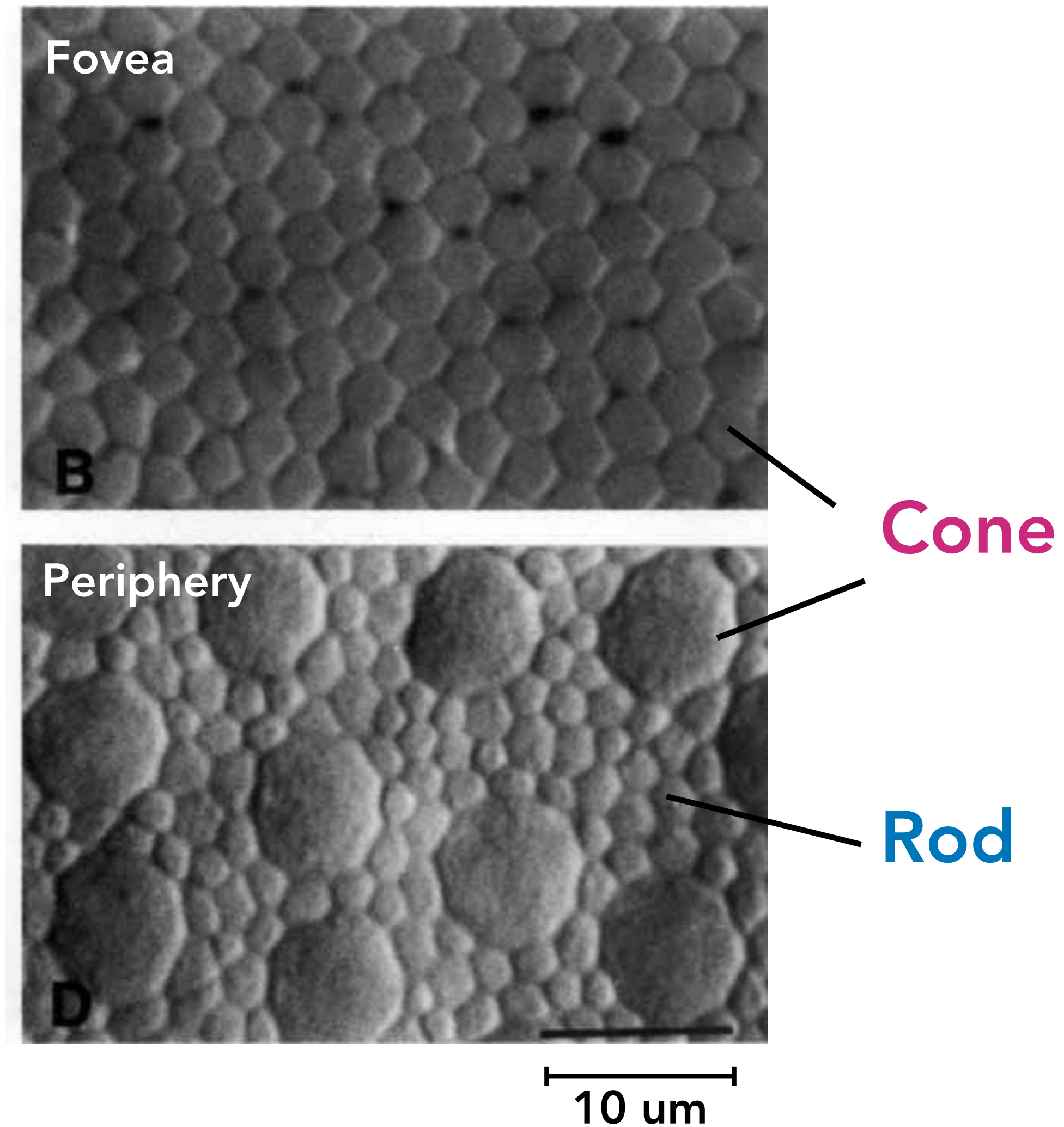


- Sensitivity from isolated photoreceptors
 - From a macaque
 - Using suction electrode to measure electrical responses
 - Measures the amount of light that's needed at each wavelength to reach a criterion level of response

Cones vs. Rods: Distribution



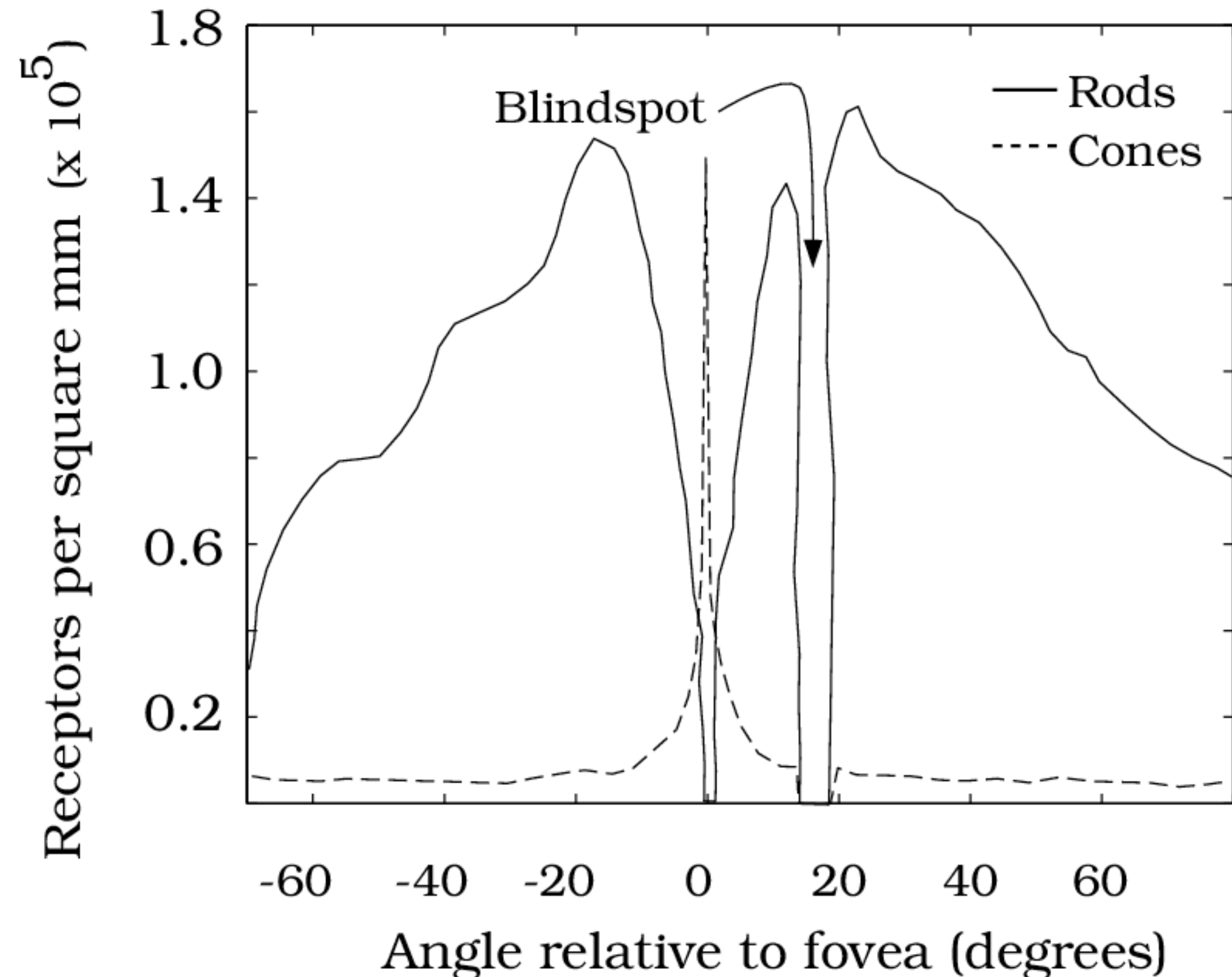
Cones vs. Rods: Distribution



Cones vs. Rods: Distribution

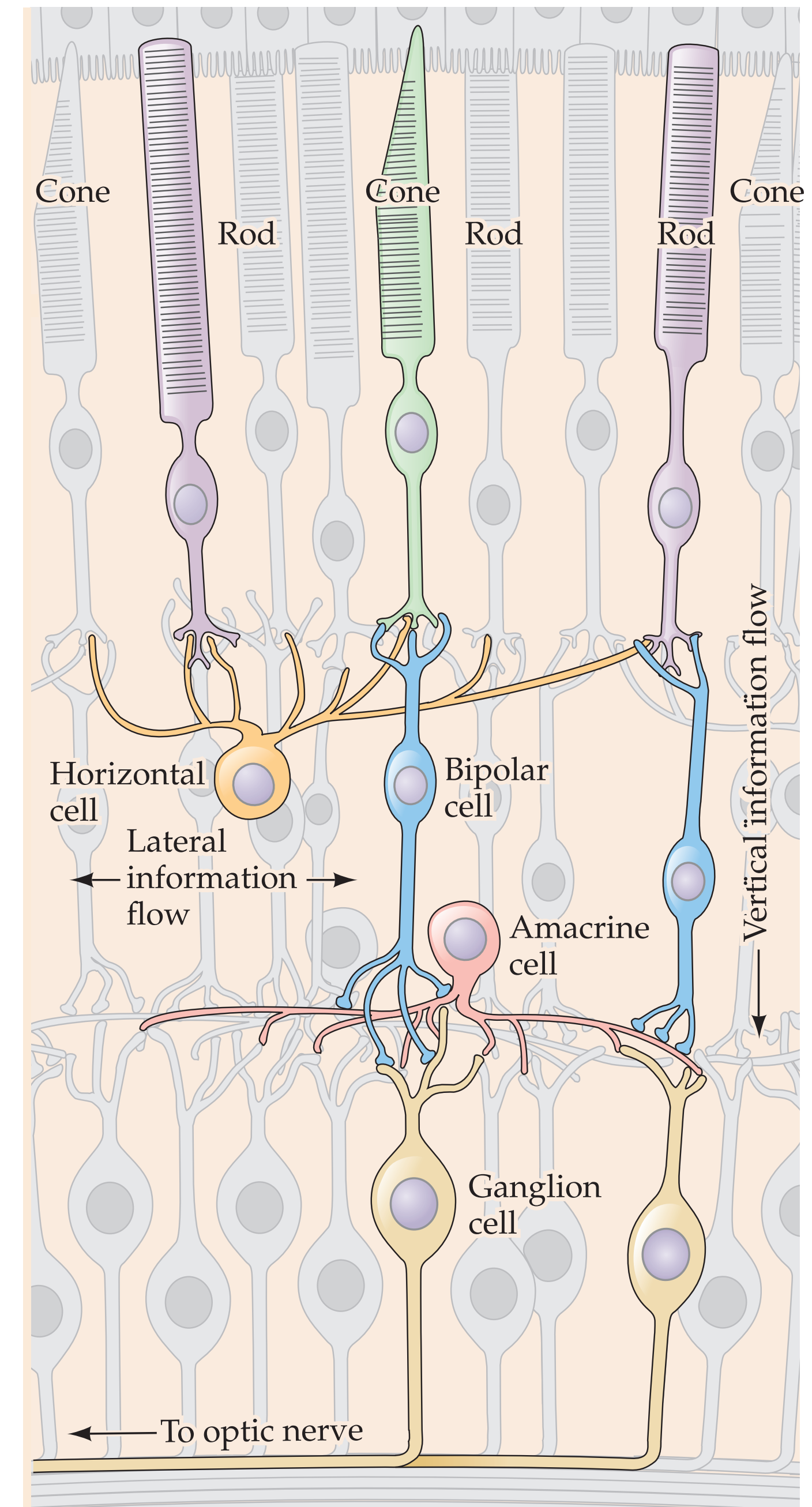
- Implications

- Can't see object details at low illumination levels if you fixate at the object. Intentionally place the object at your peripheral vision.
- Peripheral visual acuity is low (distribution and size is just one reason; more later)



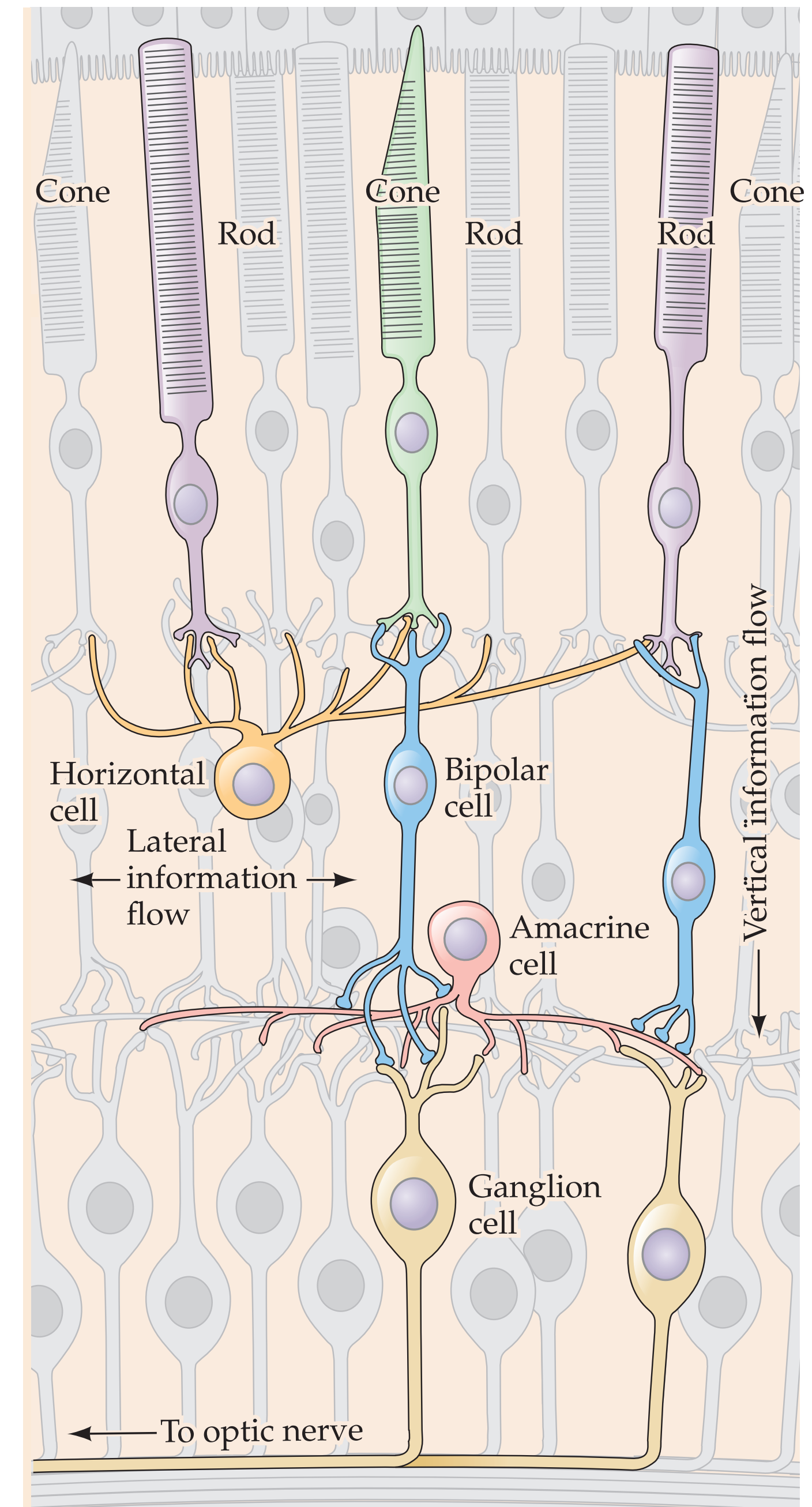
Cone vs. Rod Pathways

- Initially parallel/separated and then merge
- Photoreceptors synapse with bipolar cells
 - Each bipolar cell synapse with only rods or cones
 - So the pathways are separated
- RGCs mix rod bipolar and cone bipolar cells
 - Through amacrine cells

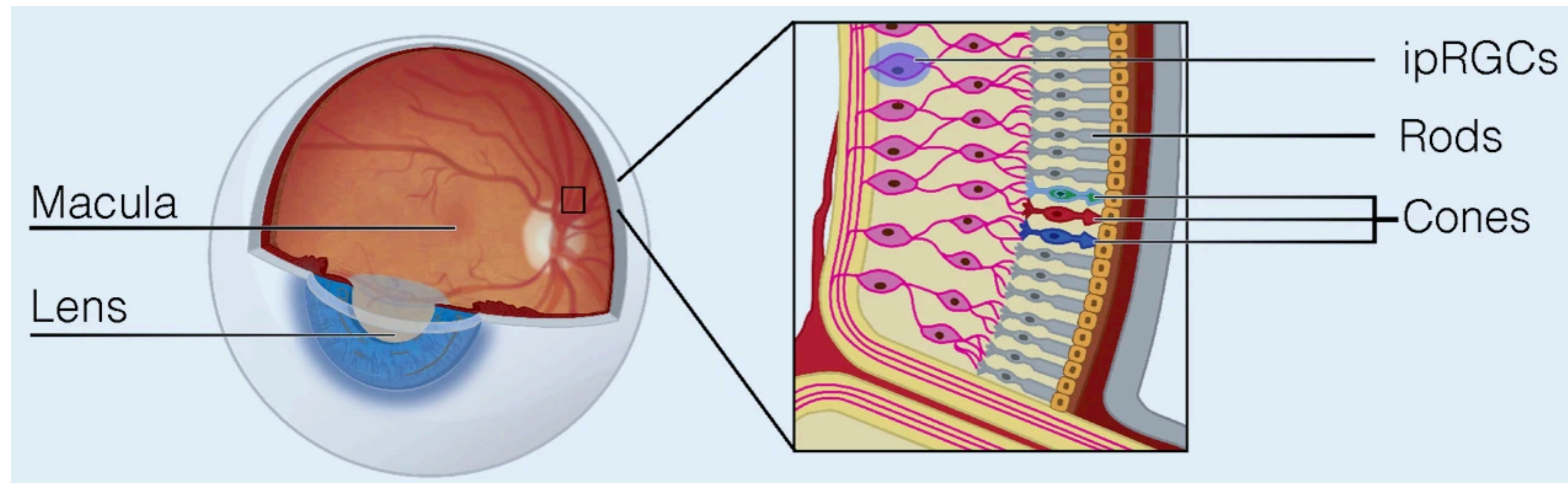


Cone vs. Rod Pathways

- Why parallel initially and then merge?
- Extract information independently
 - e.g., in dark vs. in light
- Process the information using the same “processor” to avoid duplication



ipRGCs



- Intrinsically photosensitive RGCs; big deal when discovered
- Do not contribute to image-forming vision
 - But affect things like circadian rhythm

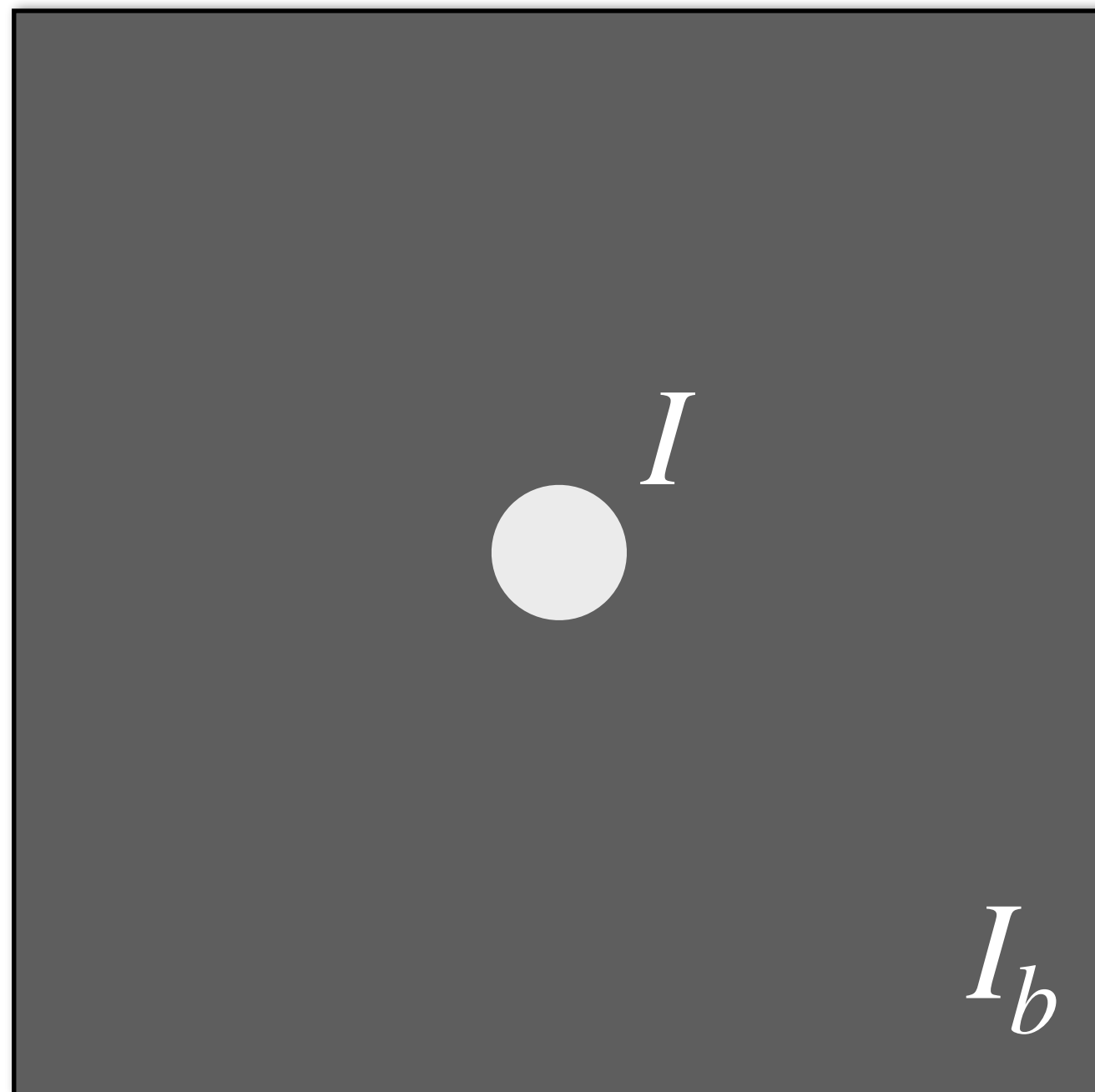
Retina Functions and Specializations

- Rods vs. Cones
- Contrast Detection
- Adaptation

Contrast: Variation over Mean

Weber Contrast

(detect object from background)



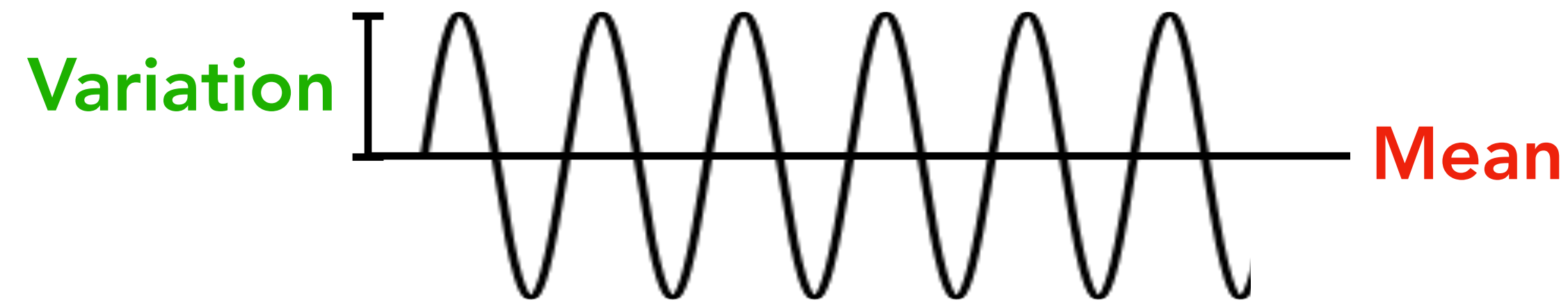
$$\frac{I - I_b}{I_b}$$

Variation of the signal
from the mean

Mean light intensity of
the entire field (patch is
relative small)



Contrast: Variation over Mean

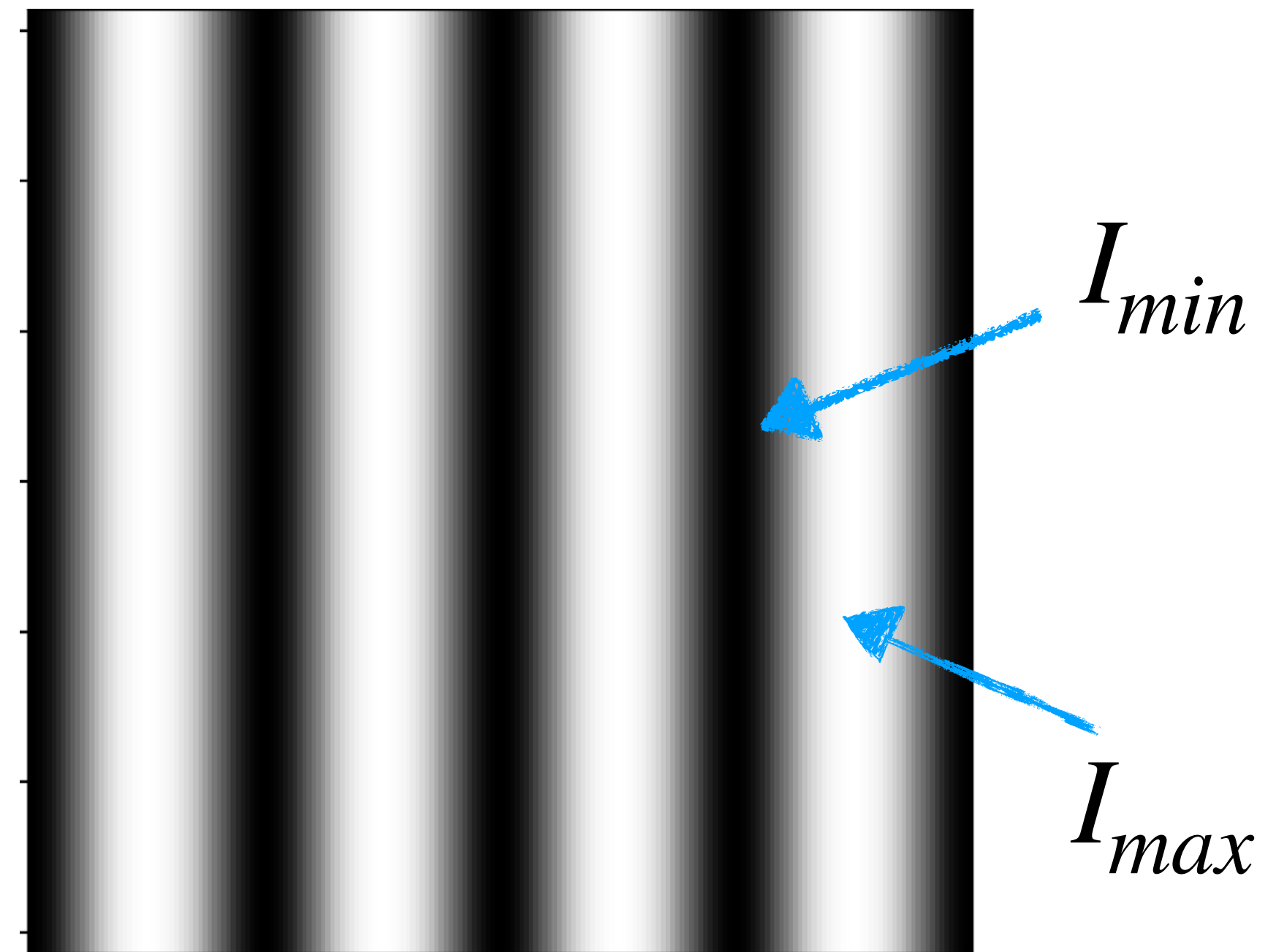


Michelson Contrast
(detect patterns)

2 x **Variation** of the
signal from the mean

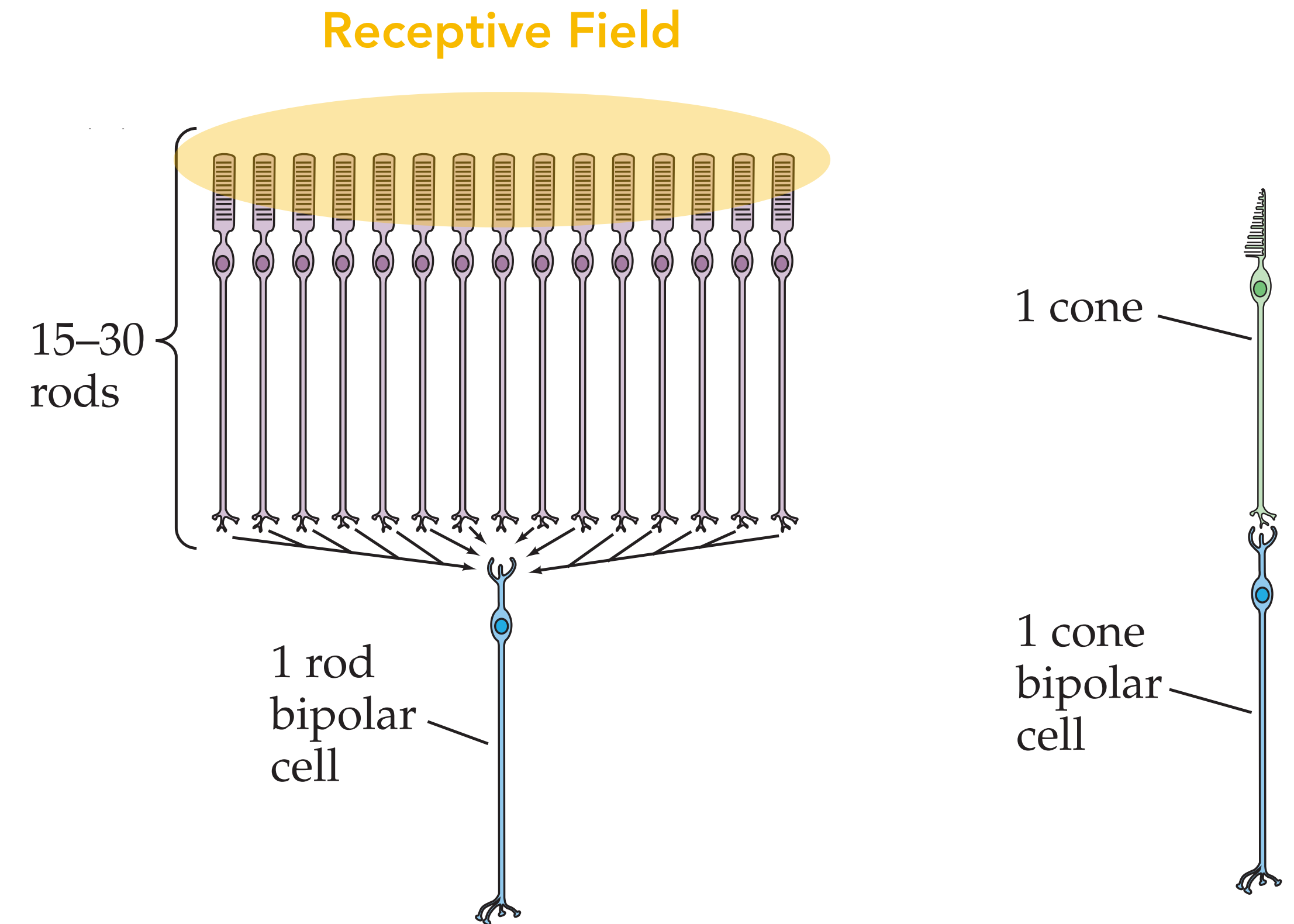
$$\frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

2x **Mean** light intensity
of the entire field



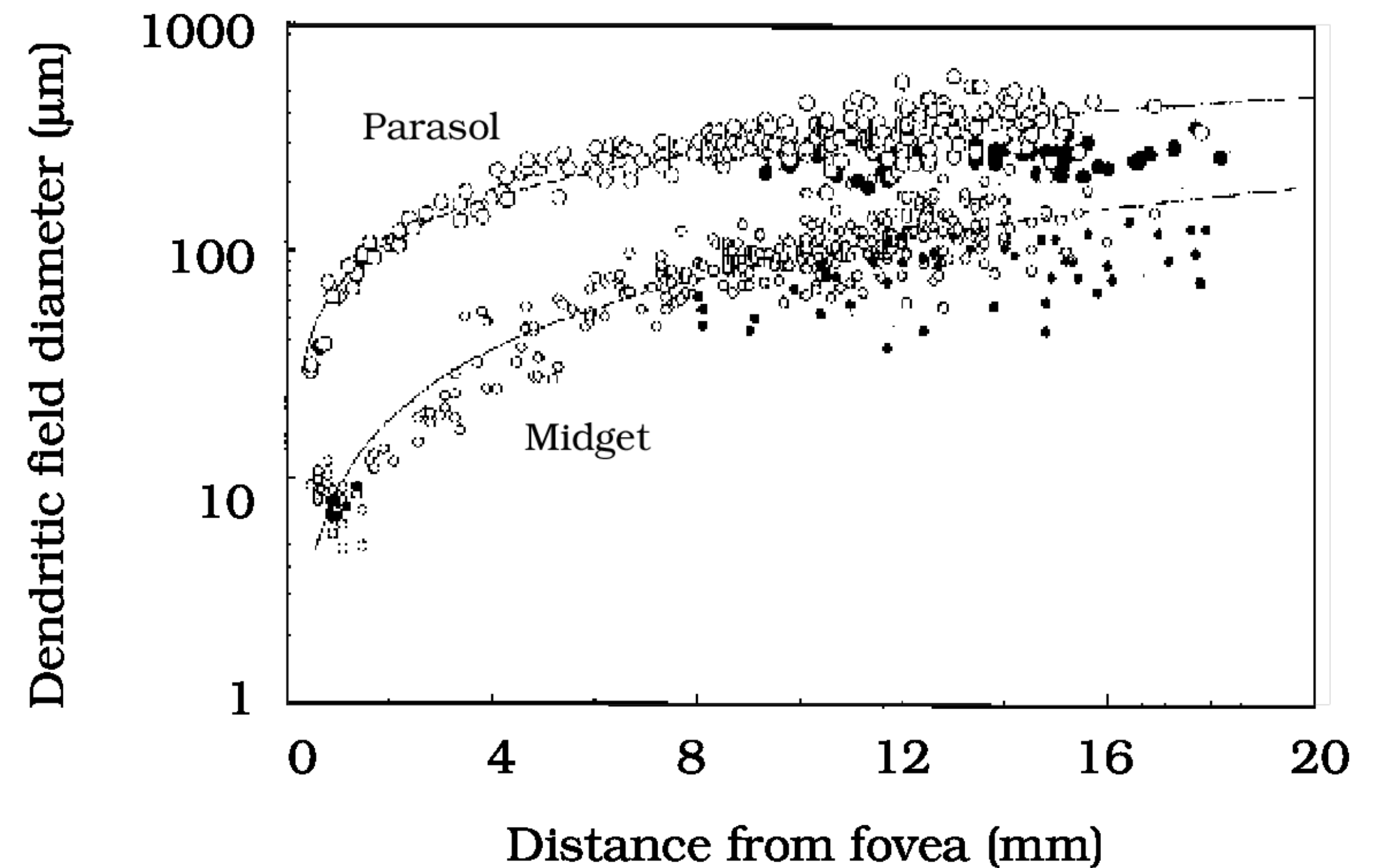
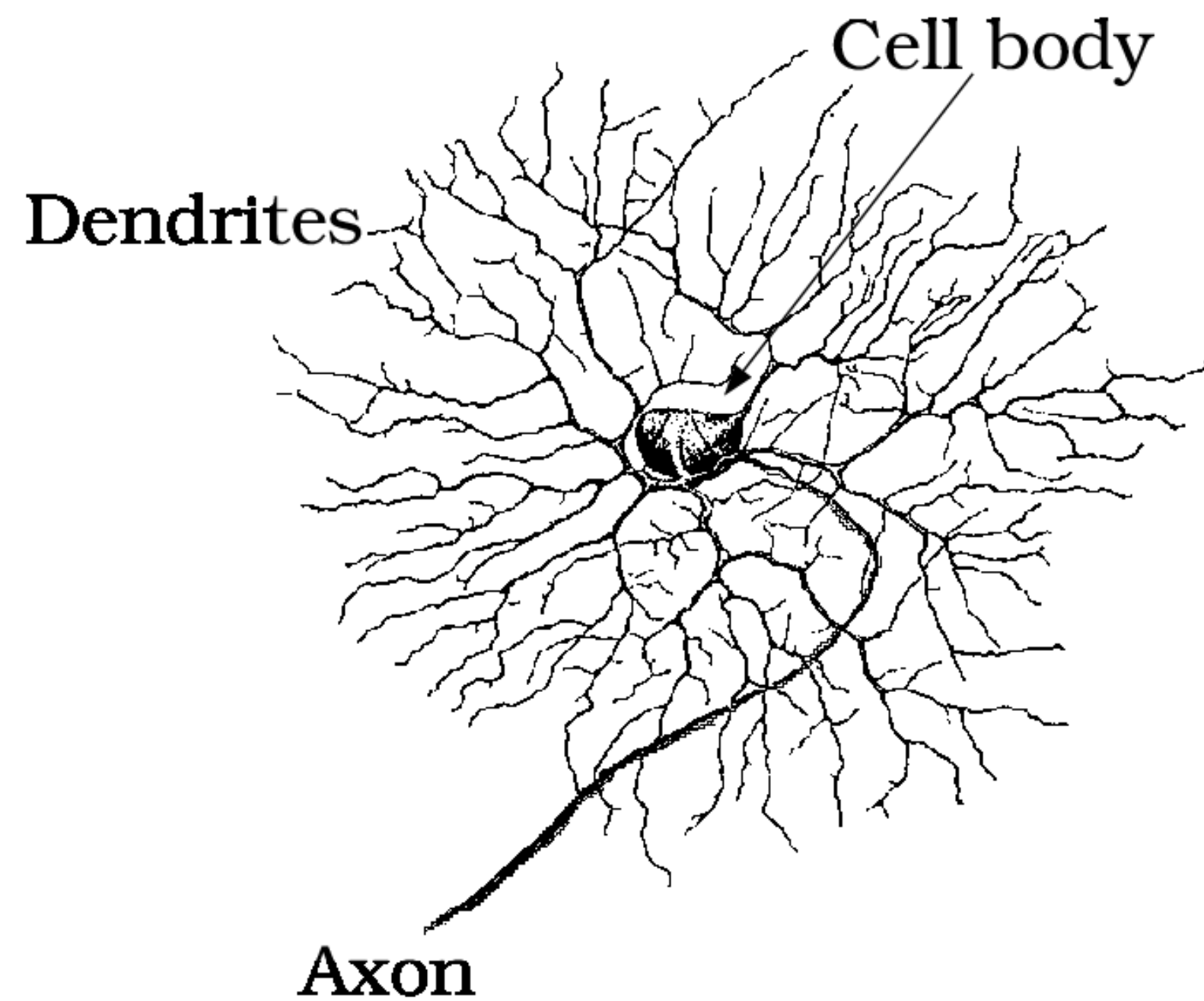
Neural Convergence and Receptive Field

- 120 million rods, 6 million cones, but only 1 million RGCs on the retina
- So some convergence has to take place
- Higher degrees of convergence for rods than cones
- Receptive field of a neuron: retinal surface that converges to the neuron

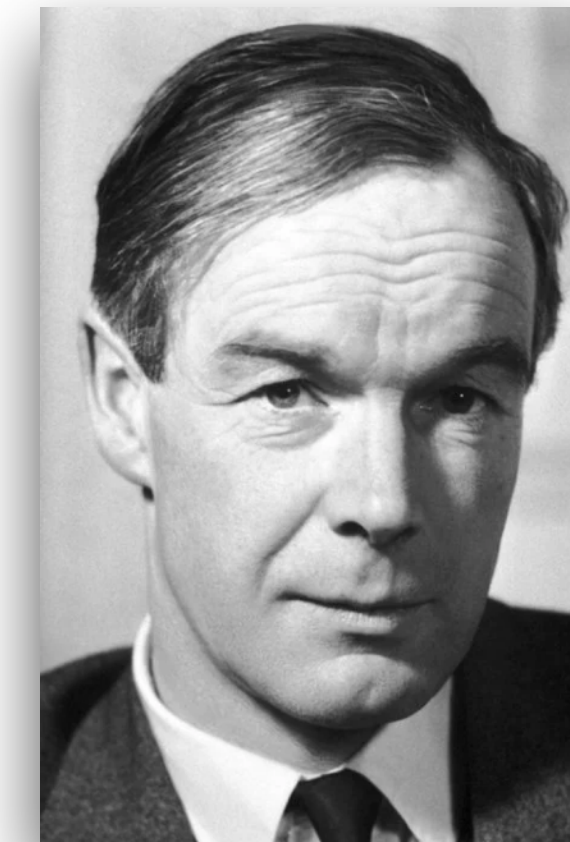


Neural Convergence

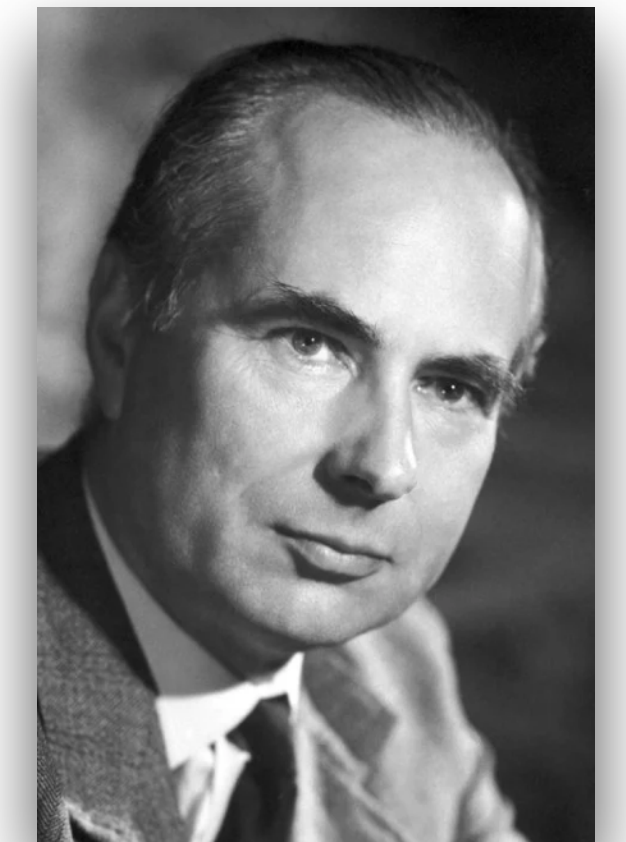
- Degree of convergence increases with eccentricity
 - Extreme case: one cone maps to many RGCs at fovea



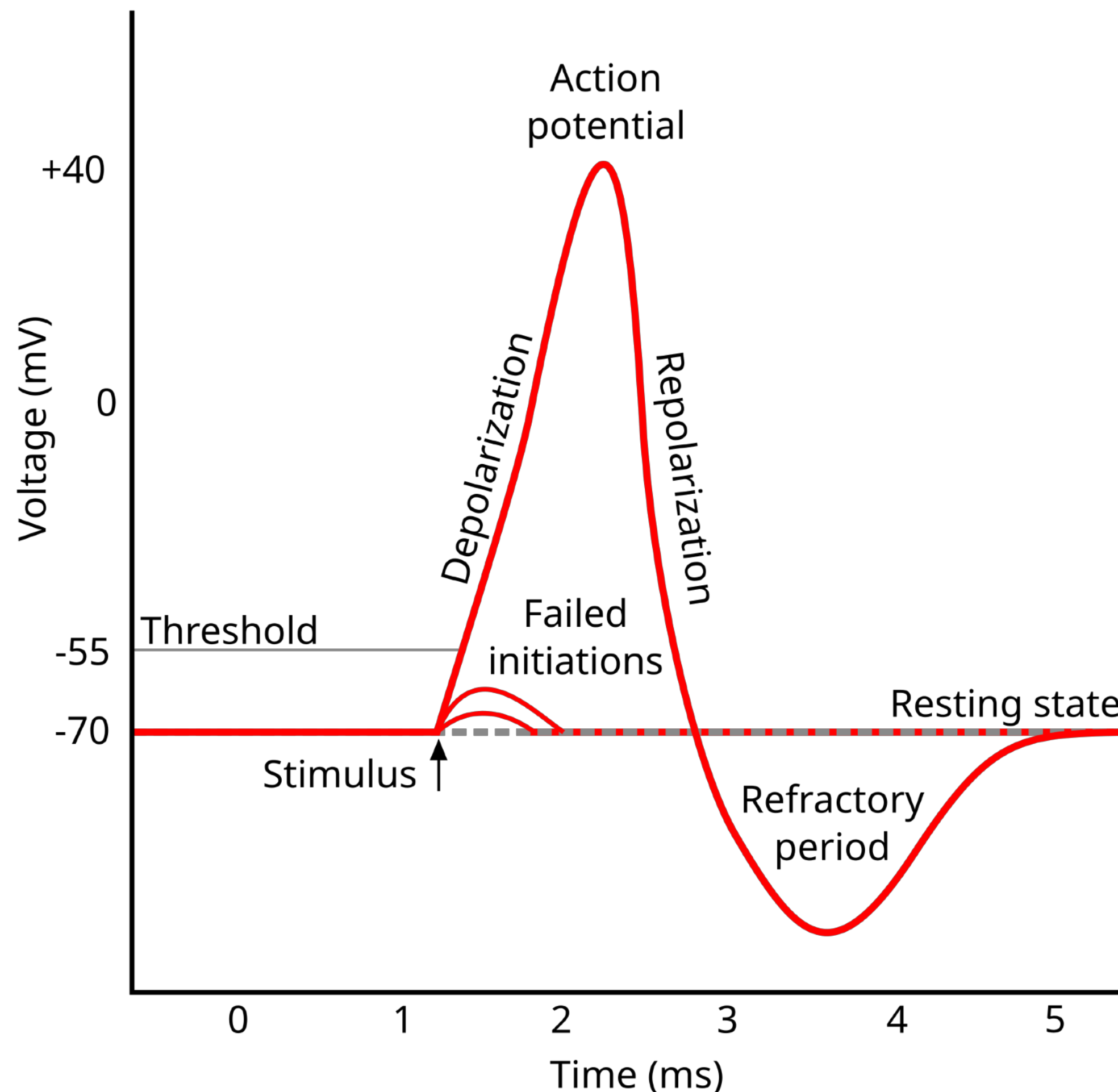
Interlude: Action Potential



Alan Hodgkin
(1963 Nobel Prize)



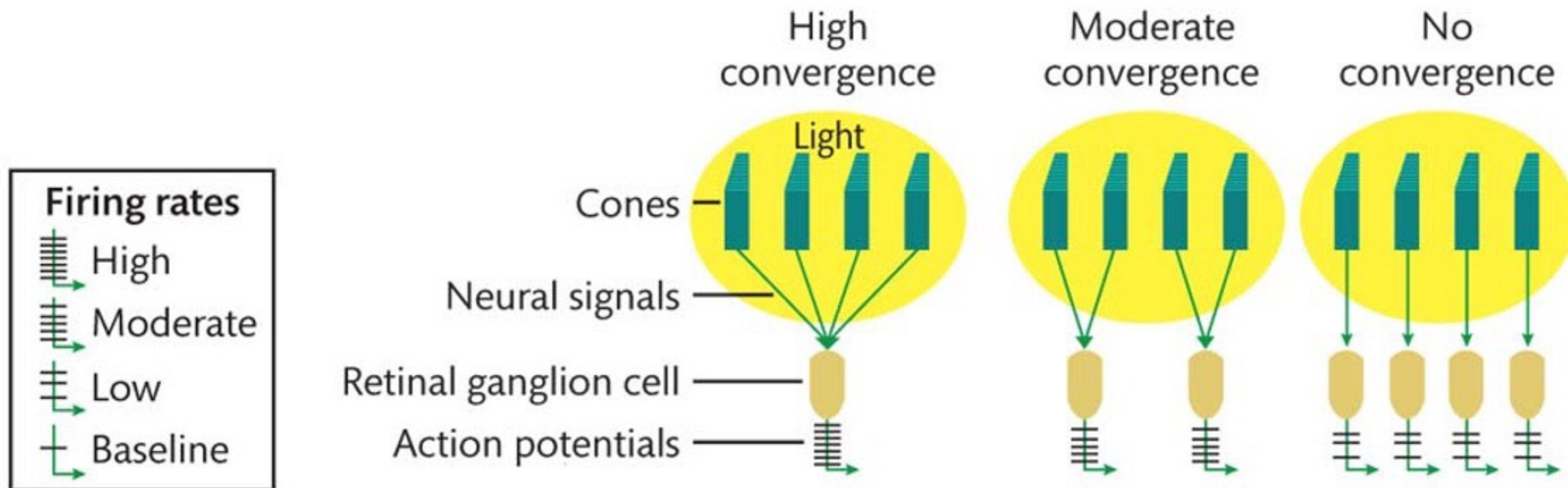
Andrew Huxley
(1963 Nobel Prize)



- **Binary, “all-or-nothing”**
 - Other names: spike, impulse, firing
- **How neurons communicate in general**
 - But, on retina only RGCs generate action potentials; others use *graded potentials* (analog, continuous responses)

Implications of Neural Convergence

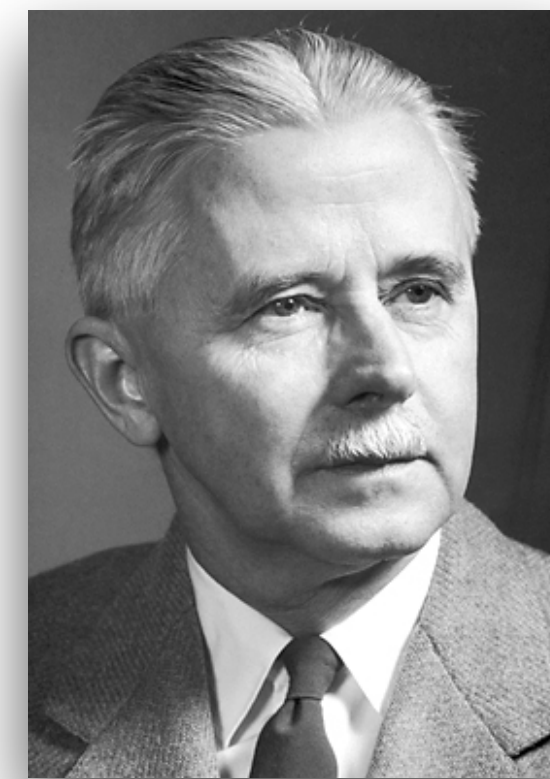
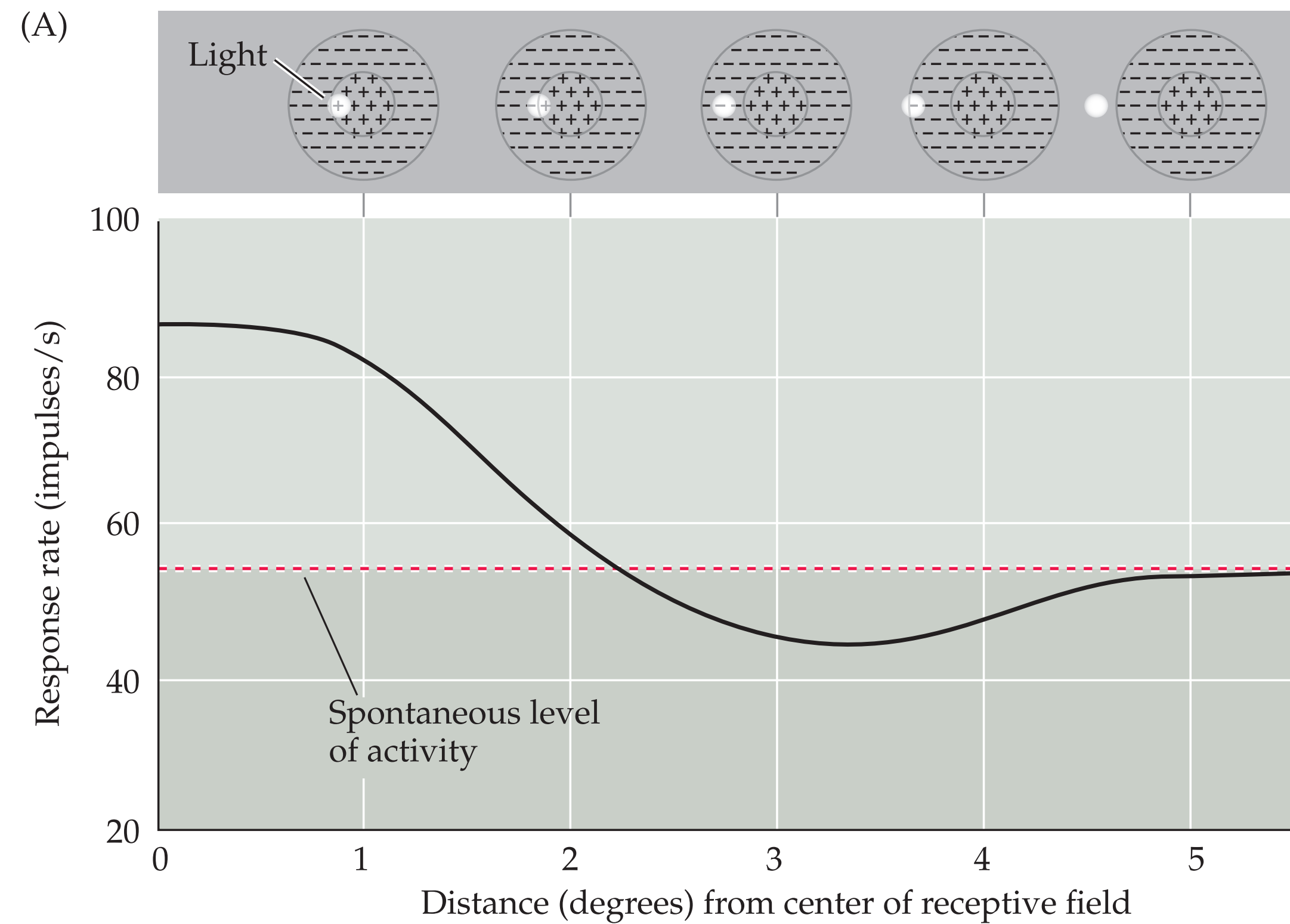
- Higher convergence usually means higher sensitivity but lower acuity
 - Assuming pure summation but there is also inhibition (later)
 - Convergence means integration, which is low-pass filtering



Implications of Neural Convergence

- Higher convergence usually means higher sensitivity but lower acuity
 - Assuming pure summation but there is also inhibition (later)
- Rod vision is more sensitive to cone vision
 - In addition to the larger single photon response we saw before
- Peripheral visual acuity is lower than fovea
 - In addition to the lower photoreceptor distribution

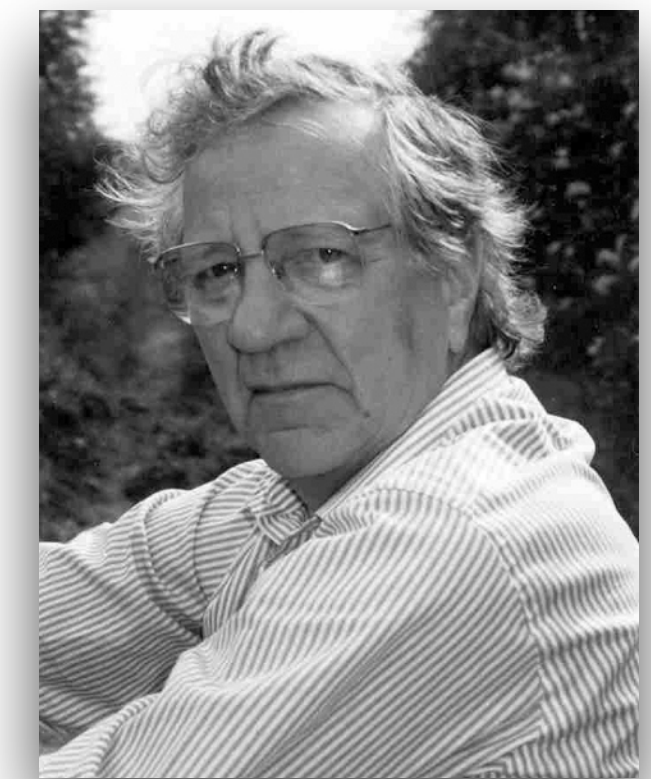
RGCs have a Center-Surround Receptive Field



Hartline
(1967 Nobel prize)

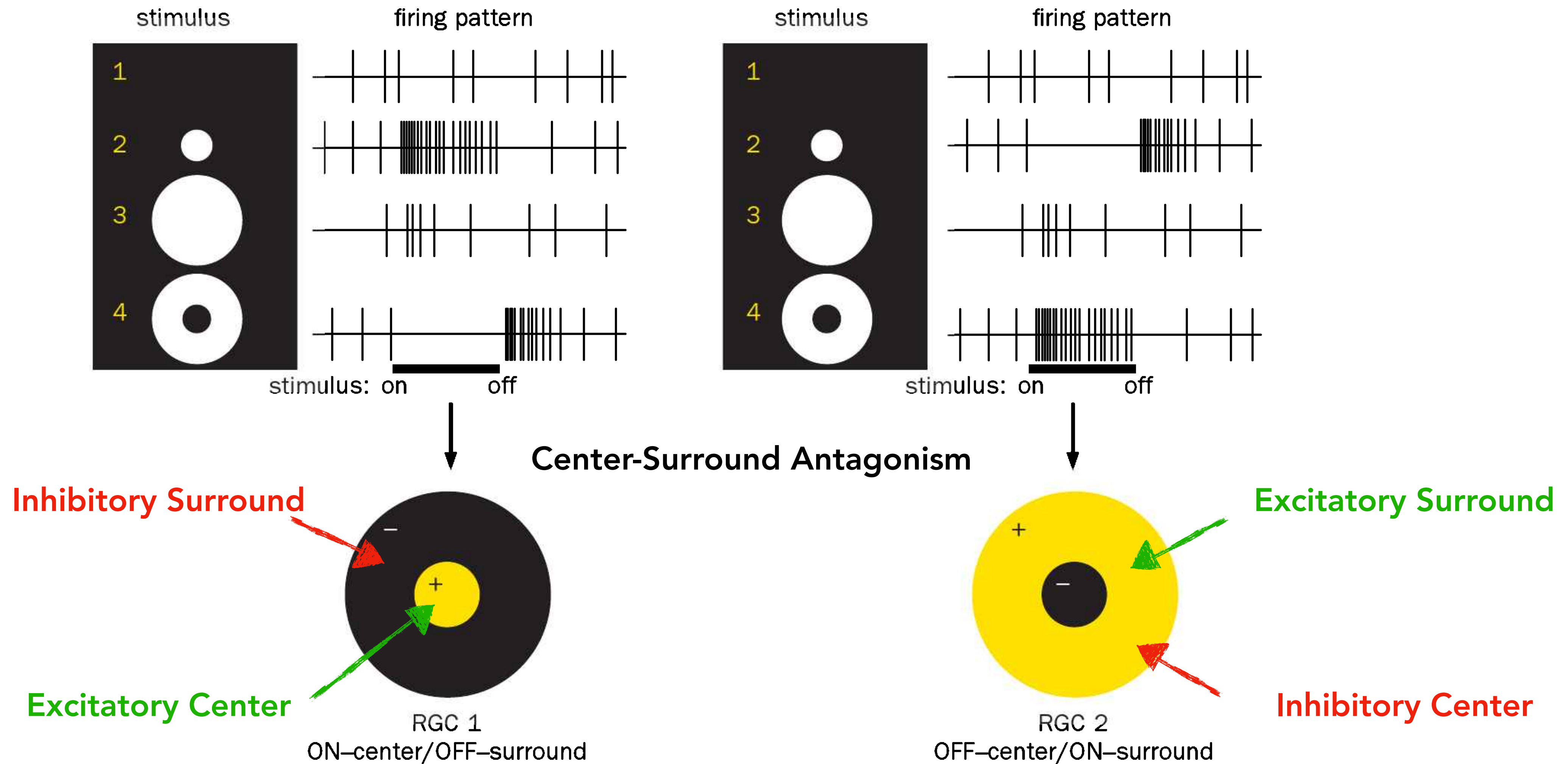


Kuffler

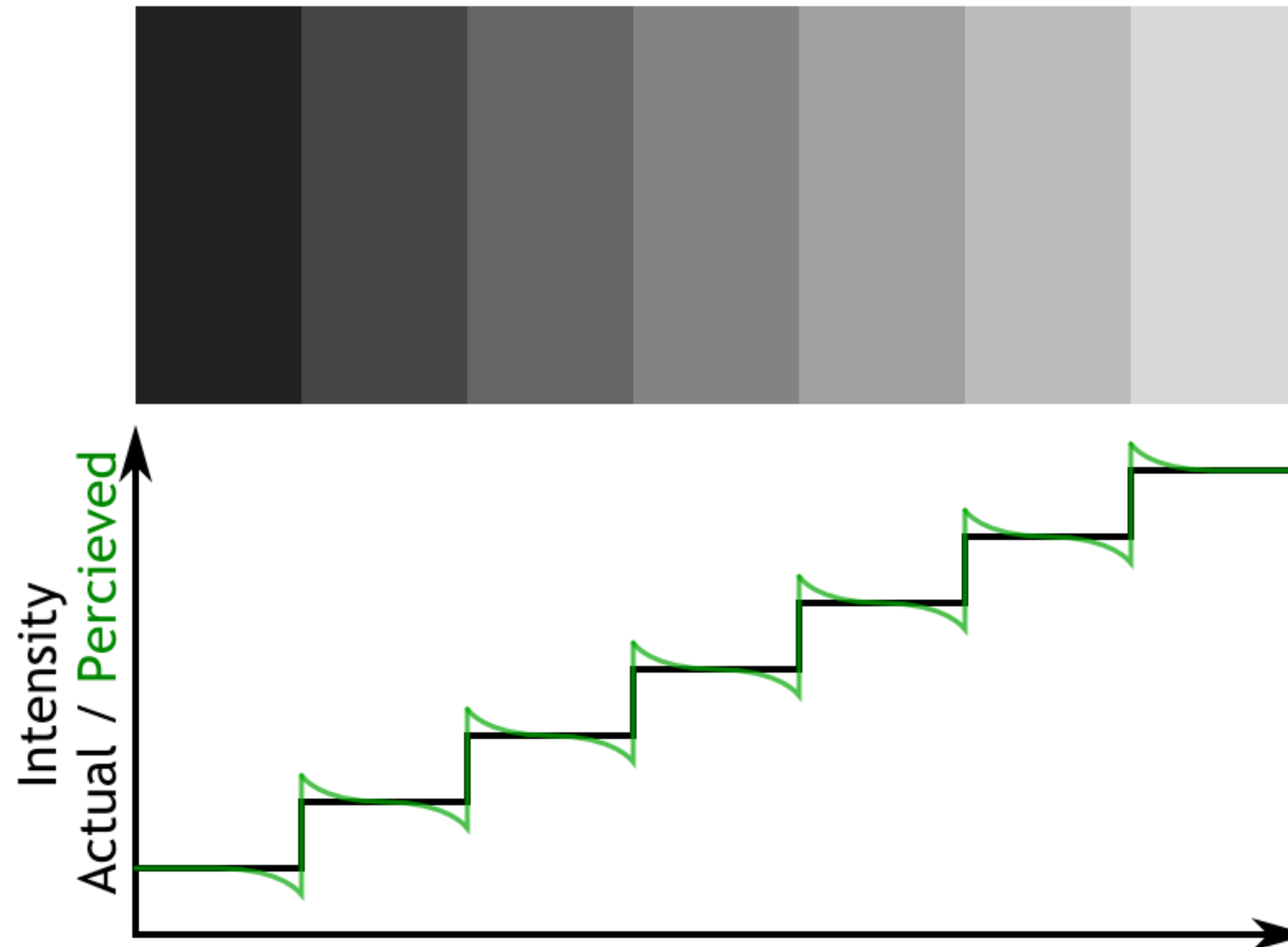


Barlow

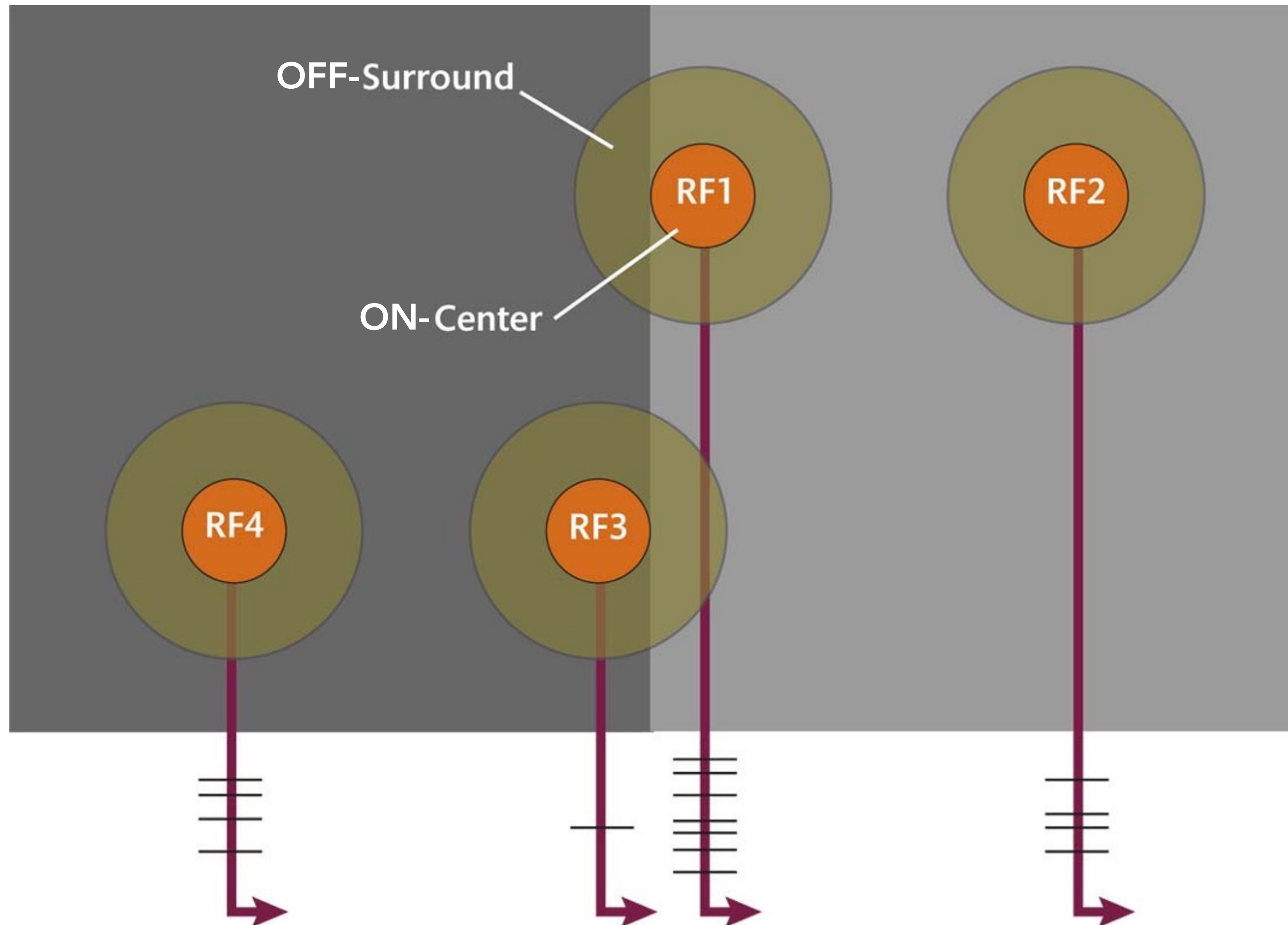
ON-Center and OFF-Center Receptive Field



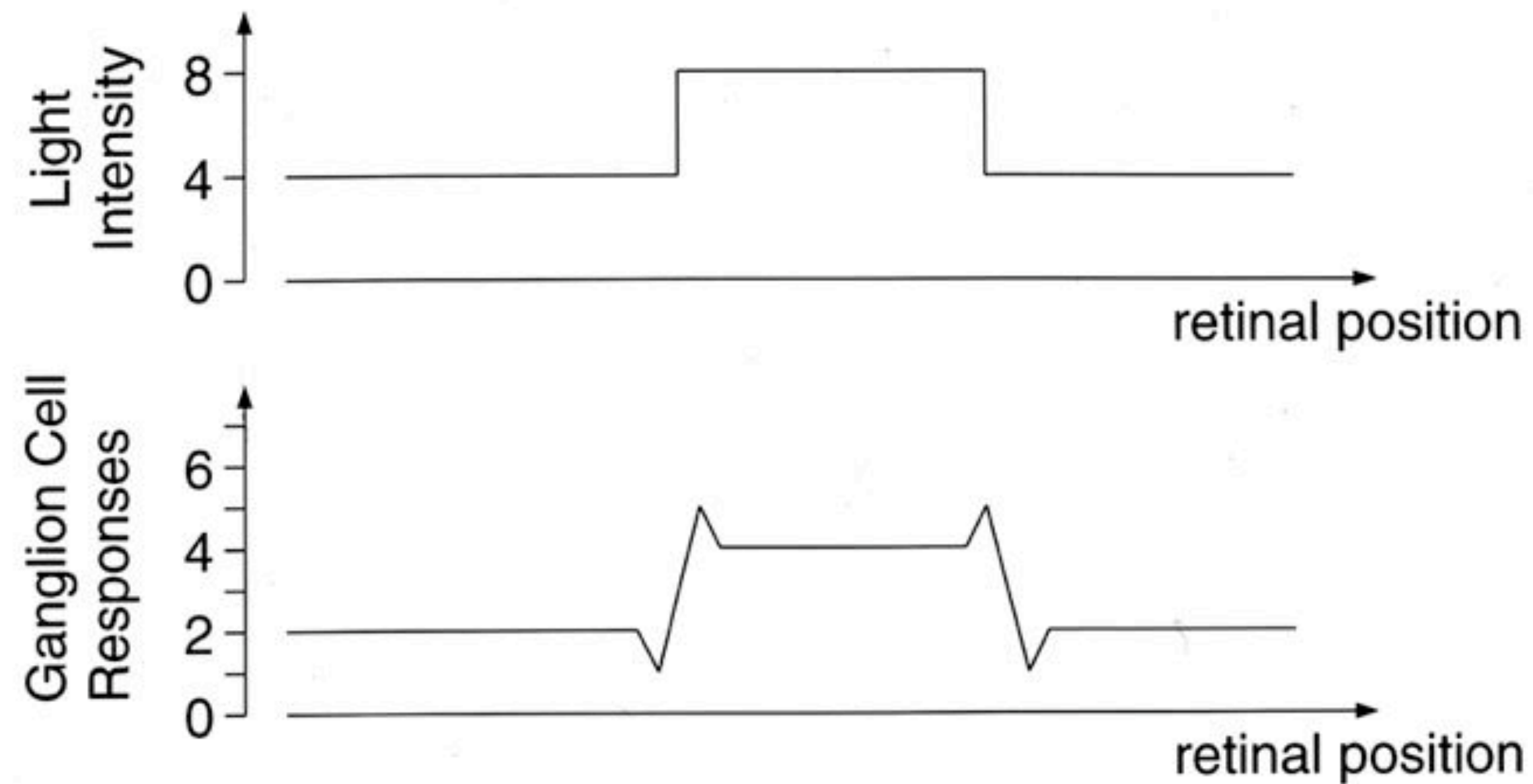
Mach Band/Chevreul Illusion



Mach Band/Chevreul Illusion



Encoding Contrast Allows Us to Detect Edges



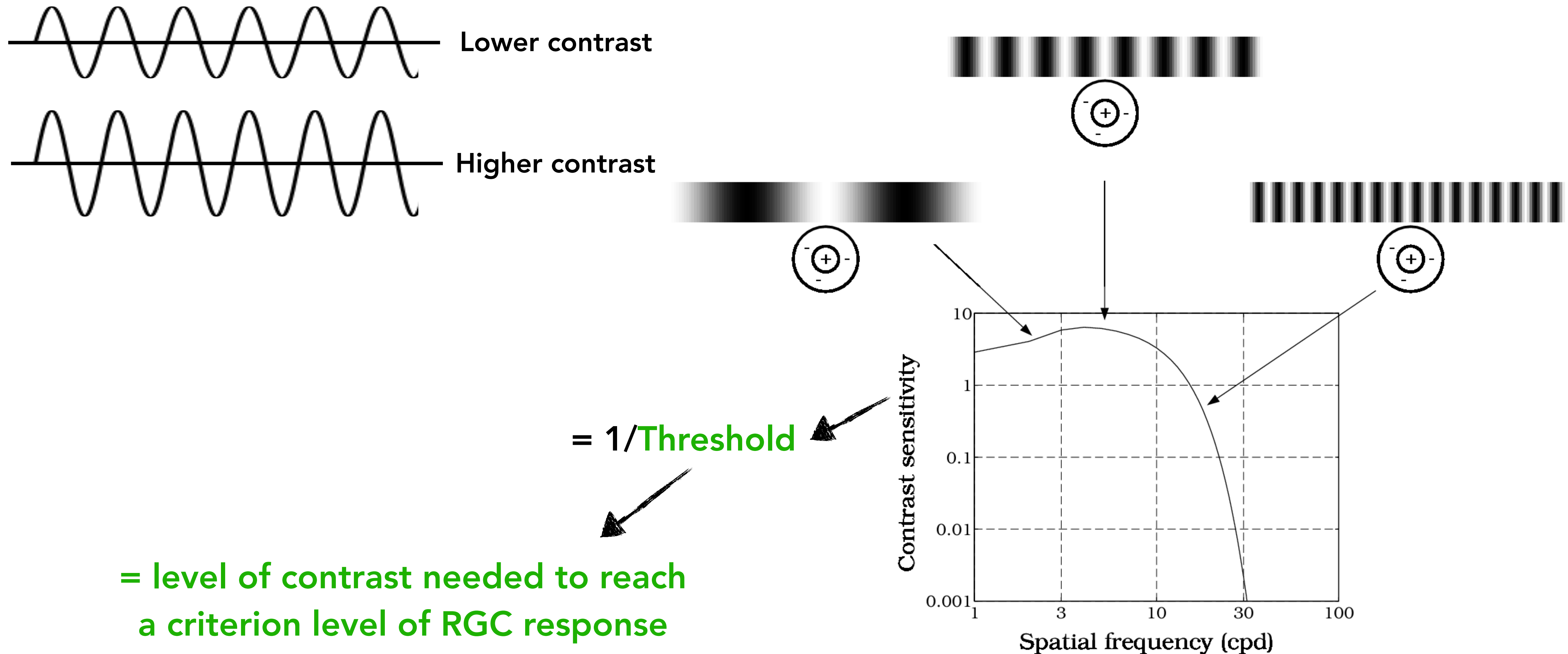
Input image
(cornea)



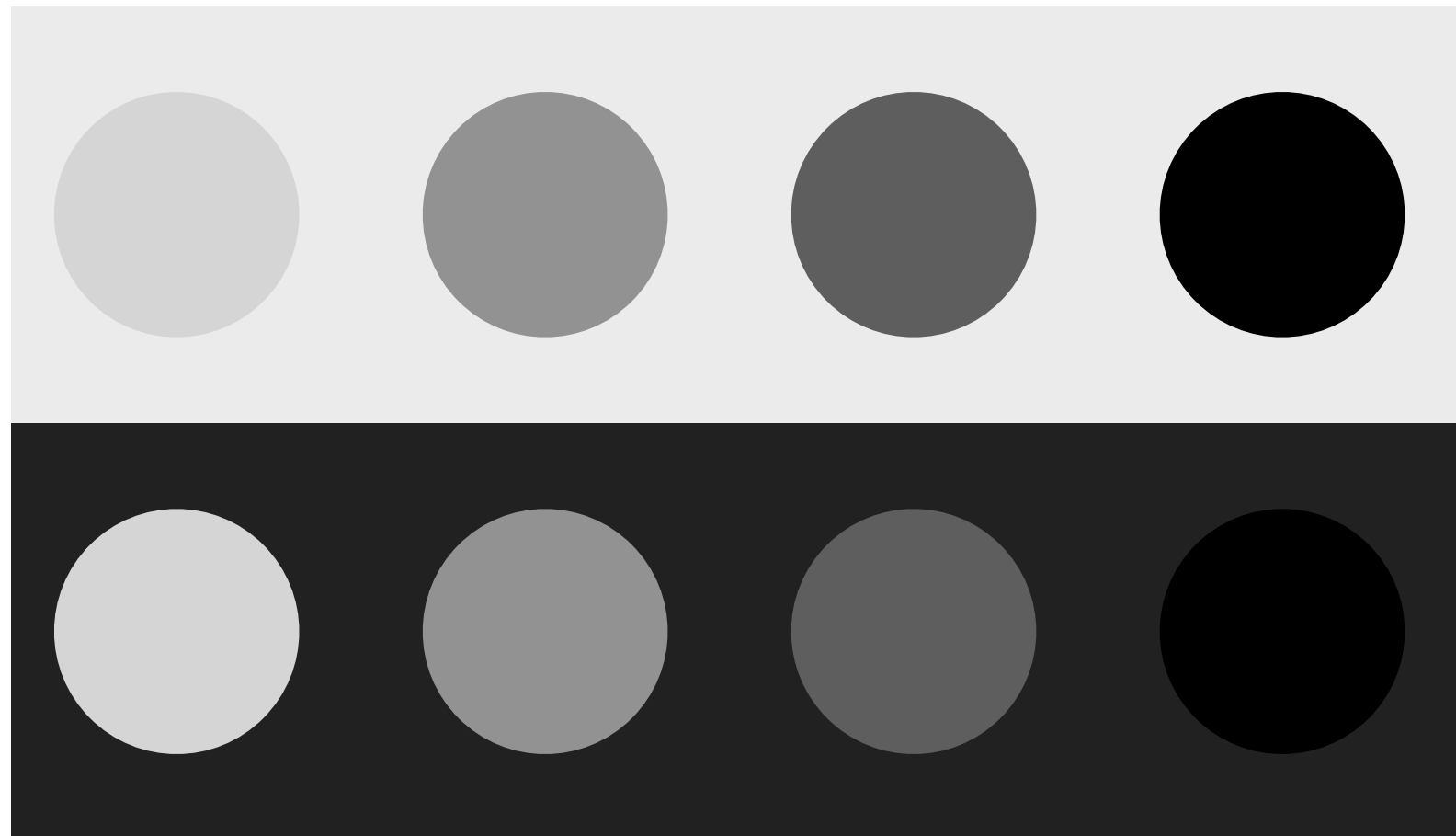
"Neural image"
(retinal ganglion cells)



(Michelson) Contrast Sensitivity Function



Now How To Explain This?



- Two exactly same rows of grays, but dark color looks darker against brighter background and vice versa.
- Maintaining local contrast is in general important in photography; otherwise a photo looks dull.
- We will have more to say about this in HDR/tone mapping lecture.

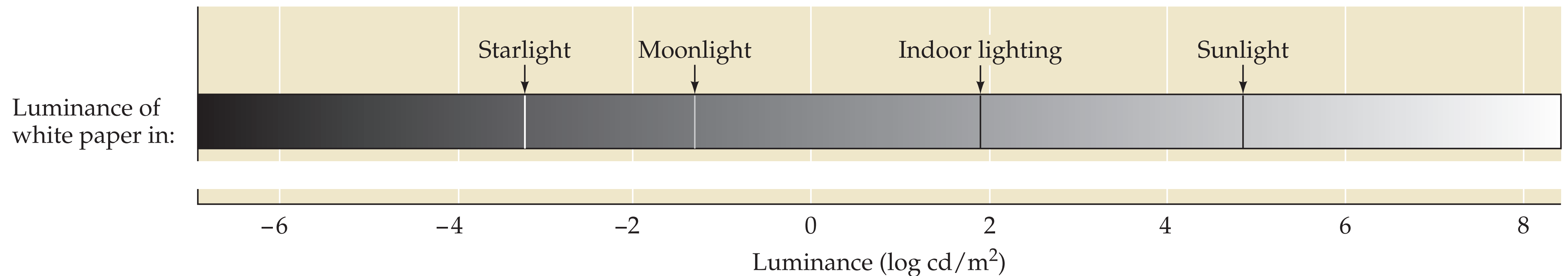


Retina Functions and Specializations

- Rods vs. Cones
- Contrast Detection
- Adaptation

Need For Adaptation

- Absolute light level varies by orders of magnitude, but the range of contrast is roughly constant.
- Adaptation means neurons “discount” absolute light intensities and encode only the contrast information.



Adaptation Mechanism

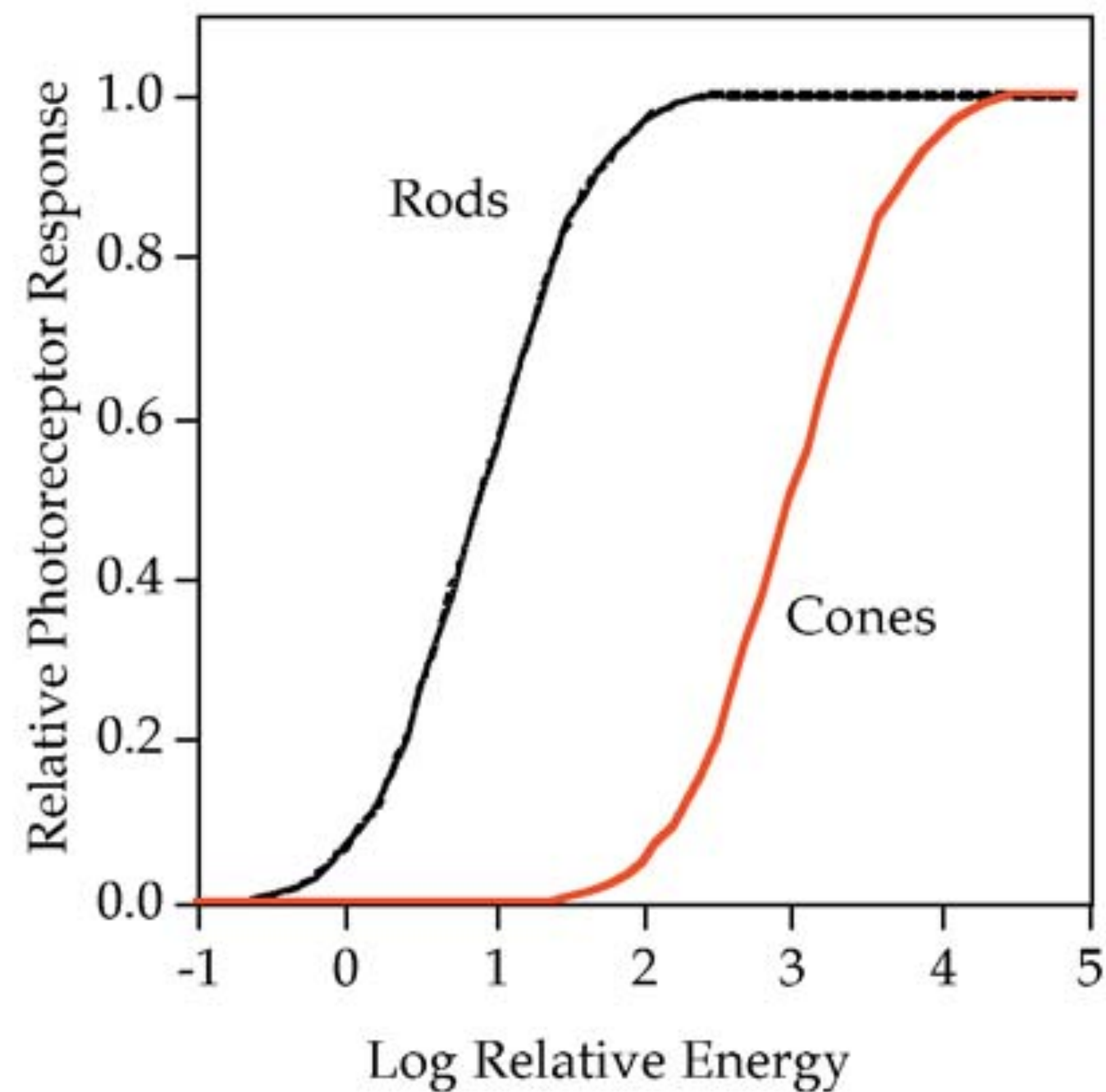


Figure 1.8 Relative energy responses for the rod and cone photoreceptors

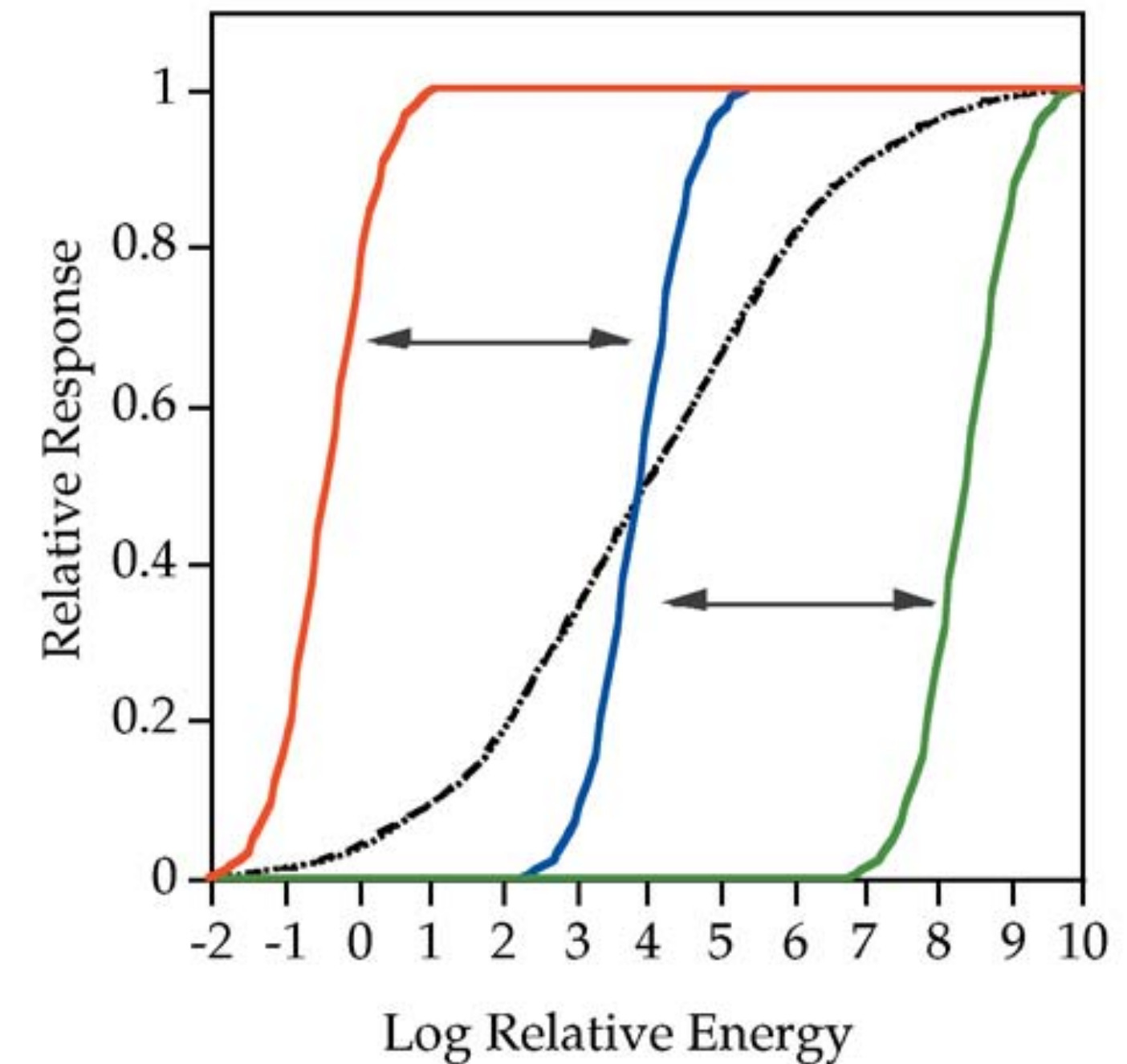
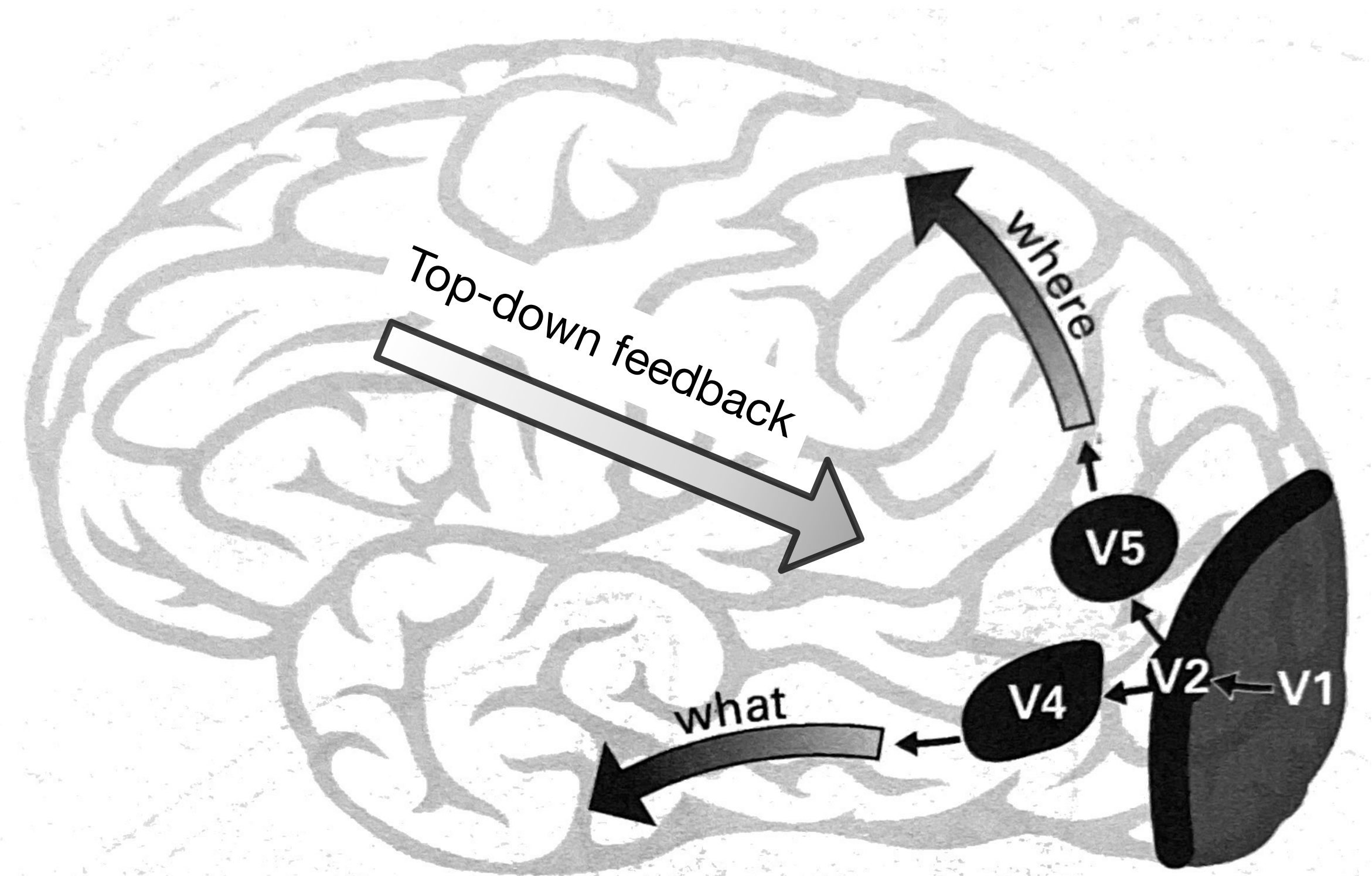
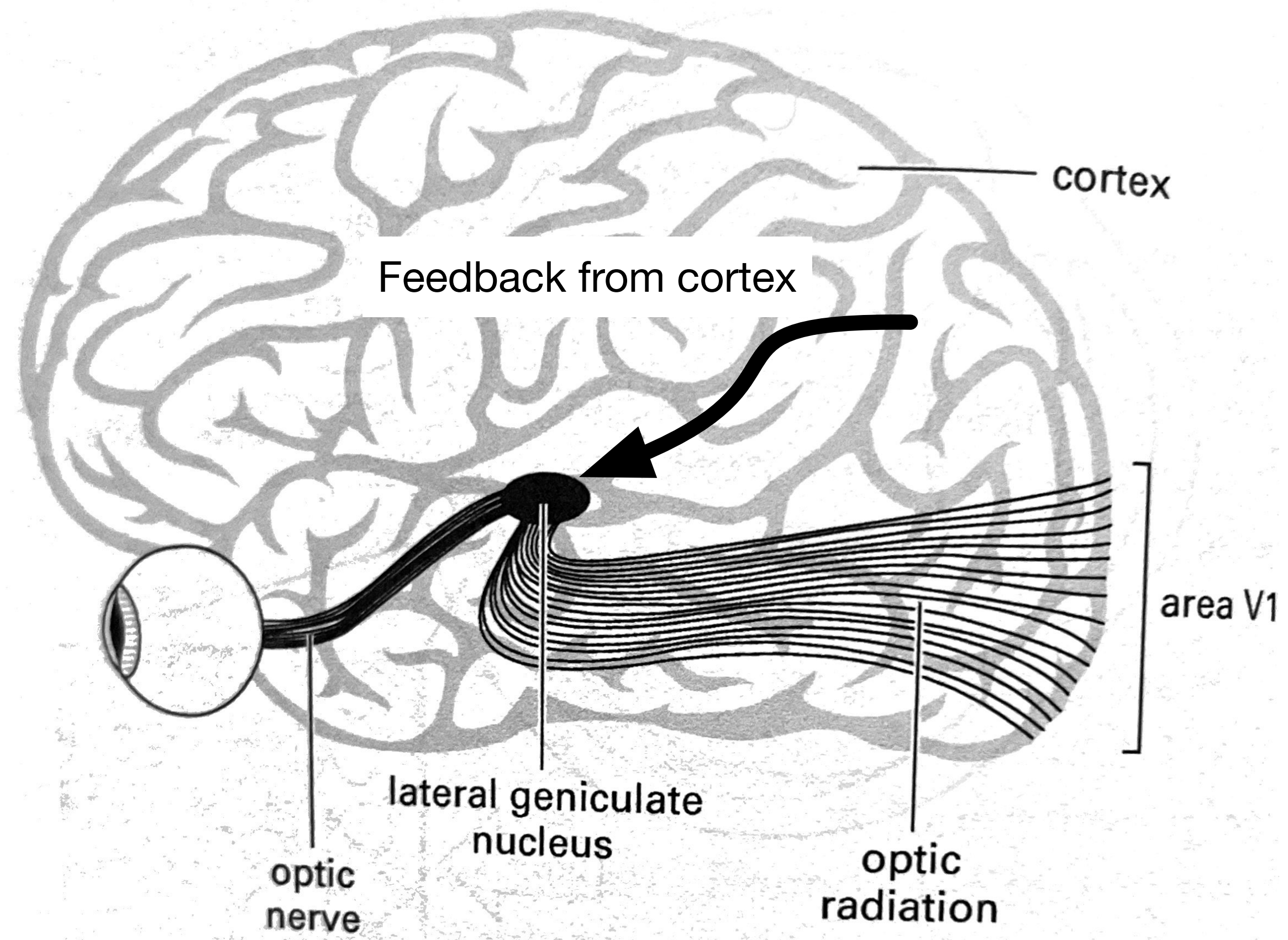


Figure 1.15 Illustration of the process of light adaptation whereby a very large range of stimulus intensity levels can be mapped into a relatively limited response dynamic range. Solid curves show a family of adapted responses. Dashed curve shows a hypothetical response with no adaptation

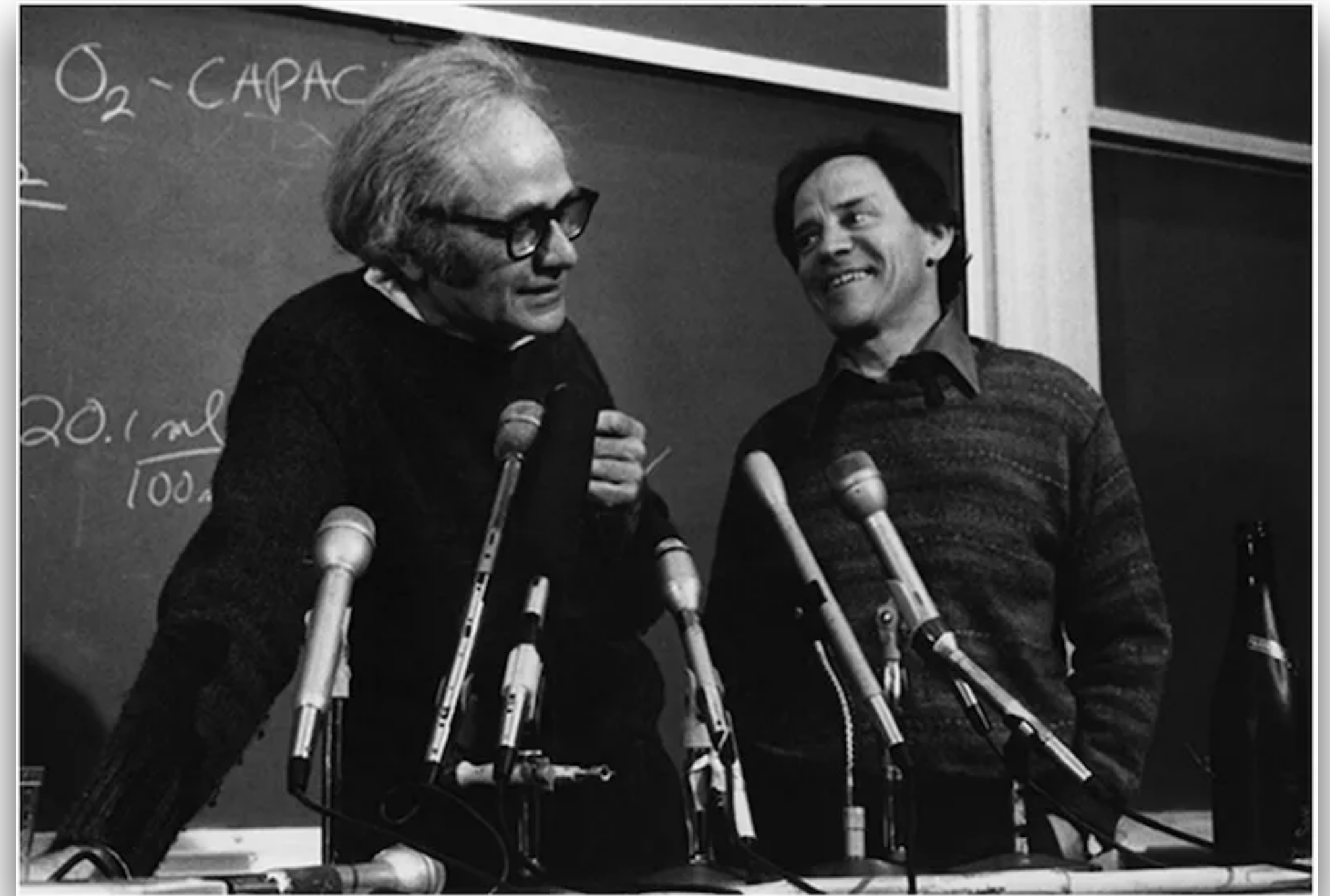
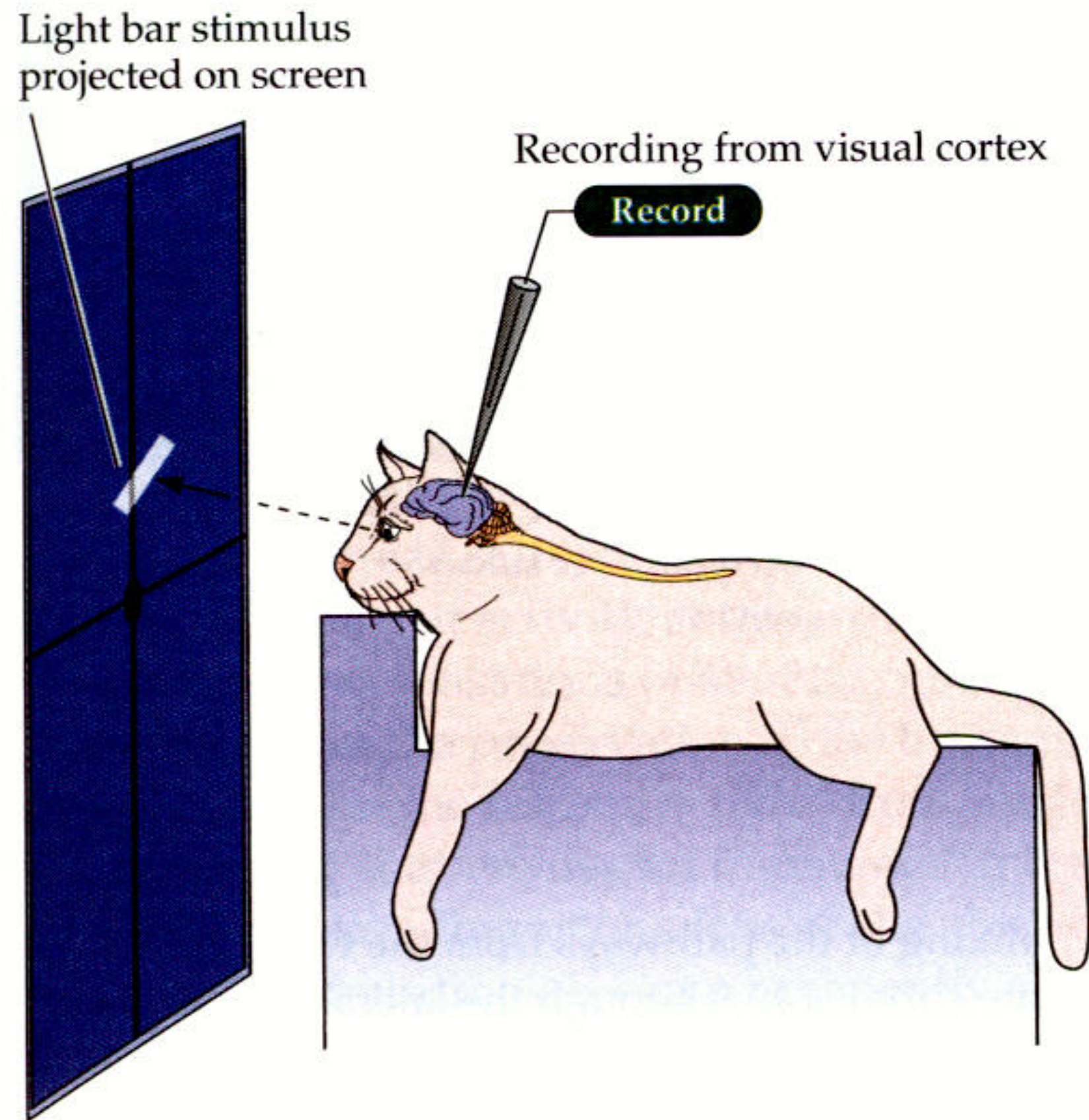
Post-Retinal Processing

LGN + Cortex



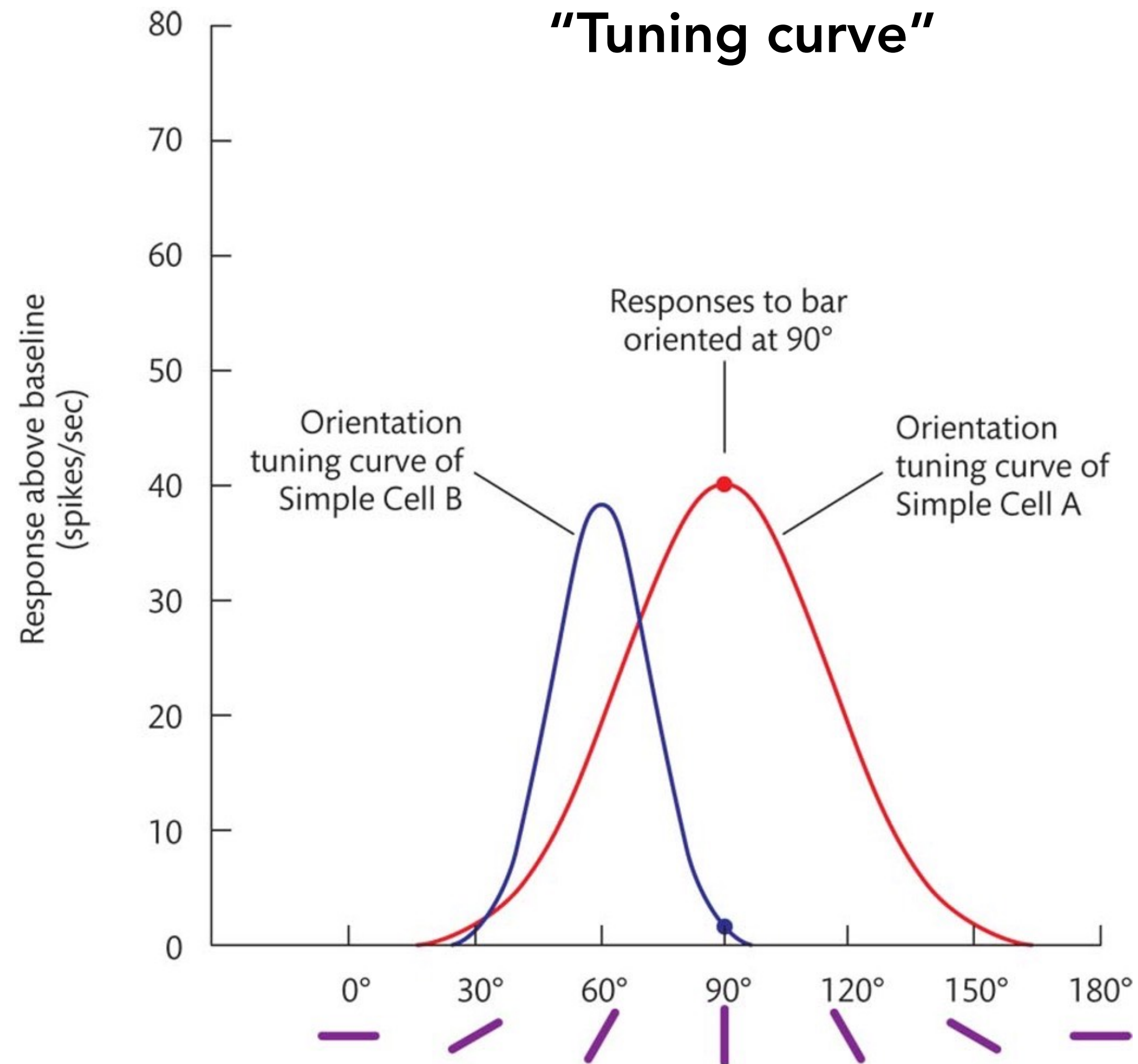
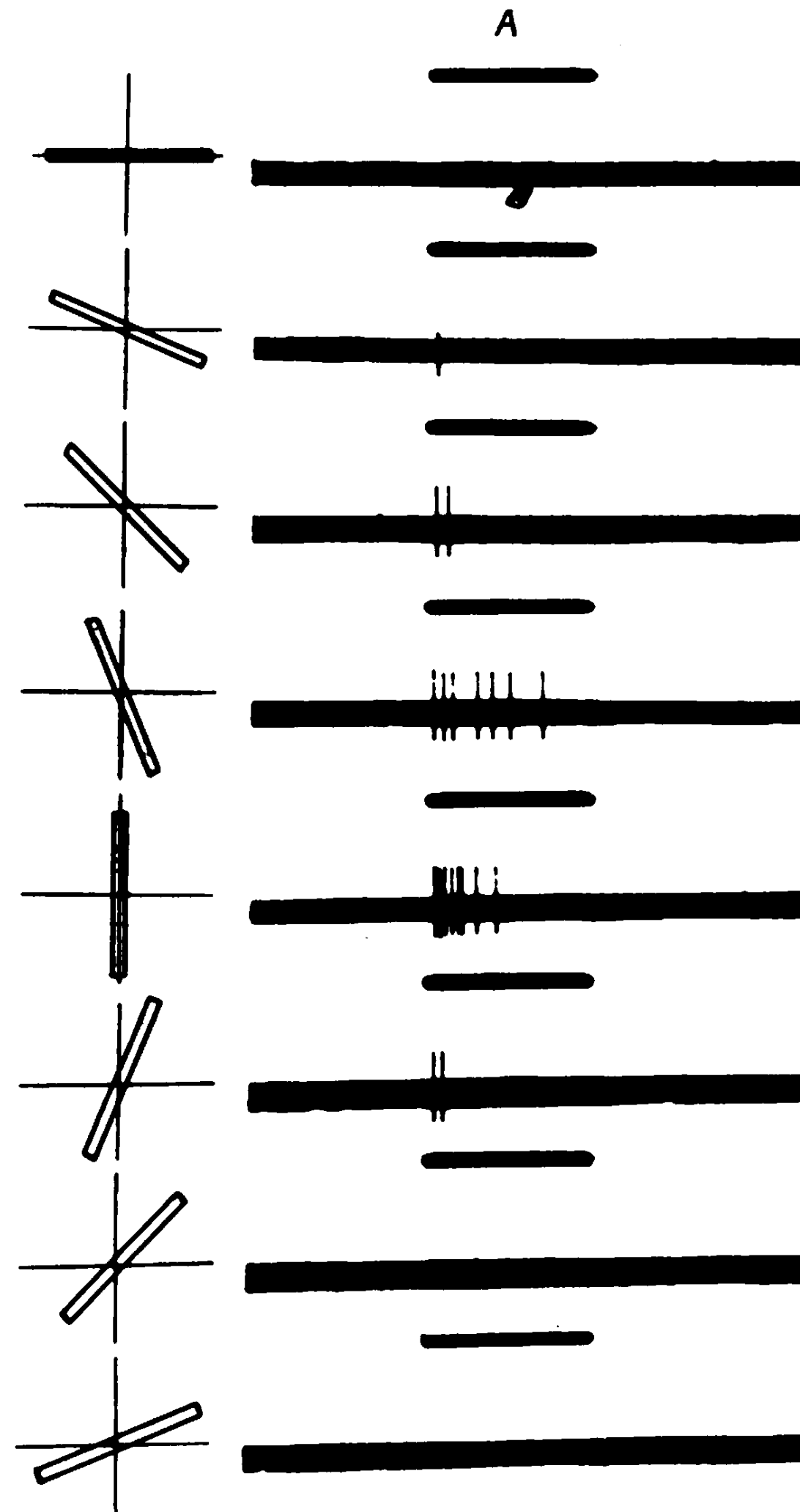
Architecture of Primary Visual Cortex (V1, Striate)

(A) Experimental setup

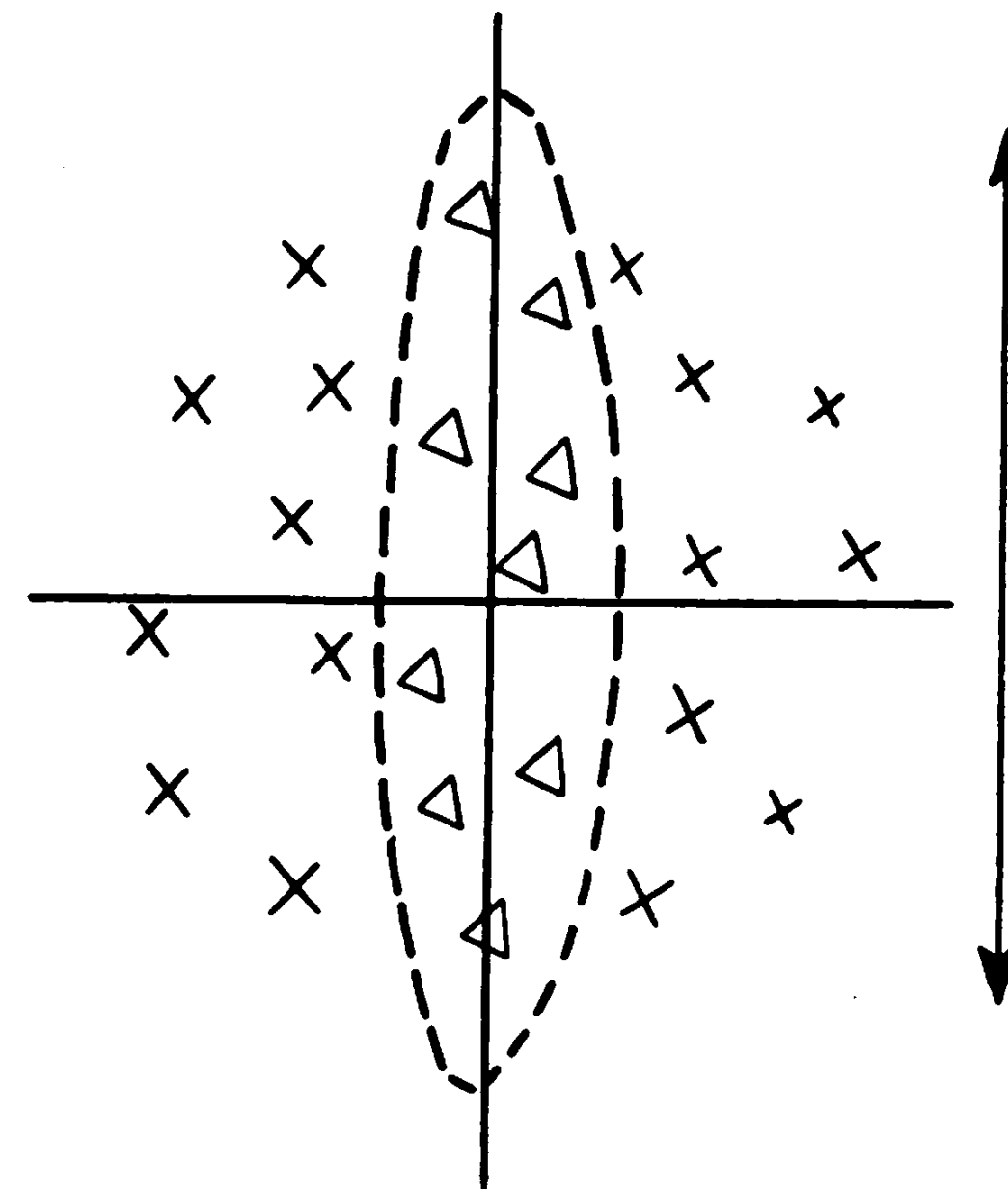
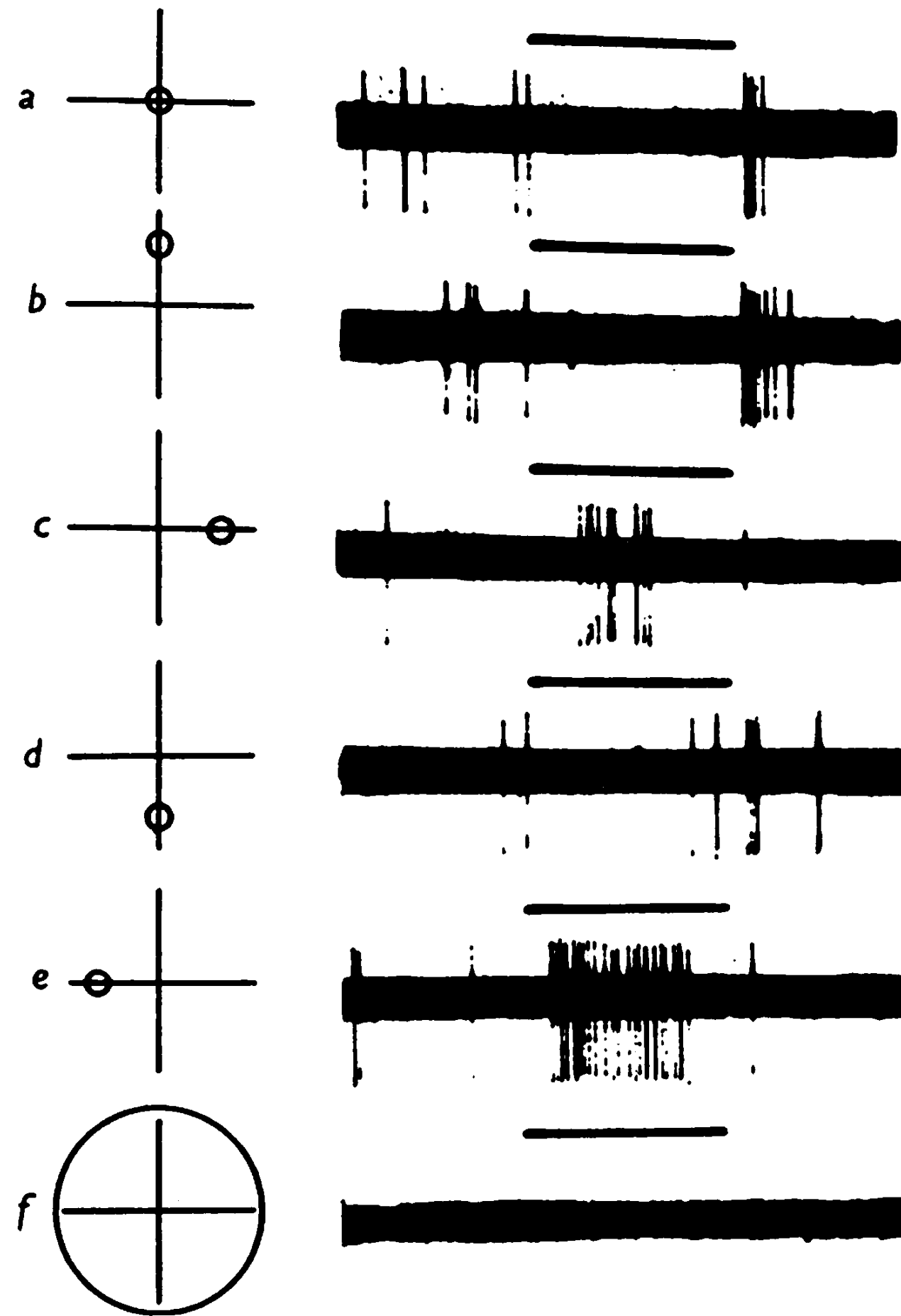


Hubel and Wiesel
(1981 Nobel Prize)

V1 "Simple Cells" Are Orientation Selective



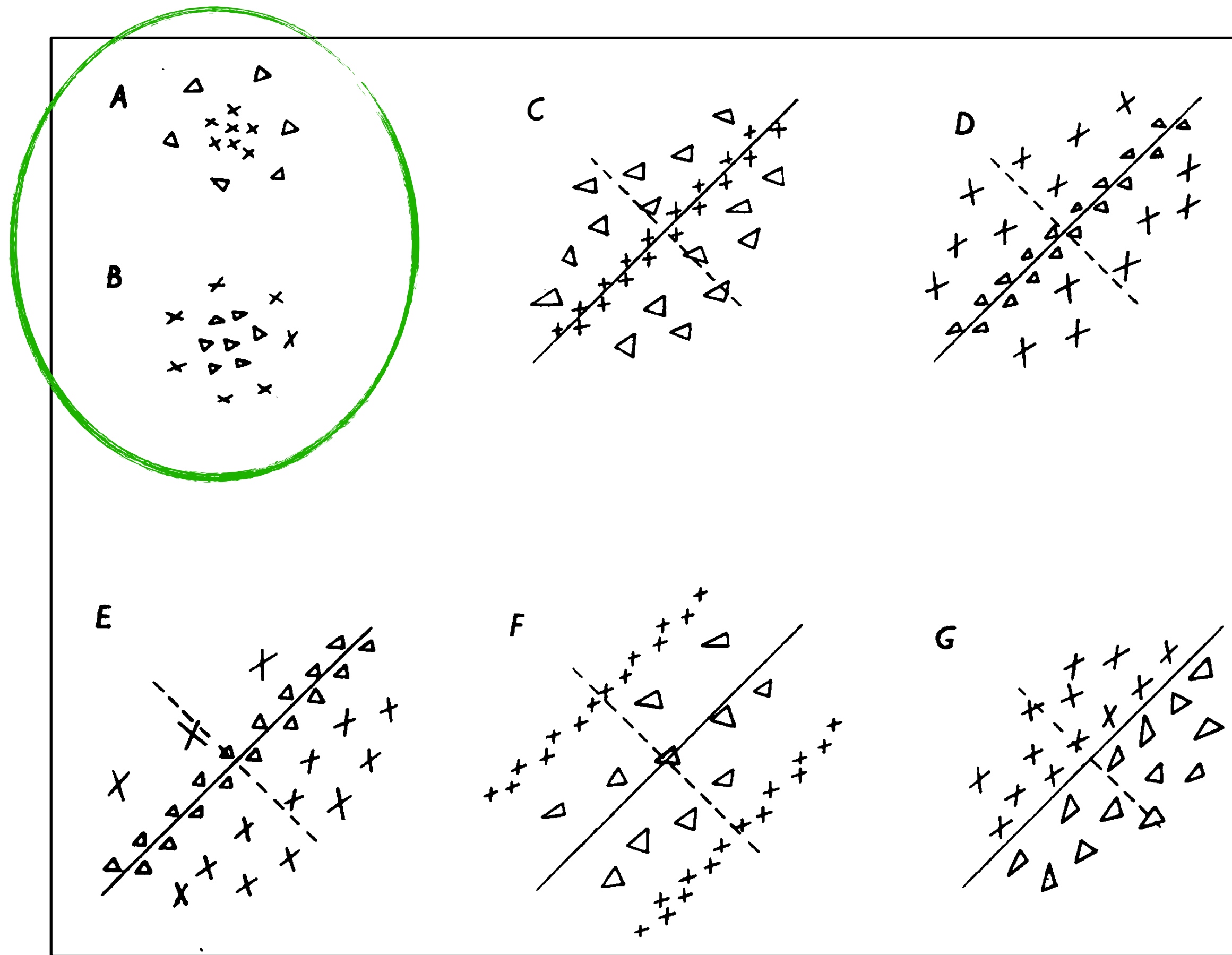
Their Receptive Fields are Oriented



- Use a spot light to probe the receptive field structure.
- Simple cells' receptive field is oriented.
 - In this case, an inhibitory central area and excitatory flanking areas.
 - There other other simple cells whose excitatory vs. inhibitory areas are oppositely organized.

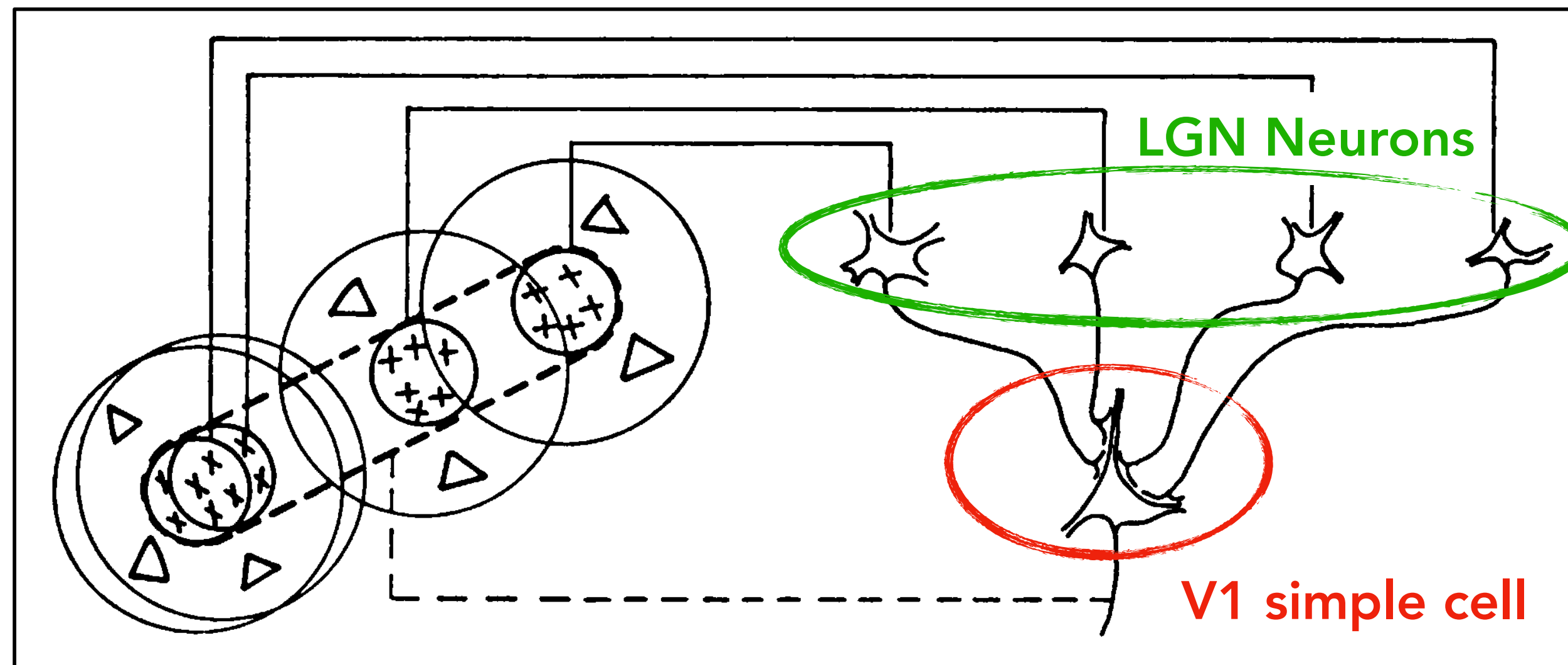
Typical Receptive Fields in V1 Simple Cells

RGC/LGN RFs



- C — G are typical RFs in simple cells; compare to A/B which are RGC/LGN neurons
- Their RFs have clear subdivisions between excitatory and inhibitory areas.
- Simple cells' responses to complex shapes can be predicted from their responses to spot lights.

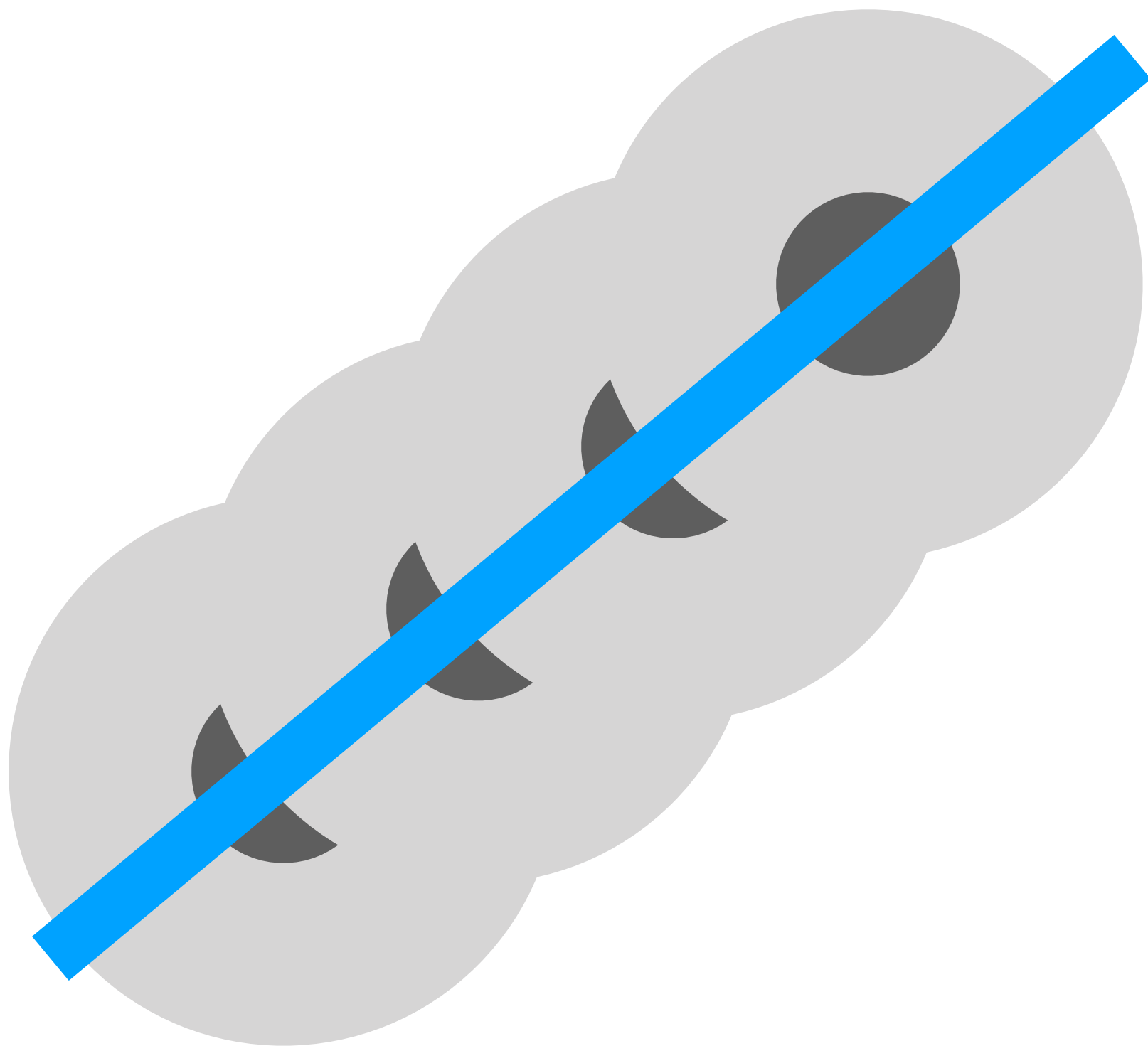
How Do They Acquire Their Oriented RFs?



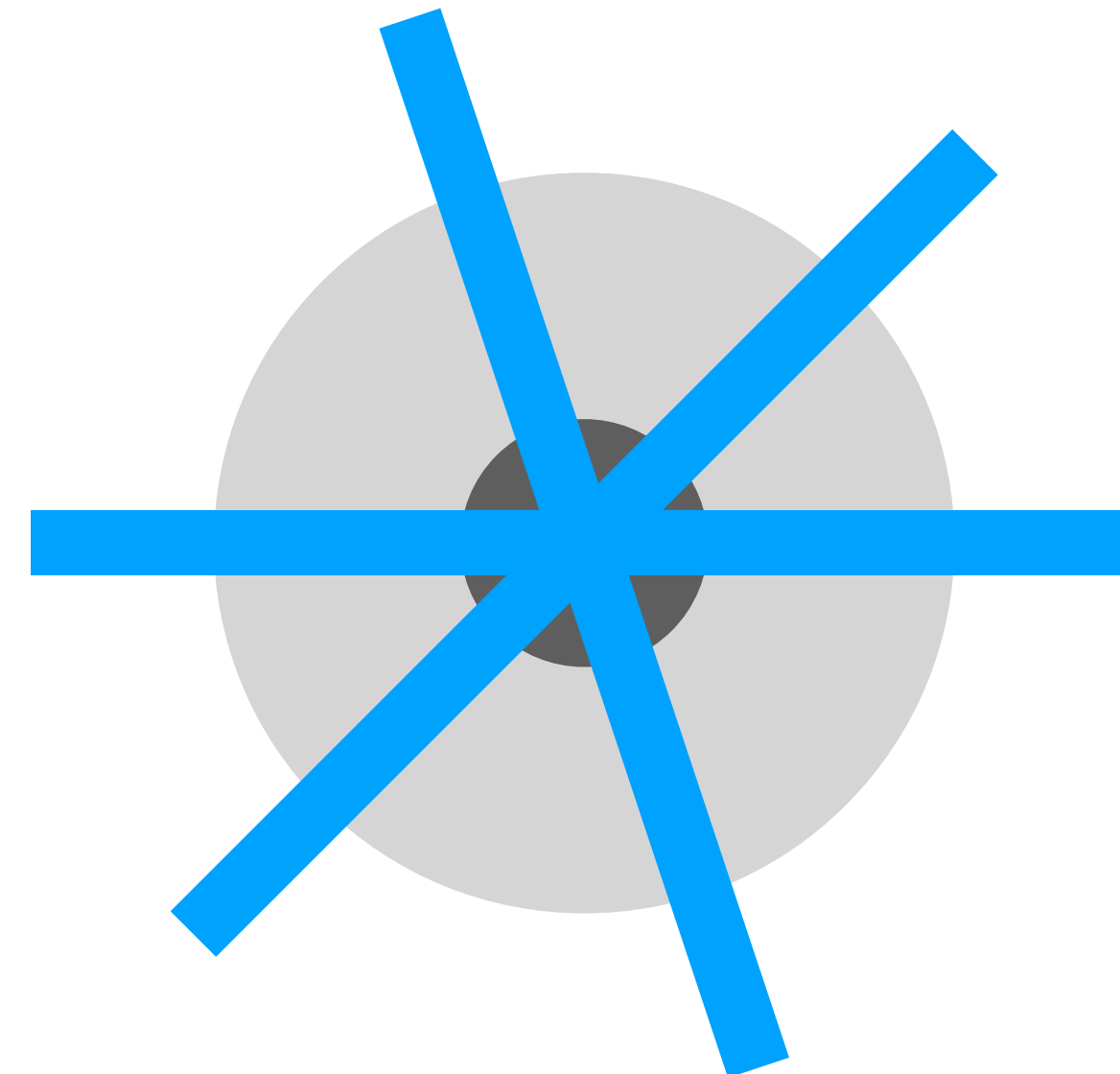
- LGN neurons have center-surround RFs.
- A V1 simple cell gets its information from LGN neurons whose RFs abut on retina.
- A simple linear superimposition of the center-surround RFs gives us an oriented RF.

Center-Surround Simply Can't Encode Orientation

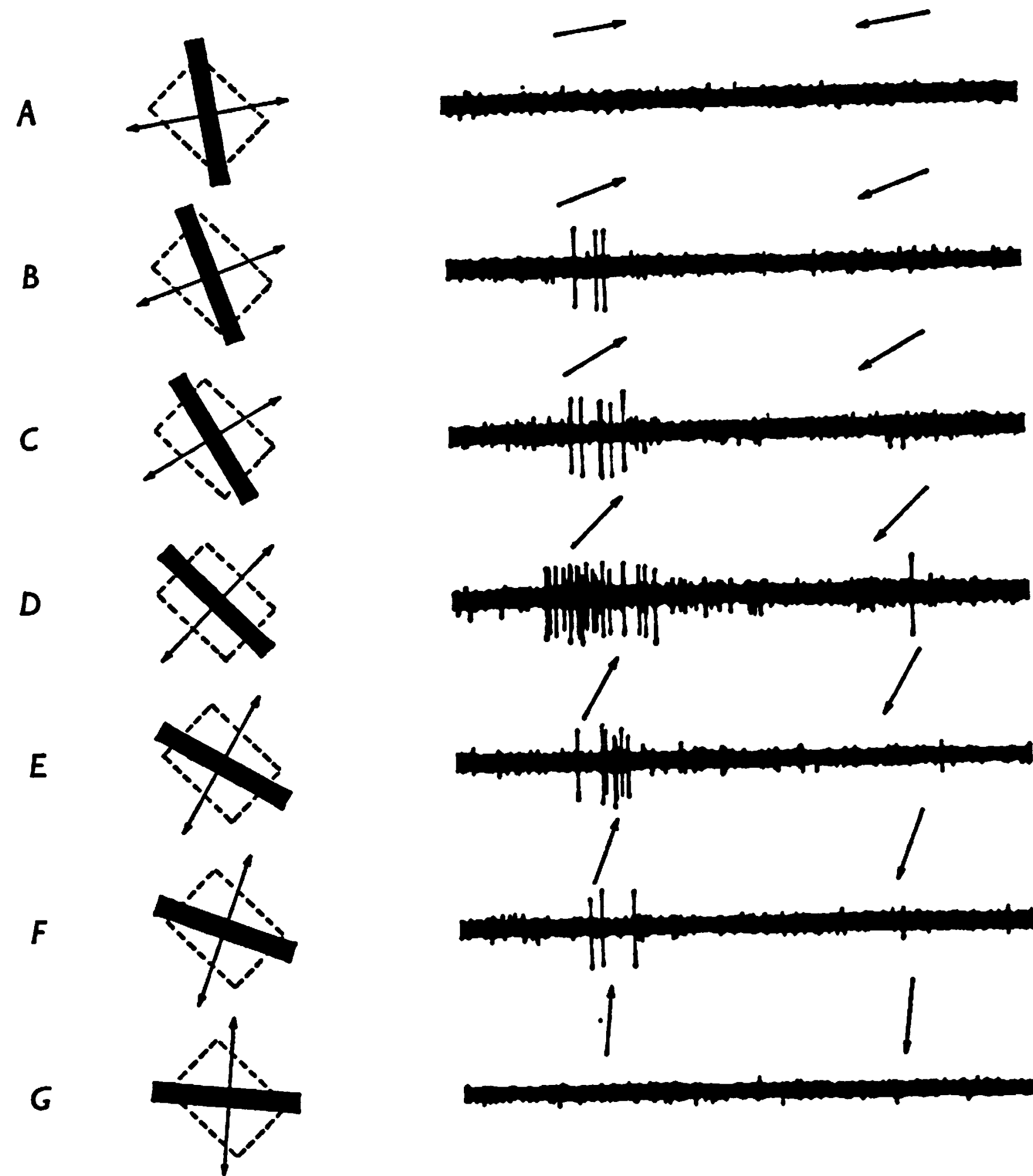
Oriented RF



Center-Surround RF

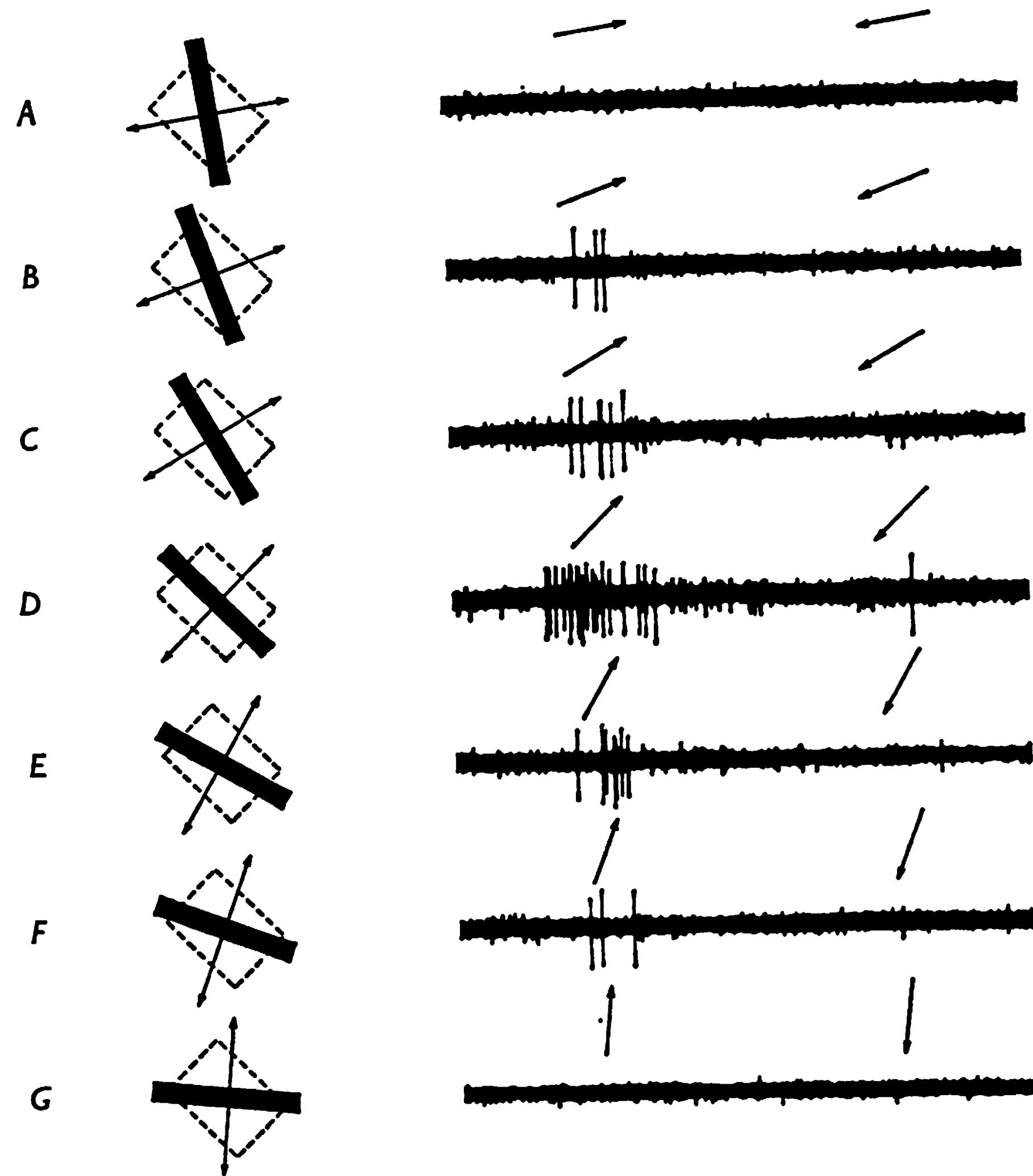


V1 Complex Cells are Sensitive to Motion



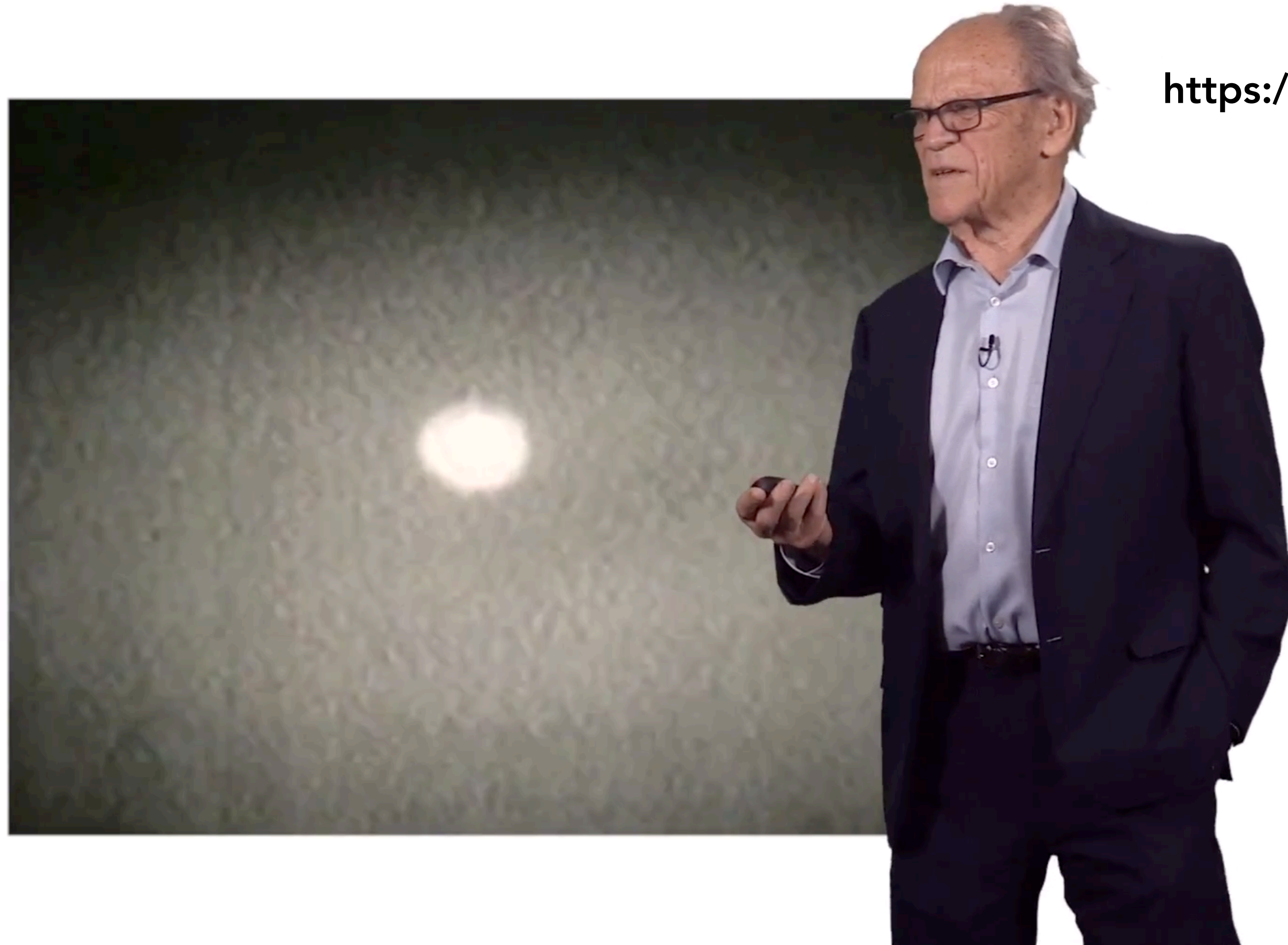
- They don't respond to spot light no matter where it is placed.
- This means the RFs in complex cells don't have a clear separation between ON and OFF areas.
- They respond when a slit of light sweeps across the RF when the slit is properly oriented

Some V1 Complex Cells are Direction Selective



- Many complex cells respond only when the movement is along a particular direction and don't at all when the movement is opposite.
- Assuming the edge is properly oriented of course.
- In this case, the neuron responds best to up-right motion but none to down-left motion

Hear from Wiesel Himself



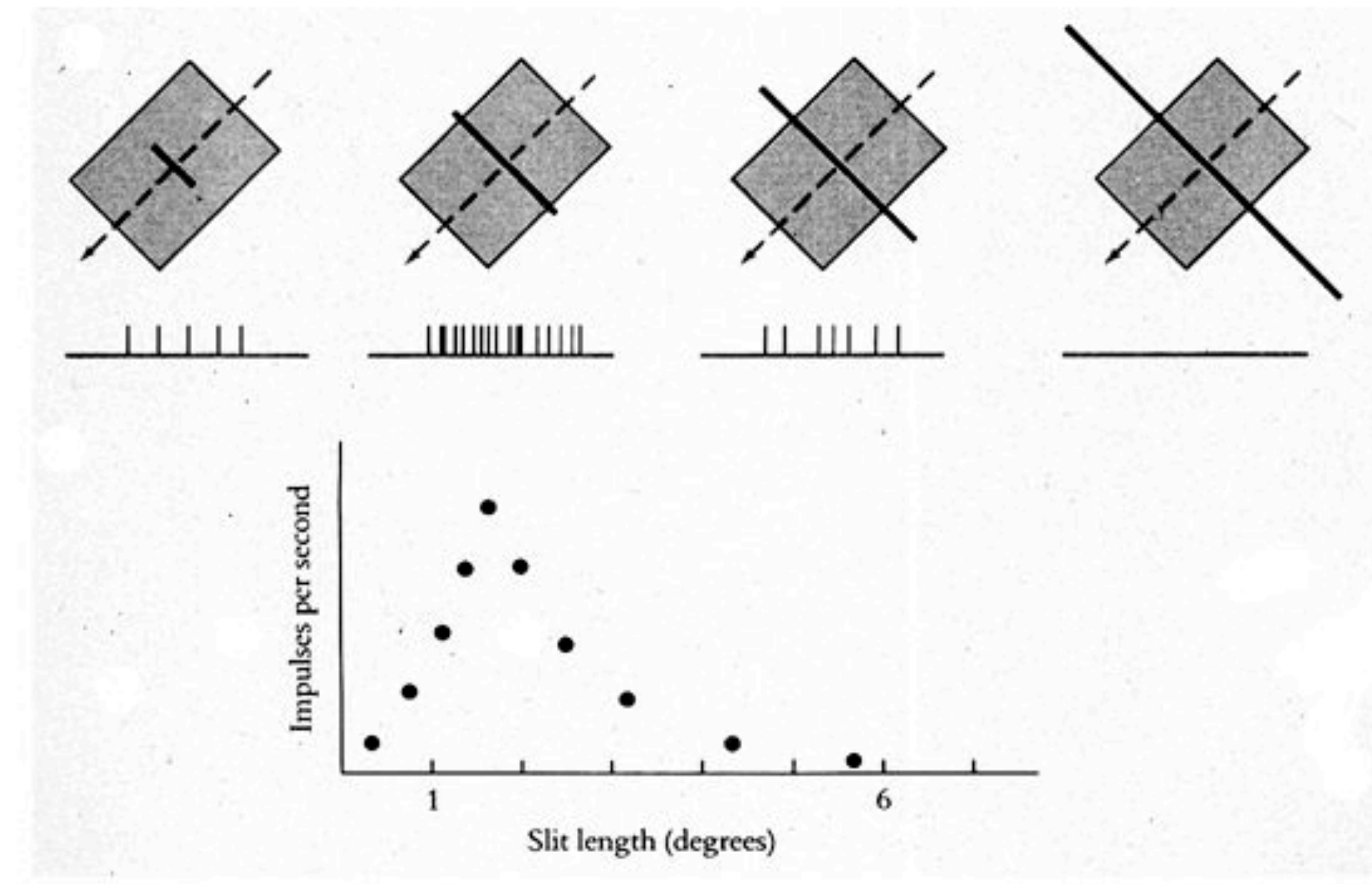
<https://www.youtube.com/watch?v=aqzWy-zALzY>

iBiology.org

Other V1 Selectivities

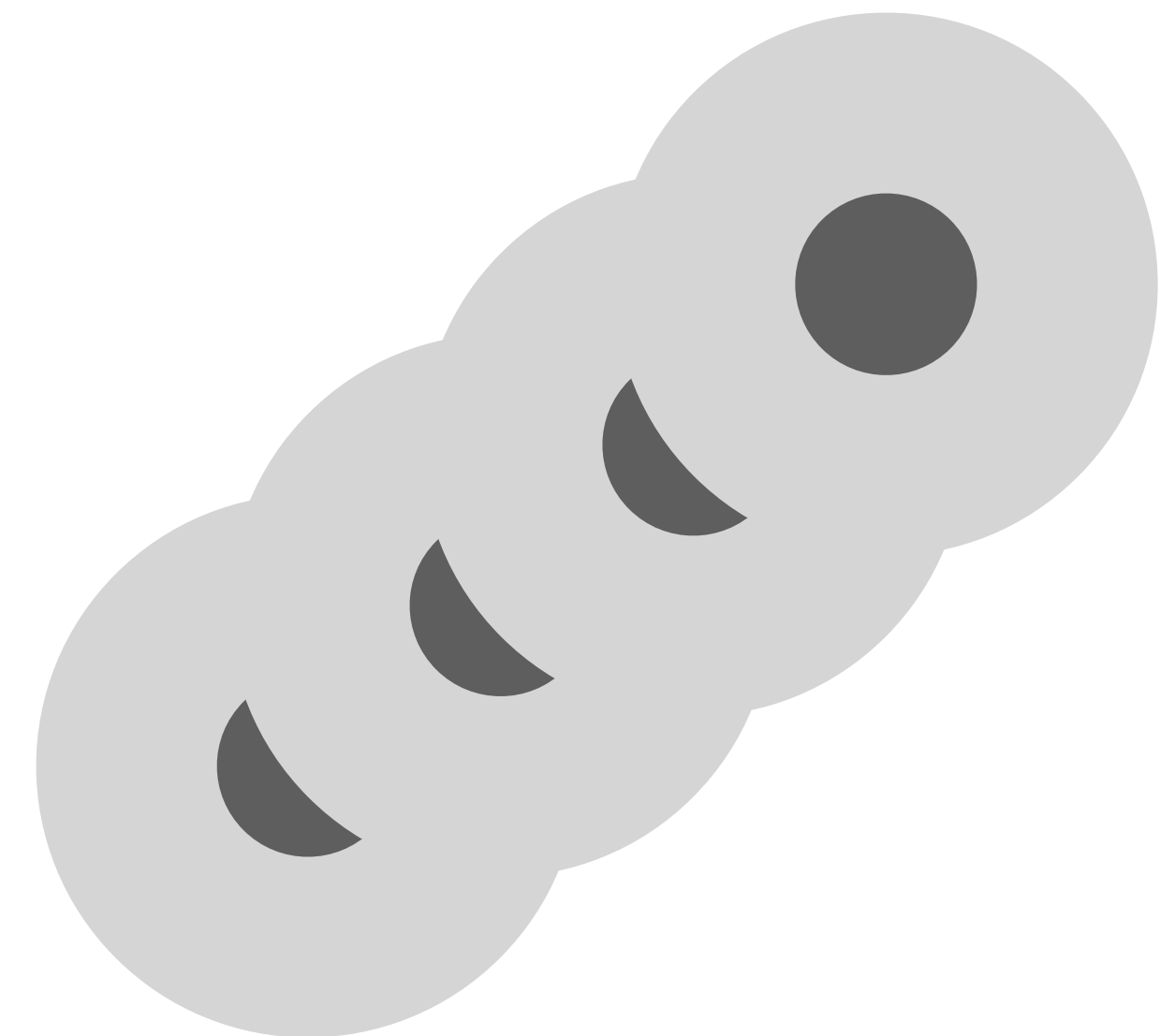
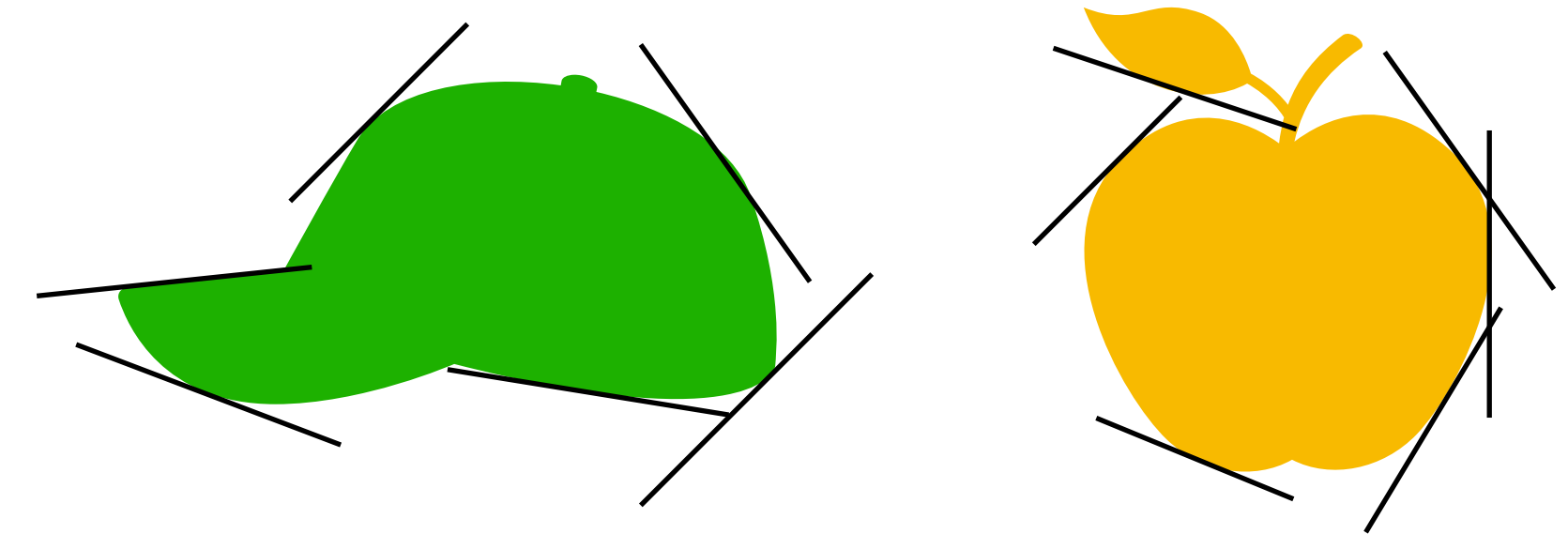
- Some V1 cells are selective to edge length
 - They are called end-stopping cells or hypercomplex cells
 - Useful for detecting corners, curvatures, line breaks, etc.

Hypercomplex cell



Comparing V1 vs. RGC/LGN

- RGC/LGN neurons extract contrasts and edges, and V1 neurons extract orientation, motion direction, etc.
- Information becomes more **specific** as signals progress along the visual pathway
 - We recognize objects by shapes, and we get shapes from orientations.
- Critically, V1 can extract orientation **precisely** because RGC/LGN neurons extract contrast!



Key Things to Take Away

- We can study HVS at different levels of abstraction
 - Psychophysics, neural networks, cellular/molecular physiology
- Spectral power distribution of lights
- Eye optics focus lights but also selectively absorb lights
- On the retina
 - Photoreceptors perform optical-to-electrical transduction
 - Rods vs. cones
 - Contrast detection and adaptation

Key Things to Take Away

- LGN gathers information from one hemi-field and sends it to the other side of the cortex.
 - Also receives feedbacks from the cortex to regular visual information sent to the cortex
- V1 extracts orientation, motion direction, etc., and is where binocular convergence takes places
- Other brain areas are specialized to different functions (simplification)
- Two main pathways in the cortex: dorsal vs. ventral