Vision: How it works, how it develops, and why you should care

Rick O. Gilmore

2021-09-03 11:23:26

Preliminaries

About me

- B.A., Cognitive Science, Brown University
- M.S. & Ph.D., Psychology (Cognitive Neuroscience), Carnegie Mellon University
- Human brain development, perception & action, computational modeling, machine vision, big data, open science
- Founding Director of Human Imaging, Penn State Social, Life & Engineering Sciences Imaging Center (SLEIC)

- Co-Founder/Co-Director of Databrary.org data library
- gilmore-lab.github.io
- banjo player, actor, cyclist, backpacker, poet, ham (K3ROG), native Coloradoan

Agenda

- What’s vision for?
- Properties of light
- The visual eye and brain
- Measuring the development of visual perception

What’s vision for?

Behavioral priorities

- Secure sustenance
- Avoid harm
- Reproduce

Behavioral primitives

- Locomotion
- Object interaction/manipulation
- Communication

Vision answers

- Where things are; where they’re moving; where/how I’m moving
- What’s out there
- How should I respond

Vision informs observers about…

- Geometry and motion of objects and surfaces
- Surface properties (color, texture, rigidity)
- Object properties (animate/inanimate; familiar/un-; person/animal…)

Properties of light

Physics of sensation

Informal name	Source
Vision	Electromagnetic radiation
Audition	Mechanical vibration in air/water
Touch	Mechanical vibration of skin on surface
Vestibular	Rotation & linear acceleration of head
Olfaction	Chemical patterns in air/water
Gustation	Chemical patterns in mouth

Informal name	Source
Electroception	Electromagnetic radiation
Magnetoreception	Electromagnetic radiation patterns
Kinesthesia	Position, velocity, acceleration of limbs, body

Plenoptic function

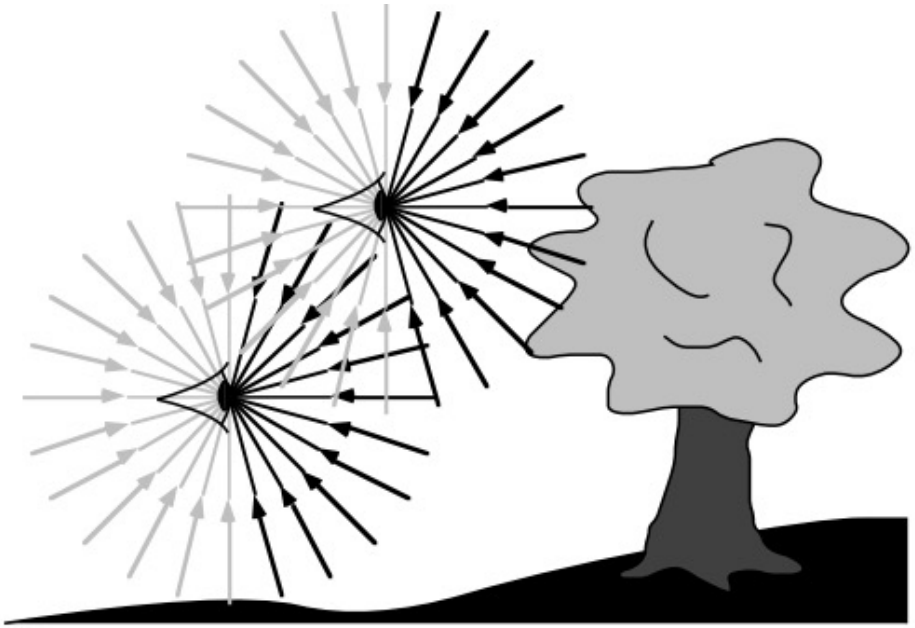
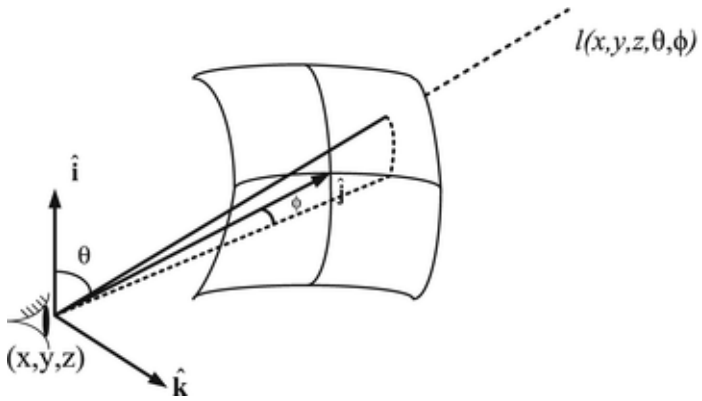


Fig.1.3
The plenoptic function describes the information available to an observer at any point in space and time. Shown here are two schematic eyes-which one should consider to have punctate pupils-gathering pencils of light rays. A real observer cannot see the light rays coming from behind, but the plenoptic function does include these rays.

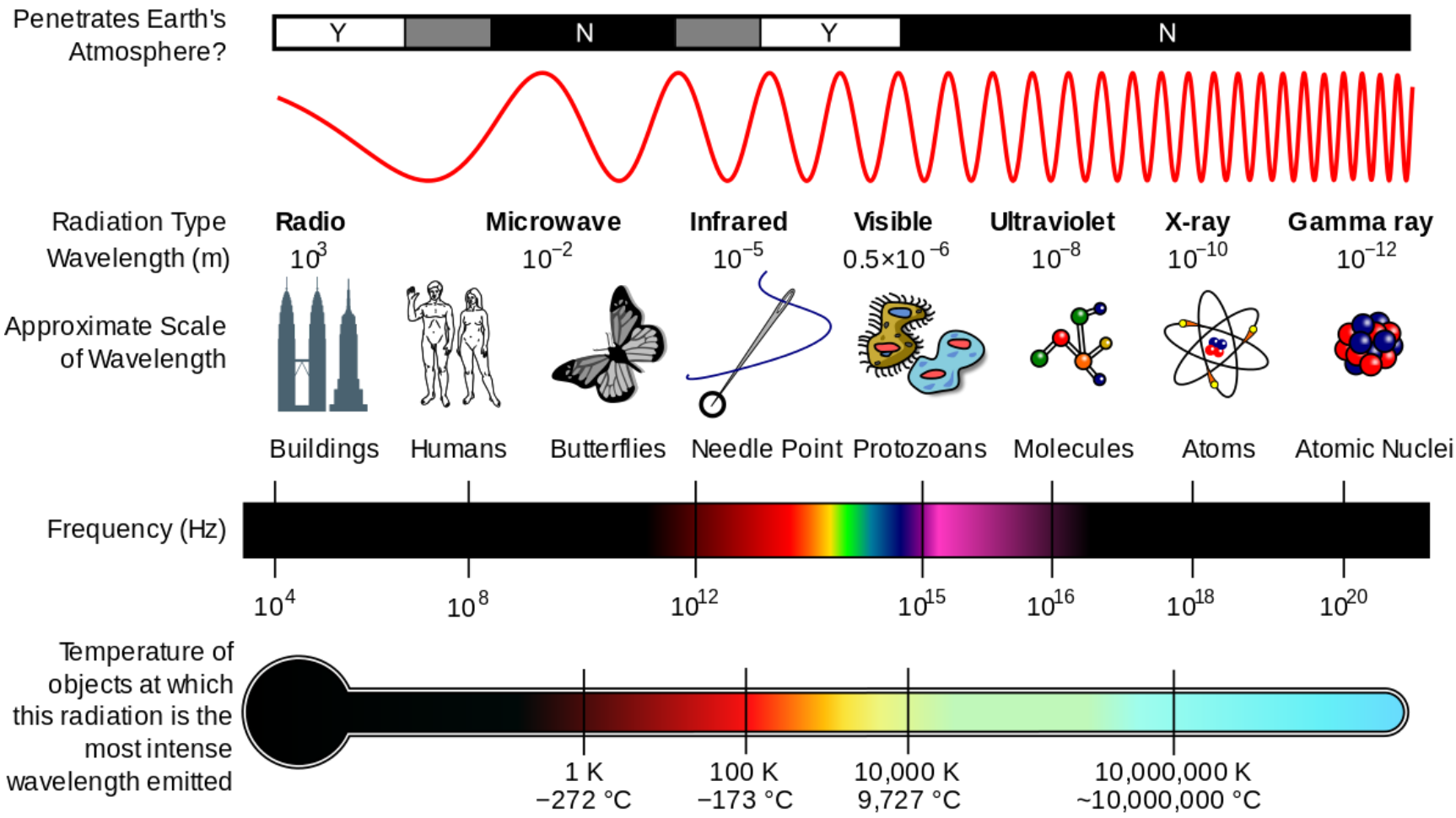
(Adelson & Bergen, 1991)



(Chan, 2014)

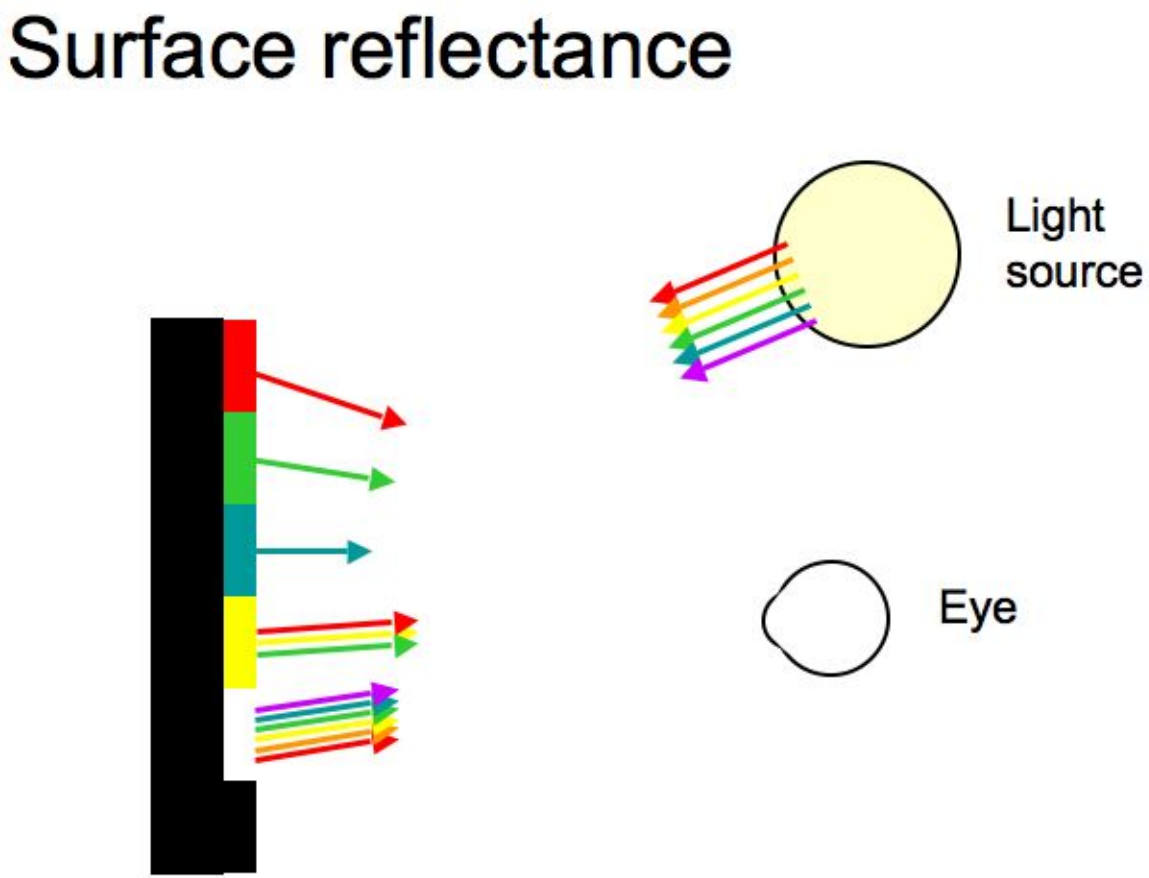
Light

- Electromagnetic (EM) radiation
- Wavelength (1/frequency) and intensity

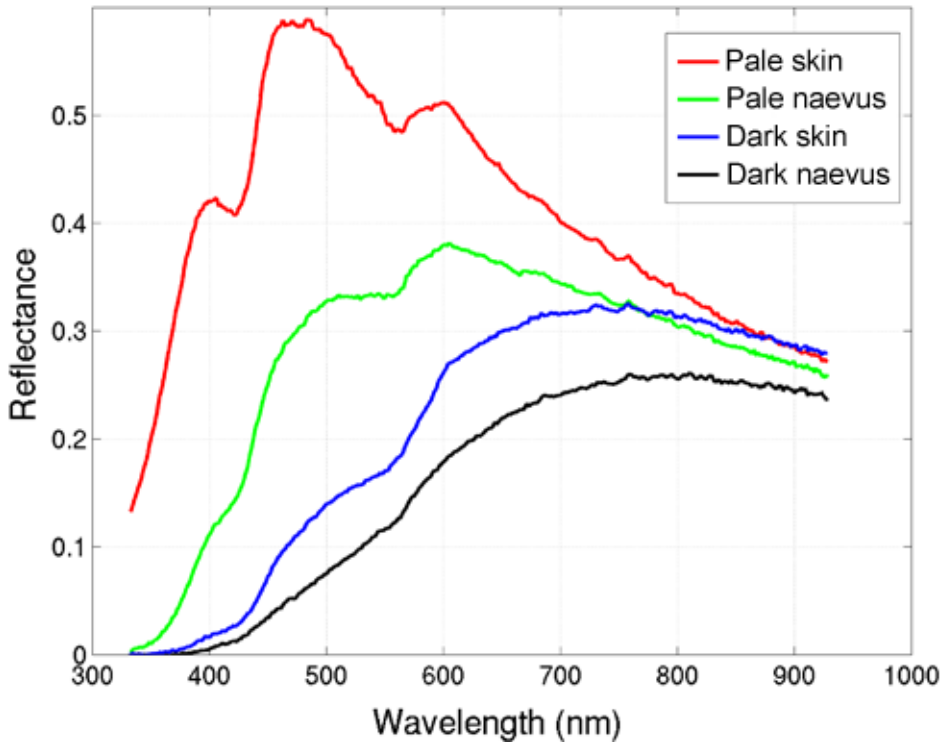


Source: Wikipedia

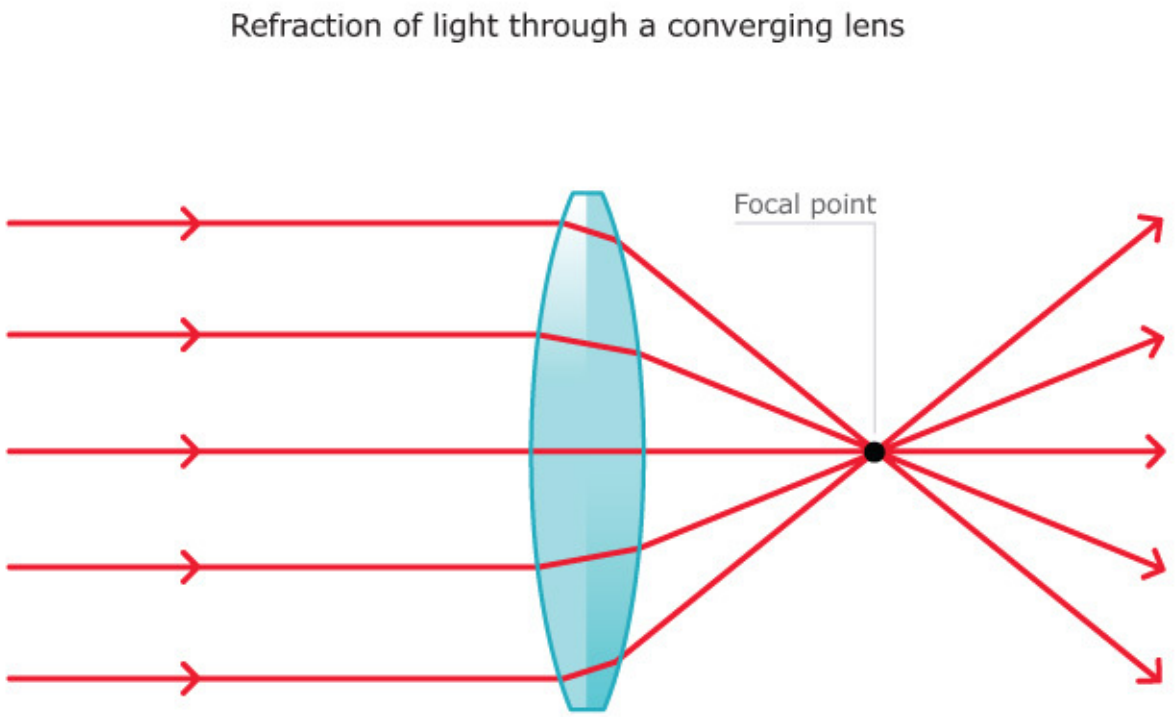
Reflects off surfaces to different degrees



Perceived color differences correspond to different patterns of light reflection.



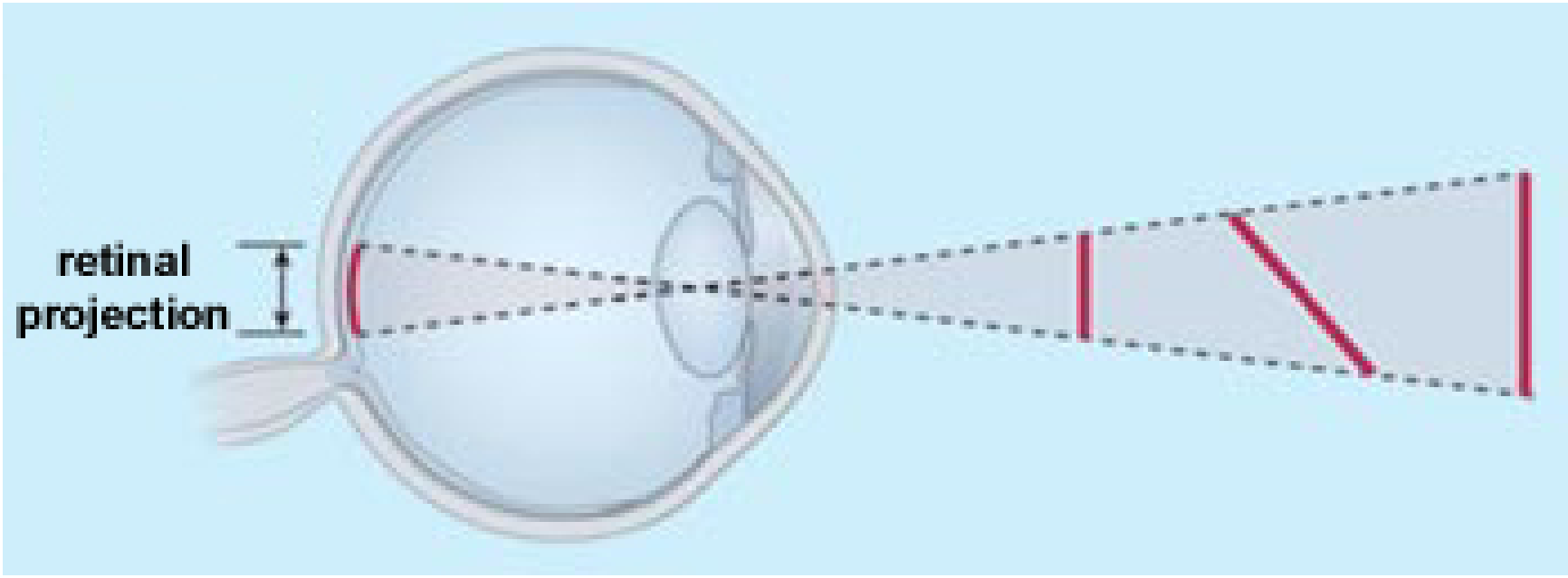
Light is refracted (bent) by some substances

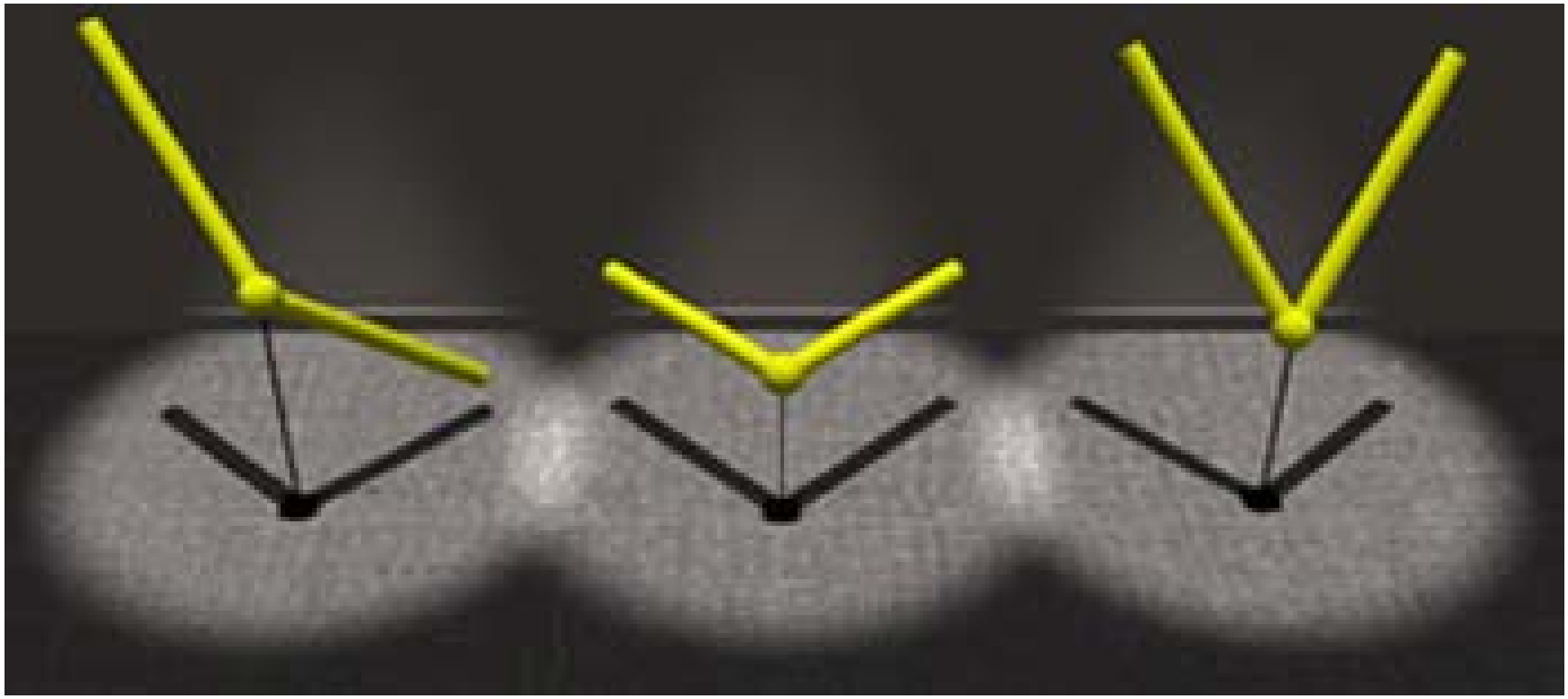


Light

- Provides fast (2.99 million m/s; 186 million mi/hr) information about surfaces at a distance
- vs. sound (340 m/s; 767 mi/hr)
- vs. chemical signals (min/mi)

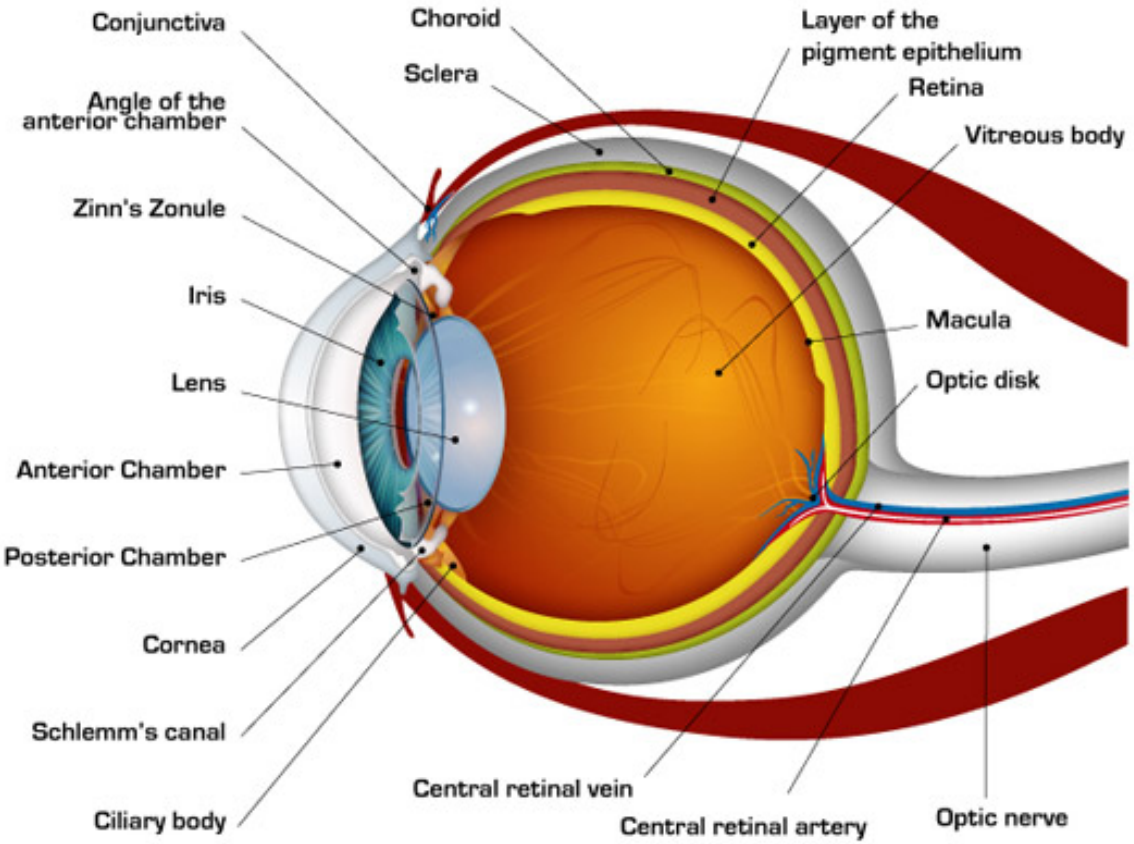
Projects images that relate to shape/orientation



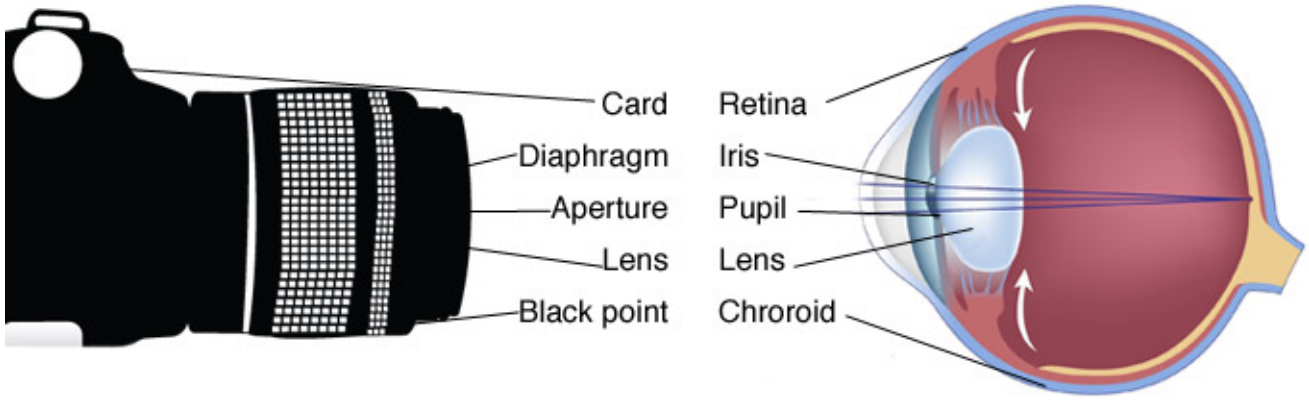


The visual eye and brain

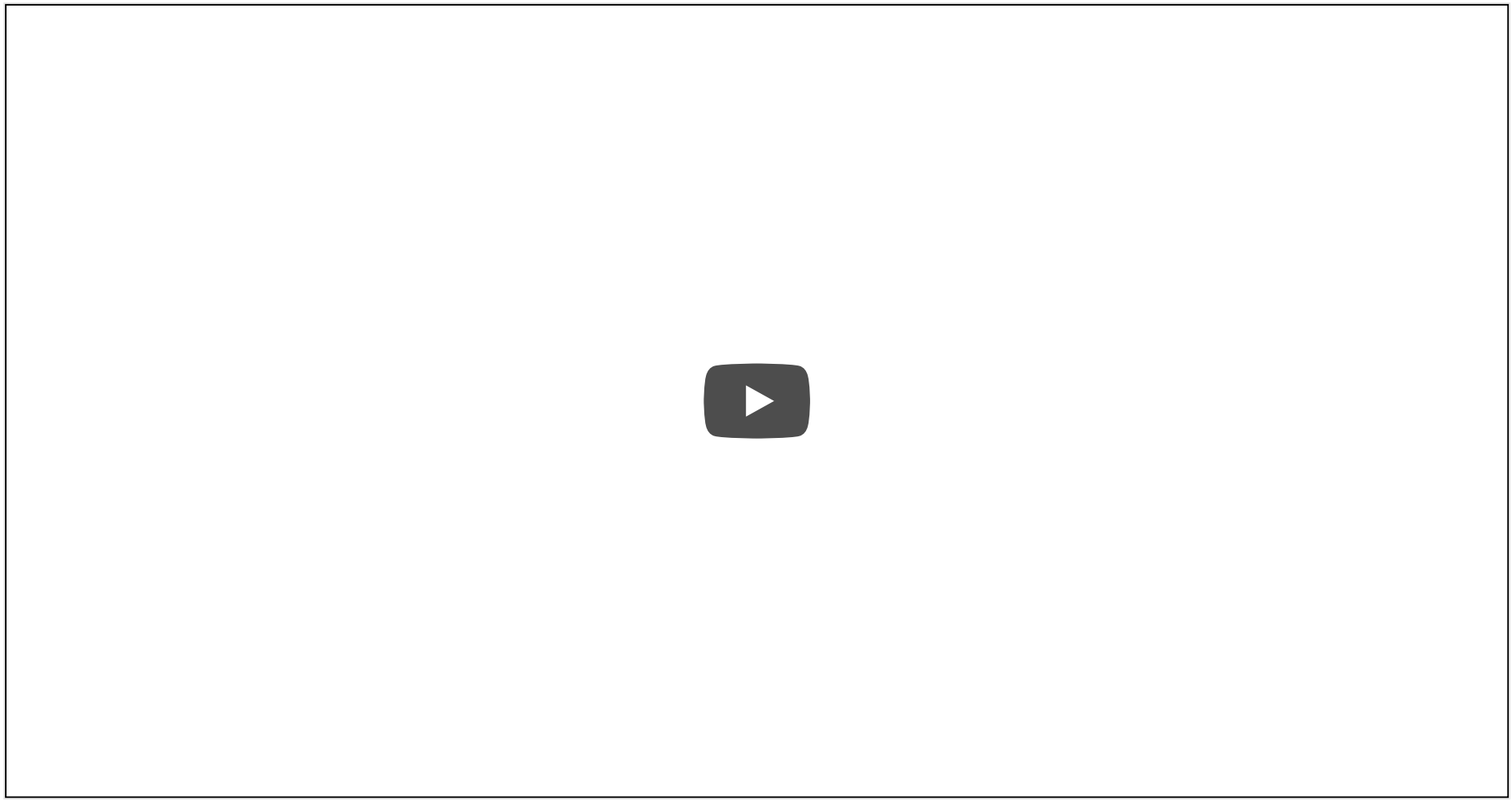
The eye


Conjunctiva
Angle of the anterior chamber
Zinn's Zonule
Iris
Lens
Anterior Chamber
Posterior Chamber
Cornea
Schlemm's canal
Ciliary body
Choroid
Sclera
Layer of the pigment epithelium
Retina
Vitreous body
Macula
Optic disk
Central retinal vein
Central retinal artery
Optic nerve

as an auto-focus, auto-exposure camera…

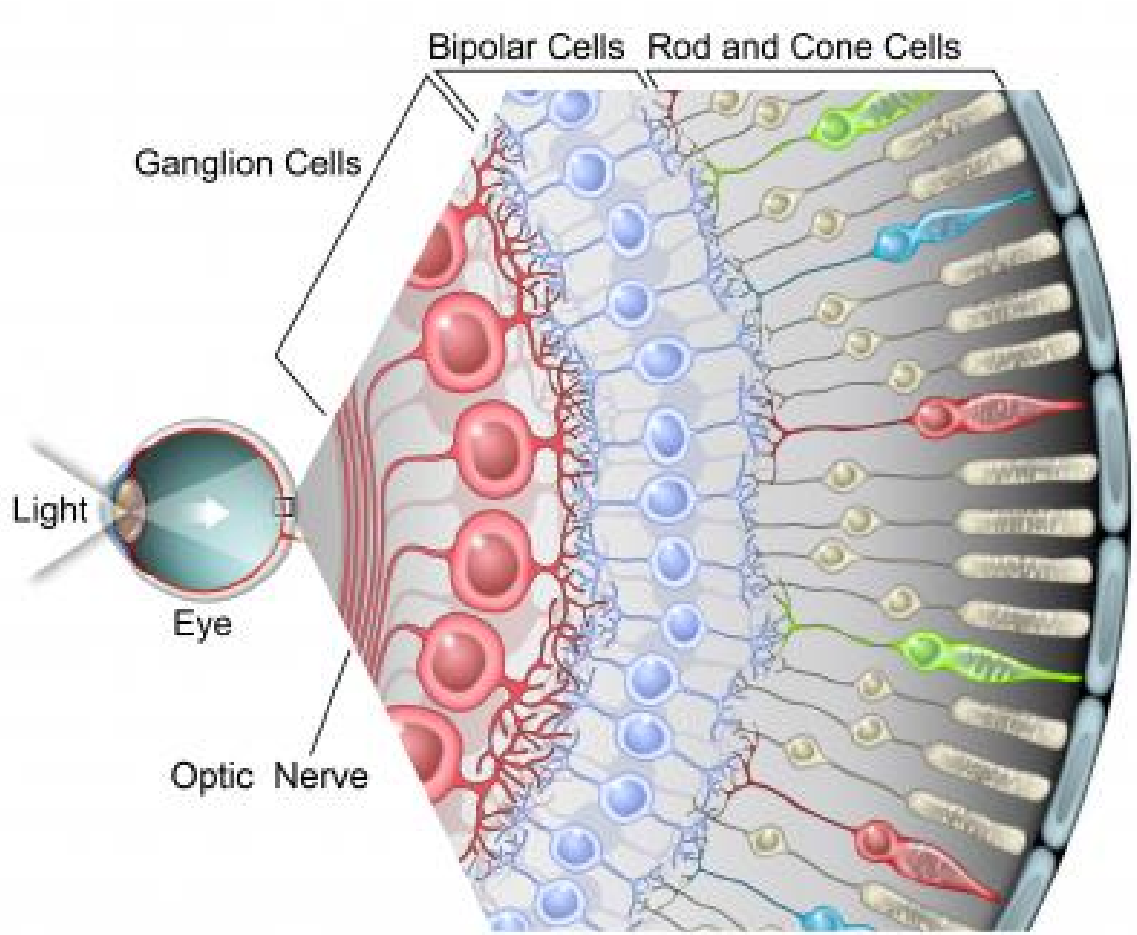


part of a self-stabilizing system…



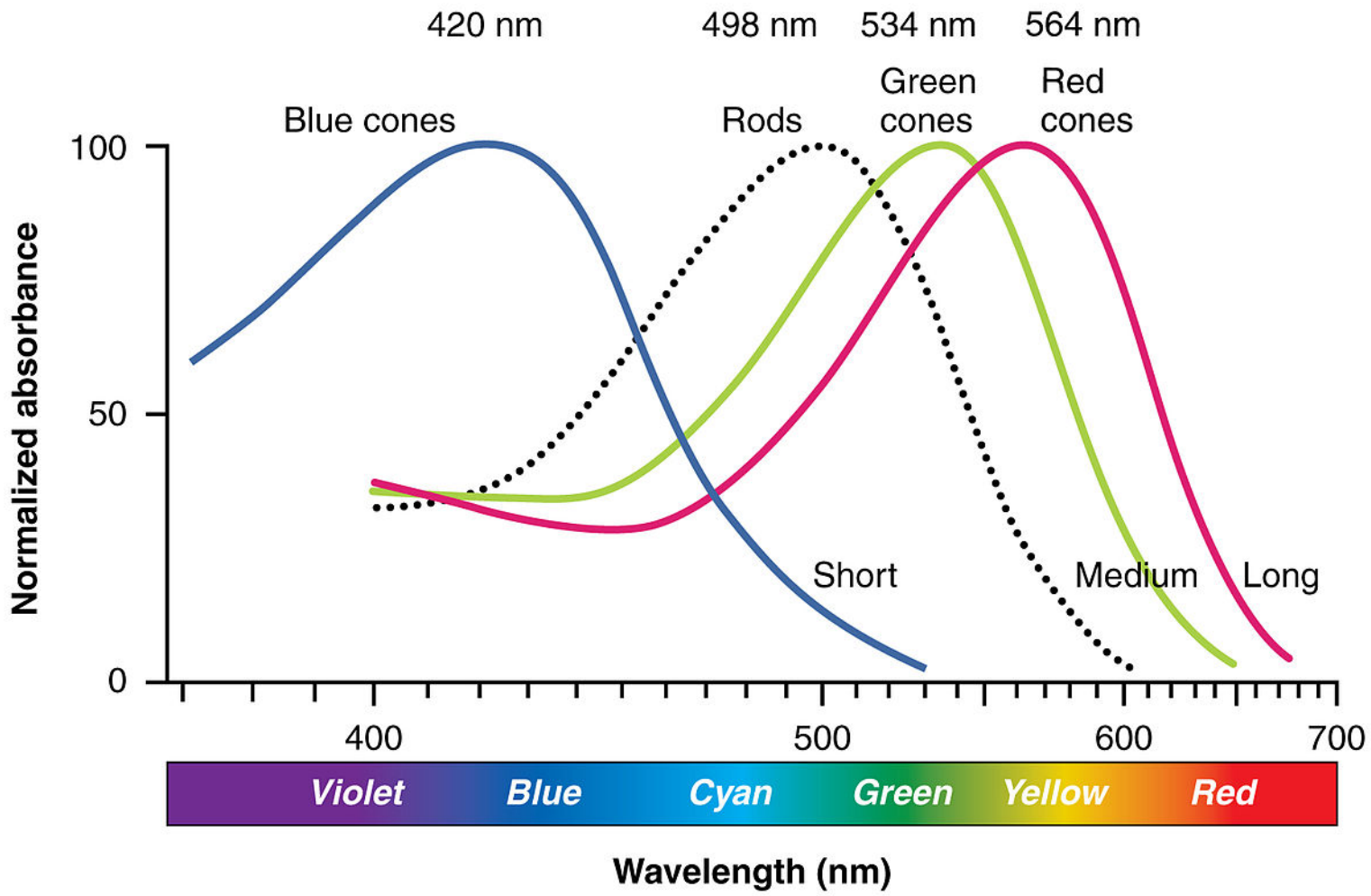
https://www.youtube.com/embed/JGArTWOJtXs

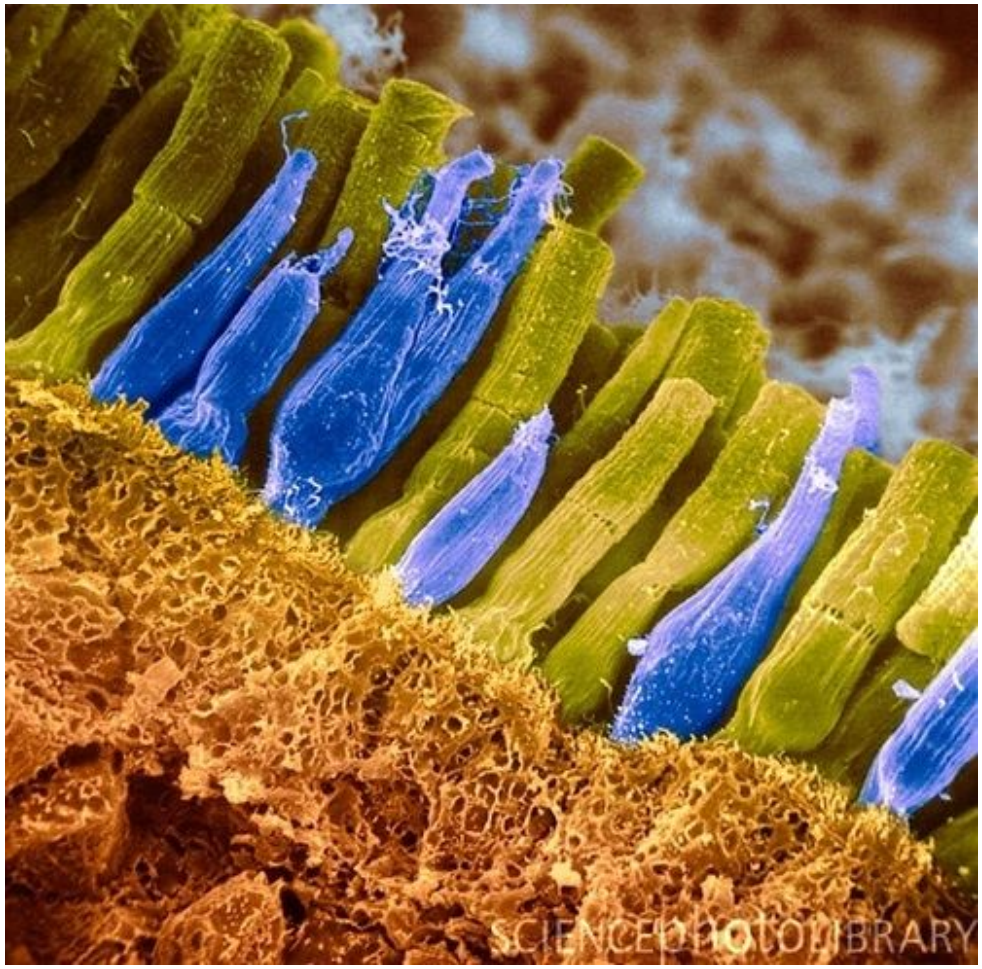
The retina…


Bipolar Cells
Rod and Cone Cells
Ganglion Cells
Light
Eye
Optic Nerve

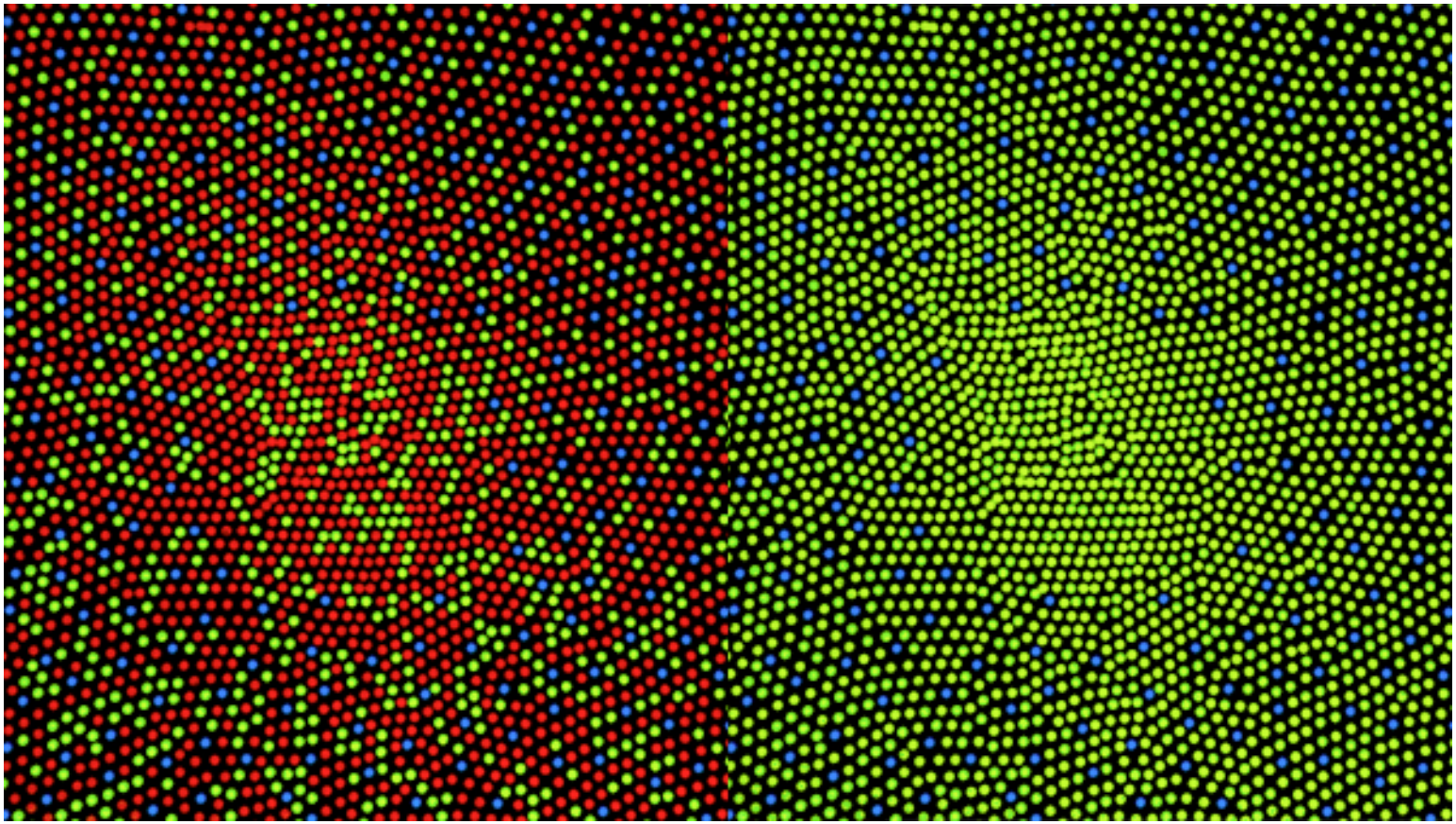
…samples light intensity, wavelength, and spatial pattern

via ‘wavelength-tuned’ photoreceptors

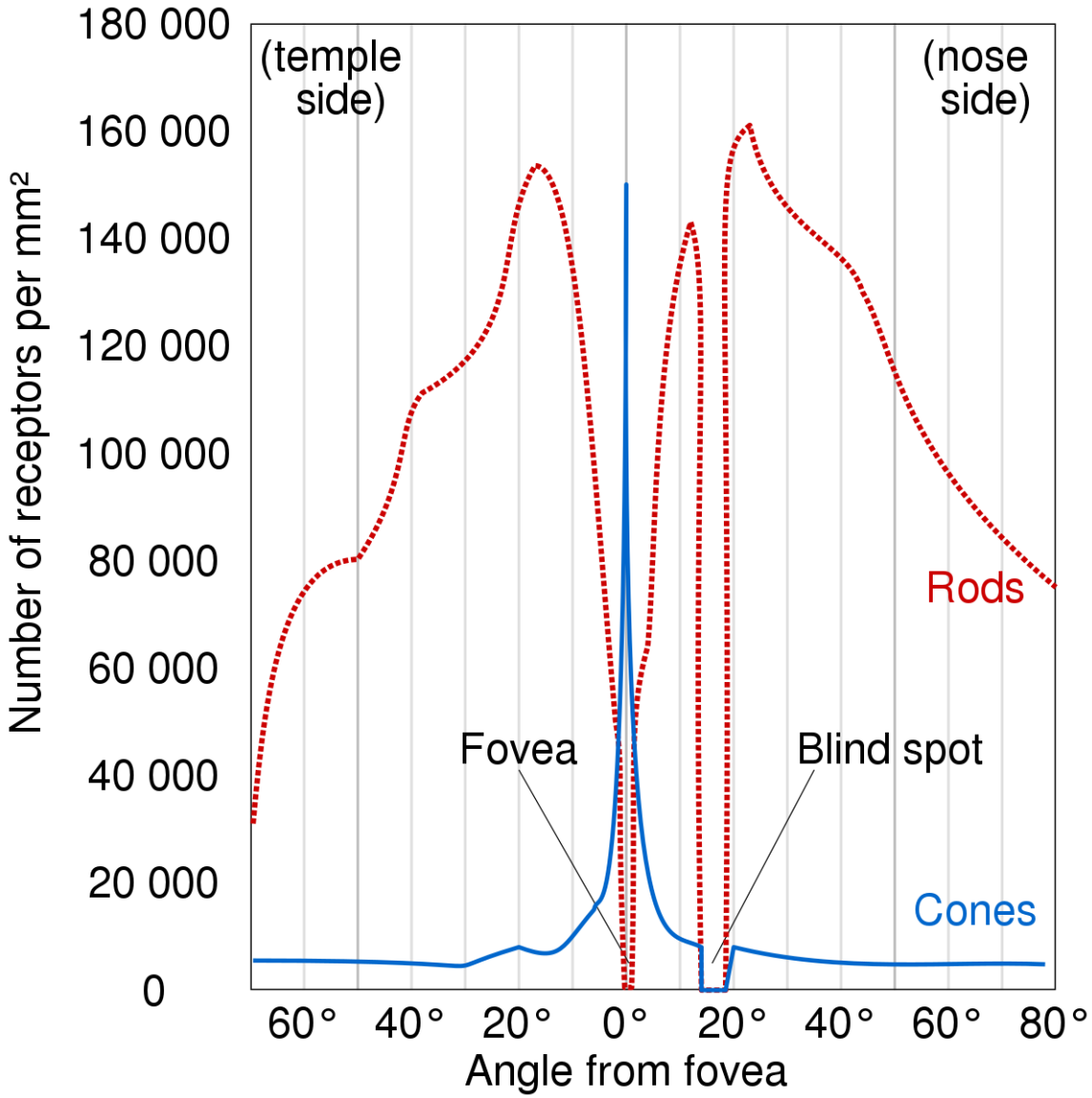




Peripheral retina



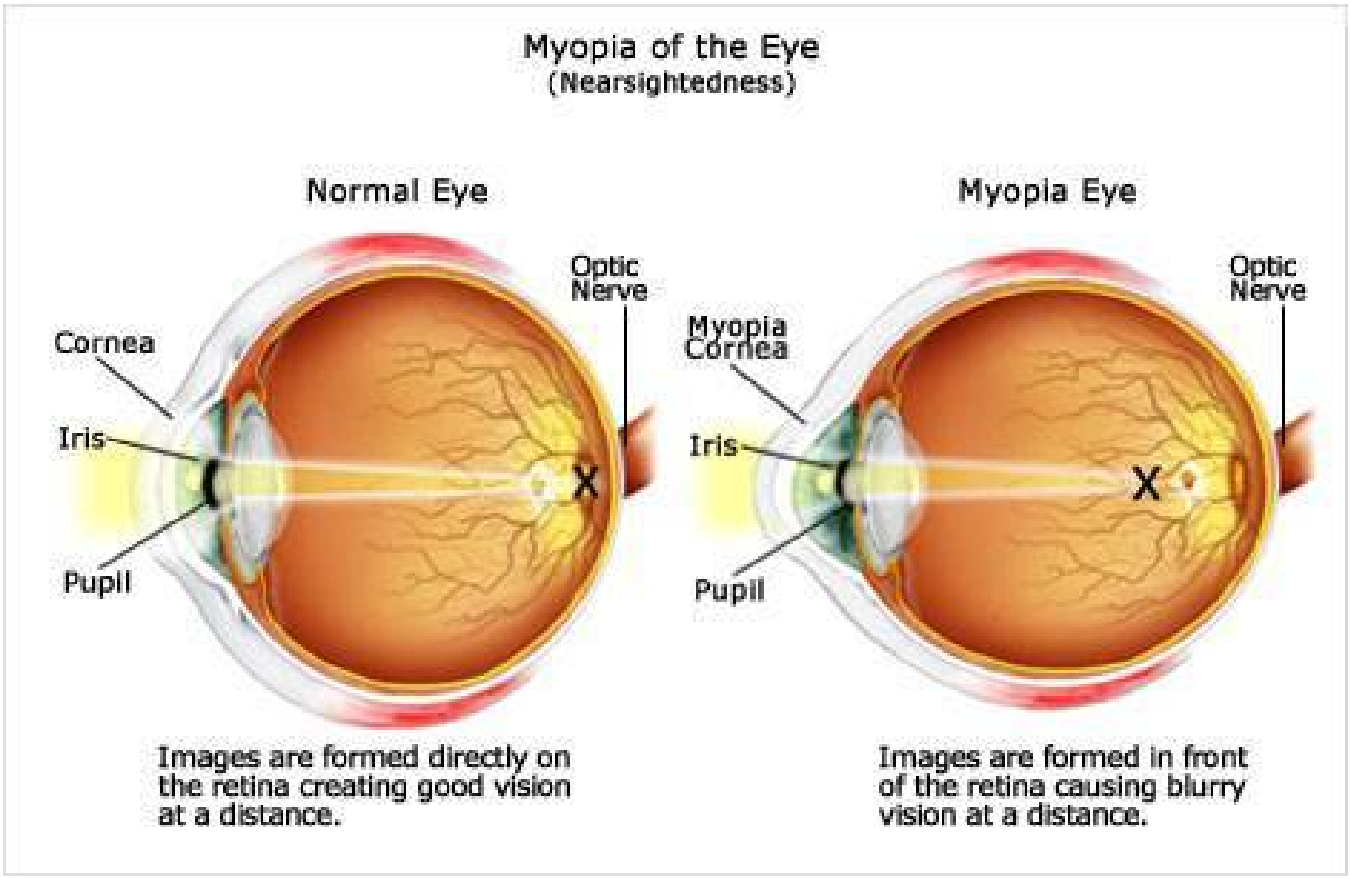
Central retina



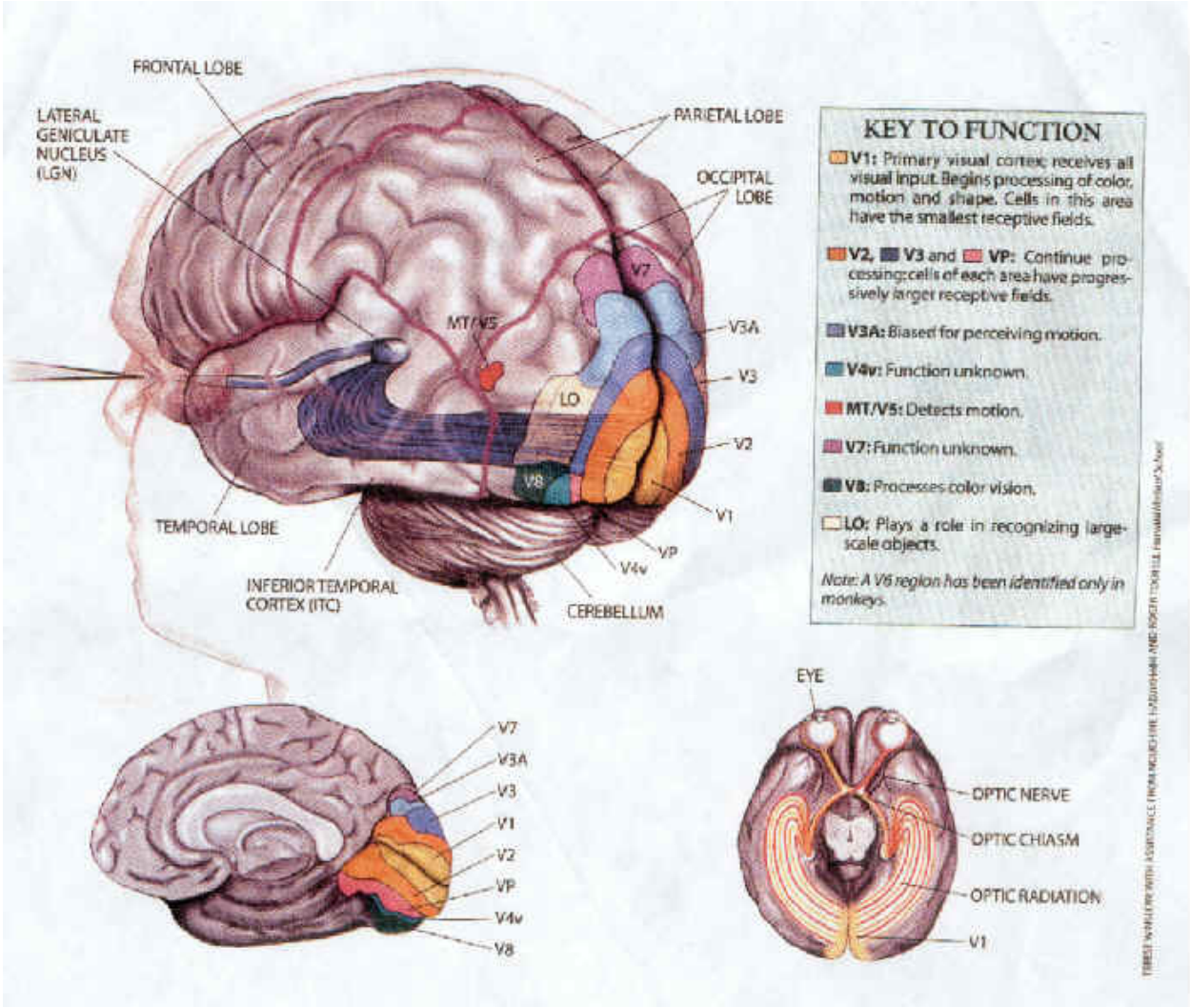
Source: Wikipedia

Photoreceptor information processing

- Separate channels for short, medium, long wavelengths (cones): chromatic
- Black/gray/white or overall illumination (rods): achromatic
- Point by point, topographic image
- Non-uniform resolution (center >> periphery)
- Focused by cornea (passive) + lens (active), except…


Myopia of the Eye
(Nearsightedness)
Normal Eye
Optic Nerve
Cornea
Iris
Pupil
Images are formed directly on the retina creating good vision at a distance.
Myopia Eye
Optic Nerve
Myopia Cornea
Iris
Pupil
Images are formed in front of the retina causing blurry vision at a distance.

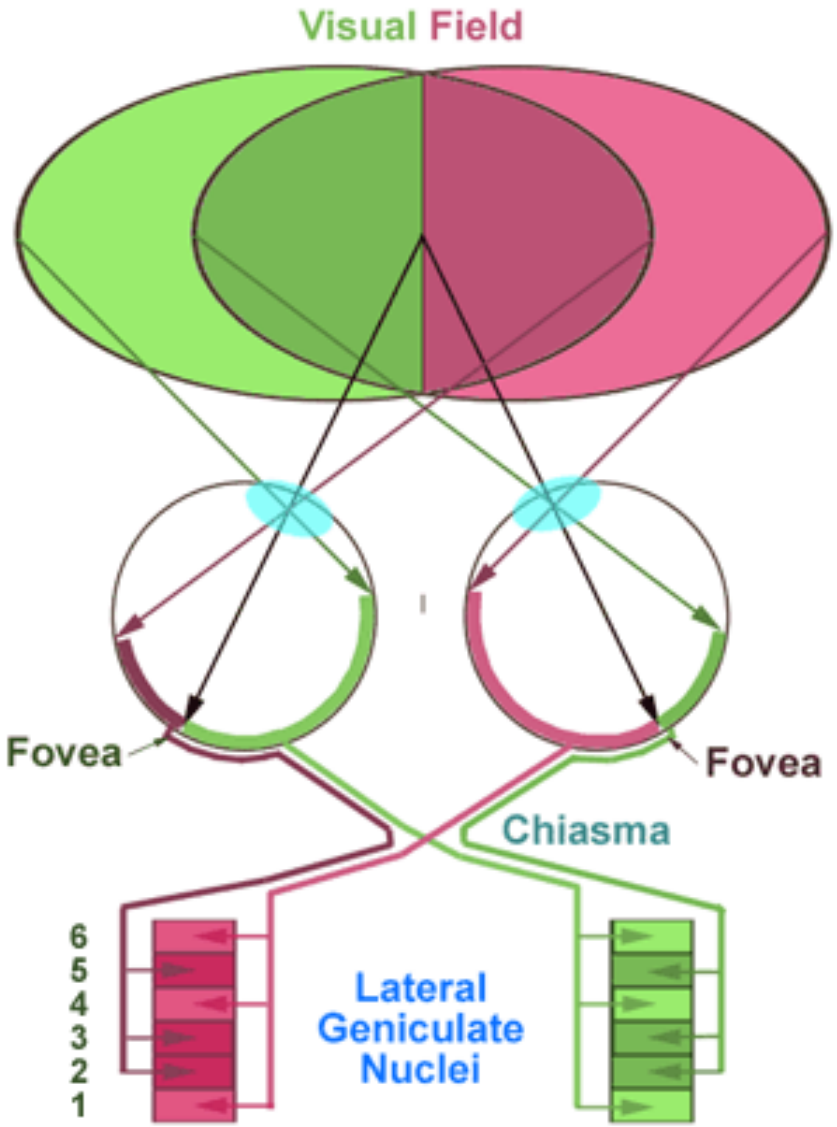
The visual brain

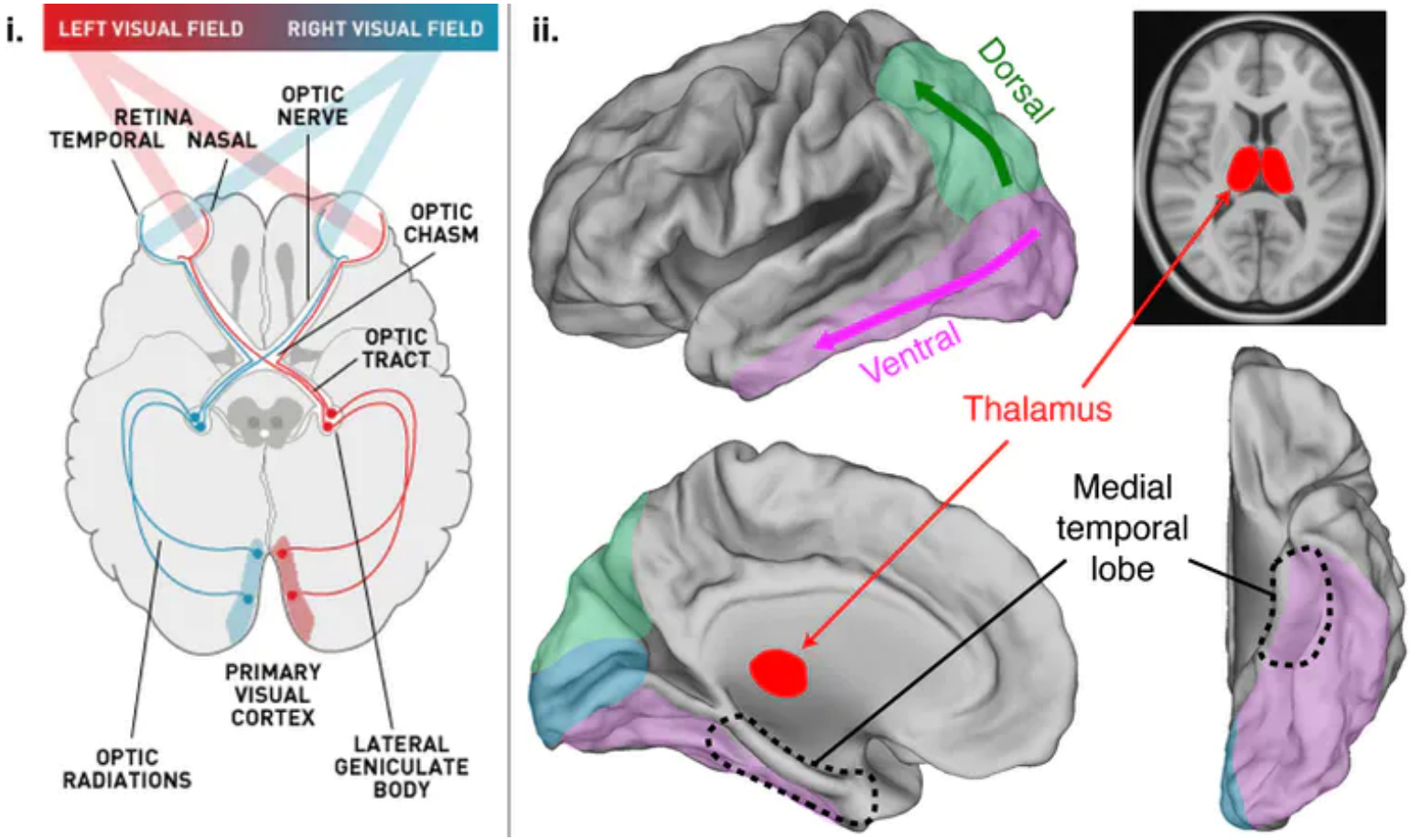


(Logothetis, N., November 1999. Vision: A window on consciousness. Scientific American

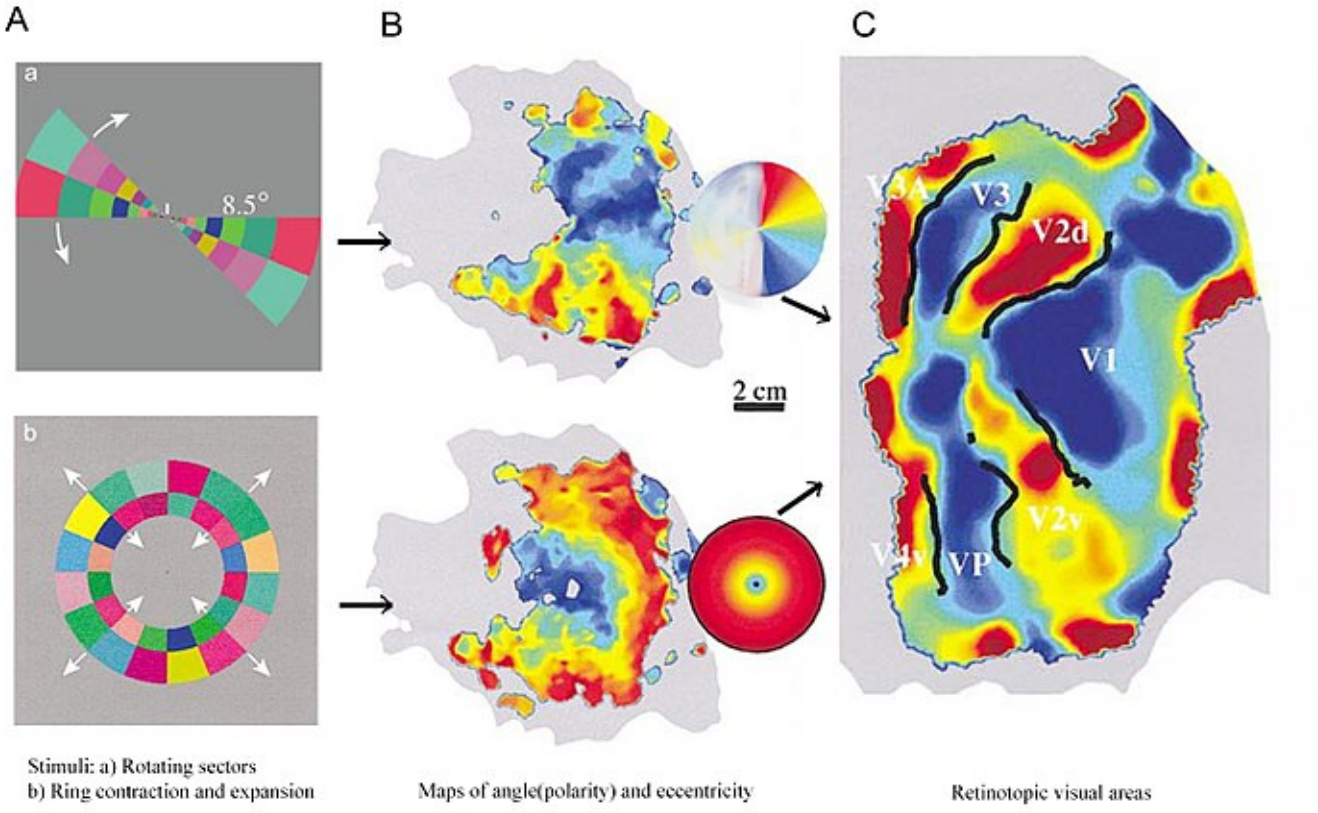
Primary (feedforward) pathway

- Retina ->
- Thalamus ->
- Primary visual cortex (V1) in occipital lobe


Visual Field
Fovea
Fovea
Chiasma
6
5
4
3
2
1
Lateral
Geniculate
Nuclei

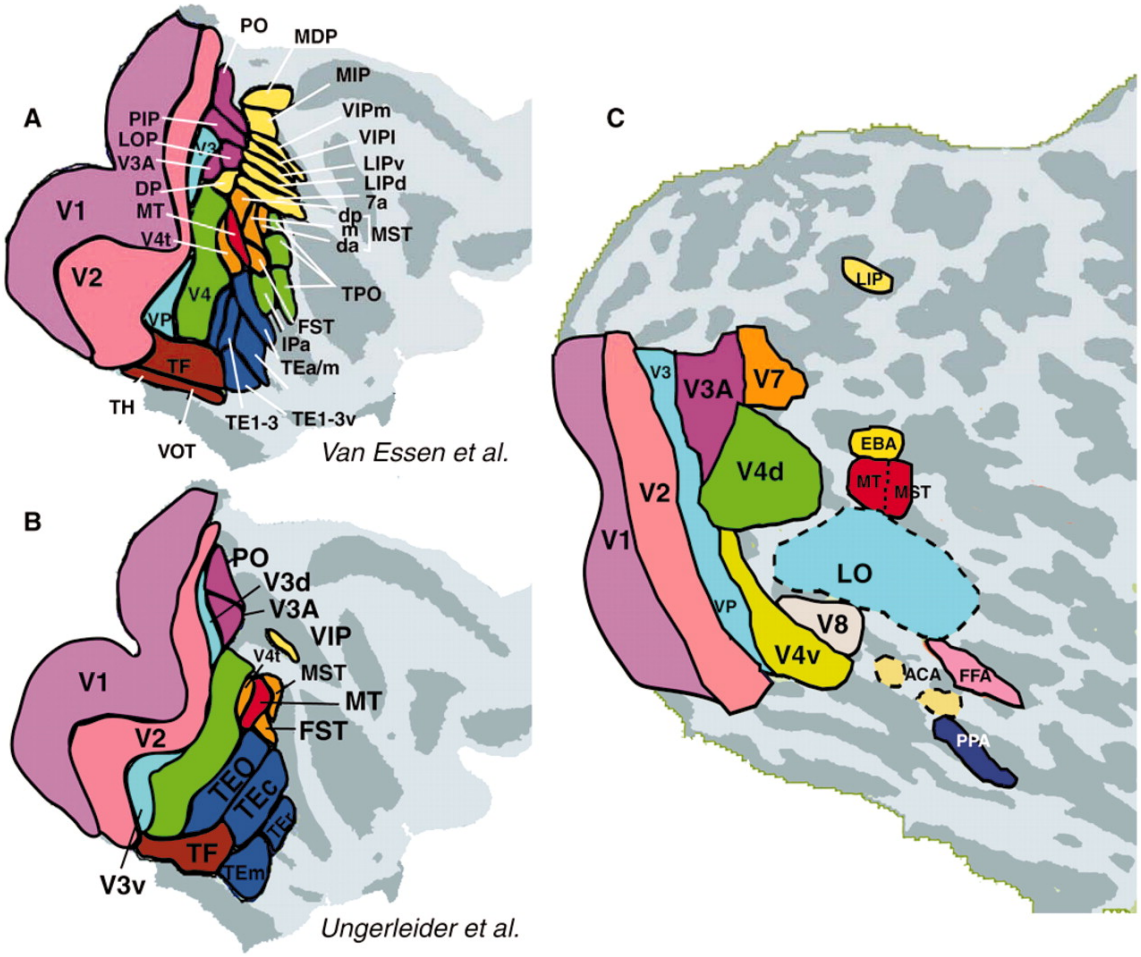

i.
LEFT VISUAL FIELD
RIGHT VISUAL FIELD
RETINA
TEMPORAL
NASAL
OPTIC NERVE
OPTIC CHASM
OPTIC TRACT
PRIMARY VISUAL CORTEX
OPTIC RADIATIONS
LATERAL GENICULATE BODY
ii.
Dorsal
Ventral
Thalamus
Medial temporal lobe

Retinotopic map



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

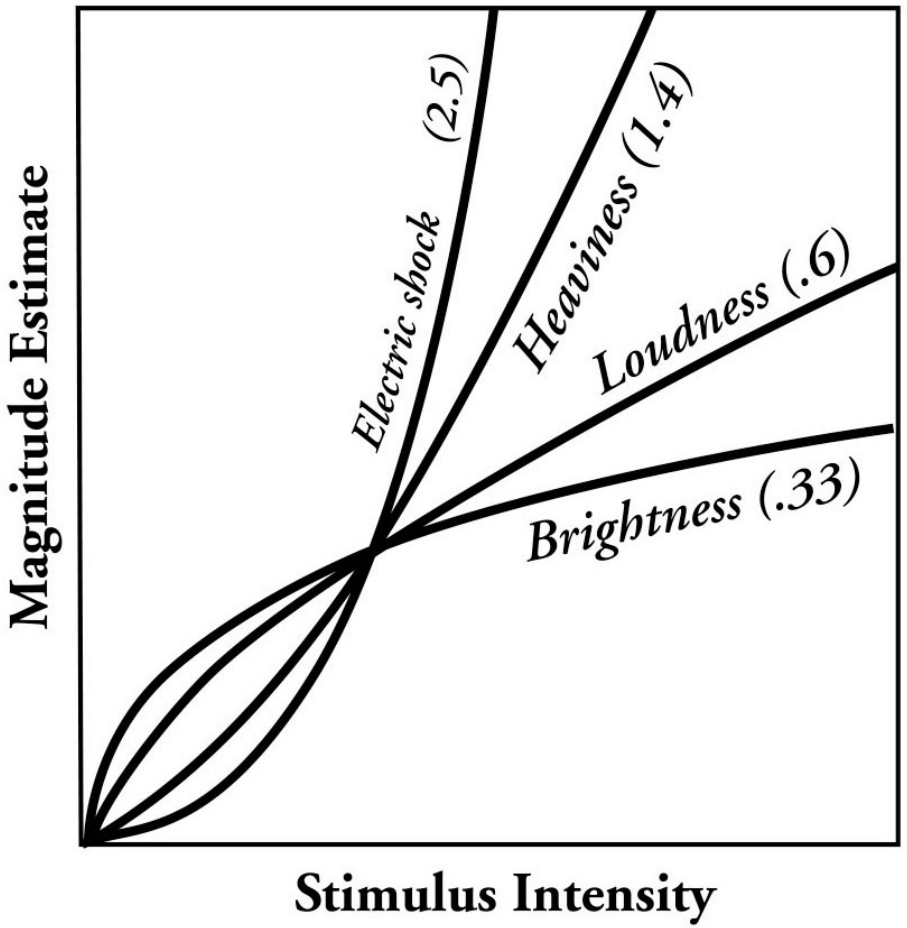
Visual processing dominates the primate brain



(Tootell, Tsao, & Vanduffel, 2003)

Measuring visual function and its development

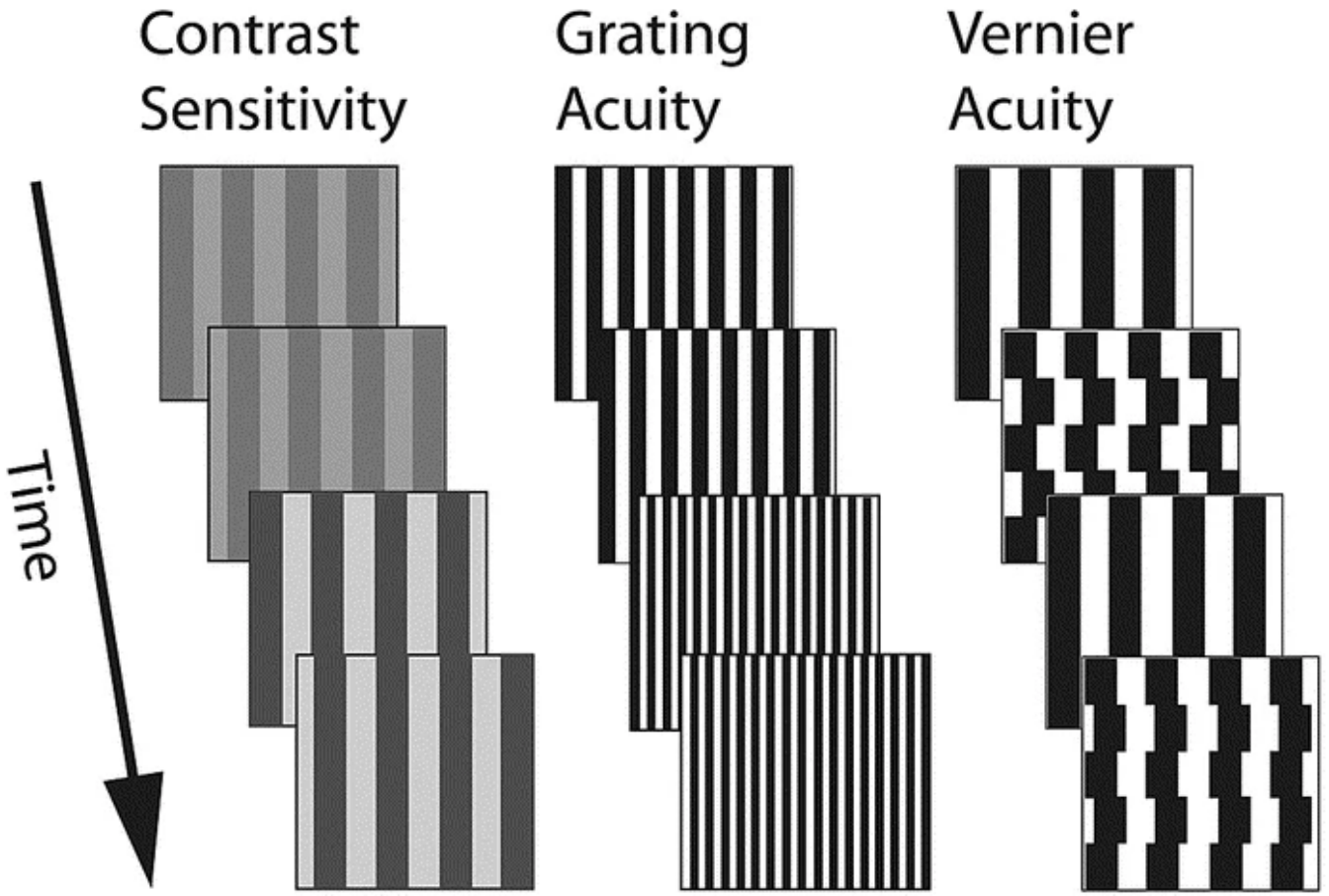
Psychophysical functions



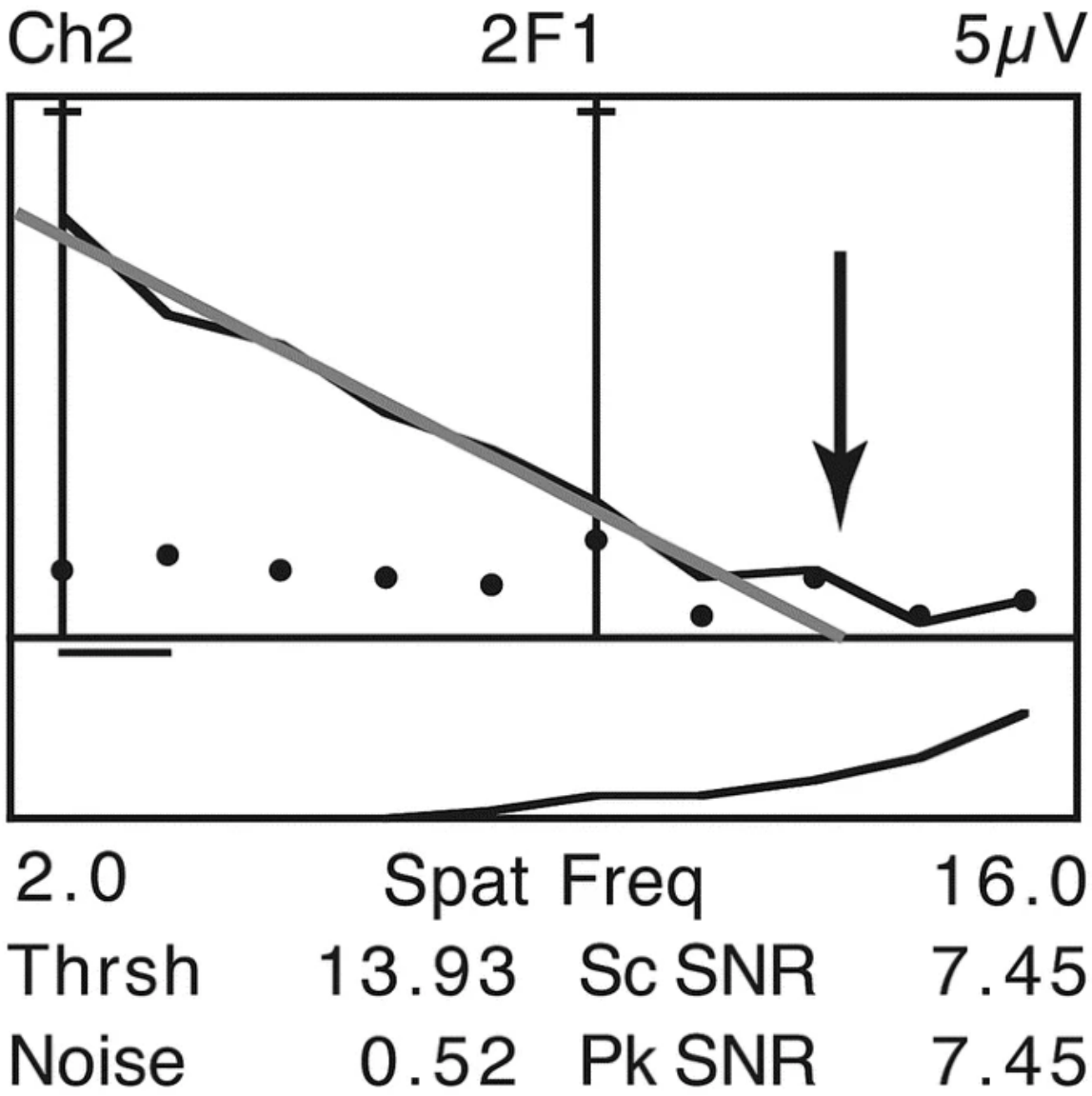
Psychophysical methods

- *Method of constants* (fixed levels)
- *Method of adjustment* (raise/lower amplitude until detectable/indetectable)
- *Method of limits* (“can you see me now? now?”; often use staircases)

Psychophys*iolog*ical functions



(Mirabella, Kjaer, Norcia, Good, & Madan, 2006)

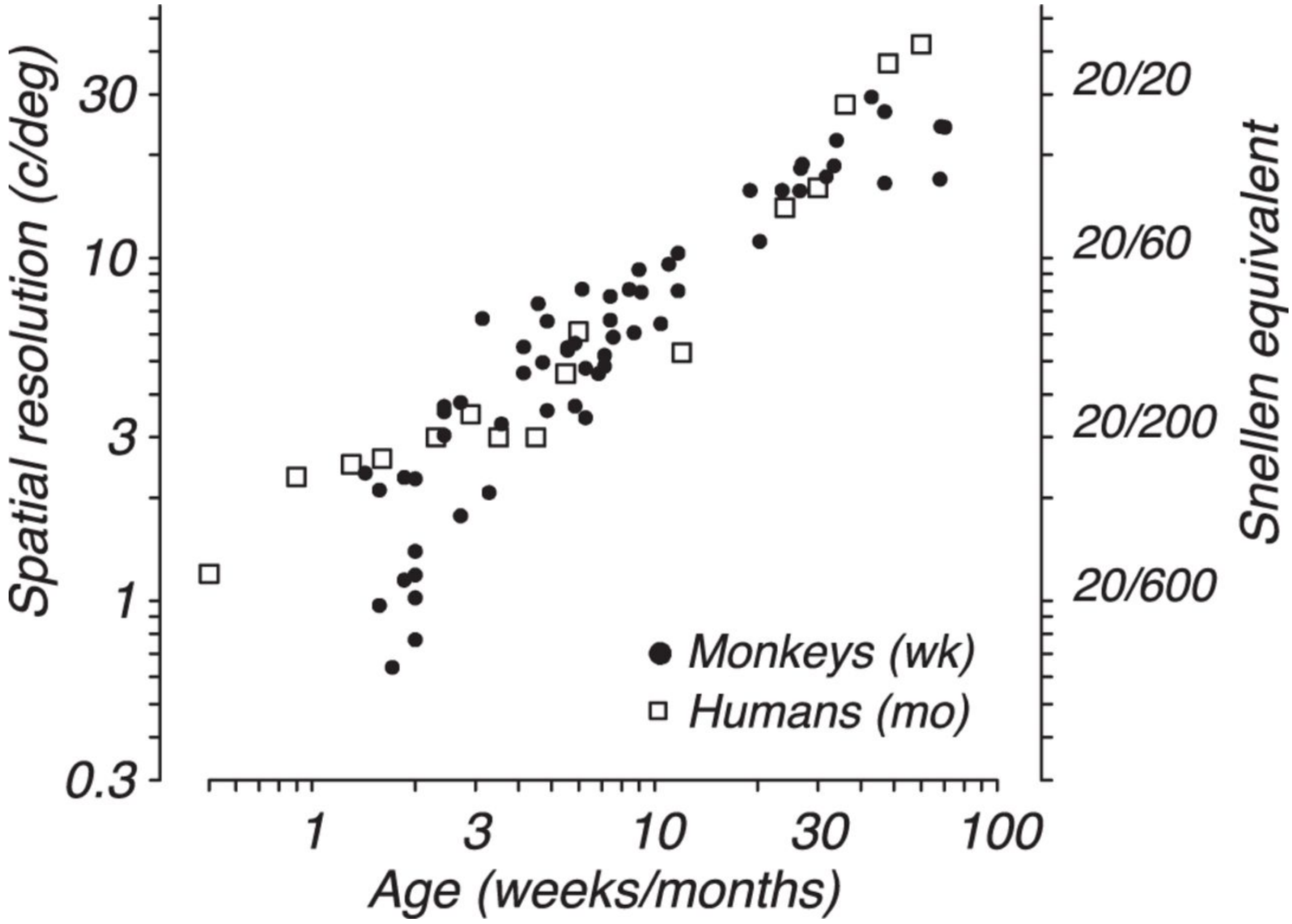


(Mirabella, Kjaer, Norcia, Good, & Madan, 2006)

Acuity (detail/pattern vision)

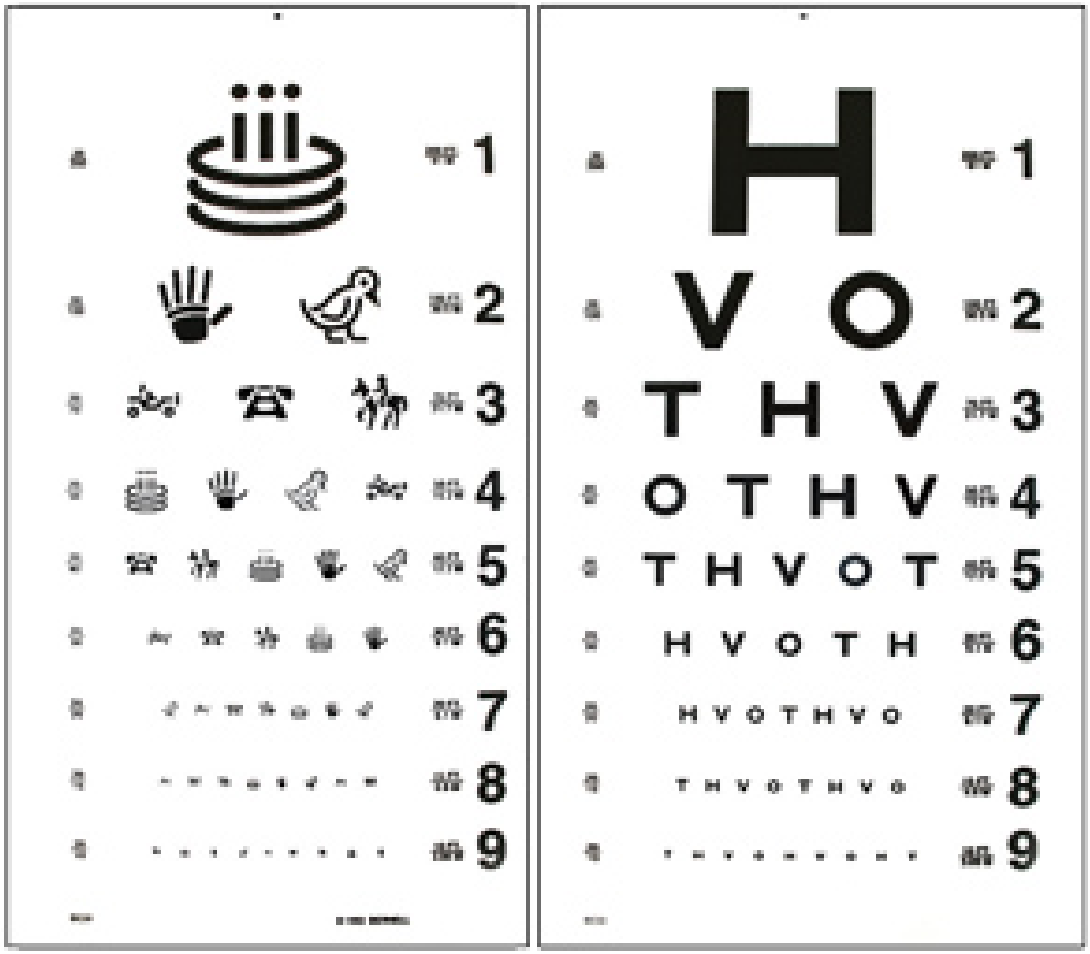
- Grating acuity
- Vernier
- Symbol/letter (optotype) acuity

Similar rates of development across primate species



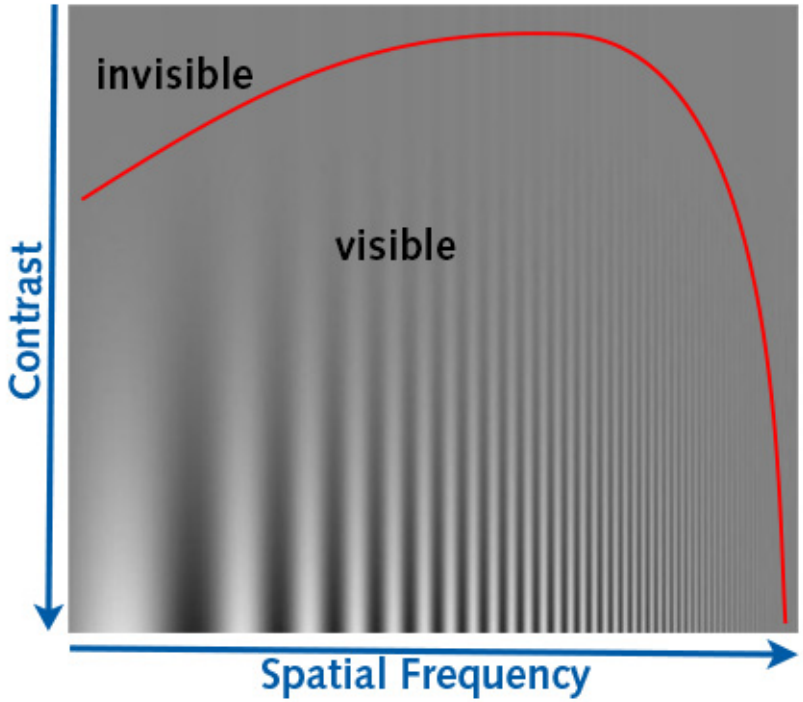
(Kiorpes, 2016)

Measuring visual acuity



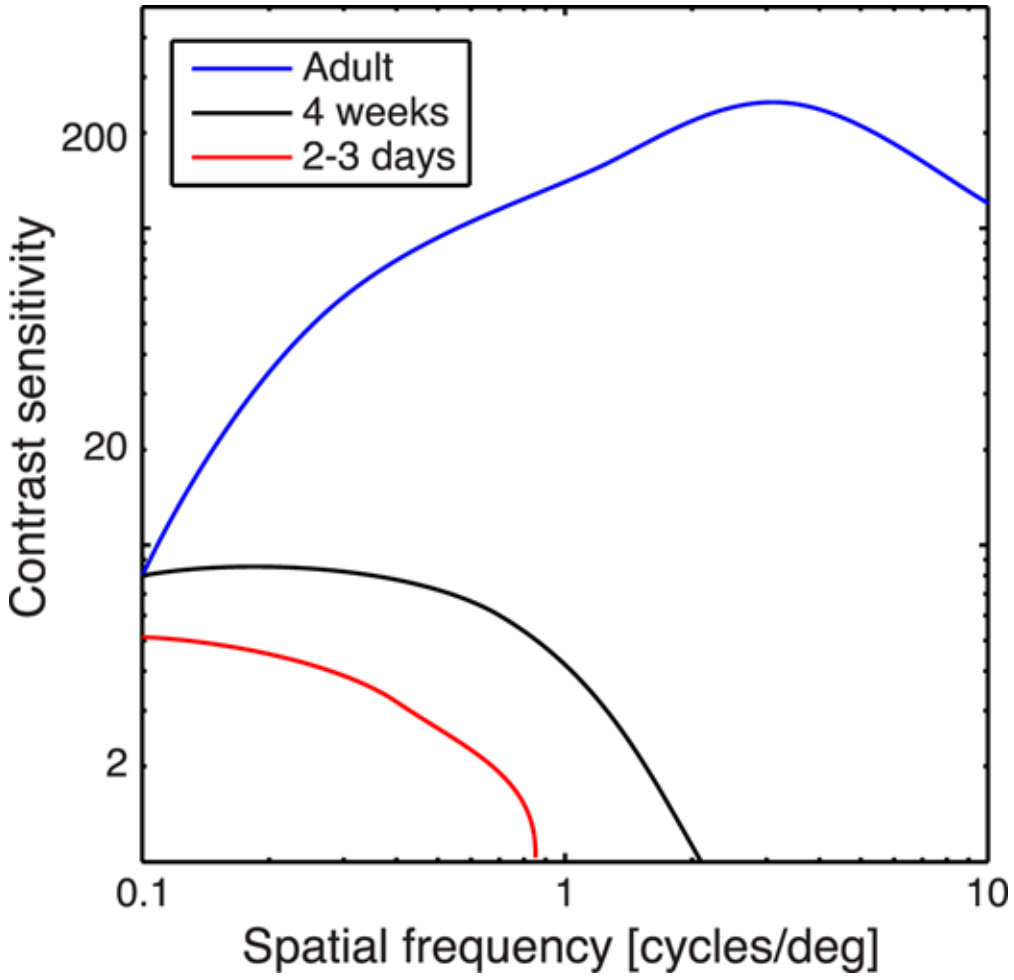
Contrast sensitivity

- Light/dark ratio vs. spatial frequency (level of detail)

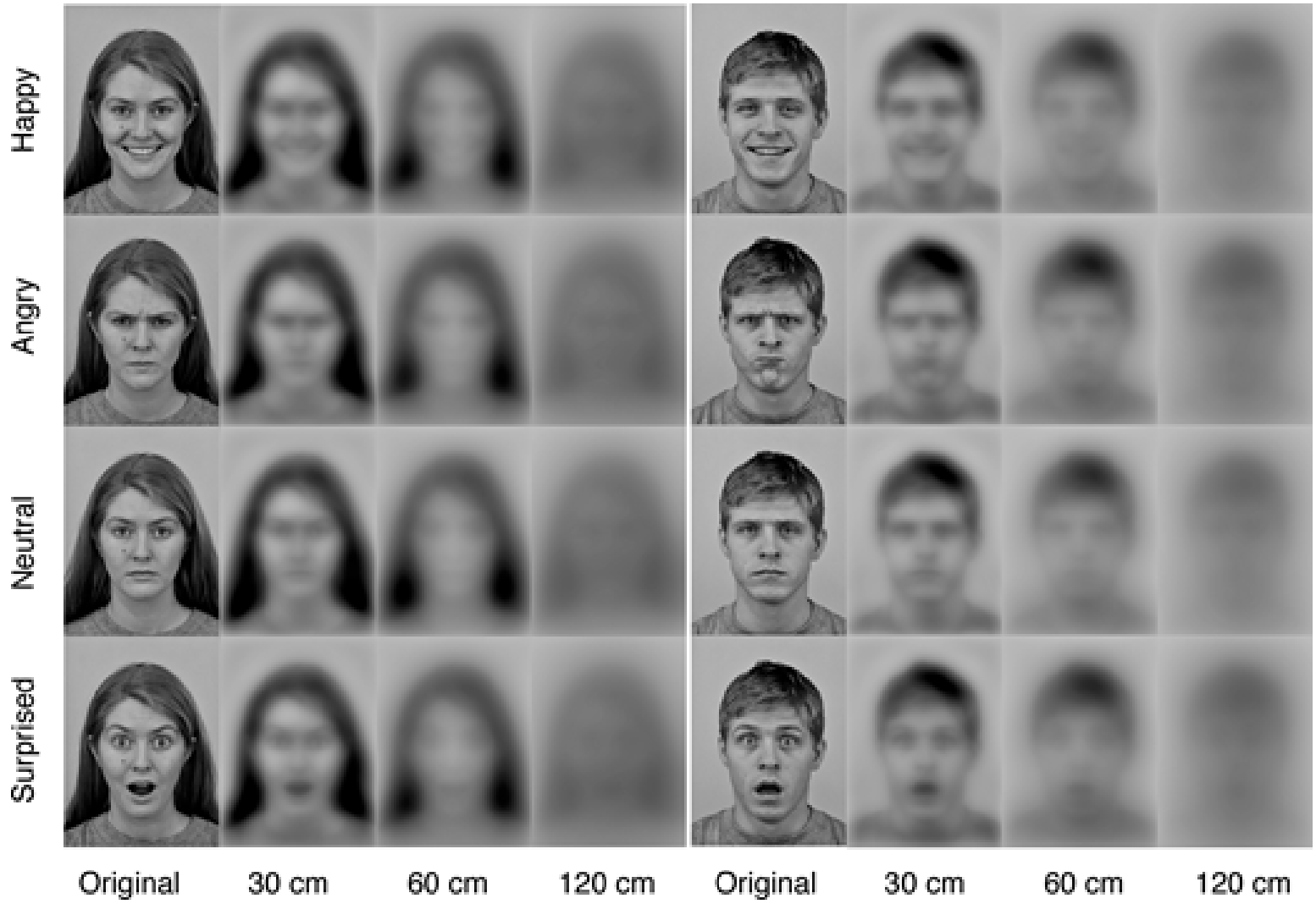


Contrast sensitivity function

Pelli-Robson Contrast Sensitivity Chart

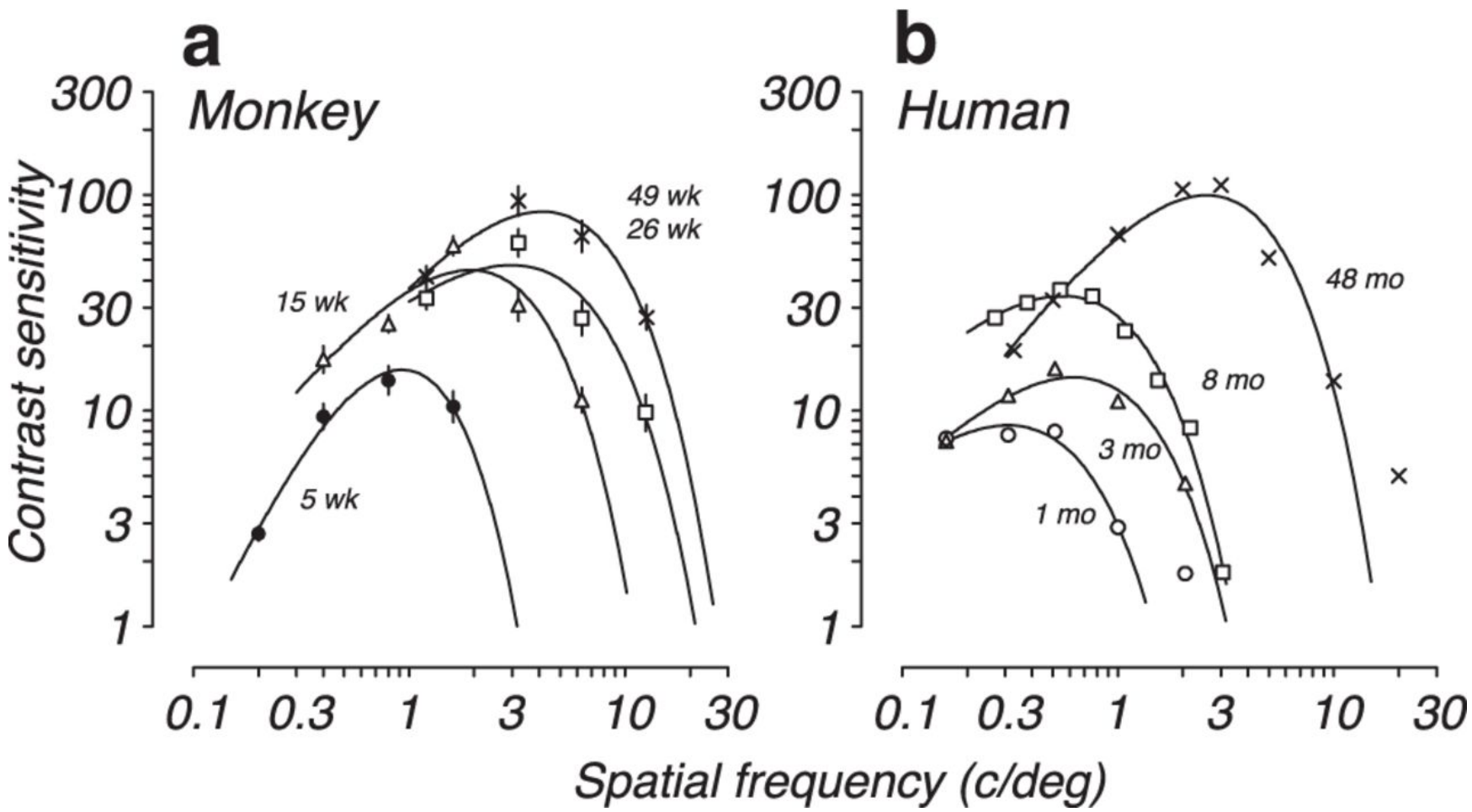


(Hofsten et al., 2014)



(Hofsten et al., 2014)

Similar rates of development across primate species



(Kiorpes, 2016)

Effects of poor contrast sensitivity on newborn vision

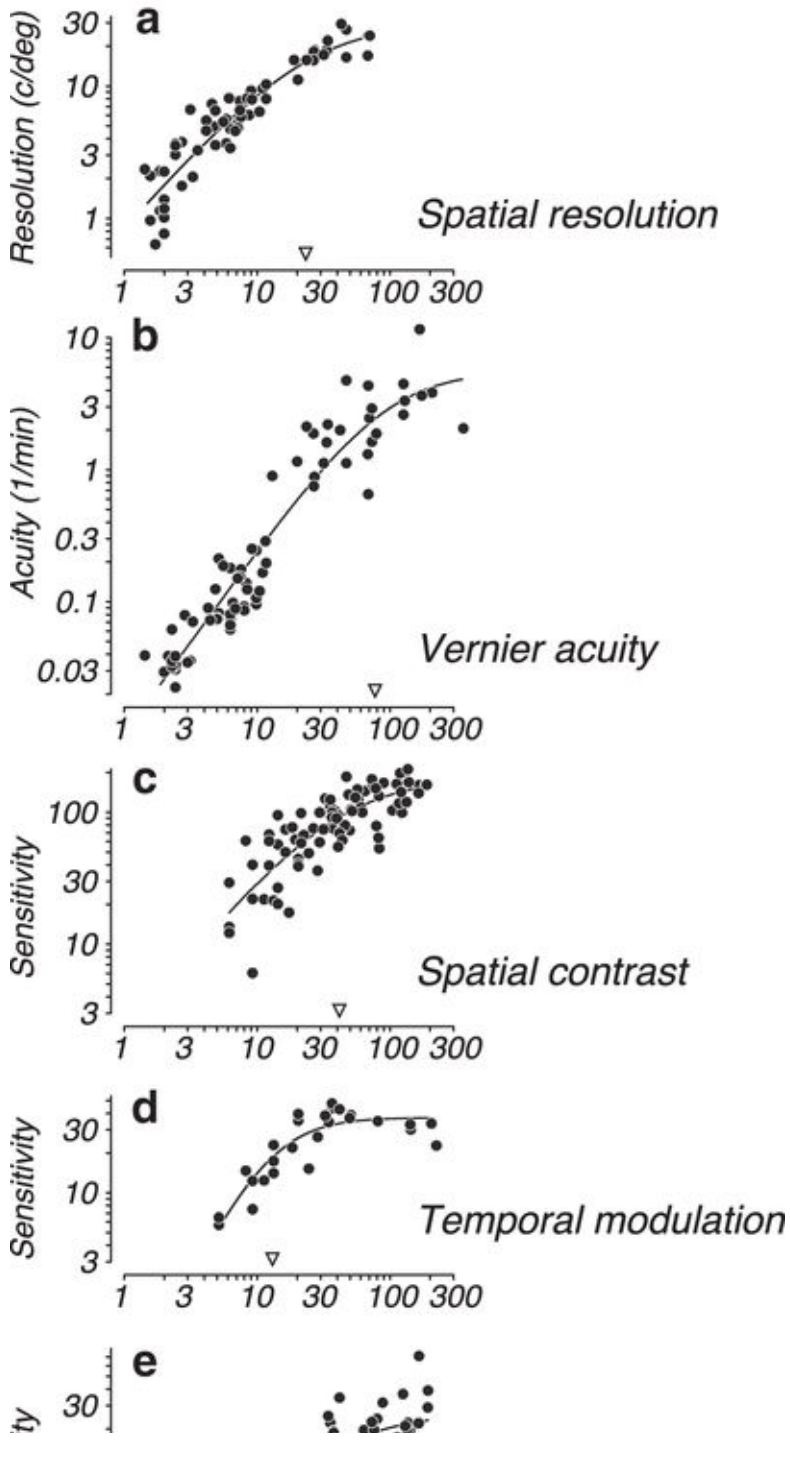
(Kiorpes, 2016)

Motion coherence (Signal vs. noise)

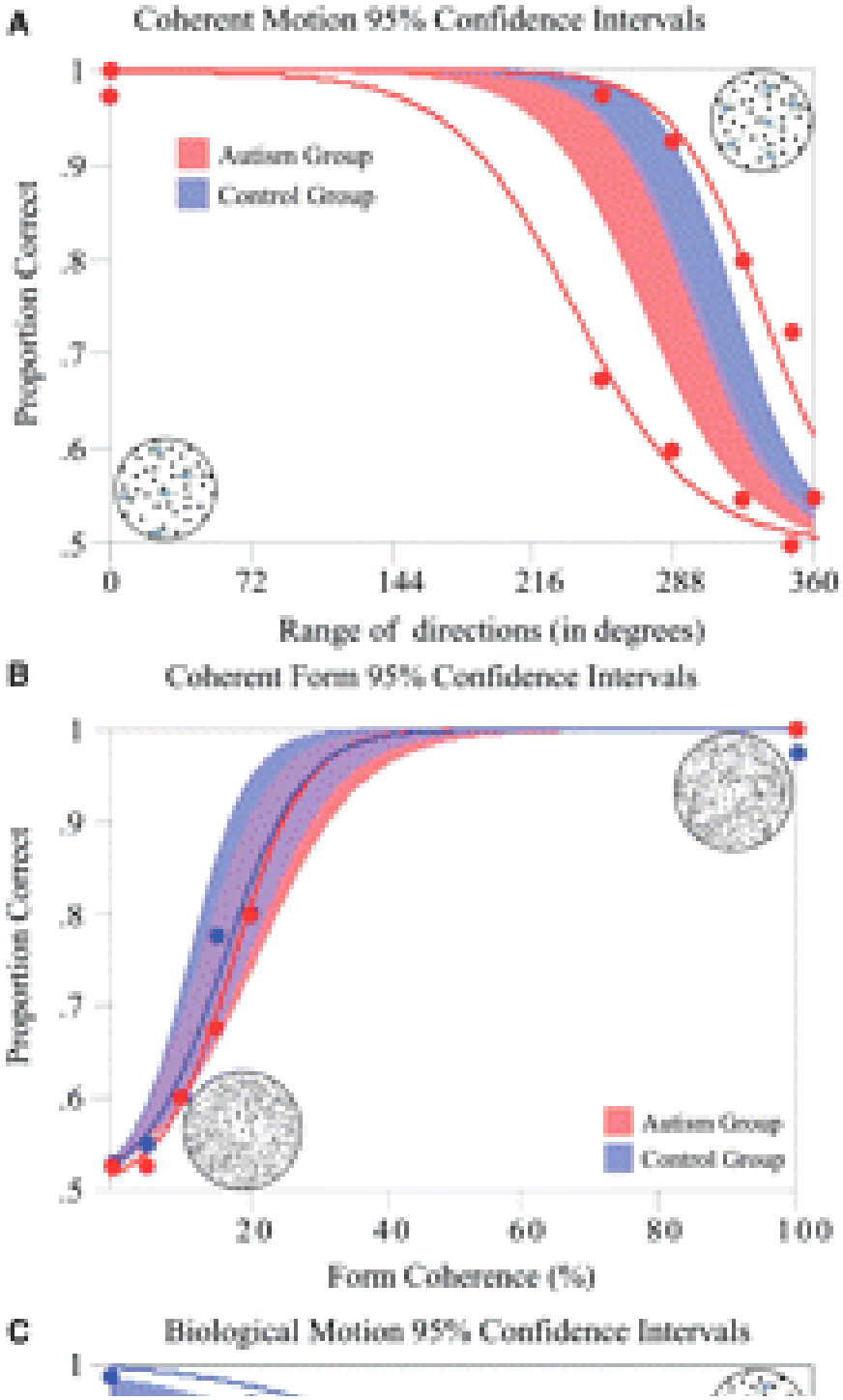
measuring motion coherence thresholds

Rate of development varies across visual functions

- Some (e.g., motion sensitivity) not adult-like until early teens


a
Resolution (c/deg)
30
10
3
1
Spatial resolution
1 3 10 30 100 300
b
Acuity (1/min)
10
3
1
0.3
0.1
0.03
Vernier acuity
1 3 10 30 100 300
c
Sensitivity
100
30
10
3
Spatial contrast
1 3 10 30 100 300
d
Sensitivity
30
10
3
Temporal modulation
1 3 10 30 100 300
e
30

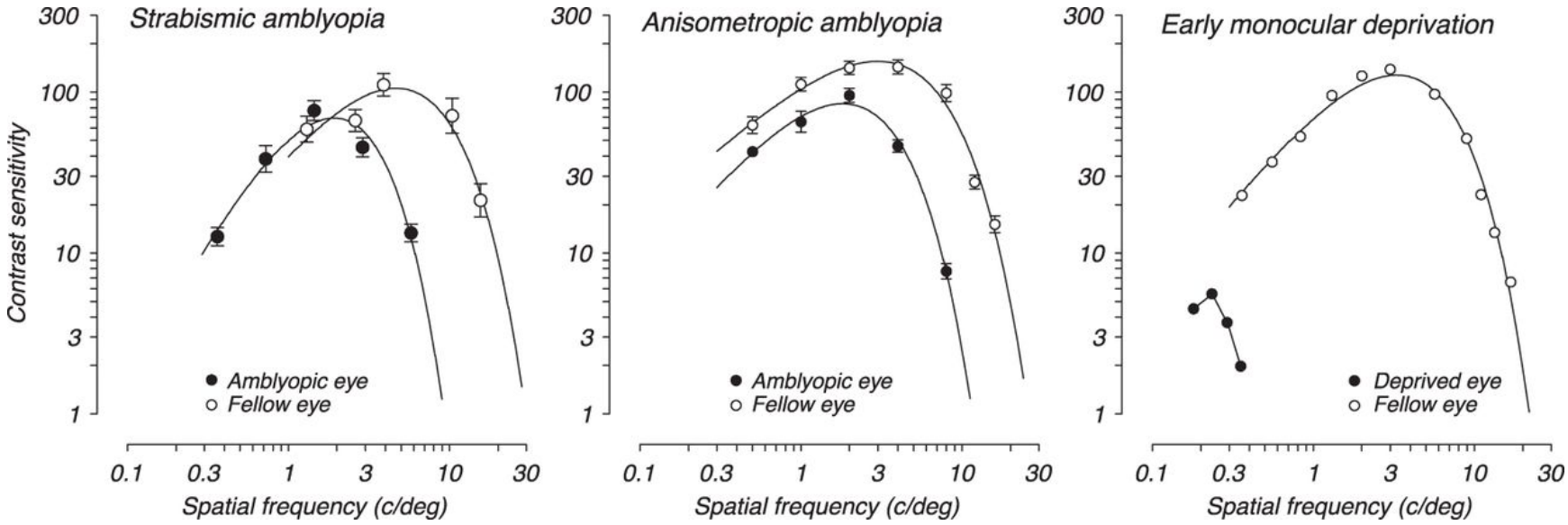
Atypical development: Autism


A
Coherent Motion 95% Confidence Intervals
Autism Group
Control Group
Proportion Correct
1
.9
.8
.7
.6
.5
0
72
144
216
288
360
Range of directions (in degrees)
B
Coherent Form 95% Confidence Intervals
Proportion Correct
1
.9
.8
.7
.6
.5
Autism Group
Control Group
20
40
60
80
100
Form Coherence (%)
C
Biological Motion 95% Confidence Intervals
1

Atypical development: Amblyopia

- **Amblyopia**: Reduced visual acuity in one or both eyes relative to the other without an obvious defect or change in the eye
- **Strabismus**: Misalignment of the eyes
- **Anisometropia**: Difference in refractive power

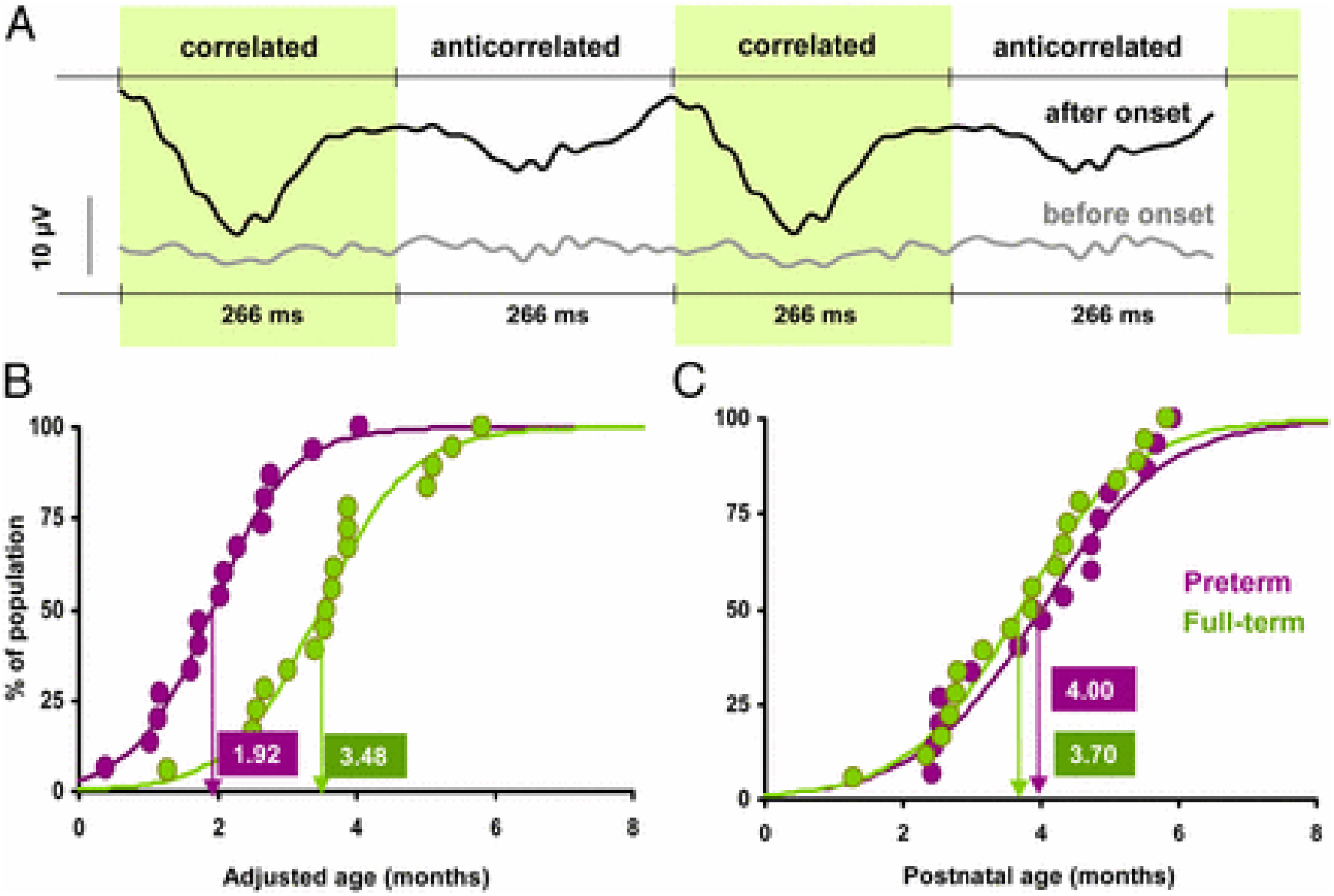
Wikipedia



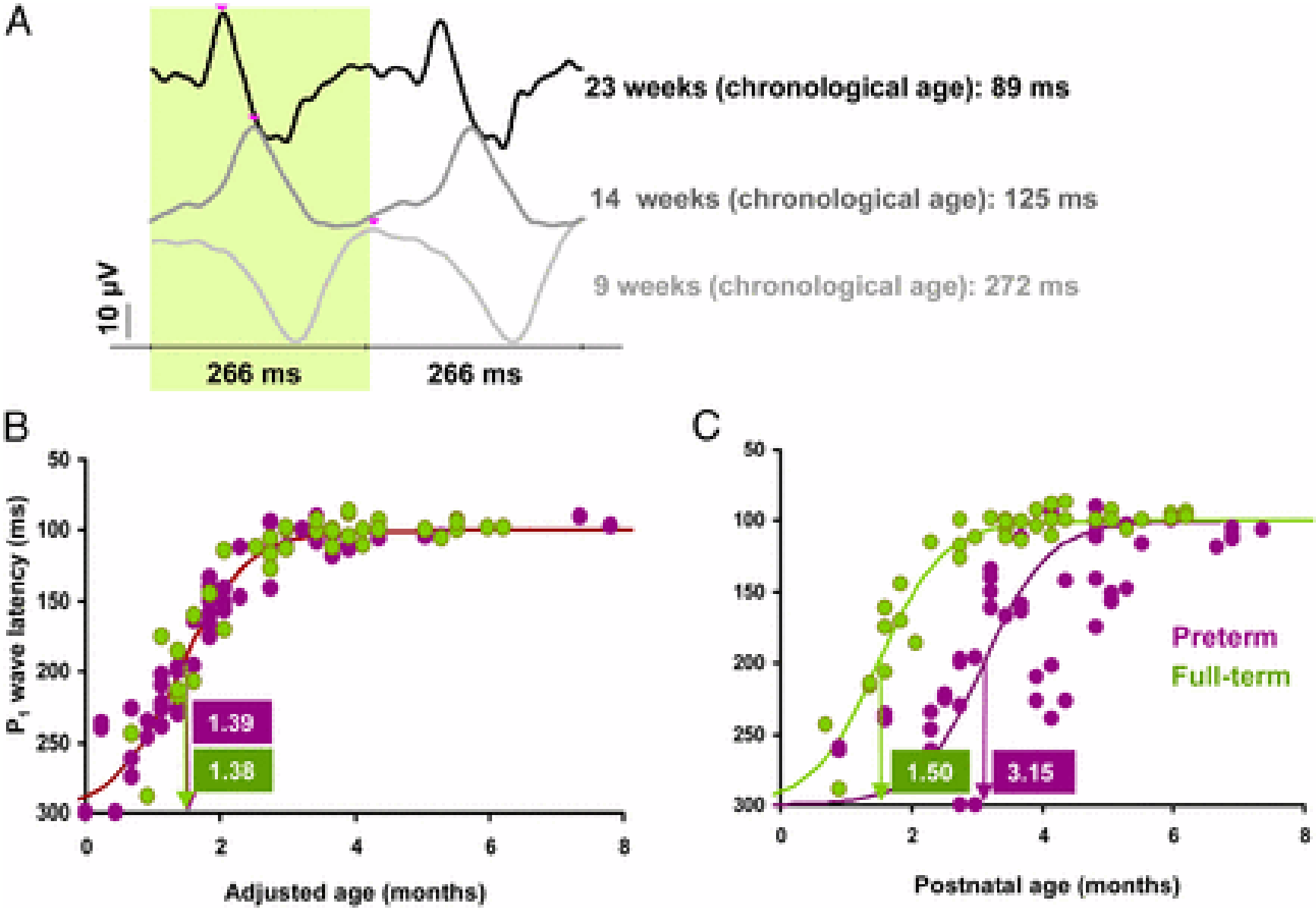
(Kiorpes, 2016)

Atypical development: Prematurity

Some (binocular functions) are experience-dependent



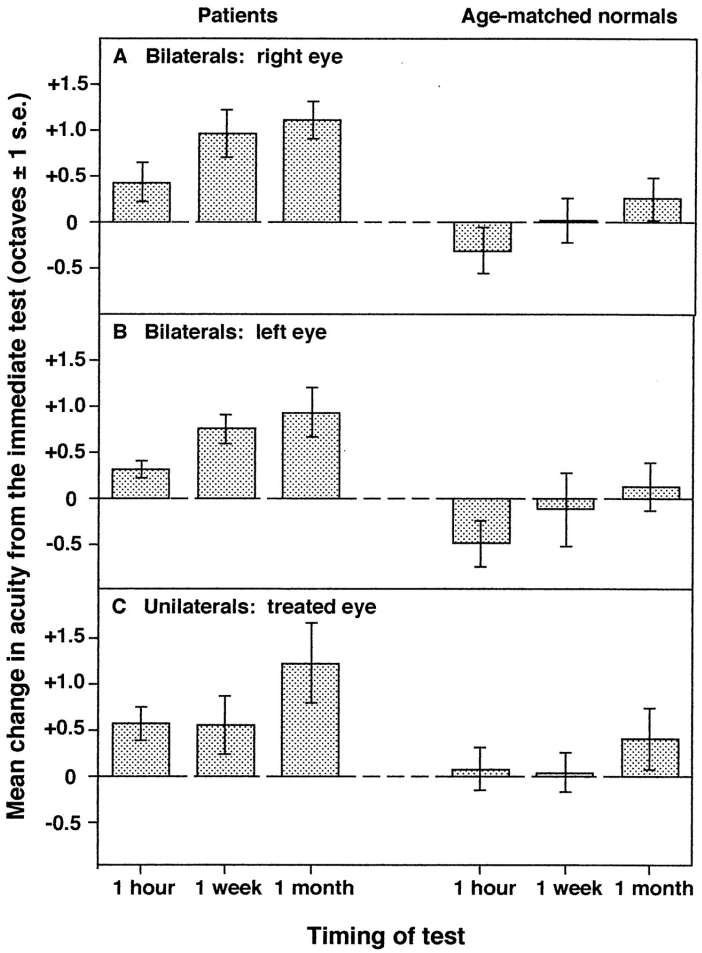
Others (pattern/contrast reversal) are not



(Jandó et al., 2012)

Atypical development: Cataract

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



(Maurer, Lewis, Brent, & Levin, 1999)

The big picture

“For me, one of the major attractions of visual science is the **promise it holds for empirical attacks on the mind-body problem**—that is, for working out meaningful ways to explain psychophysically defined visual functions on the basis of properties of the neural substrate.”

Davida Teller

“…A critical locus or critical computation for a particular perceptual function can be defined as an anatomic or computational stage at which information concerning that function is lost or importantly reorganized…”

Davida Teller

“or more poetically, as a stage or computation that leaves its mark on that perceptual capacity.”

Davida Teller

“Part of the appeal of visual development is its potential for extending this promise. **Visual functions mature because the visual substrate matures**, and the causes of functional maturation undoubtedly lie in neural maturation.”

Davida Teller

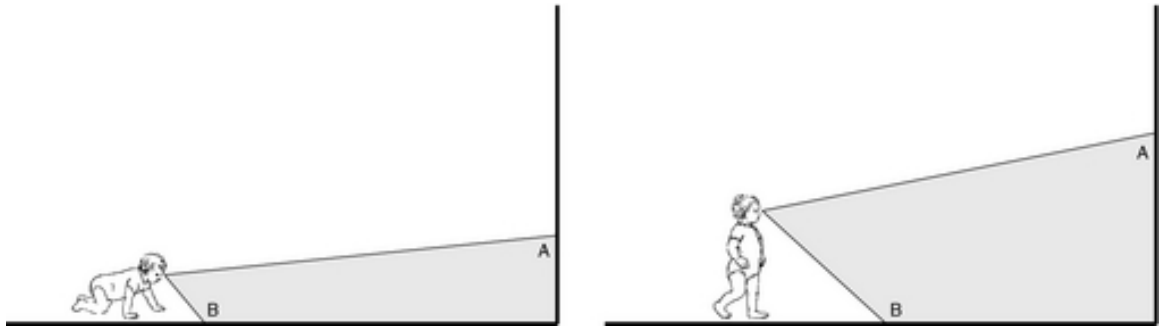
“But the length of the big toe matures too, and we do not see it as causal in relation to the development of grating acuity. The puzzle is, **which of the many immaturities of the visual substrate provide the critical immaturities** that limit a particular visual capacity at a particular age?”

Davida Teller

Other things change, too…

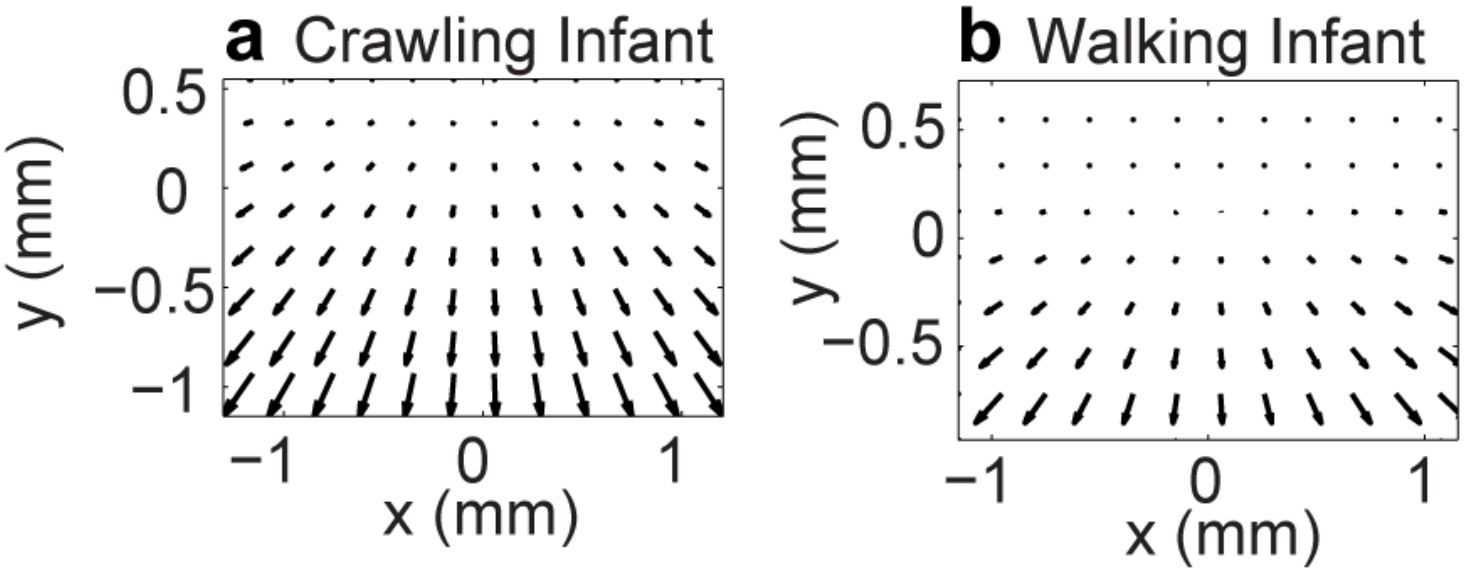
Simulating effects of posture change on motion

Parameter	Crawling Infant	Walking Infant
Eye height	0.30 m	0.60 m
Locomotor speed	0.33 m/s	0.61 m/s
Head tilt	20 deg	9 deg



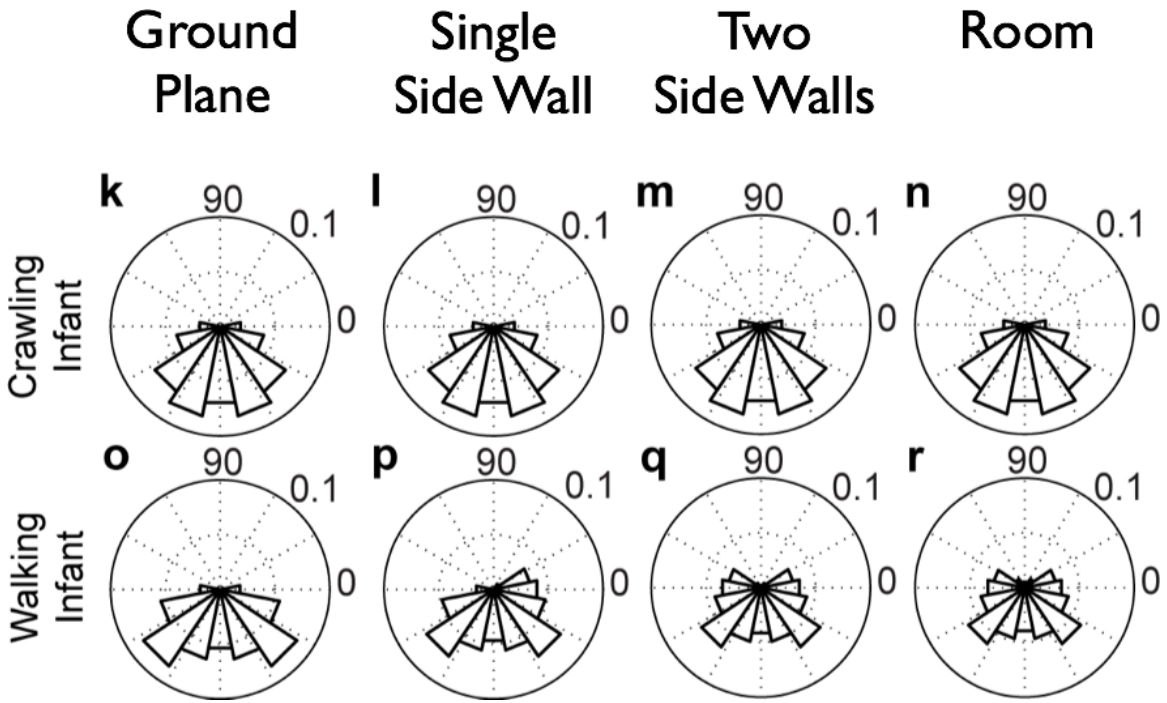
Kretch et al., 2014

Simulating Flow Fields



Gilmore et al, 2015

Flow Direction Distributions by Geometry & Posture



Gilmore et al, 2015

Simulated Flow Speeds (m/s)

Type of Locomotion	Ground Plane	Room	Side Wall	Two Walls
Crawling	14.41	14.42	14.43	14.62
Walking	9.38	8.56	7.39	9.18

But, what's the input? The *real* input?

(Gilmore et al., 2015)

(Gilmore et al., 2015)

(Adolph, 2015)

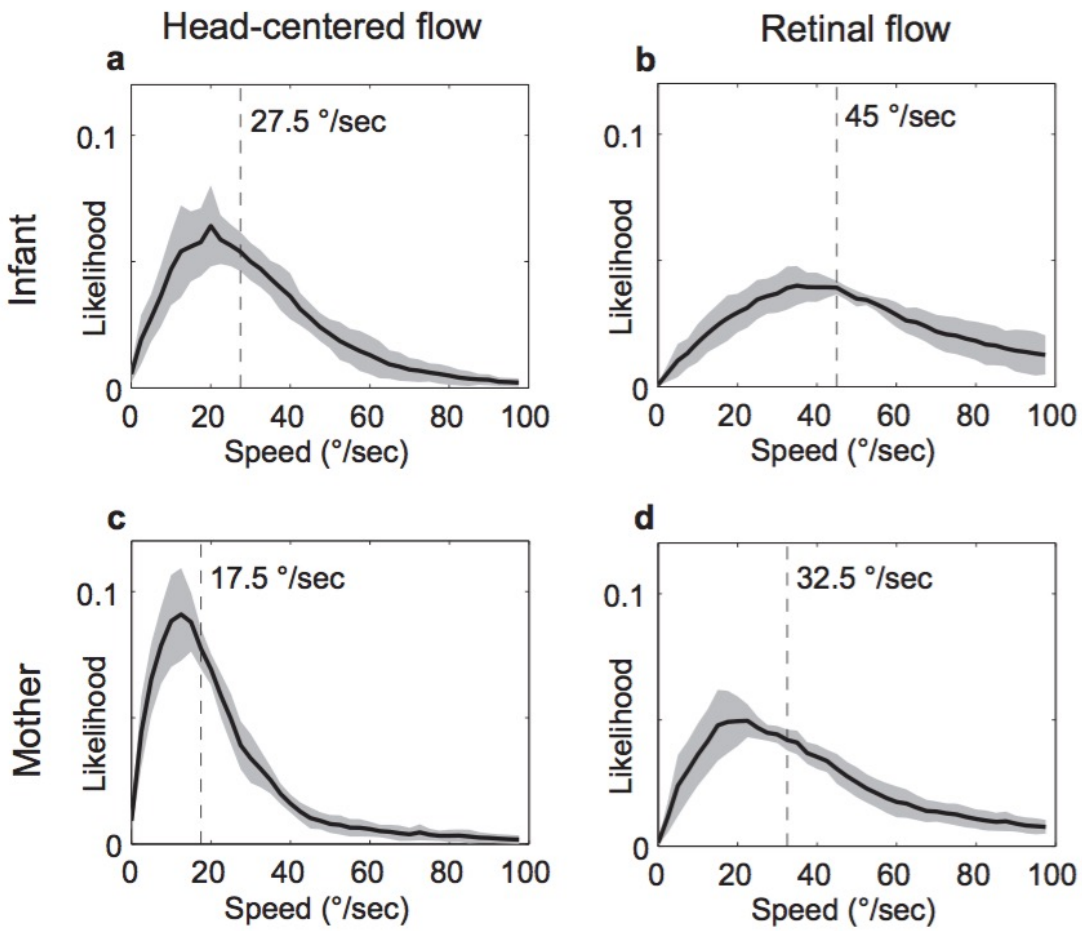
Frame-by-frame video analysis

(Jayaraman et al., 2015)

0:00 / 0:24

0:00 / 0:24

Findings



(Raudies & Gilmore, 2014)

Findings

- Infant (passengers) experience faster visual speeds than mother
- Controlling for speed of locomotion, environment
- Motion “priors” for infants ≠ mothers

Summing up…

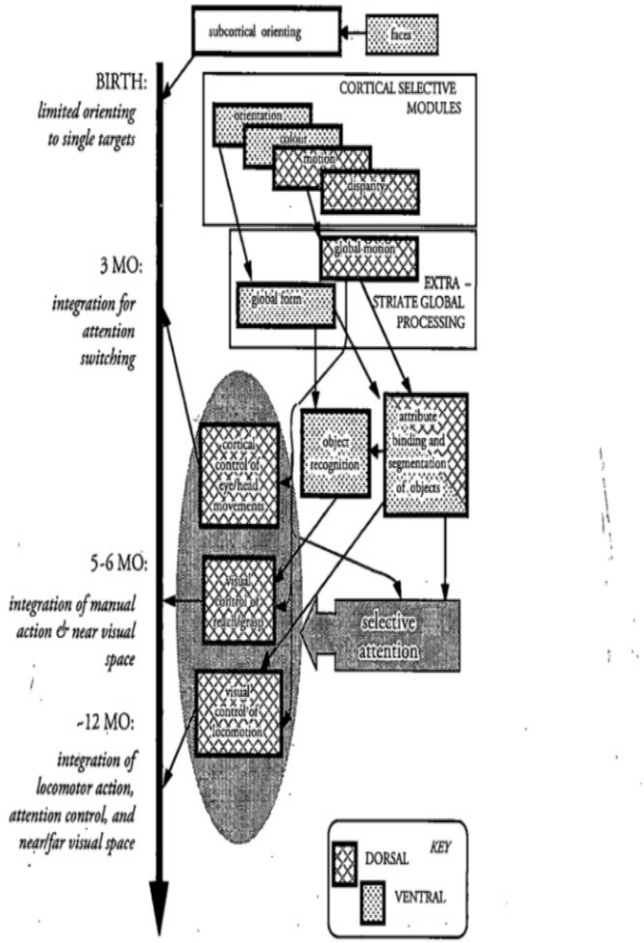


Figure 10.1. Model of visual spatial development in the first year, with behavioral milestones and brain processes in dorsal and ventral streams that become functional at different stages of development. (Developed from Atkinson, 2000, and Atkinson & Braddick, 2003.)

Atkinson & Braddick 2010, Fig 10.1

- Vision develops rapidly, but approaches asymptote slowly
- Complex interplay of brain and behavioral changes

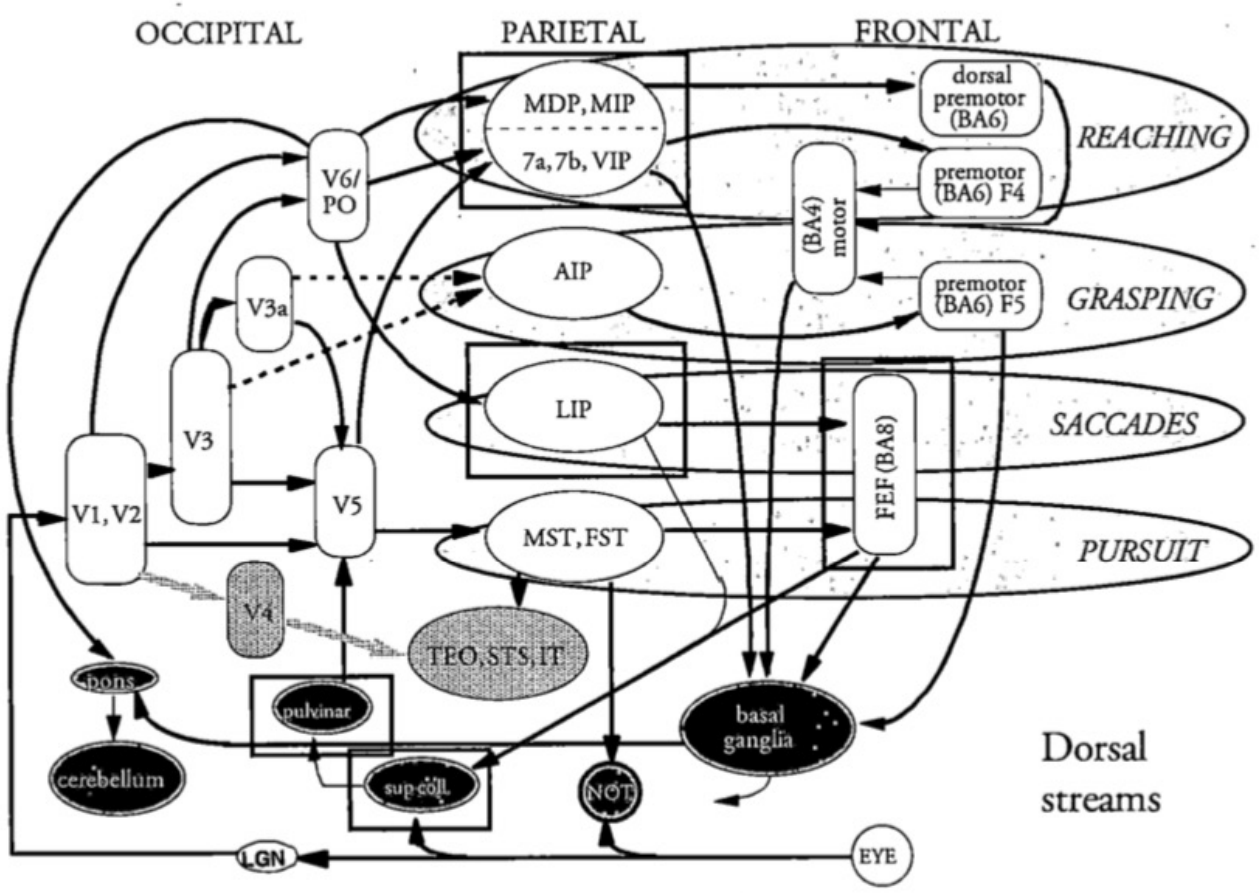


Figure 10.4. Schematic summary of action modules within the dorsal stream for visual control of four behaviors—arm movements for reaching, hand movements for grasping, saccadic eye movements, and smooth-pursuit eye movements. Brain areas in white are dorsal stream, shaded areas are ventral stream, and black are subcortical structures. Rectangular boxes enclose areas that have been shown to be involved in spatial direction of attention. Networks shown are based on primate studies and human neuropsychology.
Key to abbreviations for brain areas: V1–5, visual areas 1–5; PO, parietal-occipital; MDP, medial dorsal parietal; MIP, medial intraparietal; AIP, anterior intraparietal; VIP, ventral intraparietal; LIP, lateral intraparietal; BA6, Brodmann area 6 (F4, F5, etc. are fields within BA6); FEF, frontal eye fields; NOT, nucleus of the optic tract; sup coll, superior colliculus; TEO, a posterior region of inferotemporal cortex; STS, superior temporal sulcus; IT, inferotemporal.

Atkinson & Braddick 2010, Fig 10.4

Thank you!

Materials

This talk was produced on 2021-09-03 in RStudio using R Markdown. The code and materials used to generate the slides may be found at https://github.com/gilmore-lab/csd-vision-course/.

Information about the R Session that produced the code is as follows:

```
## R version 4.1.0 (2021-05-18)
## Platform: x86_64-apple-darwin17.0 (64-bit)
## Running under: macOS Big Sur 10.16
##
## Matrix products: default
## LAPACK: /Library/Frameworks/R.framework/Versions/4.1/Resources/lib/libRlapack.dylib
##
## locale:
## [1] en_US.UTF-8/en_US.UTF-8/en_US.UTF-8/C/en_US.UTF-8/en_US.UTF-8
##
## attached base packages:
## [1] stats     graphics  grDevices utils     datasets  methods   base
##
## loaded via a namespace (and not attached):
##  [1] Rcpp_1.0.7         databraryapi_0.2.6 knitr_1.33         servr_0.23
##  [5] magrittr_2.0.1     R6_2.5.0           jpeg_0.1-9         rlang_0.4.11
##  [9] highr_0.9          stringr_1.4.0      httr_1.4.2         tools_4.1.0
## [13] websocket_1.4.1    xfun_0.24          jquerylib_0.1.4    htmltools_0.5.1.1
## [17] yaml_2.2.1         digest_0.6.27      assertthat_0.2.1   keyring_1.2.0
## [21] processx_3.5.2     later_1.2.0        sass_0.4.0         promises_1.2.0.1
## [25] ps_1.6.0           curl_4.3.2         evaluate_0.14      mime_0.11
```

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