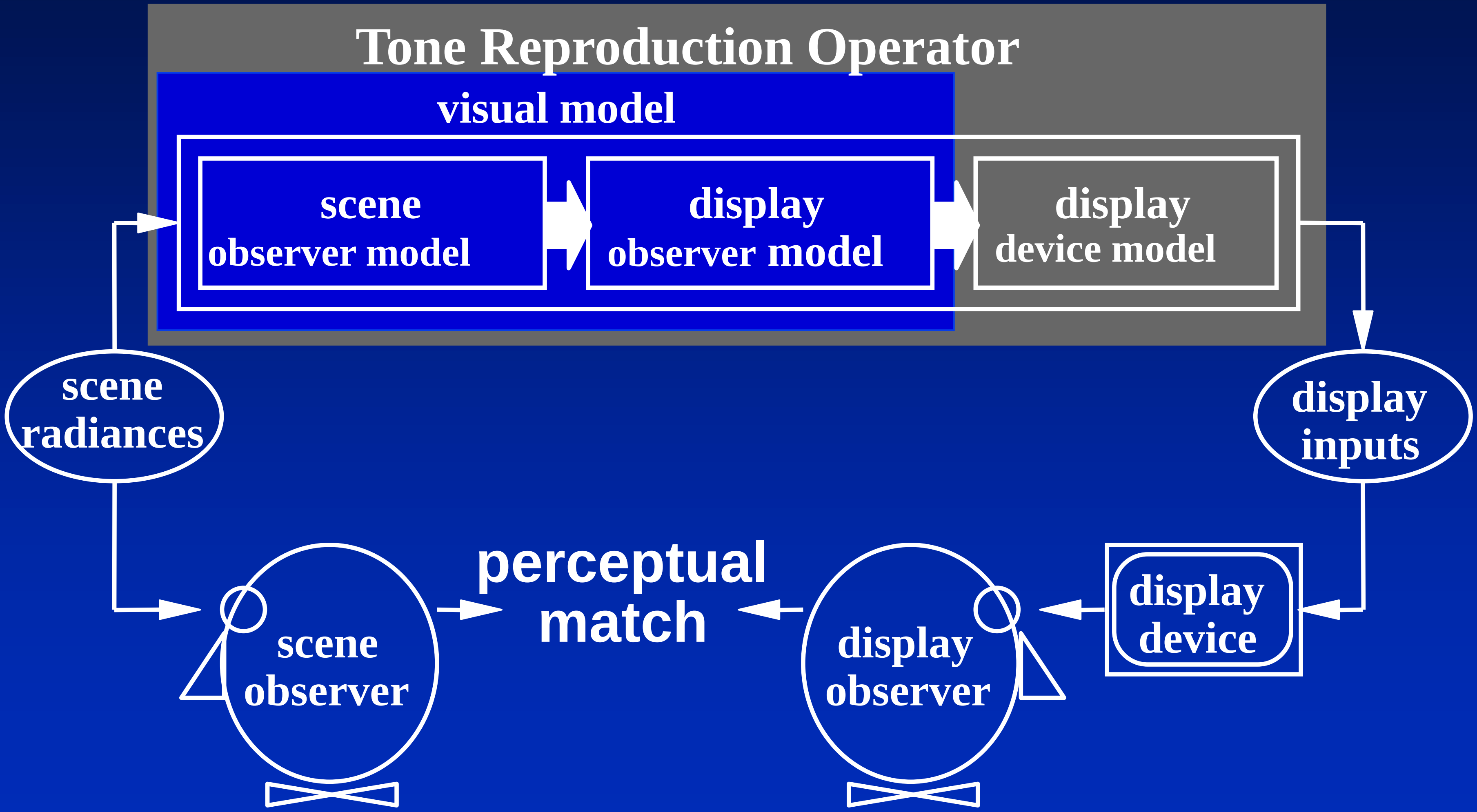
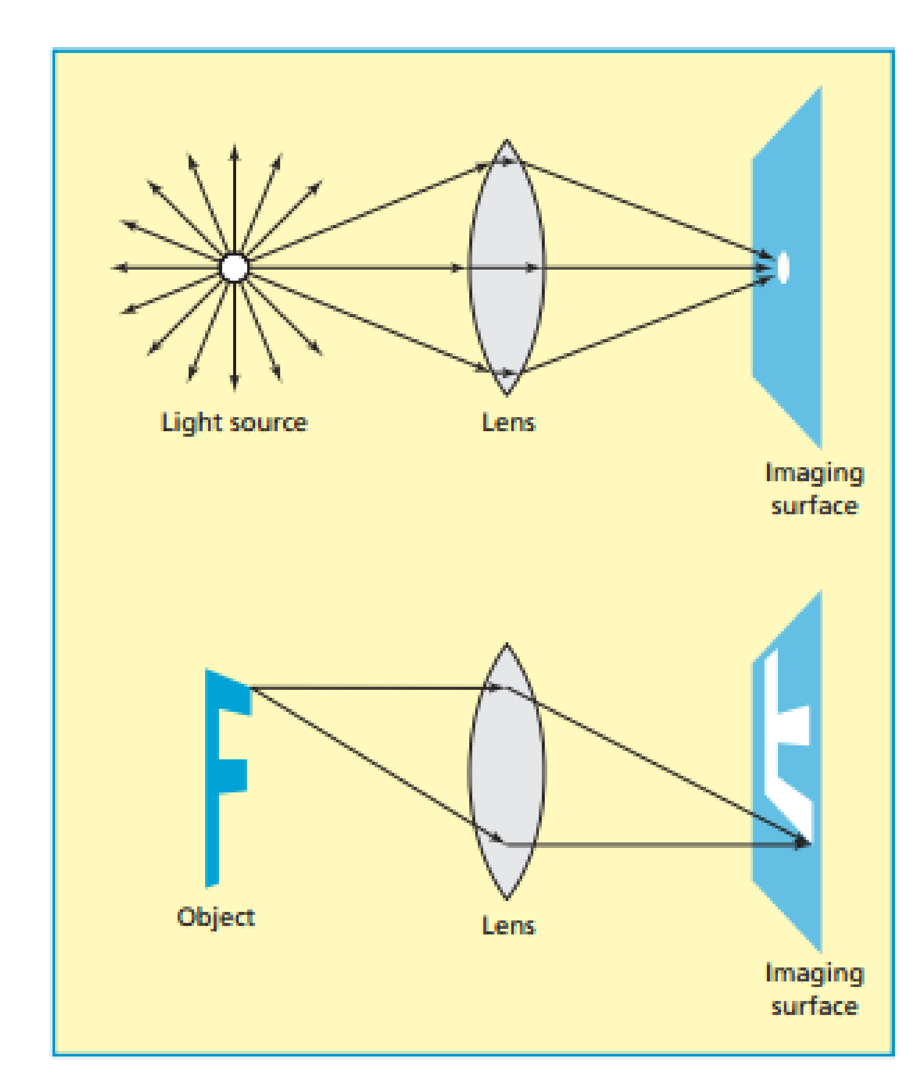
The Physiology of the Human Visual System

Lecture #19
November 10, 2020
Prof. Donald P. Greenberg

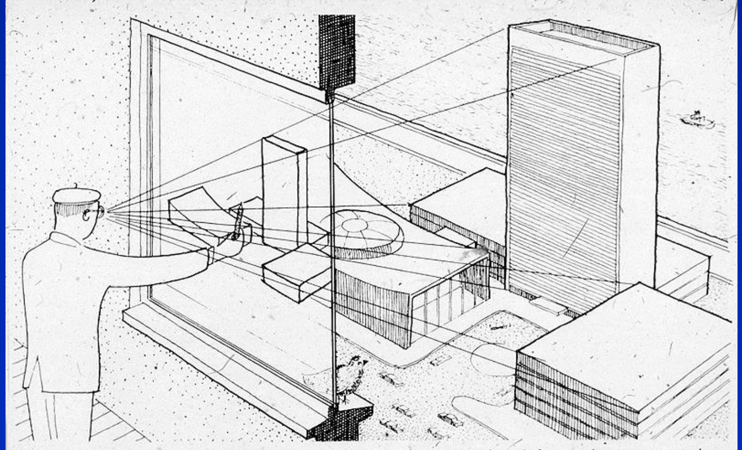
The goal of tone reproduction operators



Light as Rays

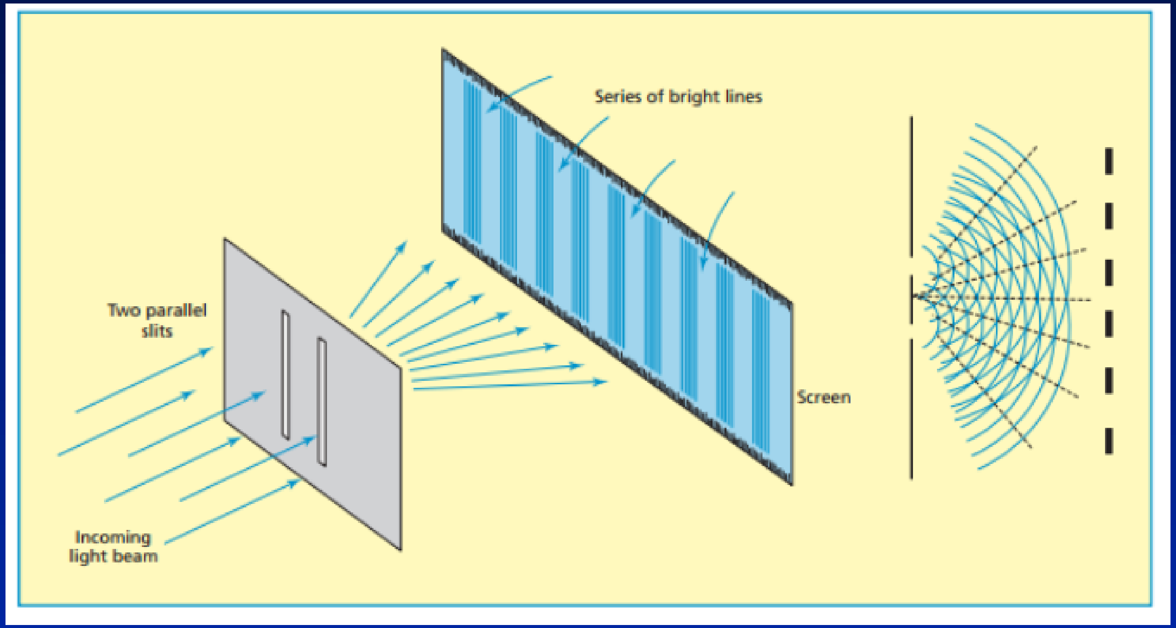


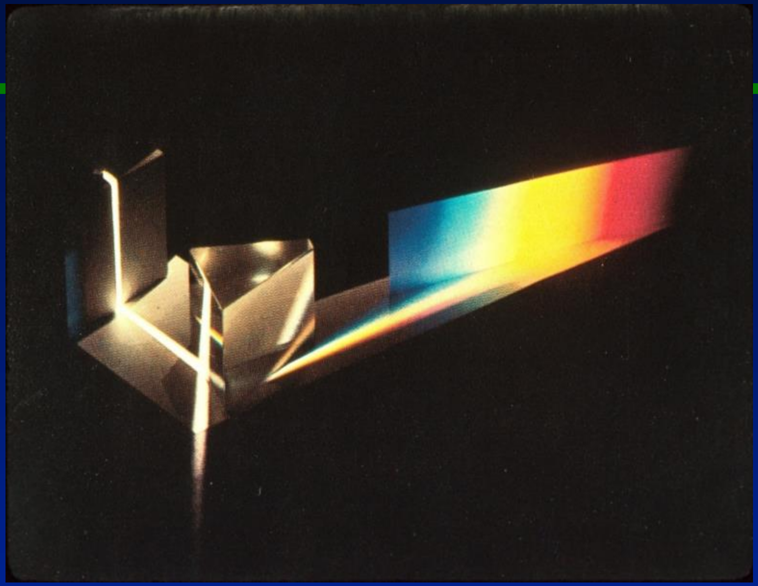
Basis Of Perspective – Lines Of Sight Through A Picture Plane [19]

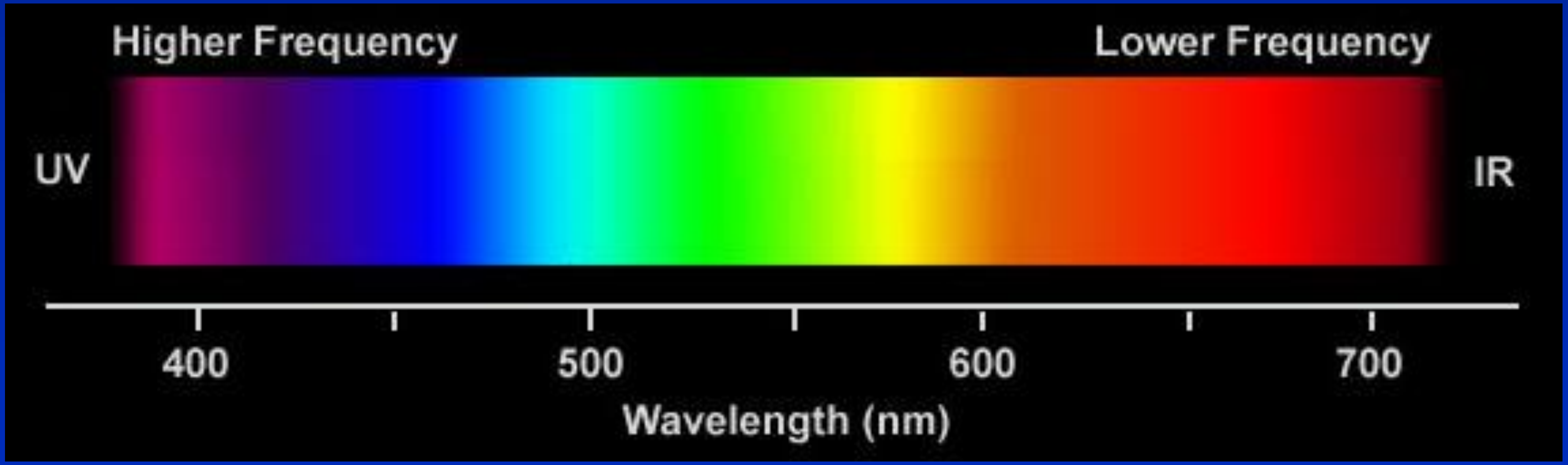


The concept of the picture plane may be better understood by looking through a window or other transparent plane from a fixed viewpoint. Your lines of sight, the multitude of straight lines leading from your eye to the subject, will all intersect this plane. Therefore, if you were to reach out with a grease pencil and draw the image of the subject on this plane you would be "tracing out" the infinite number of points of intersection of sight rays and plane. The result would be that you would have "transferred" a real three-dimensional object to a two-dimensional plane.

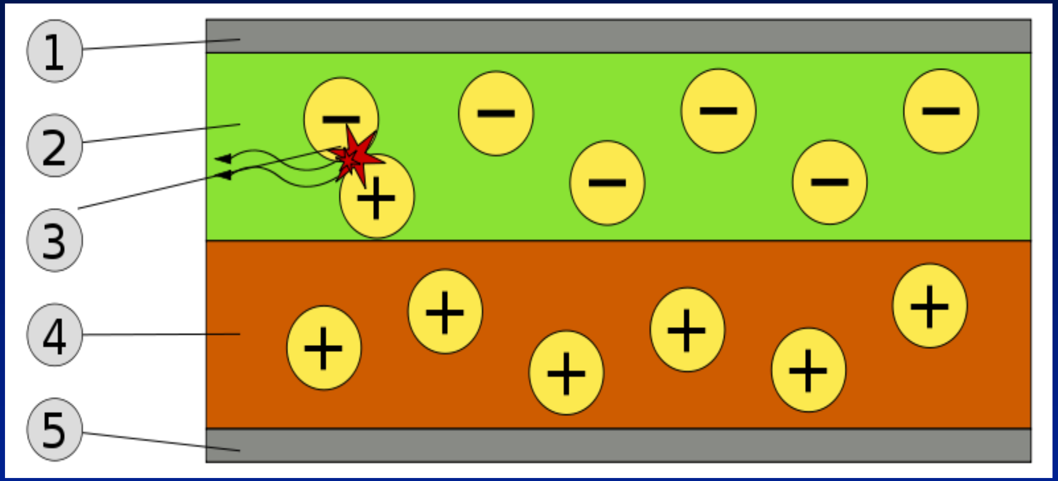
Light as Waves

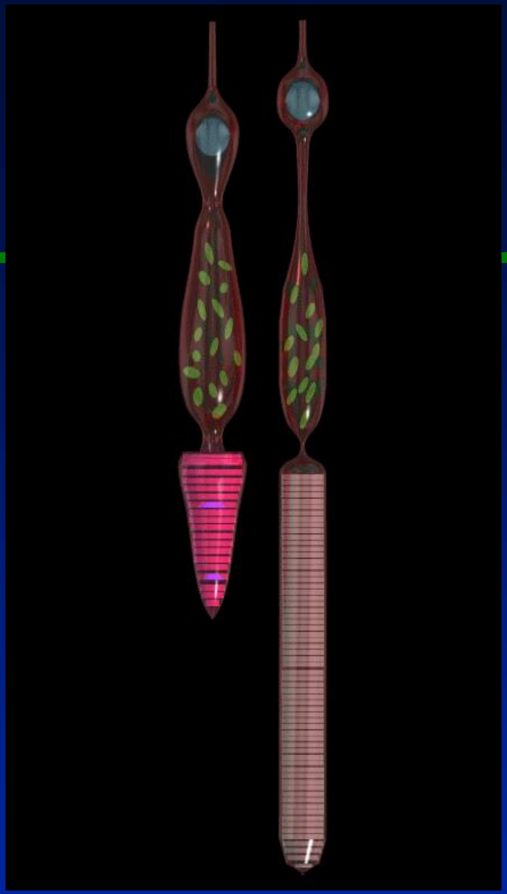


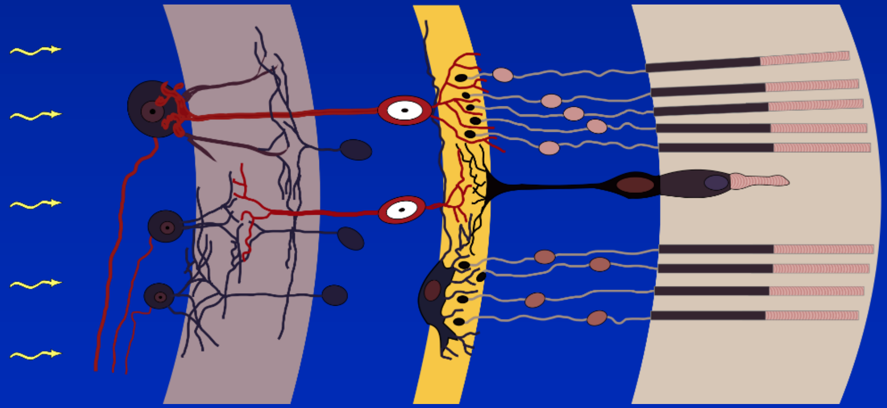


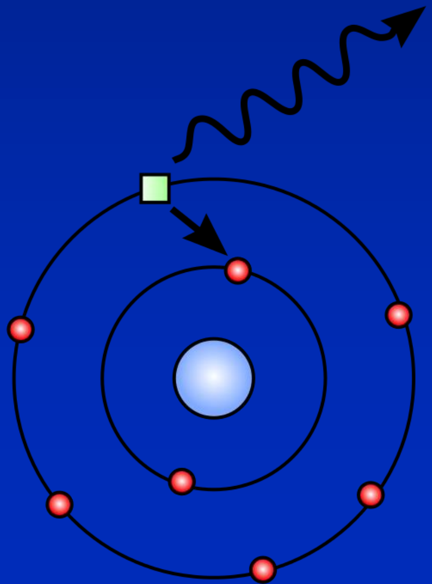


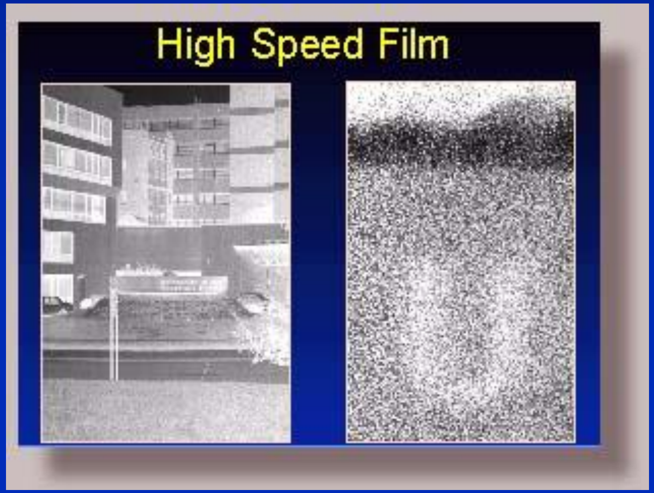
Light as Photons











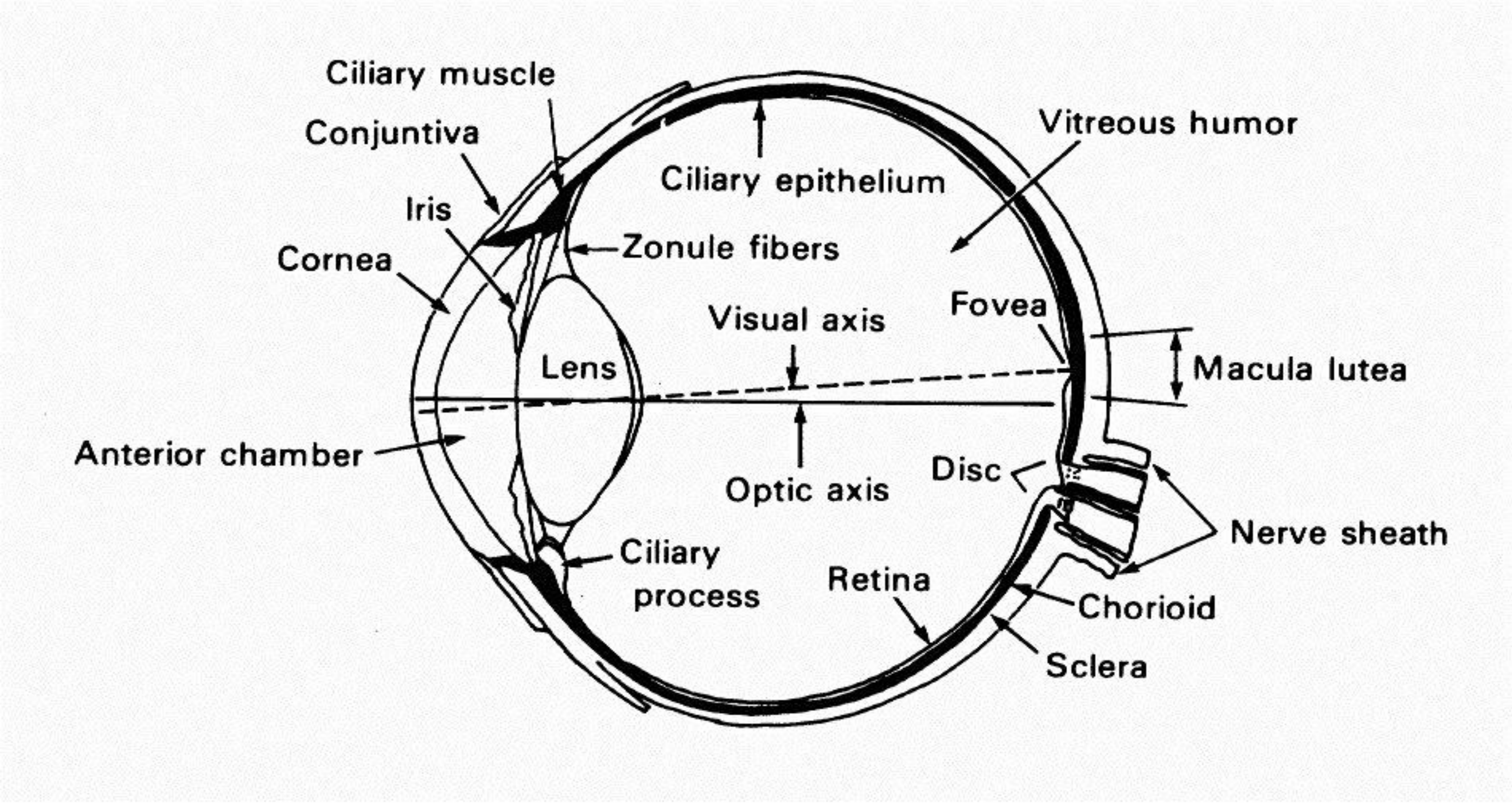
Use of all Three Descriptions of Light

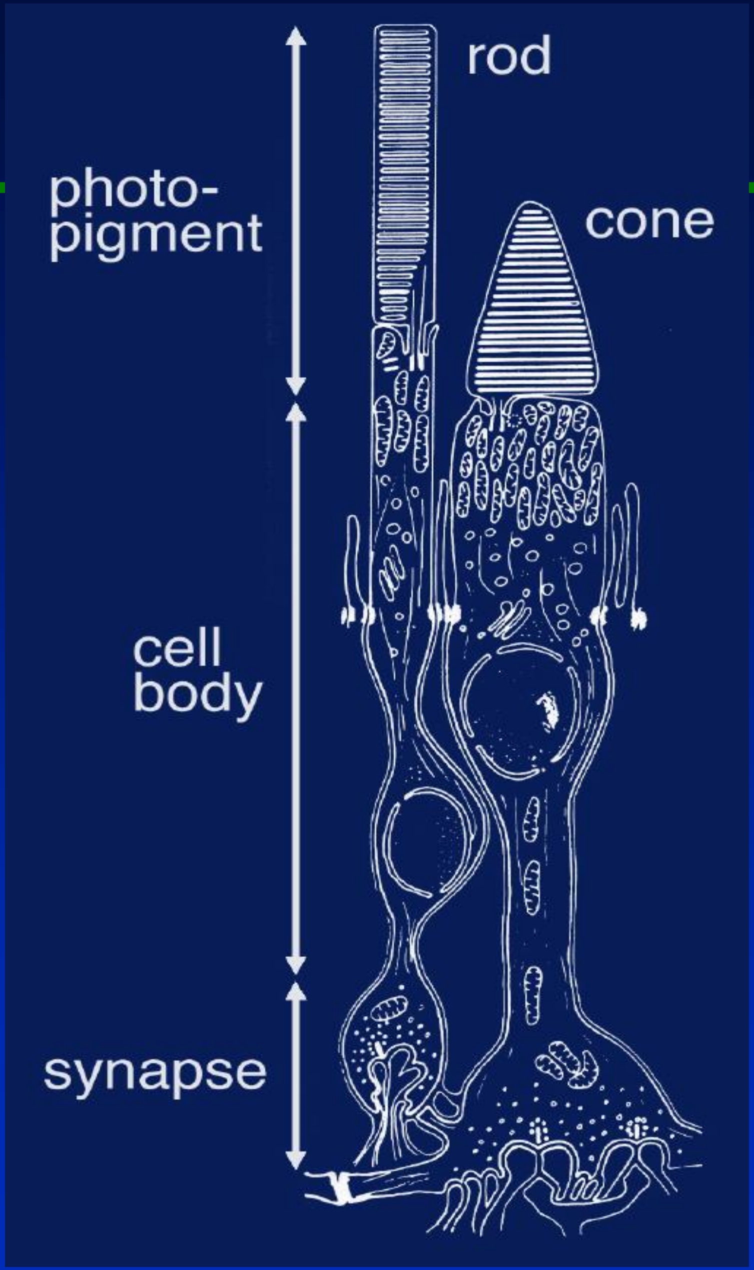
- We use rays to determine which cones are stimulated.
- We use wave lengths to specify which Rodopsins are chemically effected (Color SML)
- The number of photons received define the intensity of the particular cone.

Fundamentals of Human Perception

- Retina, Rods & Cones, Physiology
- Receptive Fields
- Visual Acuity of Resolution
- Field of View
- Depth Perception
- Saccades and Eye-Tracking

Cross Section of Eye & Retina



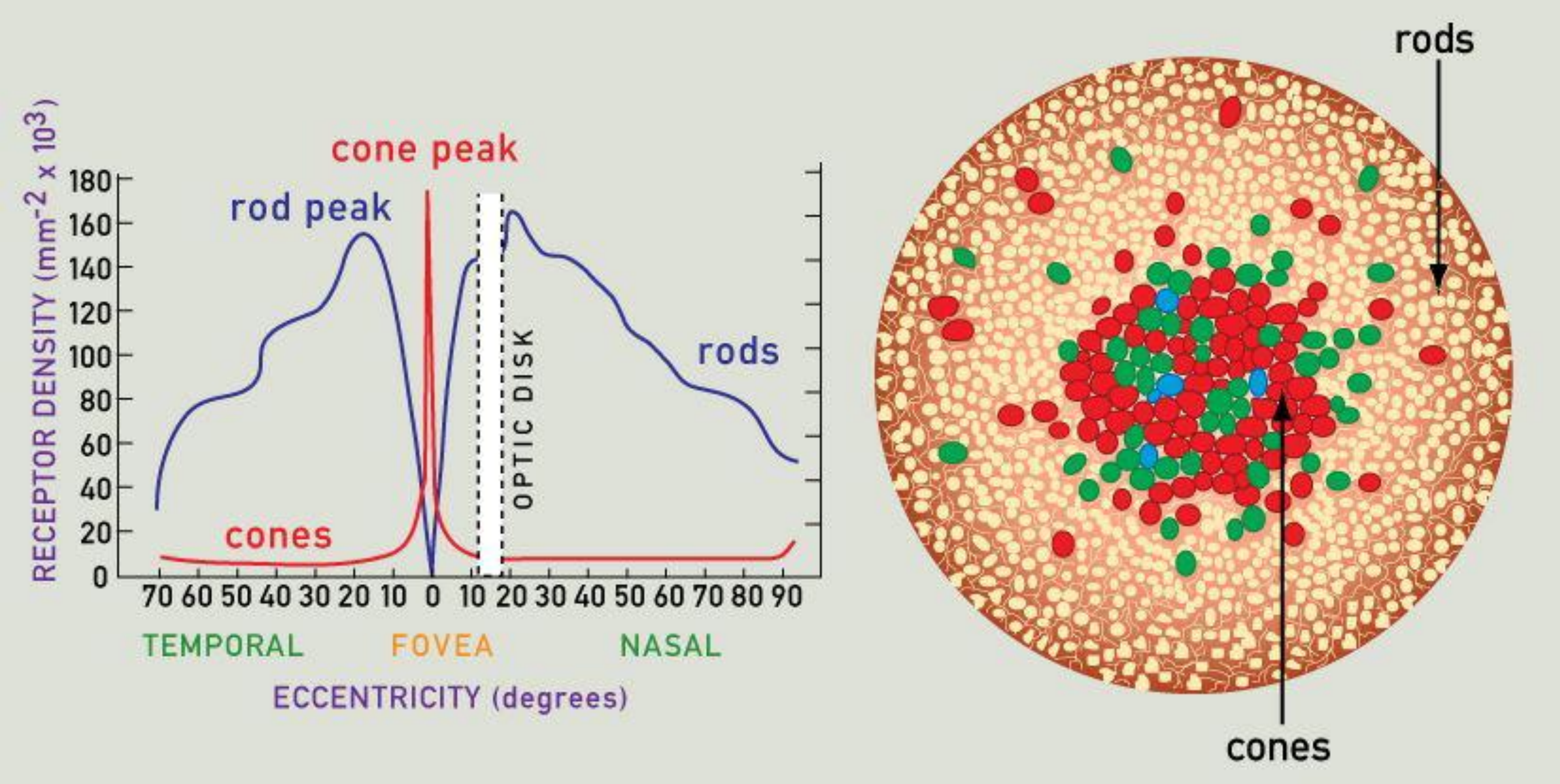


Photoreceptors

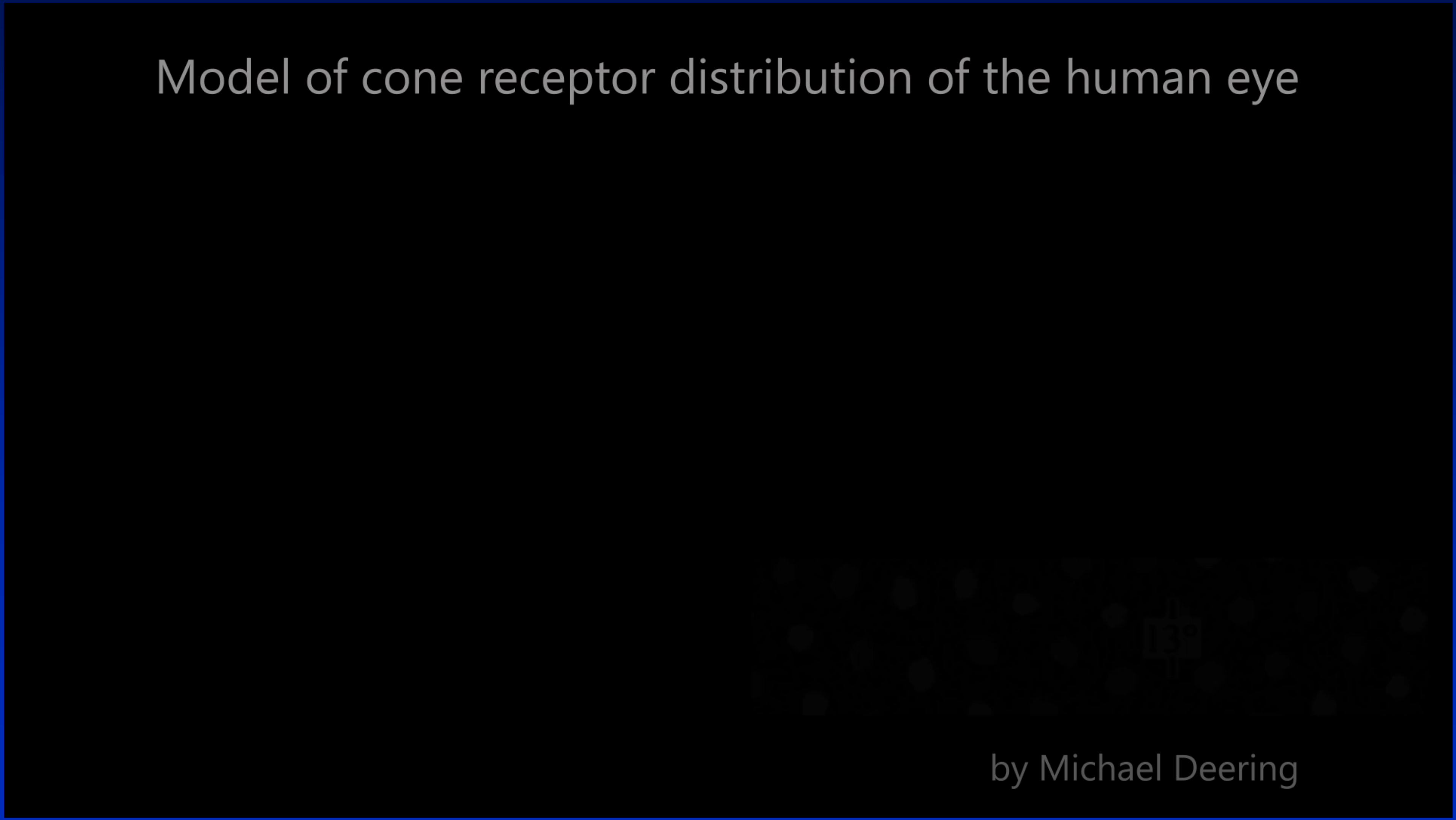
- 120 million rods
- 7-8 million cones
  in each eye

Adapted from Levine, Vision in Man and Machine © McGraw-Hill, 1985.

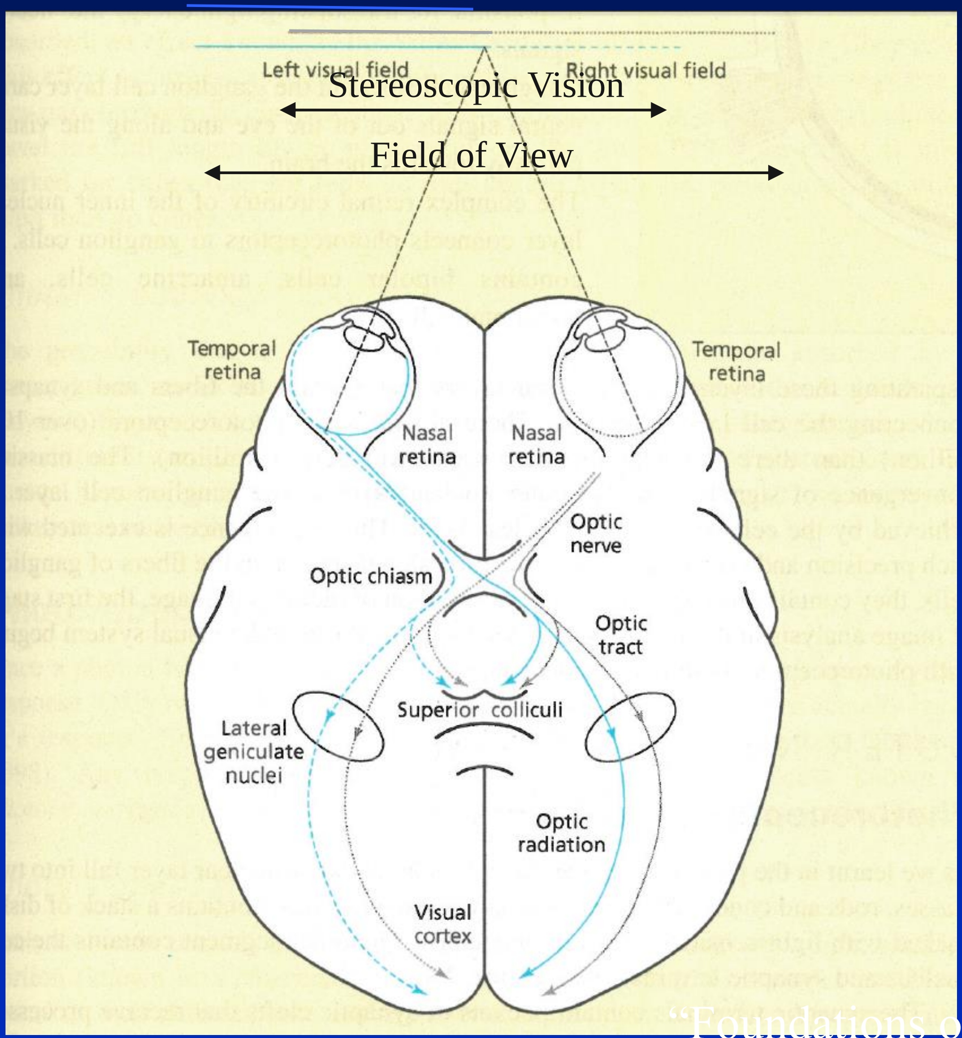
Receptor Distribution

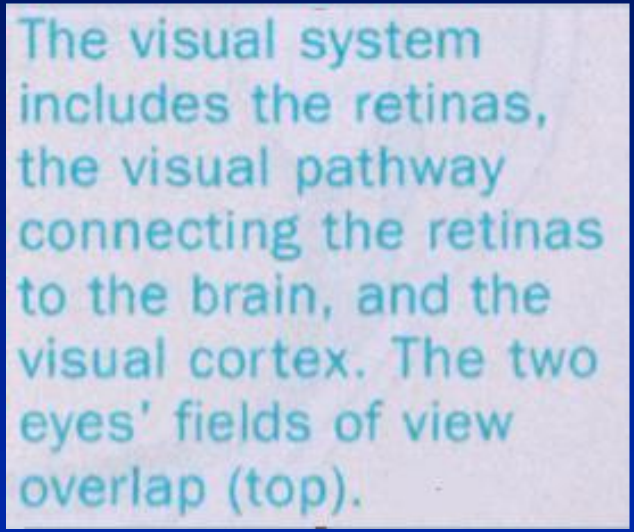


Cone Receptor Distribution of the Human Eye



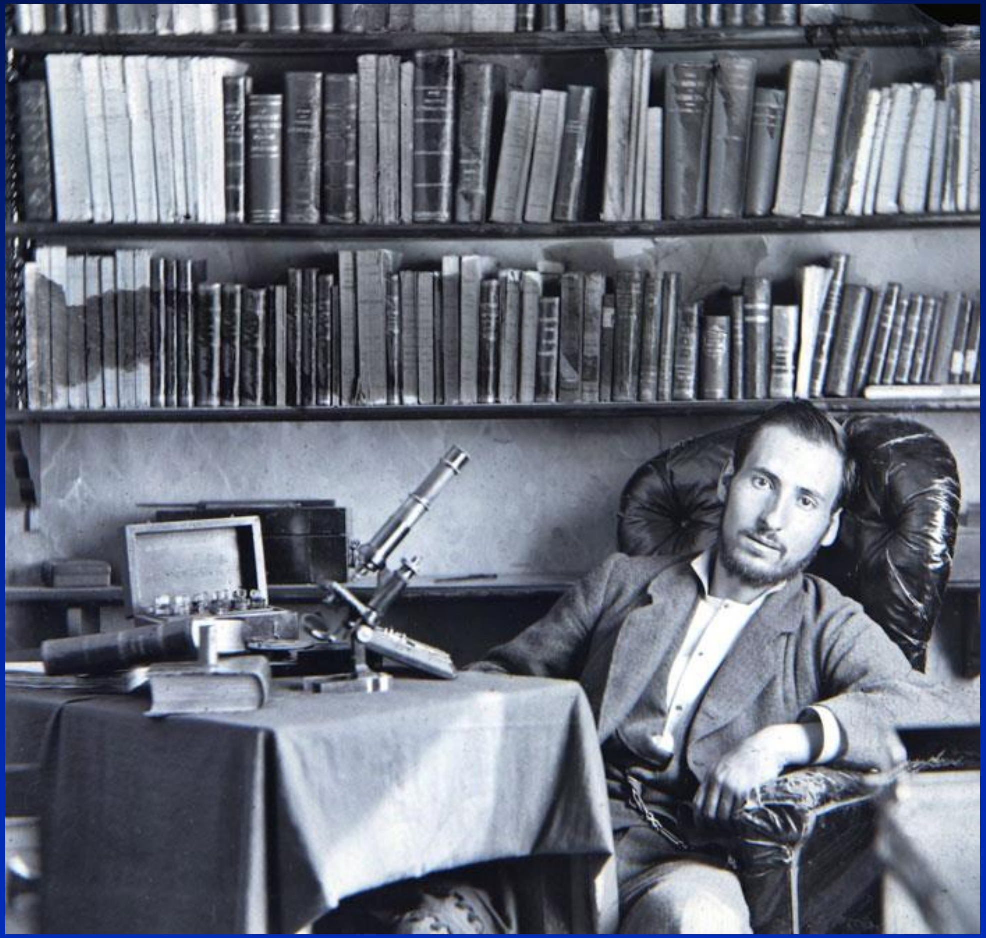
Field of View of the Human Eye



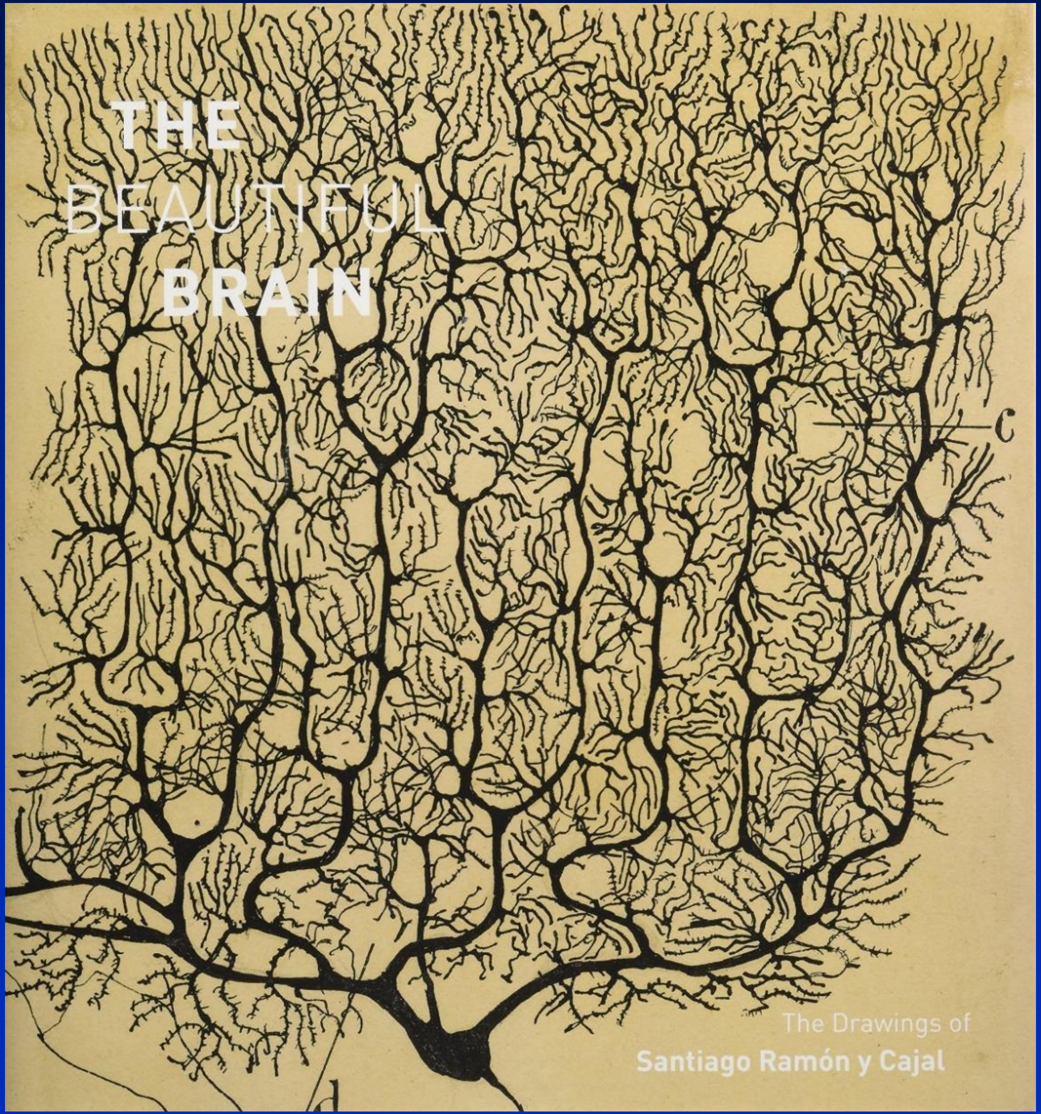


"Foundations of Sensation and Perception." Mather, George. 2009.

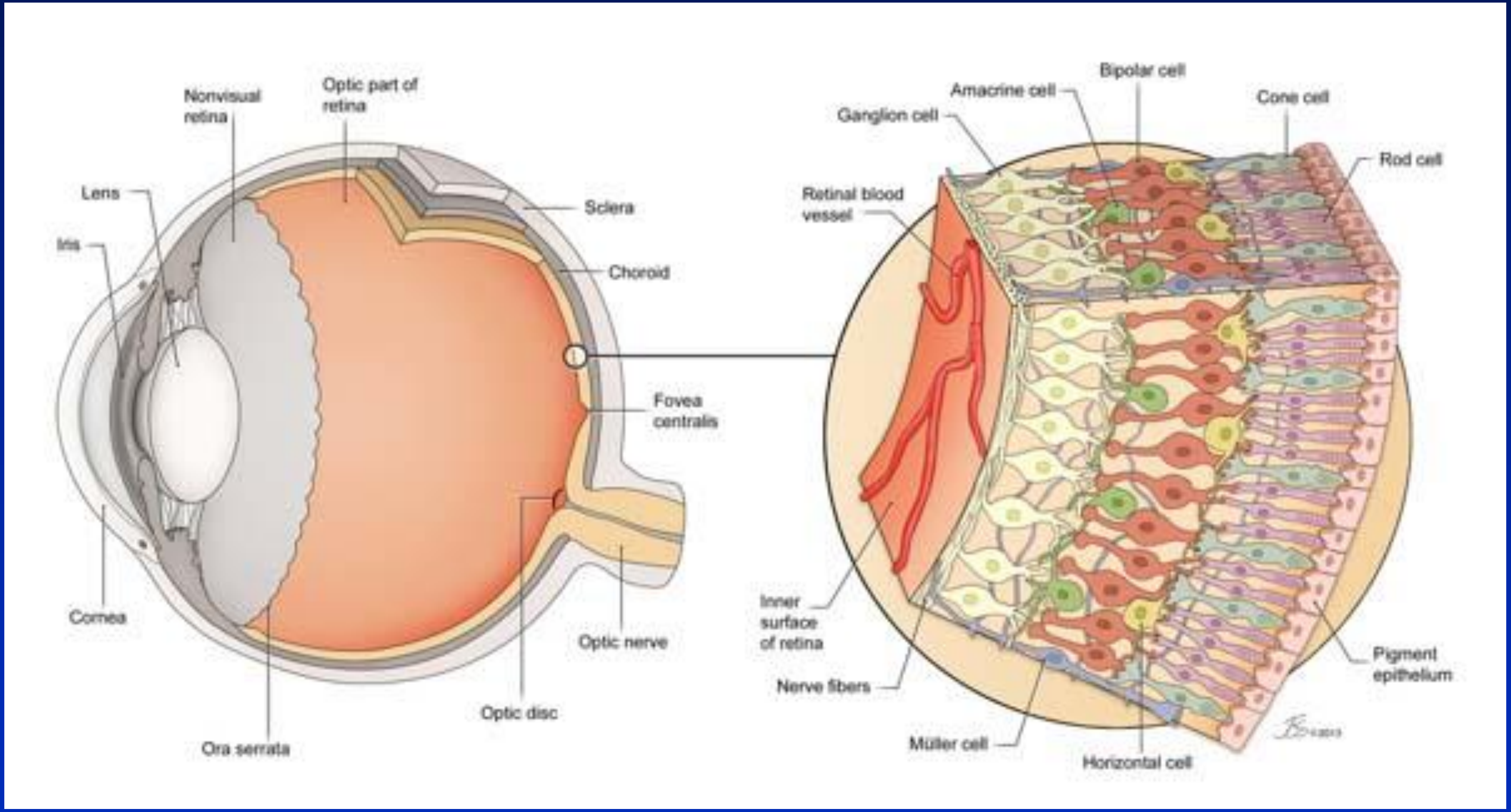
Santiago Ramon y Cajal & Camillo Golgi 1906



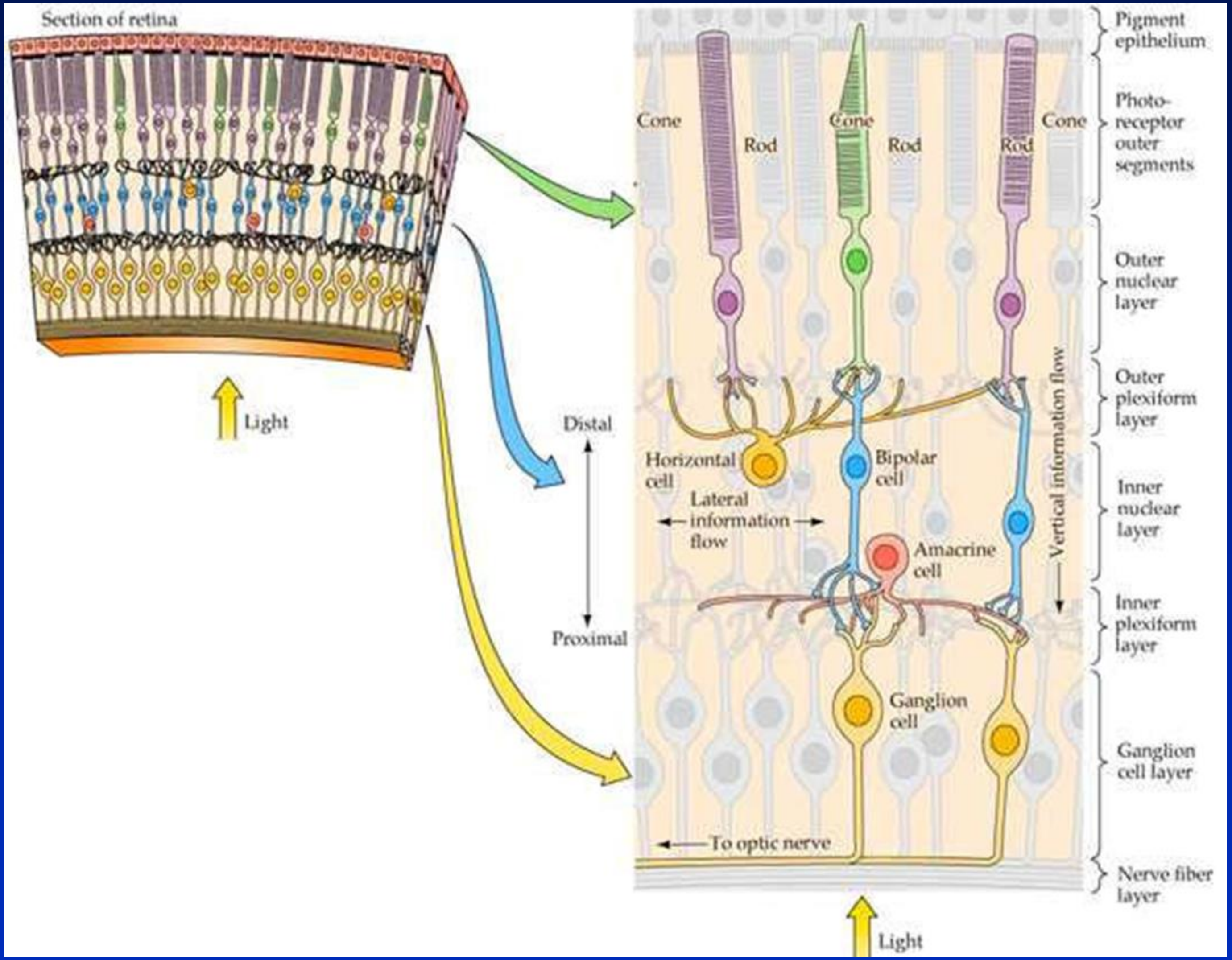
Drawings of Santiago Ramon y Cajal



Rods and Cones and Neural Connections



Rods and Cones and Neural Connections



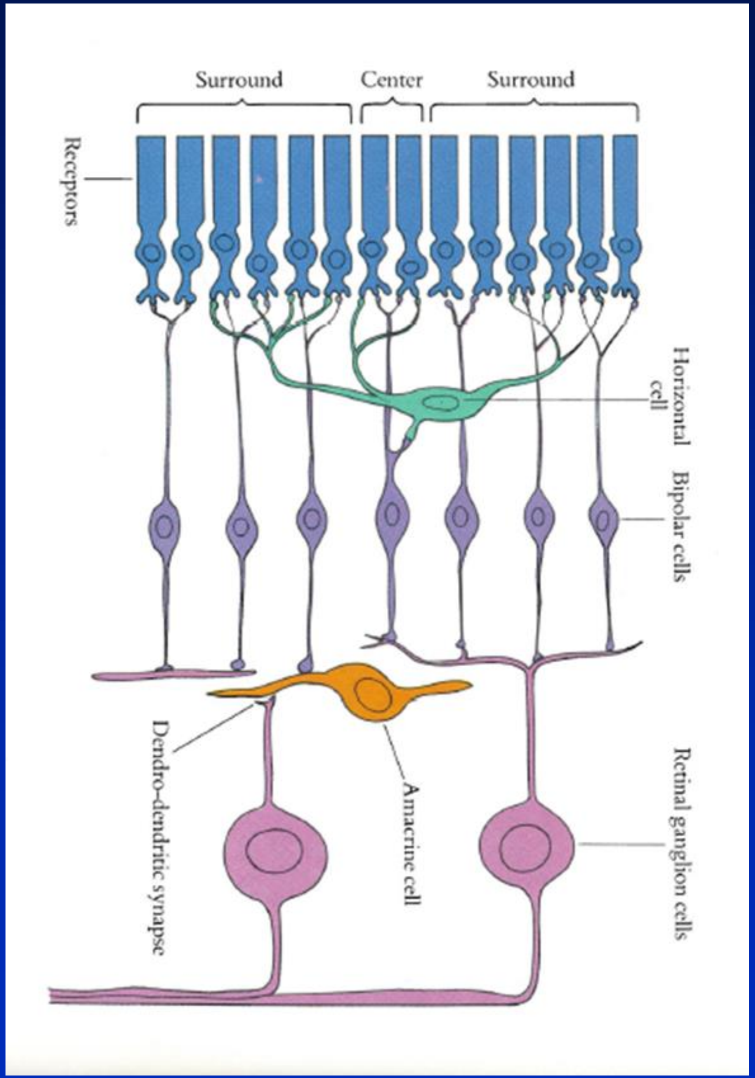
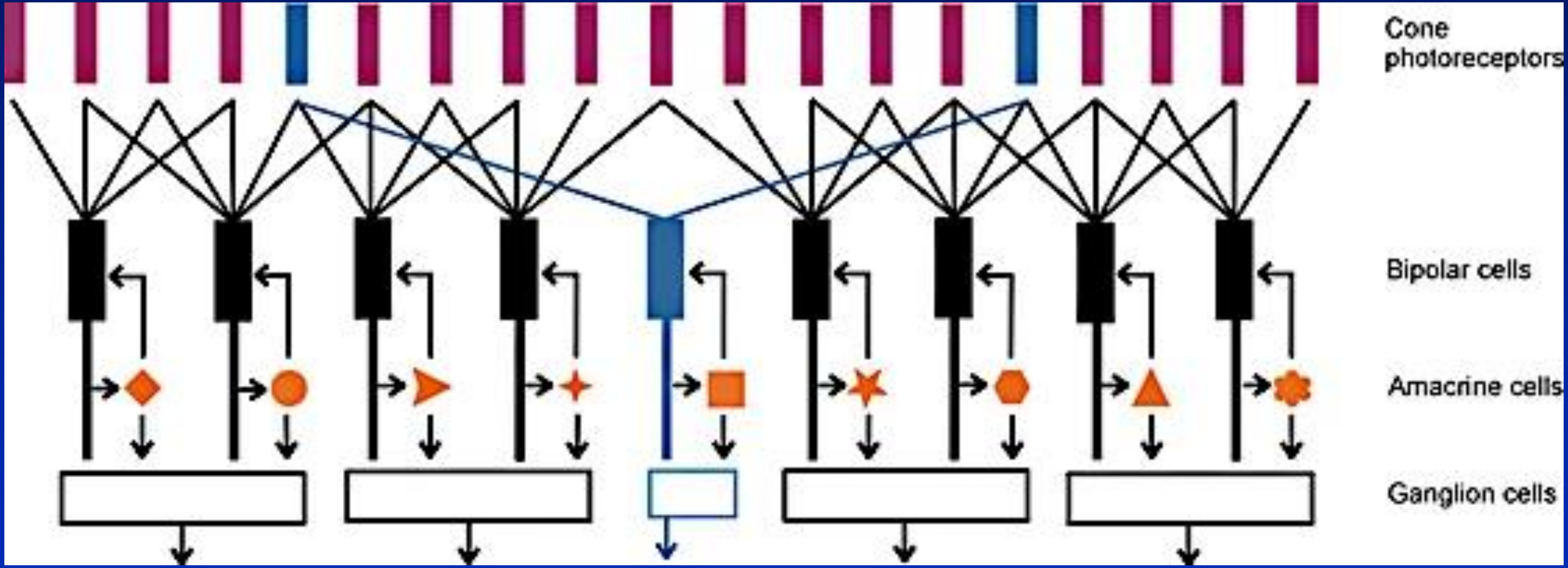


Image from “Eye, Brain, and Vision,” David Hubel, 1988

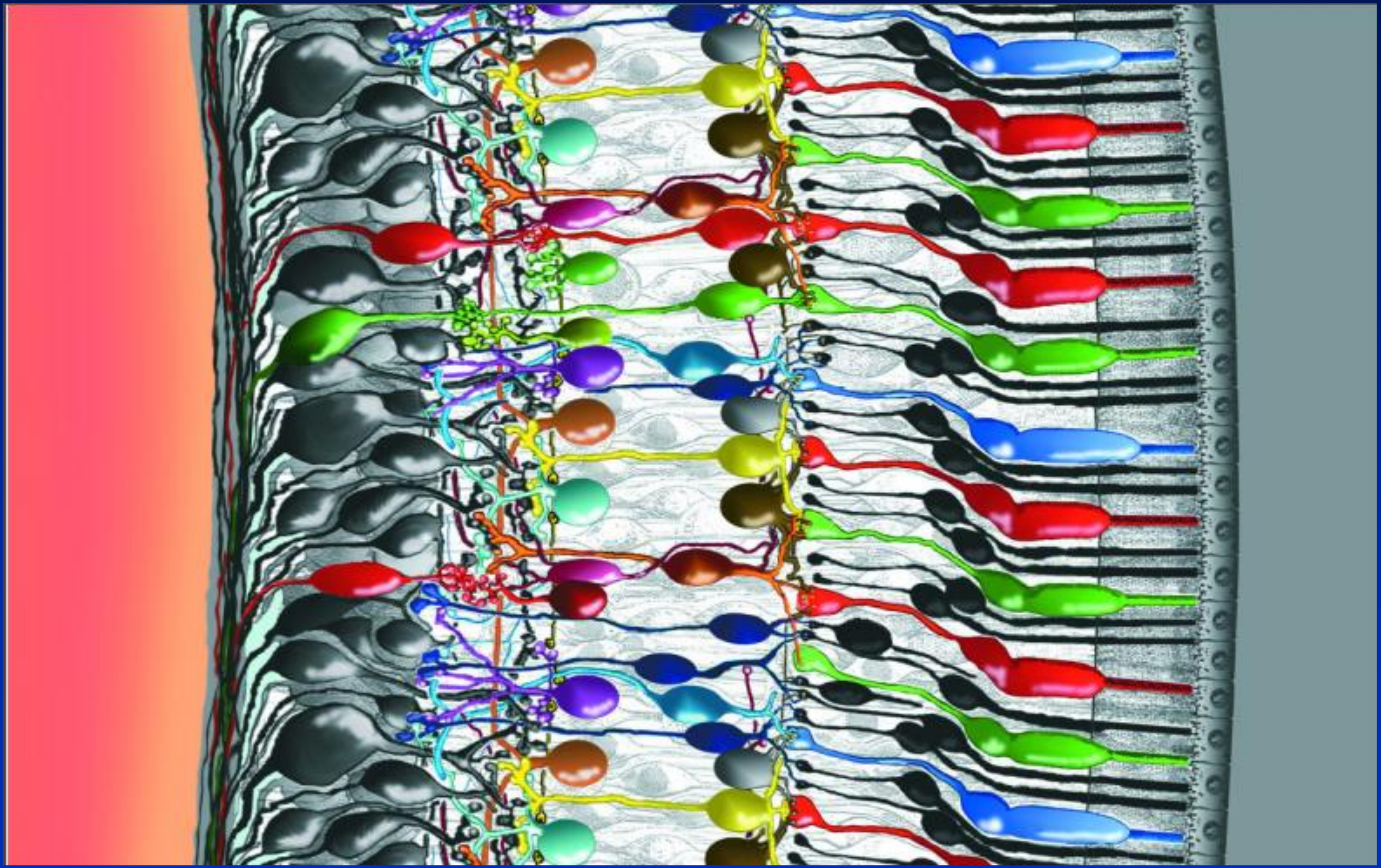
Rods and Cones and Neural Connections

Abstraction



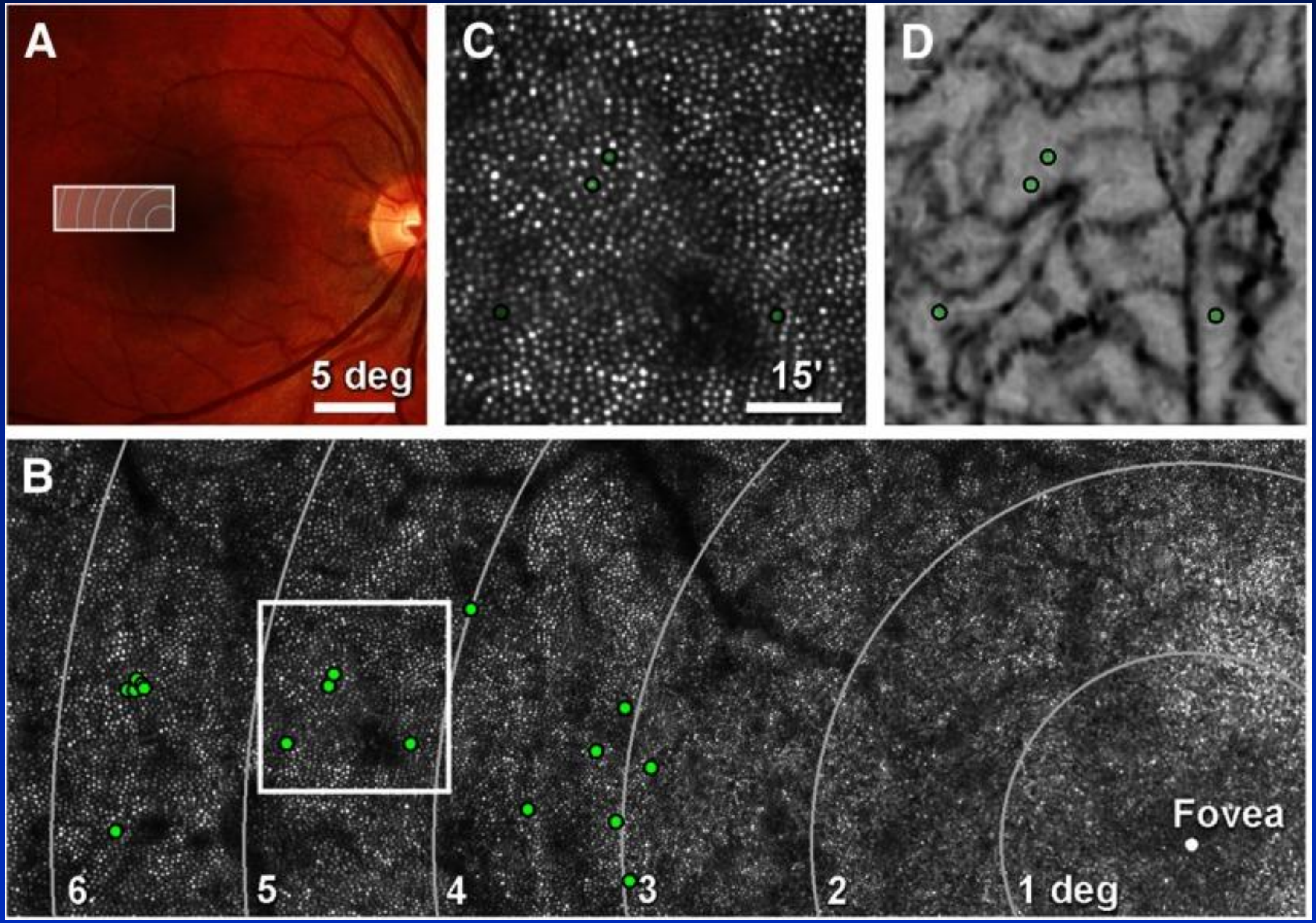
Masland, Richard. “The fundamental connections of the retina.”

Neurons in the Retina   Helga Kolb 2003



https://webvision.med.utah.edu/wp-content/uploads/2011/01/2003-01Kolb.pdf   American Scientist, Volume 91

Mapping the Human Retina Austin Roorda



A- areas where cones were selected.

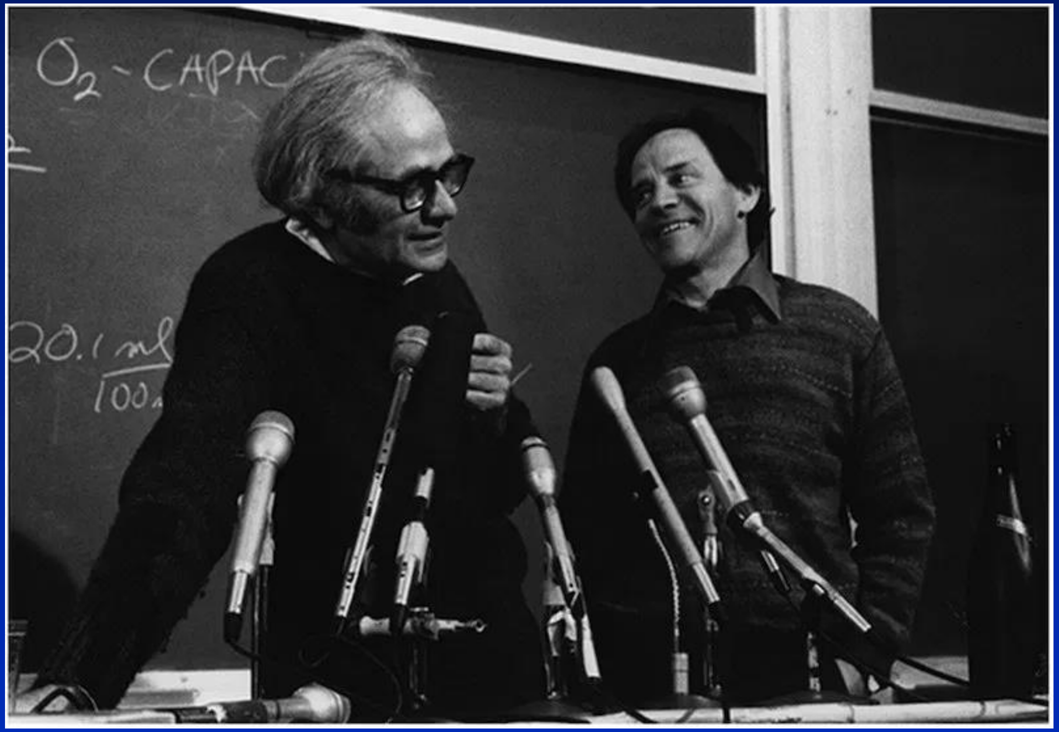
B- green circles indicate stimulation sites.

C- enlarged field of cones from B.

D- same region with vascular structures

Journal of Neuroscience, April 16, 2014

Hubel and Weisel 1981



Fundamentals of Human Perception

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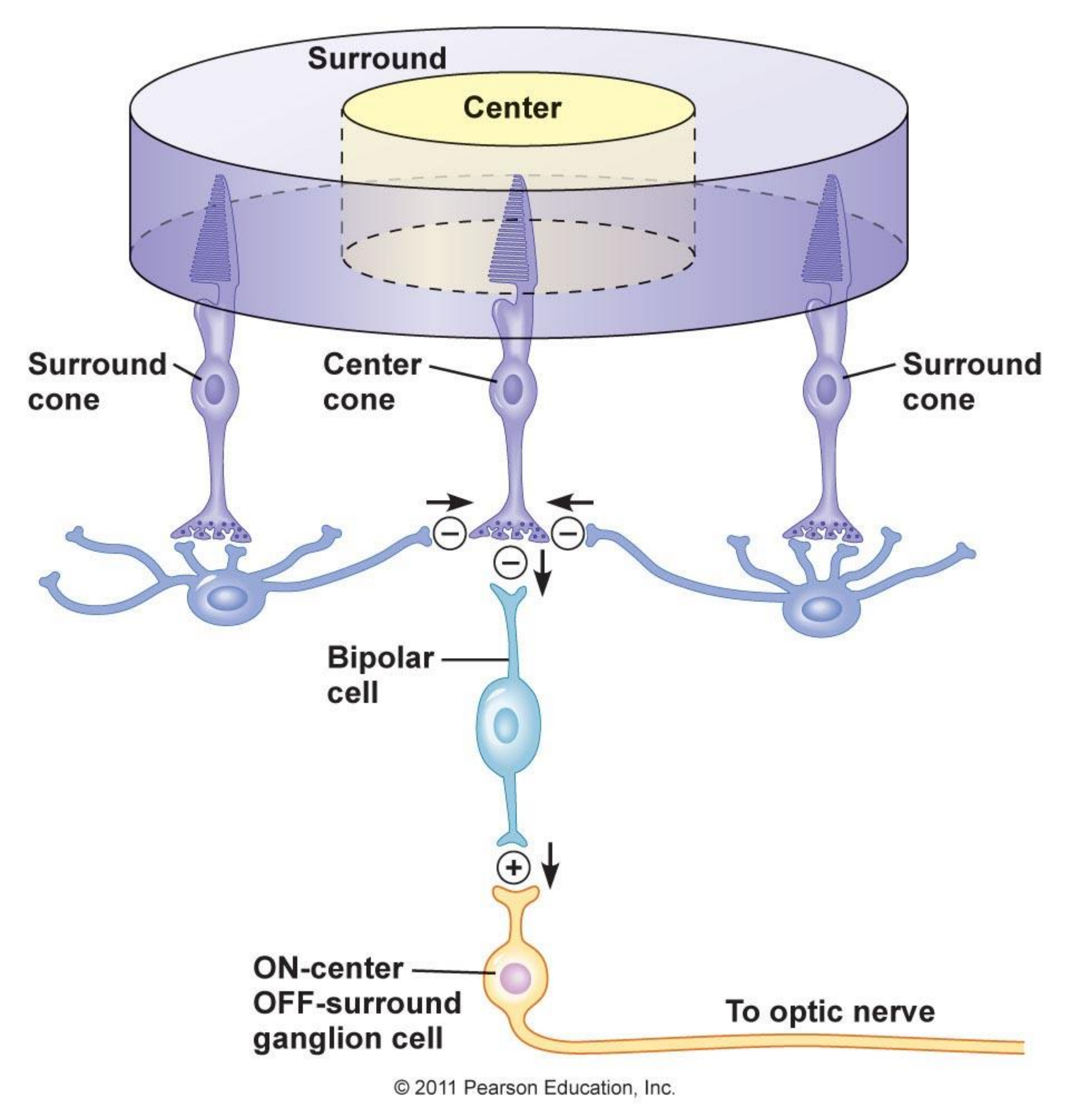
Receptive Fields

Individual cone signals can either add together or be subtracted from one another.

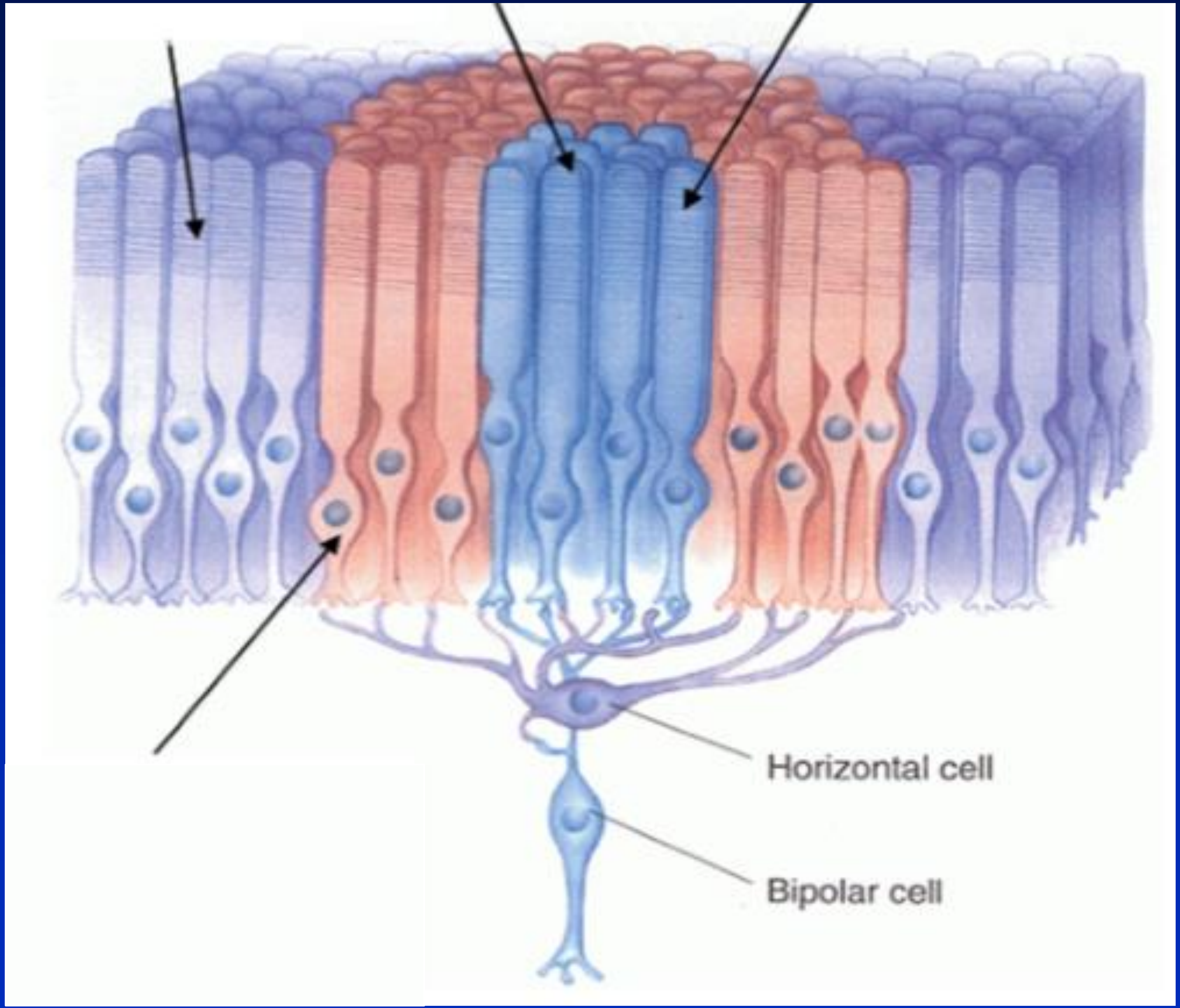
The ability to resolve fine details depends ultimately on both the spatial mosaic of the receptors and how they interconnect.

Receptive Fields



http://droualb.faculty.mjc.edu/Course%20Materials/Physiology%20101/Chapter%20Notes/Fall%202007/figure_10_39_labeled.jpg

Receptive Fields



S. Deleniv. The Neurosphere. 2016.

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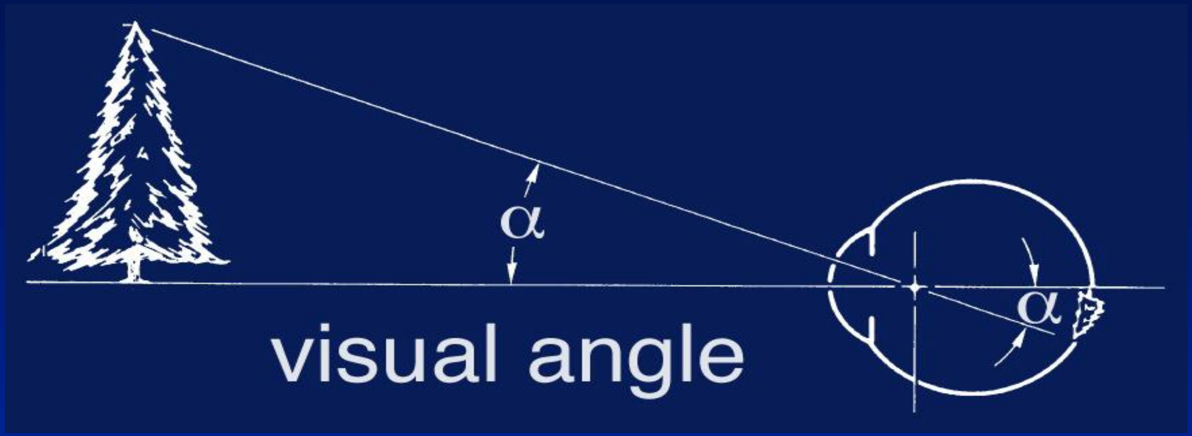
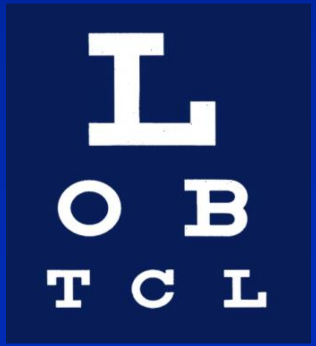
Measures of Acuity



detection

resolution

localization



min. detectable
0.5”

min. resolvable
30”

Snellen letters
30”

vernier
5-7”

Visual Acuity

- Visual acuity is defined as “1/a where a is the response in arc-minutes”.
- This acuity is usually measured by a grating test pattern and thus is defined using a line pair.
- It takes two pixels to generate a line pair (black and white).
- Based on a large number of tests, the resolution of the human eye is approximately 0.3 arc minutes.

How many megapixels are necessary to match the resolution of the human eye?

- What is the distance from the surface of the eye to the screen in VR?
- How many pixels per inch are necessary at roughly 1.25 inches?

Visual Acuity Example

Assume 120 degree x 90 degree field of view

120 * 90 * 60 * 60 / 0.3 * 0.3 = 432 megapixels

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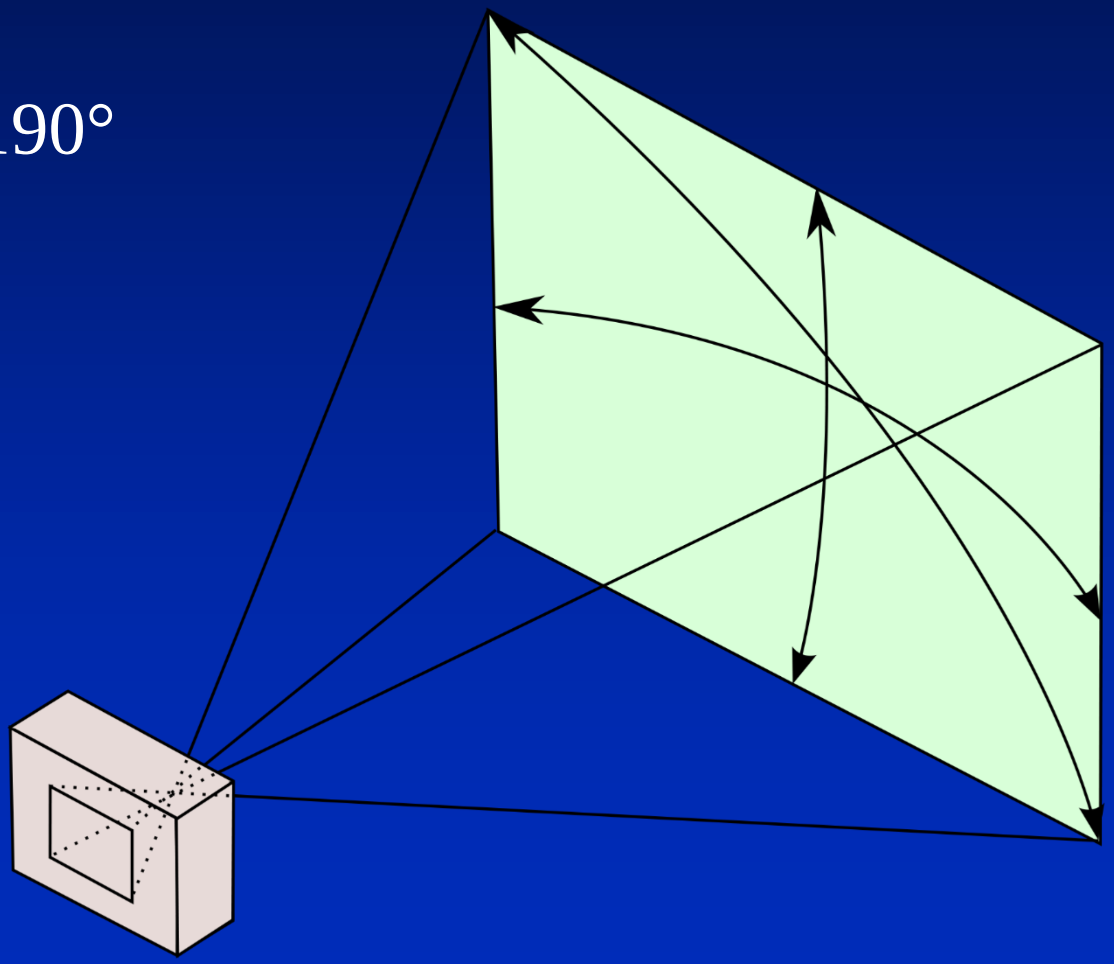
Field of view of the Human Eye

Horizontal - 180°-190°

Vertical - 135°

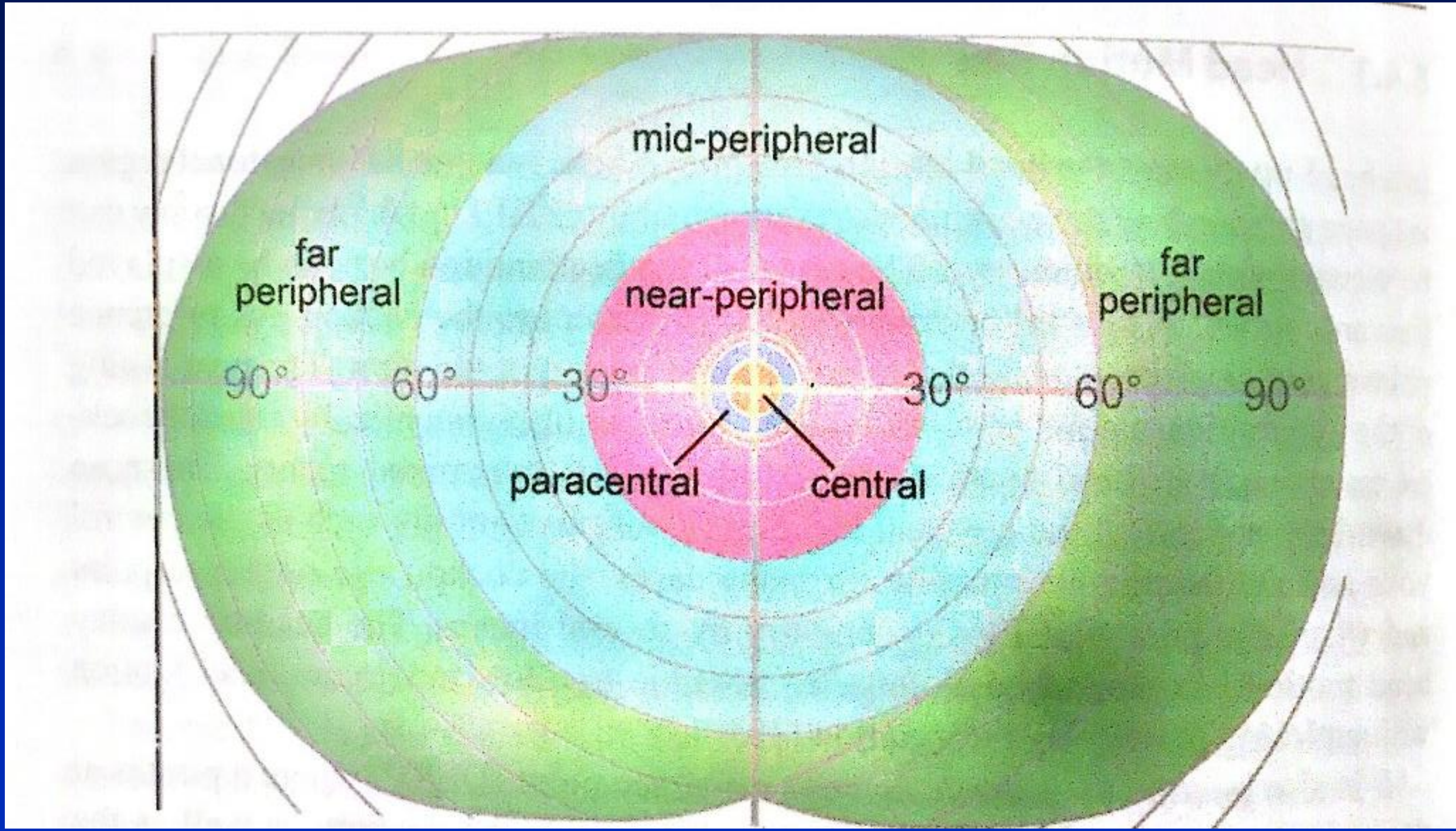


Wikipedia

Field of View for Humans

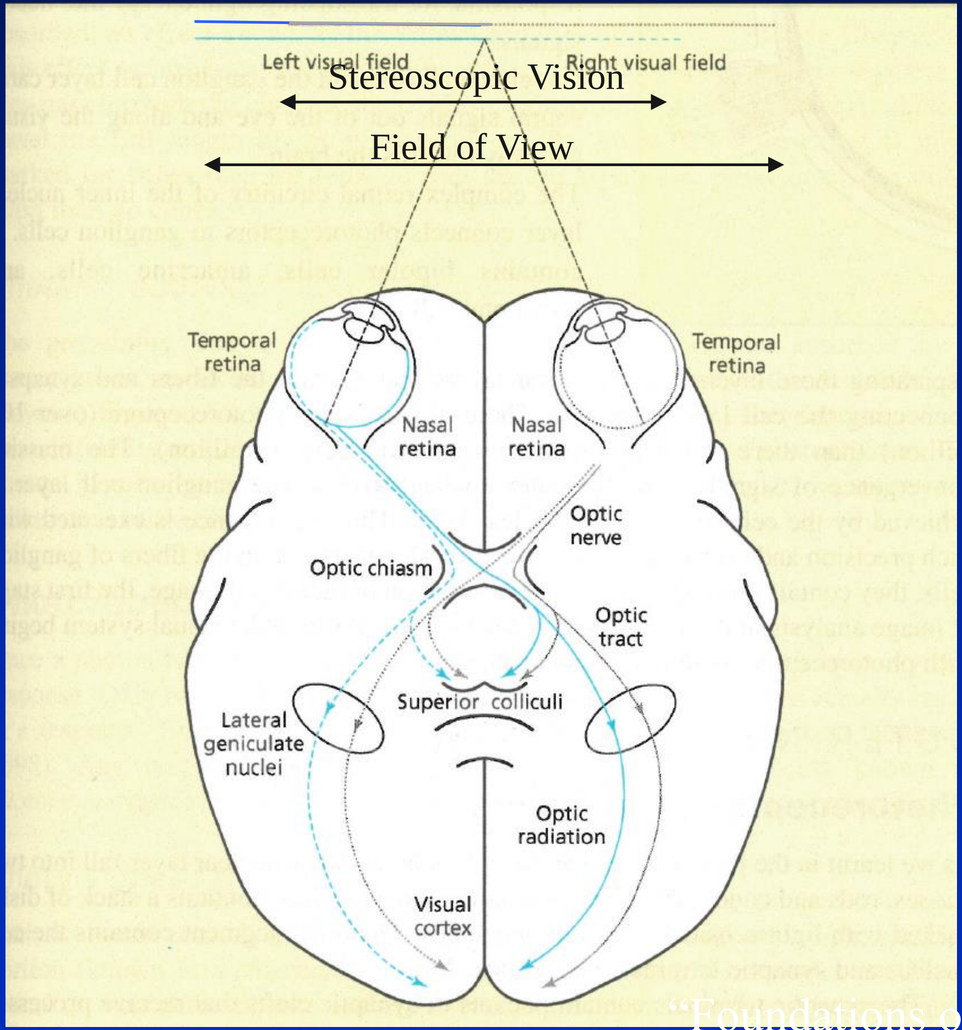
- Humans have an almost 180 degree frontal horizontal field of view
- The vertical range of the visual field is approximately 135 degrees
- The resolution, color discrimination, and reaction times is not uniform across the field of view

Field of View of the Human Eye



Wikipedia

Field of View of the Human Eye



The visual system includes the retinas, the visual pathway connecting the retinas to the brain, and the visual cortex. The two eyes' fields of view overlap (top).

"Foundations of Sensation and Perception." Mather, George. 2009.

Fundamentals of Human Perception

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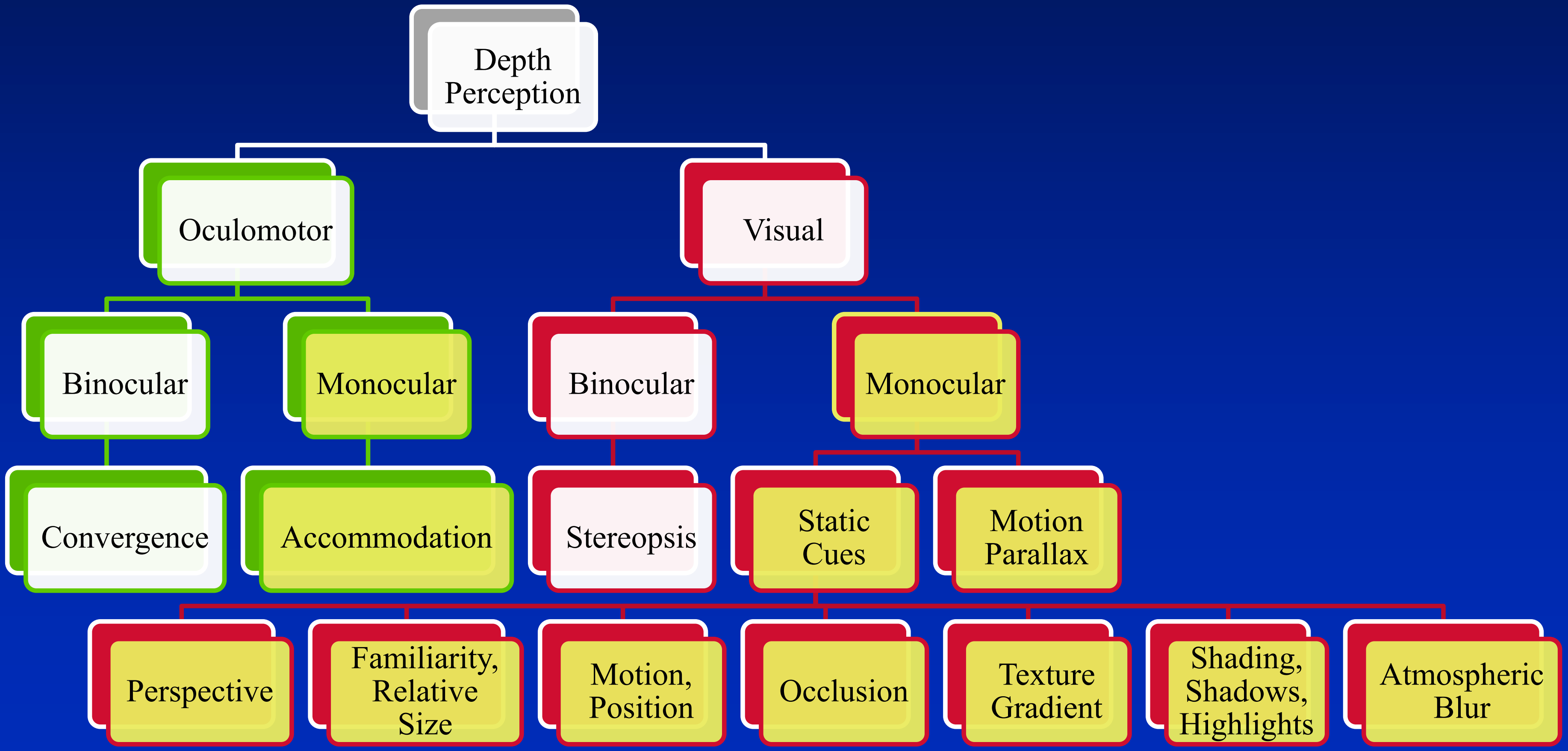
Monocular Vision

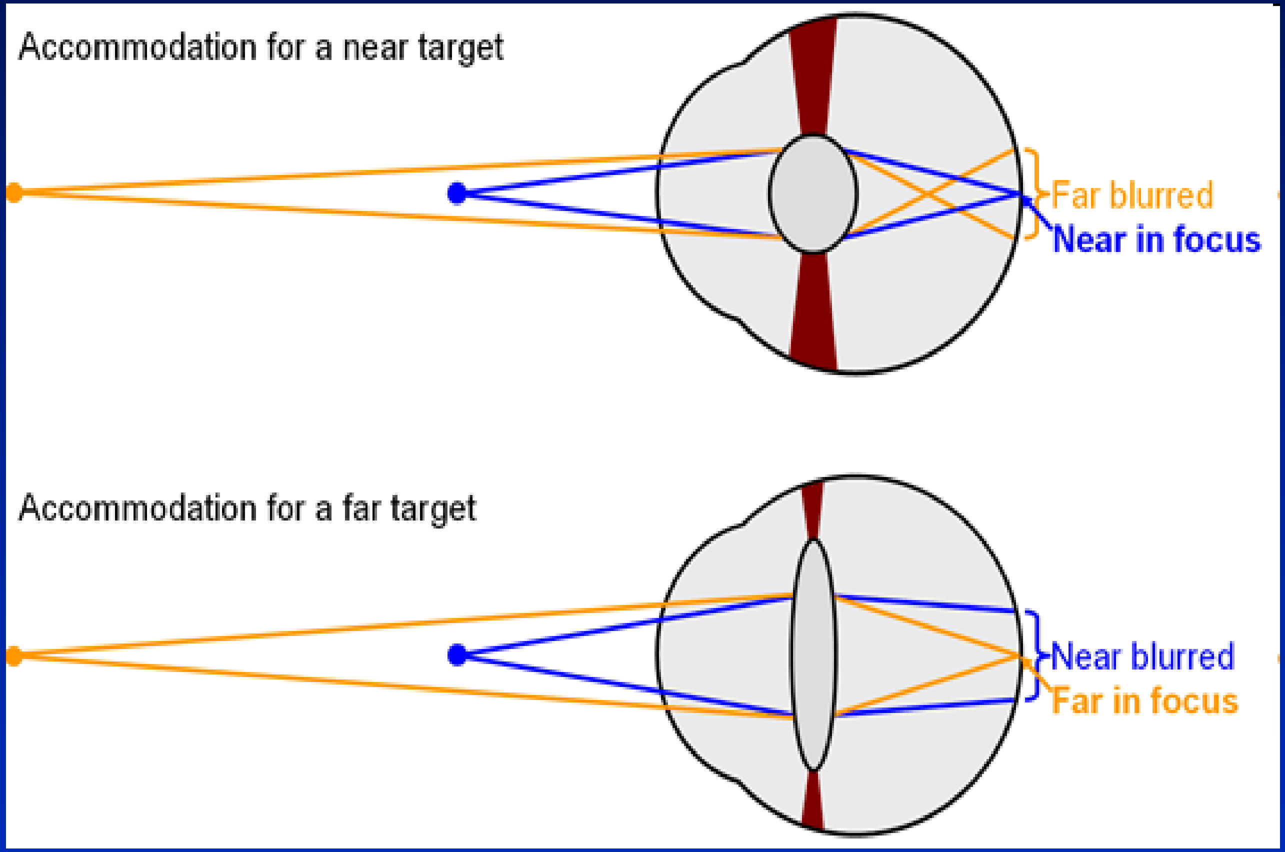
- Sixty to seventy degrees have no binocular vision (because only one eye can see those portions of the visual field)

Human Depth Perception



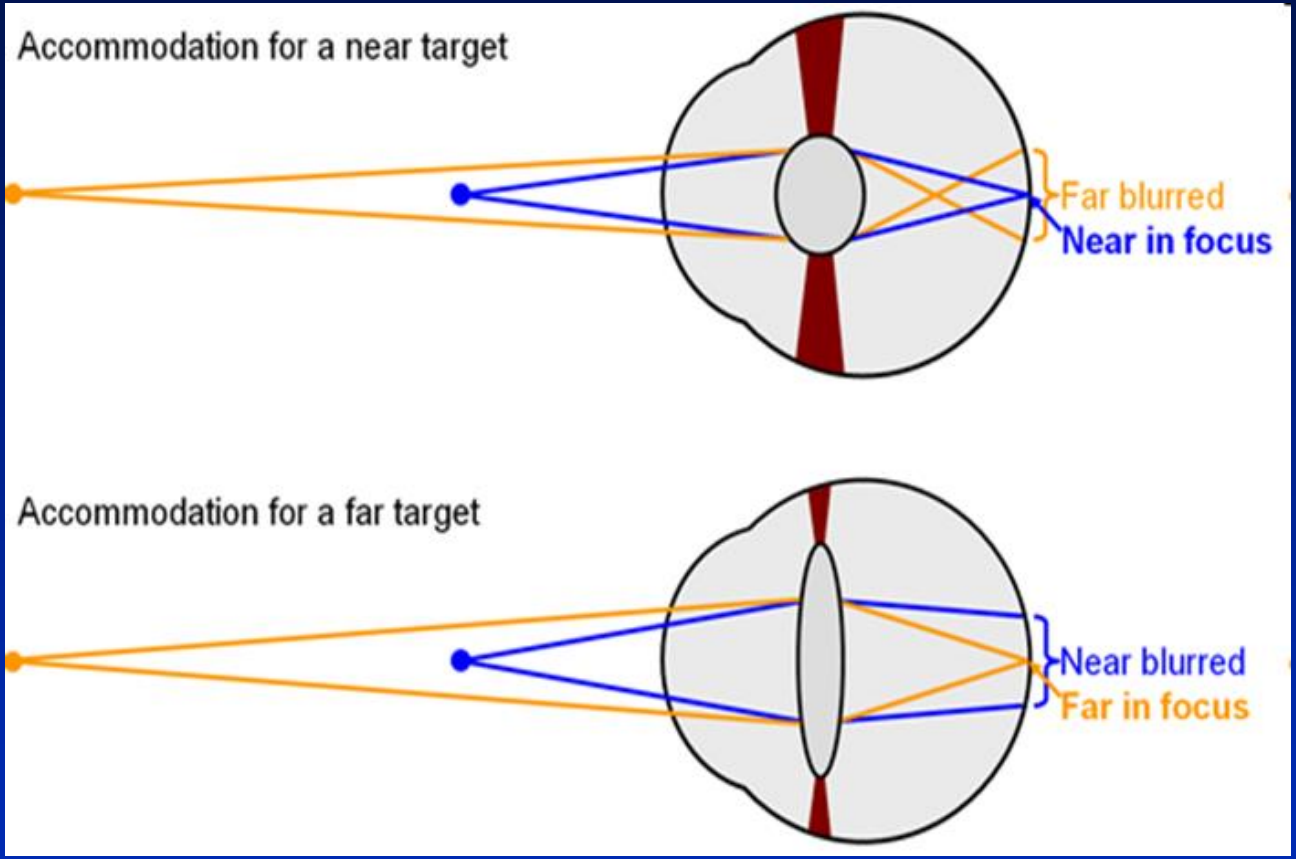
Monoscopic Depth Cues

- Perspective
- Depth from Motion, Relative Size, Position, Familiarity
- Occlusion
- Texture Gradient
- Parallax from Motion
- Shadows and Specular Highlights
- Atmospheric Blur
- Accommodation



Note change in lens shape

Accommodation



The reflex can be controlled but cannot be 'felt'

Accommodation amplitude declines with age

"Vision and Visual Disabilities – An Introduction," by Gerd Waloszek, SAP User Experience

Vergence

- The simultaneous movement of the pupils of the eyes toward or away from one another during focusing.

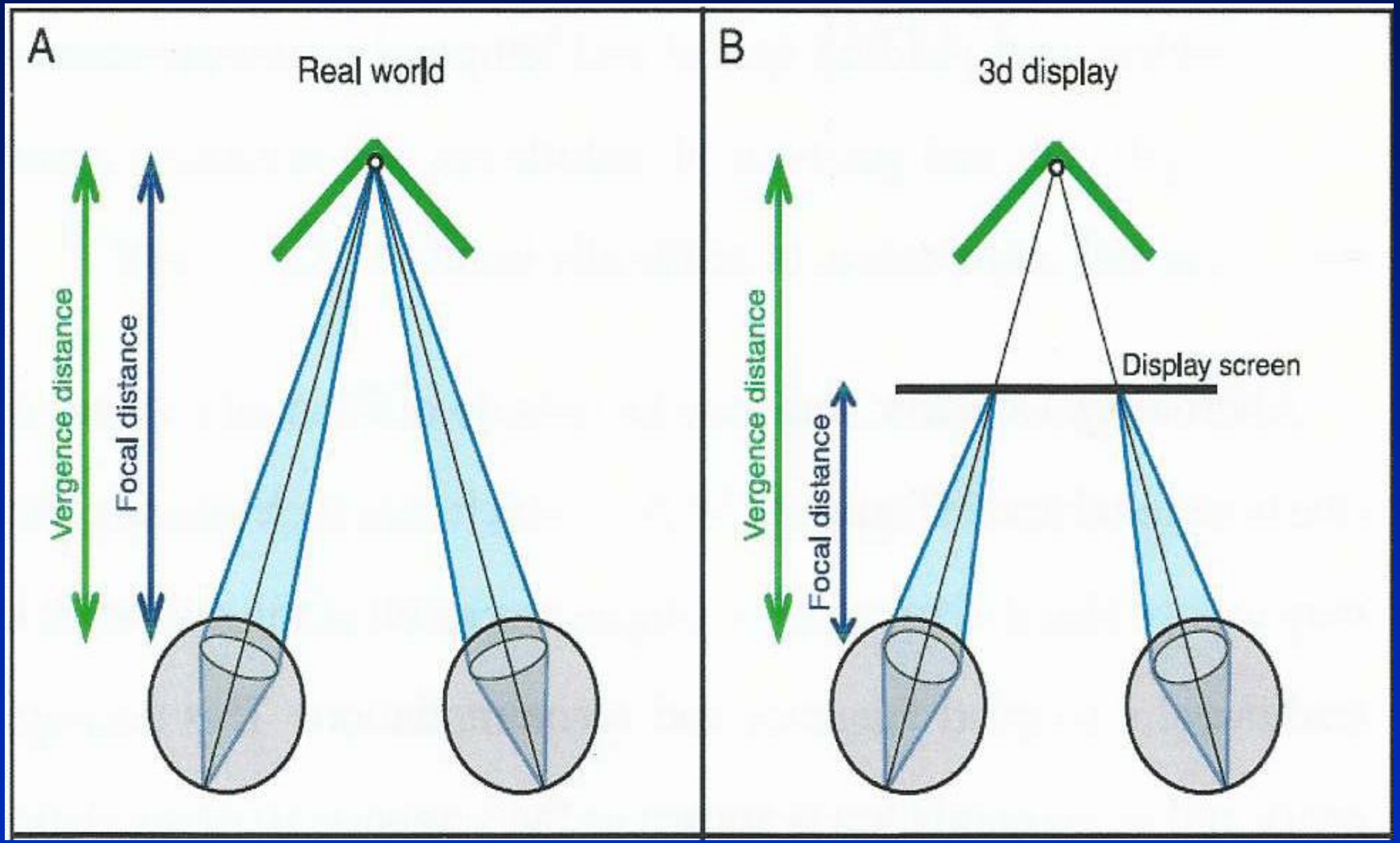
- This measure of the convergence or divergence of a pair of light rays is defined as vergence.

Vergence Accommodation Conflict

- Computer and projection displays present images on a single surface but have a focal distance (blur on the retina) which may be in front of or behind the screen
- The inability to fuse the binocular stimuli causes discomfort and fatigue to the viewer

David M. Hoffman, Ahna R. Girschick, Kurt Akeley, Martin S. Banks. “Vergence-accommodation conflicts hinder visual performance and cause visual fatigue, Journal of Vision, vol. 8, no. 3, article 33, March 28, 2008.

Diagram of Vergence



Binocular Vision

- Sixty to seventy degrees have no binocular vision (because only one eye can see those portions of the visual field)
- Binocular Vision, which is the basis for stereopsis is important for depth perception and covers 114 degrees (horizontally) of the human visual field.

Changing Lens Shape

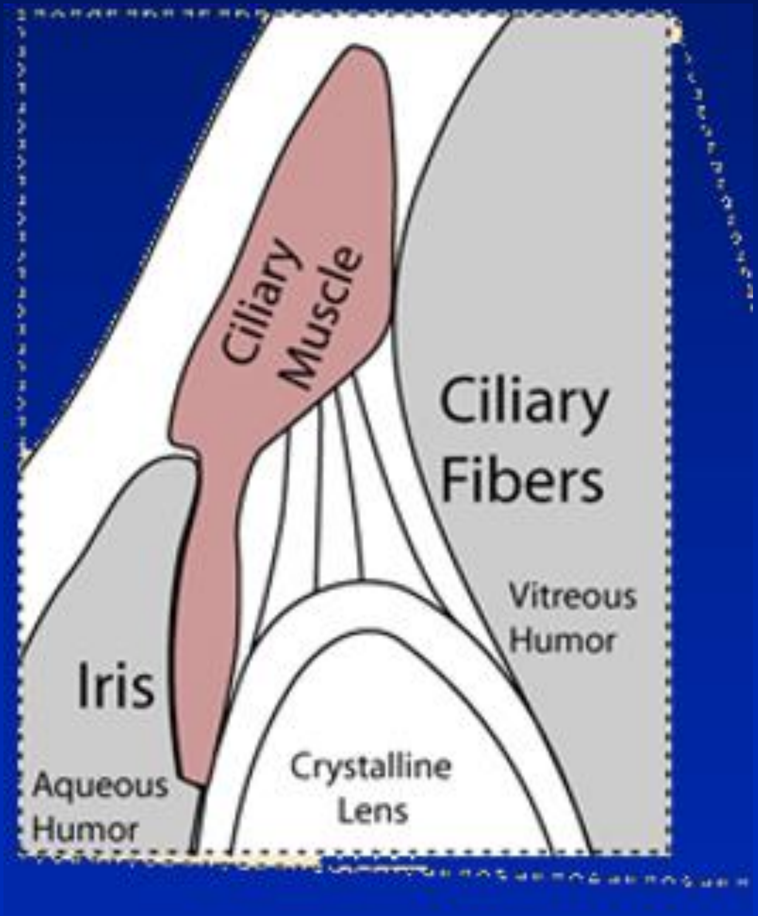
Ocular Motor Systems (OMS)

- With normal visual perception, the ocular motor systems control the movement of the eyes to focus on the object of interest (voluntarily controlled)

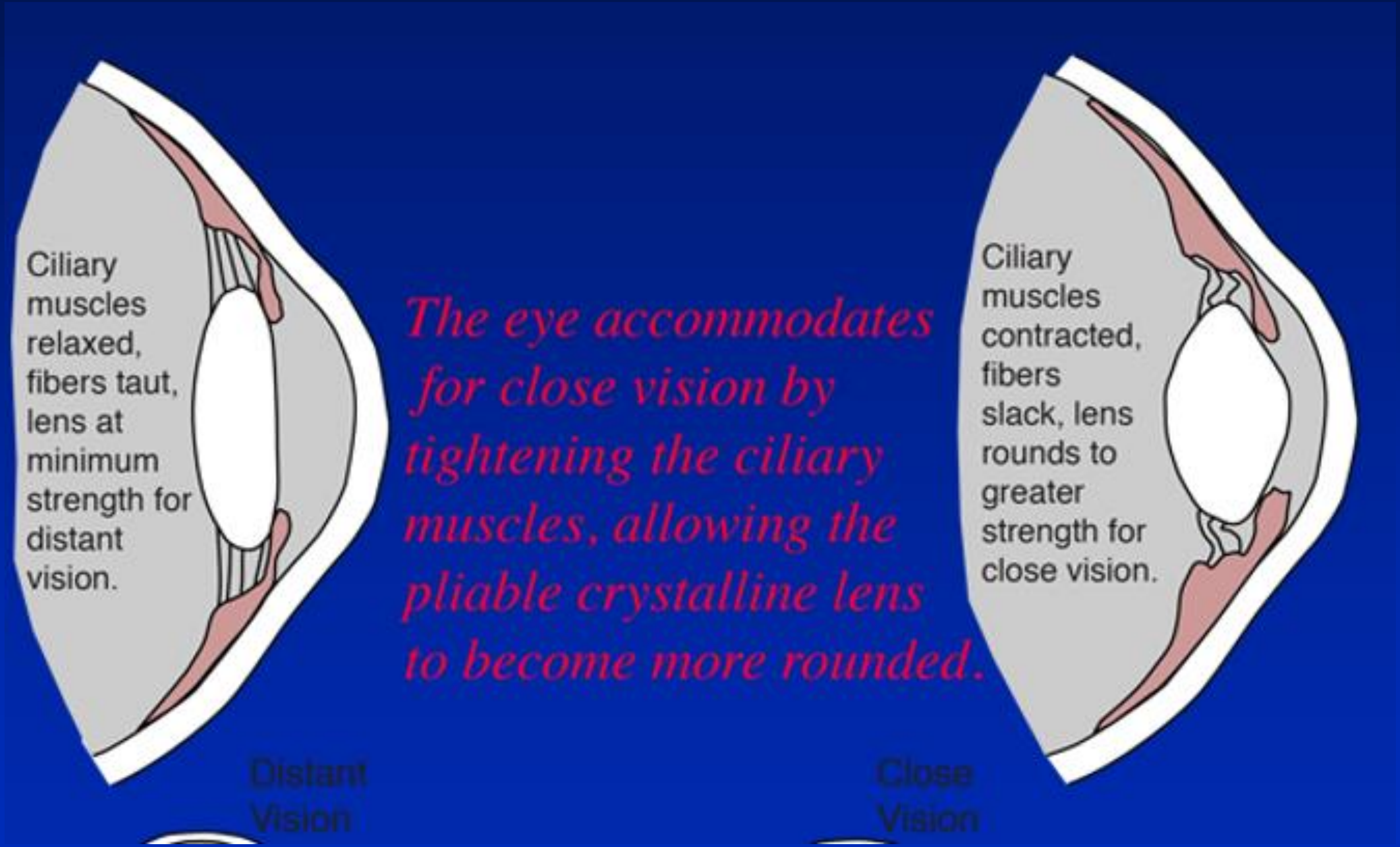
- The OMS produces adjustments in pupil size, lens refraction, and accommodation.

- Accommodation involves the convergence of the two eyes to direct their images on to the fovea.

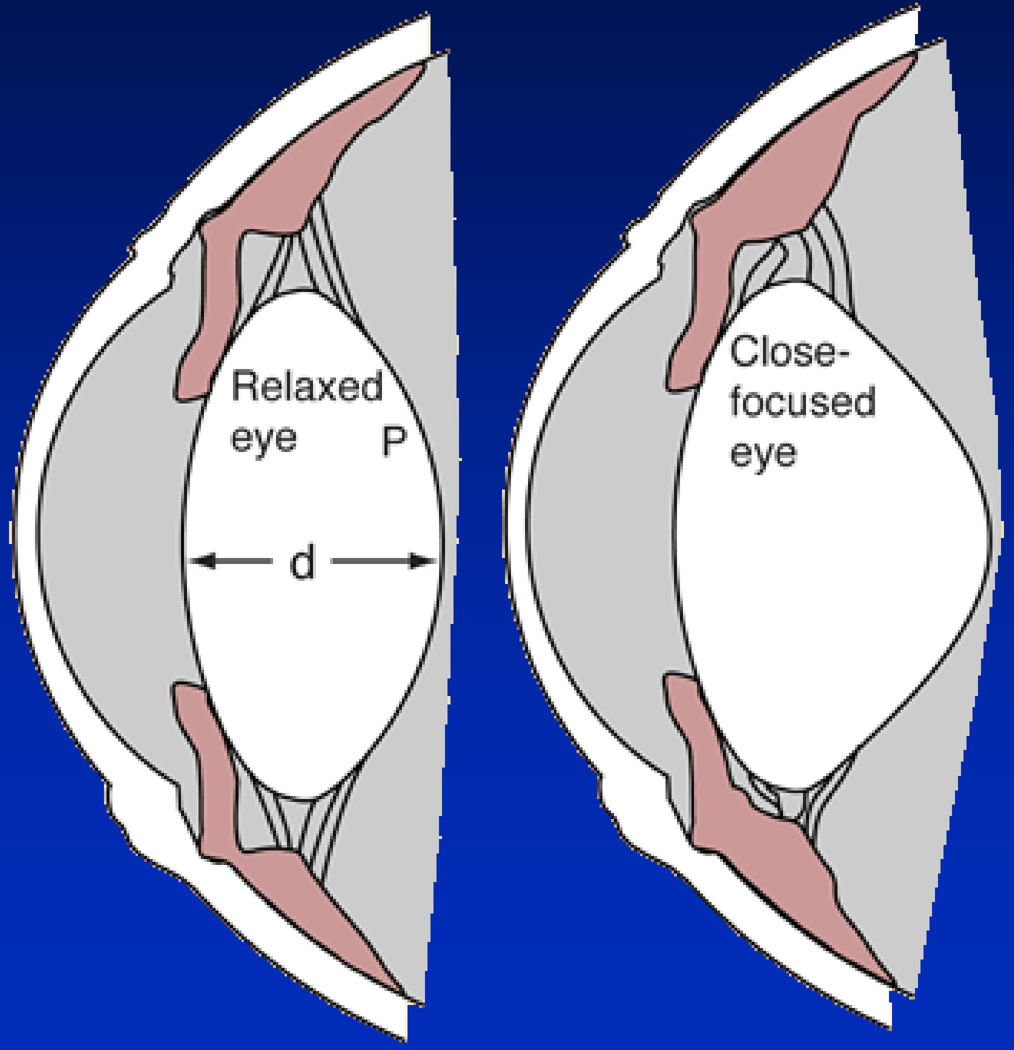
Ciliary Muscles



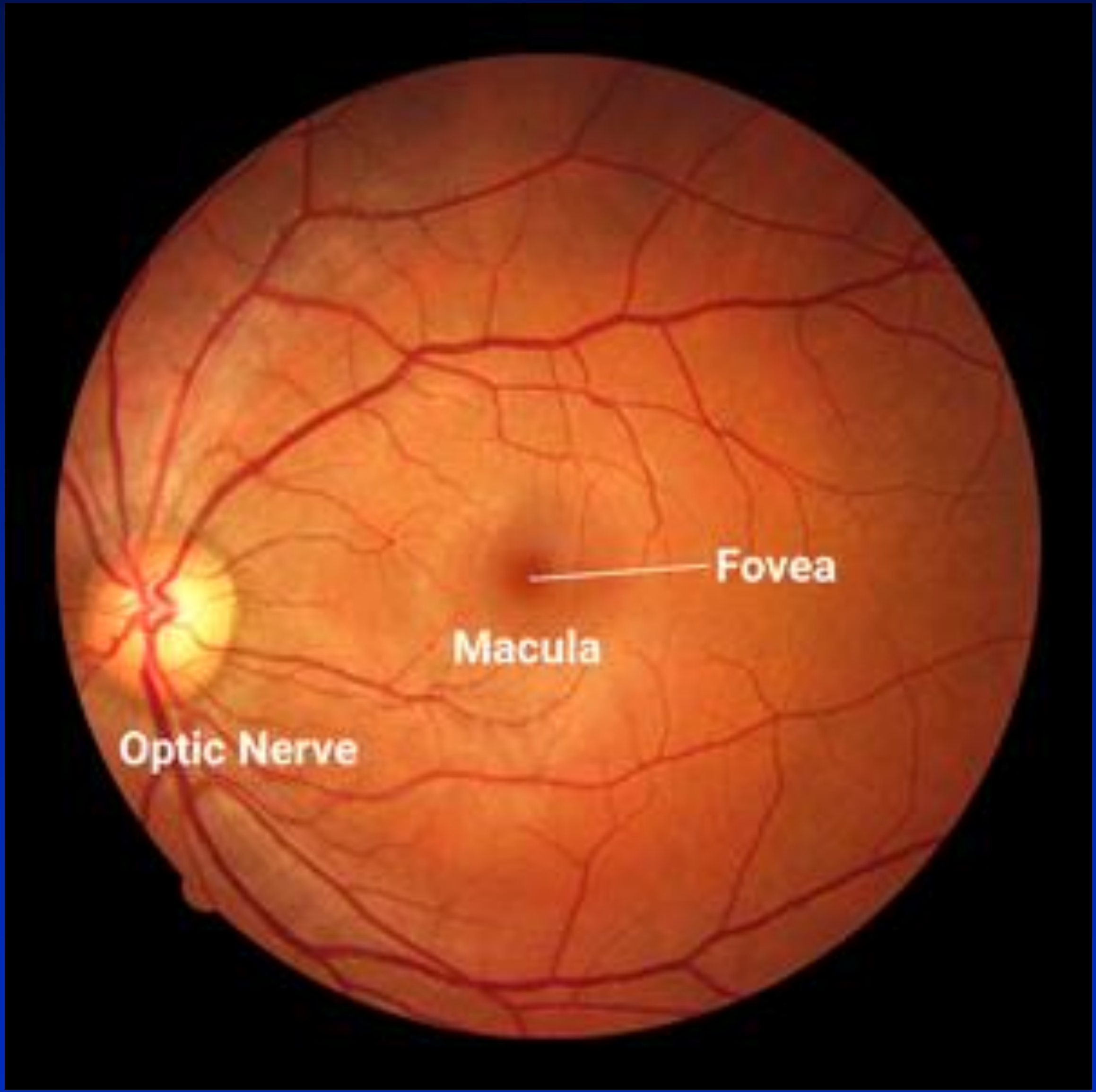
Ciliary Muscles



Cilary Muscles



Fovea



Saccadic Motion

The eye jumps, comes to rest momentarily (producing a small dot on the record), then jumps to a new locus of interest.

- David H. Hubel. EYE, BRAIN, AND VISION, 1988 Scientific American Books, Inc. p. 80.

Extraocular Muscles

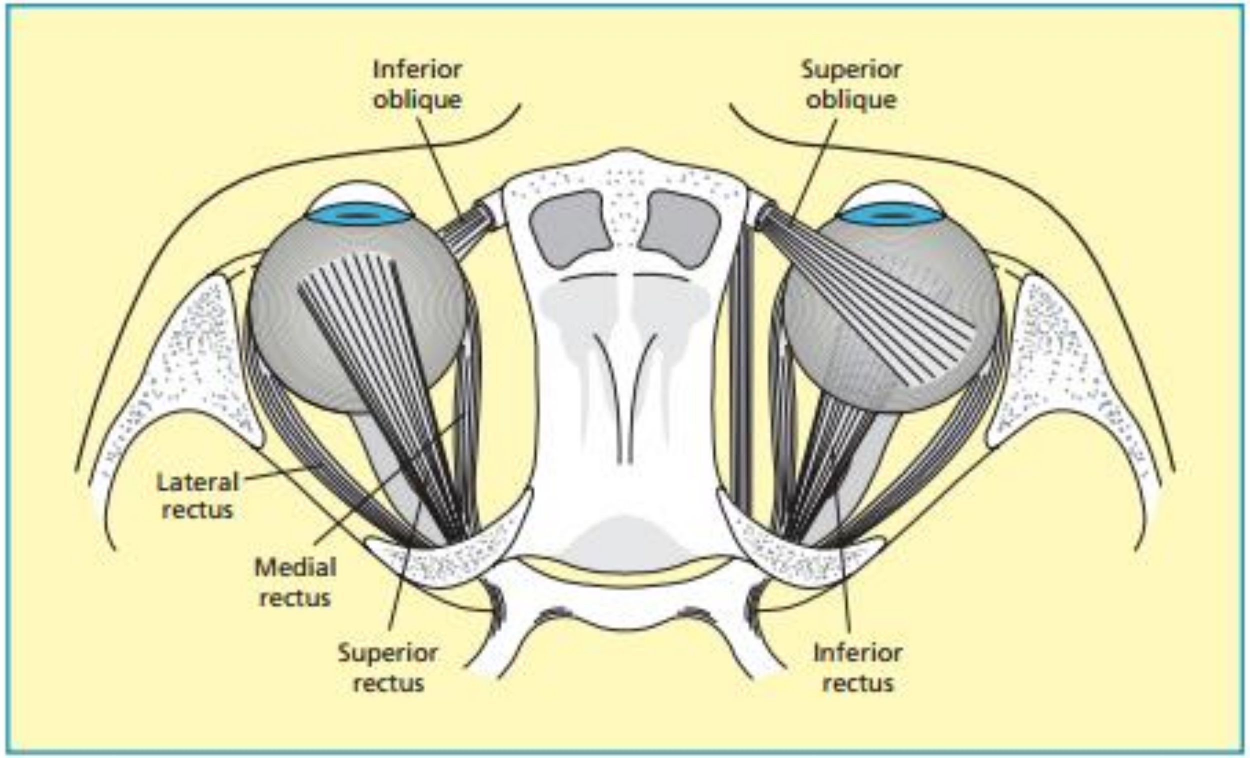


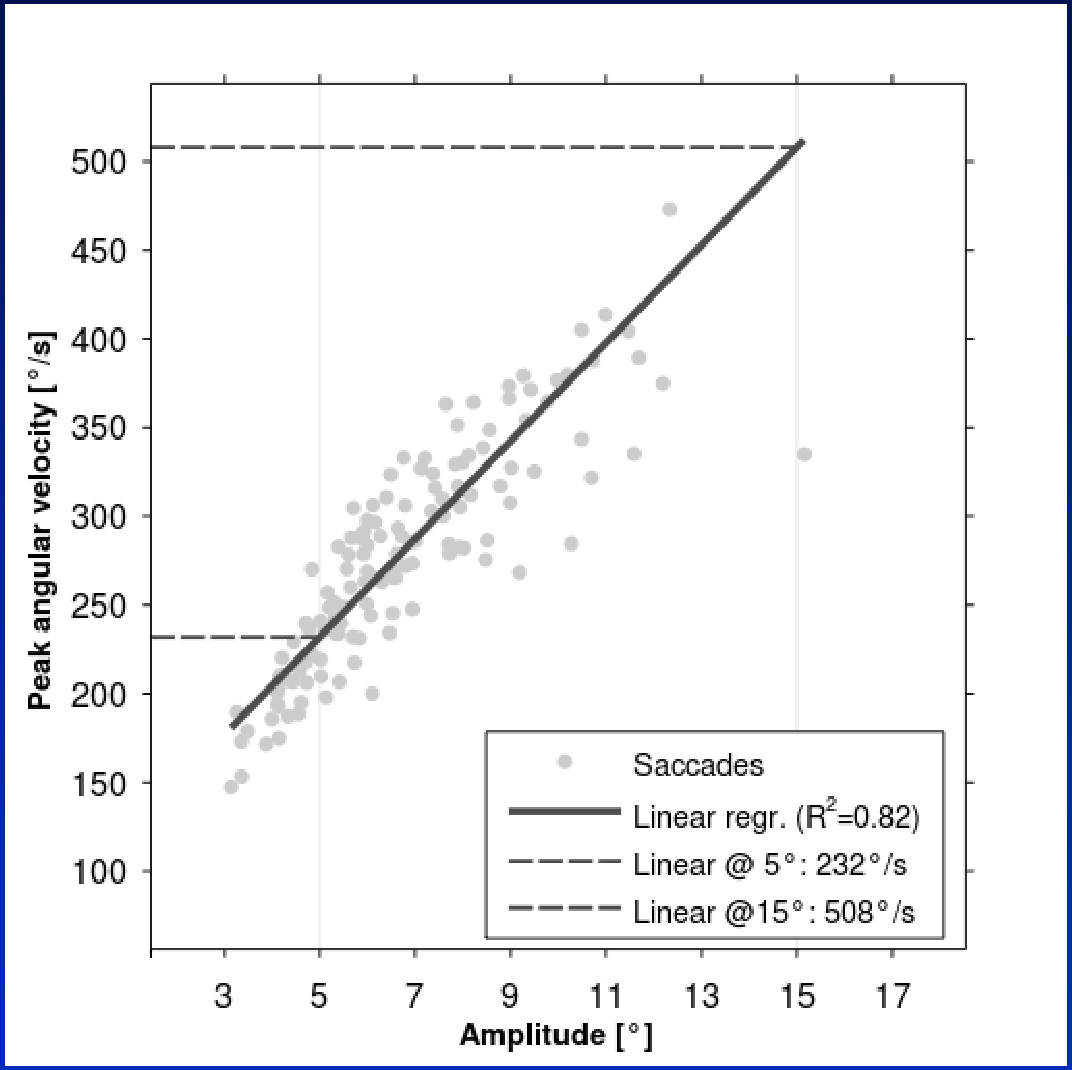
FIGURE 6.13
The extraocular muscles. Six muscles working in three pairs allow each eye to rotate in its socket about the three possible axes (based on Walls, 1963).

“Foundations of Sensation and Perception.” Mather, George. 2009.

Saccade Control

- Saccade control is the ability of the eye(s) to move quickly from one fixation point to another (100-300 ms)
- To obtain a complete picture, normal adults perform 3-5 saccades (“snapshots”) per second
- Fixation “restops” are ≈ 50-100 ms

Saccades Peak Angular Velocity



Wikipedia

Saccadic Masking

- There are two major types of saccadic masking or suppression
- **Flash suppression** is the inability of the eye to see a flash of light during a saccade
- **Suppression of image displacement** is characterized by the inability to perceive whether a target has moved during a saccade.

A.L. Yarbus 1914-1986

Yarbus Eye Tracking

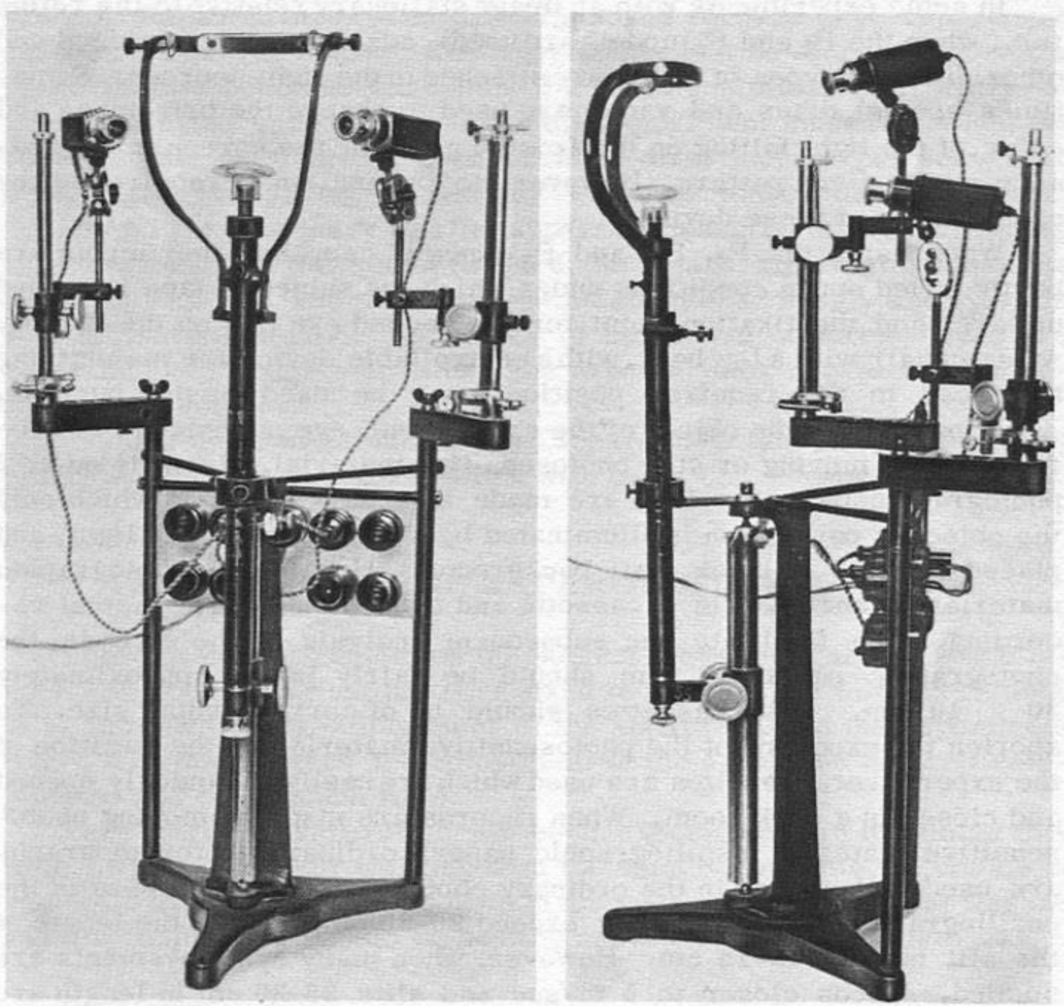


Fig. 21. The apparatus used in recording eye movements.

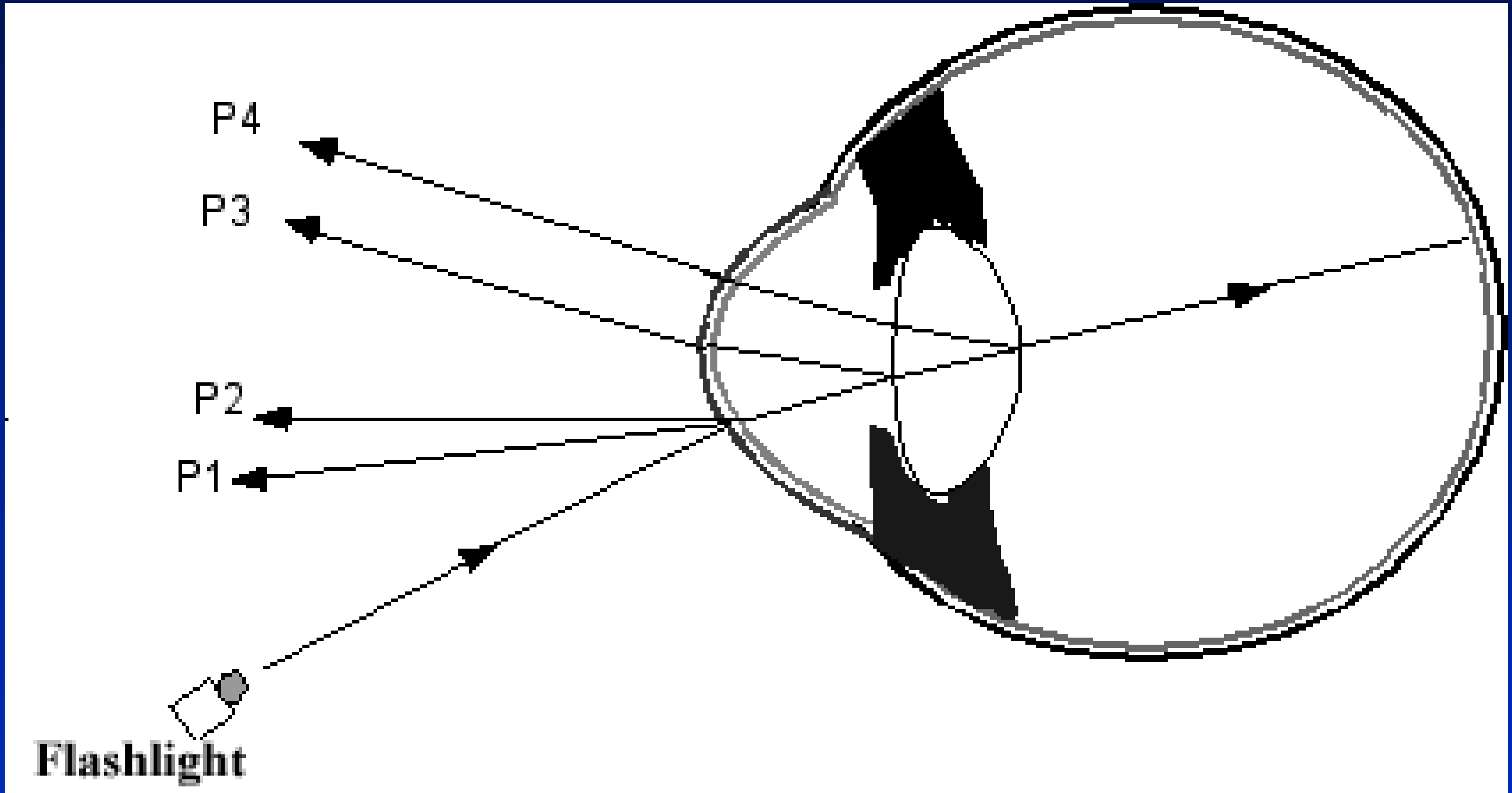
https://commons.wikimedia.org/wiki/File:Yarbus_eye_tracker.jpg

Yarbus Experimental Apparatus 1950-60’s

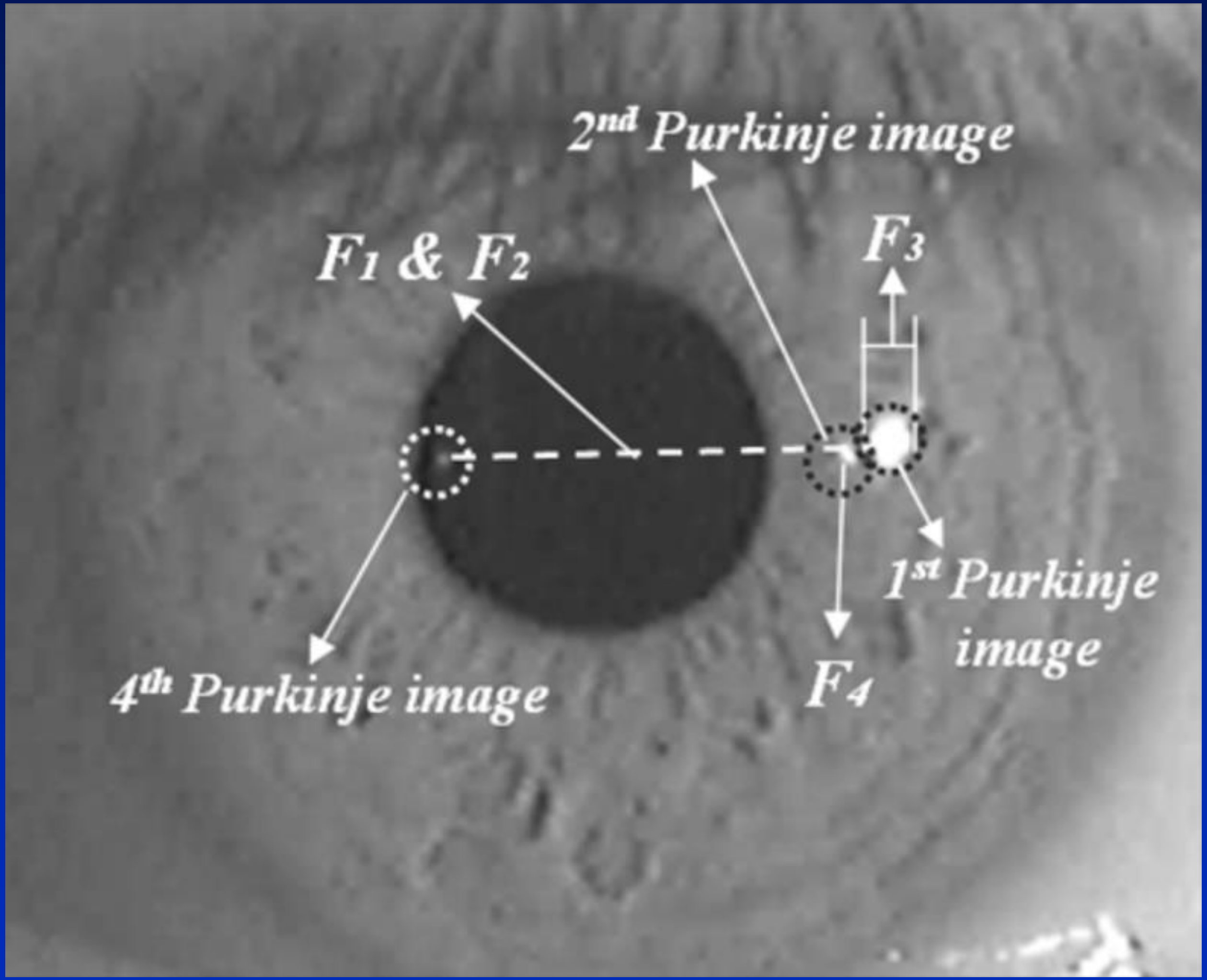
Eye Tracking   Side view of the human eye

Wikipedia

Purkinje Reflections

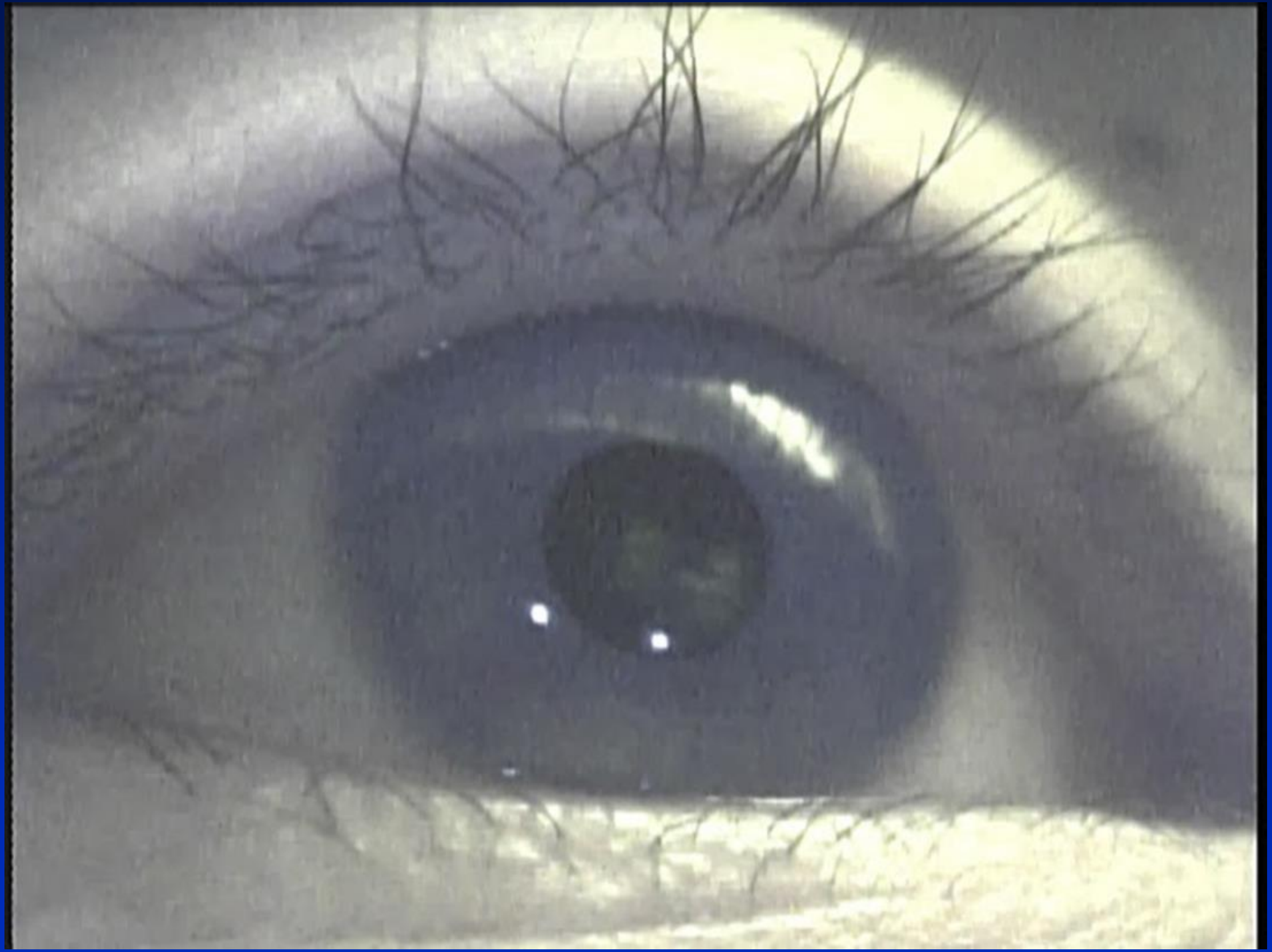


Purkinje Reflections



Eye Tracking

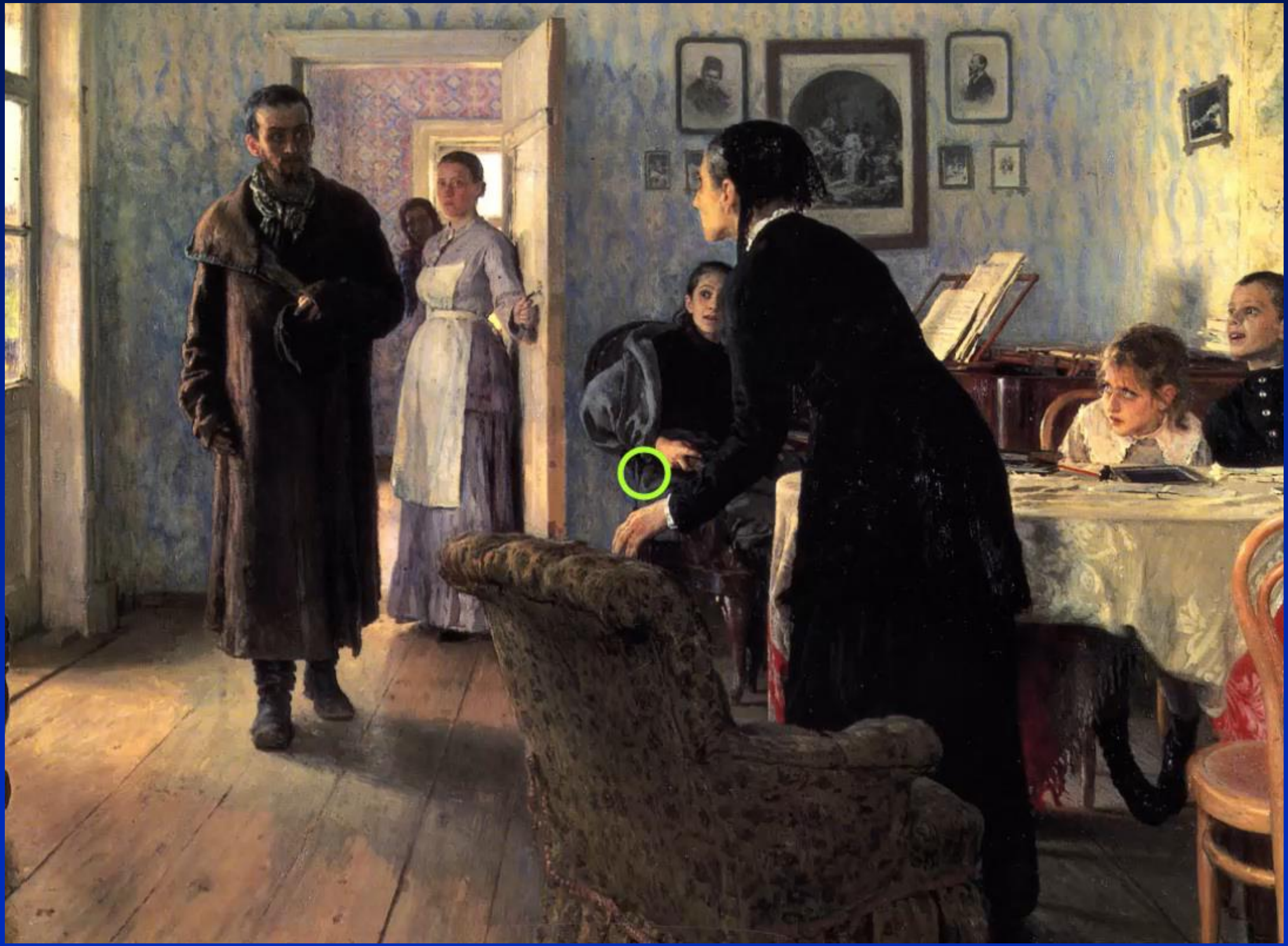
1st and 4th Purkinje Reflections



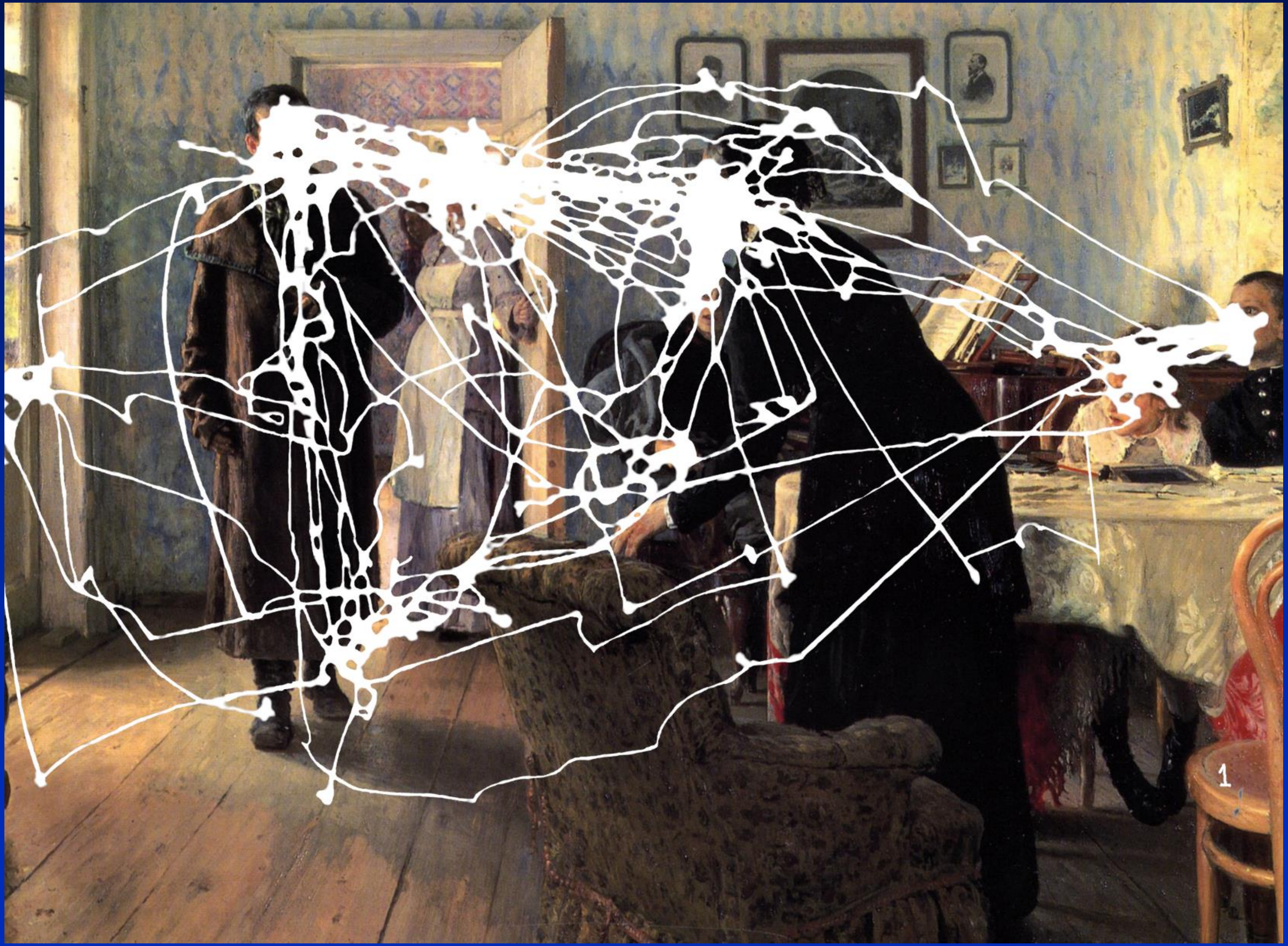
The Unexpected Visitor Ilya Repin, 1888

2391 x 1759

The Unexpected Visitor Ilya Repin, 1888



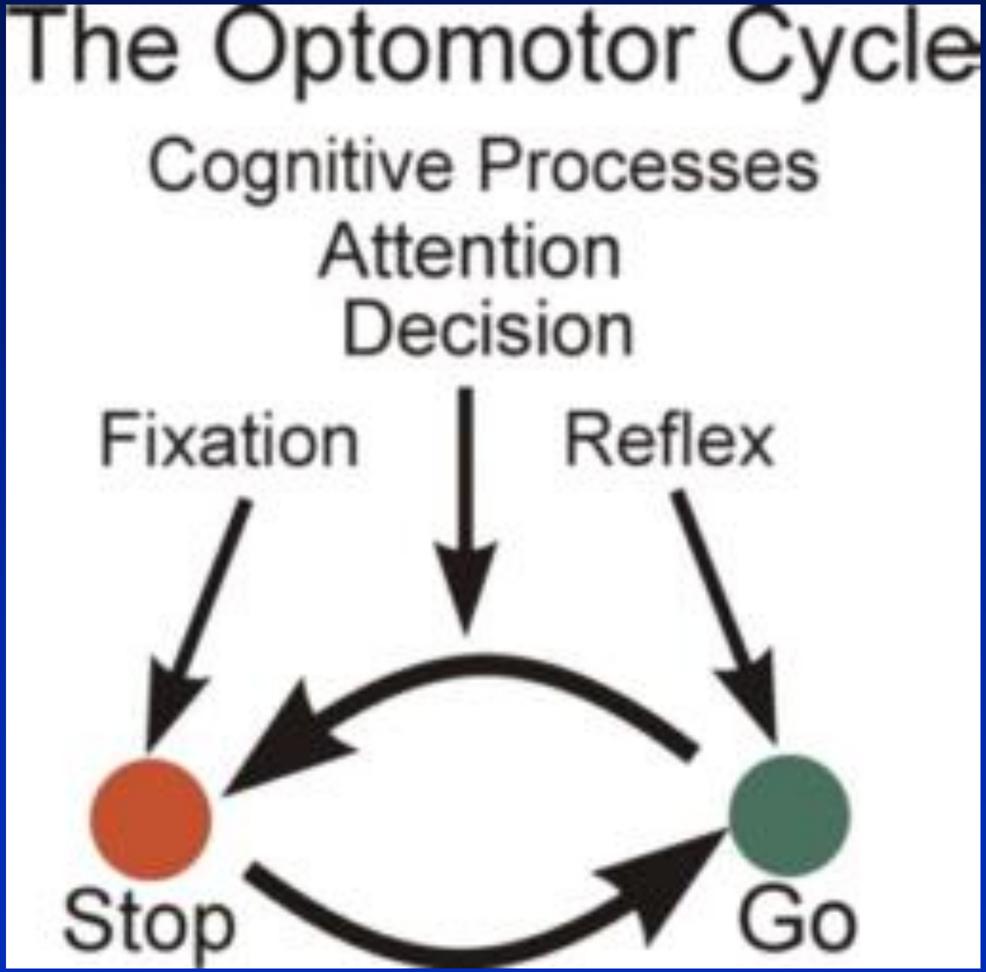
Foveal Eye Tracking



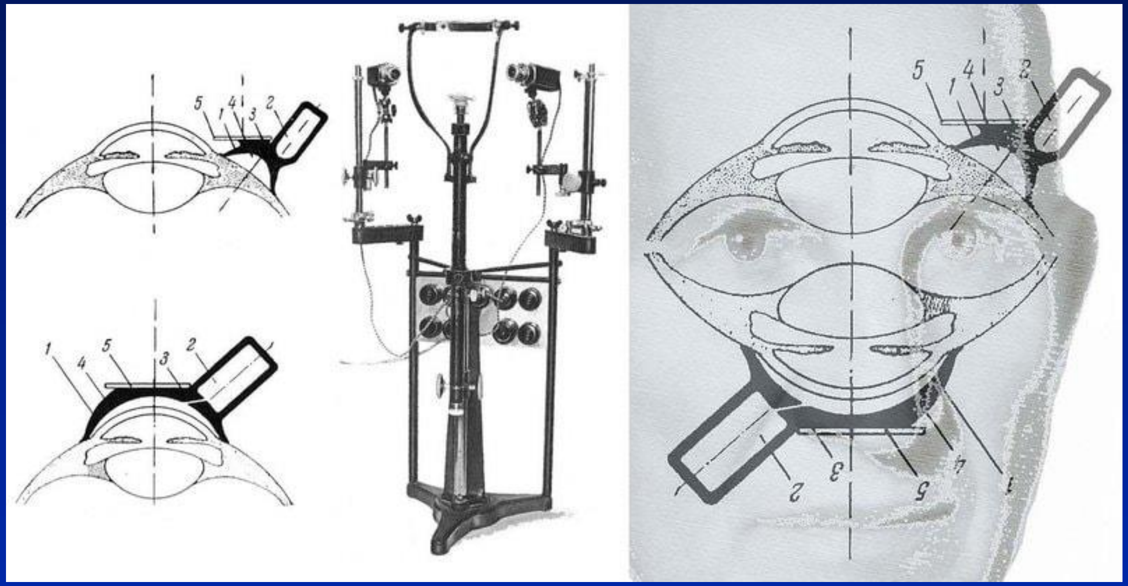
Free

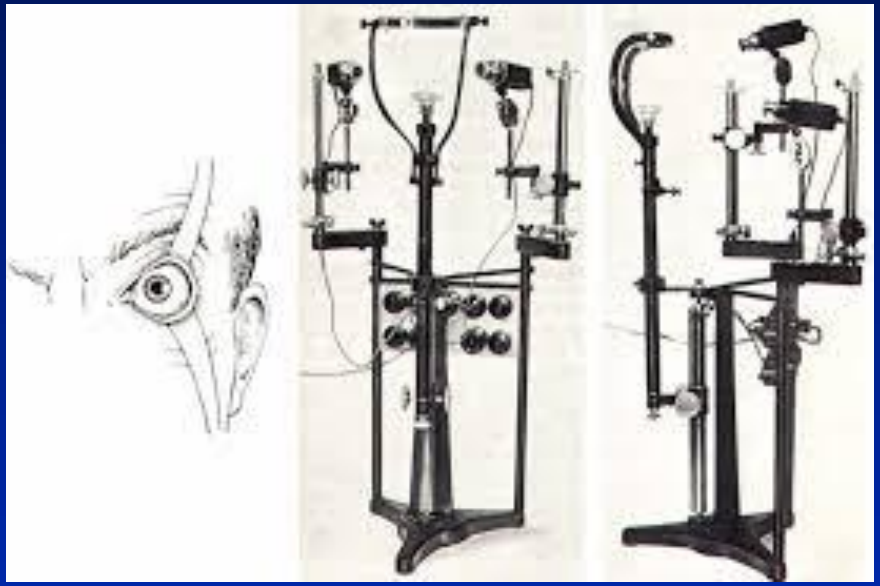
End

The Optomotor Cycle



Yarbus Experimental Apparatus 1950-60's

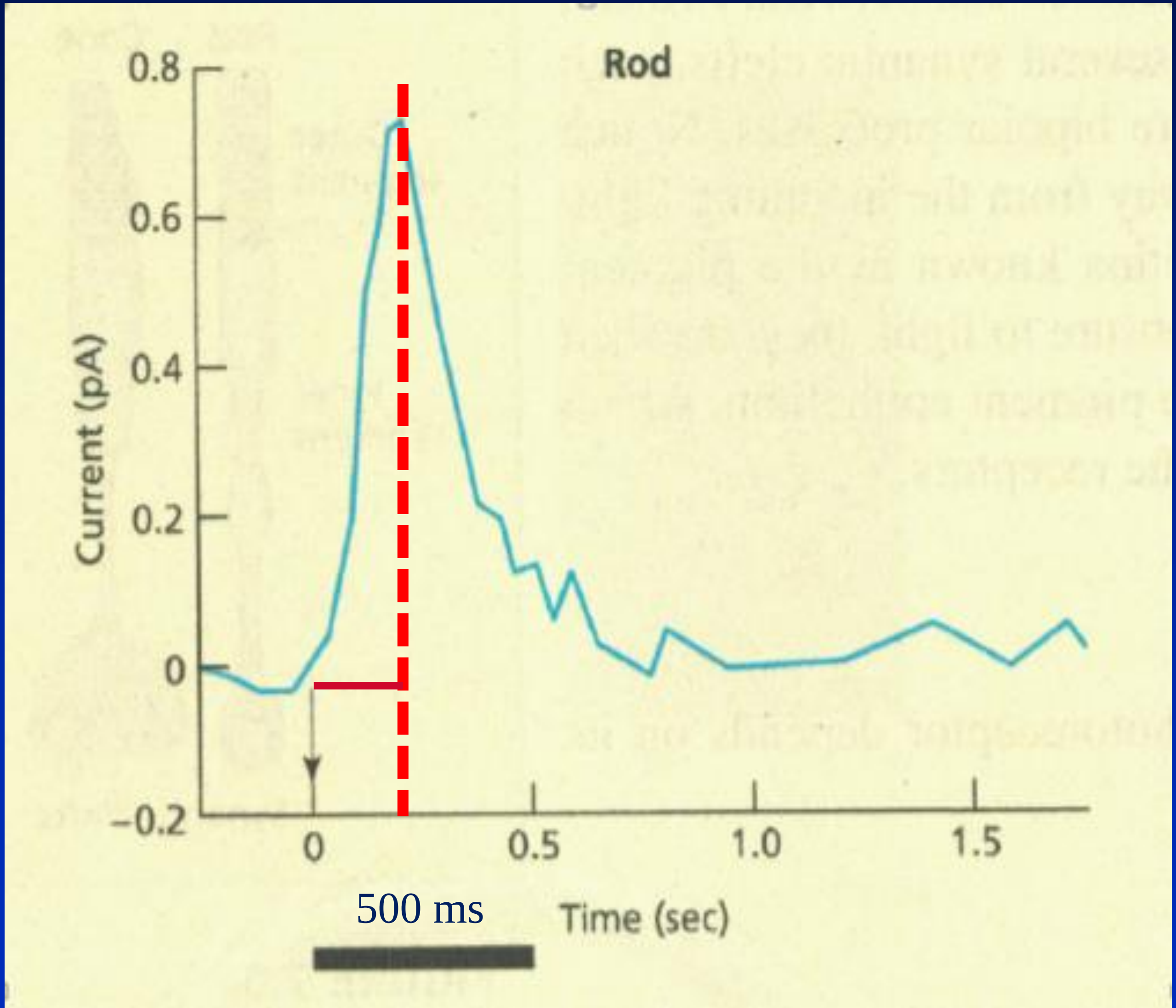




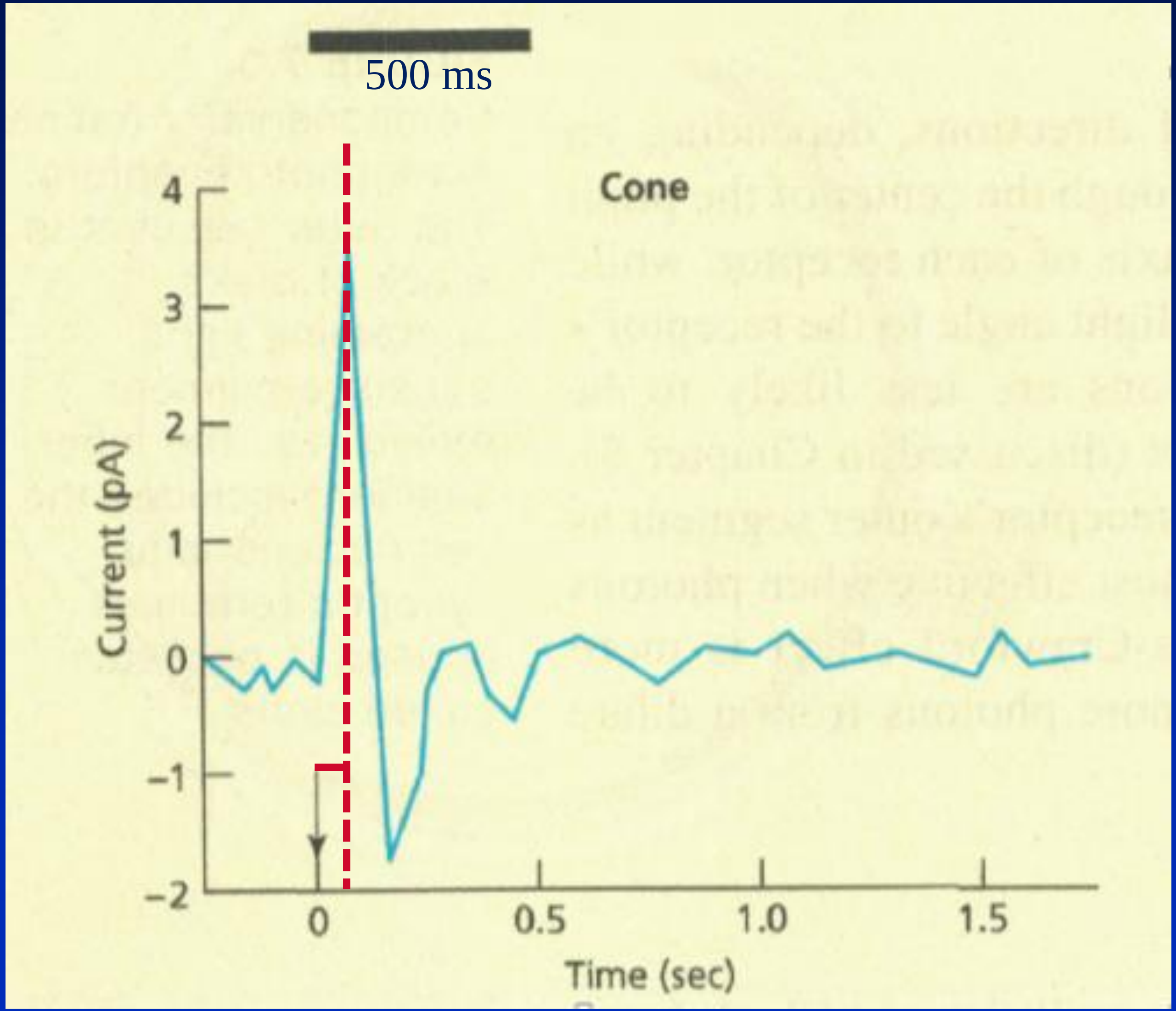
The Unexpected Visitor Ilya Repin, 1888

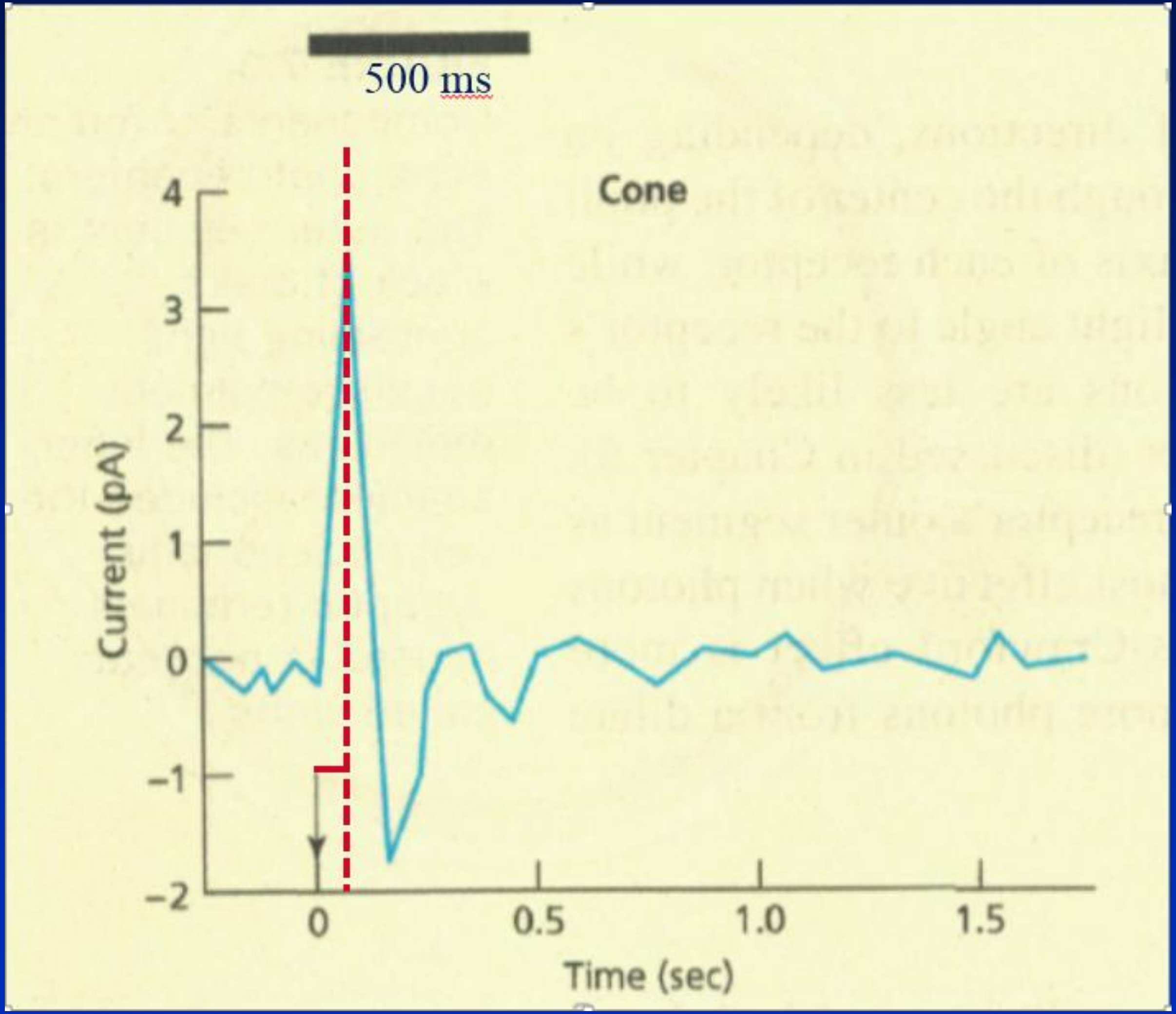
2391 x 1759

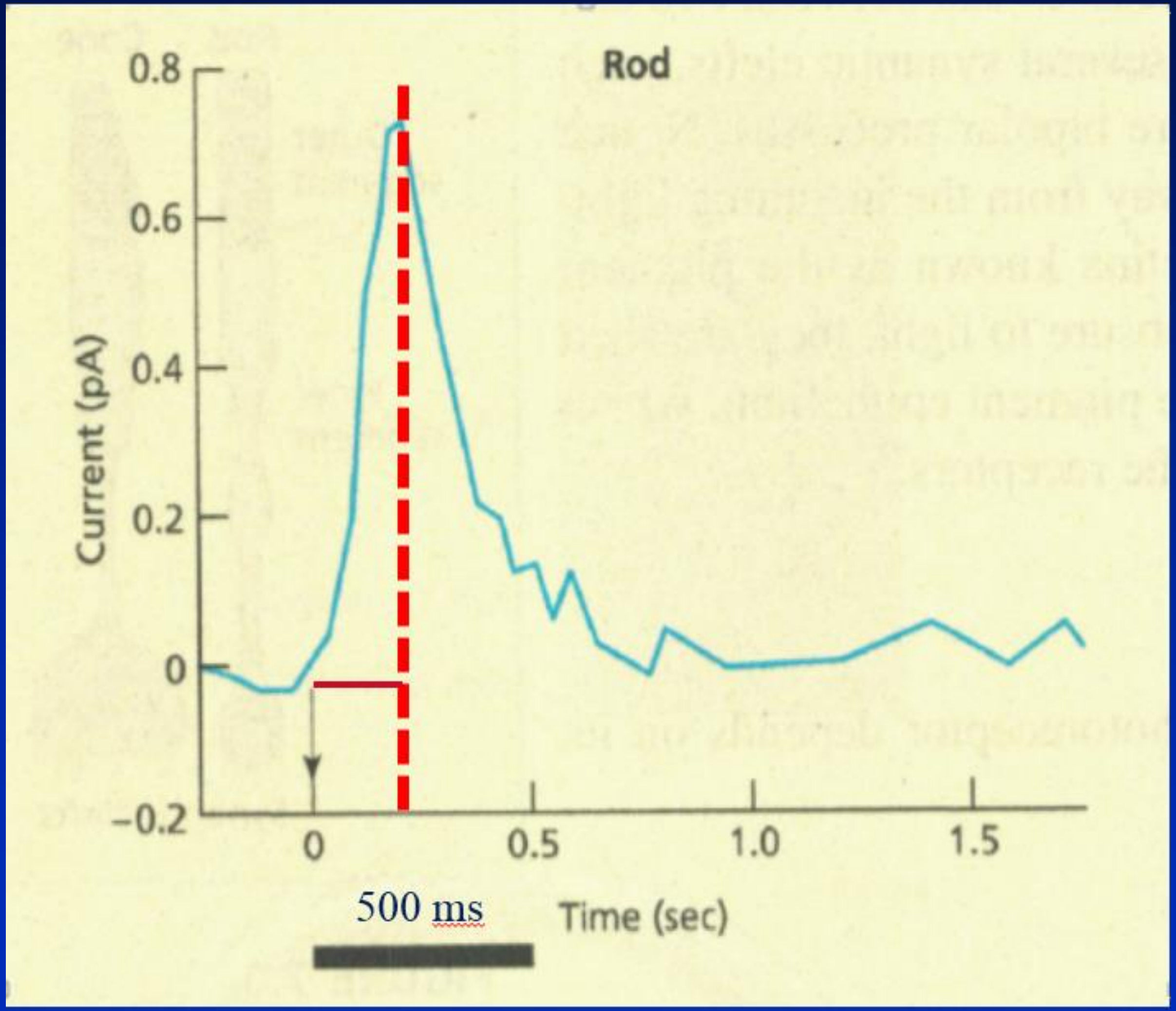
Time Response of Rods



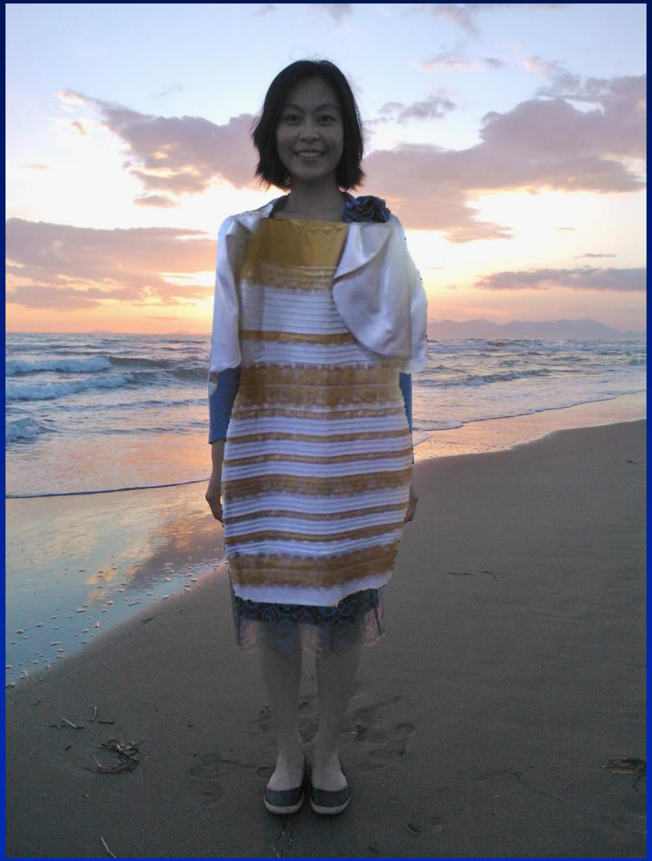
Time Response of Cones




500 ms
Cone
Current (pA)
Time (sec)


Rod
Current (pA)
500 ms
Time (sec)

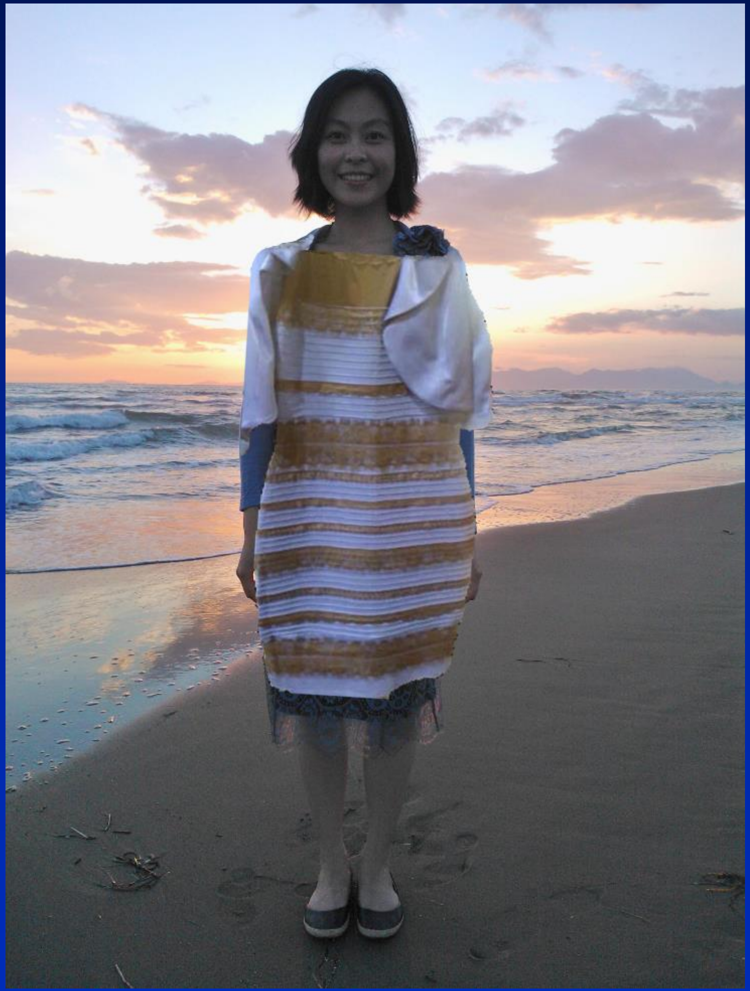
Dress in Shadow



Dress in shadow. The same picture of the dress as in Figure 1 cut out and pasted into in the shadow where it appears gold and white to most observers. Figure 10 shows a context in which the dress appears blue and black to most observers. To see the differences in color perception between Figure 2 and Figure 10 more clearly, they are shown at separate locations in the text. Ideally, it is best not to have previously seen the other photos. Photograph of the dress used with permission. Copyright Cecilia Bleasdale.

Dress in the sun

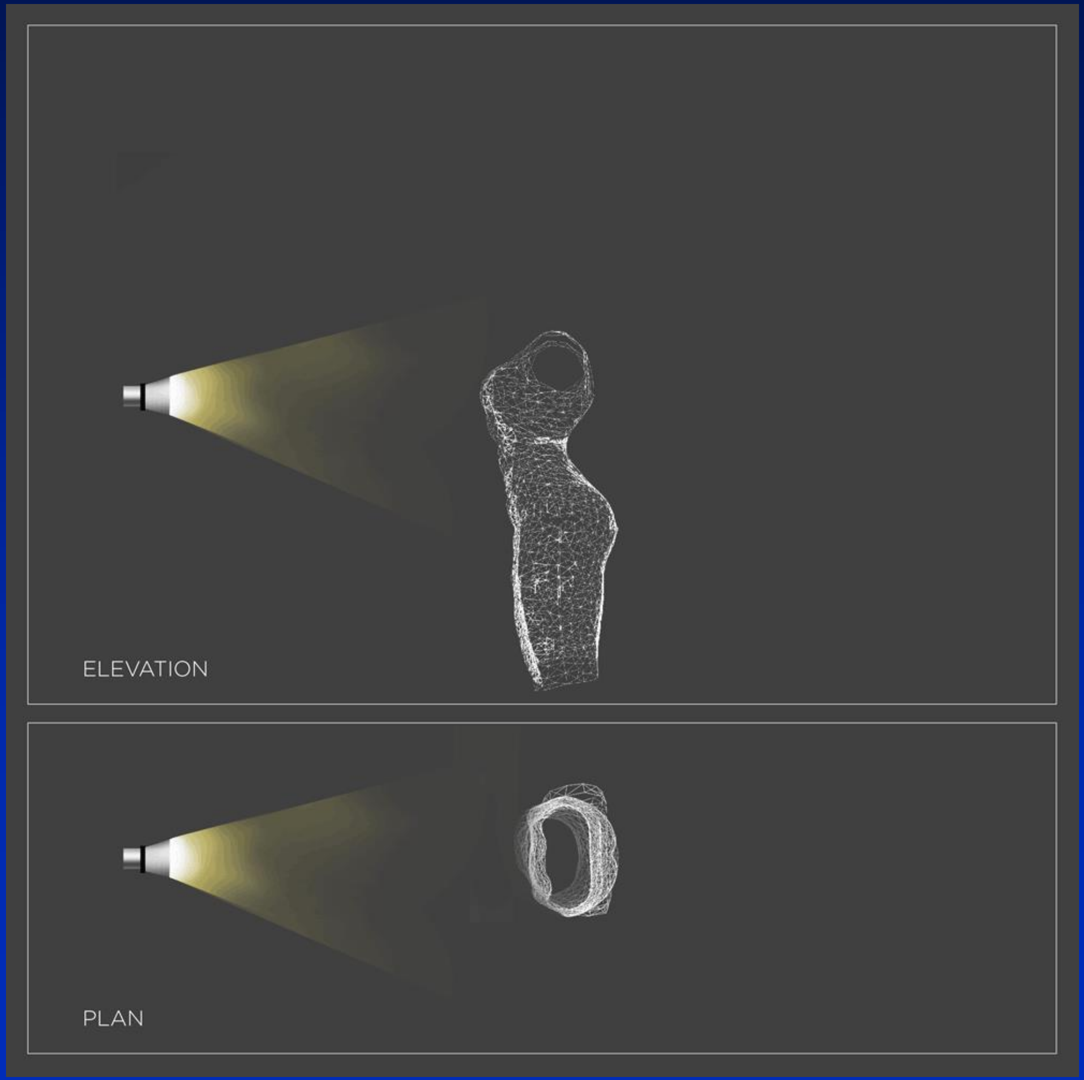
Dress in the sun. The same picture of the dress as in Figure 1 and Figure 2 cut out and pasted in the sun where it appears black and blue (note that it is better not to have previously seen Figure 1 and Figure 2 to see this). Showing observers one or the other disambiguated photo in Figure 2 and this figure prior to seeing the original photo in Figure 1 determines how observers see the colors of the dress in the original photo of Figure 1 (see text for detailed results). Photograph of the dress used with permission. Copyright Cecilia Bleasdale.




White/Gold Dress

White/Gold Dress

White/Gold Dress




Original
White/gold
Blue/black

Nvidia DGX 2018

4X Tesla V100
500 TFLOPS
20,480 CUDA Cores
256 GB memory

Fundamentals of Human Perception

- Retina, Rods & Cones, Physiology
- Receptive Fields
- Field of View
- Visual Acuity of Resolution
- Opponent Color Theory
- Compression
- Bandwidth Limitations
- Saccades

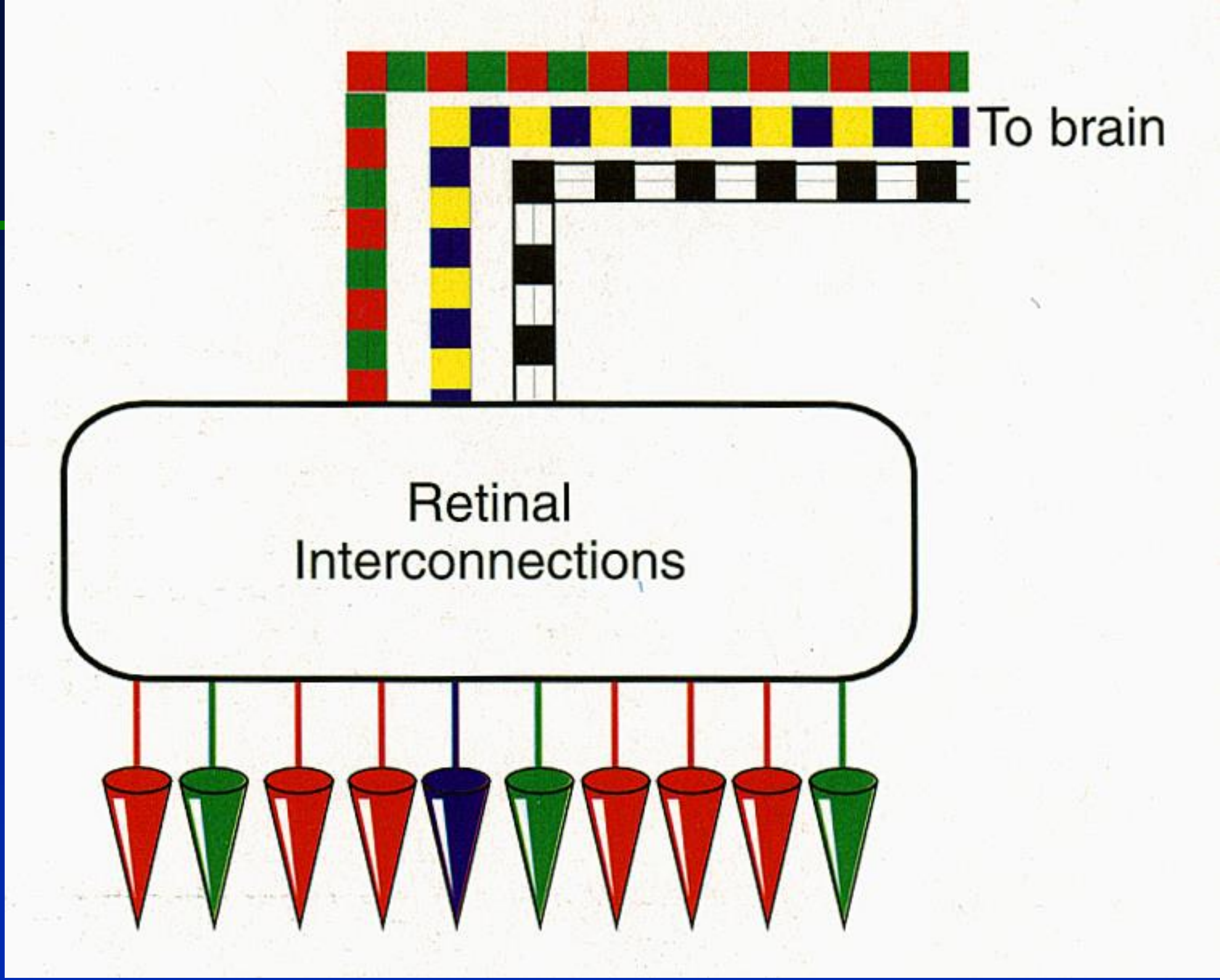
Opponent Color Theory

Channel	Combination	Resolution
black - white	M + L	very high
Green - red	M – L	High
yellow - blue	M + L – S	low

Opponent Color Theory Hering 1892

There are three types of color receptive fields called *opponent channels*.

Black – White (luminance) channel	M + L
Green – Red channel	M - L
Yellow – Blue channel	M + L - S



Cones interconnect in the retina, eventually leading to opponent-type signals.

Roy S. Berns. "Billmeyer and Saltzman's Principles of Color Technology, 3rd Ed. 2000, John Wiley & Sons, Inc. p. 16.

Opponent Color Theory Analog Computing

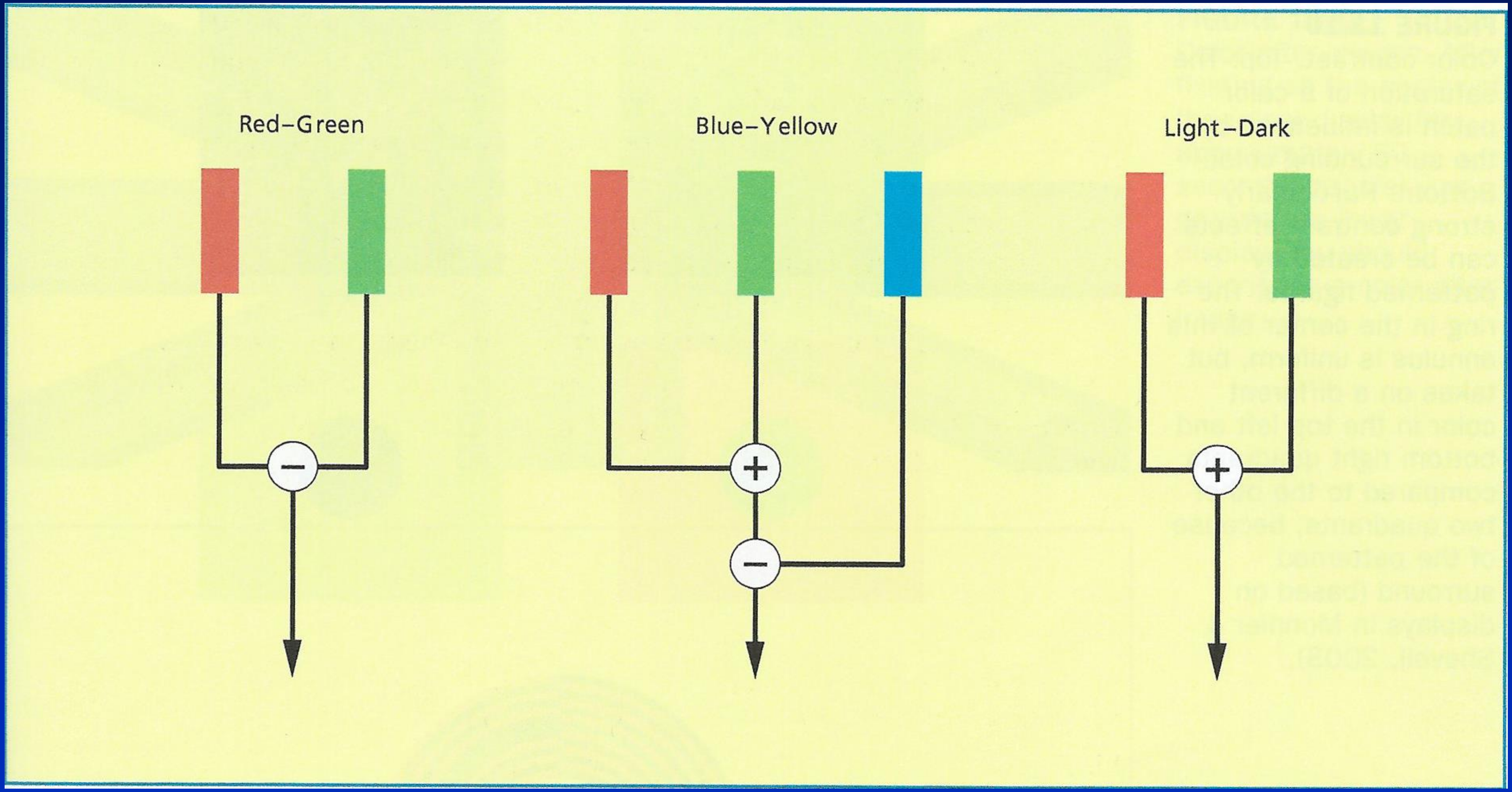


Figure 12.9– Foundations of Sensation and Perception, George Mather

Fundamentals of Human Perception

- Retina, Rods & Cones, Physiology
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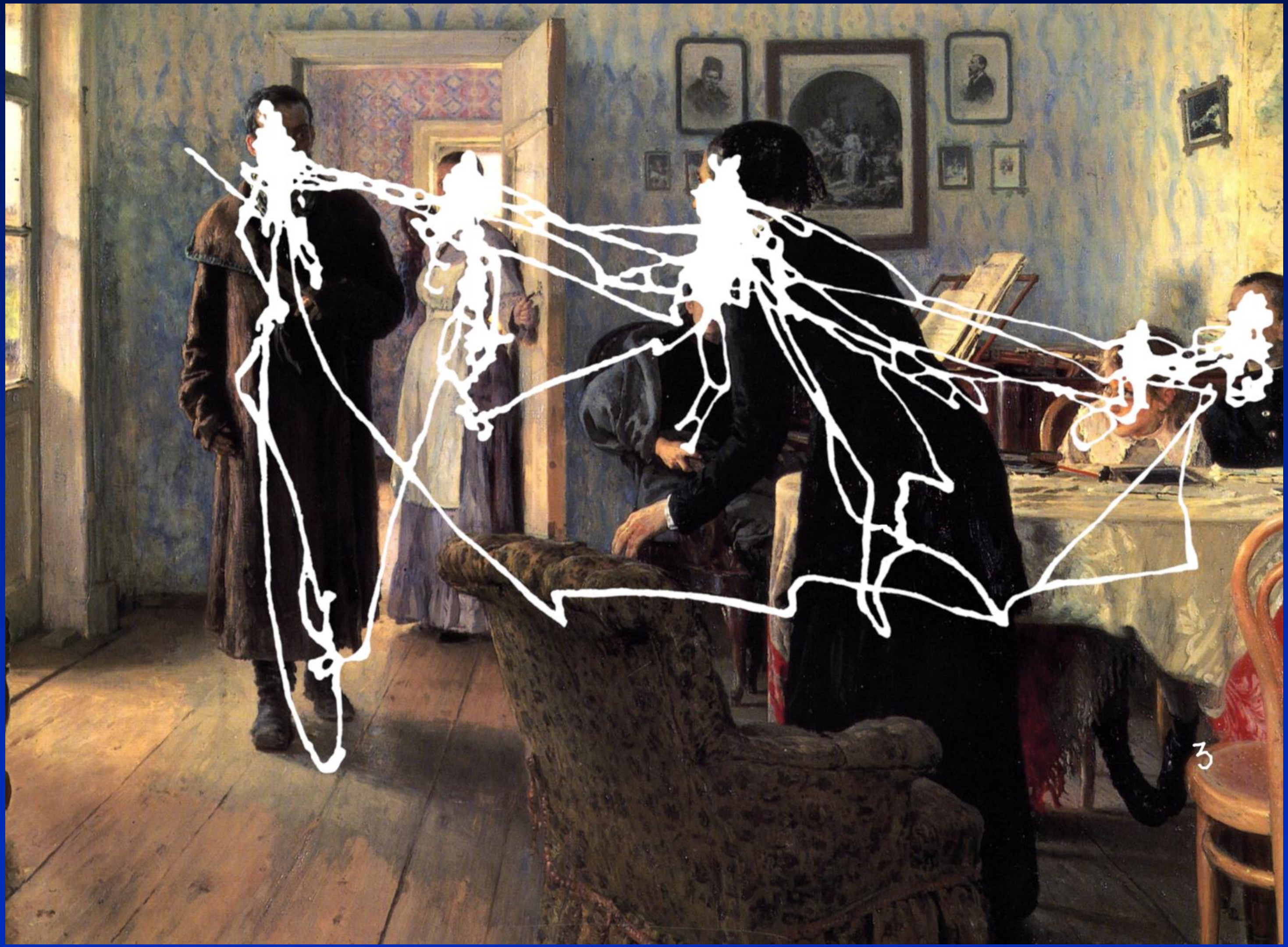
Visual Memory and History

Yarbus Heat Maps 1965

The Unexpected Visitor Ilya Repin, 1888

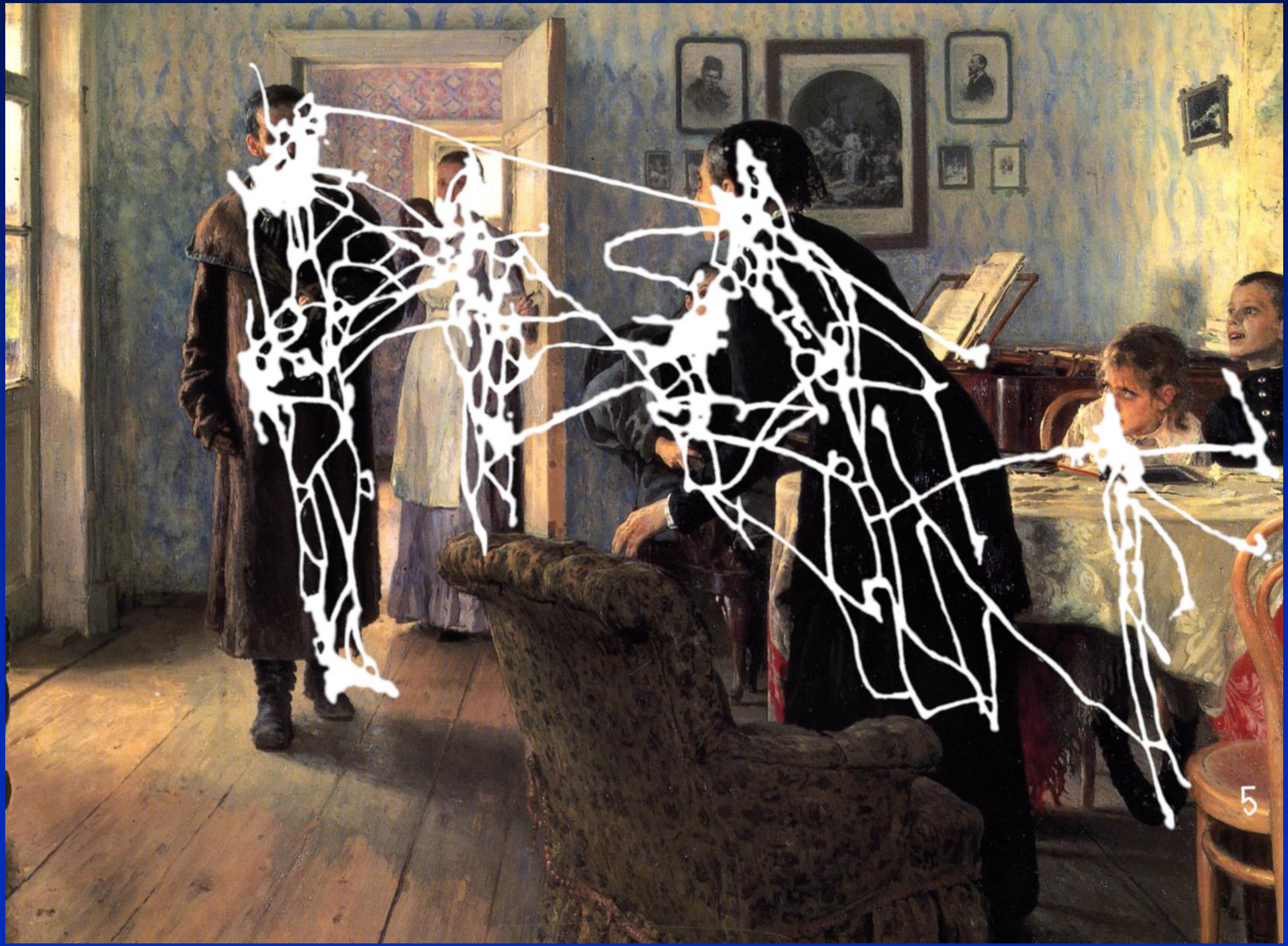
2391 x 1759

Foveal Eye Tracking



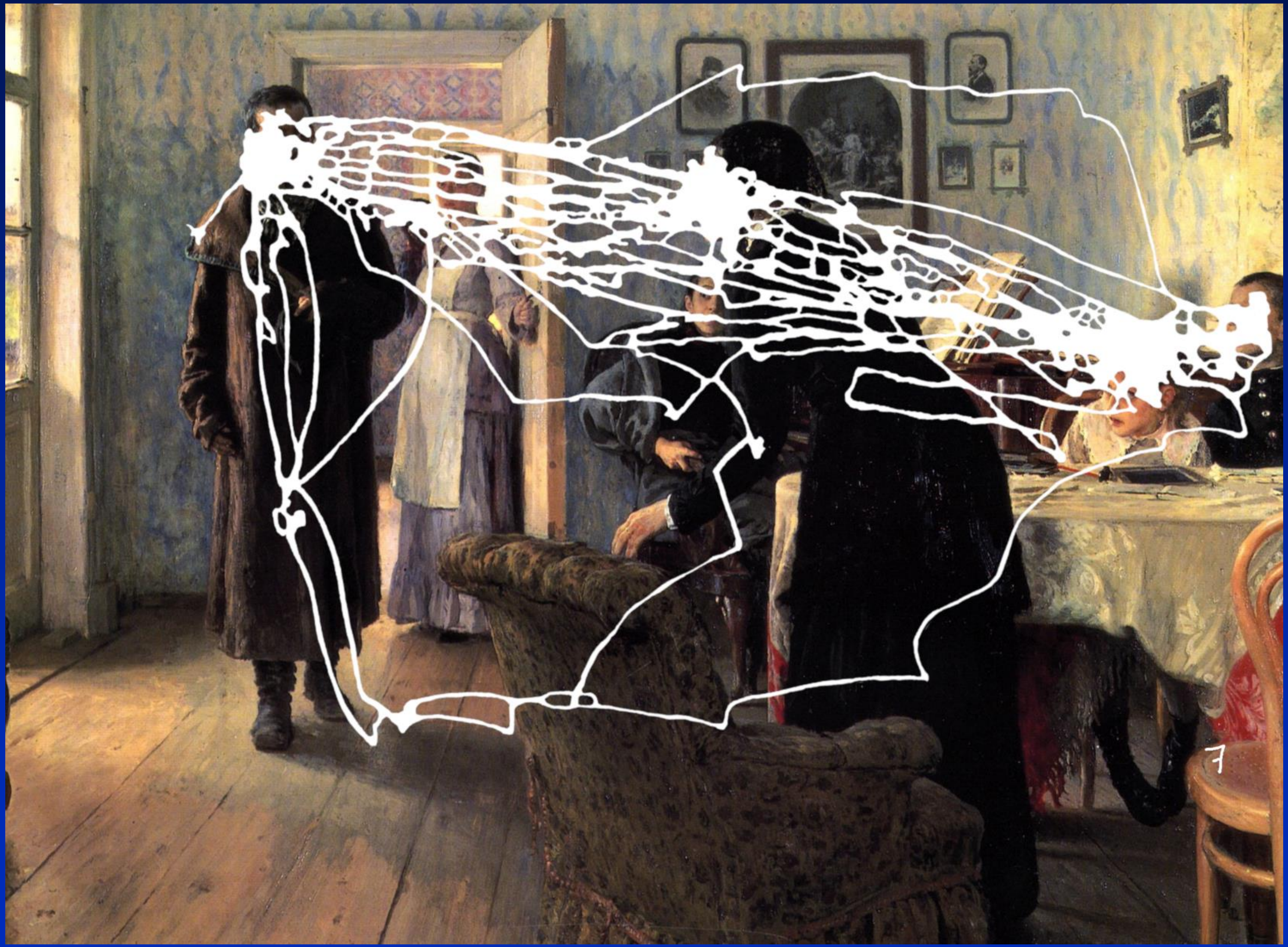
Age

Foveal Eye Tracking



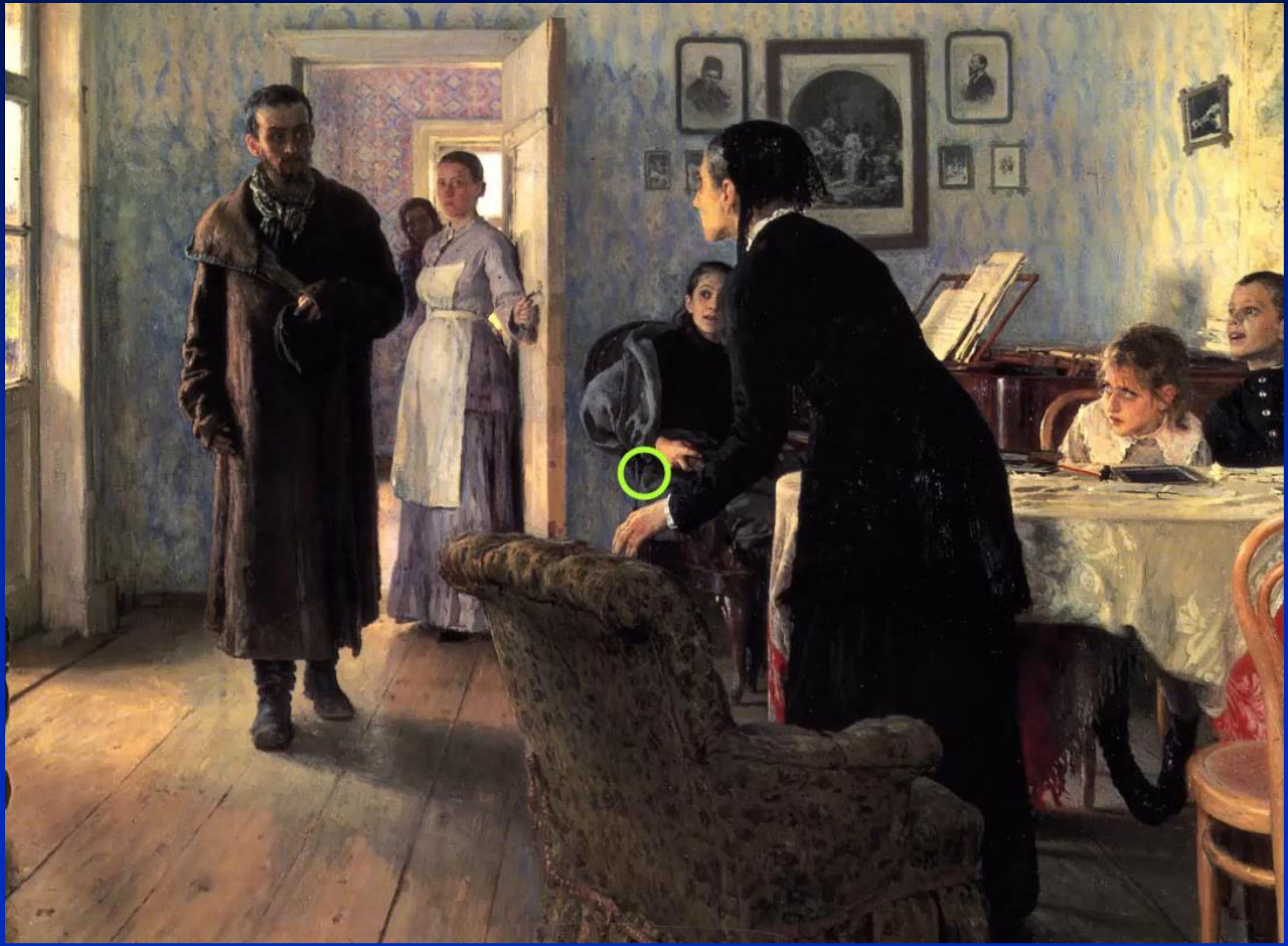
Clothes

Foveal Eye Tracking



Length of absence

Saccades Motion (length of absence)



Caravaggio

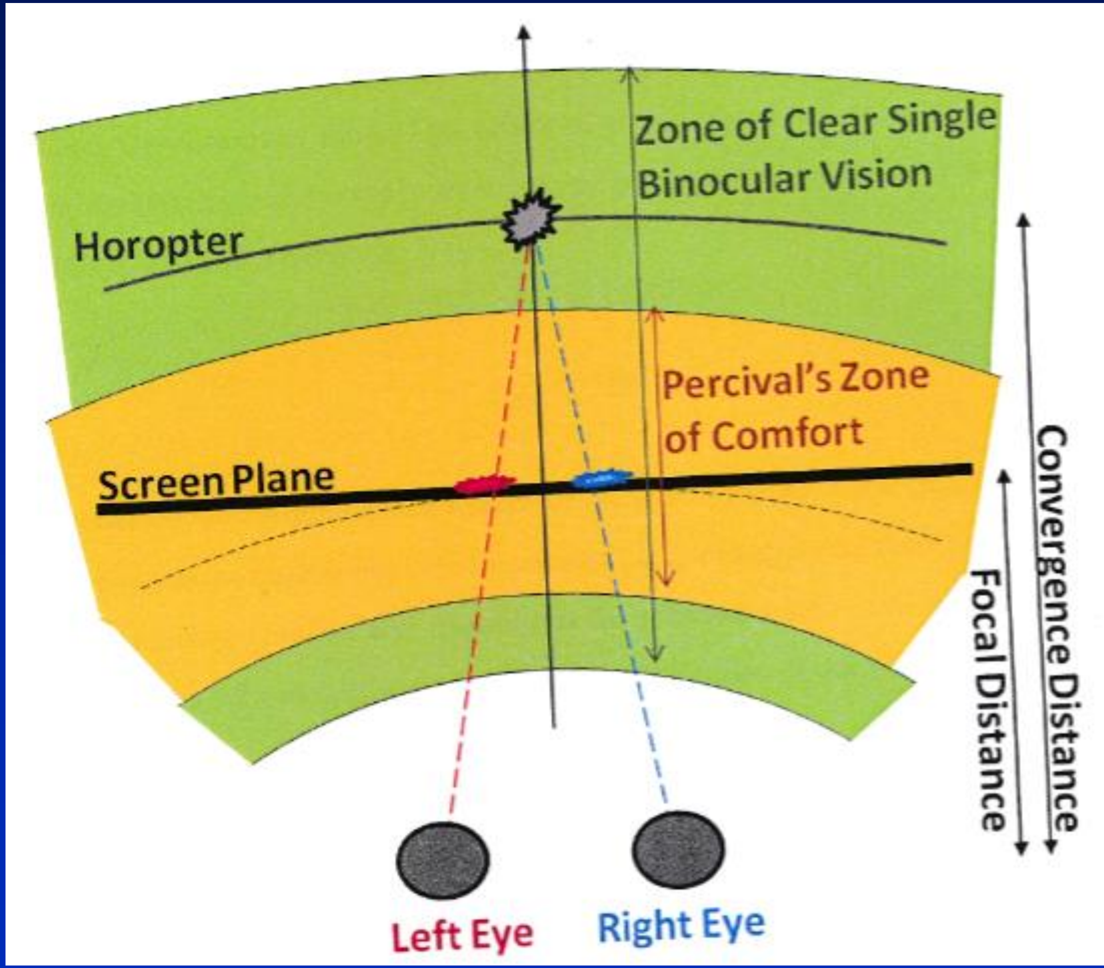
Picture exploration

Card sharps

Sensing Methods: Retinal Tracking

- Hard problem with current technologies
  - Extremely difficult to illuminate
    - Must bounce light off of retina
    - Light comes back through iris
  - Light must be extremely bright
  - Too much exposure will damage retina
- Typically done in ophthalmological setting
- Presently can only detect faint images of blood vessels, companies working on it
- Very high angular resolution, but would presently require occlusion of vision

Matt M. Low 2011

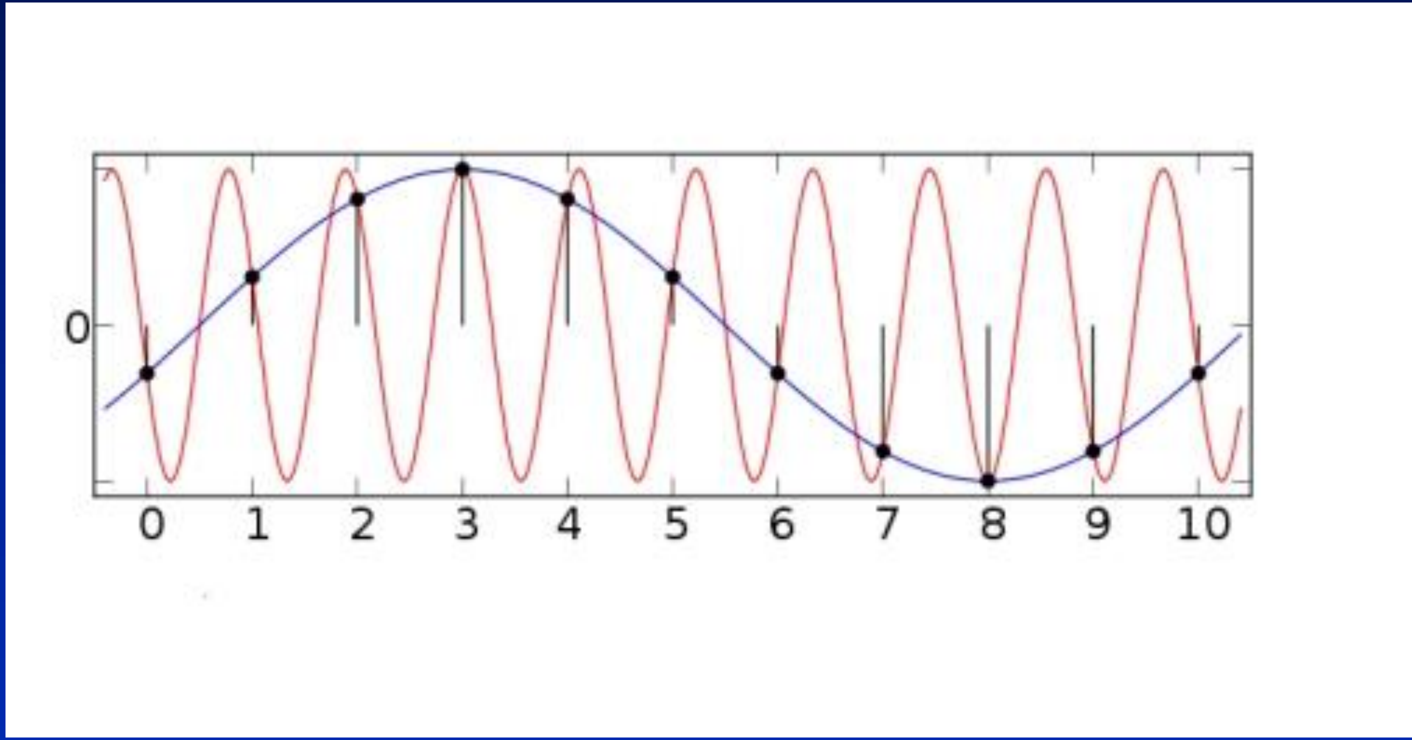


Saccadic Masking

- Visual saccadic suppression
- The brain selectively blocks visual processing during eye movements
- Neither the motion of the eye or subsequent motion blur of the image nor the time gap in visual perception is noticeable to the viewer

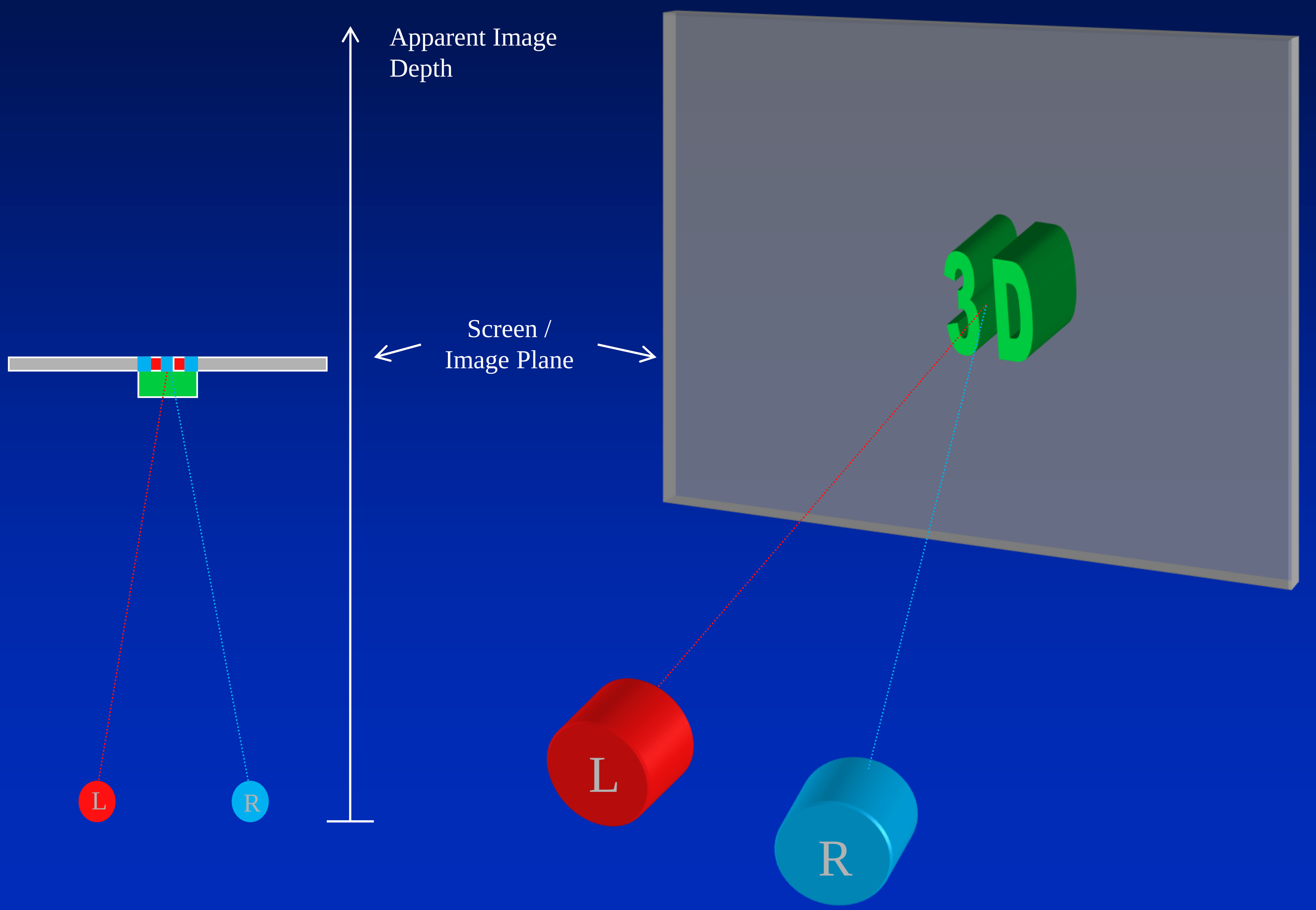
Picket Fence

Sampling Frequency

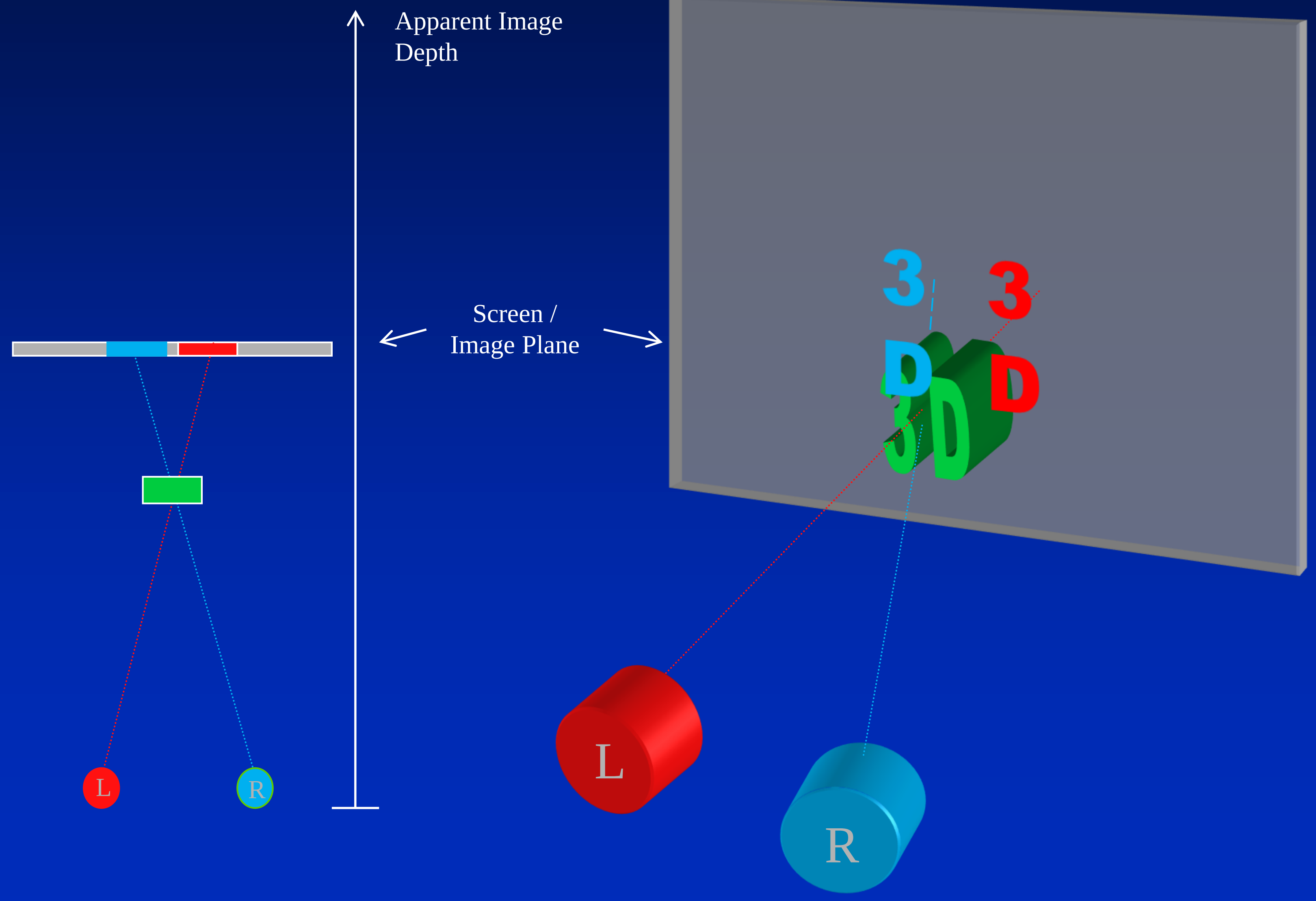


The Nyquist sampling rate states that an object must be sampled at twice its frequency to be able to reconstruct its characteristics.

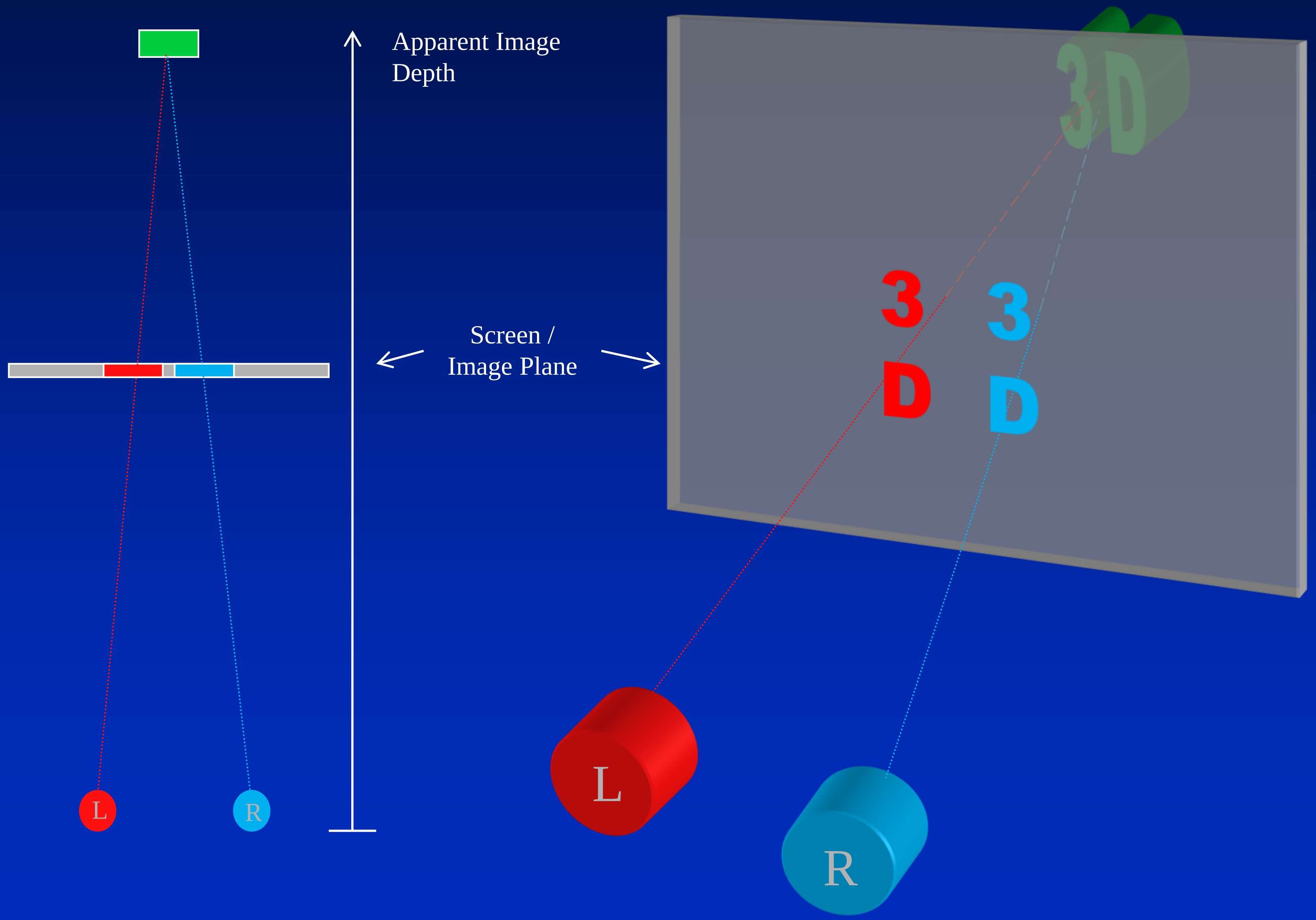
Stereoscopic Vision: At The Screen



Stereoscopic Vision: In Front Of The Screen (Convex)



Stereoscopic Vision: Behind The Screen (Concave)



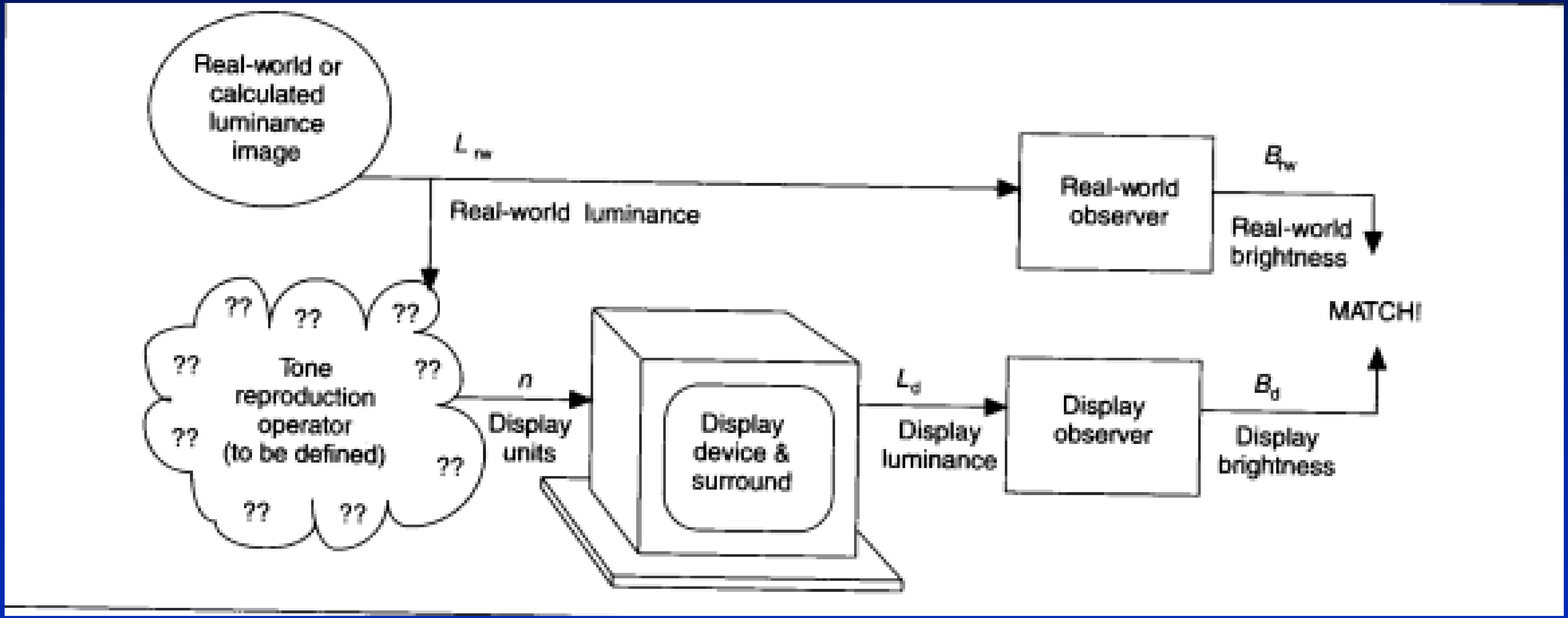
Saccadic Motion

- David H. Hubel. EYE, BRAIN, AND VISION, 1988 Scientific American Books, Inc. p. 80.

Saccadic Motion

- David H. Hubel. EYE, BRAIN, AND VISION, 1988 Scientific American Books, Inc. p. 80.

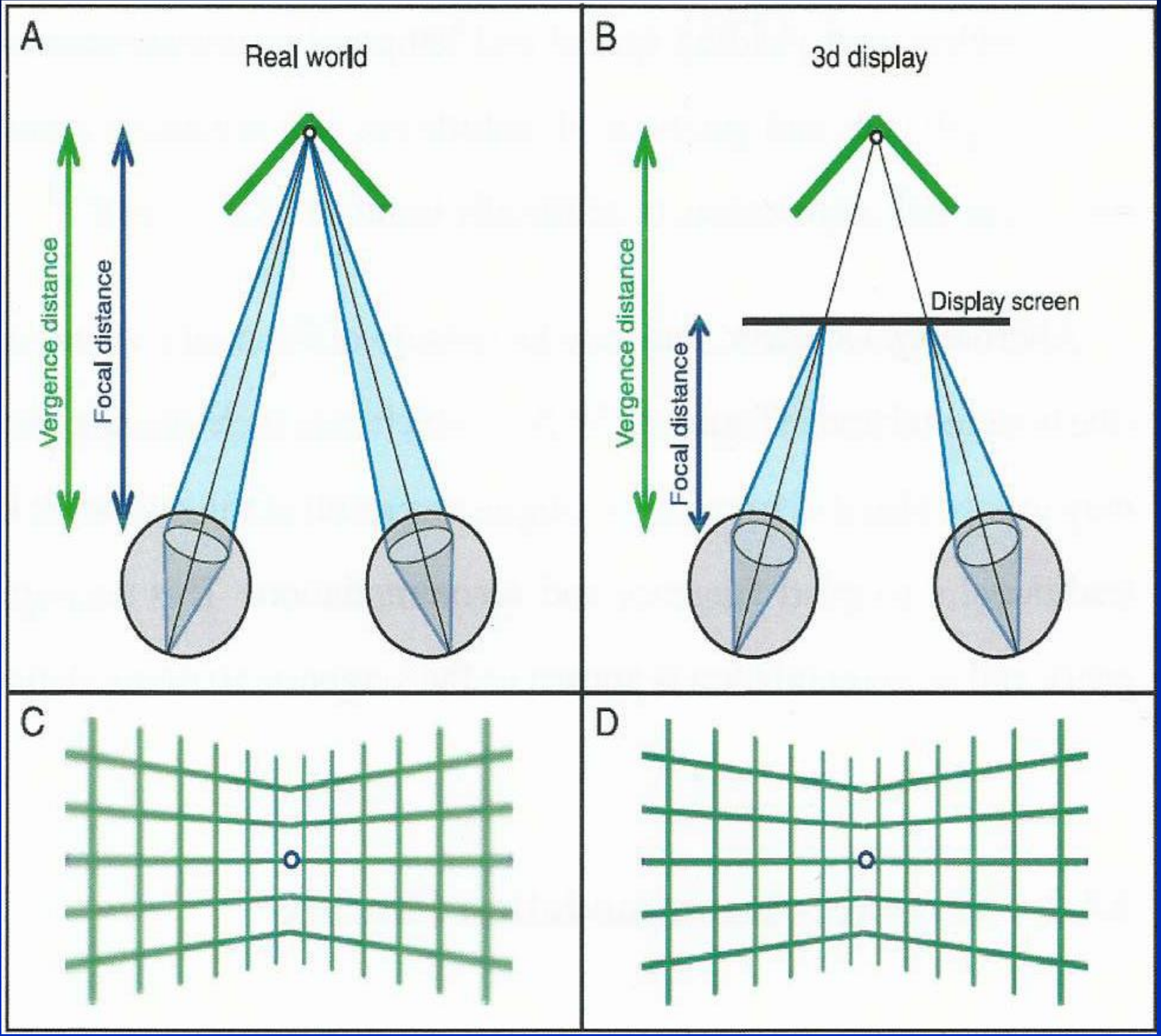
From Real World to Display



Tumblin, Jack & Rushmeier, Holly. (1993). Tone Reproduction for Realistic Images. Computer Graphics and Applications, IEEE. 13. 42-48. 10.1109/38.252554.

Light as Rays, Waves and Photons

Vergence – Accommodation Conflict



Vergence – Accommodation Conflict