Lecture 5: Human Visual System: An Overview

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CSC 259/459, Fall 2024
Computer Imaging & Graphics

Logistics

Written assignment 2 is up and is due Sept. 18 11:30 AM.

- Can work in groups of 2.

Project proposal due 10/16 11:30 AM.

- I've put up a list of ideas. In the past, many choose to implement some concepts discussed in the class.
- Can work in groups of 2.

Will release the first programming assignment later this week.

A collaborator seeking students interested in working on computational photography composition; see blackboard announcement.

The Roadmap

Theoretical Preliminaries

Human Visual Systems

Color in Nature, Arts, & Tech
(a.k.a., the birth, life, and death of light)

Digital Camera Imaging

Modeling and Rendering

Applications

Introduction and Overview

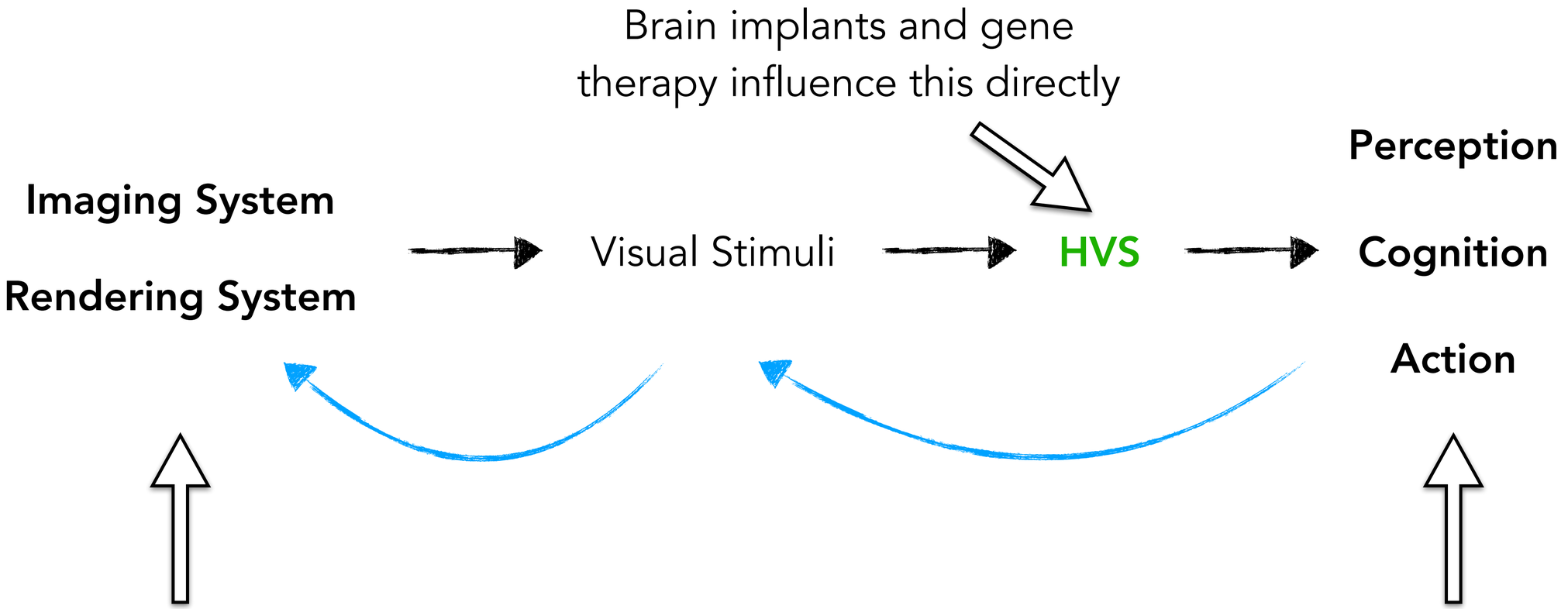
Photoreceptors

The Rest of the Retina

Light and Dark Adaptation

Color Vision and Colorimetry

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



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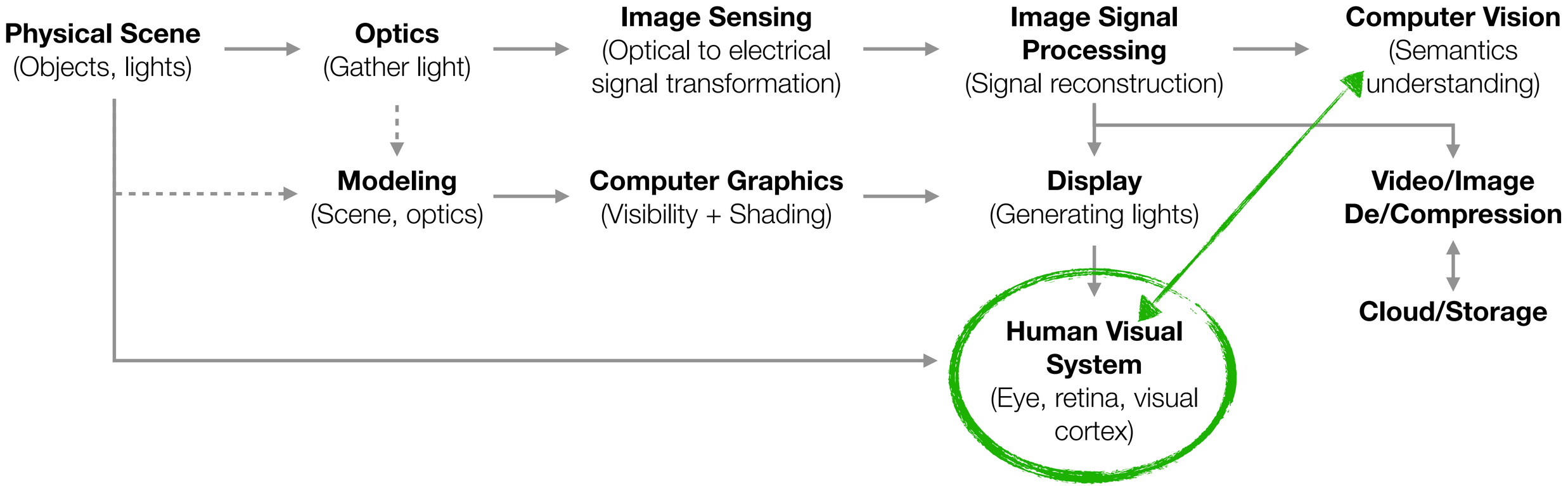
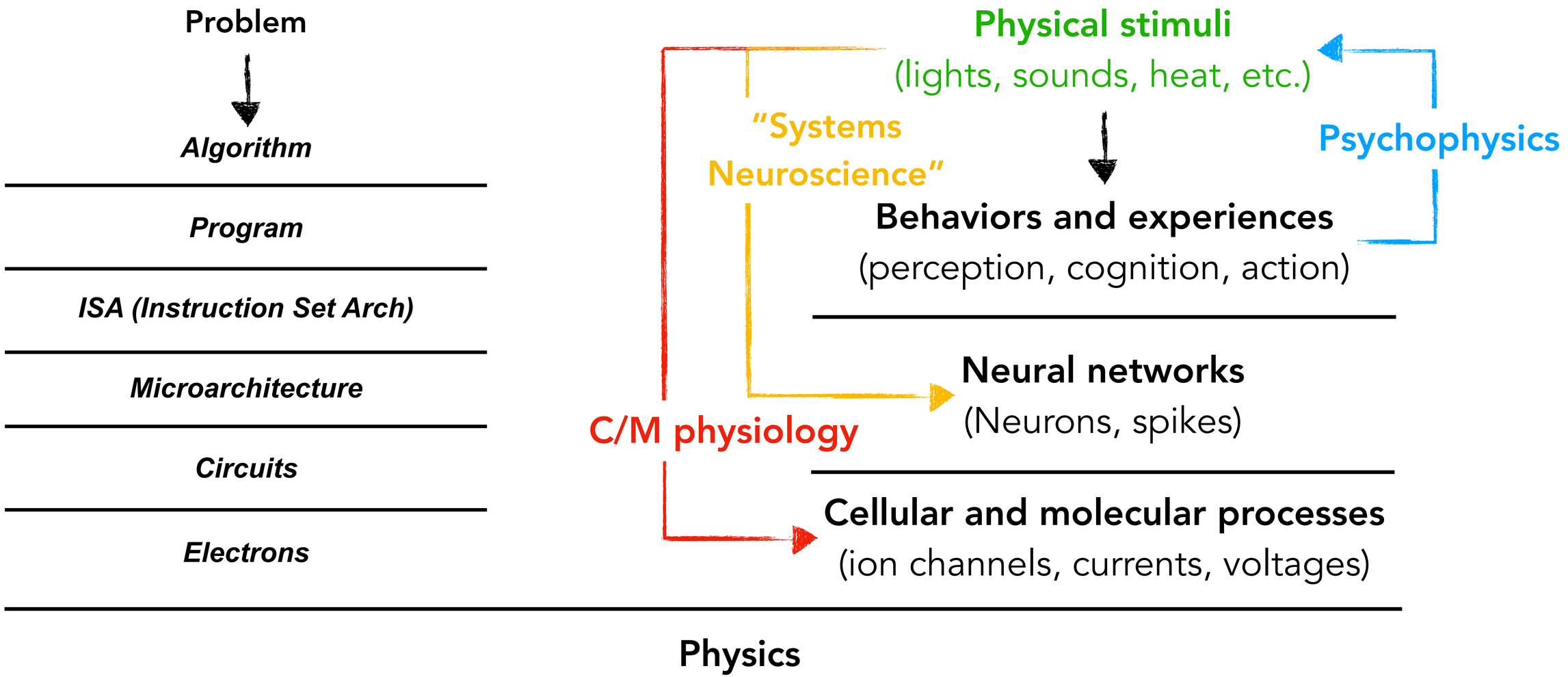
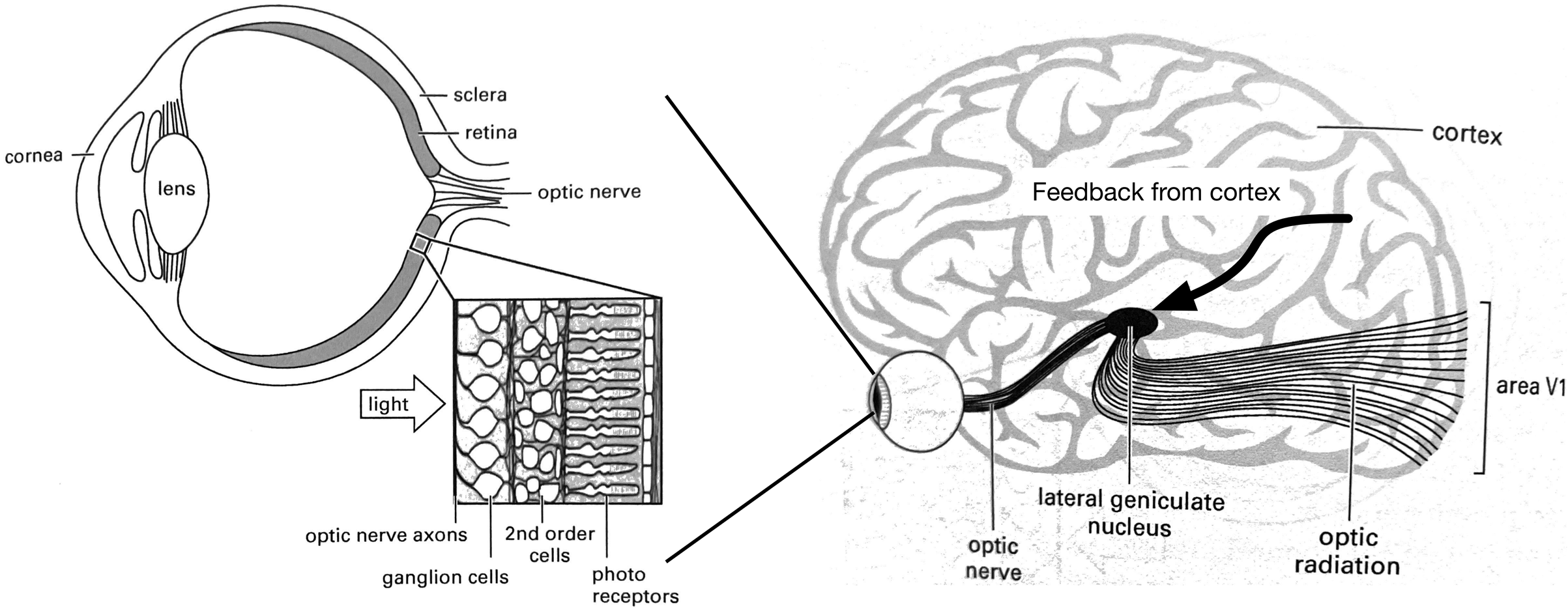


The Big Picture

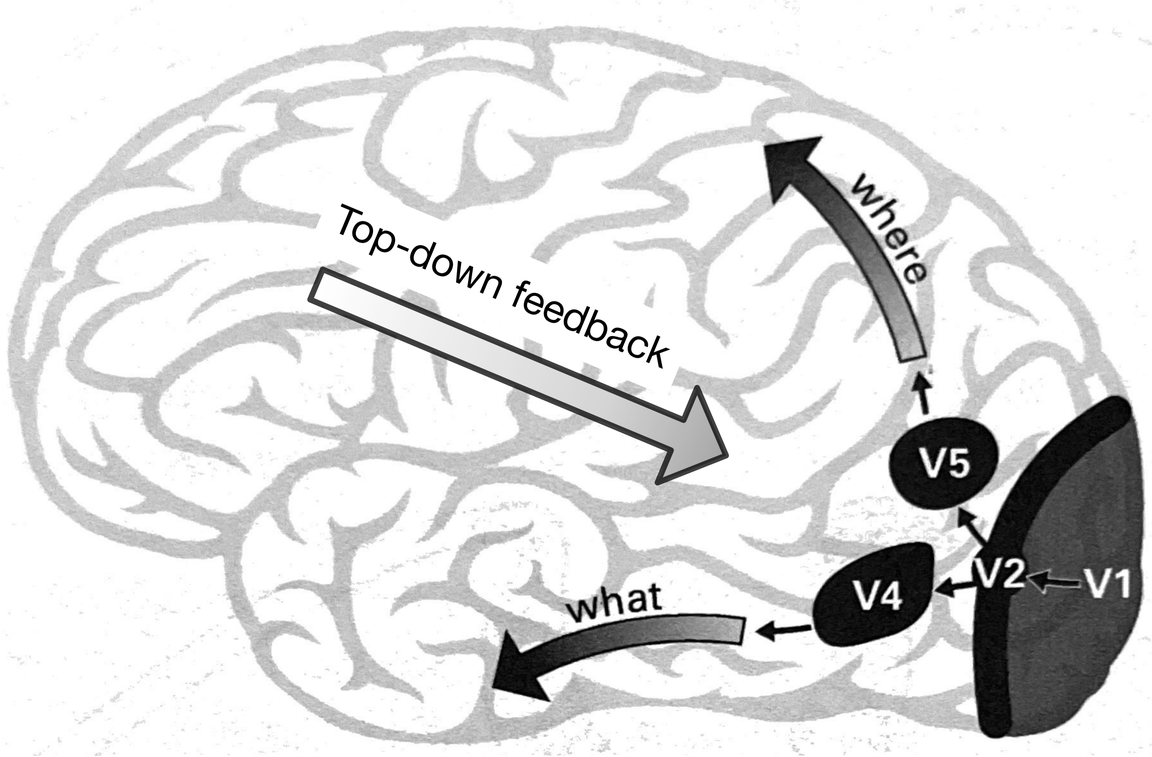
Levels of Abstraction

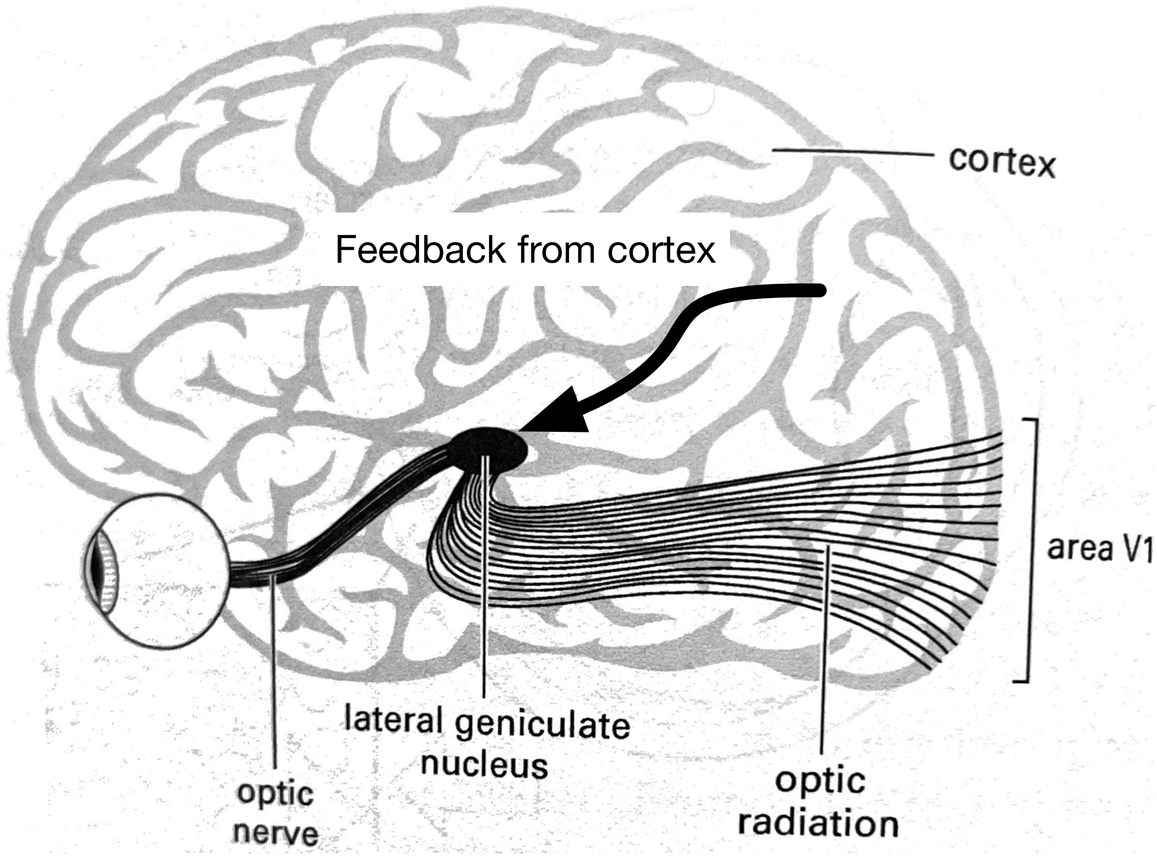


Retino-Geniculo-Cortical Pathway



Once in the Cortex





Spectral Power Distribution of Lights

Light

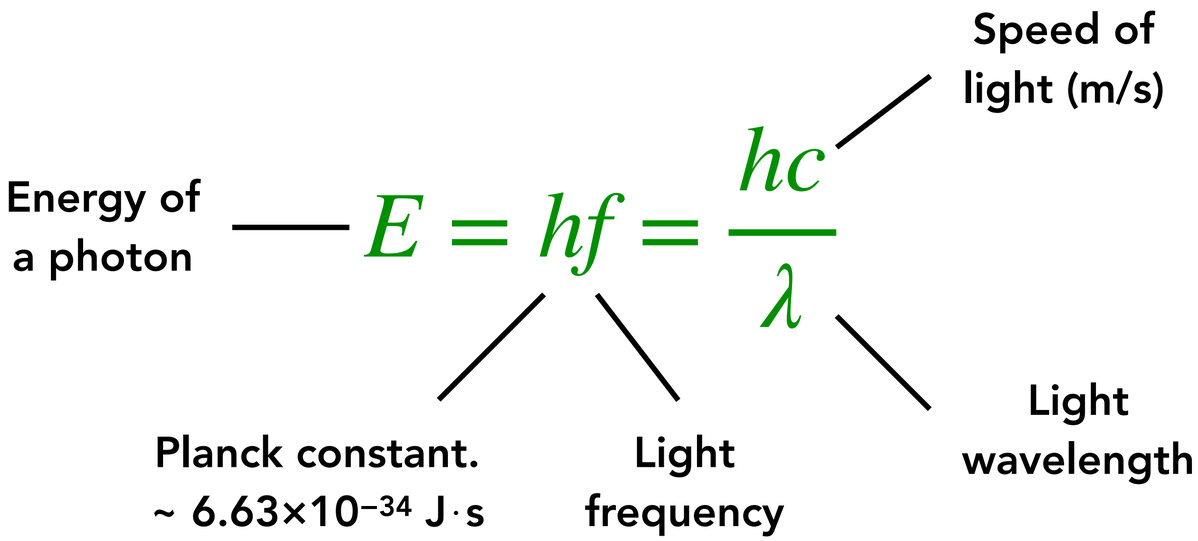
For the purpose of understanding color, we consider light as photons.

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

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

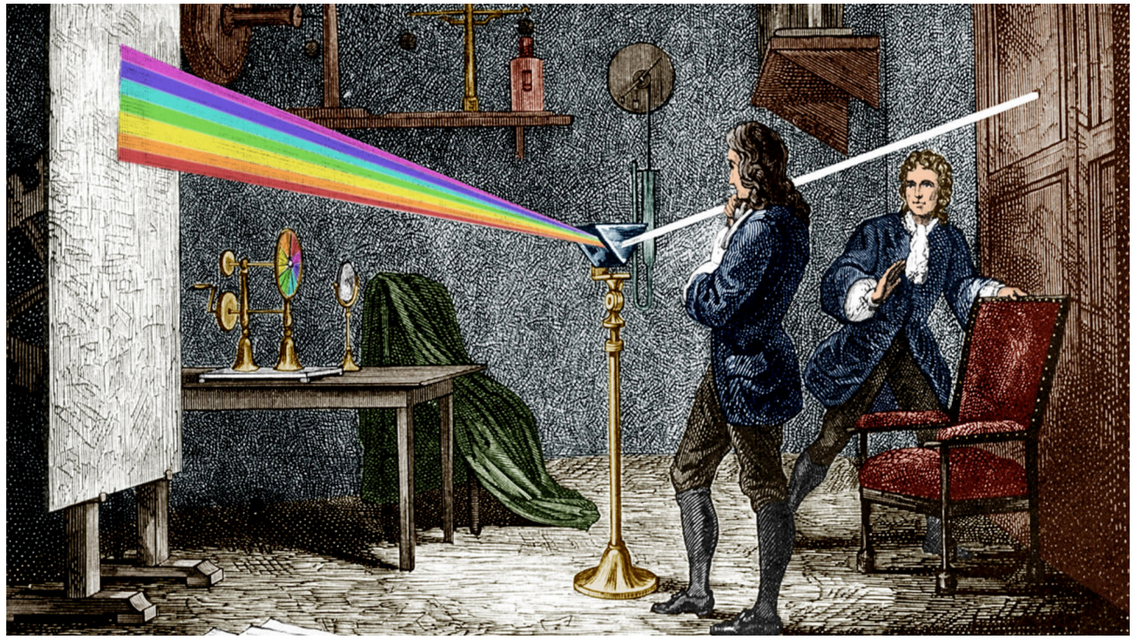
Energy of a λ = 500 nm photon: ~4 x 10^{-34} J

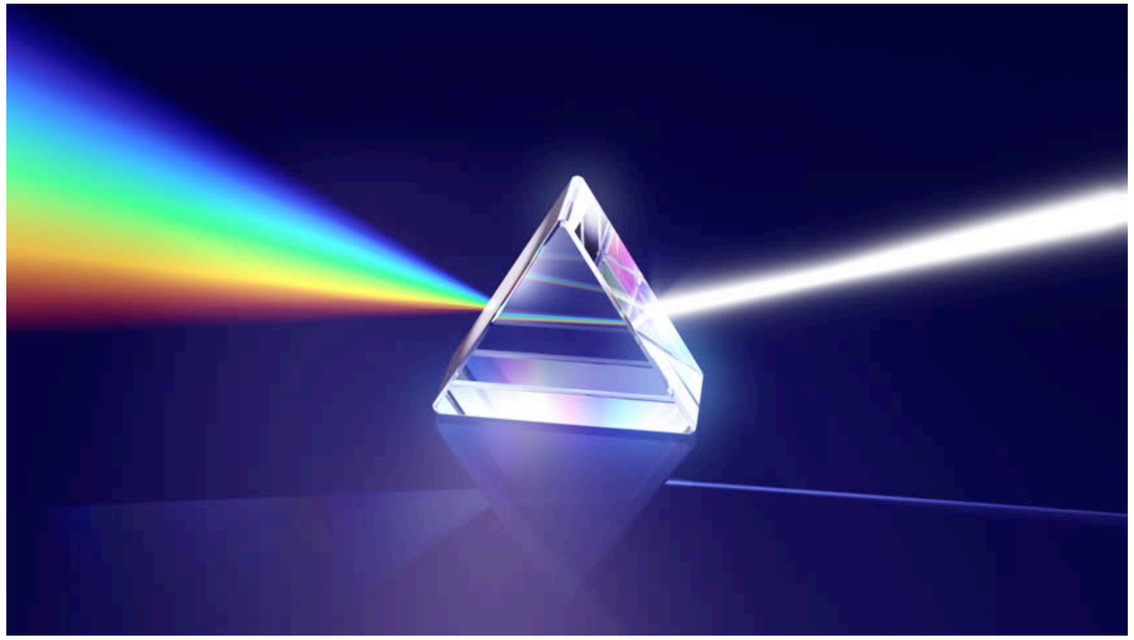
Energy of a λ = 750 nm photon: ~2.7 x 10^{-34} J



Light Spectrum

Most light sources mix photons of different wavelengths.

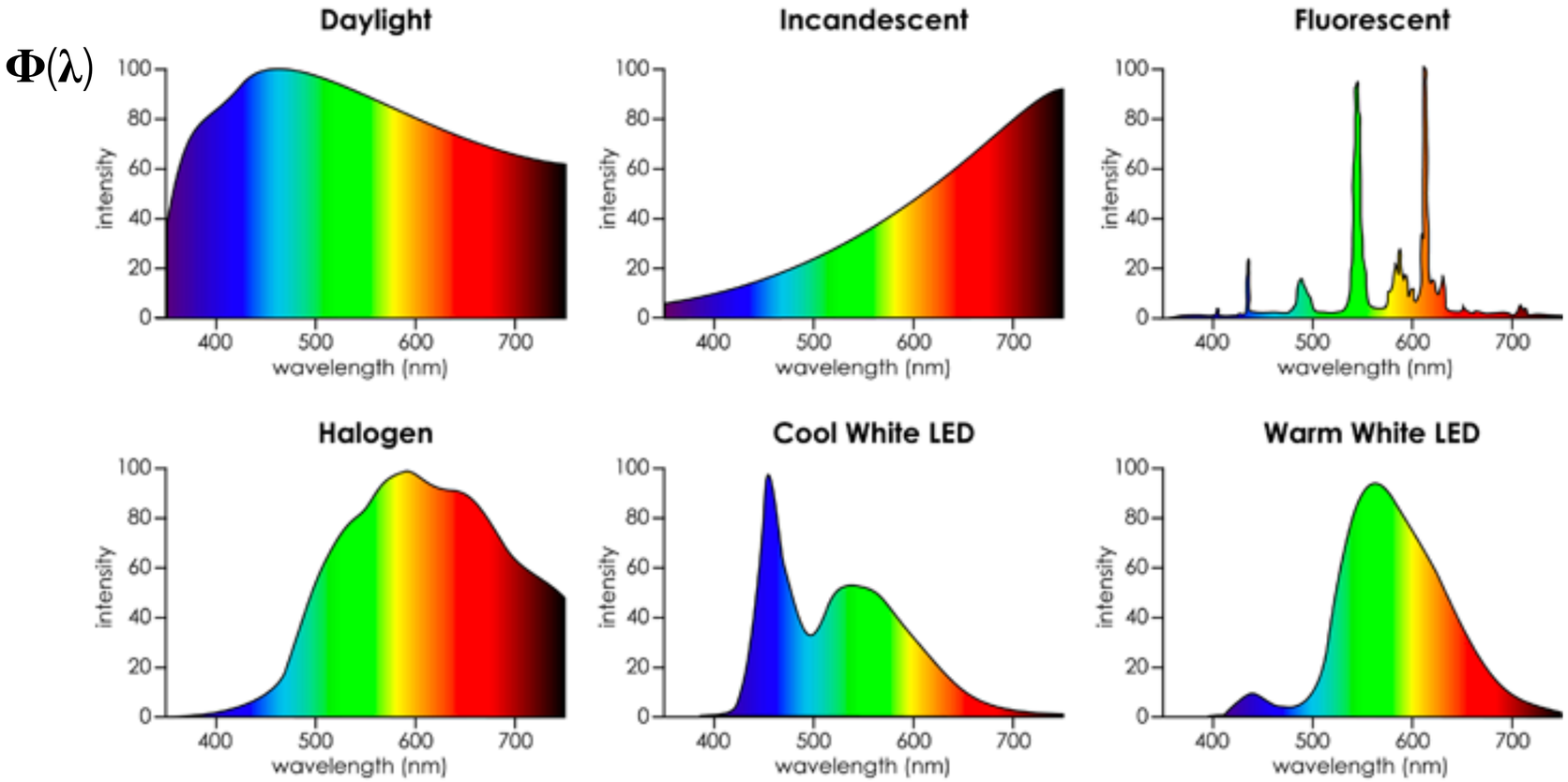




https://waldina.com/2020/01/04/happy-377th-birthday-isaac-newton/ https://www.shutterstock.com/video/clip-369937-prism---light-dispersion-seamless-loop-hd1080p

Spectral Power Distribution

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

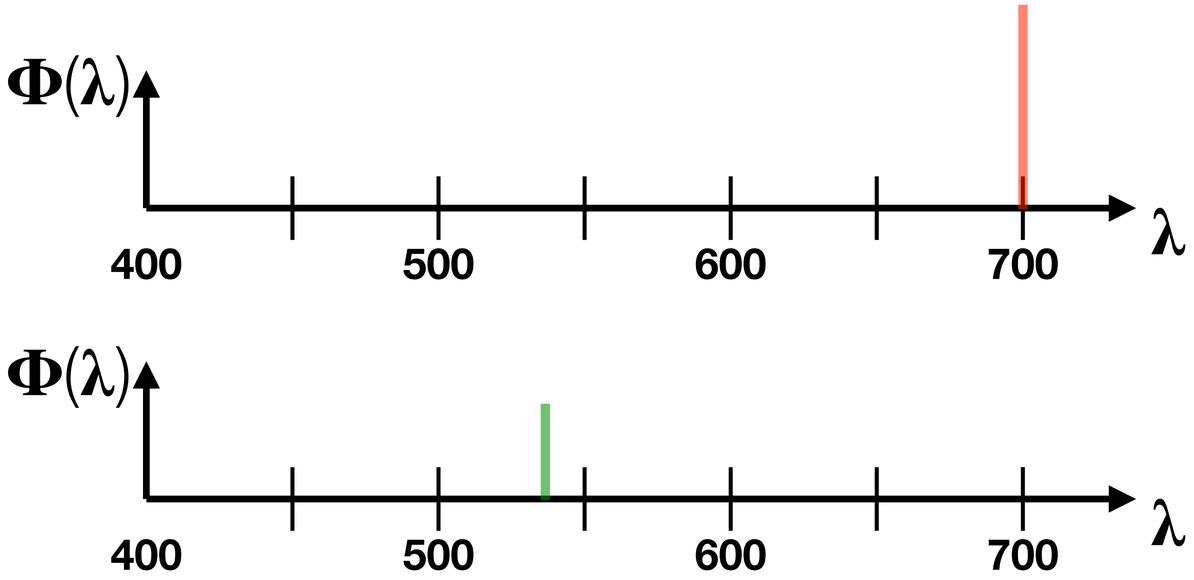


https://www.quora.com/Is-there-a-difference-between-sun-rays-and-normal-bulb-light

Spectral Light

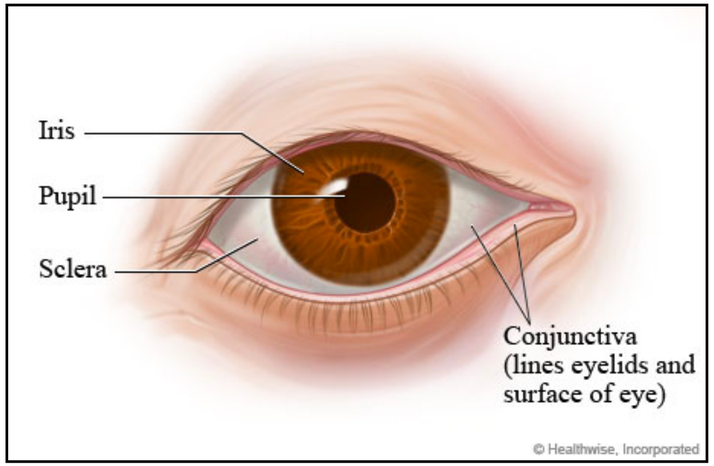
Single-wavelength (monochromatic) light are called **spectral light**.

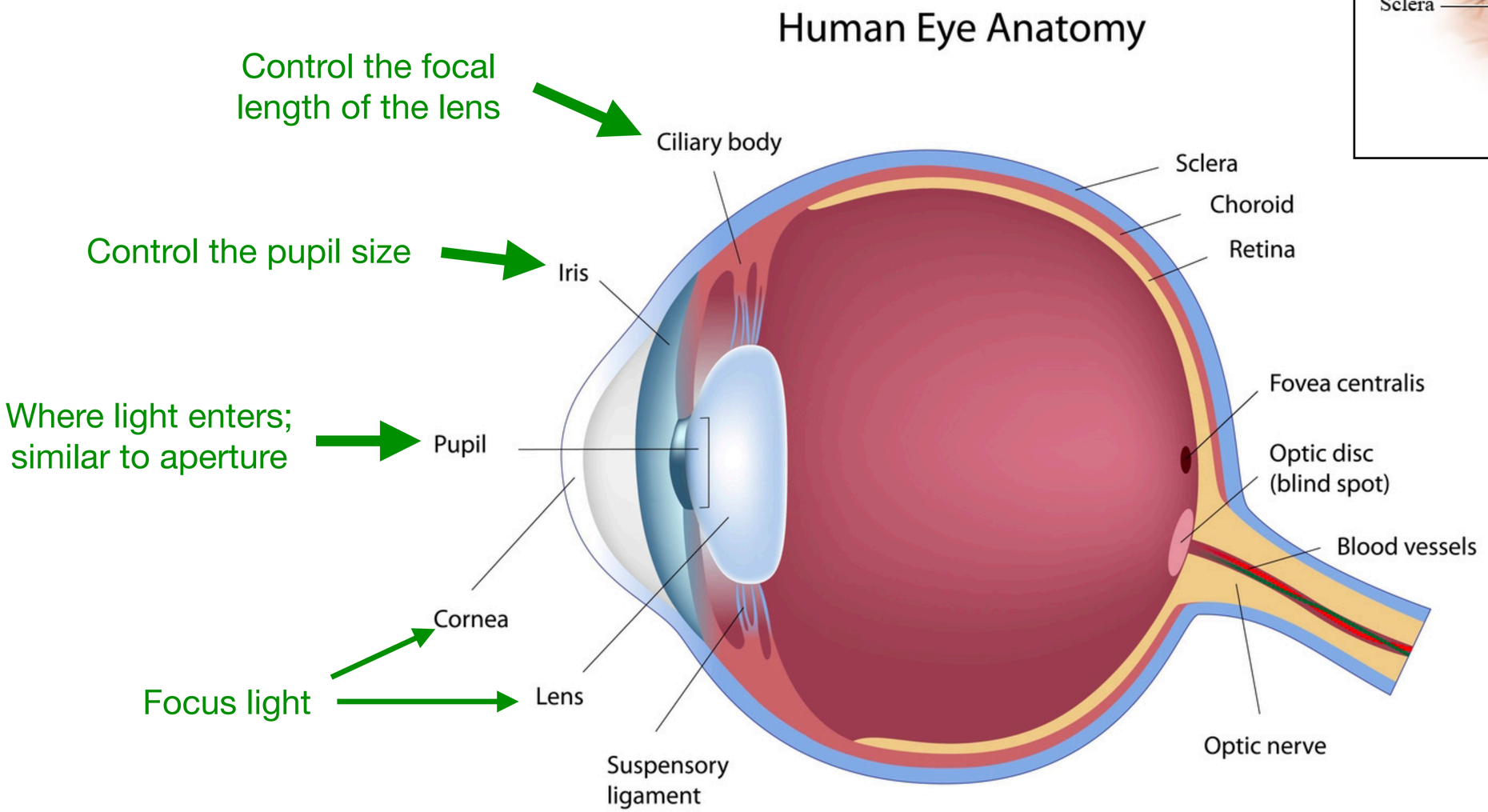
- SPDs of spectral lights are very narrow spikes.
- Few natural lights are spectral lights. Lasers can generate spectral lights.
- Mixing spectral lights to produce arbitrary lights



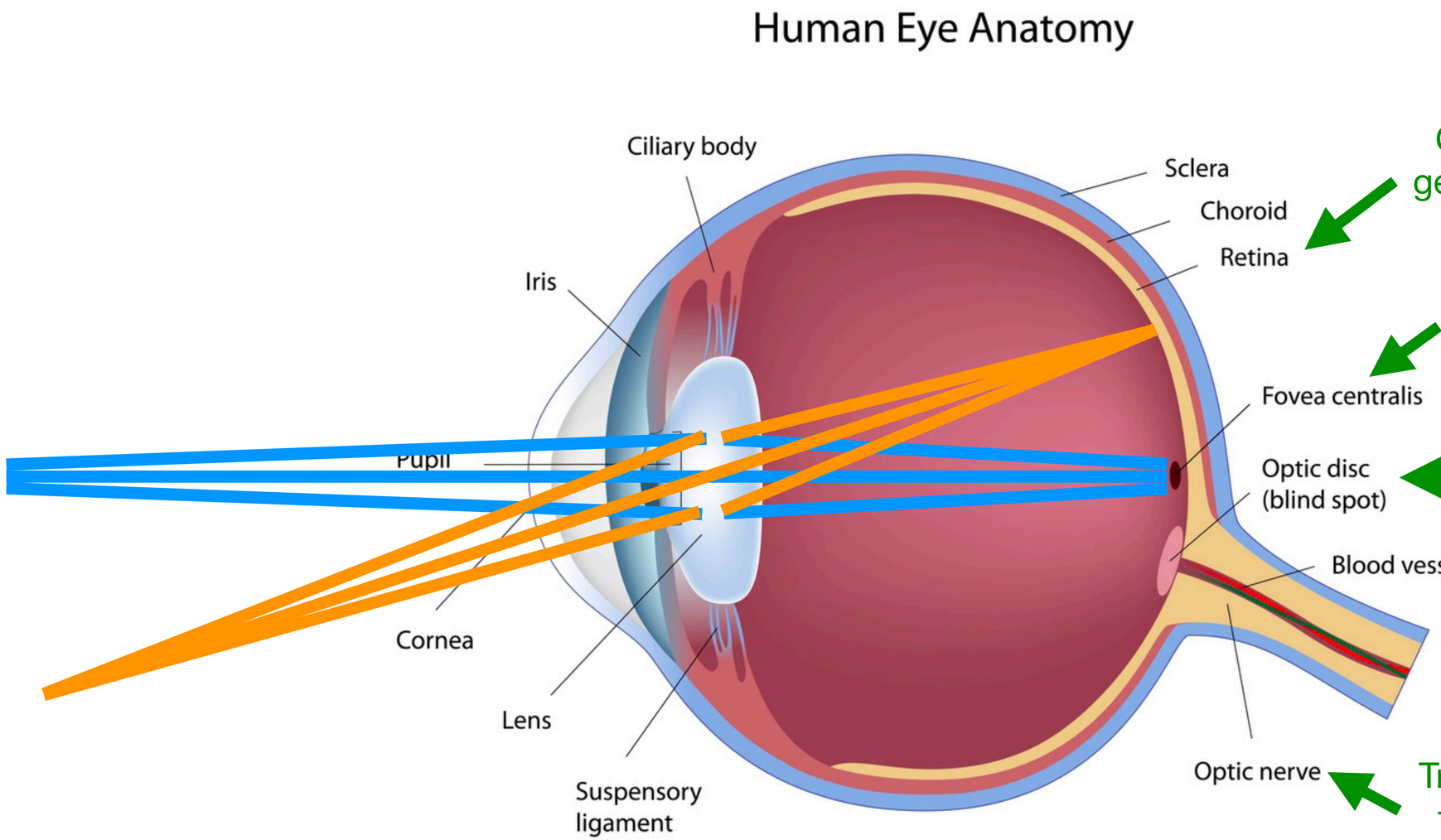
The Eye

Human Eye Anatomy





Human Eye Anatomy



Contains **photoreceptors**, which generate electrical signals from light

Highest cone density and thus highest visual acuity

Free of photoreceptors

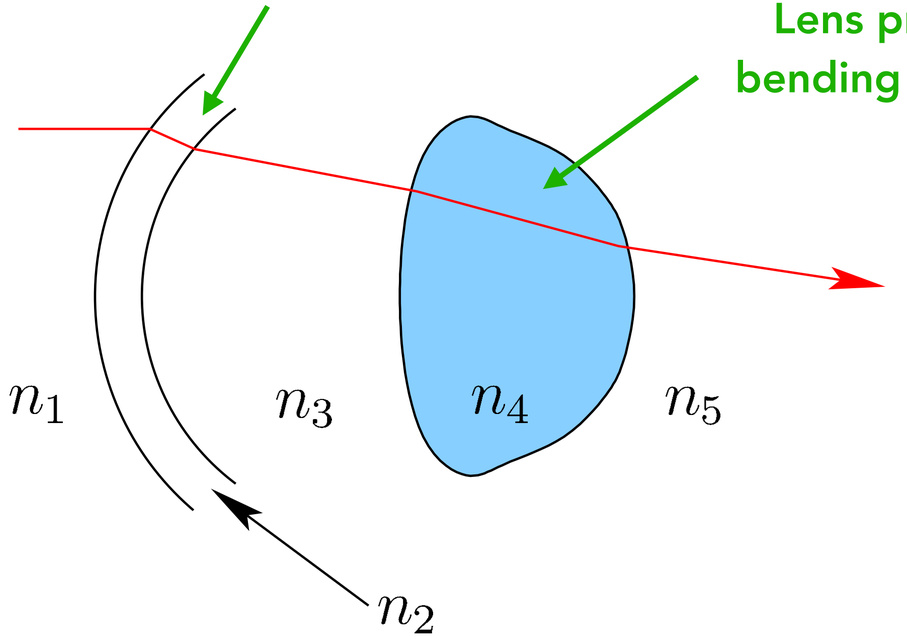
Transports electrical signals to the rest of the visual system

https://garetina.com/patient-education/about-the-eye/

Eye Optics Focuses Lights

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

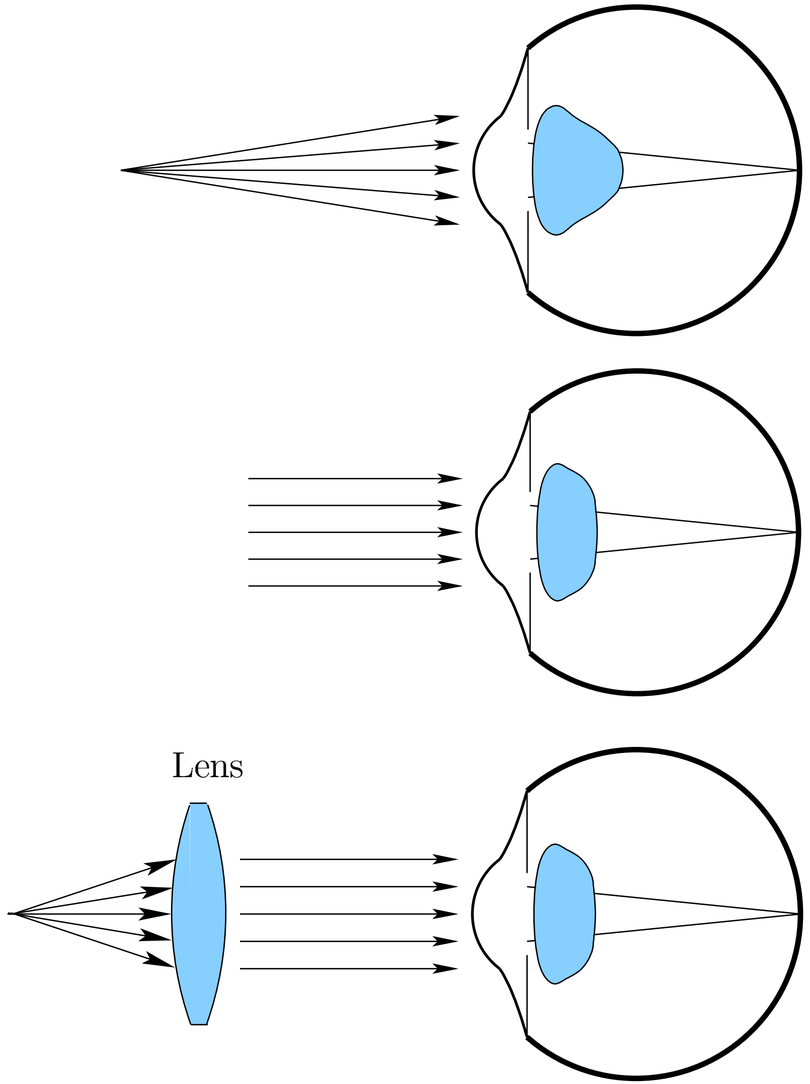
Lens provides the remaining bending power and is malleable

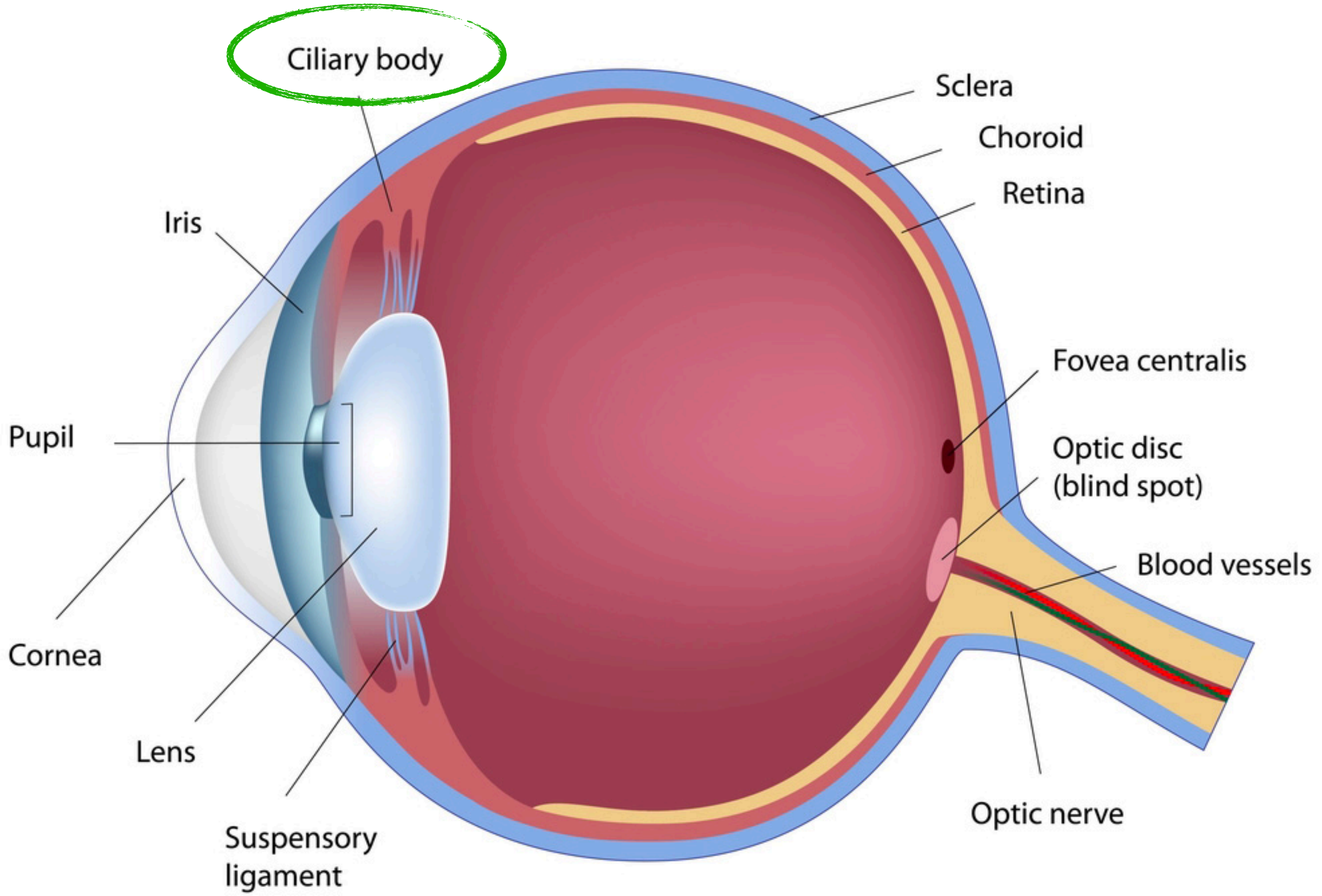


1. $n_1 = 1.009$ (air)
2. $n_2 = 1.376$ (cornea)
3. $n_3 = 1.336$ (aqueous fluid)
4. $n_4 = 1.413$ (lens)
5. $n_5 = 1.337$ (vitreous fluid)

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

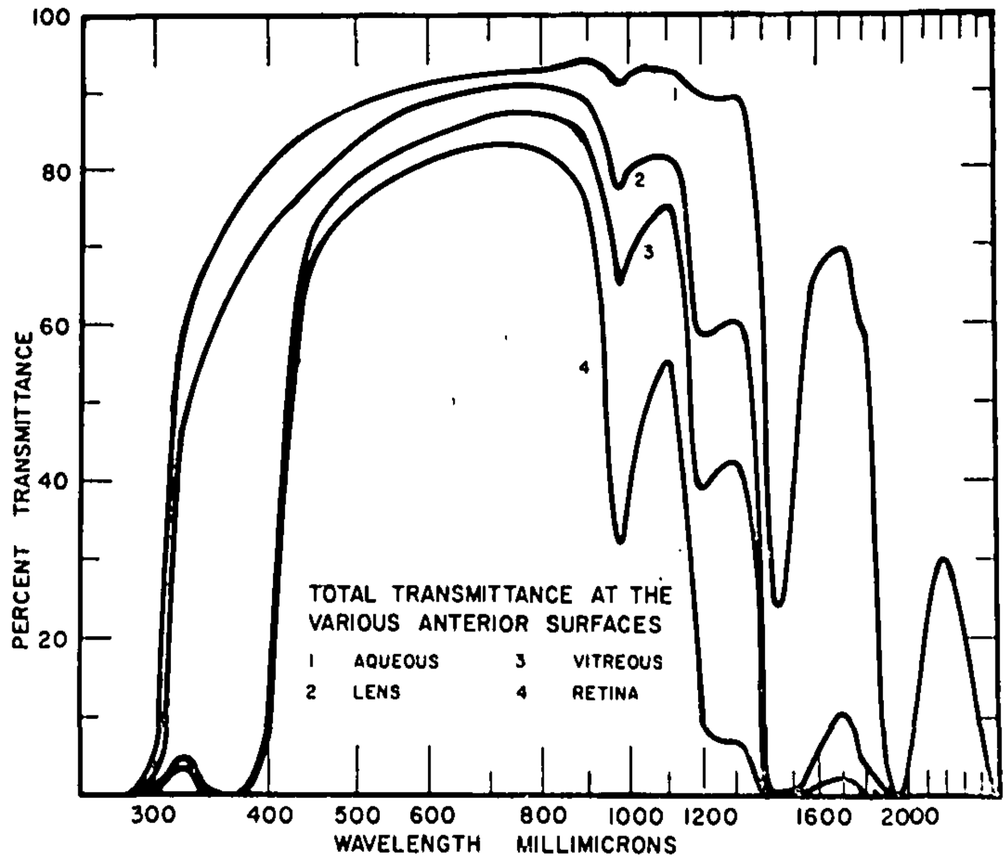


Fig. 7. Total transmittance through entire eye.

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

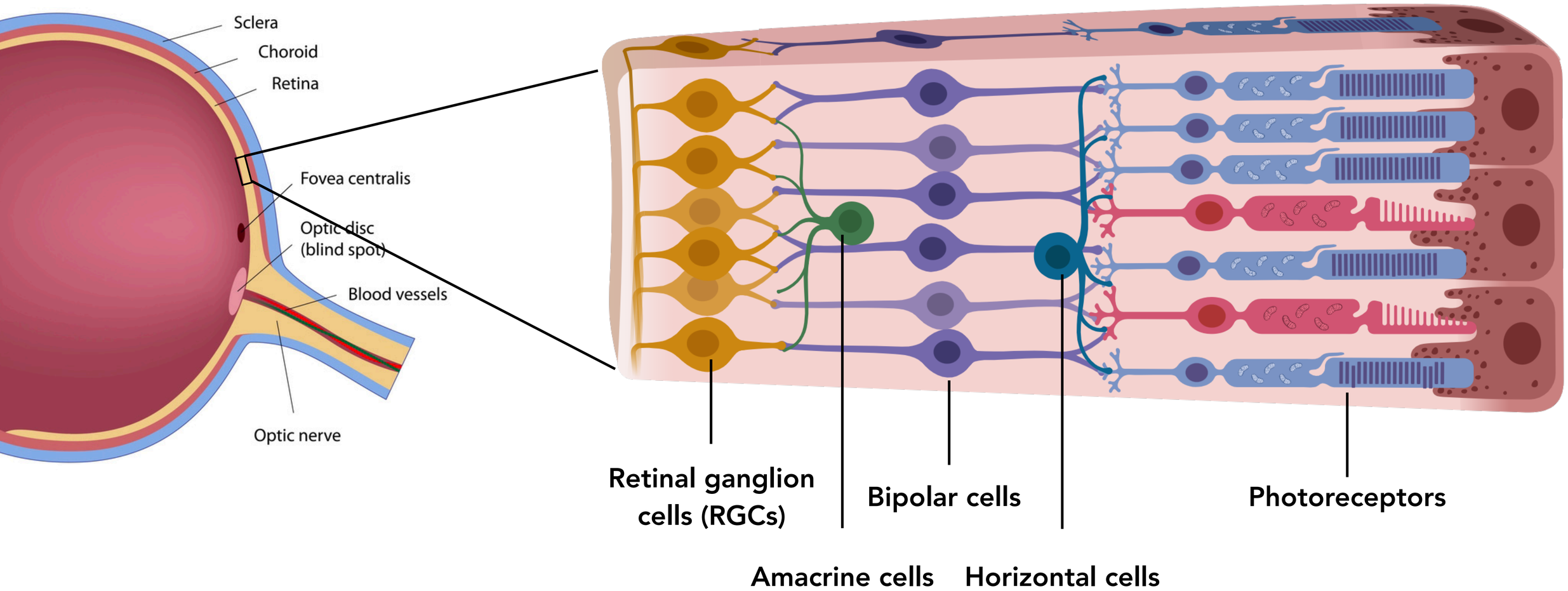
- Results at the retina show the total amount of lights left after ocular absorption.
- This includes both direct transmission and forward scattering.
- 380 nm — 780 nm is “visible range”.

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

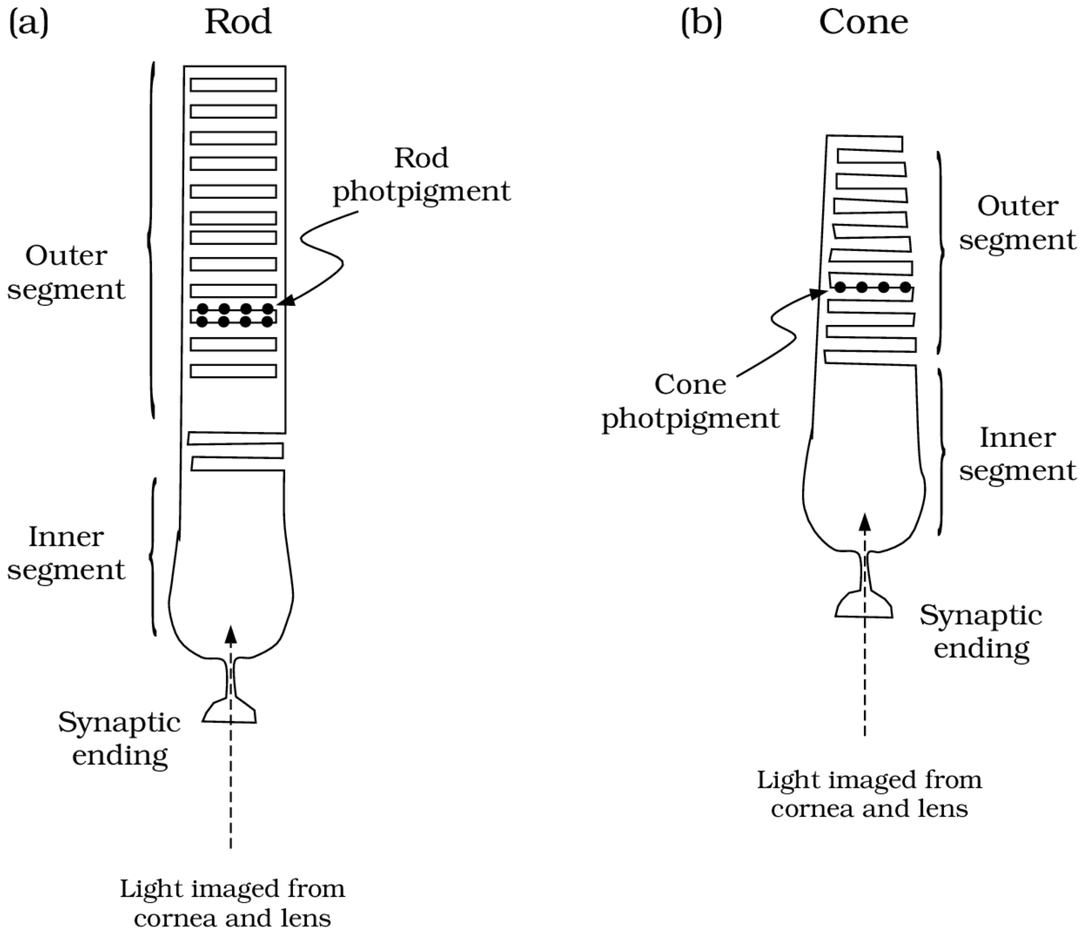
Boettner and Wolter, 1962

The Retina

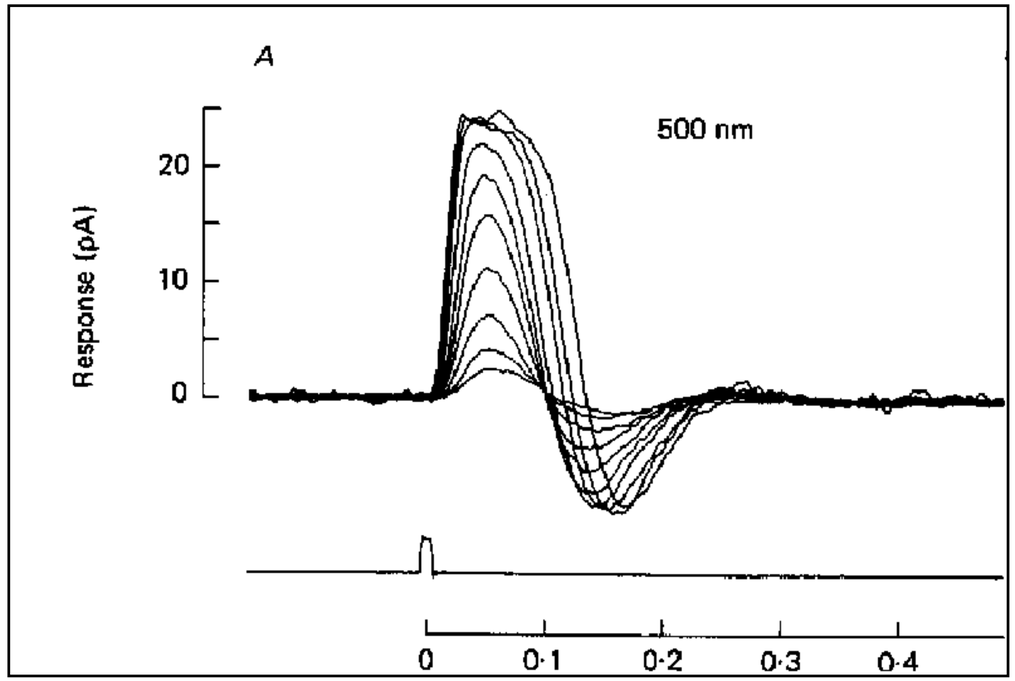
Neurons on the Retina



Photoreceptors: Optical Signals → Electrical Signals



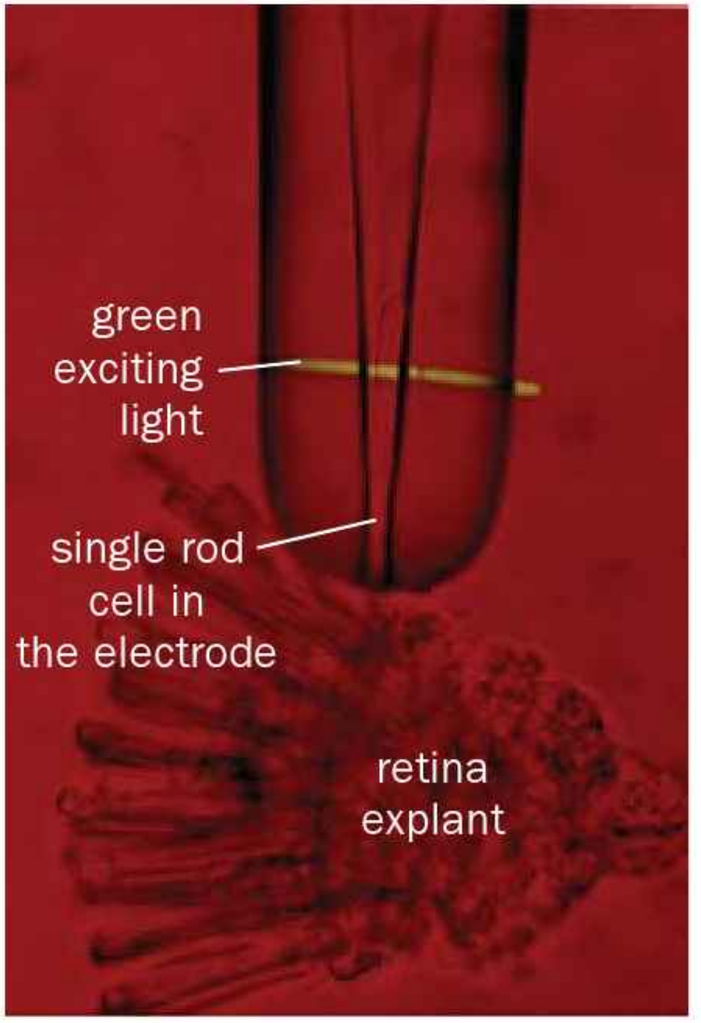
Photocurrents in response to photon absorption

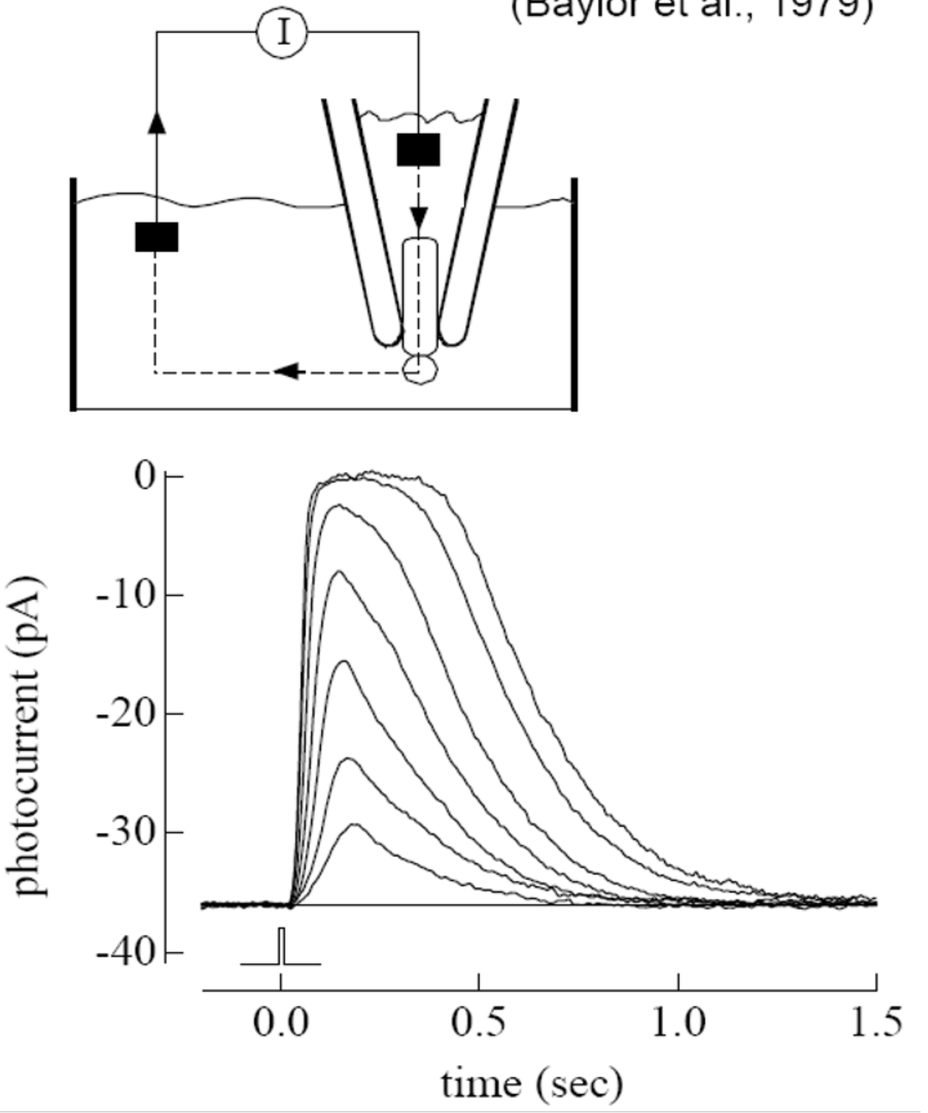


Wandell, FoV 1995; Baylor Nunn and Schnapf, 1987

SUCTION ELECTRODE RECORDING

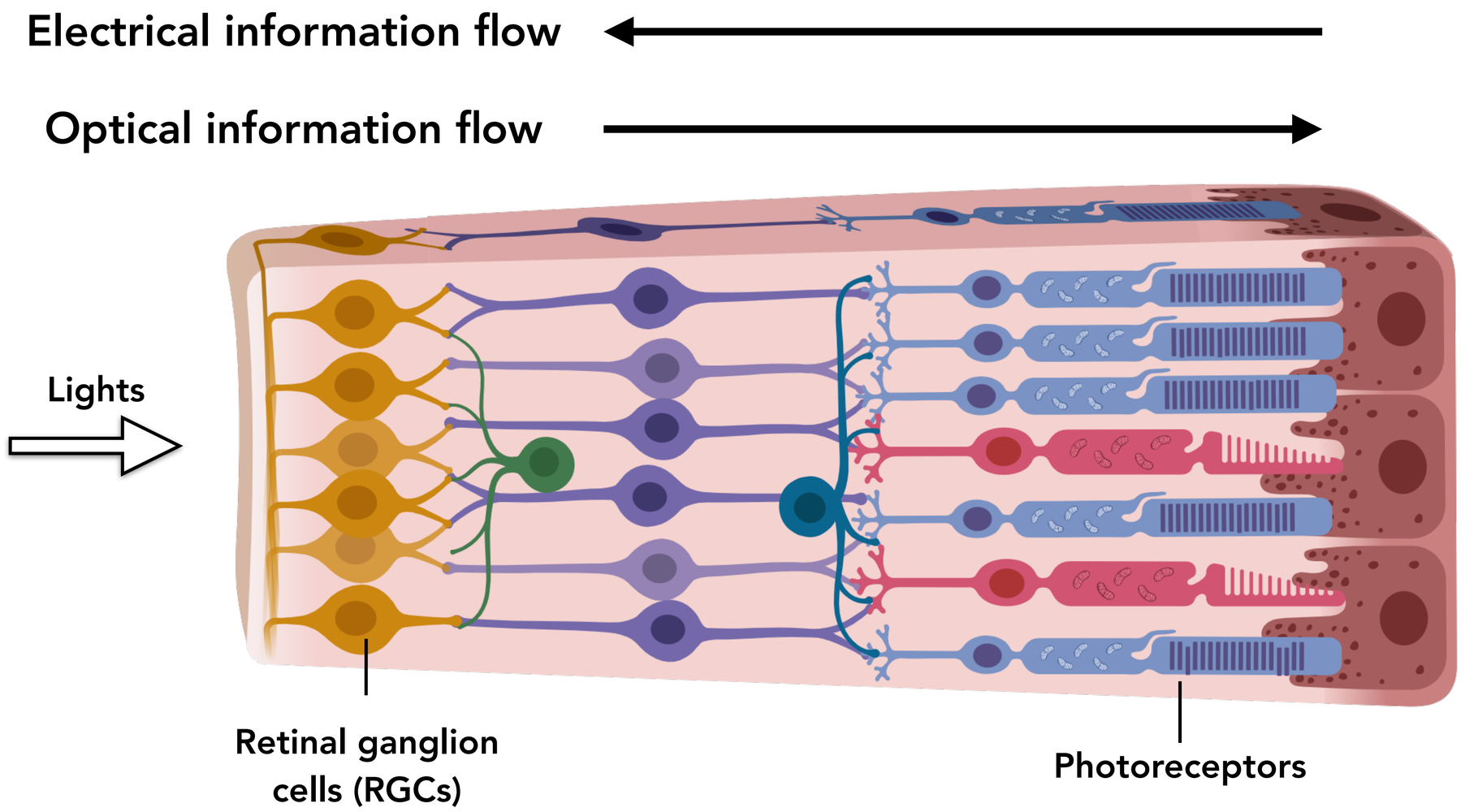
(Baylor et al., 1979)



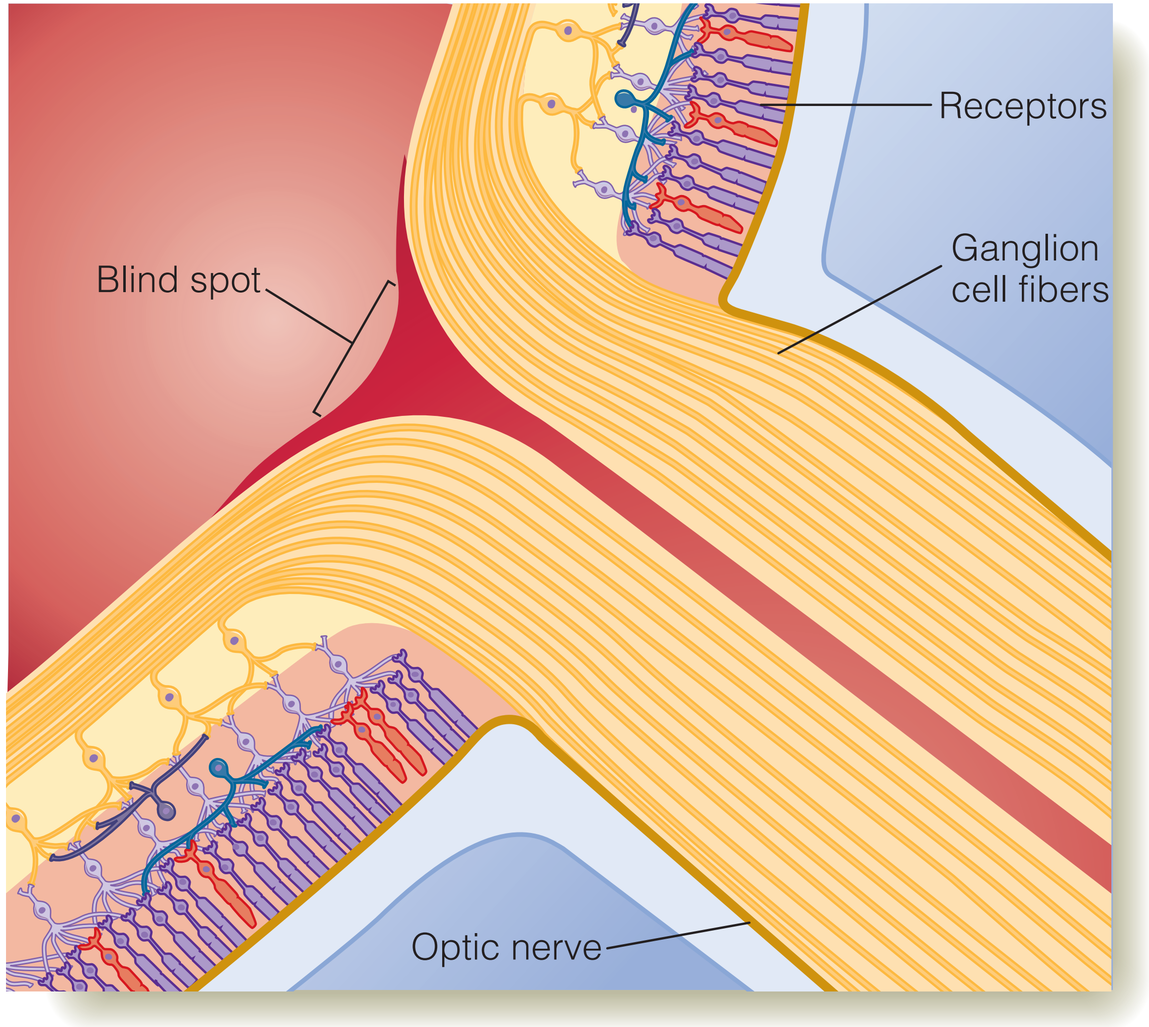


Slide credits: Donald Macleod; Principle of Neurobiology 1ed (p. 123)

Opposite Functional and Anatomical Organizations

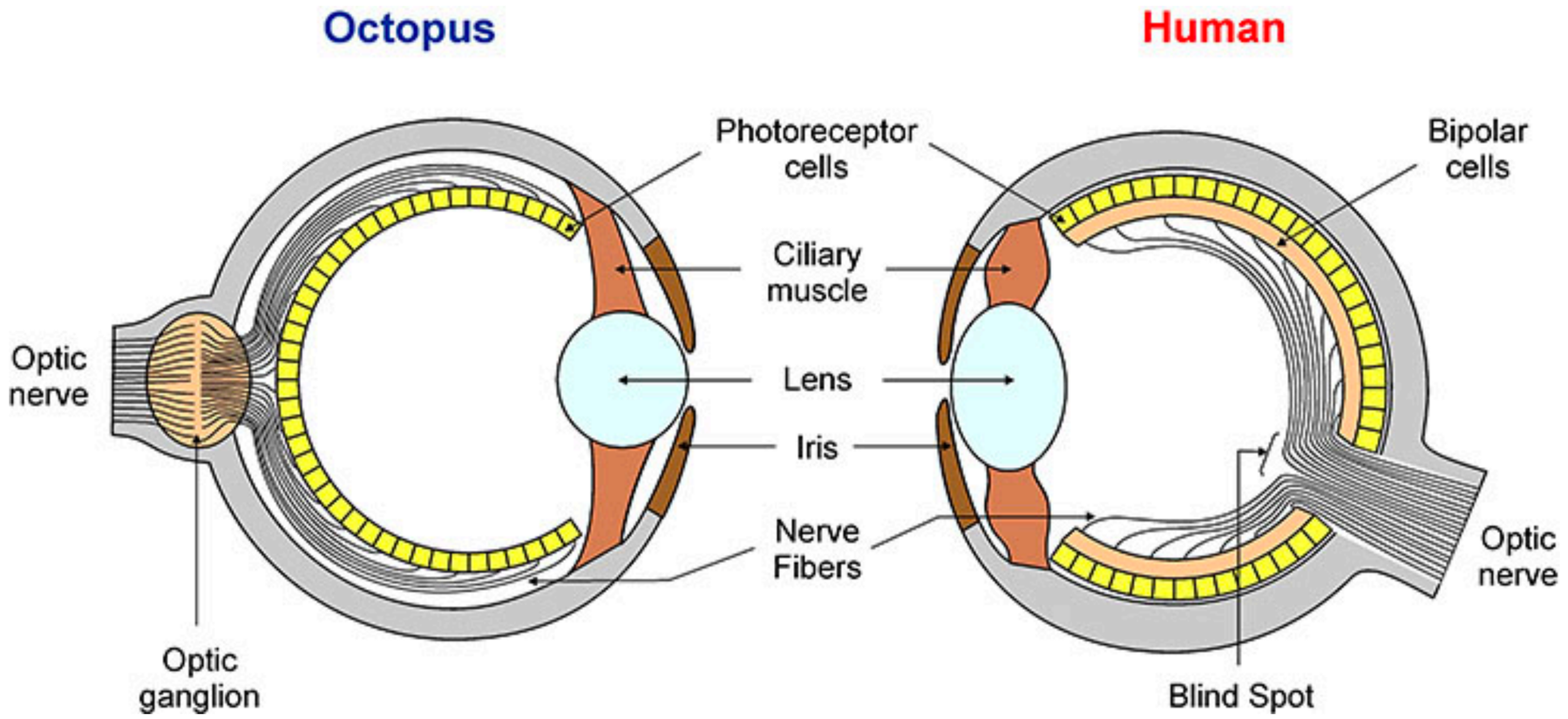


Blind Spot



Blind Spot

Optic nerves route *before* the retina in human eyes



https://www.reddit.com/r/interestingasfuck/comments/6ifcn6/our_similarity_with_cephalopod_eyes_despite_our/

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.

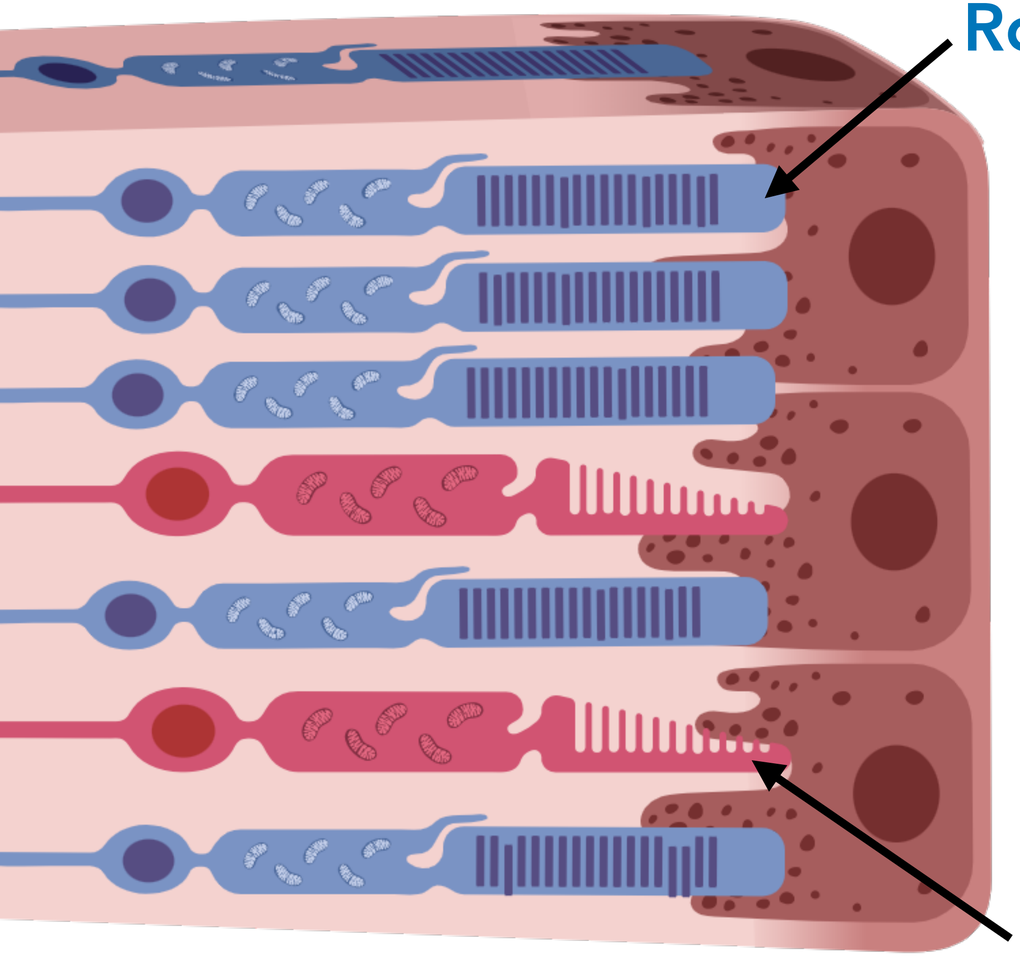
Blind spot doesn’t appear dark because your brain “makes stuff up”

https://visionaryeyecare.wordpress.com/2008/08/04/eye-test-find-your-blind-spot-in-each-eye/

Retina Functions and Specializations

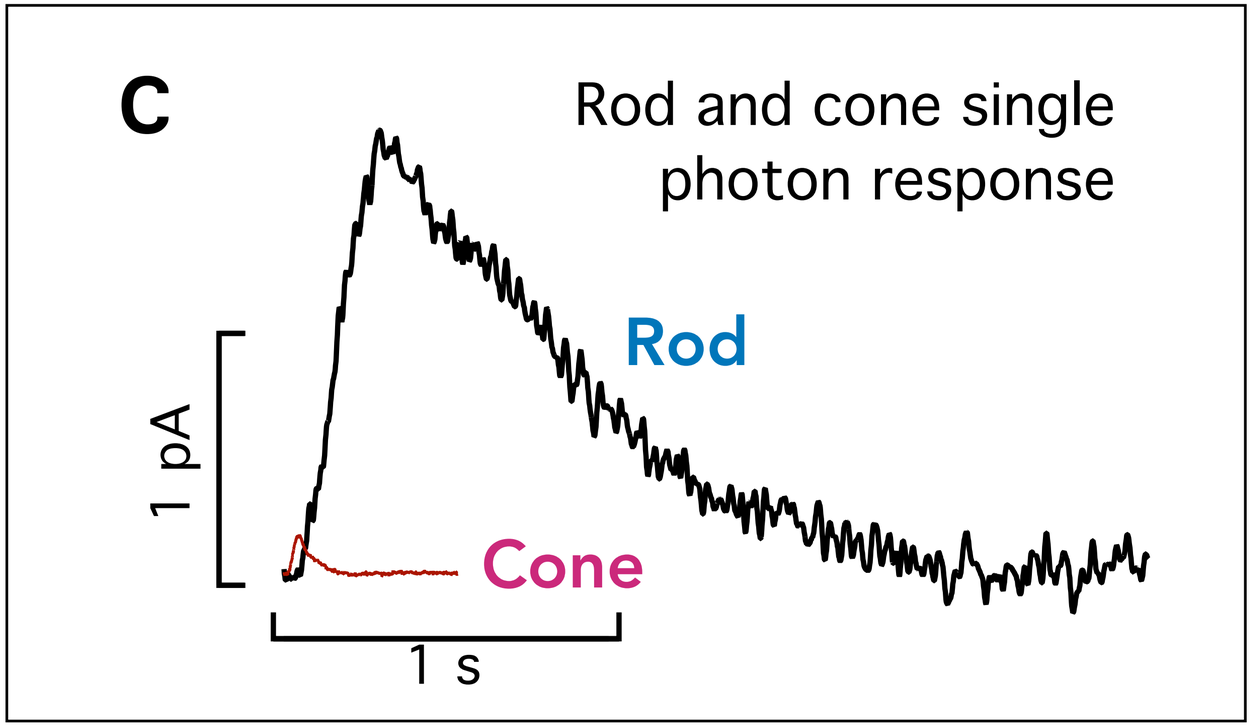
- Rods vs. Cones
- Contrast Detection
- Adaptation

Cones vs. Rods: Sensitivity



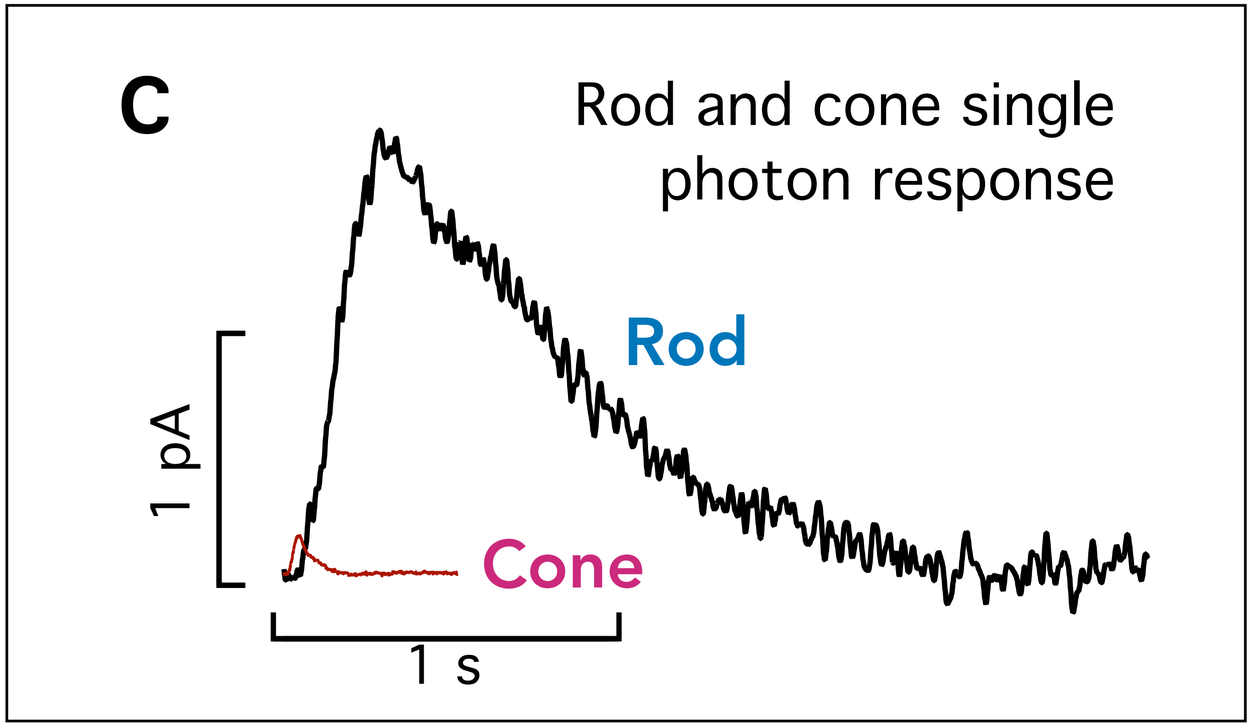
Rod (~120 million in total)

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

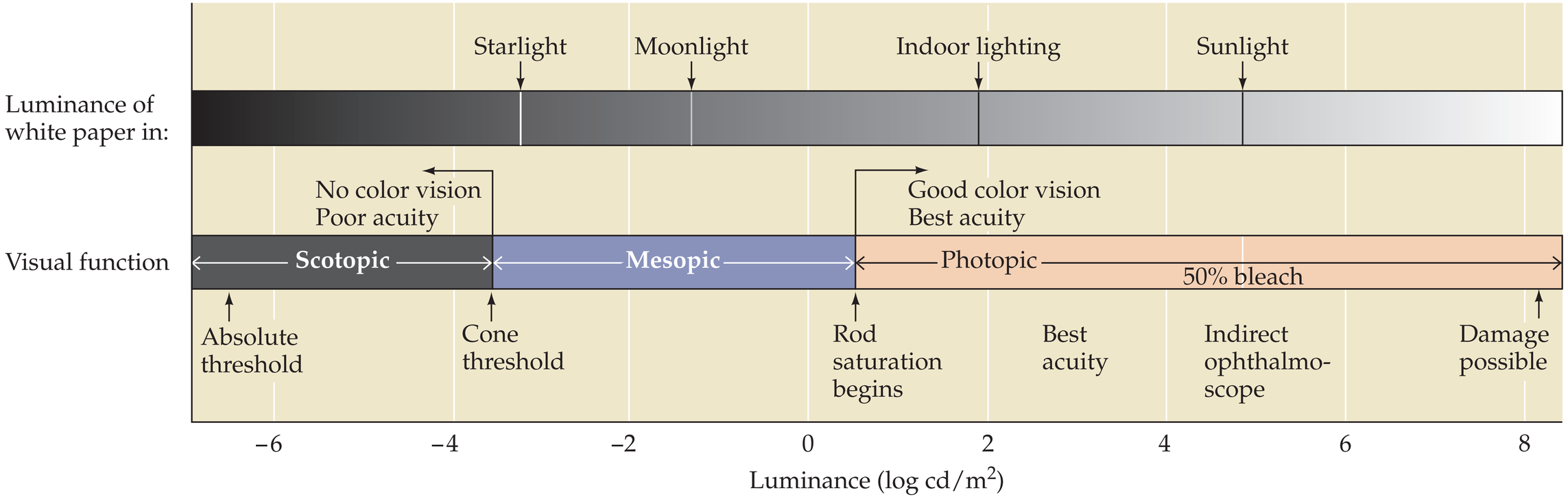
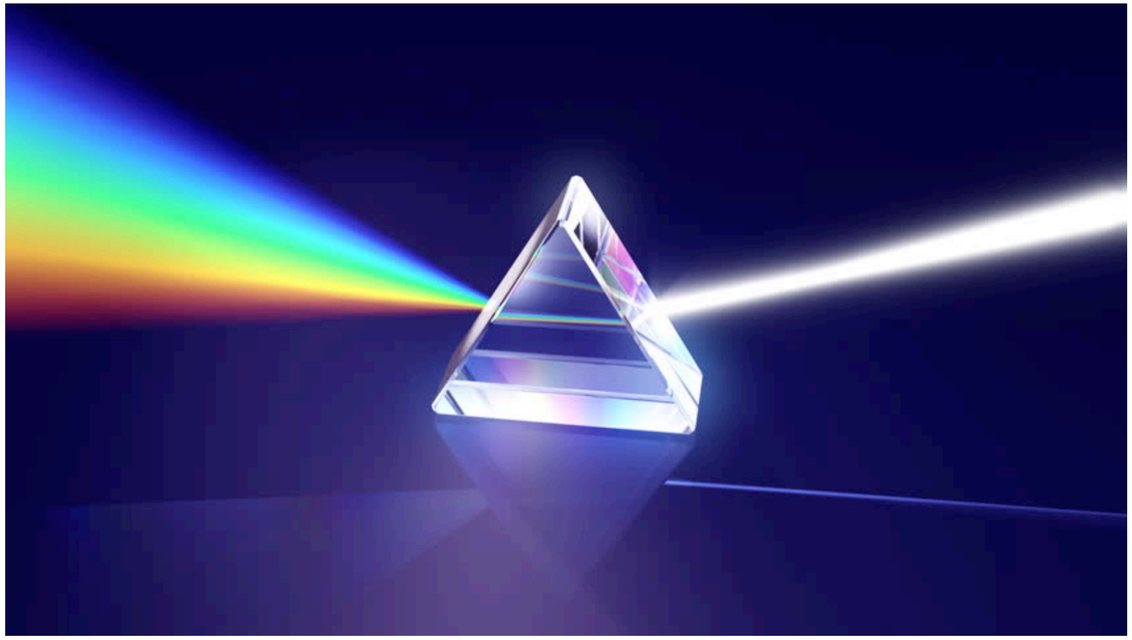


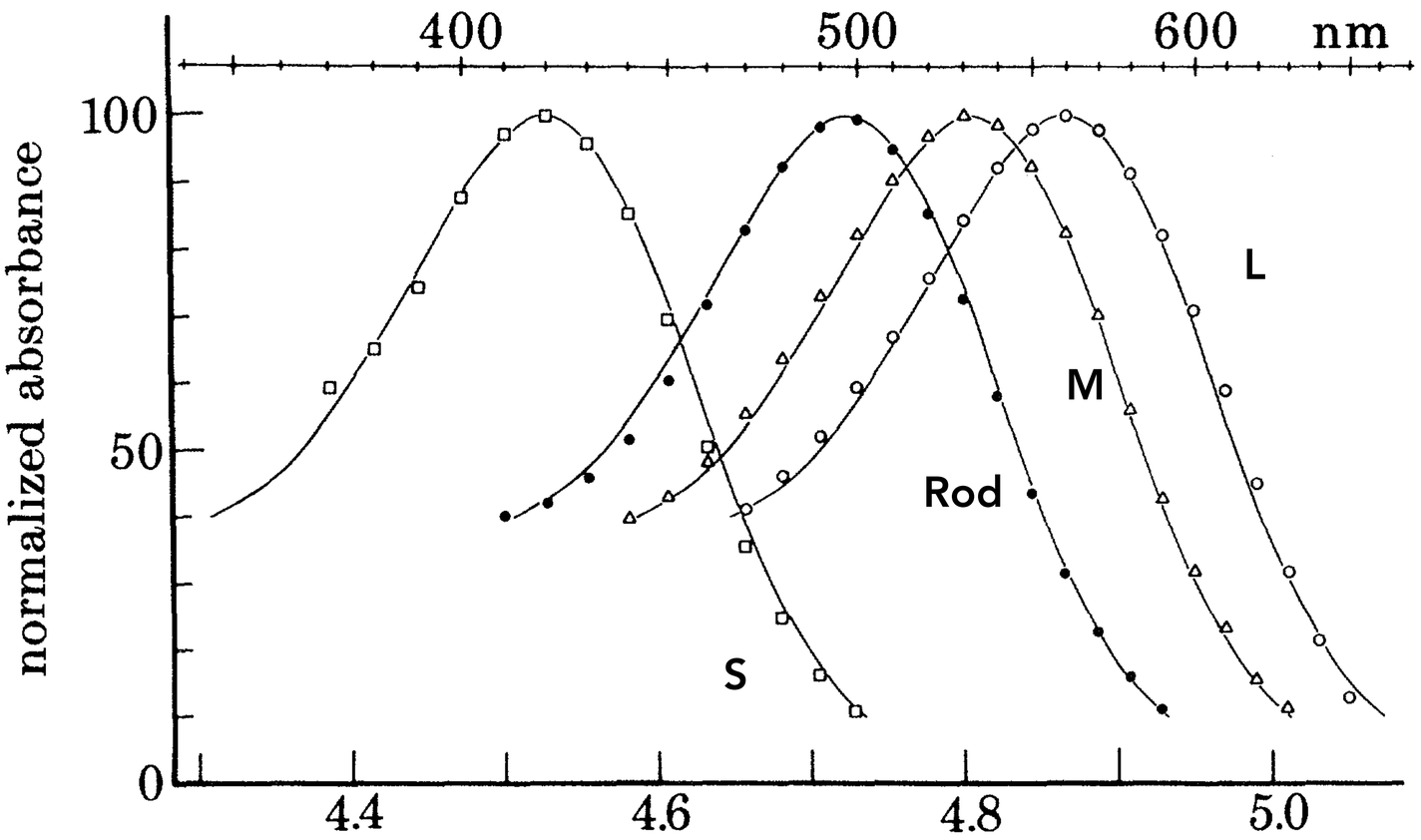
FIGURE 11.11 The range of luminance values over which the visual system operates. At the lowest levels of illumination, only rods are activated. Cones begin to contribute to perception at about the level of starlight and are the only receptors that function under relatively bright conditions.

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



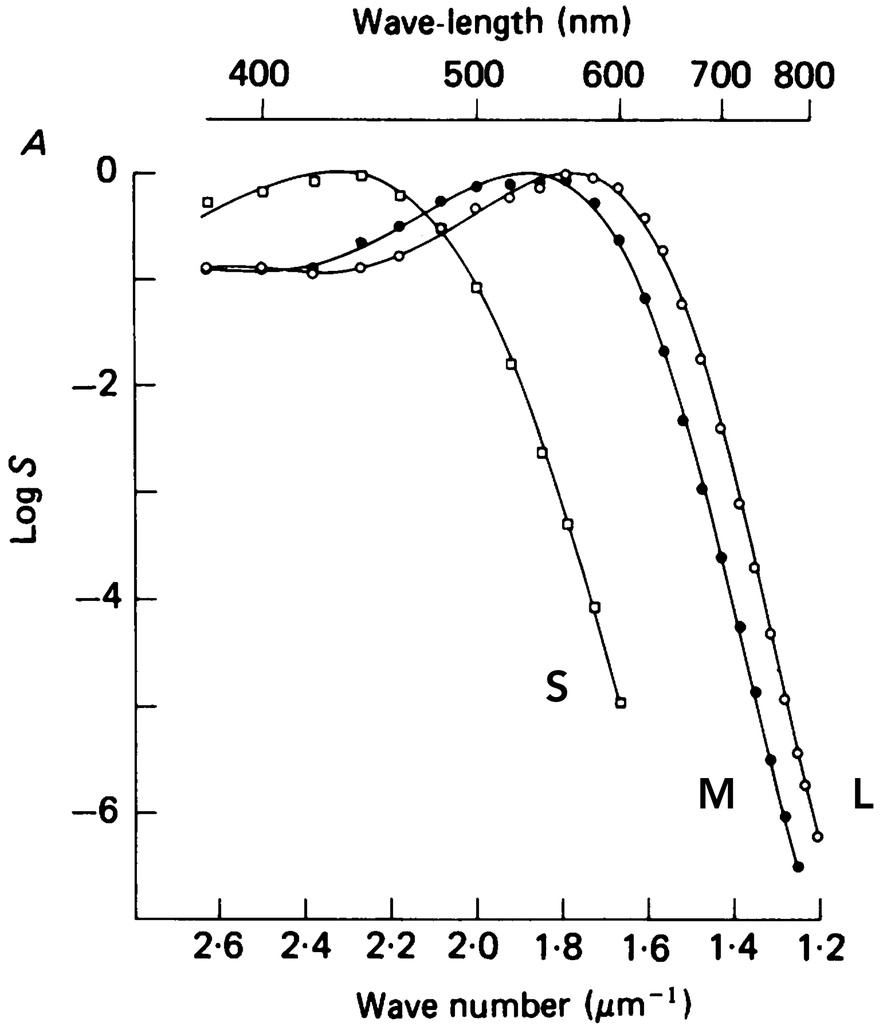
Spectral Sensitivity and Color



- Absorbance spectra from microspectrophotometry
  - Absorbance is proportional to fraction absorbed under certain simplifications (see lecture notes)
  - Data from humans
- Three cone types
  - Long, Medium, Short

Dartnall et al. 1983

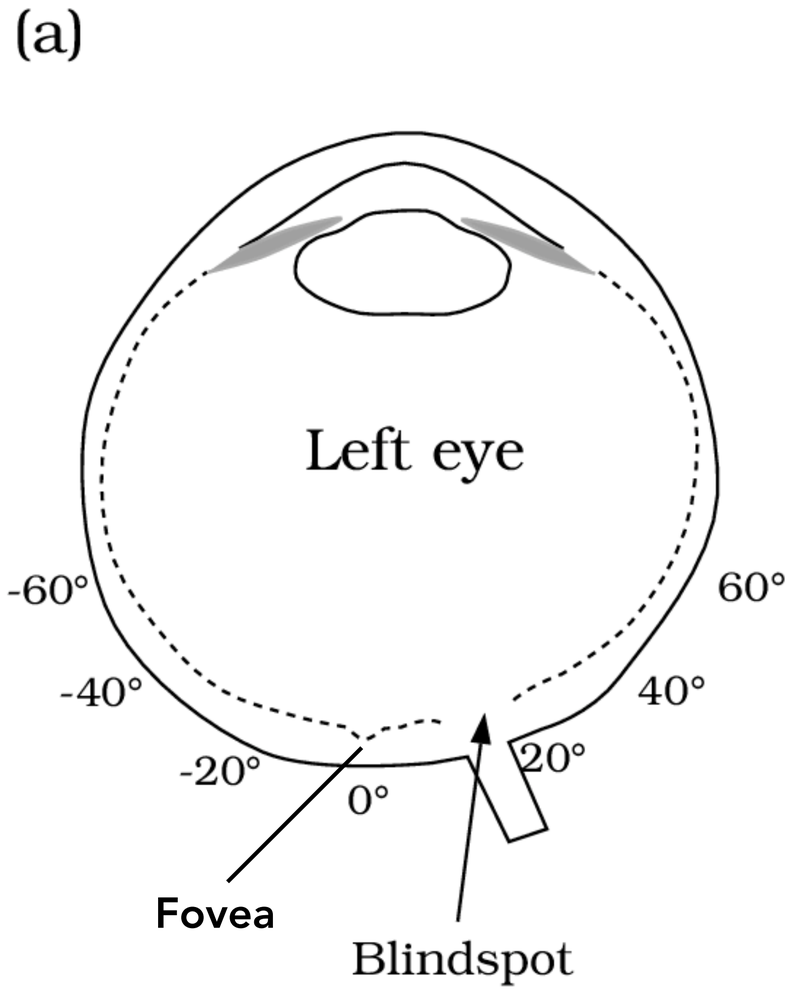
Spectral Sensitivity and Color

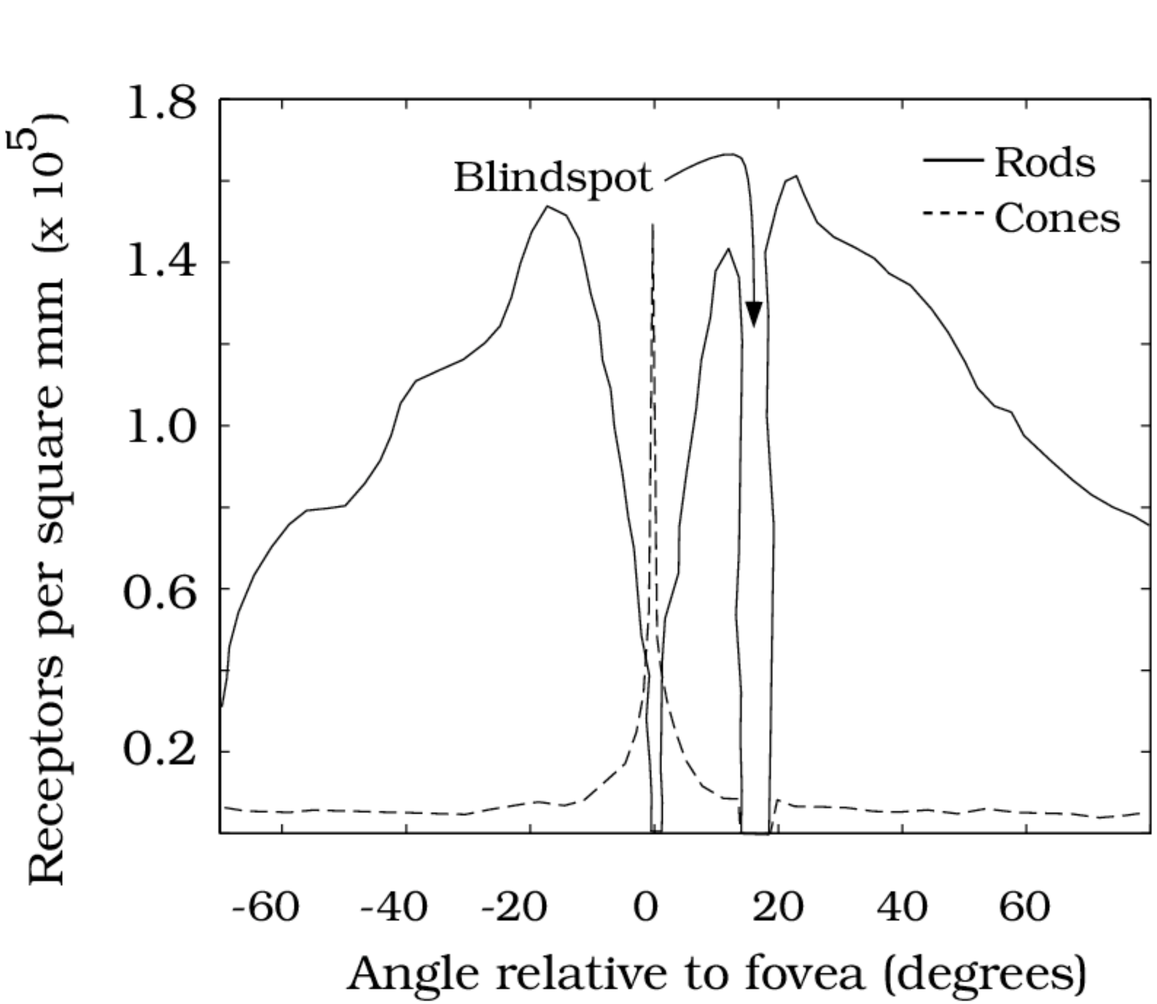


- Sensitivity from isolated photoreceptors
  - From a macaque
  - Using suction electrode to measure electrical responses
  - Measures the amount of light that's needed at each wavelength to reach a criterion level of response

Baylor et al. 1987

Cones vs. Rods: Distribution





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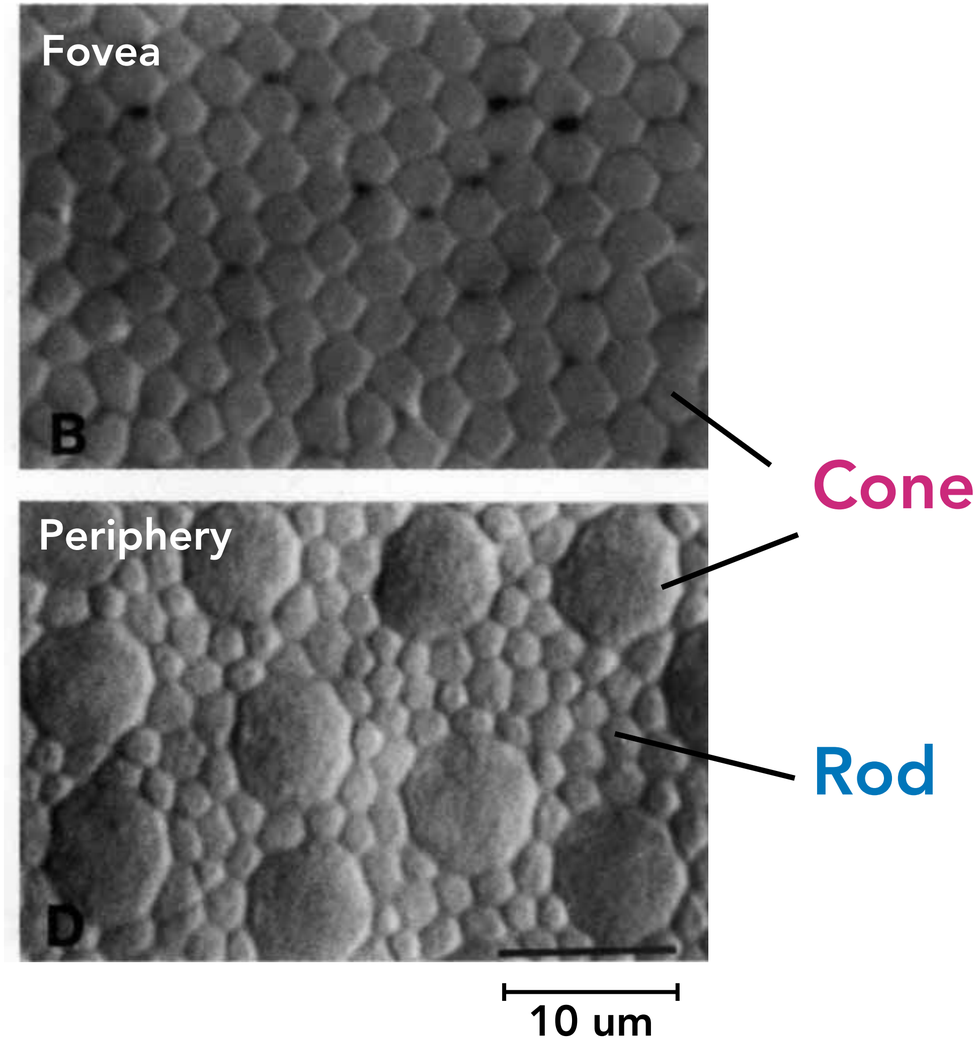
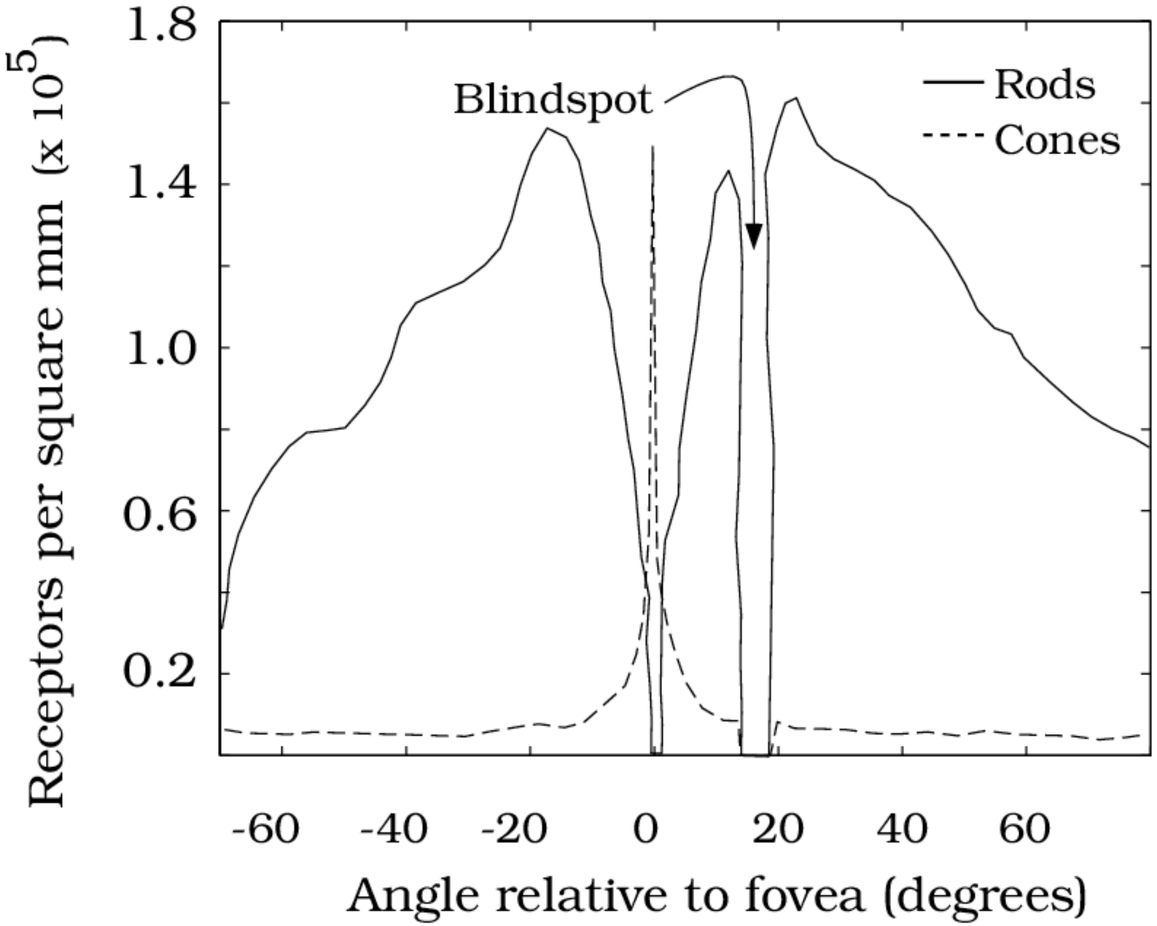
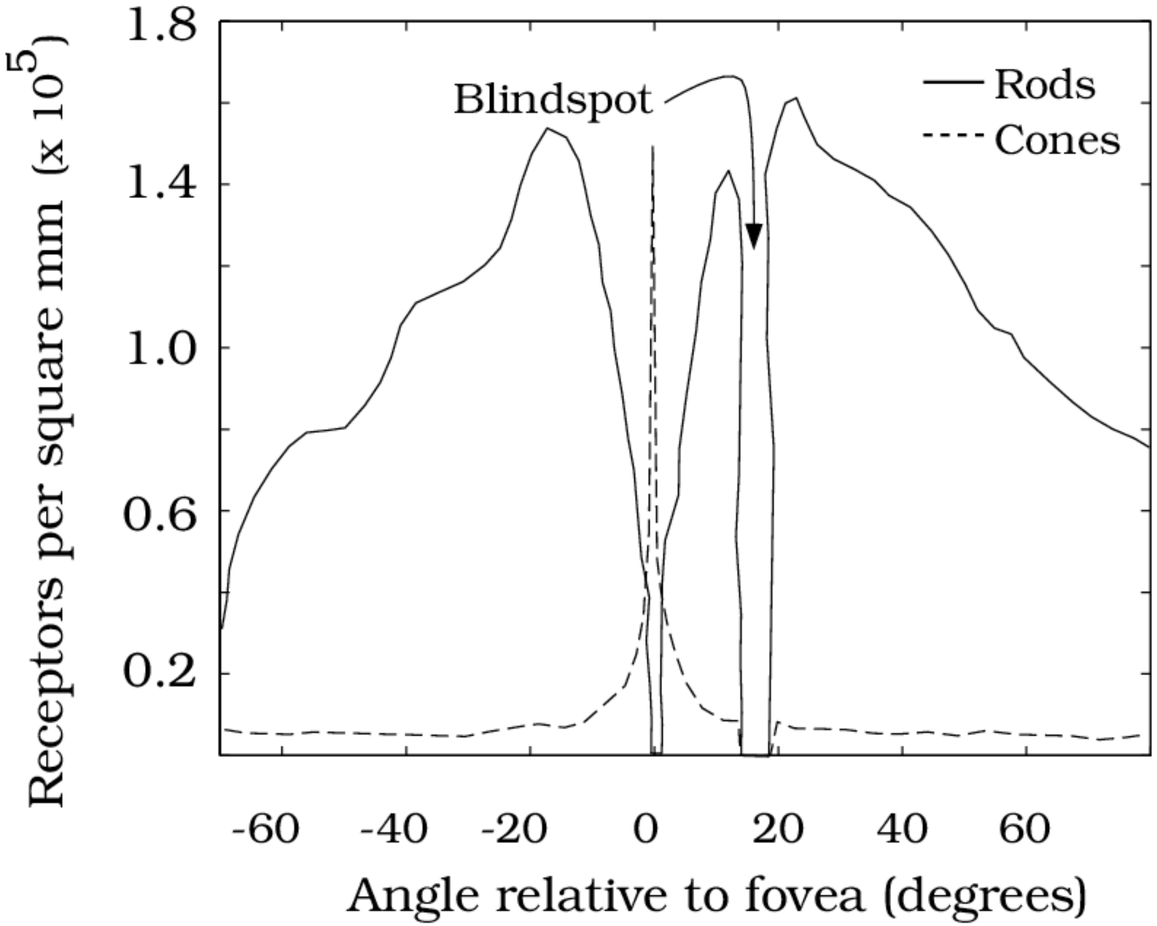




Wandell, FoV 1995; Crucio et al. 1990

Cones vs. Rods: Distribution

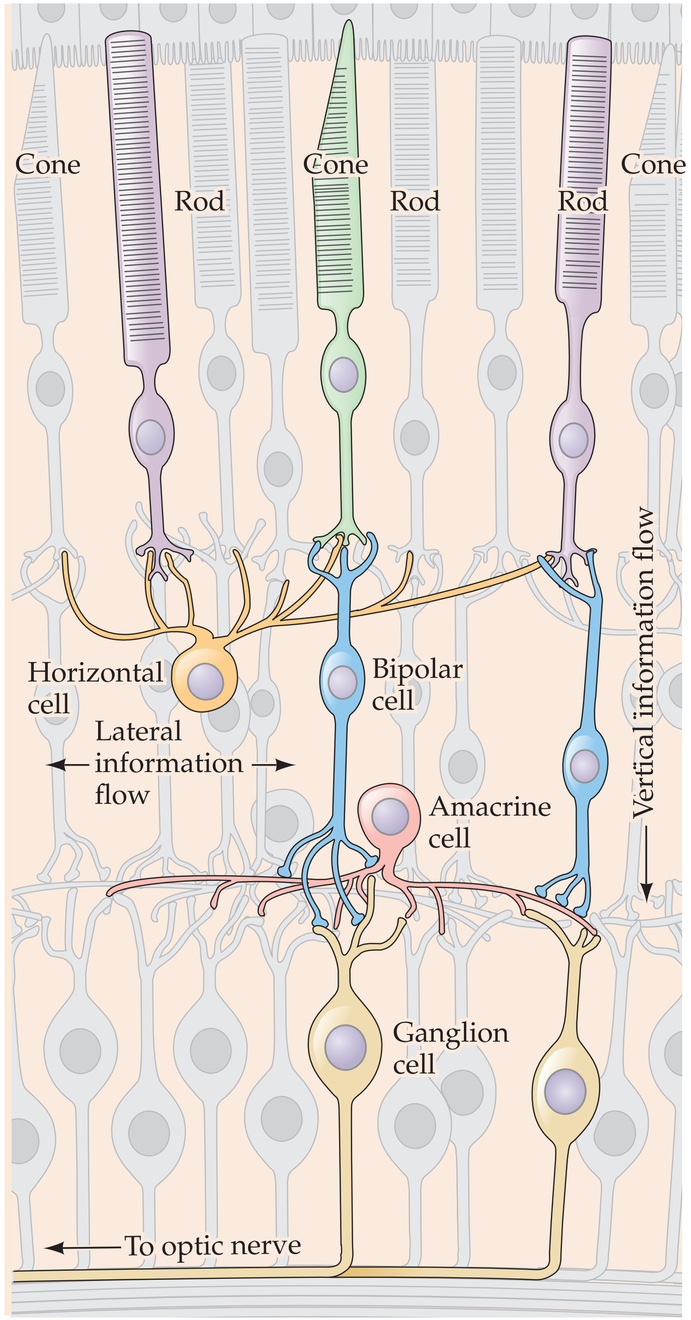
- Implications
  - Can't see object details at low illumination levels if you fixate at the object. Intentionally place the object at your peripheral vision.
  - Peripheral visual acuity is low (distribution and size is just one reason; more later)



Wandell, FoV 1995

Cone vs. Rod Pathways

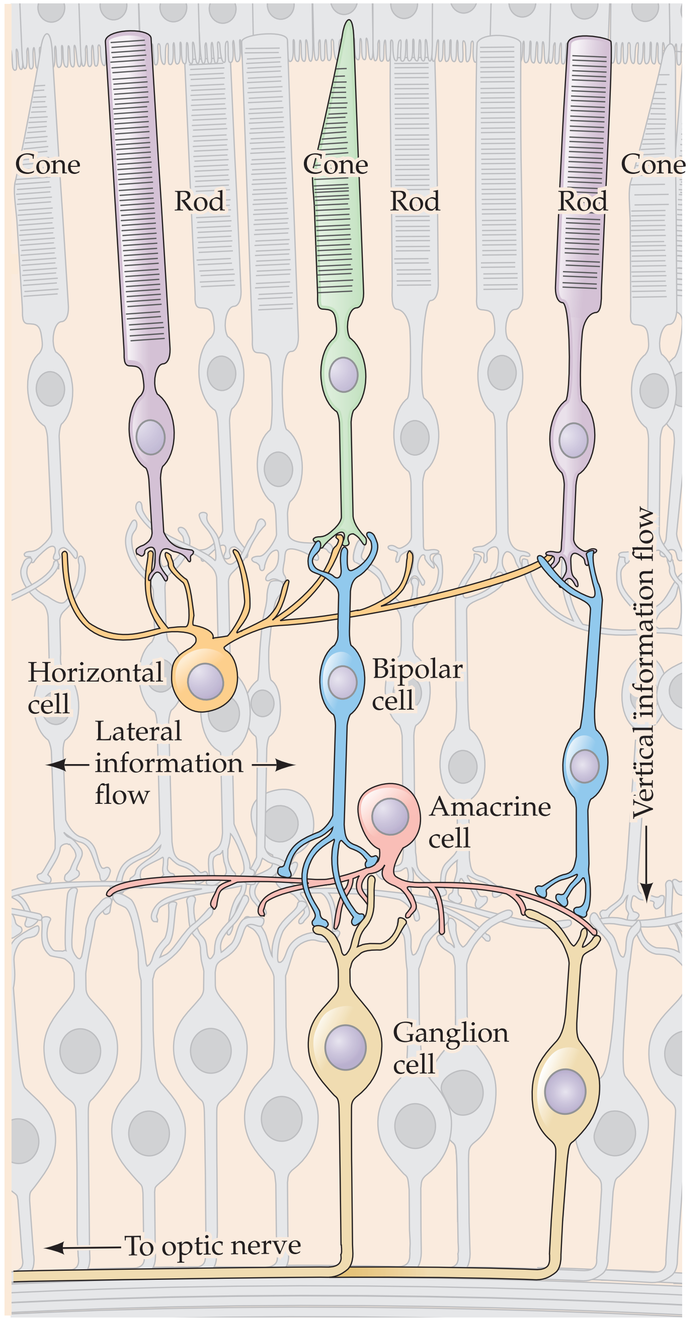
- Initially parallel/separated and then merge
- Photoreceptors synapse with bipolar cells
  - Each bipolar cell synapse with only rods or cones
  - So the pathways are separated
- RGCs mix rod bipolar and cone bipolar cels
  - Through amacrine cells



Purves et al. Neuroscience 6ed

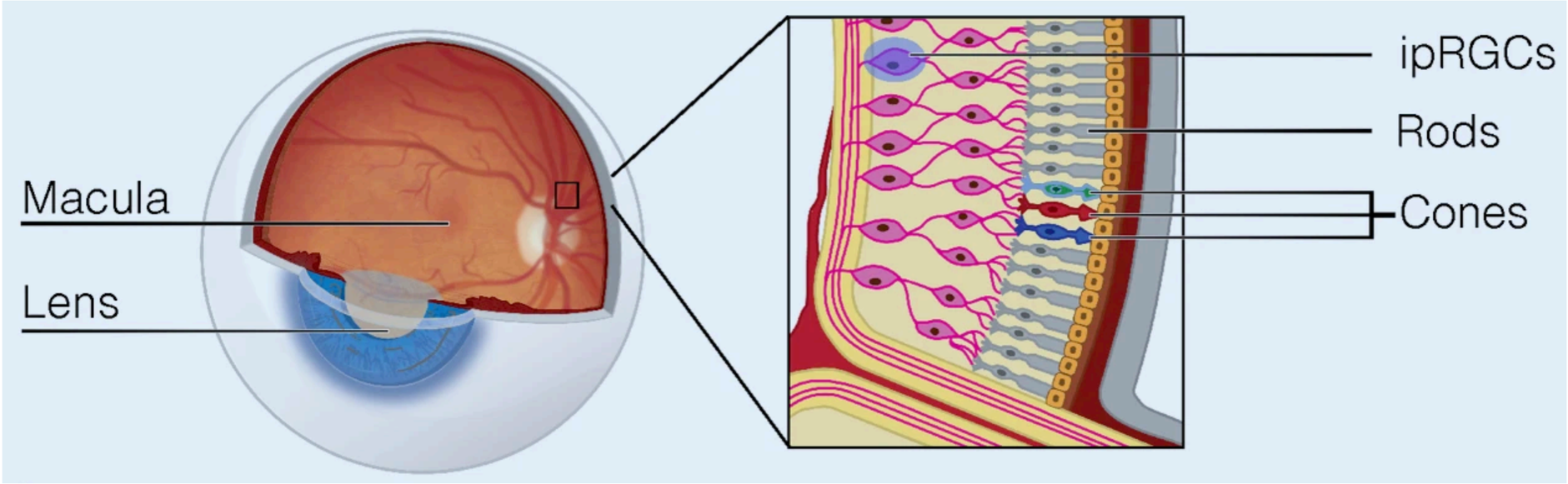
Cone vs. Rod Pathways

- 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



Purves et al. Neuroscience 6ed

ipRGCs



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

https://en.wikipedia.org/wiki/Intrinsically_photosensitive_retinal_ganglion_cell

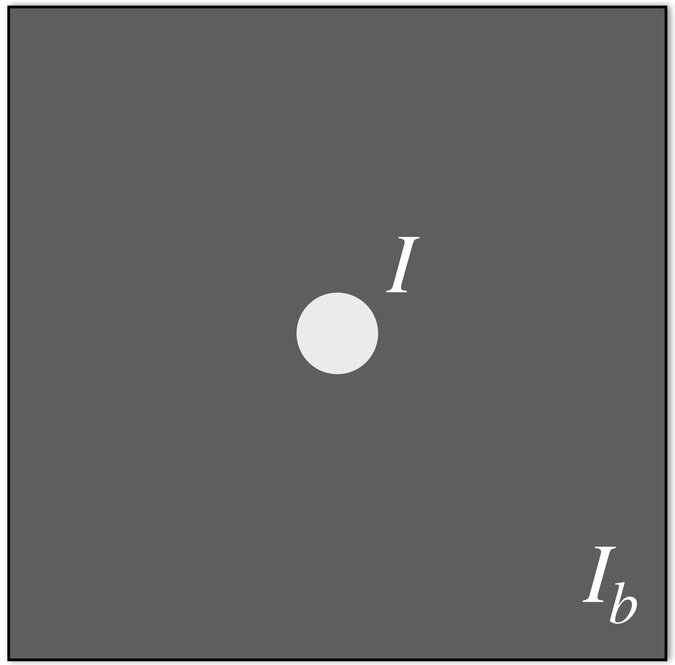
Retina Functions and Specializations

- Rods vs. Cones
- Contrast Detection
- Adaptation

Contrast: Variation over Mean

Weber Contrast

(detect object from background)

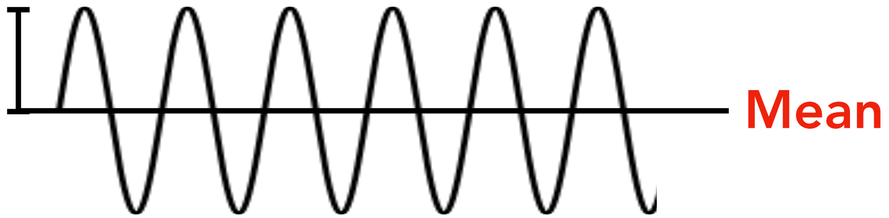


$$\frac{I - I_b}{I_b}$$

Variation of the signal from the mean

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

Contrast: Variation over Mean

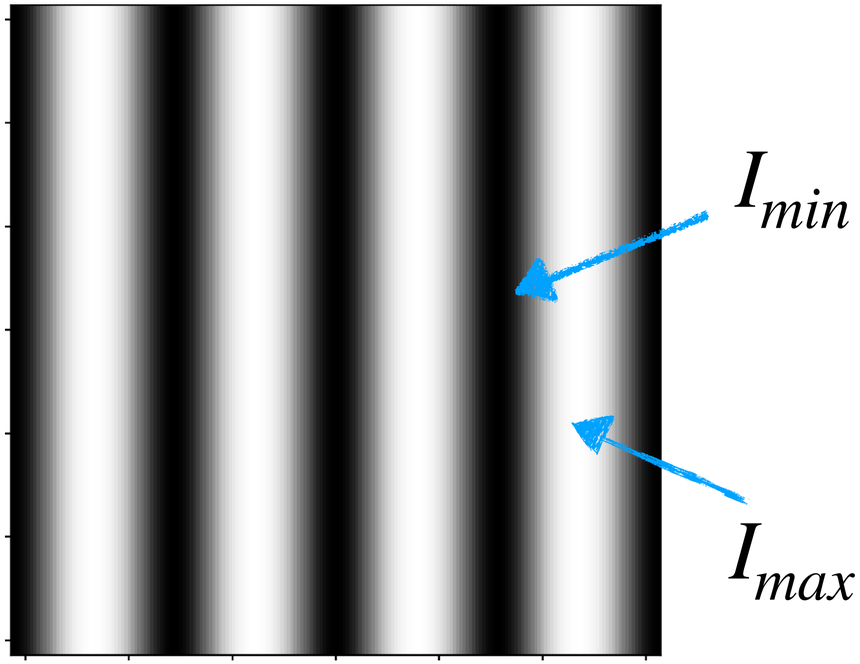


2 x **Variation** of the signal from the mean

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

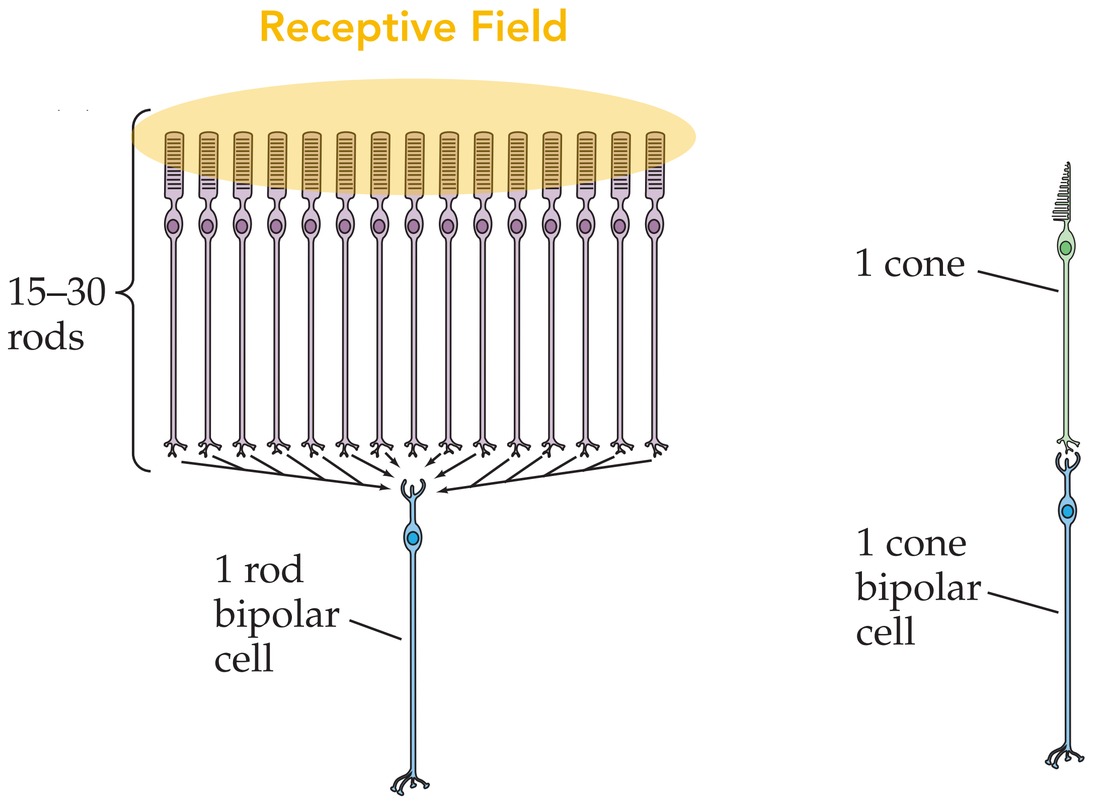
2x **Mean** light intensity of the entire field

Michelson Contrast
(detect patterns)



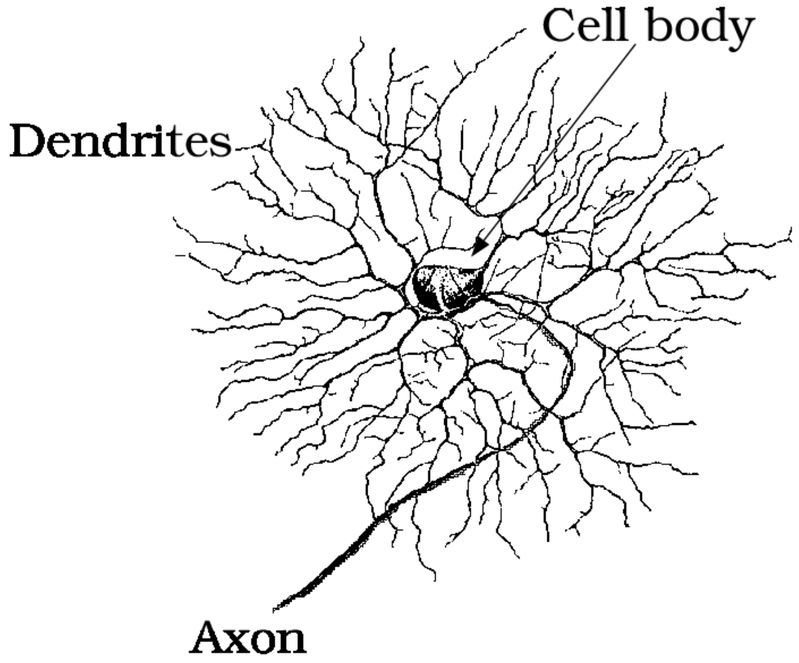
Neural Convergence and Receptive Field

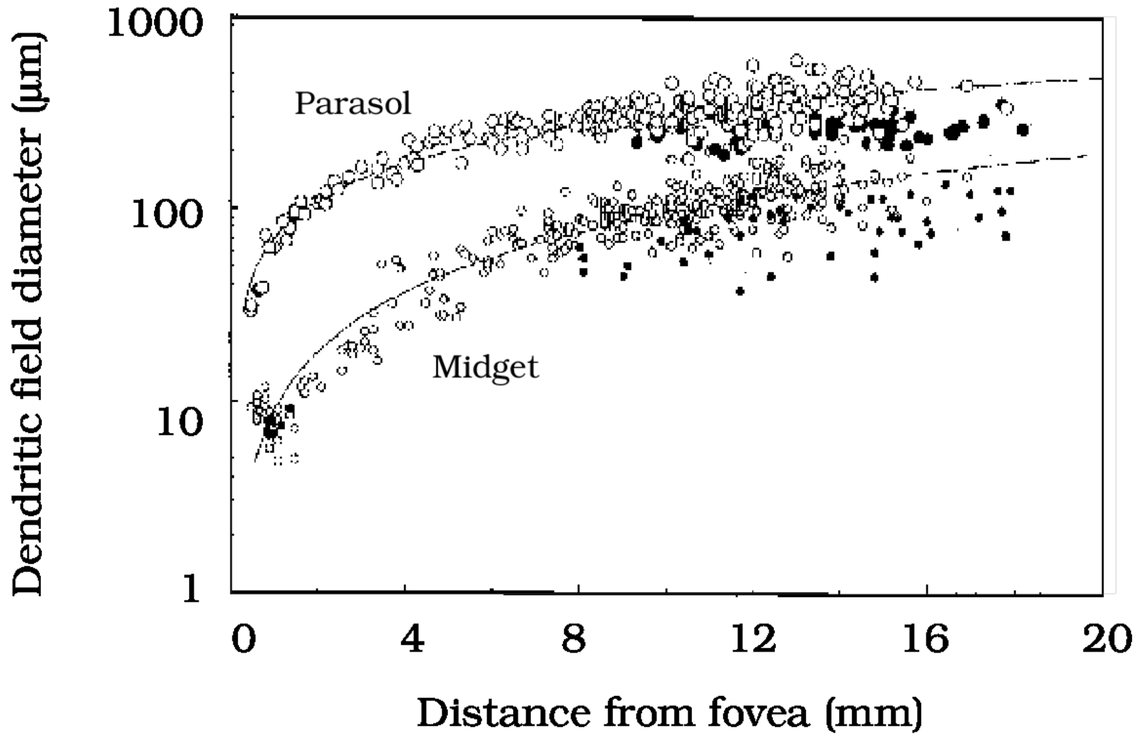
- 120 million rods, 6 million cones, but only 1 million RGCs on the retina
  - So some convergence has to take place
  - Higher degrees of convergence for rods than cones
- Receptive field of a neuron: retinal surface that converges to the neuron



Neural Convergence

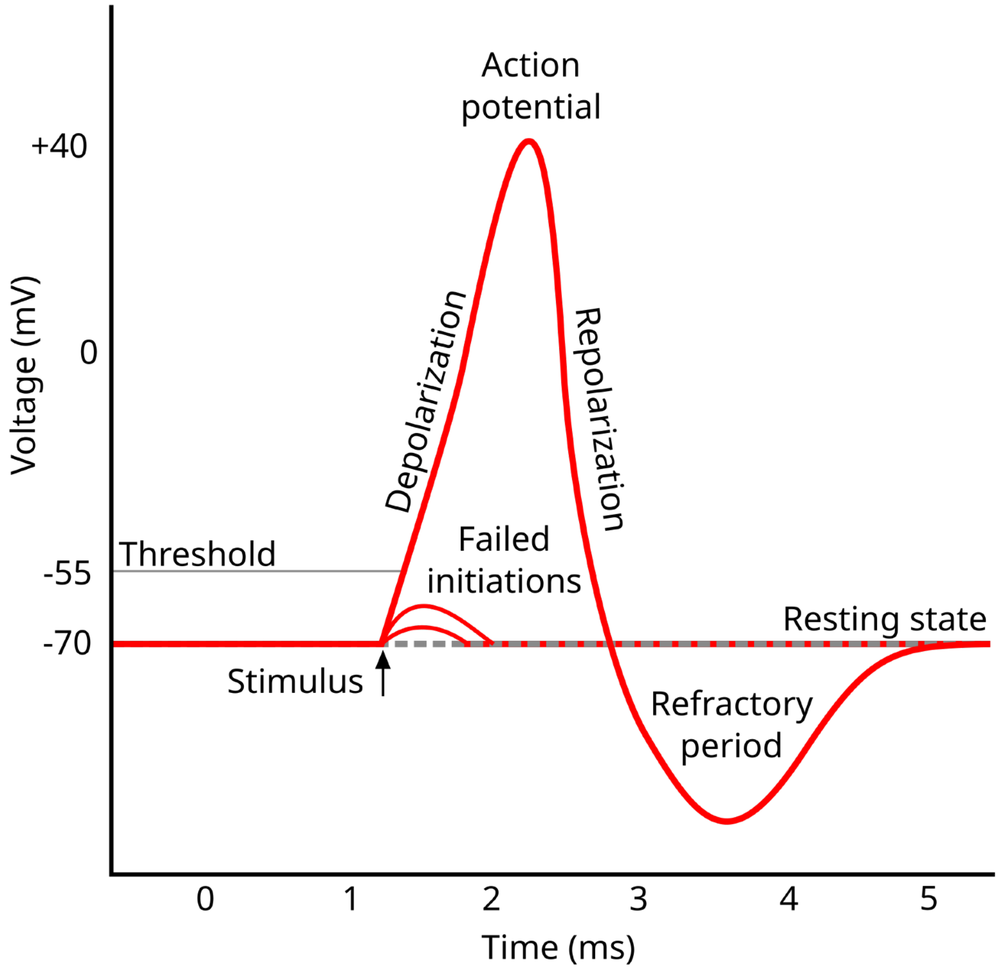
- Degree of convergence increases with eccentricity
  - Extreme case: one cone maps to many RGCs at fovea

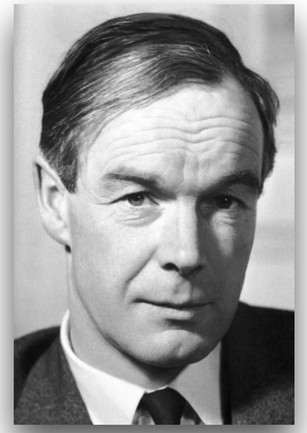




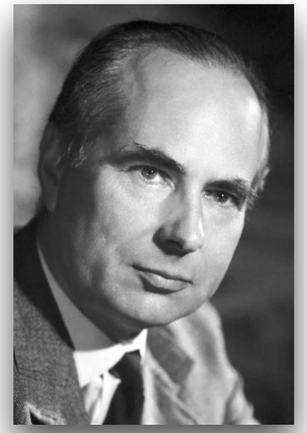
Wandell, FoV 1995; Dacey and Petersen, 1992

Interlude: Action Potential





Alan Hodgkin
(1963 Nobel Prize)



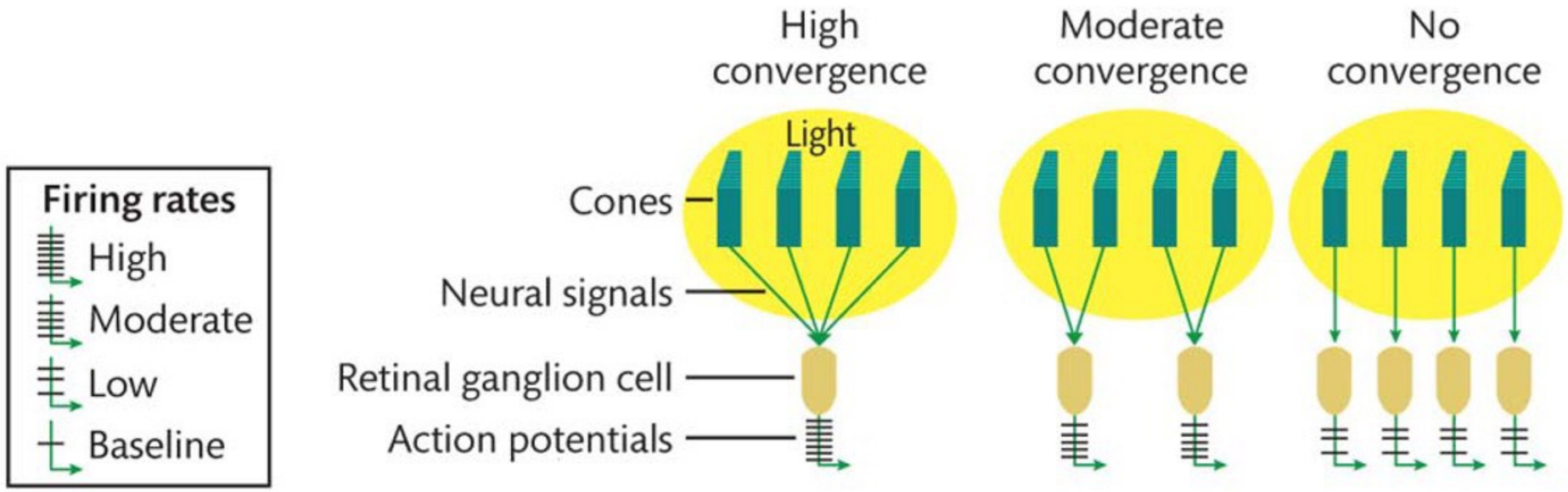
Andrew Huxley
(1963 Nobel Prize)

- 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)

https://en.wikipedia.org/wiki/Action_potential

Implications of Neural Convergence

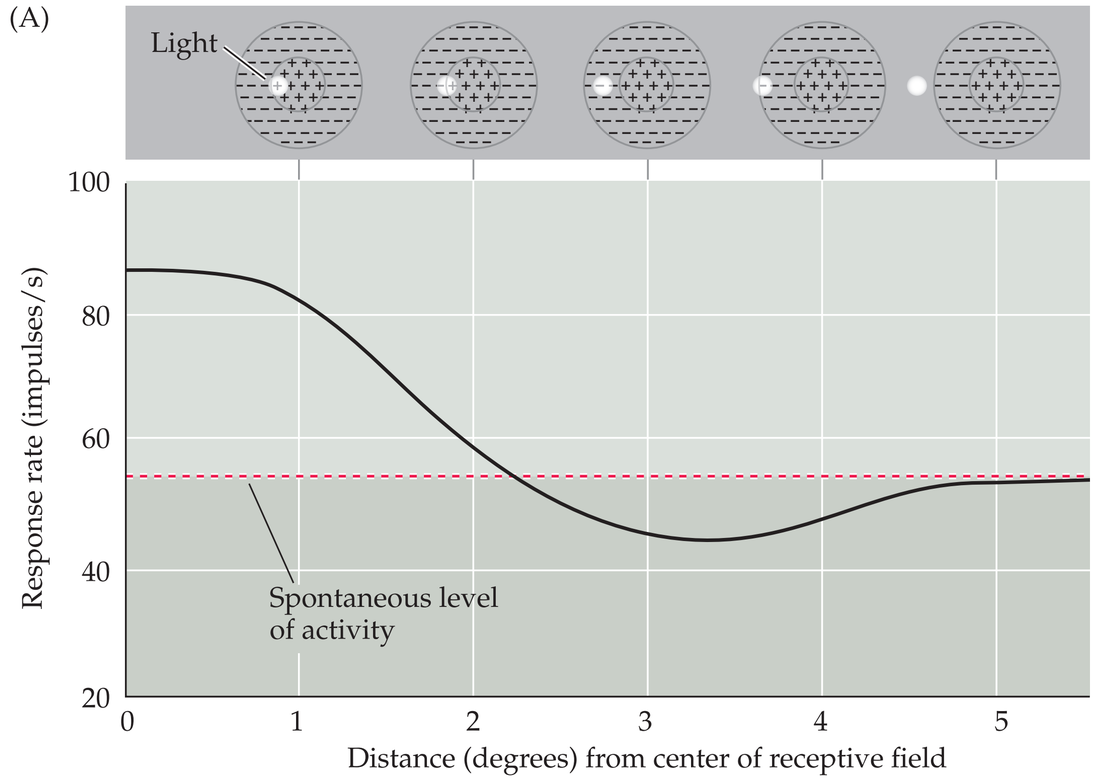
- Higher convergence usually means higher sensitivity but lower acuity
  - Assuming pure summation but there is also inhabitation (later)
  - Convergence means integration, which is low-pass filtering

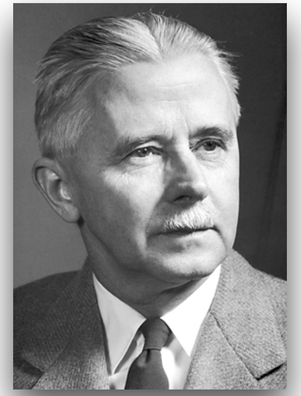


Implications of Neural Convergence

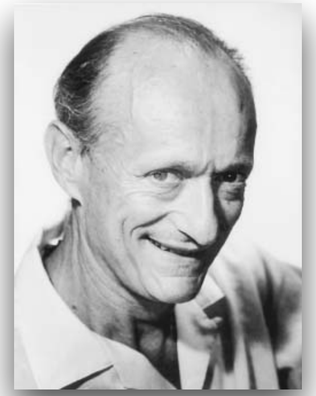
- Higher convergence usually means higher sensitivity but lower acuity
  - Assuming pure summation but there is also inhabitation (later)
- Rod vision is more sensitive to cone vision
  - In addition to the larger single photon response we saw before
- Peripheral visual acuity is lower than fovea
  -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

RGCs have a Center-Surround Receptive Field

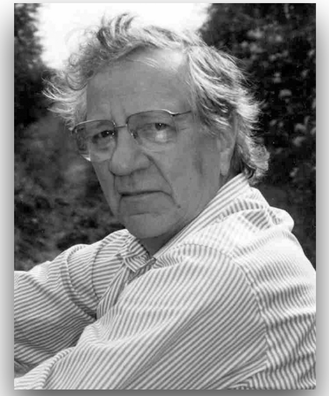




Hartline
(1967 Nobel prize)

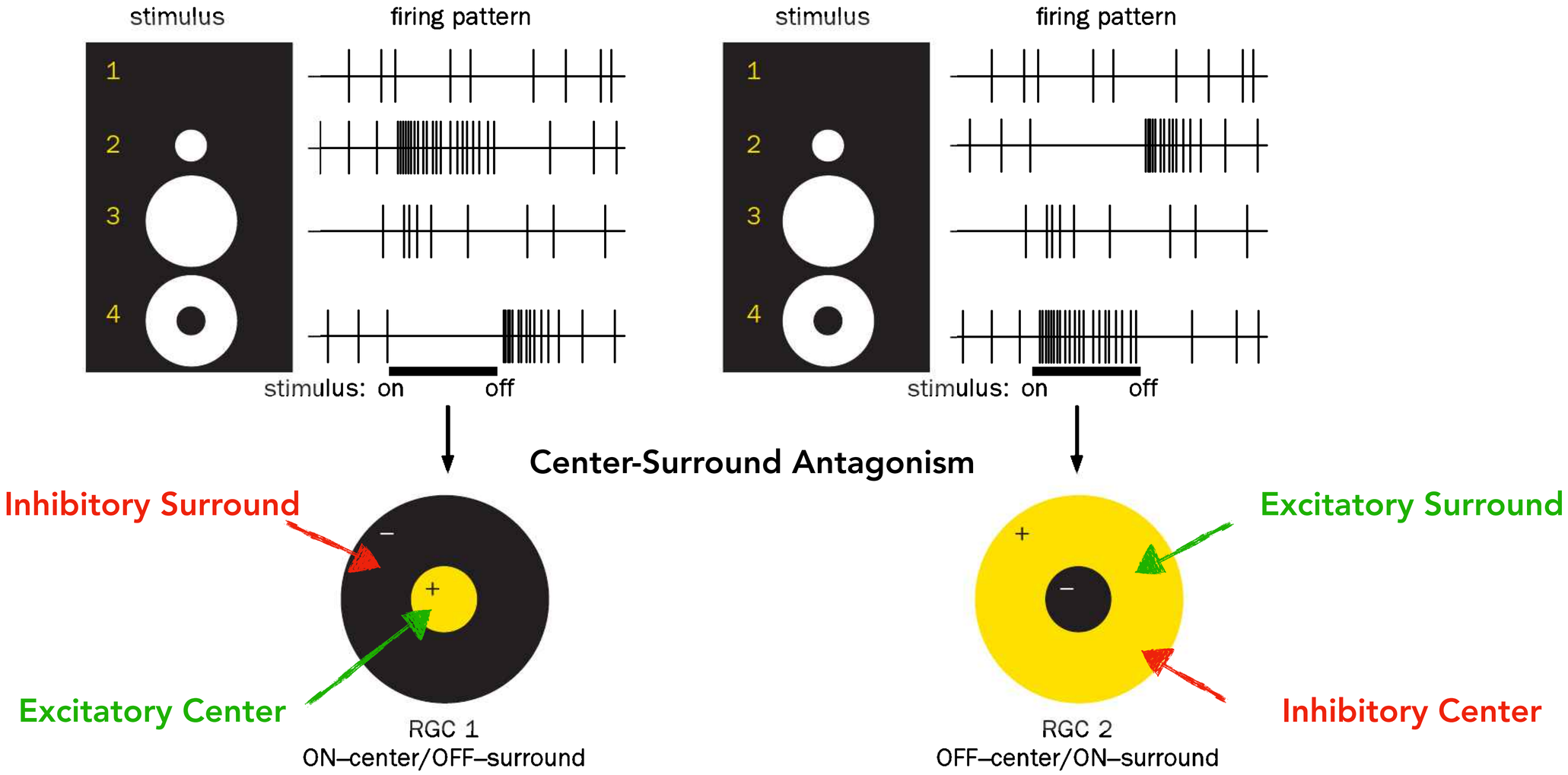


Kuffler

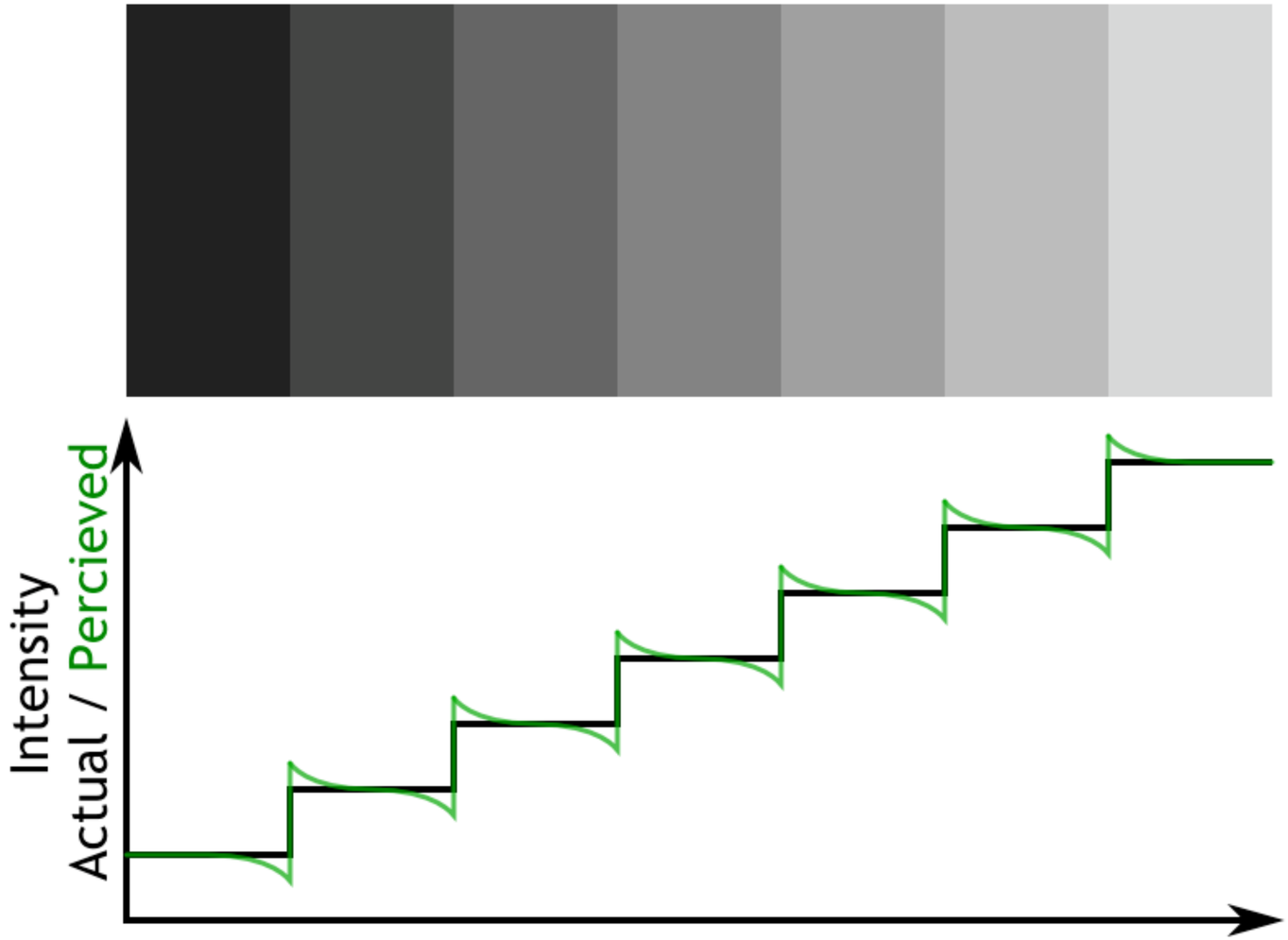


Barlow

ON-Center and OFF-Center Receptive Field

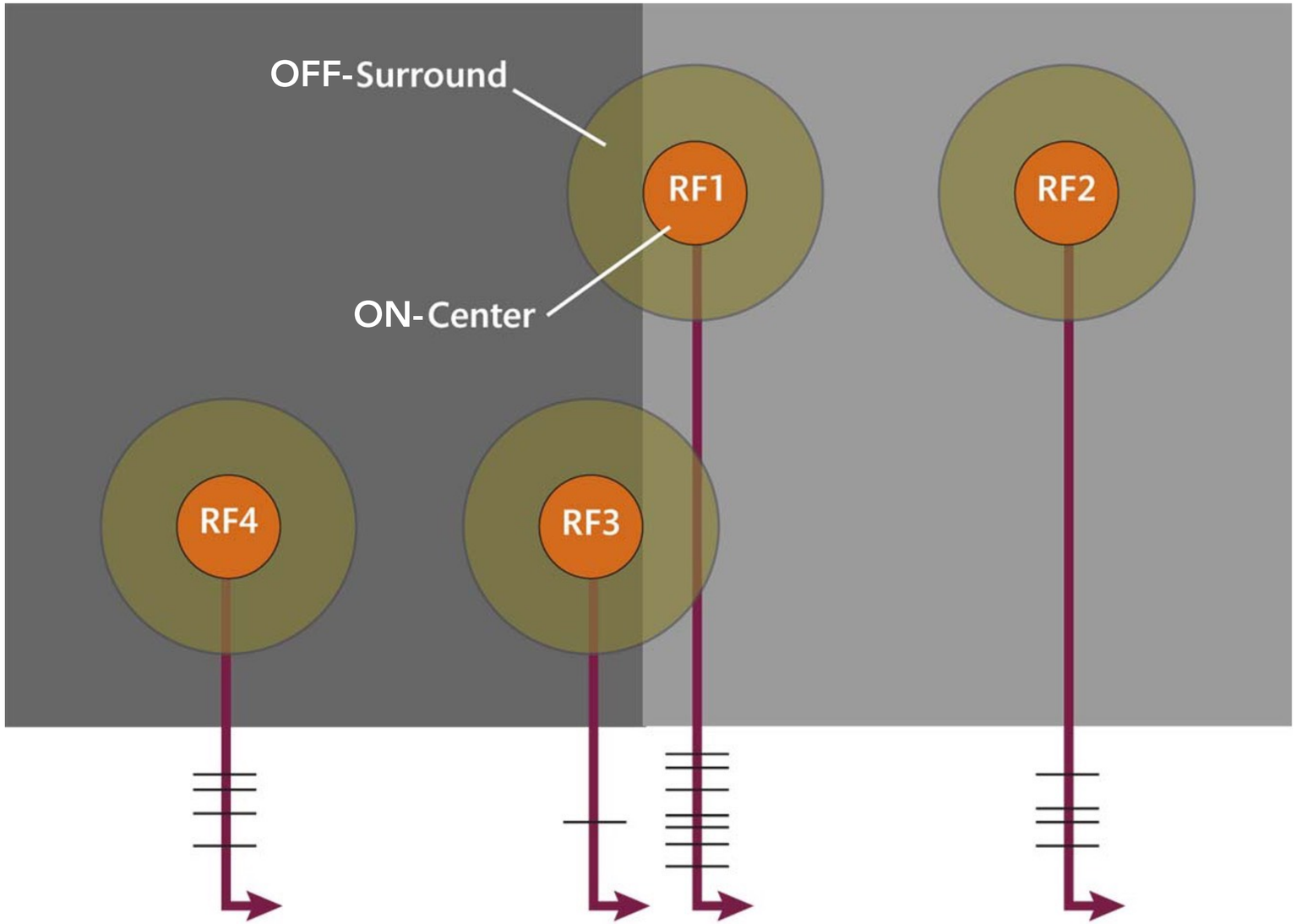


Mach Band/Chevreul Illusion

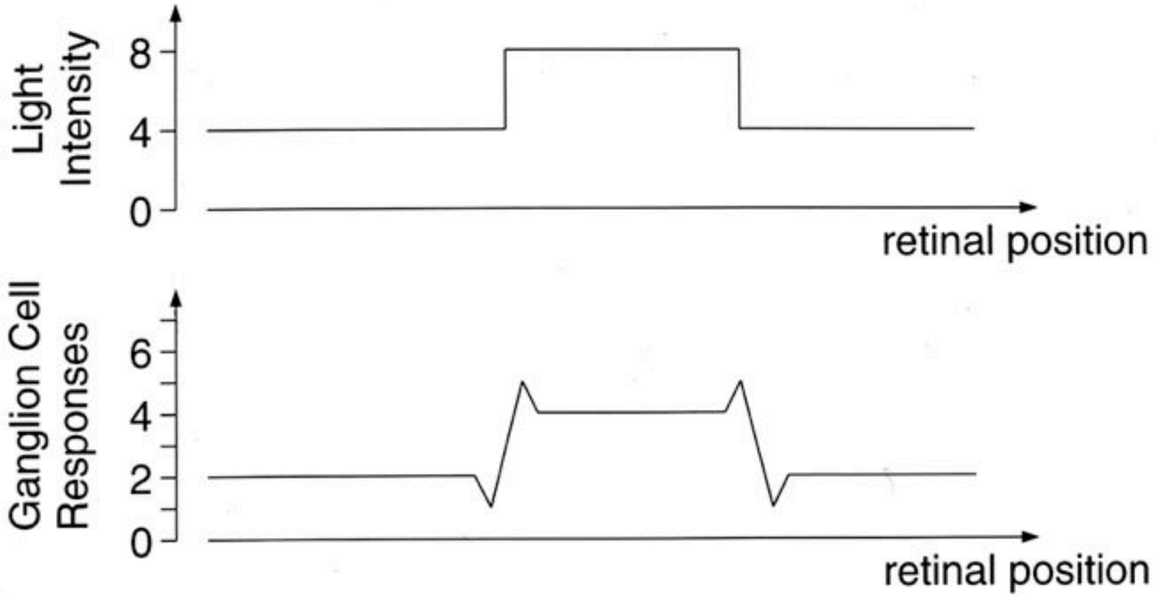


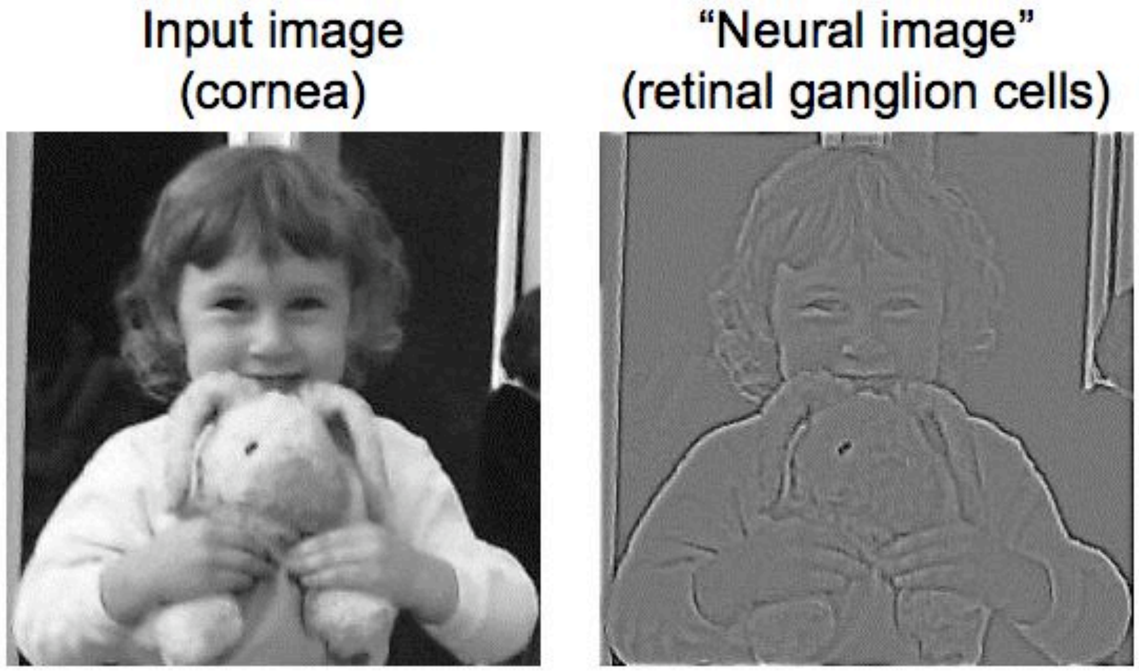
http://www.marekfiser.com/Blog/Is-16-million-colors-enough

Mach Band/Chevreul Illusion



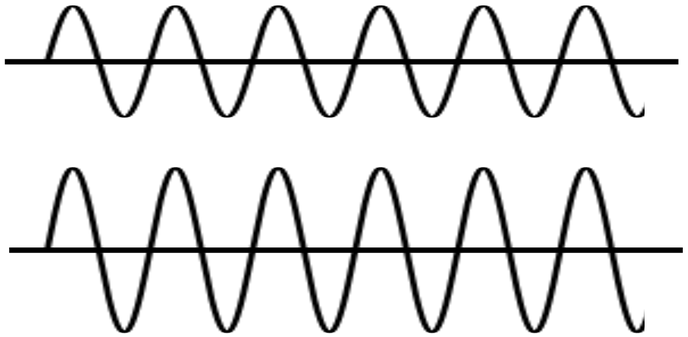
Encoding Contrast Allows Us to Detect Edges





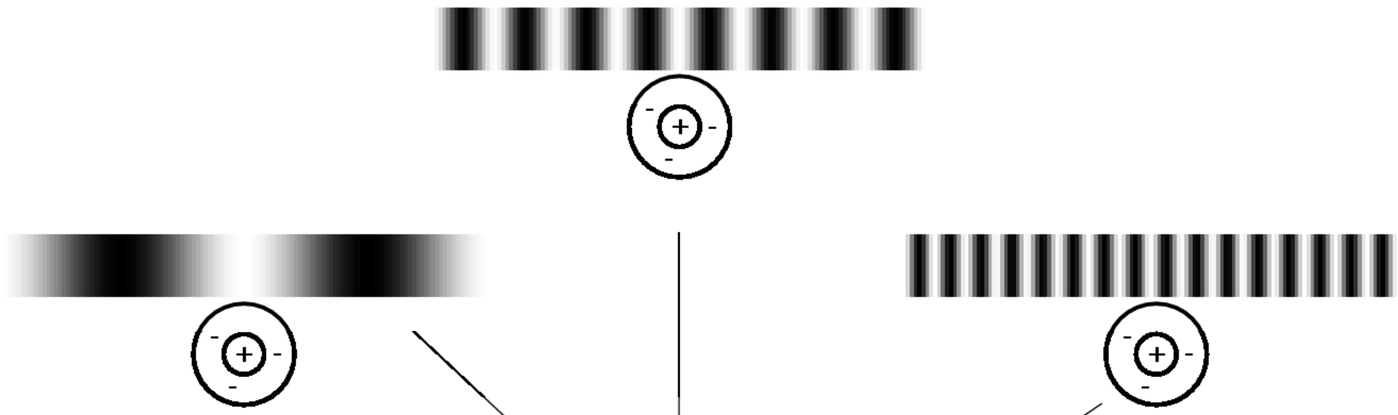
https://www.cns.nyu.edu/~david/courses/perception/lecturenotes/ganglion/ganglion.html

(Michelson) Contrast Sensitivity Function



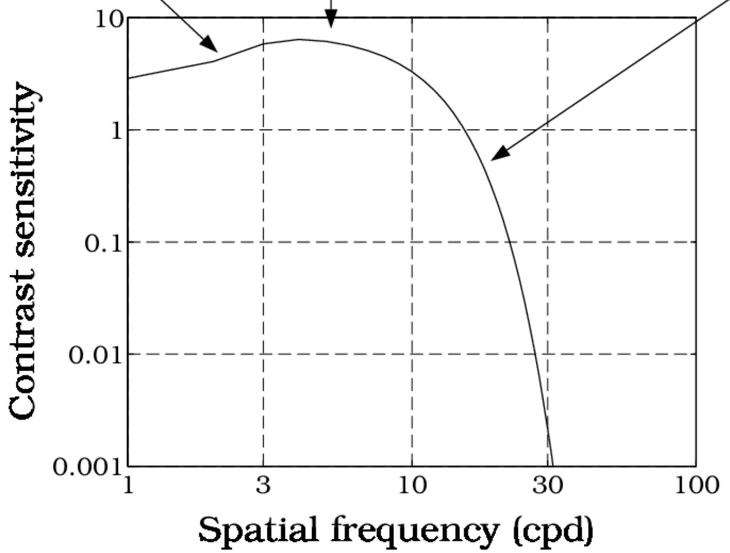
Lower contrast

Higher contrast



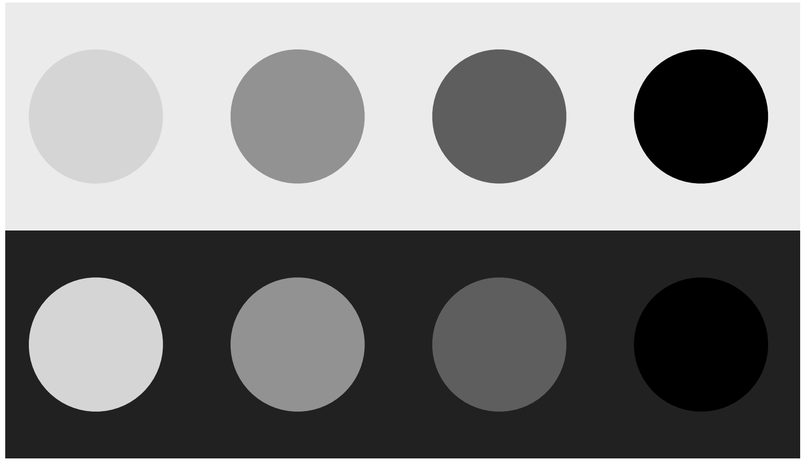
= 1/Threshold

= level of contrast needed to reach
a criterion level of RGC response



Wandell, FoV 1995

Now How To Explain This?



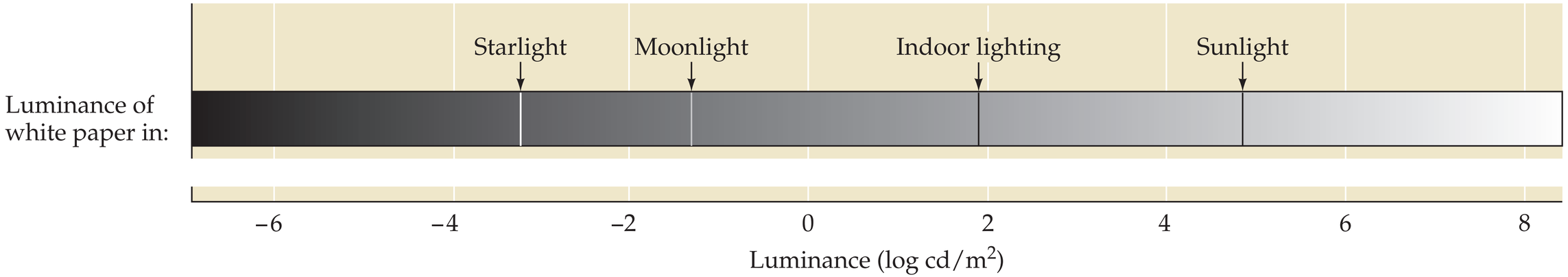
- Two exactly same rows of grays, but dark color looks darker against brighter background and vice versa.
- Maintaining local contrast is in general important in photography; otherwise a photo looks dull.
- We will have more to say about this in HDR/tone mapping lecture.

Retina Functions and Specializations

- Rods vs. Cones
- Contrast Detection
- Adaptation

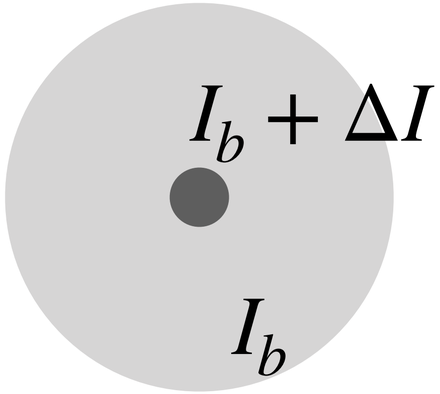
Need For Adaptation

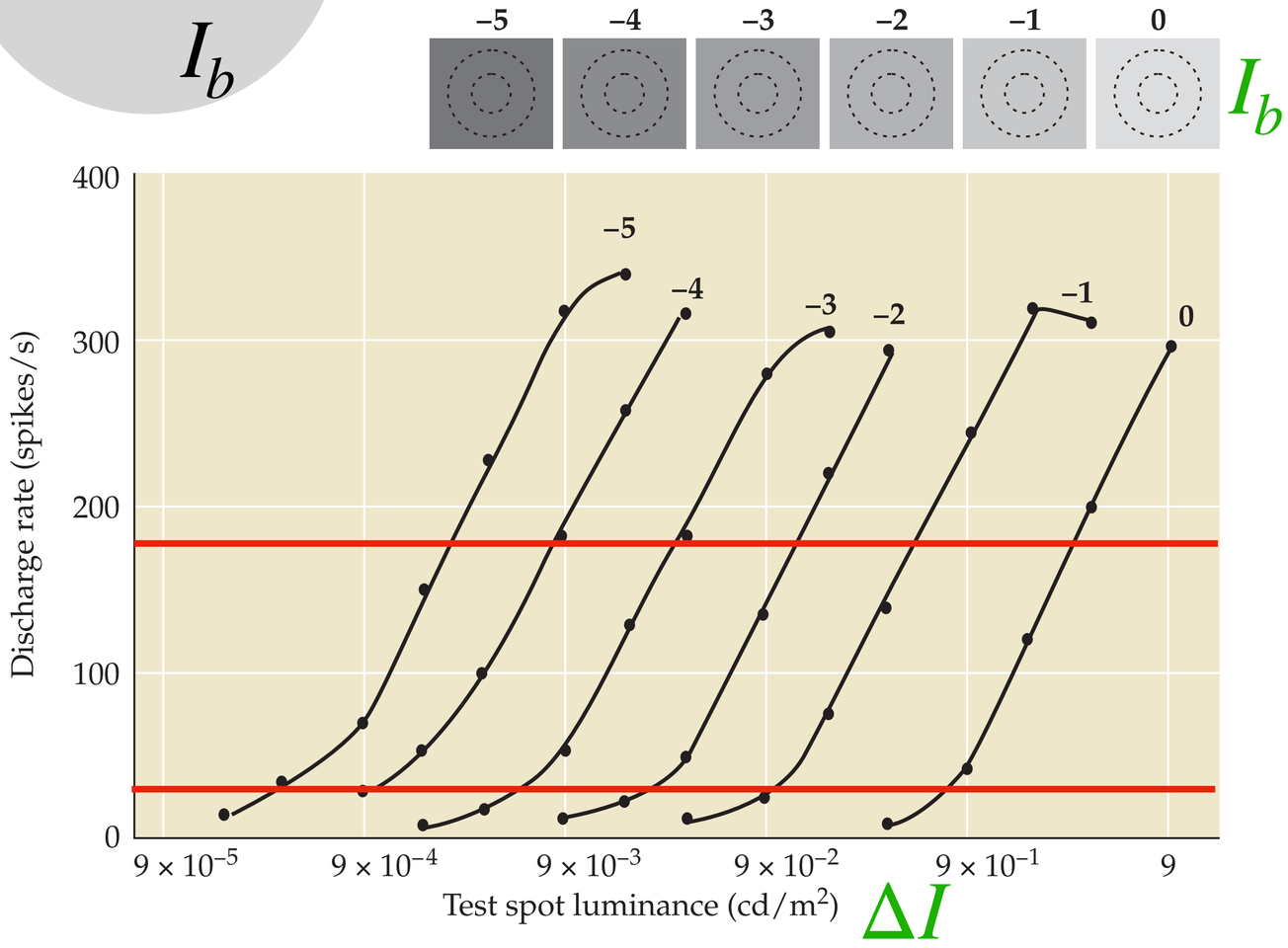
- Absolute light level varies by orders of magnitude, but the range of contrast is roughly constant.
- Adaptation means neurons “discount” absolute light intensities and encode only the contrast information.



RGC Adaptation

- RGCs use a small dynamic range to reliably signal contrast information across a much wider dynamic range in ambient light level.
- Another perspective:
  - stronger signal is needed at high light level to produce a criterion level of RGC response.
  - "Desensitization"

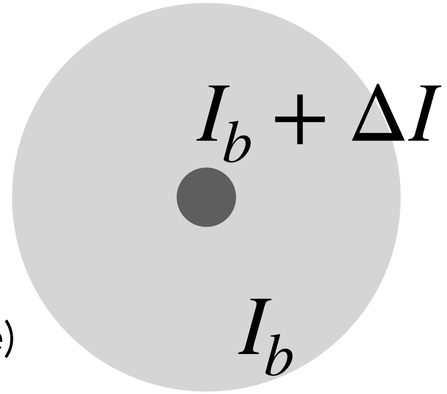


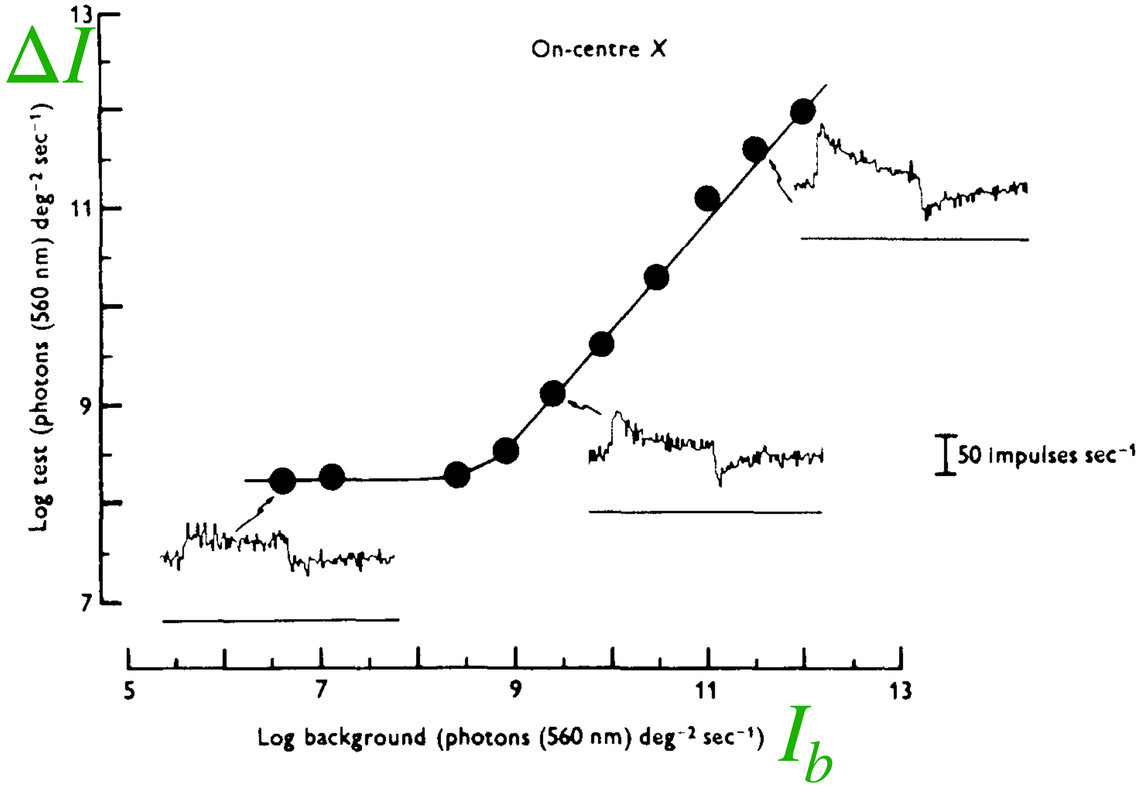


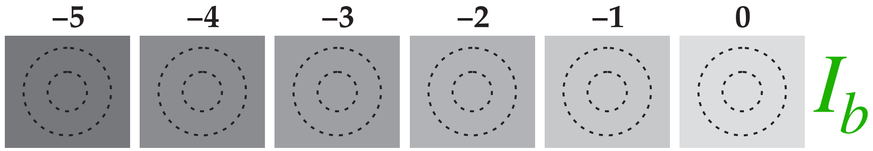
Purves et al. Neuroscience 6ed; Sakmann and Creutzfeldt 1969

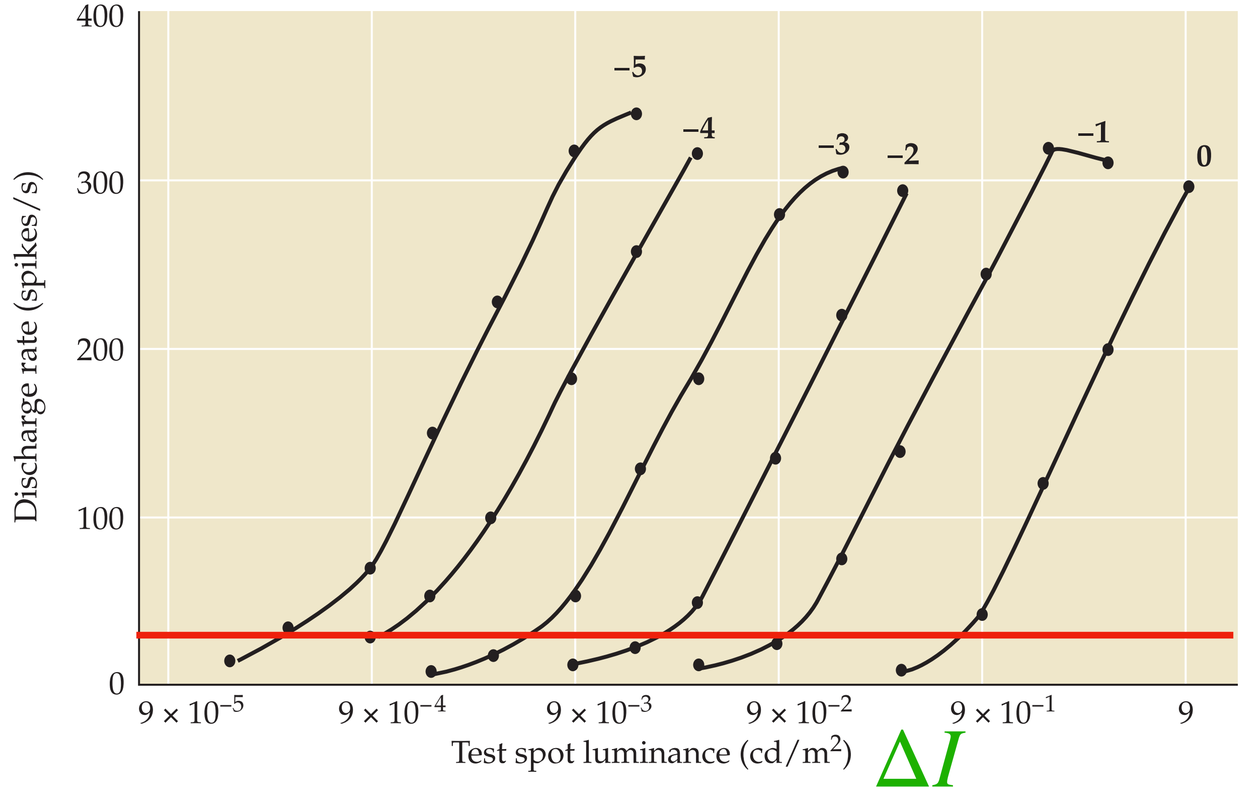
RGC Adaptation

Plots the test light intensity (y-axis) that's needed to produce a criterion level RGC response (35 spikes/s here) under different background light intensities (x-axis)





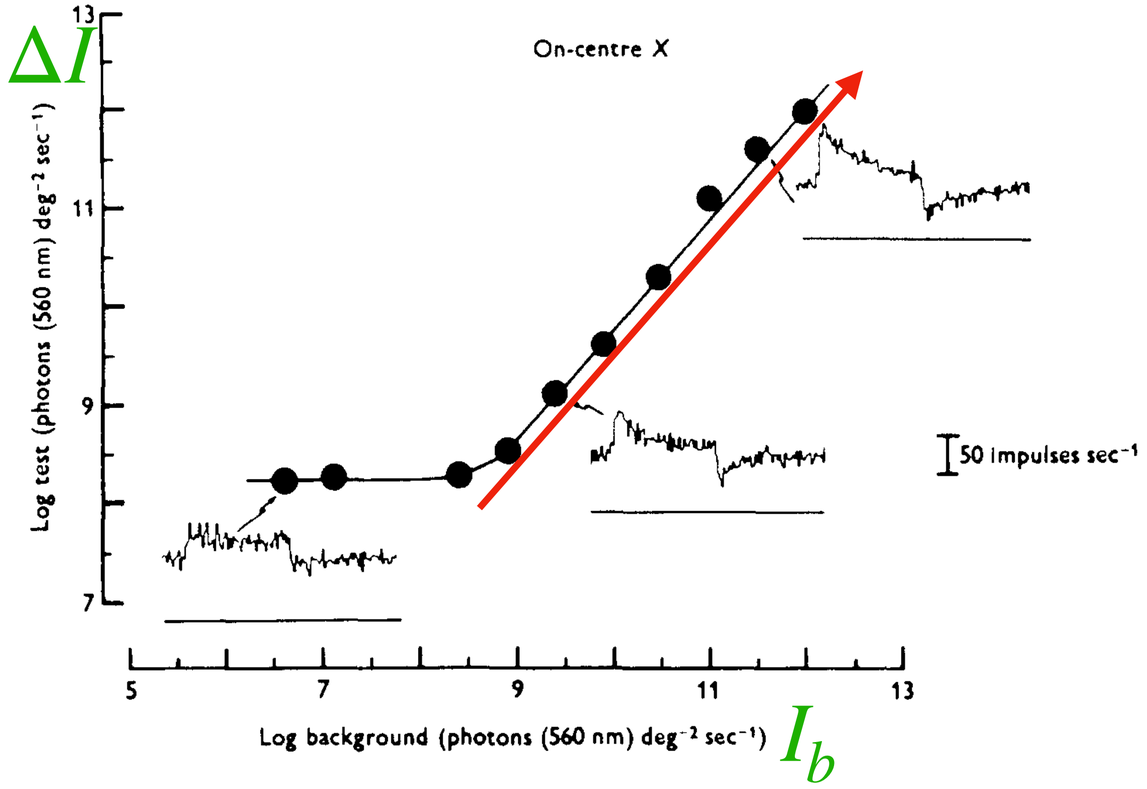


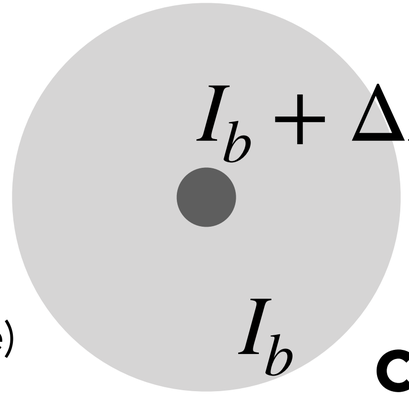


Purves et al. Neuroscience 6ed; Sakmann and Creutzfeldt 1969; Enroth-Cugell et al., 1977;

RGC Adaptation

Plots the test light intensity (y-axis) that's needed to produce a criterion level RGC response (35 spikes/s here) under different background light intensities (x-axis)



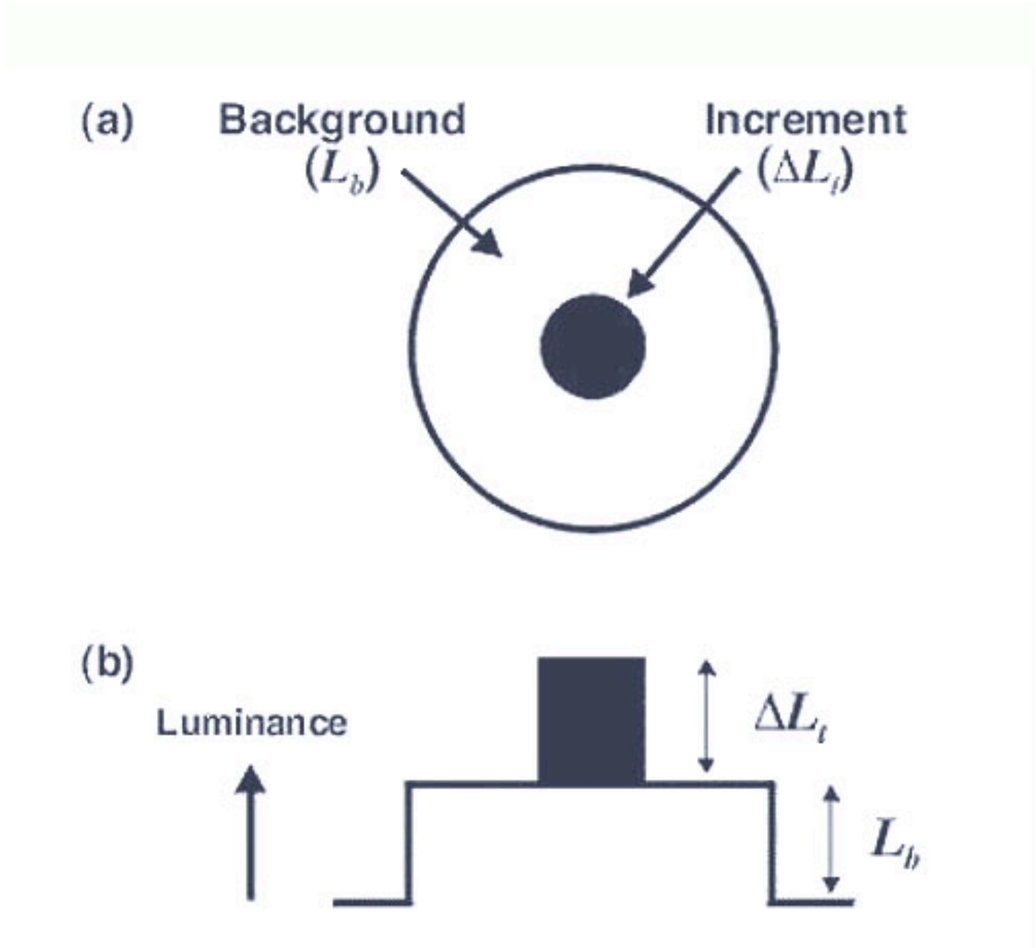


$$\textbf{contrast} = \frac{\Delta I}{I_b} \approx \textbf{constant}$$

- Over a wide range of illumination levels, the contrast needed to produce a criterion level of RGC response is constant.
- So the RGC responses encode contrast information reliably across a large range of ambient light levels.
  - This is called the Weber's Law.

Purves et al. Neuroscience 6ed; Sakmann and Creutzfeldt 1969; Enroth-Cugell et al., 1977;

Human Behavioral Adaptation (Psychophysics)

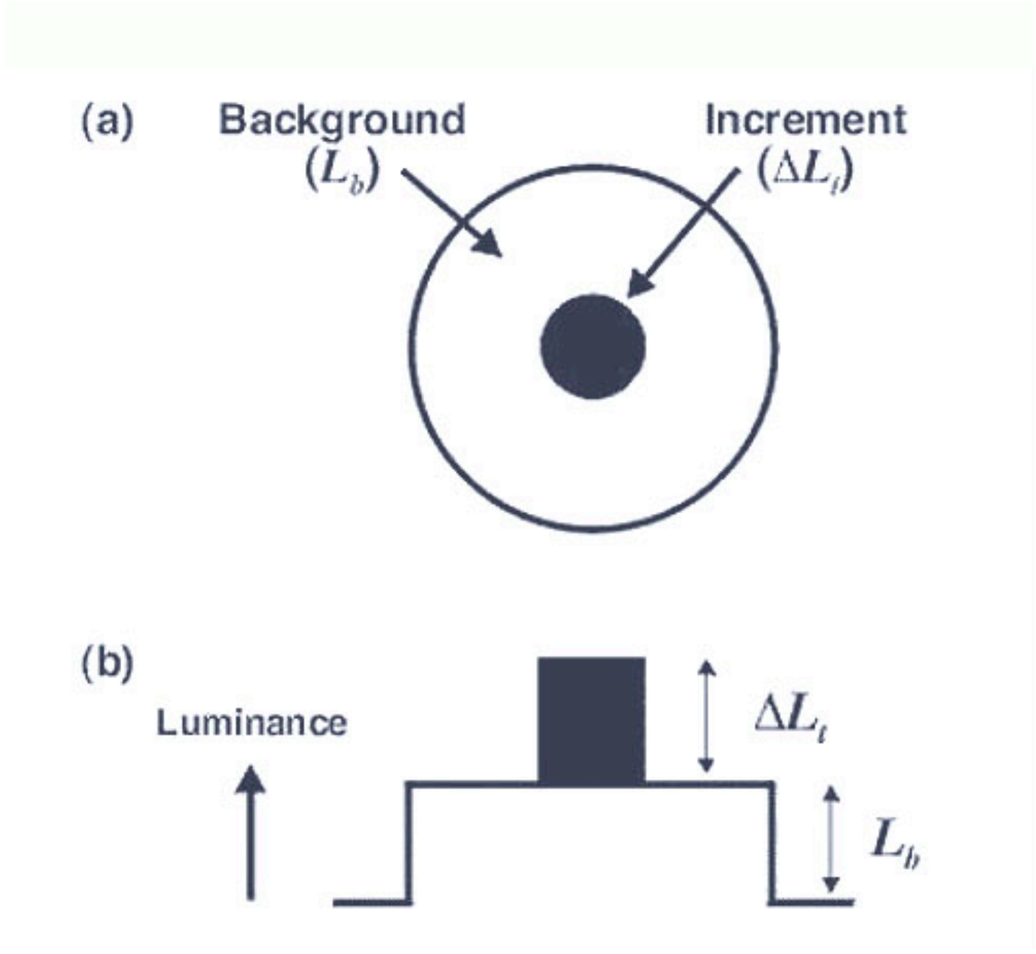


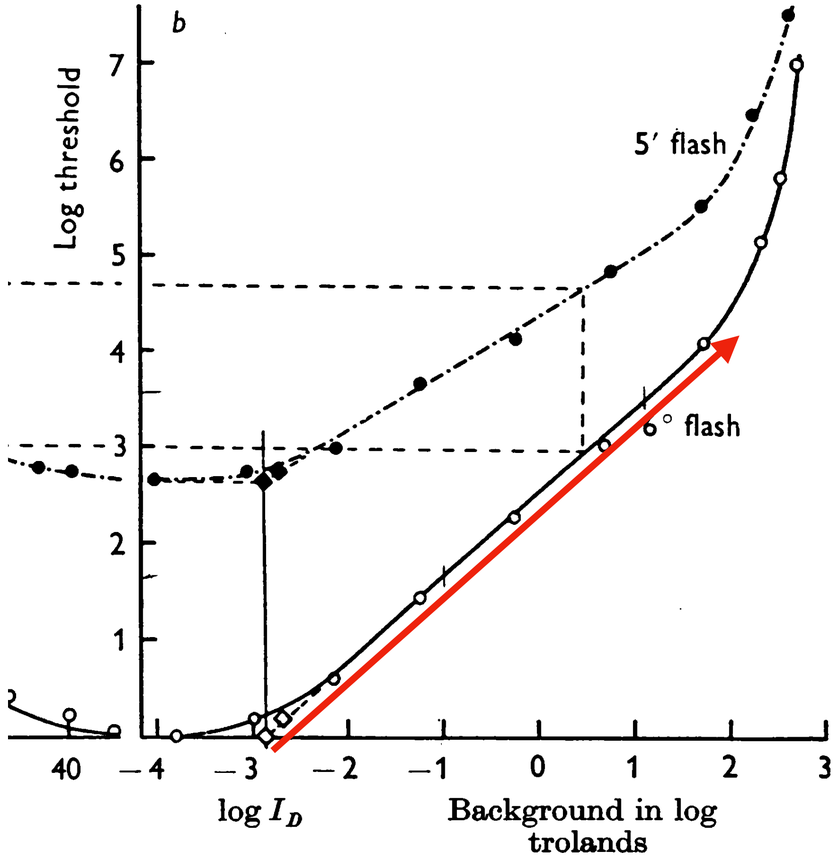
- Increment threshold experiment
  - Given a background light level (L_b), adjust the test light level ΔL_i ("increment") so that the test light is just barely noticeable.
  - ΔL_i is the Just Noticeable Difference (JND) under L_b.
  - Then repeat this for a wide range of background light levels.

https://webvision.med.utah.edu/imageswv/KallDark10.jpg

Human Behavioral Adaptation (Psychophysics)

$$\text{contrast} = \frac{\Delta L_i}{L_b} \approx \text{constant}$$

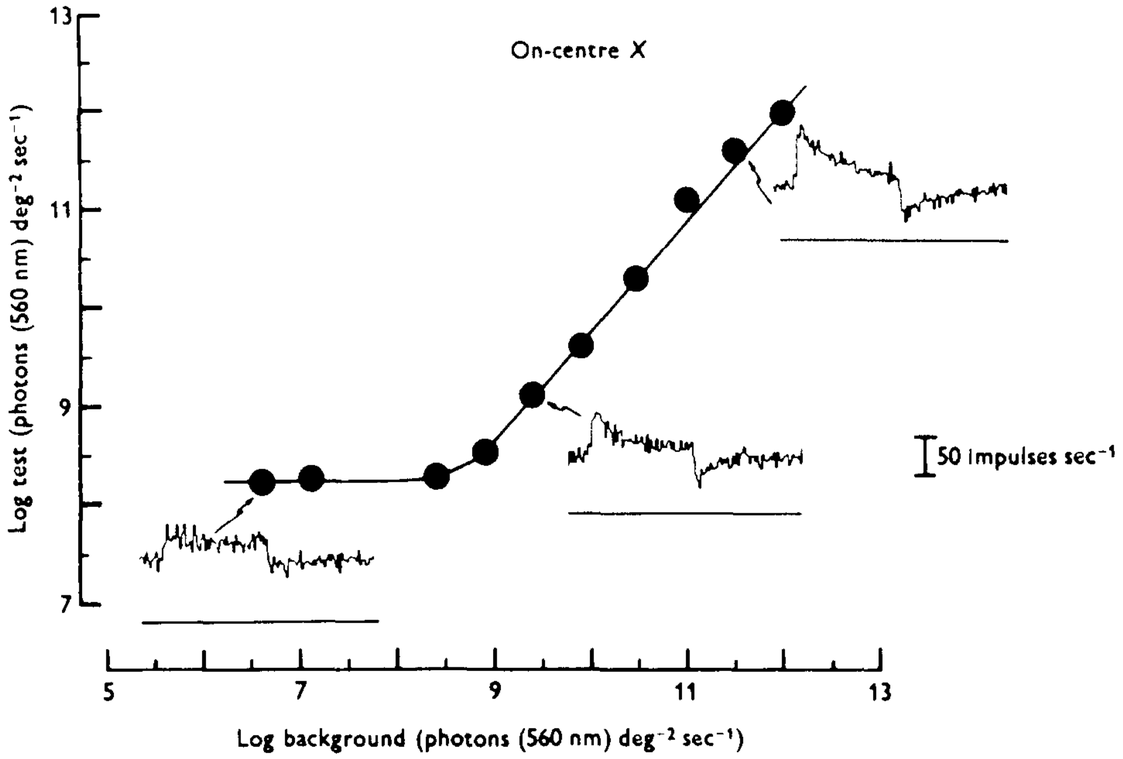




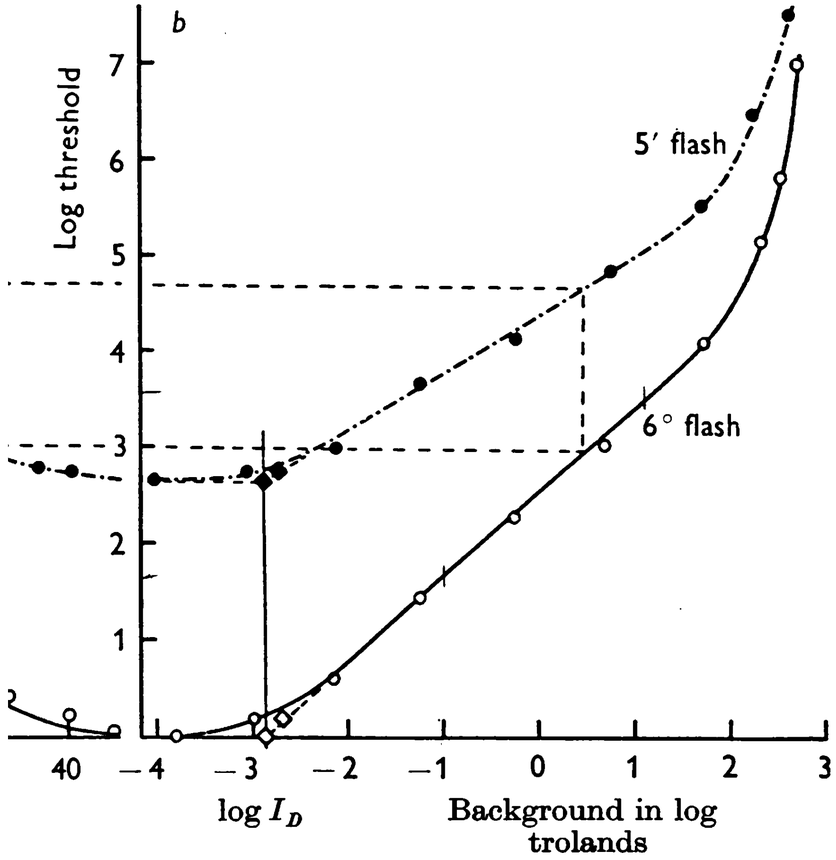
Blakemore & Rushton 1965

RGC and Human Behavioral Adaptations Match

Contrast needed to stimulate RGC is constant across background levels



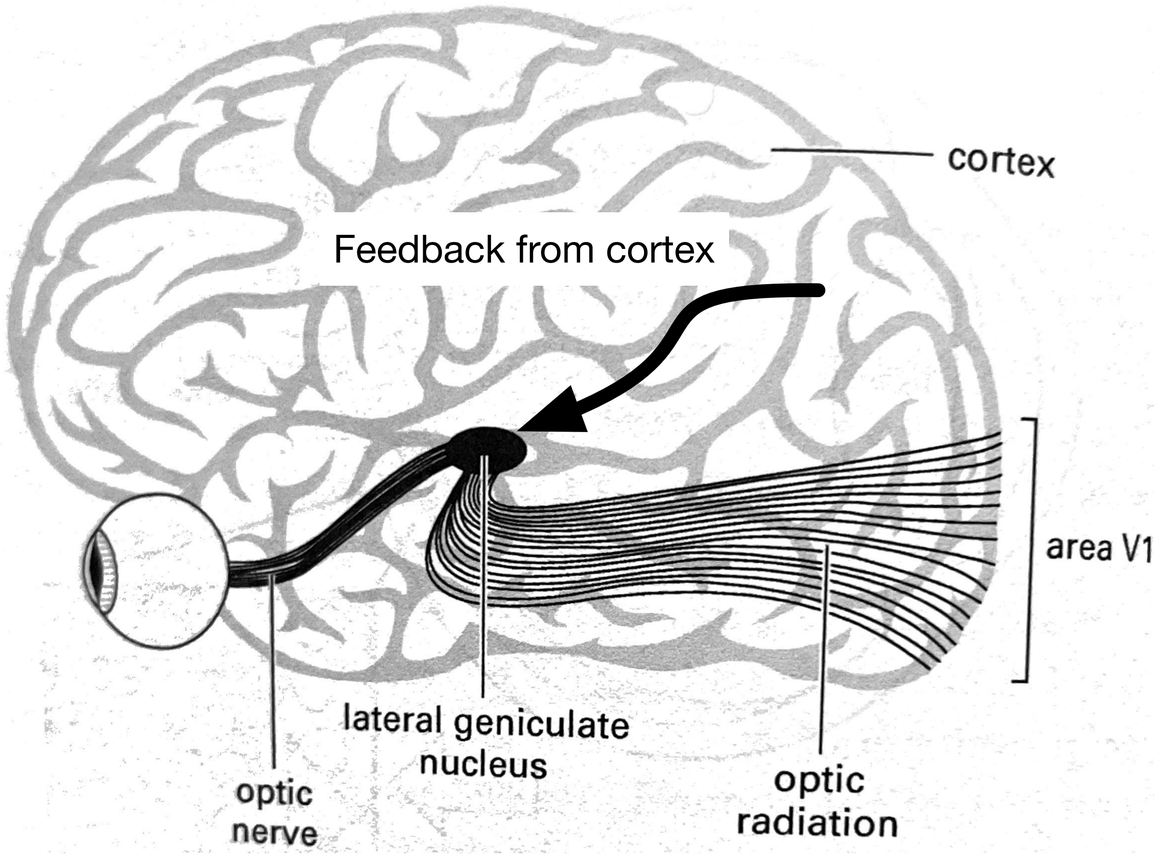
Constant needed to be noticeable by humans is constant across background levels

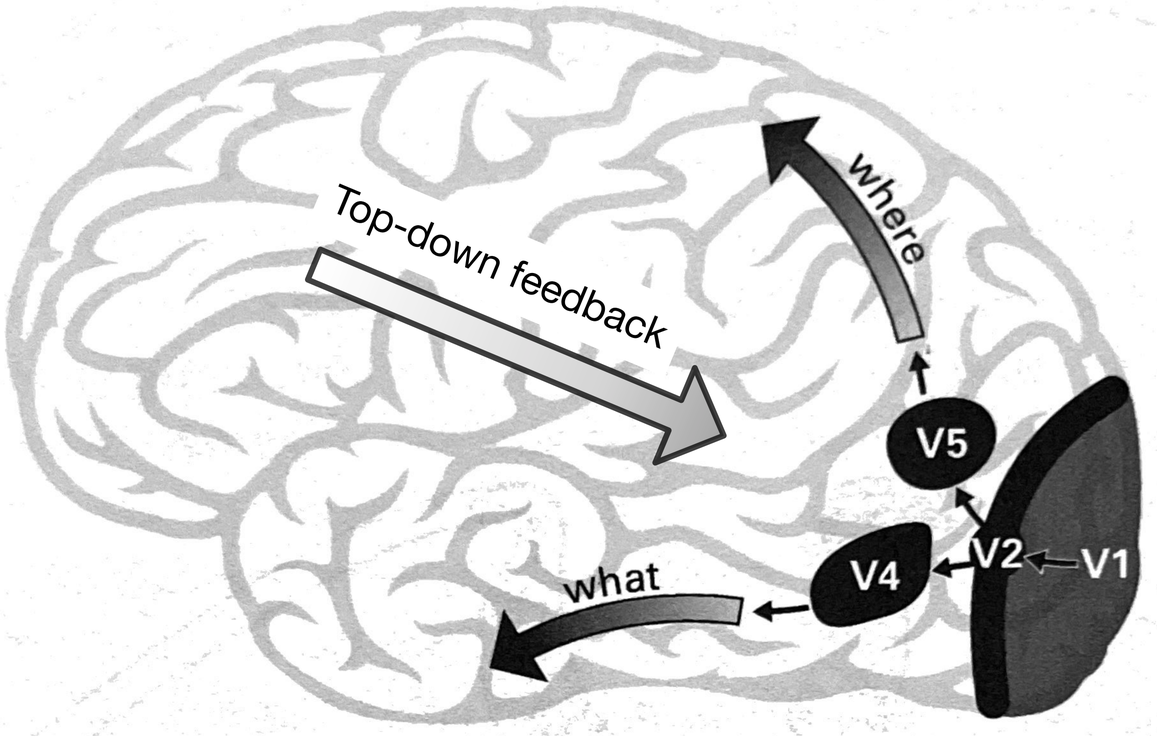


Enroth-Cugell et al., 1977; Blakemore & Rushton 1965

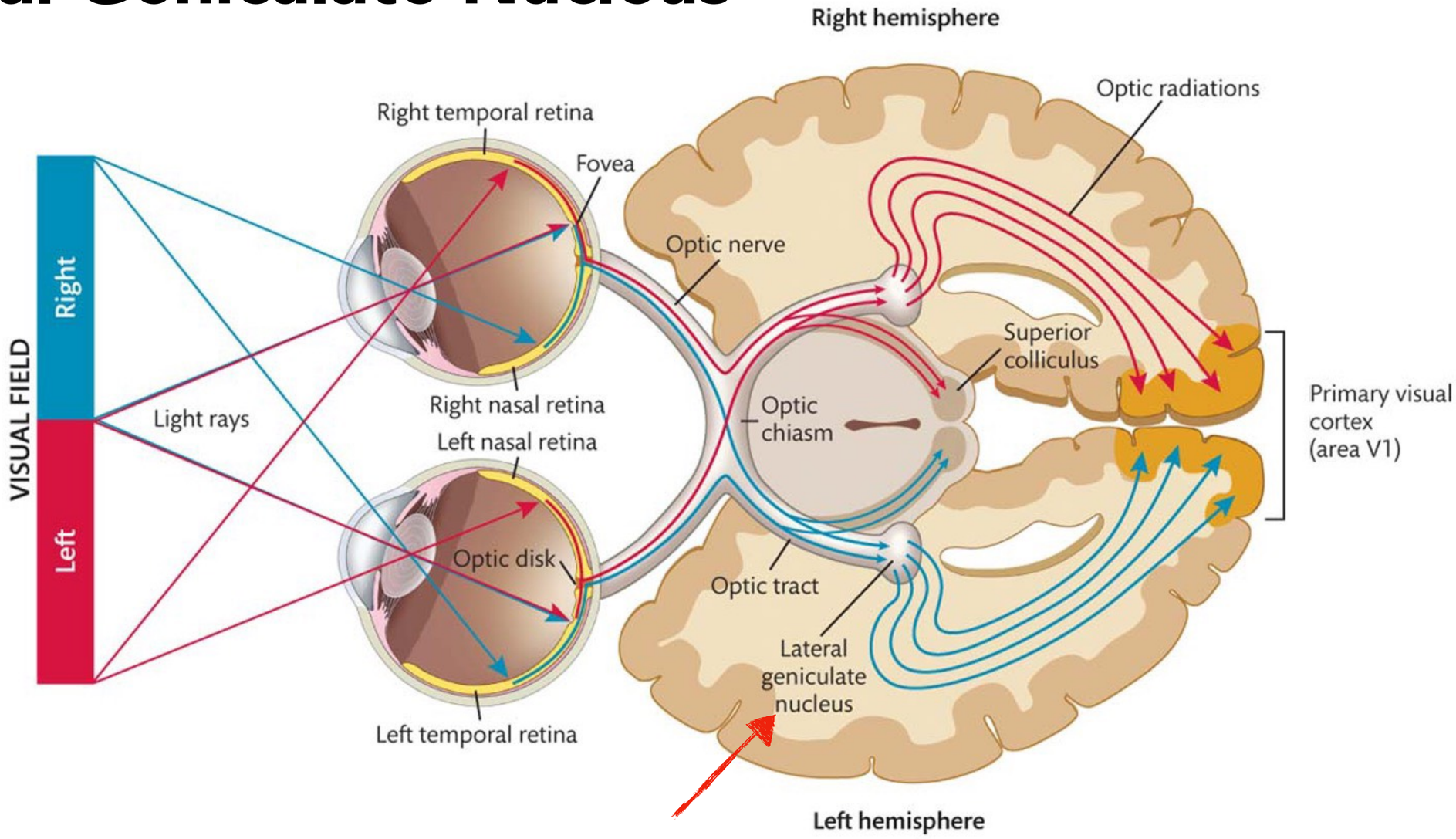
Post-Retinal Processing

LGN + Cortex


cortex
Feedback from cortex
area V1
lateral geniculate nucleus
optic nerve
optic radiation

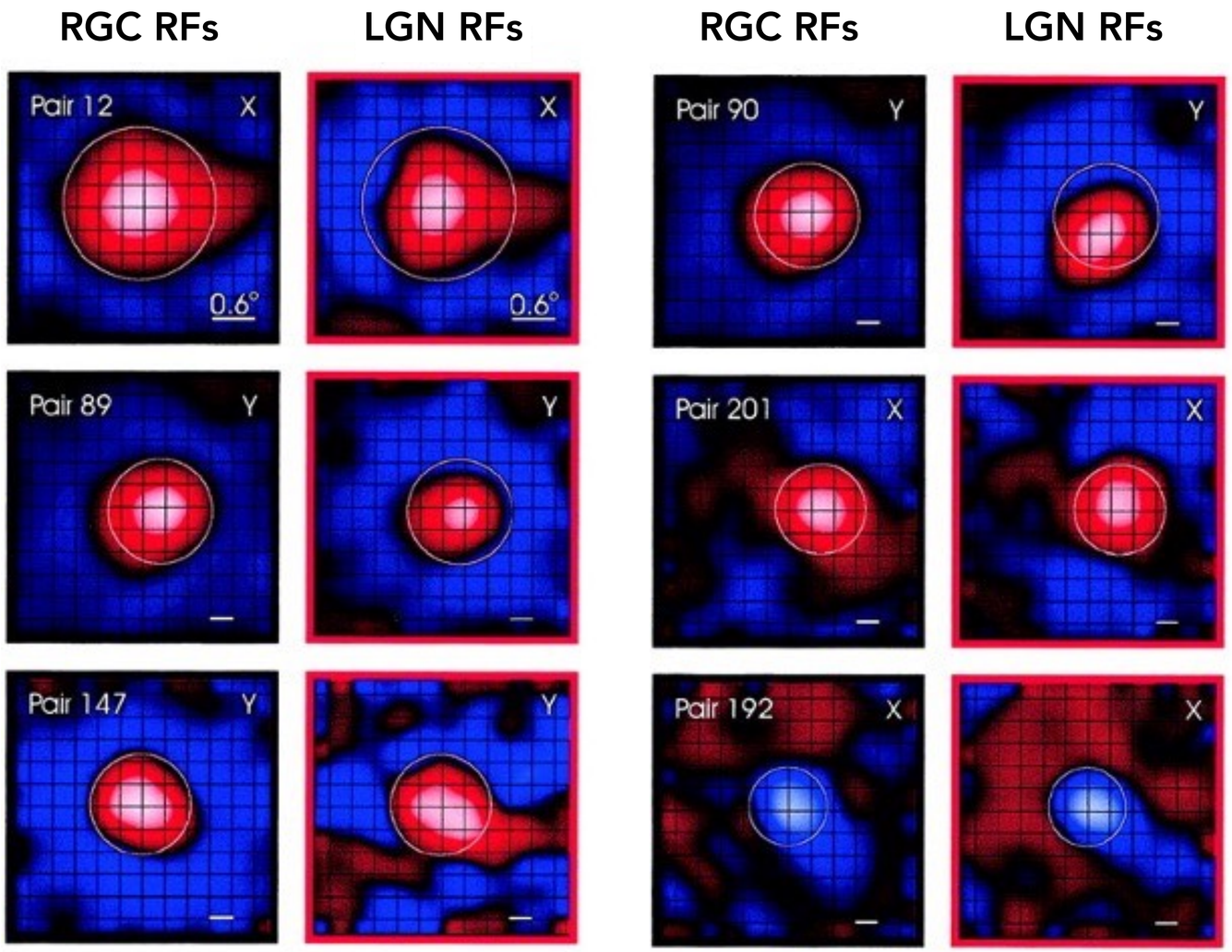

Top-down feedback
where
what
V5
V4
V2
V1

Lateral Geniculate Nucleus



Gather signals from one hemi-field and send it to the other side of the brain

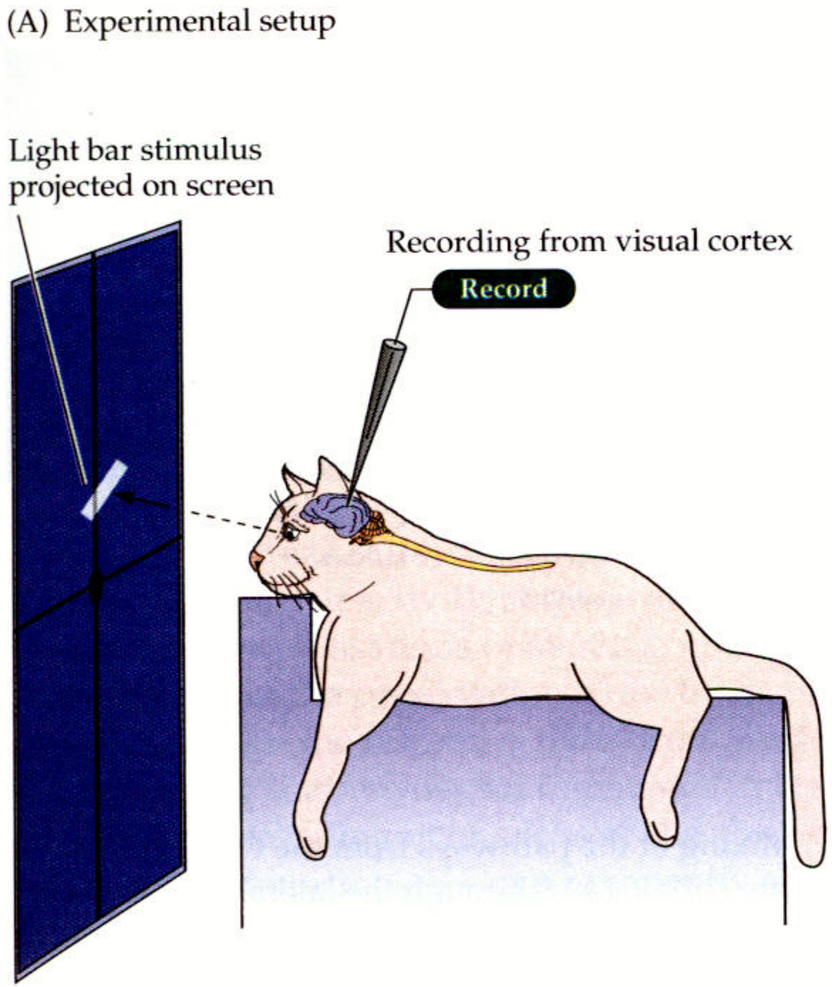
LGN Neurons and RGCs Have Similar RFs

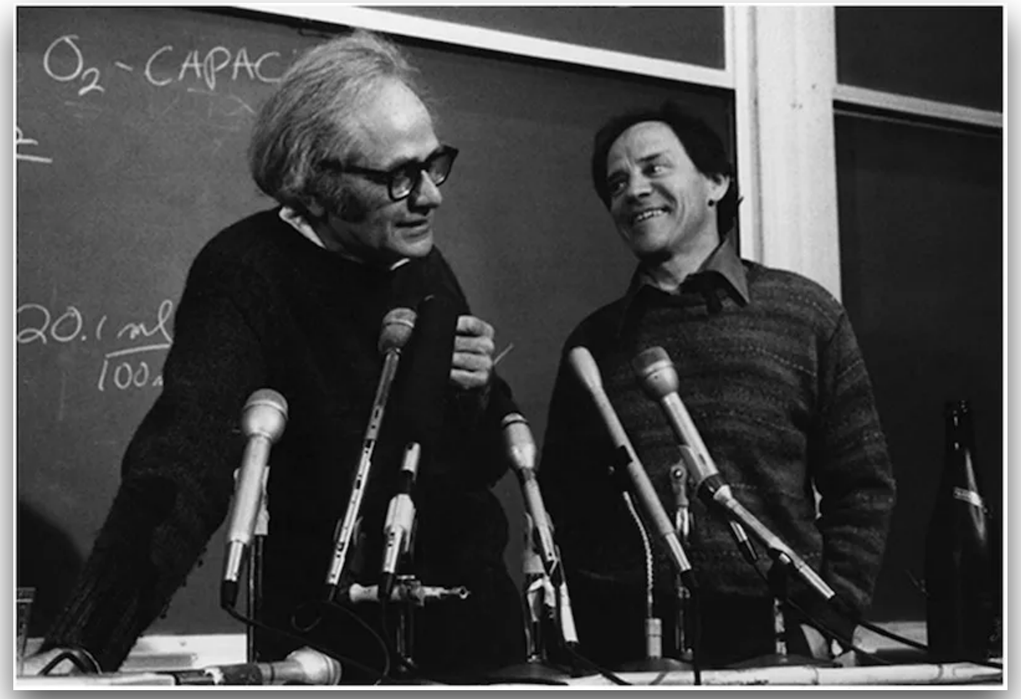


- Because RGCs directly project to LGN neurons without much processing.
  - For instance, Midget RGCs directly project to Parvocellular neurons in LGN, and Parasol RGCs project to Magnocellular neurnos in LGN.

Usrey et al, 1999

Architecture of Primary Visual Cortex (V1, Striate)

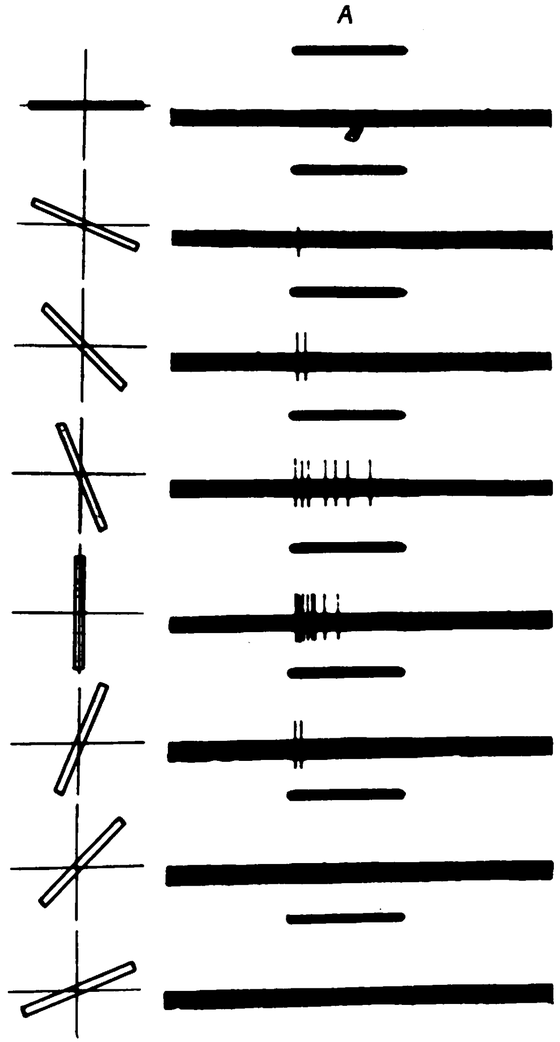


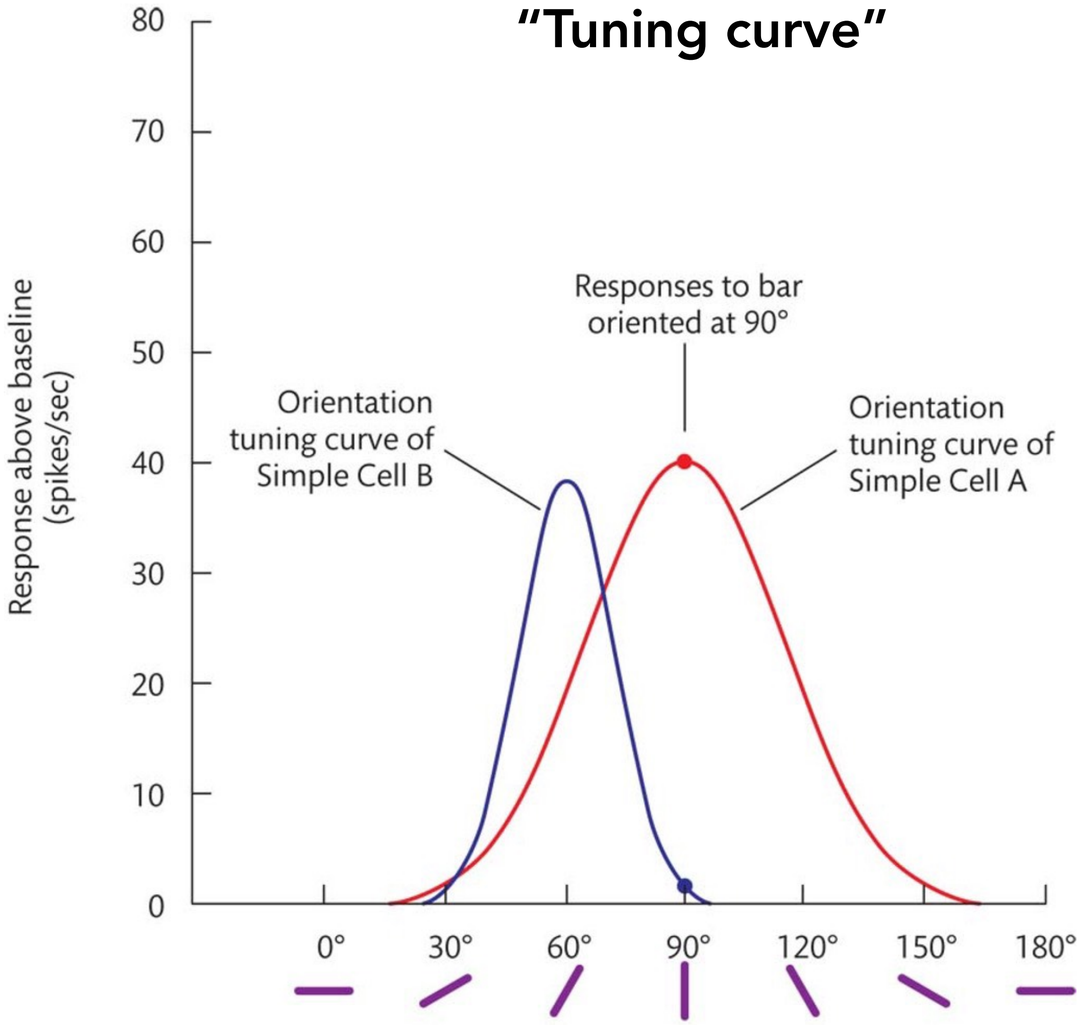


Hubel and Wiesel
(1981 Nobel Prize)

Hubel & Wiesel, 1977

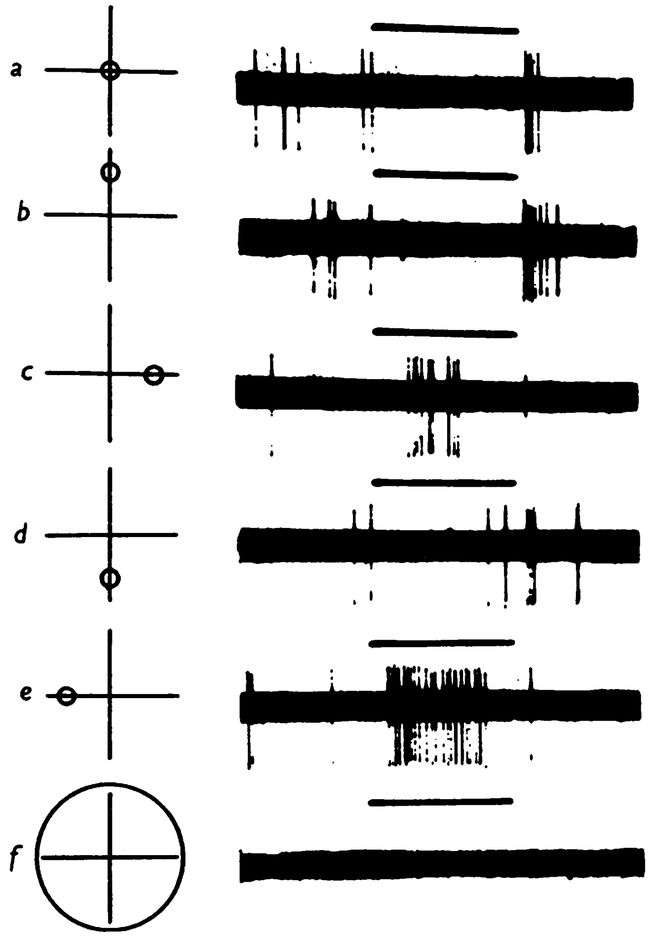
V1 "Simple Cells" Are Orientation Selective

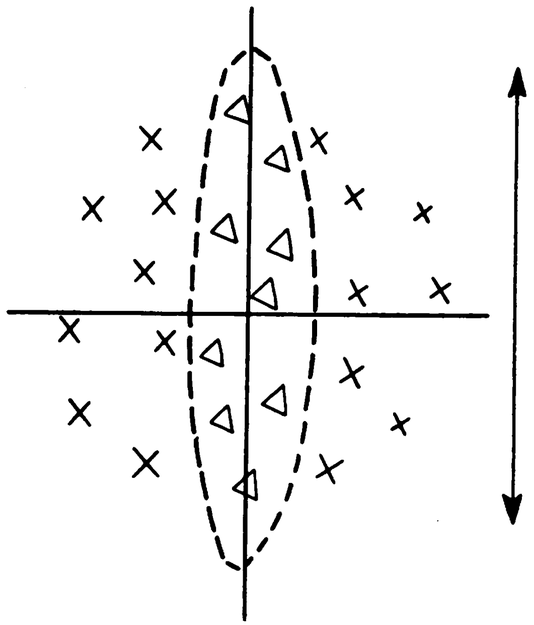




Hubel & Wiesel, 1959; Yantis and Abrams, 2ed

Their Receptive Fields are Oriented



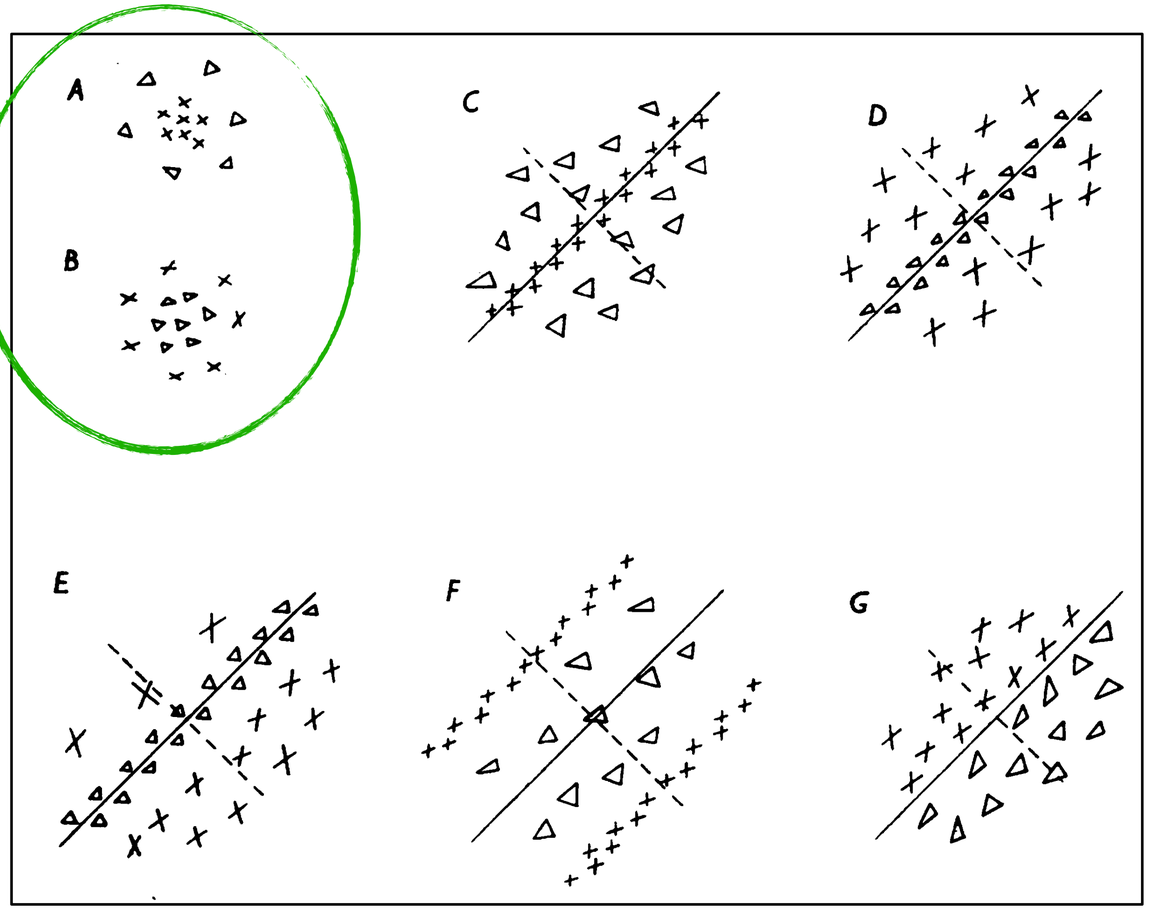


- Use a spot light to probe the receptive field structure.
- Simple cells' receptive field is oriented.
  - In this case, an inhibitory central area and excitatory flanking areas.
  - There other other simple cells whose excitatory vs. inhibitory areas are oppositely organized.

Hubel & Wiesel, 1959

Typical Receptive Fields in V1 Simple Cells

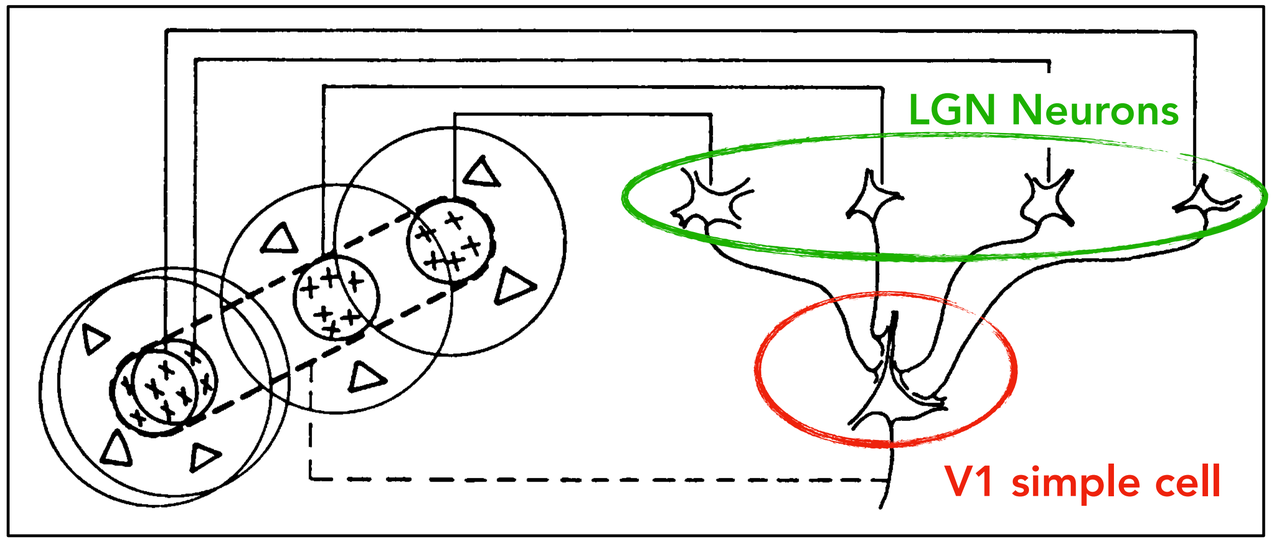
RGC/LGN RFs



- 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.

Hubel & Wiesel, 1962

How Do They Acquire Their Oriented RFs?

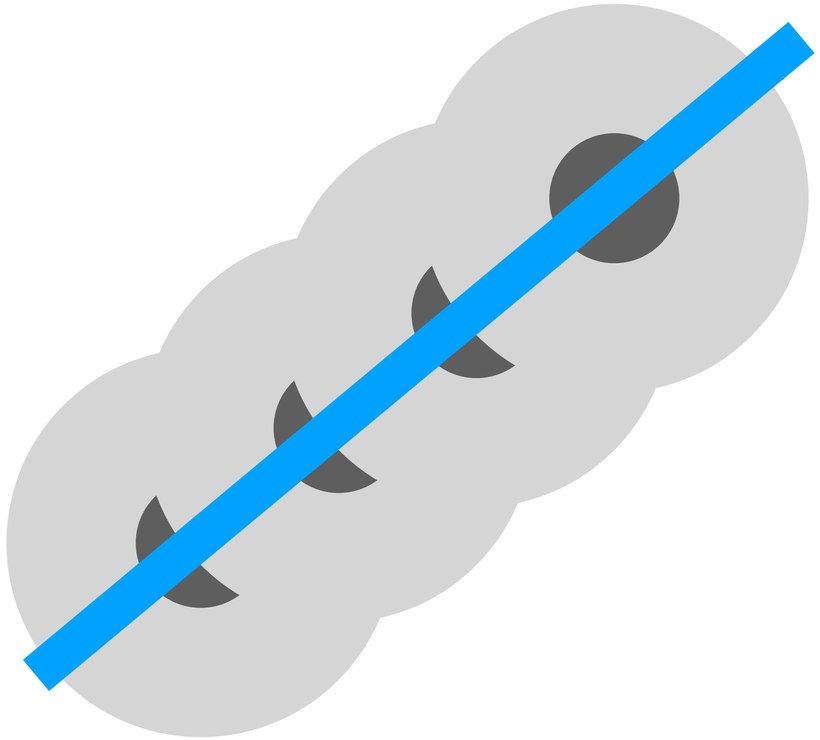


- LGN neurons have center-surround RFs.
- A V1 simple cell gets its information from LGN neurons whose RFs abut on retina.
- A simple linear superimposition of the center-surround RFs gives us an oriented RF.

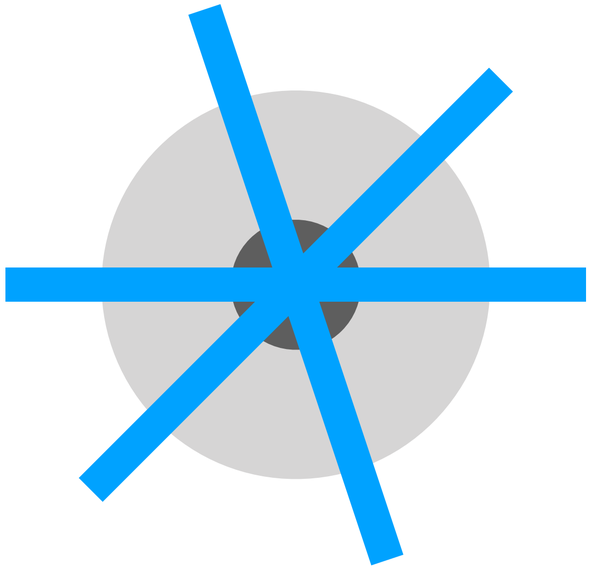
Hubel & Wiesel, 1962

Center-Surround Simply Can’t Encode Orientation

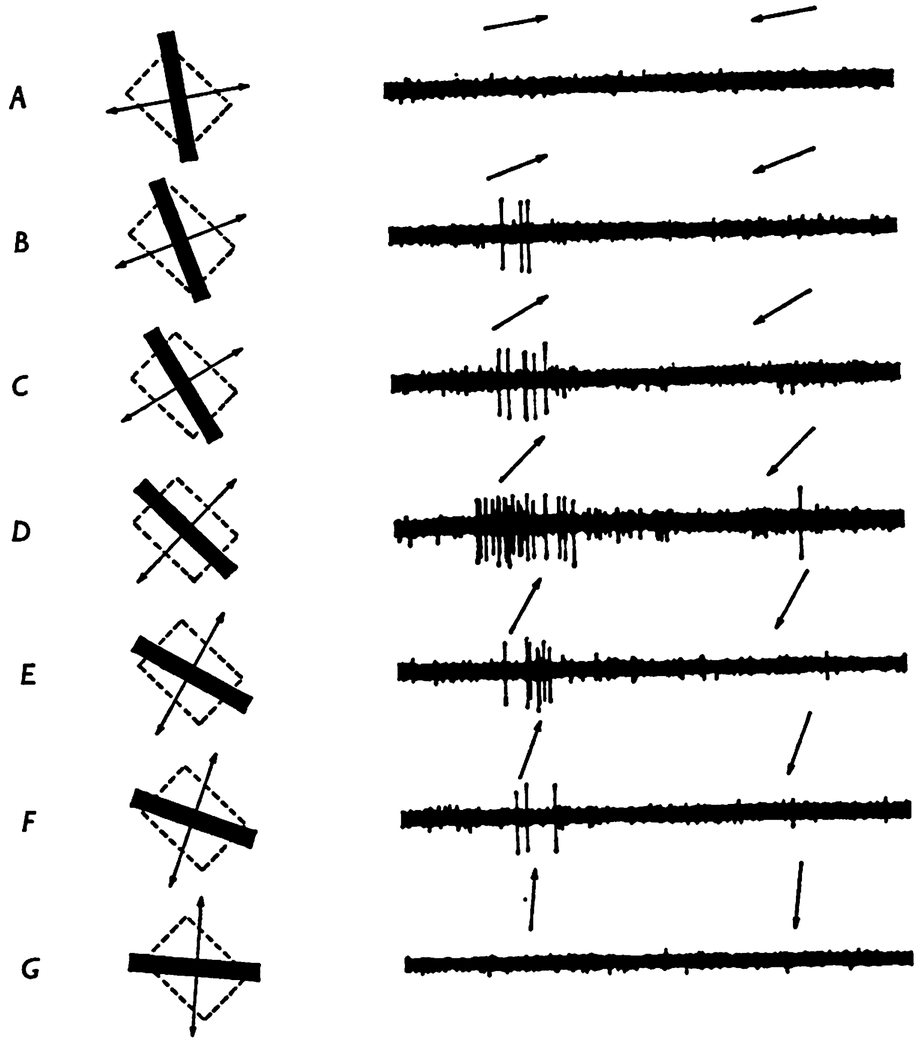
Oriented RF



Center-Surround RF



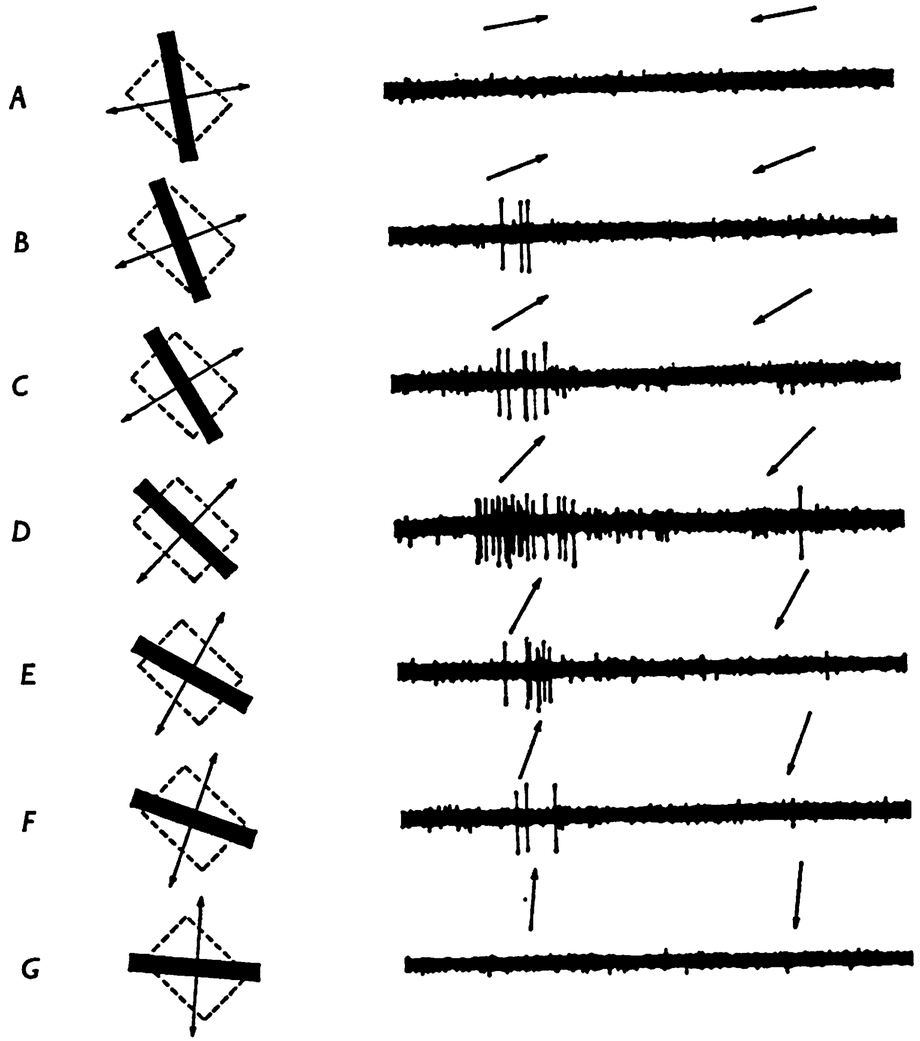
V1 Complex Cells are Sensitive to Motion



- 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

Hubel & Wiesel, 1968

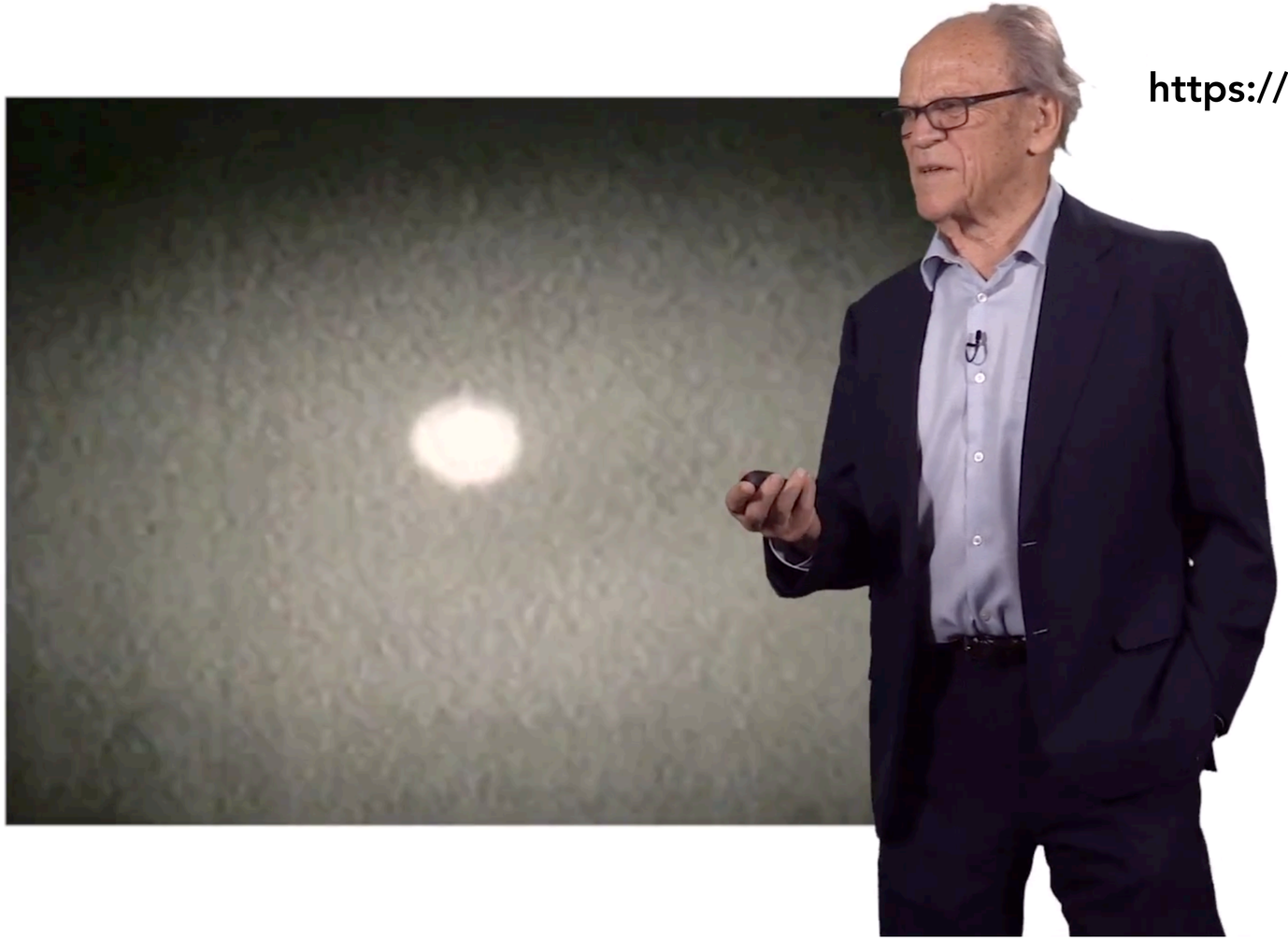
Some V1 Complex Cells are Direction Selective



- 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

Hubel & Wiesel, 1968

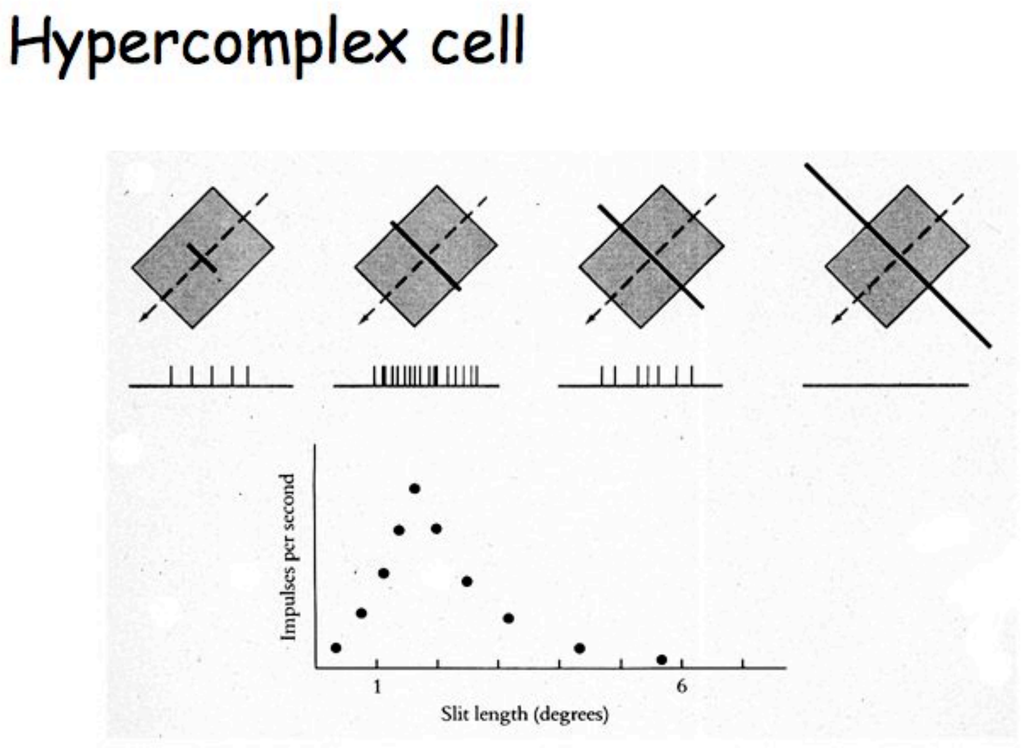
Hear from Wiesel Himself



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

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.

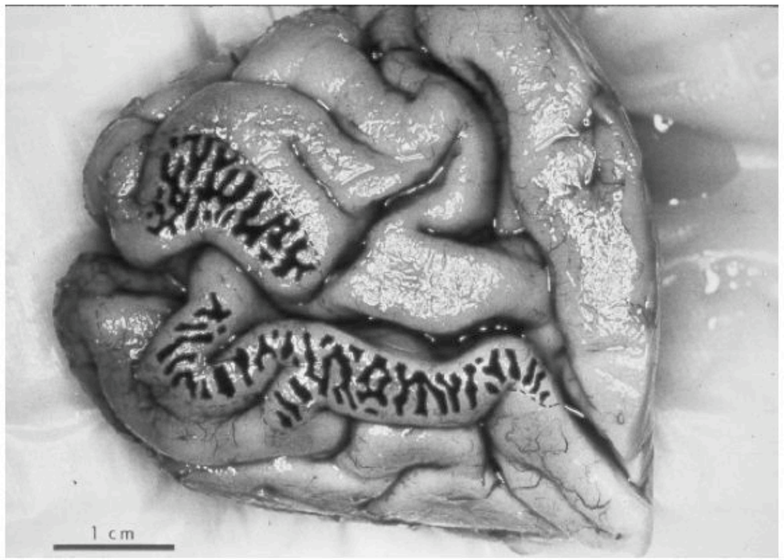


https://www.cns.nyu.edu/~david/courses/perception/lecturenotes/V1/lgn-V1.html

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.
- Monocular vs. binocular cells
  - Some cells respond only to information from left or right eye inputs
  - Others respond to both left and right eye inputs (binocular convergence)

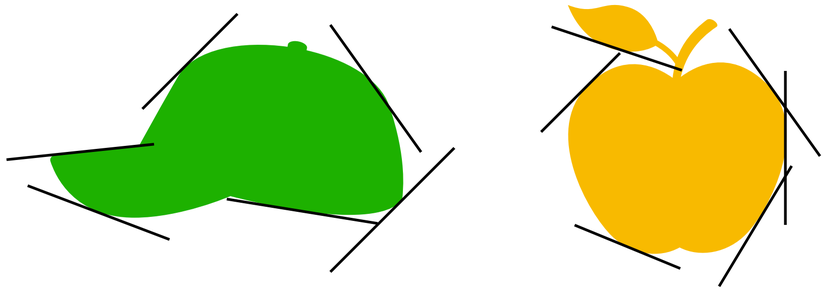
Amblyopia

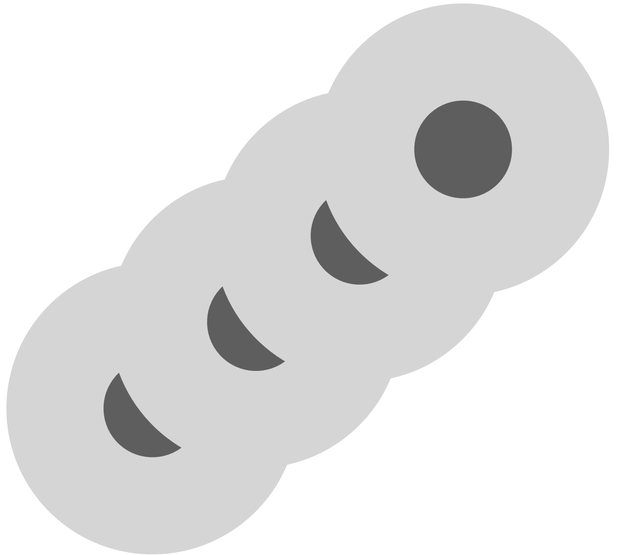


https://www.cns.nyu.edu/~david/courses/perception/lecturenotes/V1/lgn-V1.html

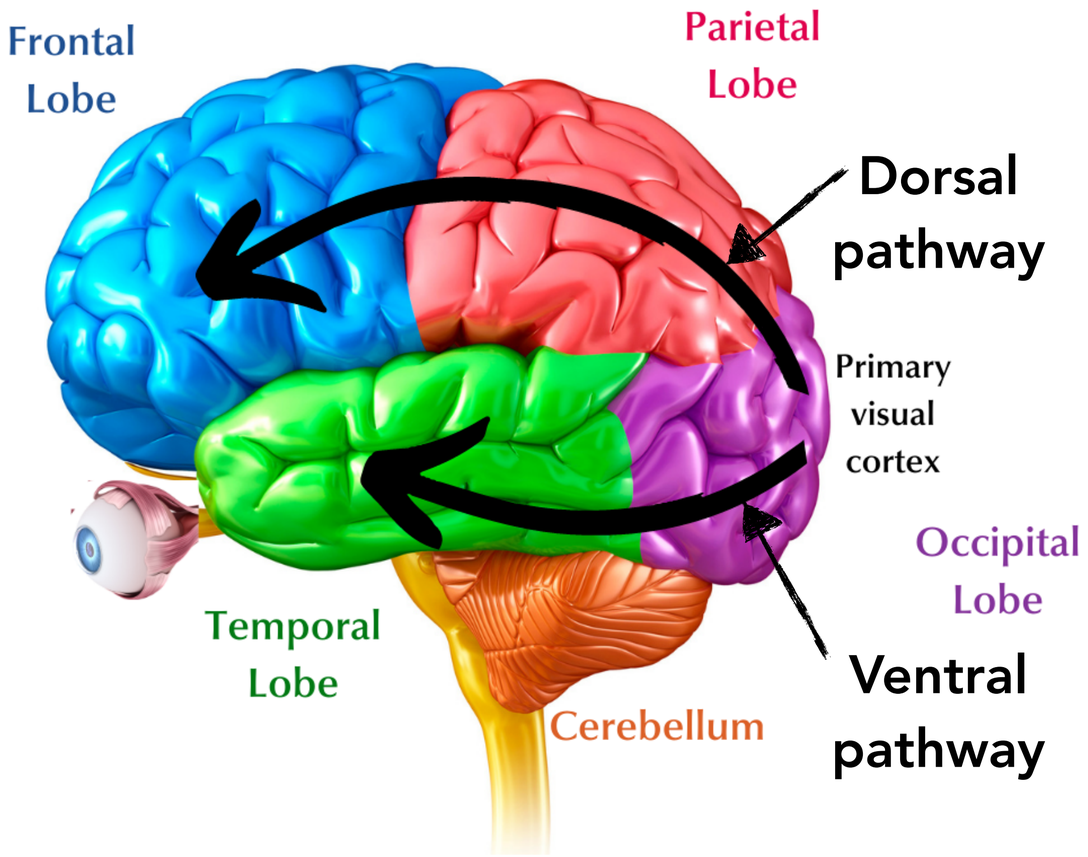
Comparing V1 vs. RGC/LGN

- 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!





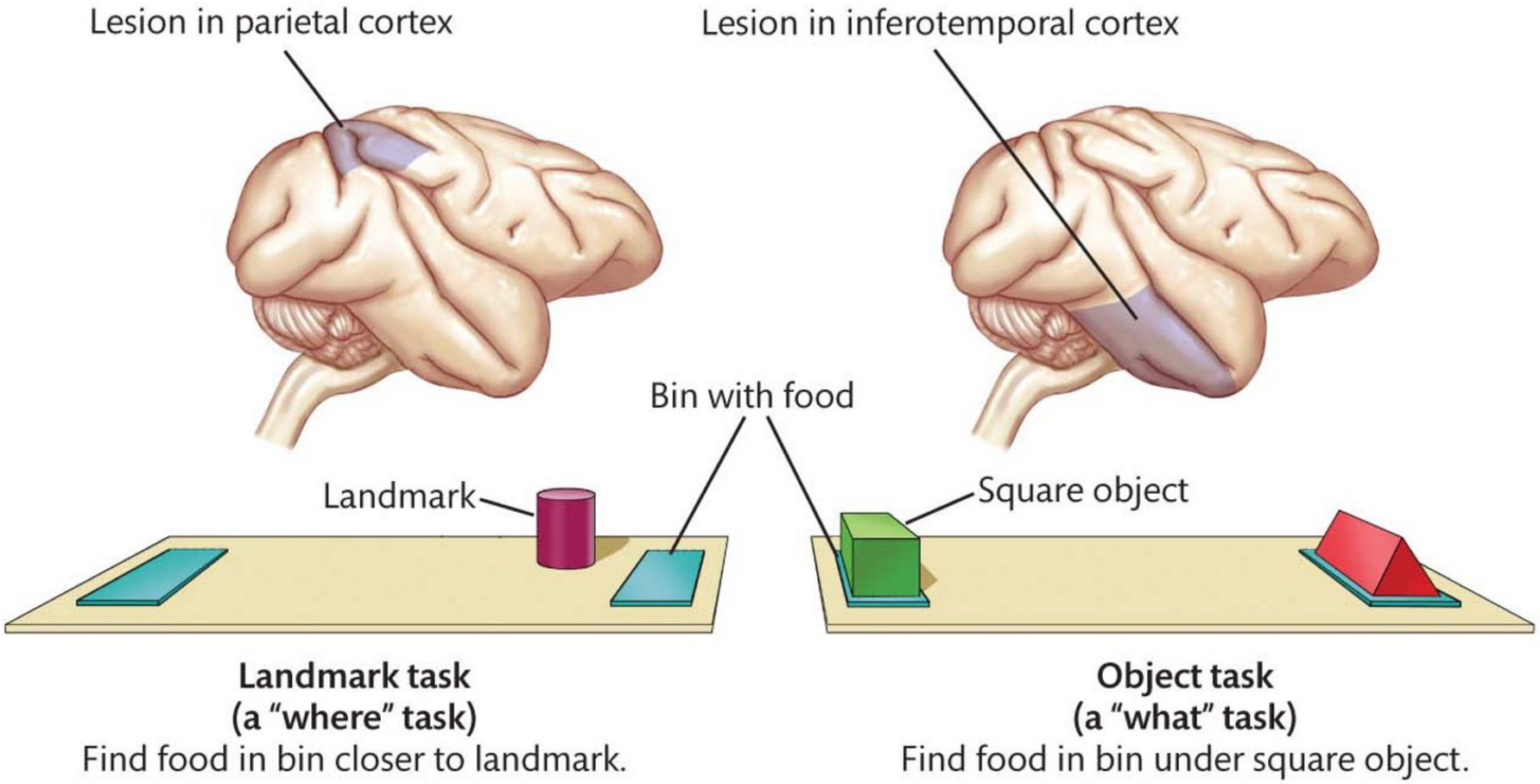
Ventral vs. Dorsal Pathways



- Ventral: “what"?
  - Spatial details
- Dorsal: “where” and “how”?
  - Spatial locations, motion, and guides action
- They interact

https://www.perkins.org/higher-order-visual-pathways-and-the-cvi-brain/

Ablation Study



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