Visual Object Recognition
Computational Models and Neurophysiological Mechanisms
Neuro 130/230. Harvard College/GSAS 78454

While we wait for everyone to join,
a brief math problem:

How many possible images are there of size 100 x 100 pixels, with 256 shades of gray per pixel?

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Class 1 [09/01/2021]. Introduction to Vision

Note: no class on 09/06/2021

Class 2 [09/13/2021]. Natural image statistics and the retina

Class 3 [09/20/2021]. The Phenomenology of Vision

Class 4 [09/27/2021]. Learning from Lesions

Class 5 [10/04/2021]. Primary Visual Cortex

Note: no class on 10/11/2021

Class 6 [10/18/2021]. Adventures into *terra incognita*

Class 7 [10/25/2021]. From the Highest Echelons of Visual Processing to Cognition

Class 8 [11/01/2021]. First Steps into in silico vision [Will Xiao]

Class 9 [11/08/2021]. Teaching Computers how to see

Class 10 [11/15/2021]. Computer Vision

Class 11 [11/22/2021]. Connecting Vision to the rest of Cognition

Class 12 [11/29/2021]. Visual Consciousness

FINAL EXAM, PAPER DUE 12/14/2021. No extensions.

Starting from the very beginning

- Let there be light, and there was light.

- Objects reflect light

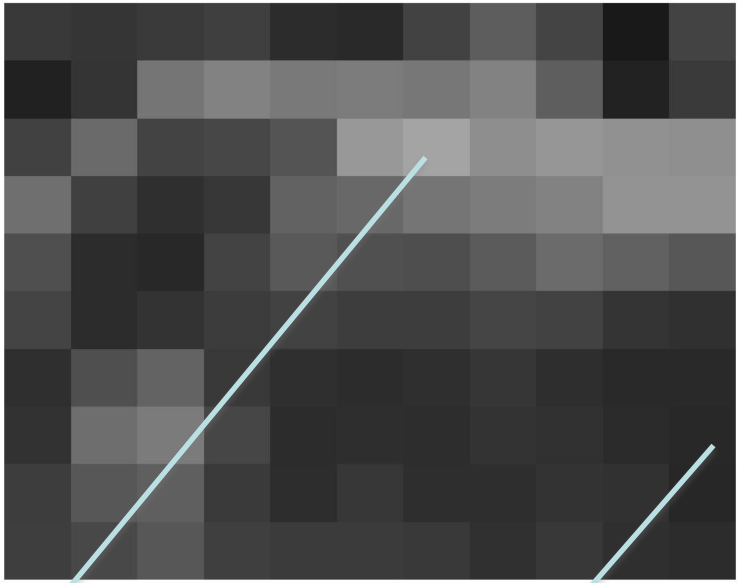
- Light photons impinge on the retina (Latin: small net)

- The retina conveys visual information to the brain

An oversimplified first-order description:

The eye functions as a very sophisticated and spectacular digital camera

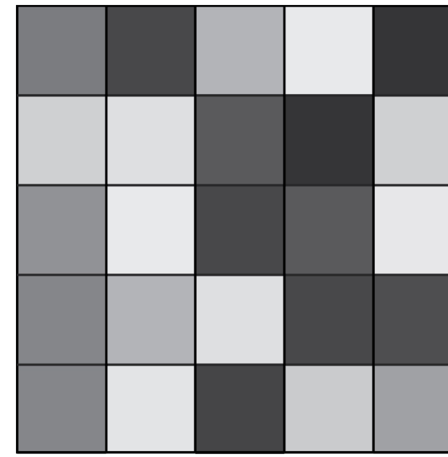
An image as a collection of pixels



57	53	58	63	44	41	66	93	68	25	67
33	52	117	130	121	124	119	130	94	34	58
65	106	67	71	84	152	164	142	150	145	143
111	64	47	55	98	104	117	124	130	147	147
79	44	40	67	89	80	78	91	107	97	87
68	44	51	60	66	61	61	69	66	52	48
47	79	99	57	47	44	47	54	46	41	41
50	110	123	70	44	46	45	51	49	43	40
61	87	95	58	45	55	46	46	51	49	39
62	72	87	63	59	59	57	48	56	47	44
49	51	52	52	52	48	48	51	52	55	56

Natural images are special

We only encounter a small subset of the space of possible images



Consider an image of size 100 x 100 pixels
Assume a pixel can have 256 shades of gray
How many such images are possible?

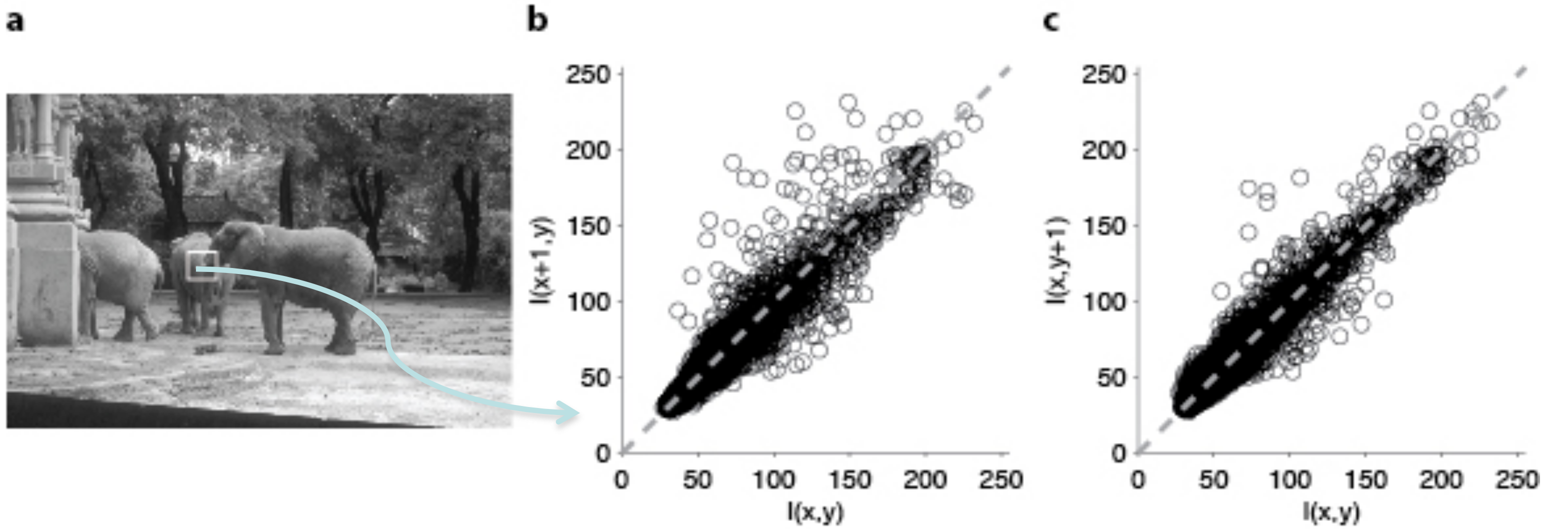
Answer
For a size of 1x1 pixel, there are 256 possible images
For a size of 1x2 pixels, there are 256^2 possible images
For a size of 100x100 pixels, there are 256^{10000} possibilities*

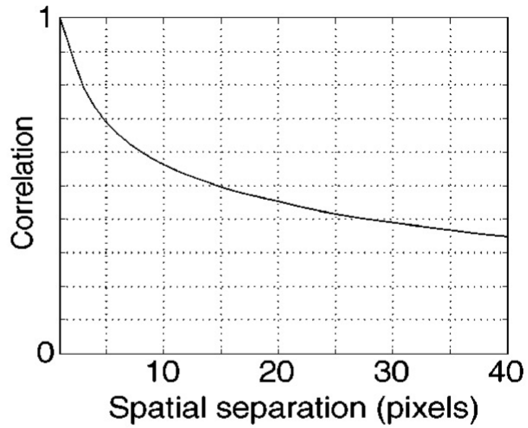
Yet, we only encounter a small fraction of these possibilities in natural images

*Some of those are “related” by translation, rotation or inversion, etc

Spatial regularities in natural scenes

The properties of nearby points are correlated





Simoncelli and Olshausen 2001

Images contain different spatial frequencies

Some are more prevalent than others

Low frequencies Middle frequencies High frequencies

Livingstone, M. (2002). Vision and Art: The Biology of Seeing. Harry N. Abrams.

Natural image statistics

Power spectrum ~ $1/f^2$

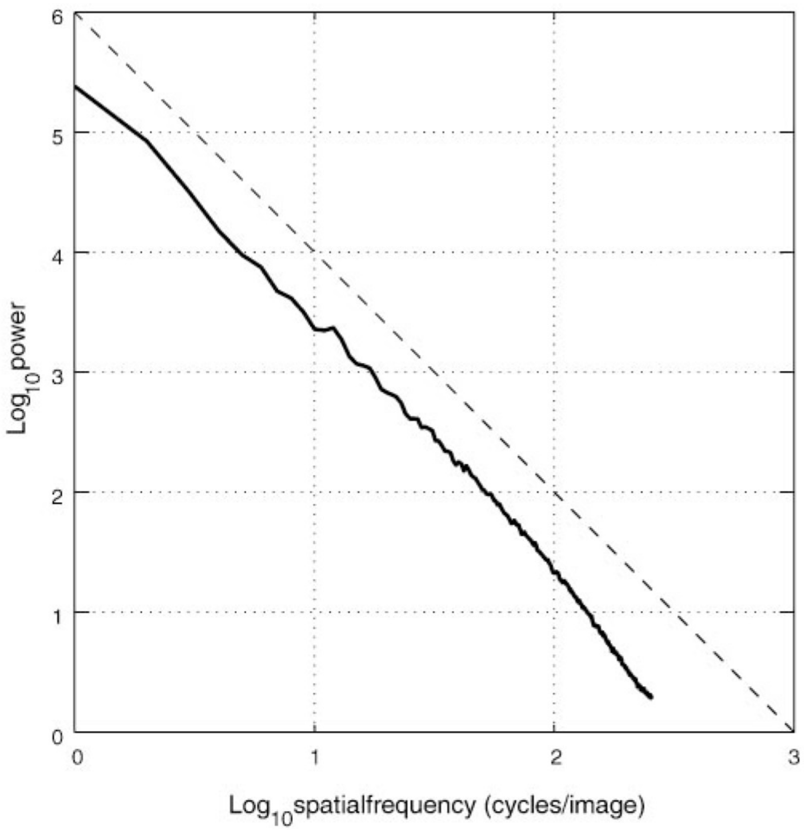


Figure 4 Power spectrum of a natural image (solid line) averaged over all orientations, compared with $1/f^2$ (dashed line).

Simoncelli and Olshausen 2001

$$\log(f(w)) = \alpha \log(w) + c$$

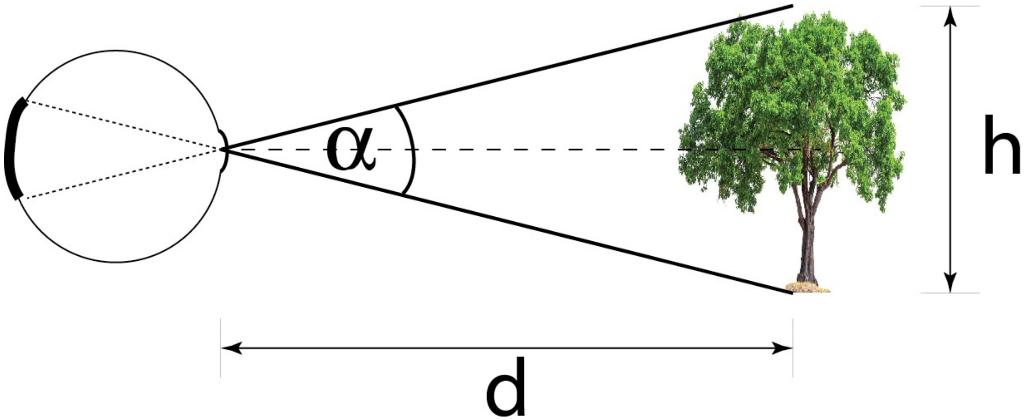
Note: Scale invariance

$$w' \to aw$$

$$\log(f(w')) = \beta \log(w) + d$$

There are multiple examples of power law distributions in physics, biology and social sciences

Sizes are measured in degrees of visual angle



$\alpha / 2 = \arctan(h/2d)$

Size of the moon ~ 0.5 degrees
Thumb at arms length ~ 2 degrees

Natural image statistics
There are also strong correlations in time

The visual input is largely static, except for:

- External object movements
- Head movements
- Eye movements

The visual image is largely static over hundreds of milliseconds

Silent Reading **225-250 ms fixation, 2 degrees saccade size (8-9 letters)**
Scene Perception **260-330 ms fixation, 4 degrees saccade**

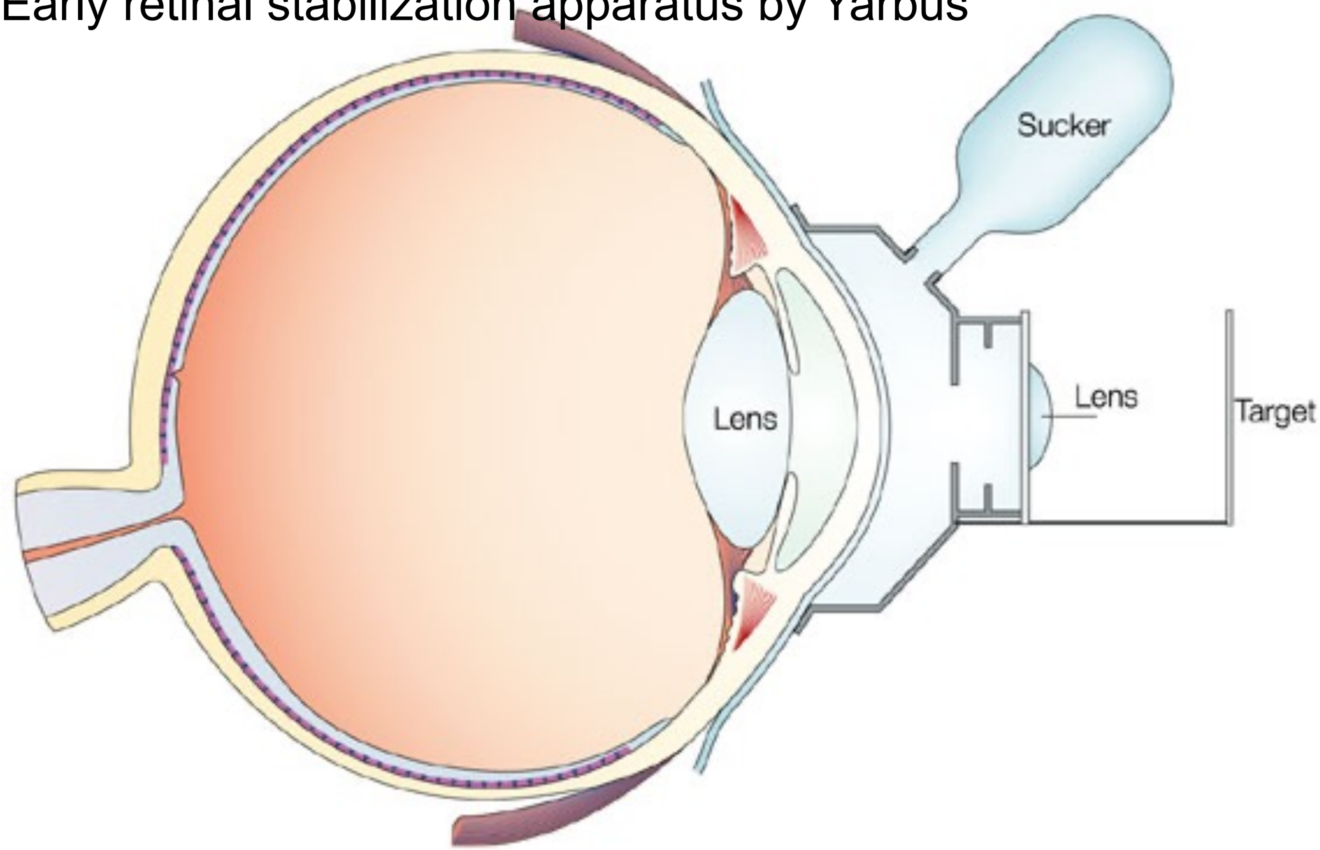
"Slowness" has been proposed as a constraint for learning about objects (Földiak 1991, Stringer et al 2006, Wiskott et al 2002, Li et al 2008)

Saccadic eye movements

Example pattern of fixations while examining an image

Microsaccades are important for perception

Early retinal stabilization apparatus by Yarbus



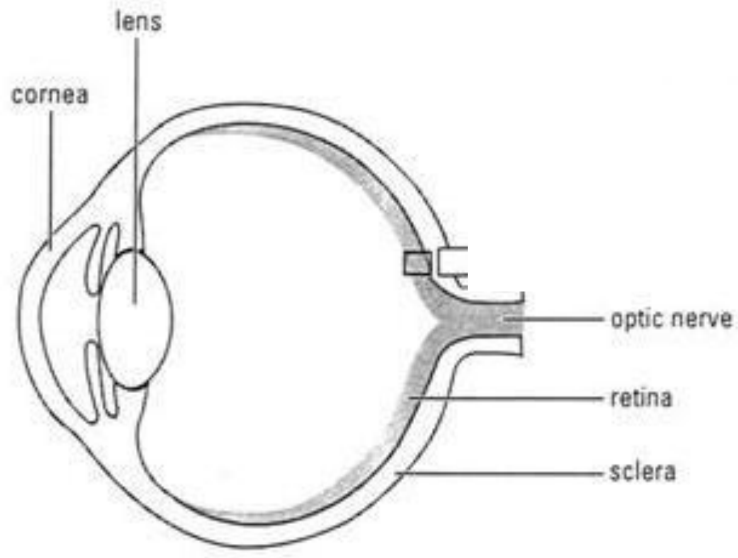
Martinez-Conde, Macknik, & Hubel, 2004

The eye constantly makes very small “fixational” movements, a.k.a. microsaccades.

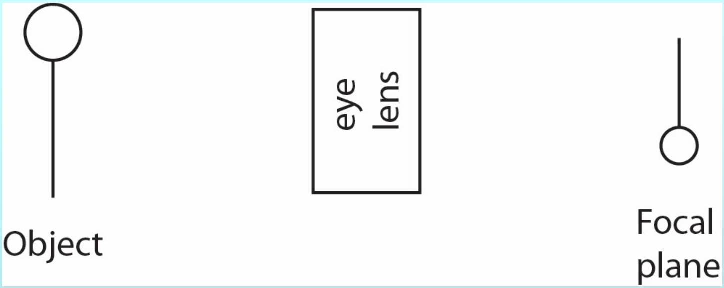
When visual stimulation is held fixed relative to the retina, visual perception rapidly fades (Ratliff & Riggs, 1950).

These microsaccades may be critical for counteracting perceptual fading (McCamy, 2012)

The image is focused onto the retina



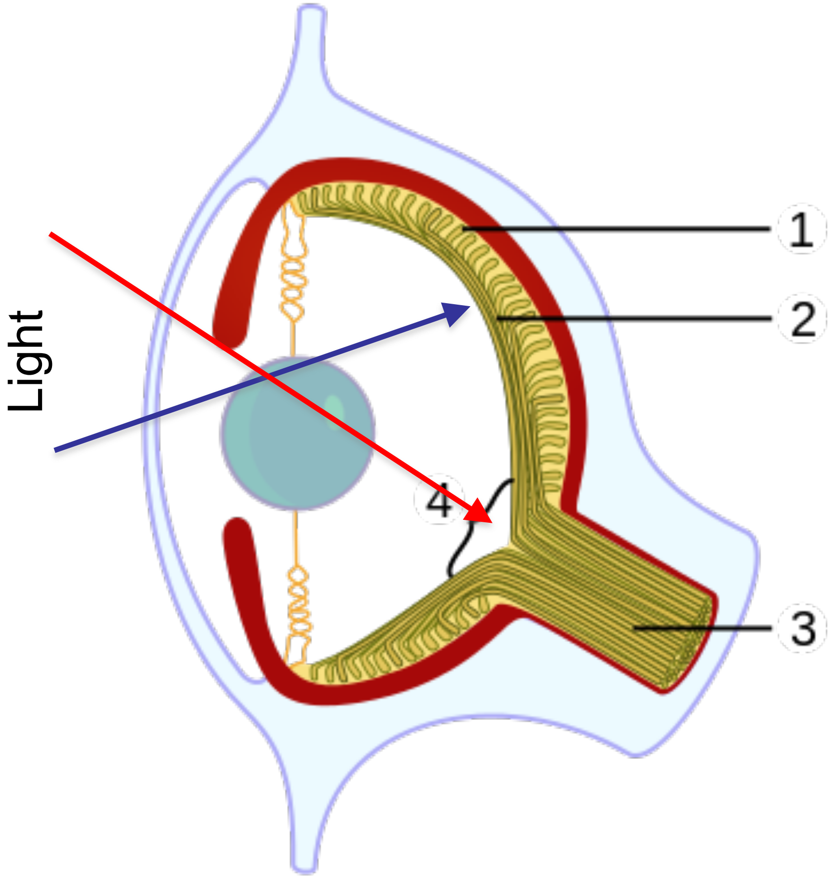
Images are inverted by the eye



Why don't we see everything upside down?

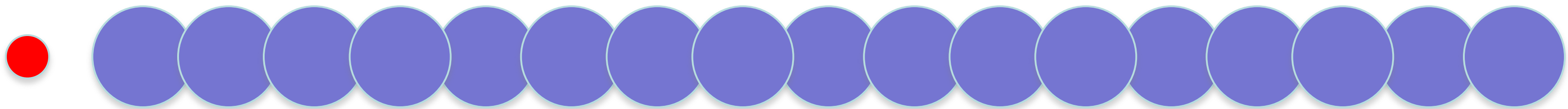
Perception can adapt to reversing the image.
Some preliminary experiments on vision without inversion of the retinal image. Stratton, 1896

The blind spot

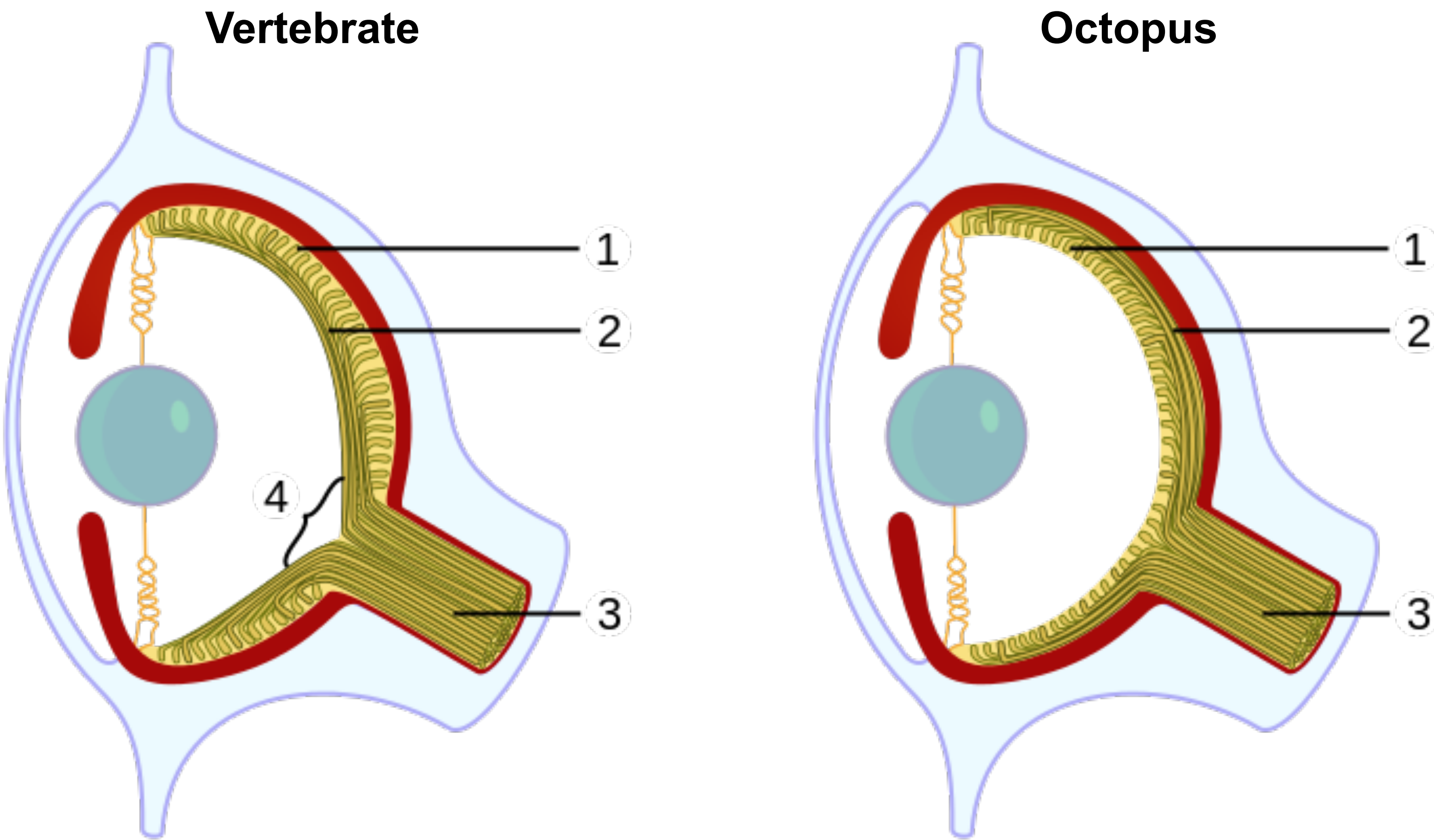


“Seeing” the blind spot

Cover your left eye
Fixate on the red circle and do not move your eyes!



Evolution of the retina



4. Blind spot is only present in vertebrates

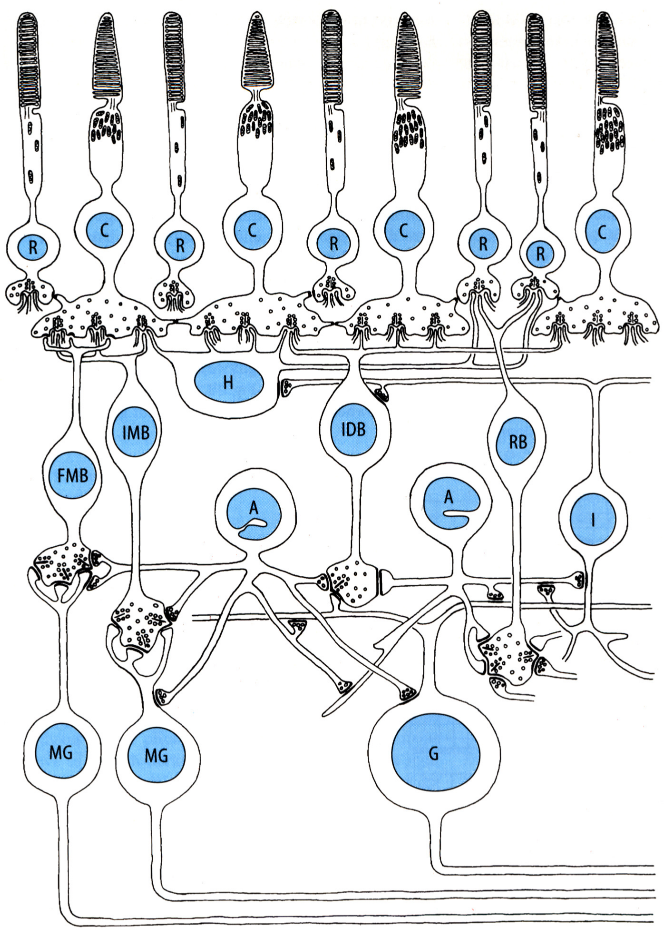
1. In octopi, light reaches directly the photoreceptors before reaching the ganglion cells

Evolution of the eye: absurd in the highest degree

"To suppose that the eye, with all its inimitable contrivances for adjusting the focus to different distances, for admitting different mounts of light, and for the correction of spherical and chromatic aberration, could have been formed by natural selection, seems, I freely confess, **absurd in the highest degree**."

Charles Darwin, The origin of species, 1859

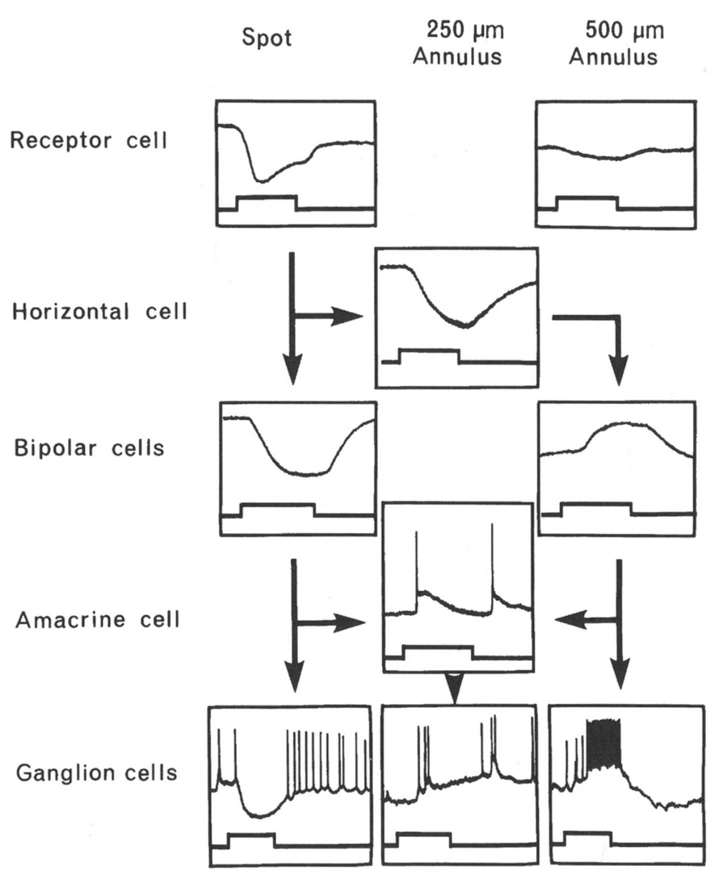
The retina: An amazingly beautiful circuitry composed of many different cell types



- ~0.5 mm thick
- 5 x 5 cm retinal area
- Three cellular layers
- Rods (low-illumination conditions, ~10^8)
- Cones (color sensitivity, ~ 10^6)
- Blind spot
- Fovea (rod free, ~0.5 mm, ~ 1.7 deg)
- Midget ganglion cells (small dendritic arbors)
- Parasol ganglion cells (large dendritic arbors)

Dowling (2007), Scholarpedia, 2:3487
Wandell (1995), Foundations of Vision. Sinauer Books

The retina: Some cells fire action potentials whereas other cells show graded responses

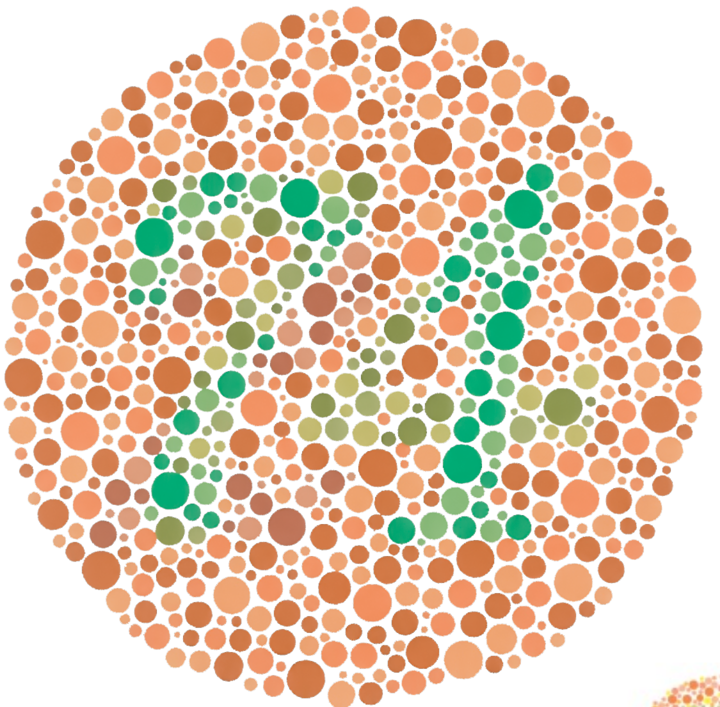


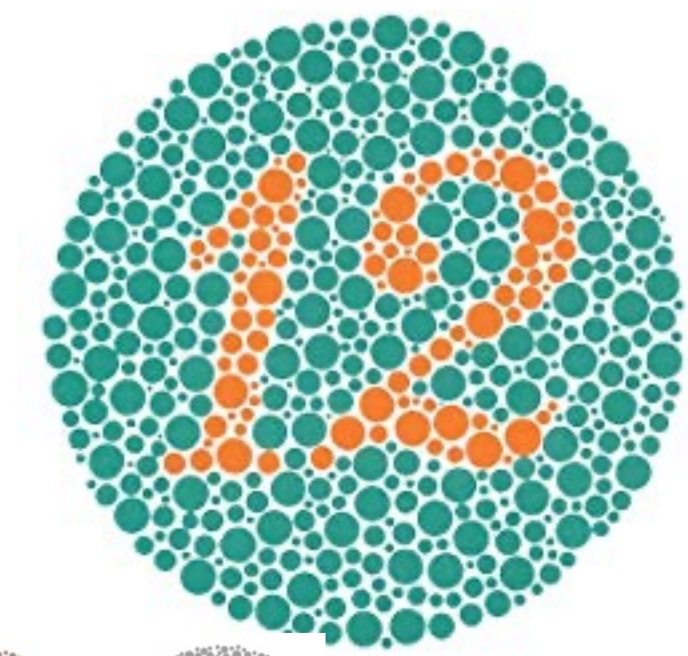
- Photoreceptors transduce incoming light input into electrical signals
- Rod to bipolar convergence increases rod-pathway sensitivity
- Cones, rods, horizontal and bipolar cells are non-spiking neurons
- Many different types of amacrine cells (some of which fire action potentials)
- Retinal ganglion cells fire action potentials and carry the output signals

John Dowling (2007), Scholarpedia, 2:3487.

Rods see largely in grayscale

Ishihara tests for color blindness





Non-uniform sampling of the visual field
There is much more detail at the *fovea*

There is much more detail at the *fovea*

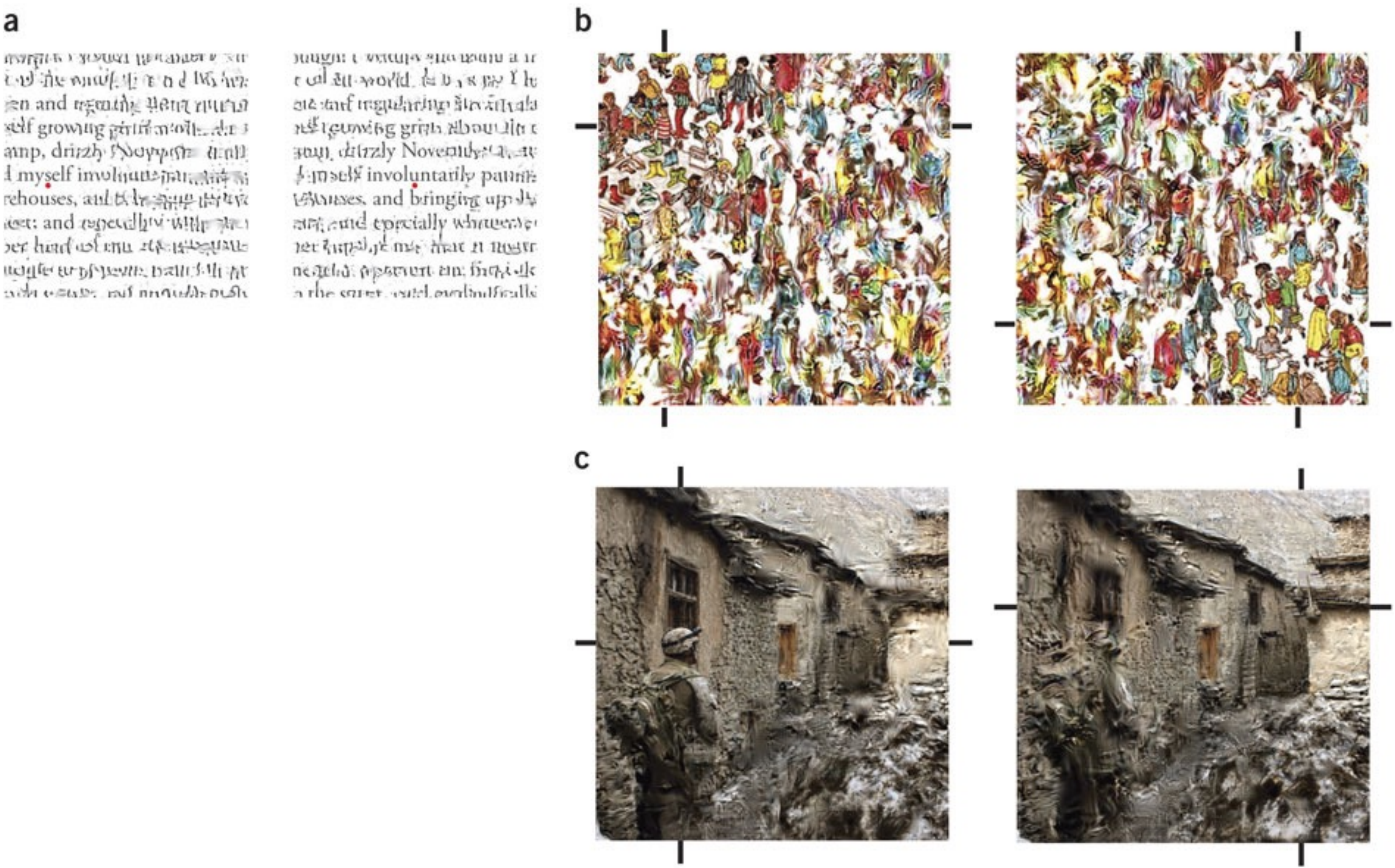
Try to read outside of your fixation spot

To be, or not to be, that is the question:
Whether 'tis nobler in the mind to suffer
The slings and arrows of outrageous fortune,
Or to take Arms against a Sea of troubles,
And by opposing end them: to die, to sleep
No more; and by a sleep, to say we end
The heart-ache, and the thousand natural shocks
That Flesh is heir to? 'Tis a consummation
Devoutly to be wished. To die, to sleep,
perchance to **Dream**; aye, there's the rub,
For in that sleep of death, what dreams may come,
When we have shuffled off this mortal coil,
Must give us pause. There's the respect
That makes Calamity of so long life:
For who would bear the Whips and Scorns of time,
The Oppressor's wrong, the *proud* man's Contumely,
The pangs of *dispised* Love, the Law’s delay,
The insolence of Office, and the spurns

There is much more detail at the *fovea*

Try to read outside of your fixation spot

There is much more detail at the fovea



Example psychophysics task

Indistinguishable images due to reduced acuity in the periphery

Picture 1 is flashed
Picture 2 is flashed
Picture 3 is flashed

Was there an L or a T in the center?

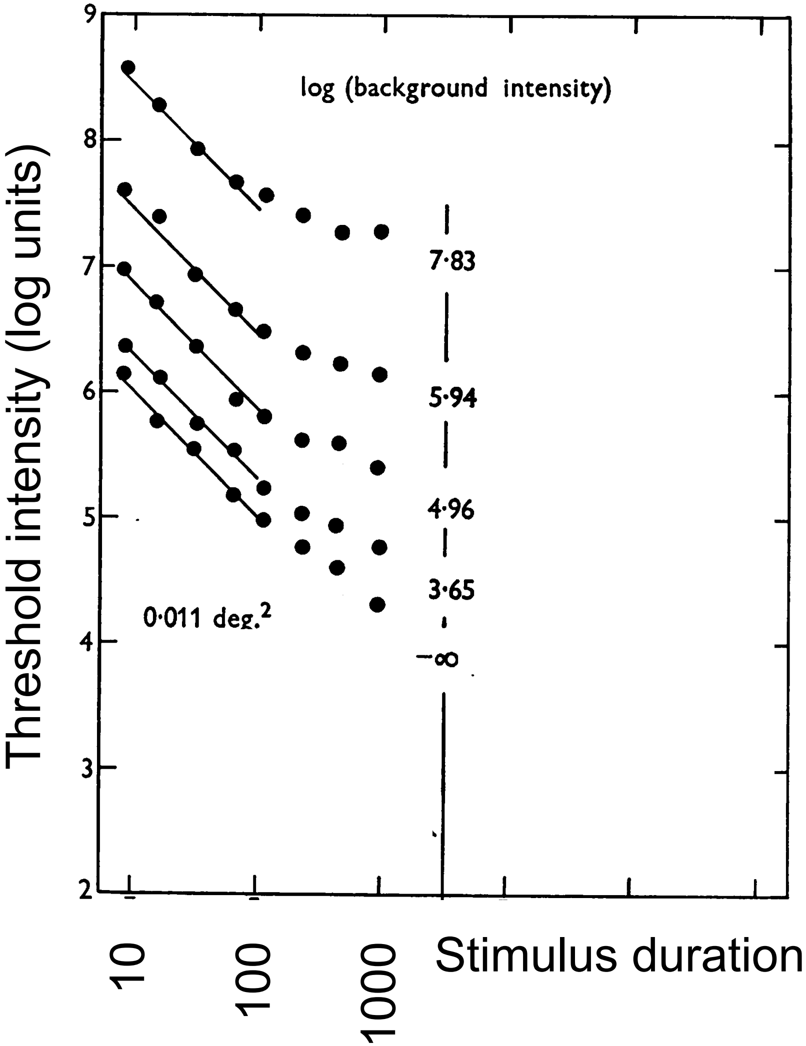
Was picture 3 more similar to picture 1 or picture 2?

Freeman and Simoncelli (2011). "Metamers of the ventral stream." Nat Neurosci **14**(9): 1195-1201


Sample 1 or 2?


1
2

The retina has a huge dynamic range



Vision works well in moonless nights and in bright sunlight (~10^9 more light intensity)

There are several mechanisms that support light adaptation:

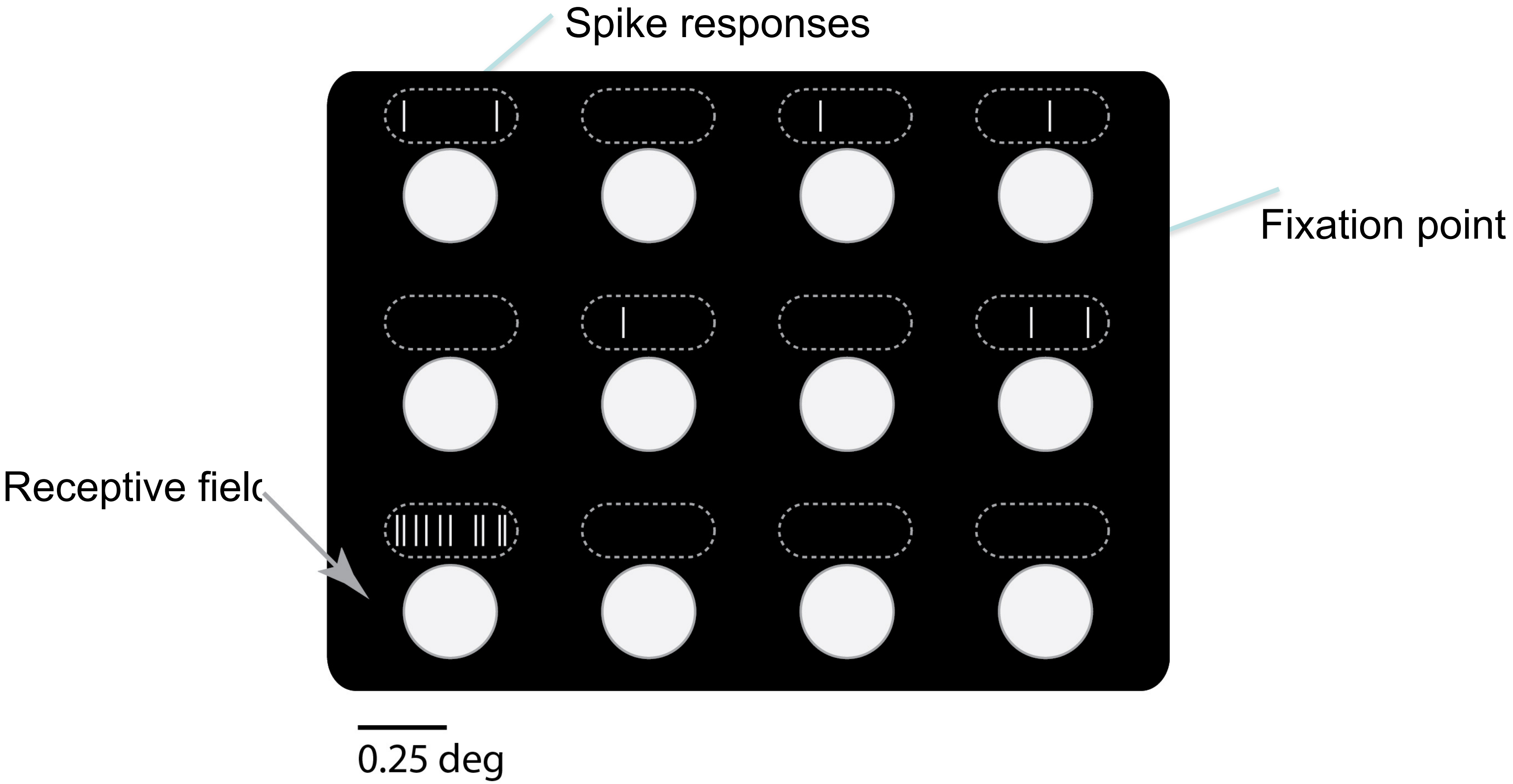
- Changing pupil size
- Reliance on rods vs. cones
- Photopigment bleaching
- Feedback from horizontal cells to photoreceptors

These mechanisms are relatively slow

Barlow, 1958

The receptive field

Neurons throughout the visual system are very picky about the stimulus location

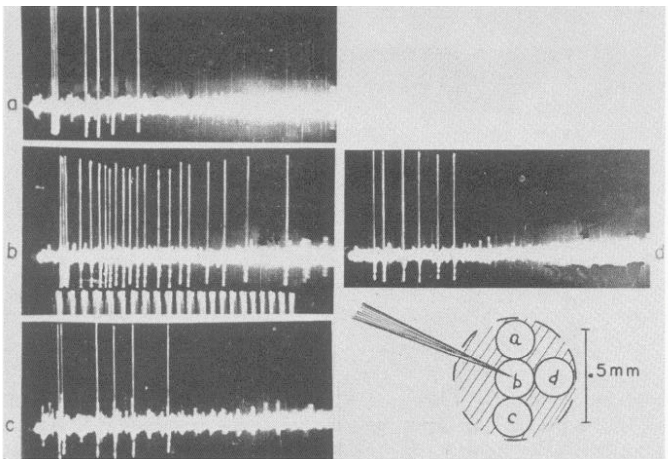


This cartoon neuron responds only when a flash of light appears in the periphery, in the lower left quadrant

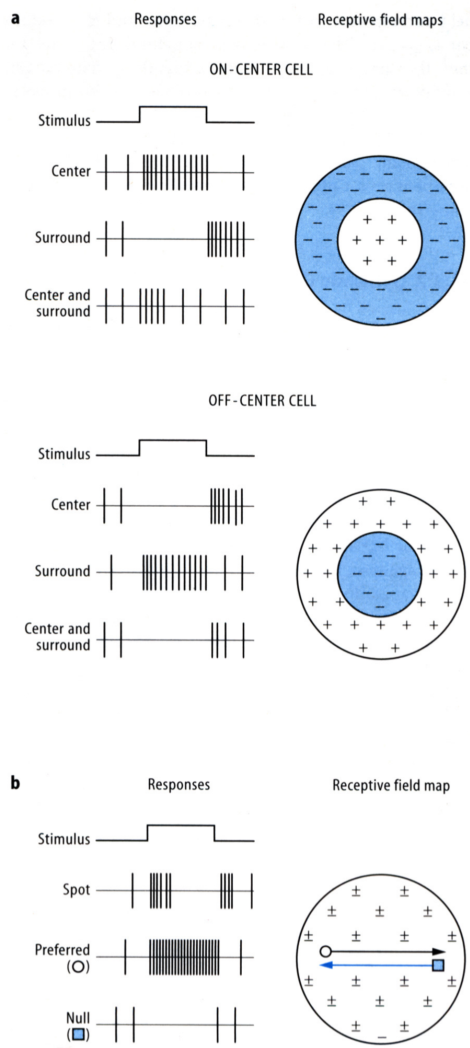
Blumberg and Kreiman, 2010

Physiology of retinal ganglion cells

The receptive field of most RGCs have a center-surround structure



Kuffler, S. (1953)
J. Neurophys. **16**: 37-68



About 1.2 million projections from each retina towards the brain

Jonas et al., *Invest. Ophth. Vis. Sci.* 1992

Diversity of retinal ganglion cells

A minority of RGCs have more complex response properties:

- Phasic cells respond briefly to stimulus onset, offset, or both
- Some phasic cells respond selectively to edge orientation
- Suppressed-by-contrast cells fire except when an edge is present in receptive field
- Bistratified RGCs lack surrounds and are color-sensitive
- Color-opponent cells have centers and surrounds with opposing color preferences
- Intrinsically photosensitive RGCs contain photoreceptors and project to regions controlling pupil size, circadian rhythm, etc.
- Direction-sensitive cells respond to direction of motion of light or dark spots

These cells likely account for approximately 10% of RGCs
Unclear to what extent, these cells contribute to visual object recognition

Stone and Fukuda, *Journal of Neurophysiology* 1974
Cleland and Levick, *Journal of Neurophysiology* 1974
Berson et al., *Science* 2002

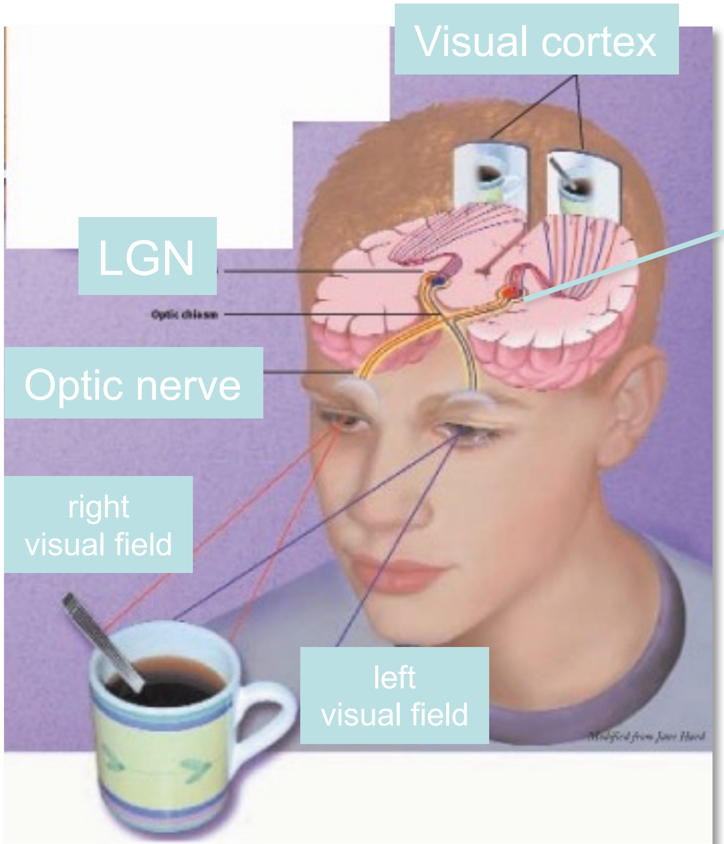
Eye versus digital cameras

	One eye	Camera (phone)
Angle of view	~ 120 degrees	~ 70 degrees
Sampling	Eccentricity dependent	Uniform
Resolution	~ 10 “MP” in the fovea	~ 20 MP (million pixels)
Sensitivity	High sensitivity in low light conditions	Struggle in low light and requires very long integration time
Energy efficiency	Small fraction of ~3 meals a day, say 14 hours of continuous use. (2500 calories / day ~ 0.12 Watts)	Continuous video recording: ~ 3 hours on one battery life (~5 Watts, hence > 12 watts a day)
Malleability	Hard to change (without additional devices like glasses, microscopes, telescopes)	Can expand in many ways
Post-processing	The human brain!	Minimal computer vision*

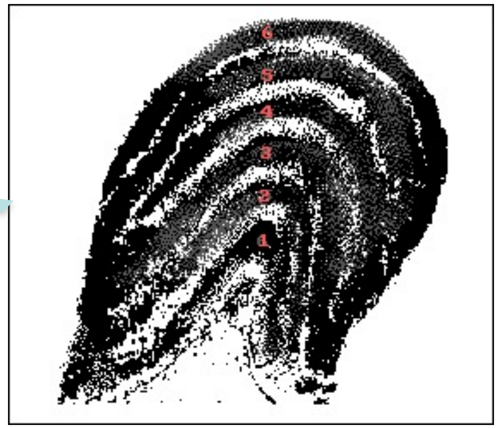
Eyes in non-human animals

	Humans	Other animals	Examples
Wavelength	“Visible” spectrum	Also UV, IR	mice, dogs, birds: UV snakes: IR
Cones	3	1-30	bat, racoon: 1 cats, dogs: 2 some dragon flies: 30
Polarization	No	Some animals	cuttlefish
Number of eyes	2	Up to 10	spiders: 8-12 horseshoe crabs: 10
Angle	Binocular: ~120^o Up to 180^o	Up to 300^o	rabbits: no binocular zone in the center cows, horses: 300^o
Eyes	Correlated	Sometimes independent	Chameleon: can move eyes independently
Resolution	~100M receptors	Wide variation	Star fish: 200 receptors Birds: higher acuity than humans

To cortex, through the thalamus:
The Lateral Geniculate Nucleus (LGN)



Modified from Society for Neuroscience Brain Facts



•LGN main visual part of the thalamus

•6 layers, contralateral visual hemifield

•The visual field is represented multiple times in the LGN

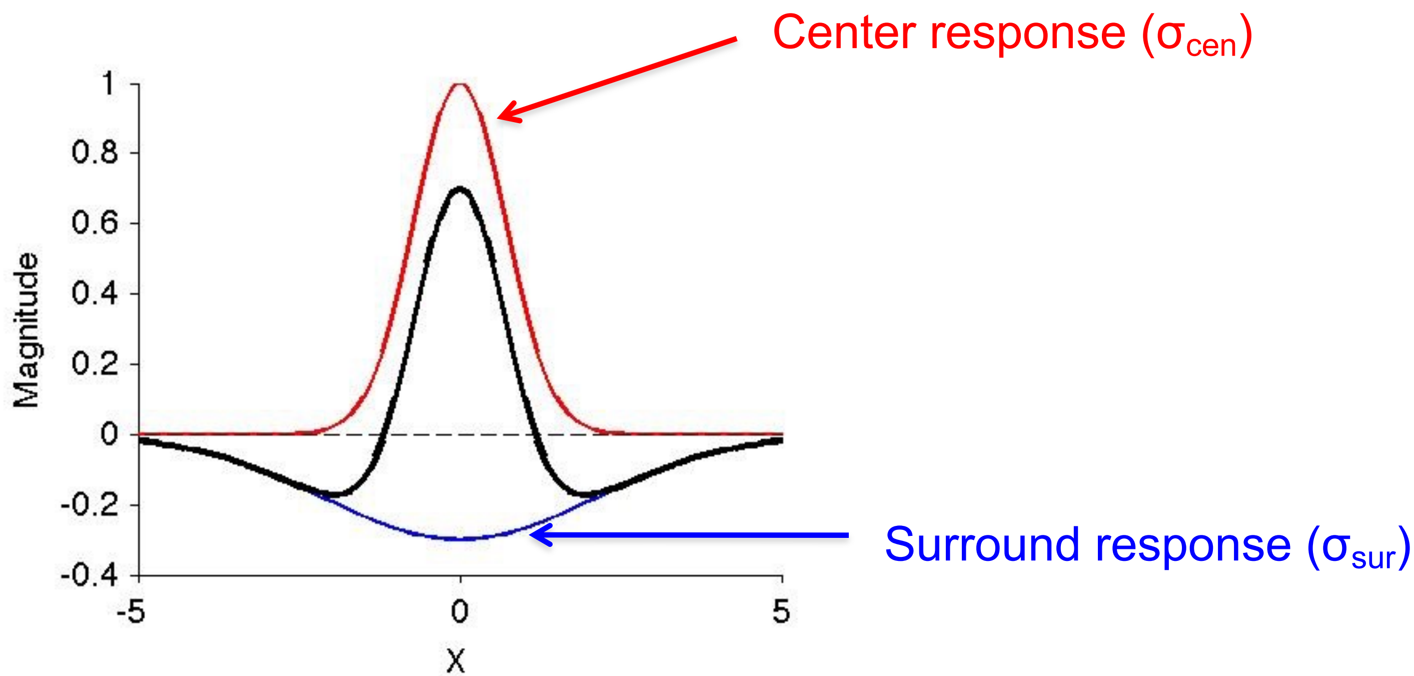
•Layers 2, 3 and 5 receive *ipsilateral* eye's input
•Layers 1, 4 and 6 receive *contralateral* eye's input
•Layers 1-2: *magnocellular* layers, input from parasol retinal ganglion cells (~ motion)
•Layers 3-6: *parvocelluar* layers, input from midget ganglion cells (~ color)
•On and Off center cells are present in all layers
•LGN does not project back to the retina

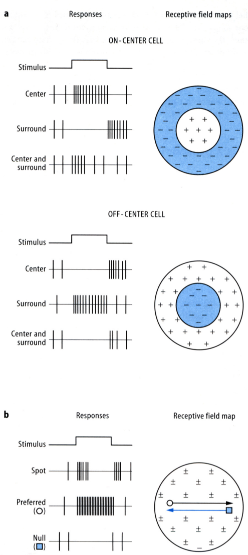
NOTE: Most of the input to the LGN comes from visual cortex and not from the retina! (e.g. Douglas and Martin 2004)

Wandell (1995)

Modeling receptive fields: difference of Gaussians

The center-surround structure can be described by a difference of gaussians (Mexican-hat)





$$D(x,y) = \pm\left(\frac{1}{2\pi\sigma_{cen}^2}\exp\left[-\frac{x^2+y^2}{2\sigma_{cen}^2}\right] - \frac{B}{2\pi\sigma_{sur}^2}\exp\left[-\frac{x^2+y^2}{2\sigma_{sur}^2}\right]\right)$$

Dayan and Abbott. (2001) Theoretical Neuroscience. The MIT Press

Neurons respond with transient bursts of activity

Dynamic receptive fields in the retina/LGN

$$D(x,y,t) = \pm\left(\frac{D_{cen}(t)}{2\pi\sigma^2_{cen}}\exp\left[-\frac{x^2+y^2}{2\sigma^2_{cen}}\right] - \frac{BD_{sur}(t)}{2\pi\sigma^2_{sur}}\exp\left[-\frac{x^2+y^2}{2\sigma^2_{sur}}\right]\right)$$

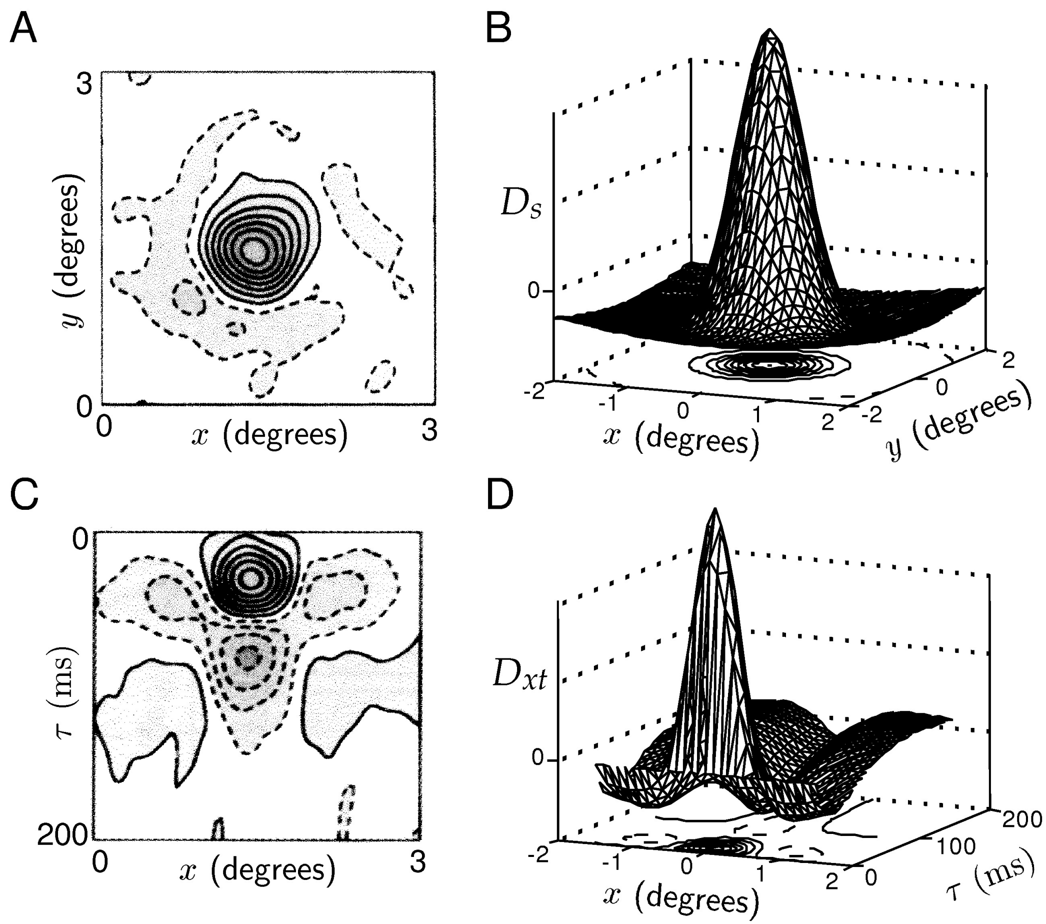
$$D_{cen}(t) = \alpha^2_{cen} t \exp[-\alpha_{cen} t] - \beta^2_{cen} t \exp[-\beta_{cen} t]$$

$$D_{sur}(t) = \alpha^2_{sur} t \exp[-\alpha_{sur} t] - \beta^2_{sur} t \exp[-\beta_{sur} t]$$

Dayan and Abbott. (2001) Theoretical Neuroscience. The MIT Press

Difference of Gaussians in space and time

The center-surround structure can also be seen in receptive field dynamics



Dayan and Abbott. (2001) Theoretical Neuroscience. The MIT Press

Information from the retina goes to many places
Subcortical visual pathways

Retinal projections

Lateral geniculate nucleus (LGN)

Superior Colliculi — Main visual pathway in birds, reptiles, fish

Implicated in saccade generation in mammals

Suprachiasmatic Nucleus — Hypothalamus: involved in circadian rhythms

Pretectum

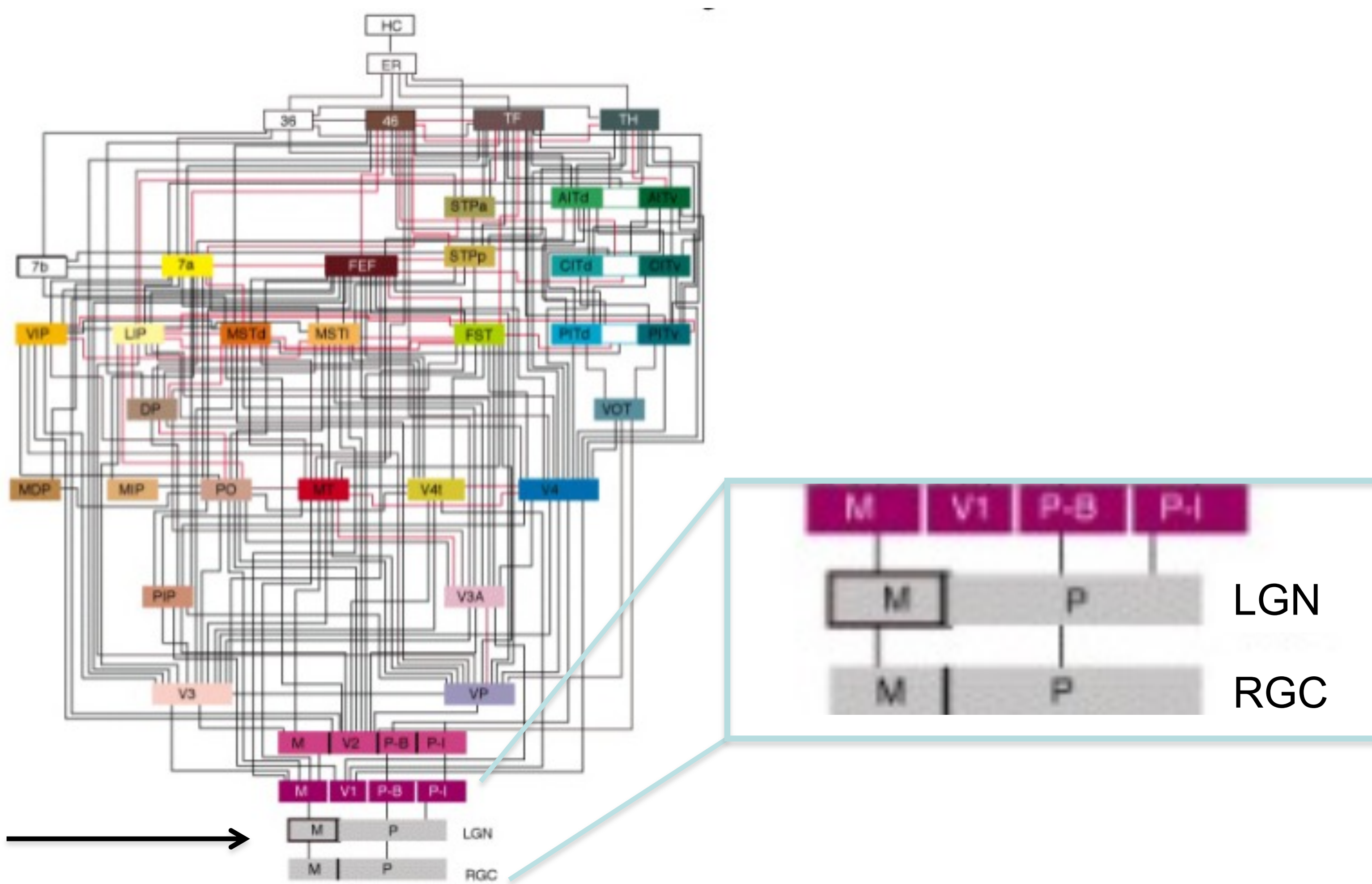
Pregeniculate

Accesory optic system

> Primates can recognize objects after lesions to the Superior Colliculus or Suprachiasmatic Nucleus, but not after lesions to V1 (Gross 1994).

Visual system circuitry

You are here



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