NYU

Virtual and Augmented Reality

CS-GY 9223/CUSP-GX 6004

https://nyu-icl.github.io/courses/2022fall-vr-ar

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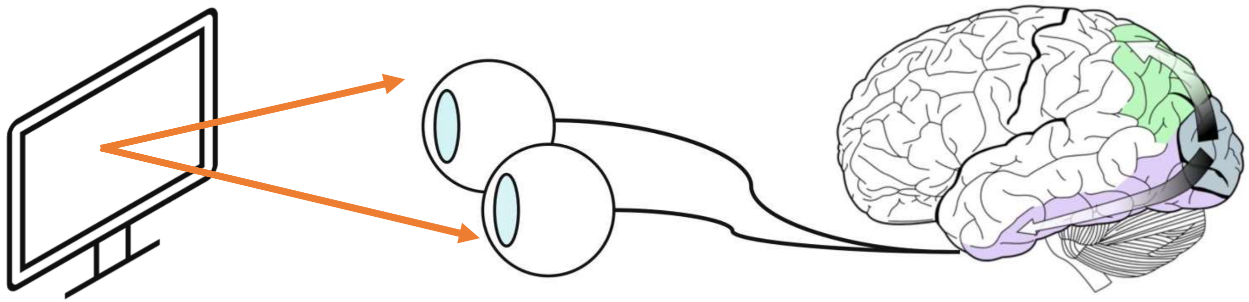
Logistics

- Everyone gets a Google Cardboard
- Tutorial/workshop today
- Assignment 1 recap

The Human Visual System

- **visual field**: ~200°monocular, ~120°binocular, ~135°vertical
- **visual acuity**: 20/20 is ~1 arc min; varies over retina
- **depth cues** in 3D displays: disparity, vergence, accommodation, blur, …
  - **accommodation range**: ~8cm to ∞, degrades with age
- **temporal resolution**: ~60 Hz (depends on contrast, luminance)
- **temporal behaviors:** saccade, pursuit, etc



Anatomy

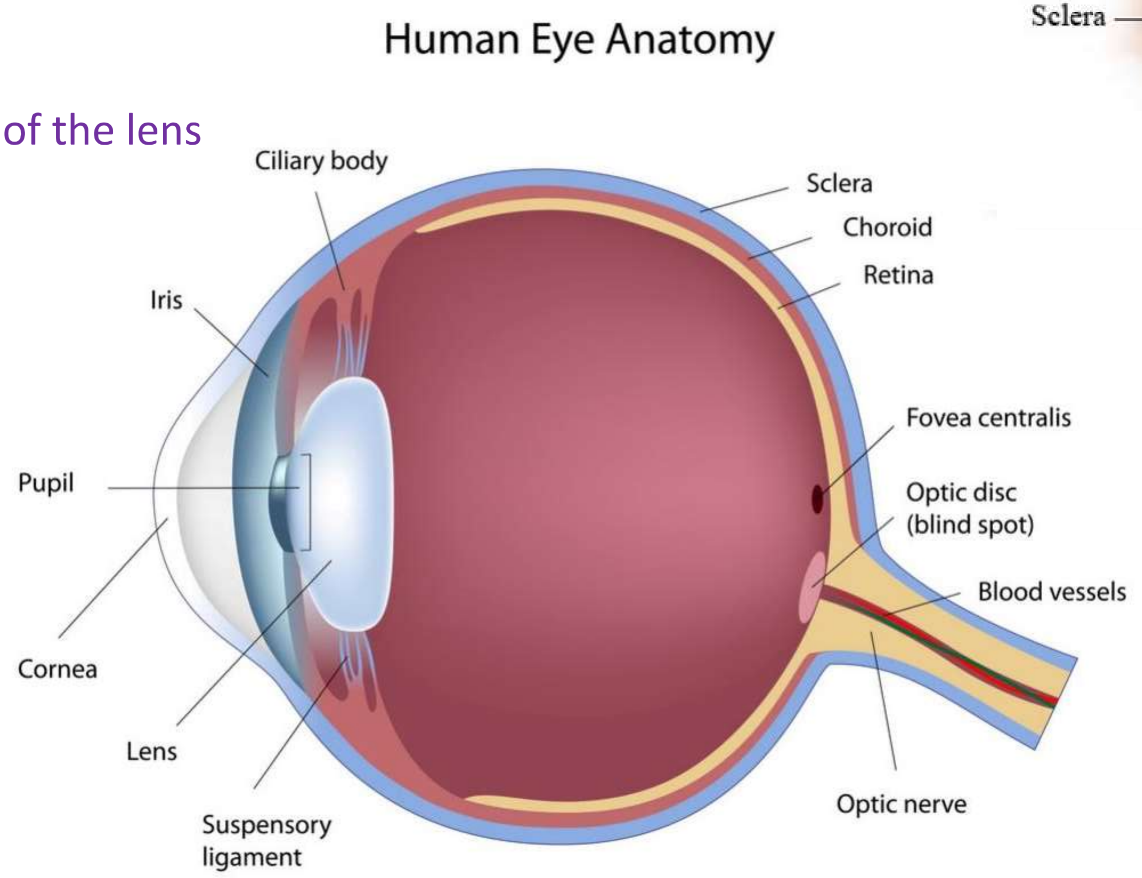
The Human Visual System

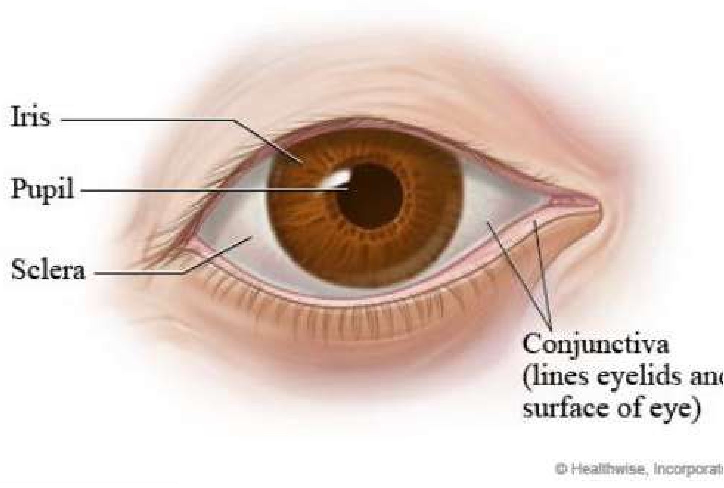
Control the focal length of the lens

Control the pupil size

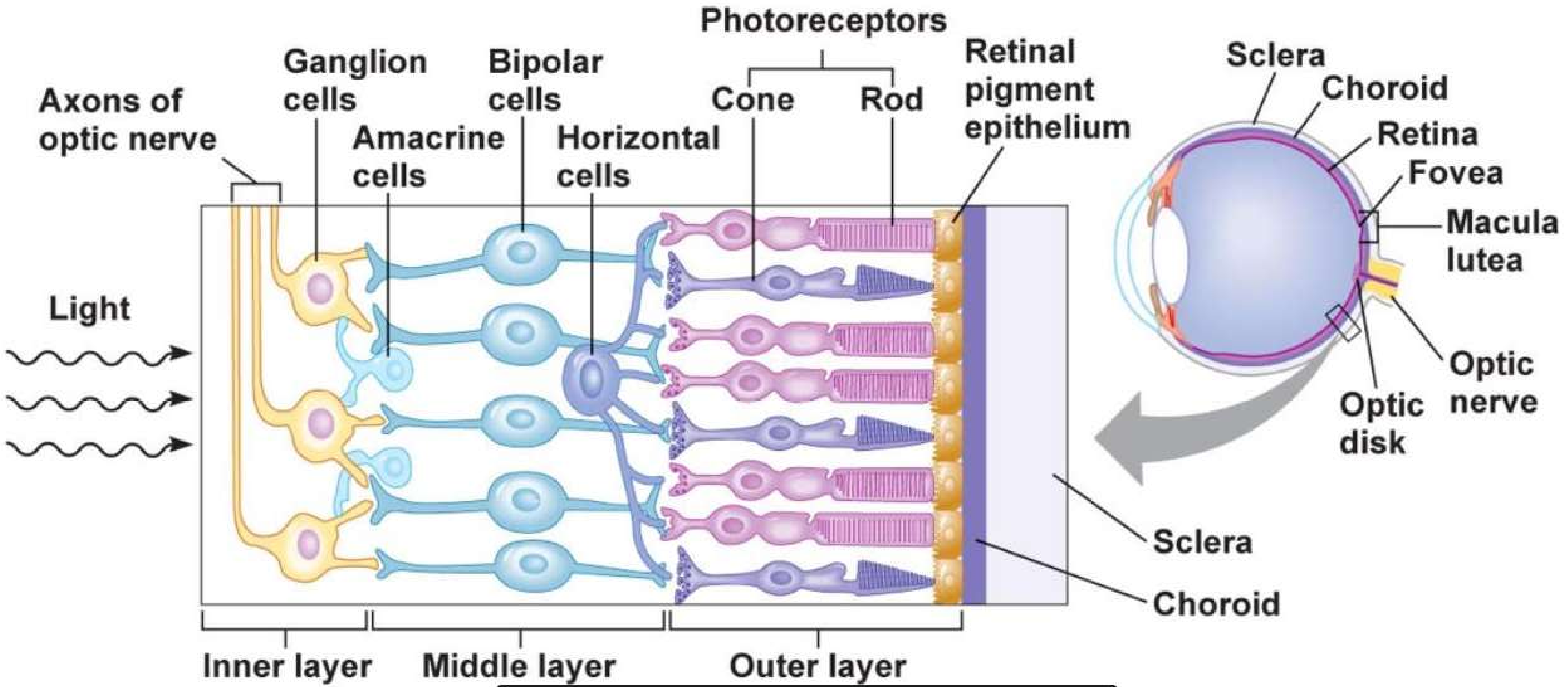
Where the light enters

Focus the light





The Human Visual System



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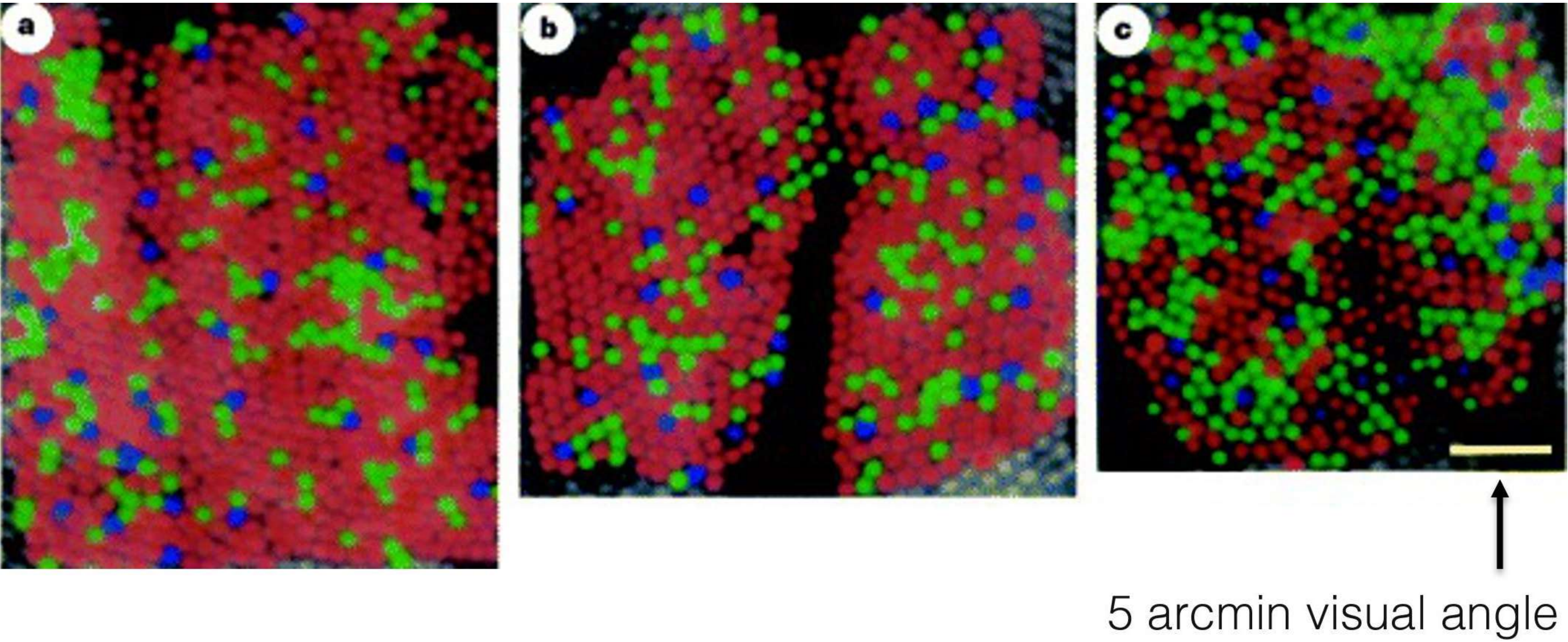
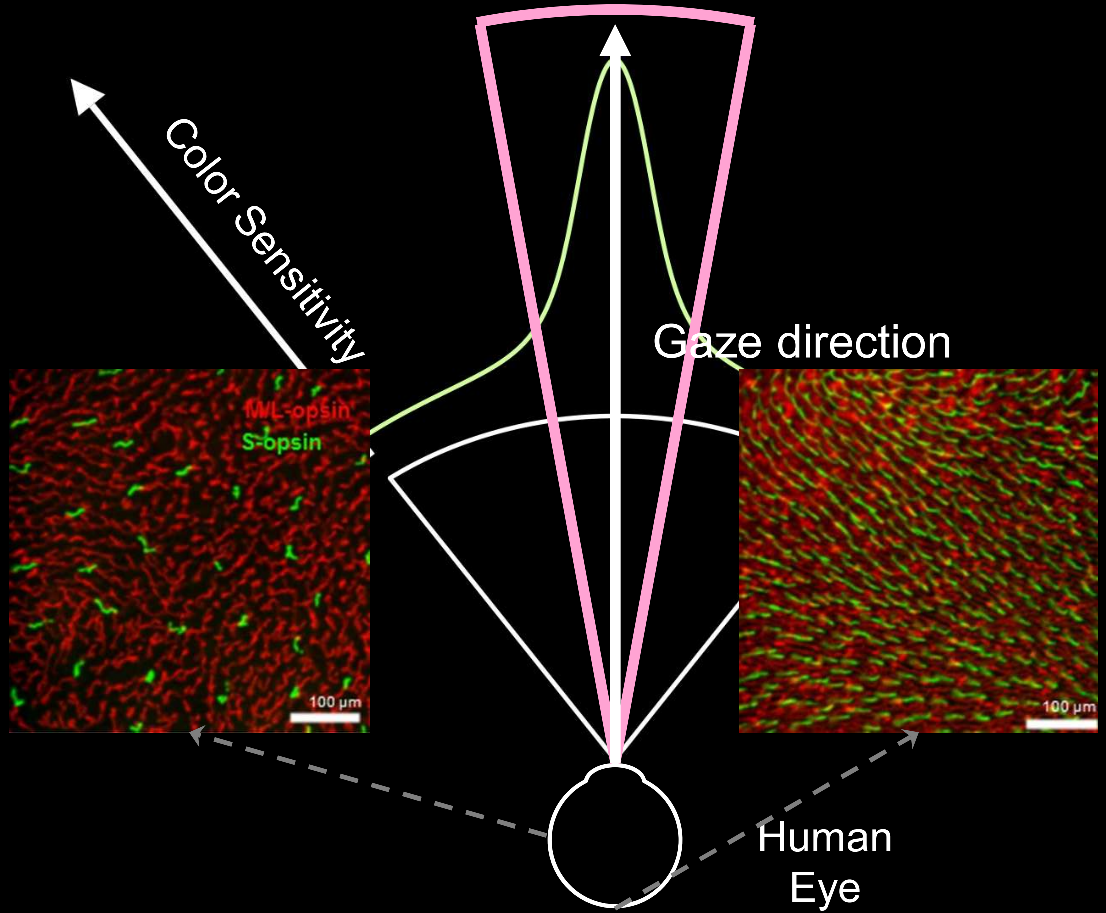
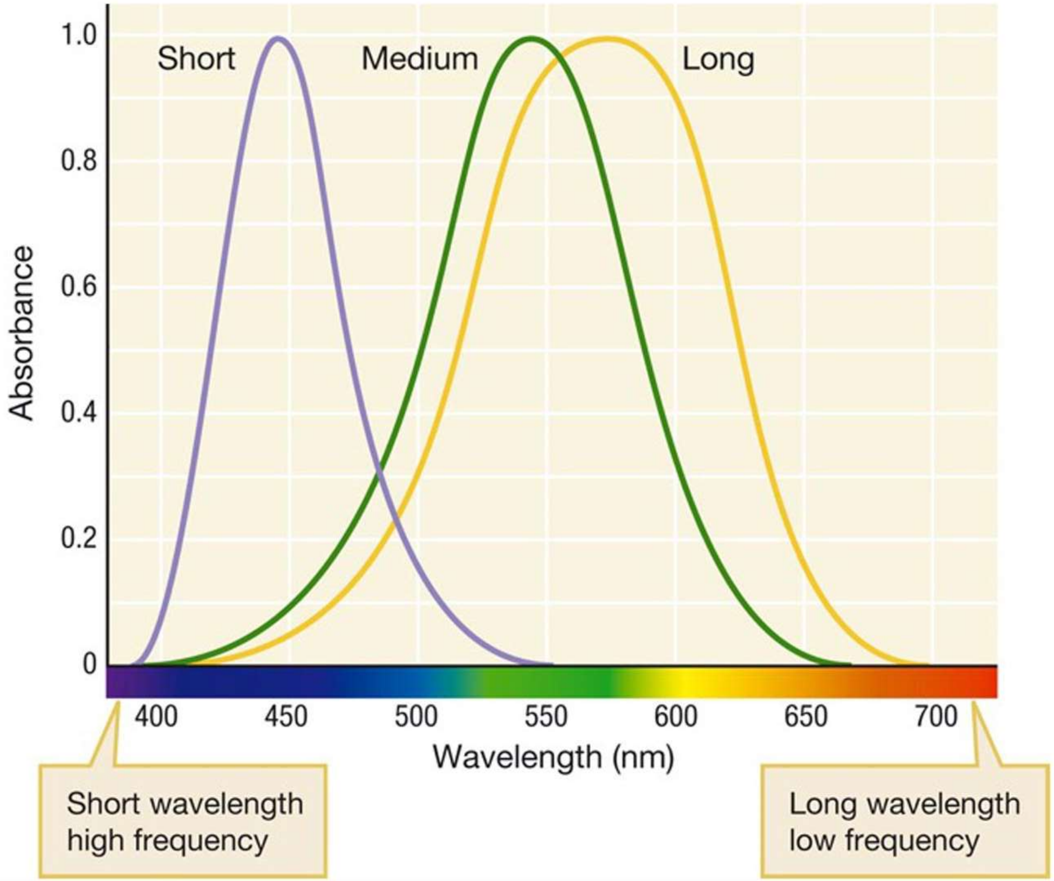
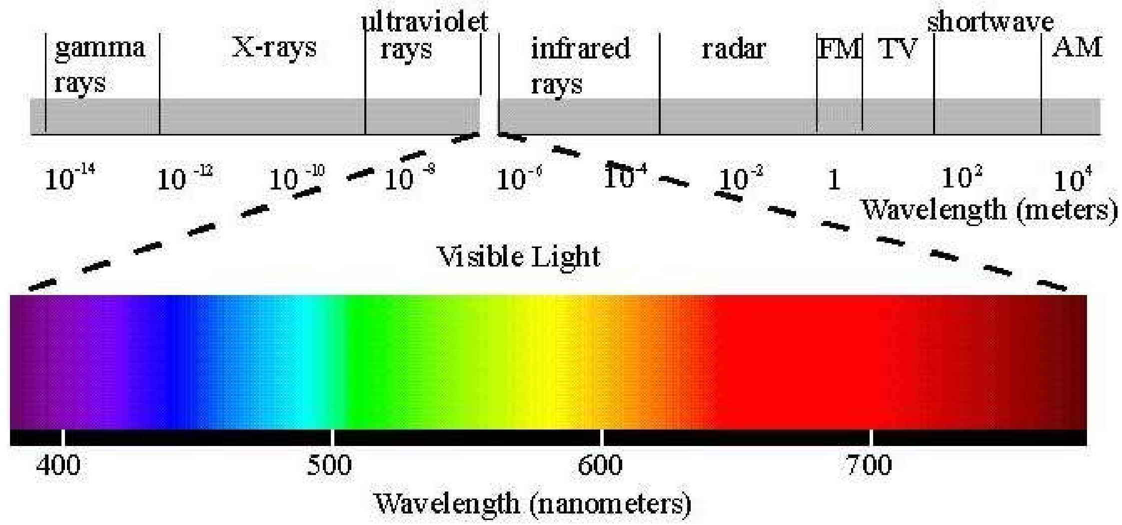




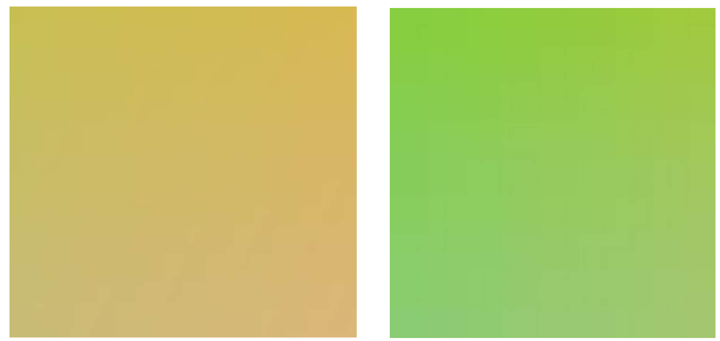
Color-Perception-Guided Display Power Reduction for Virtual Reality
Budmonde Duinkharjav et al., ACM ToG (SIGGRAPH Asia 2022)

The Human Visual System





Perceptual Color Space



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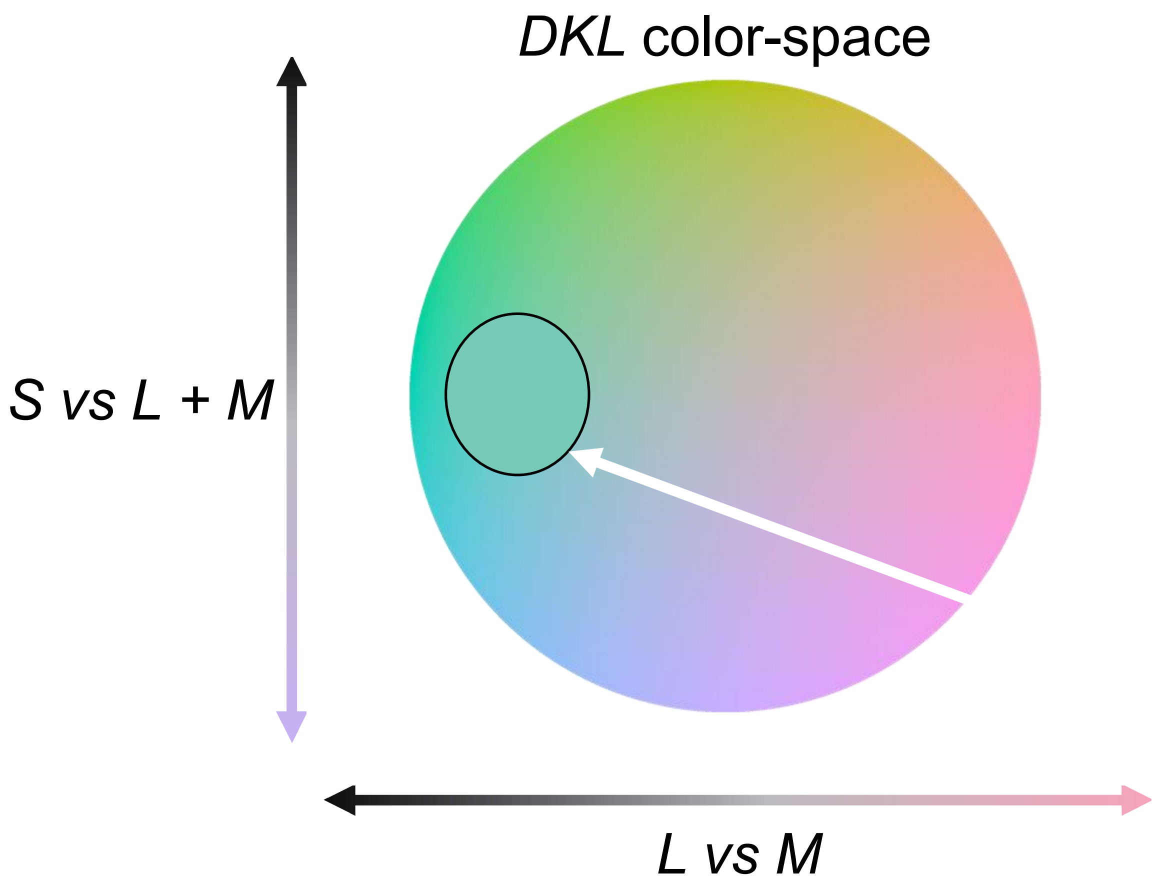
Perceptual Color Space – Opponency Theory



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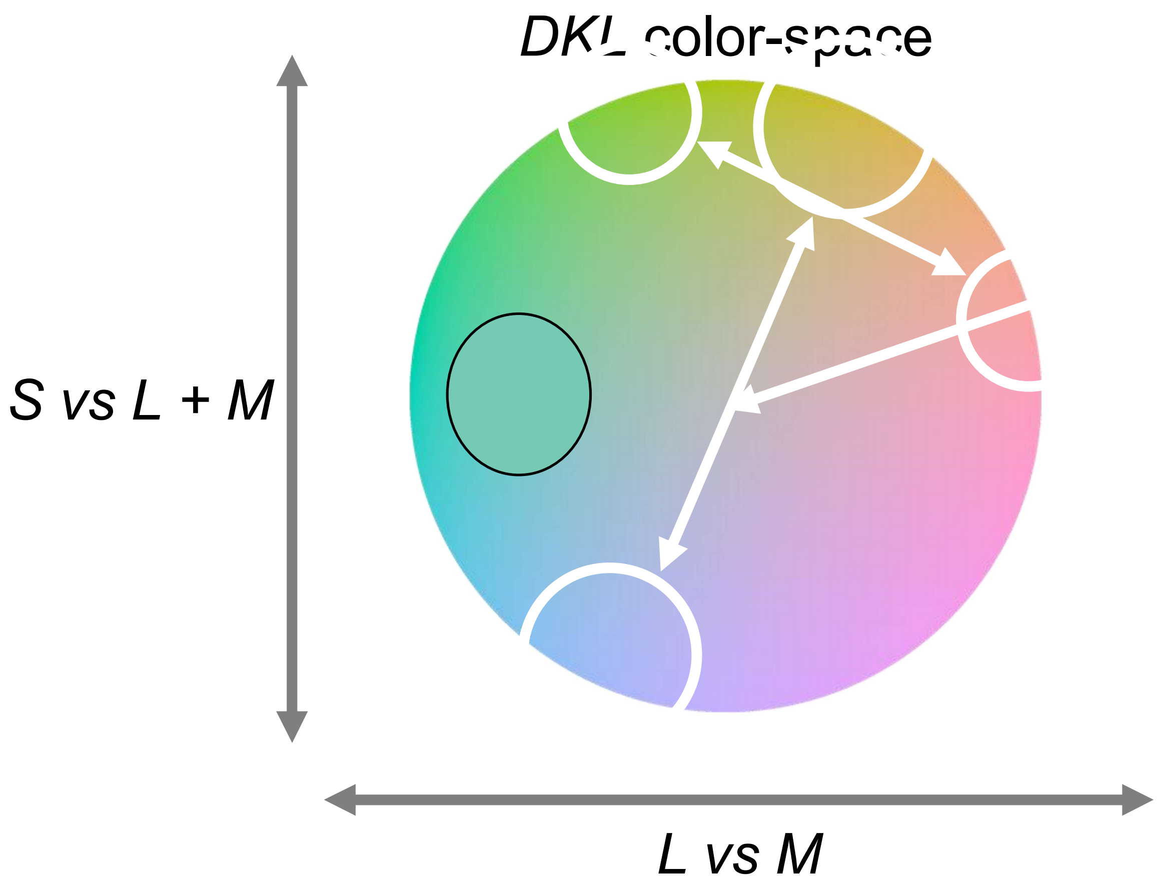
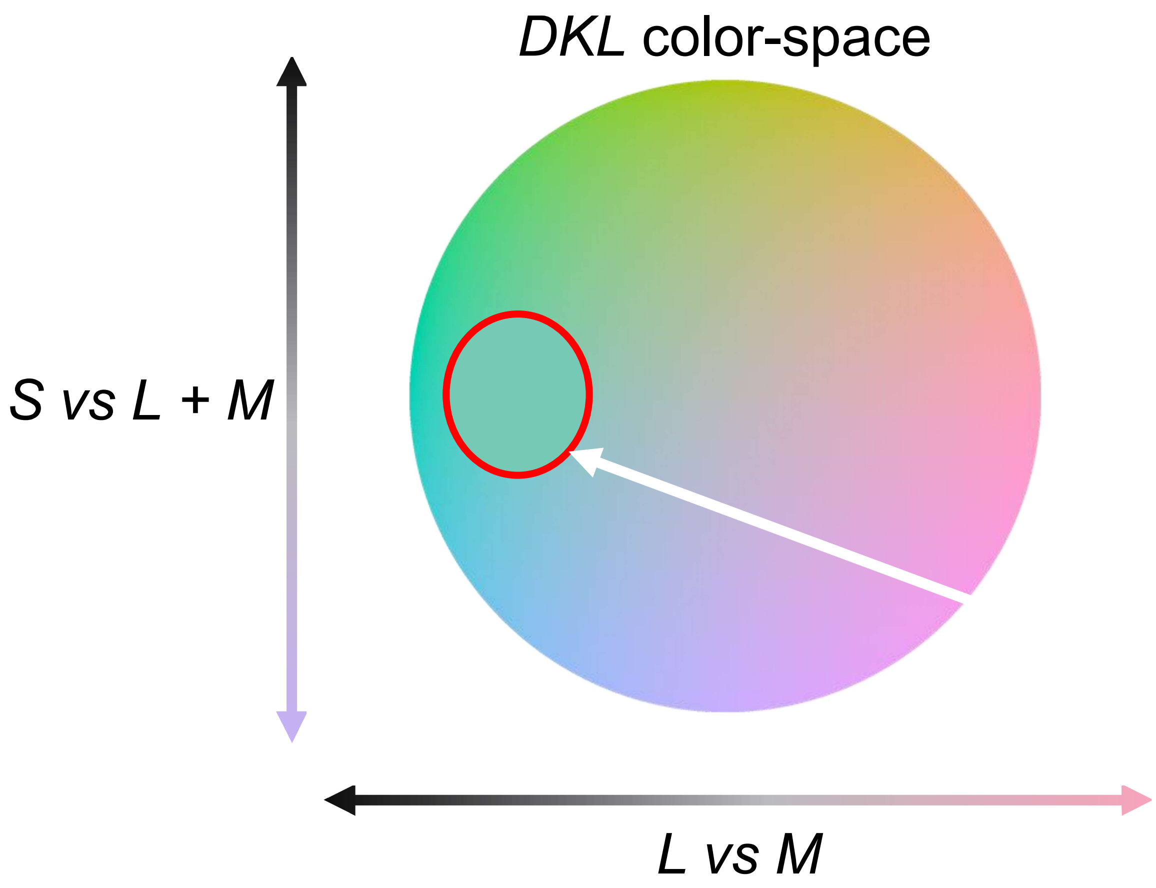
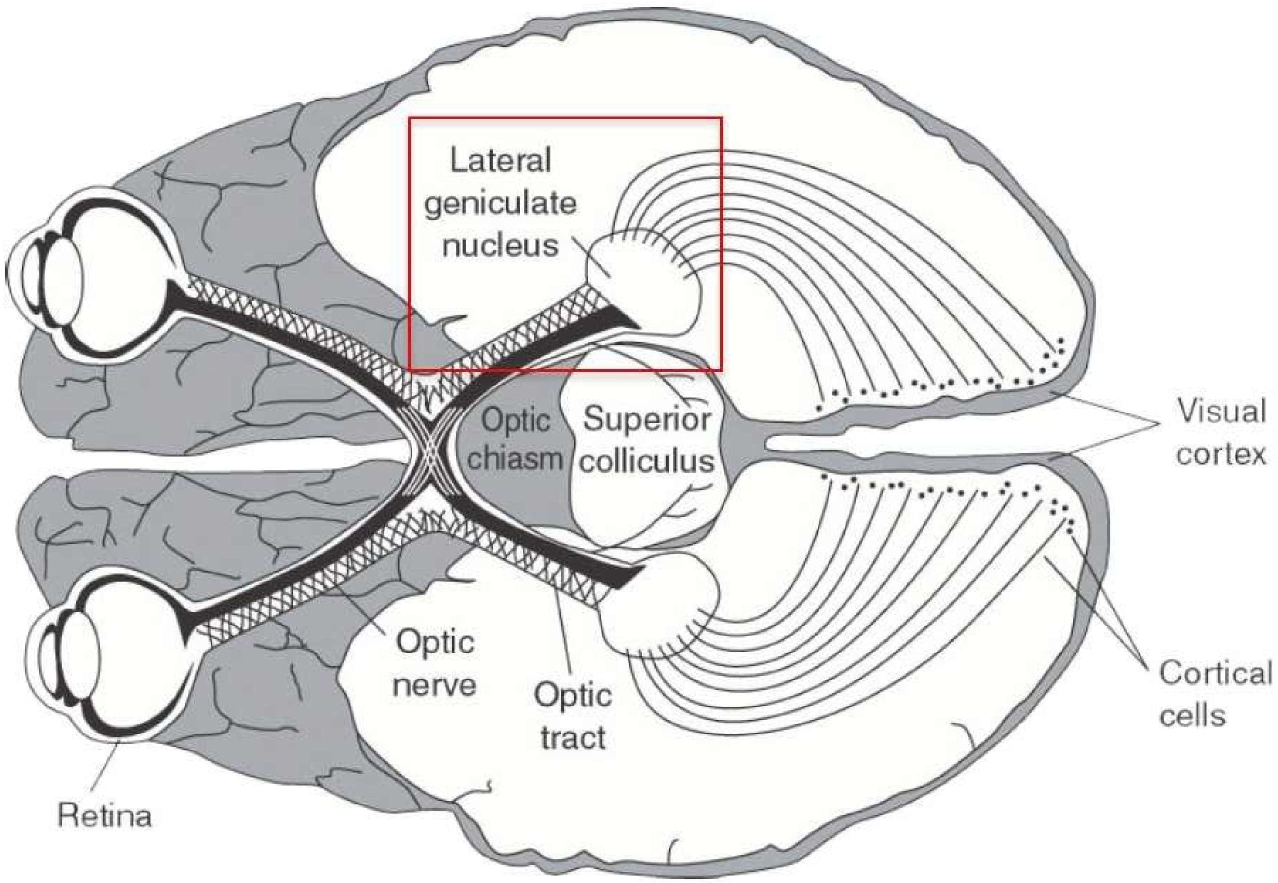


Neutral Gray

Perceptual Color Space – Opponency Theory



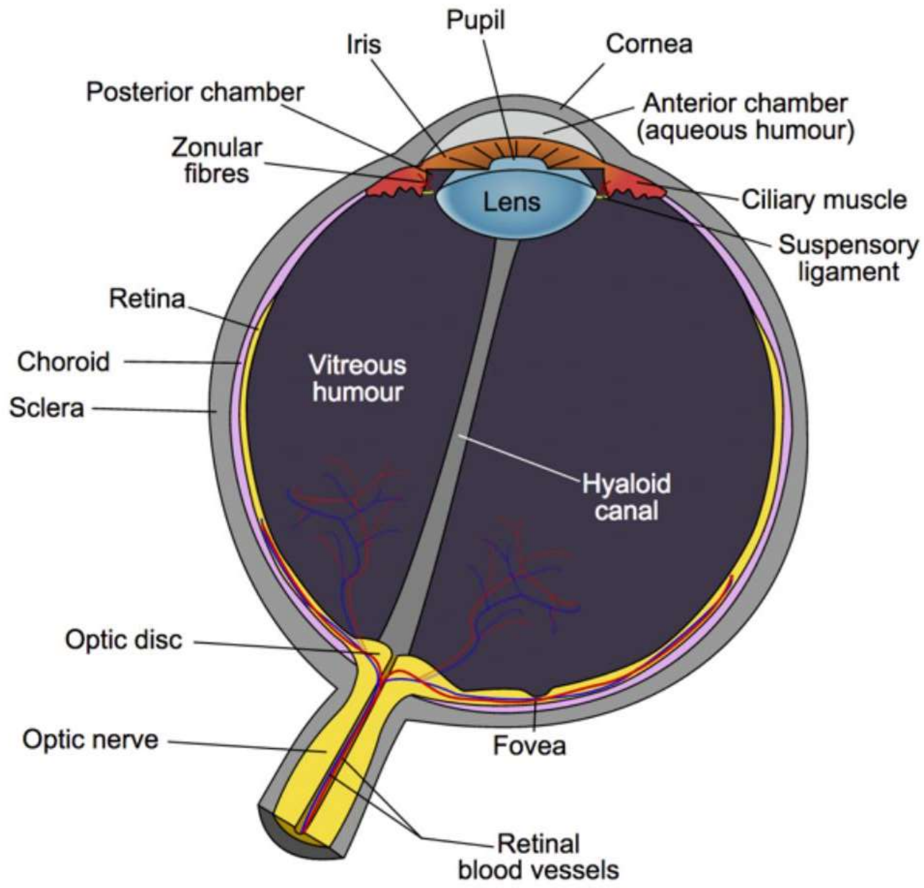
The Brain



Lateral geniculate nucleus
Optic chiasm
Superior colliculus
Visual cortex
Cortical cells
Optic nerve
Optic tract
Retina

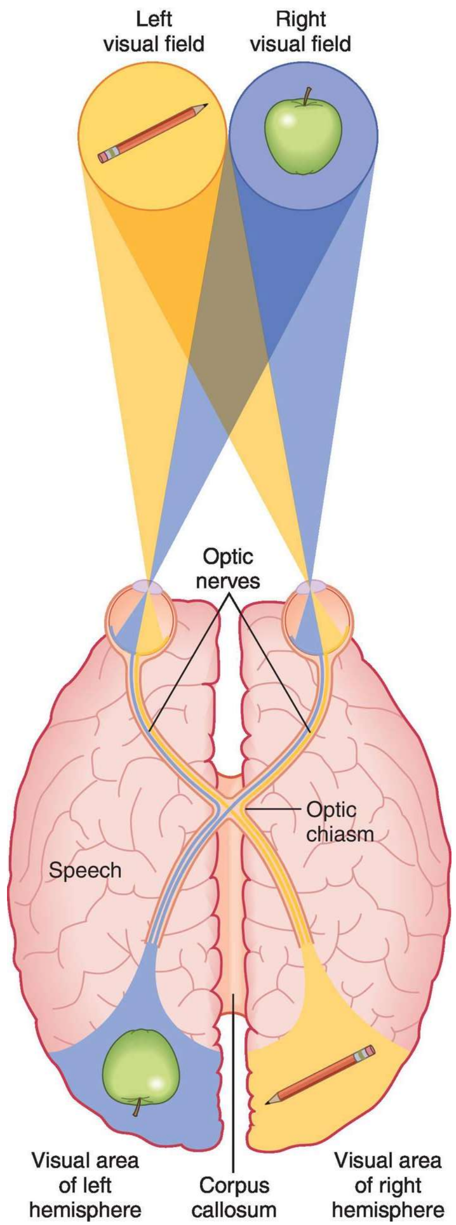
Overview

- Visual field
- Visual acuity
- Depth cue
- Temporal behaviors/perceptic

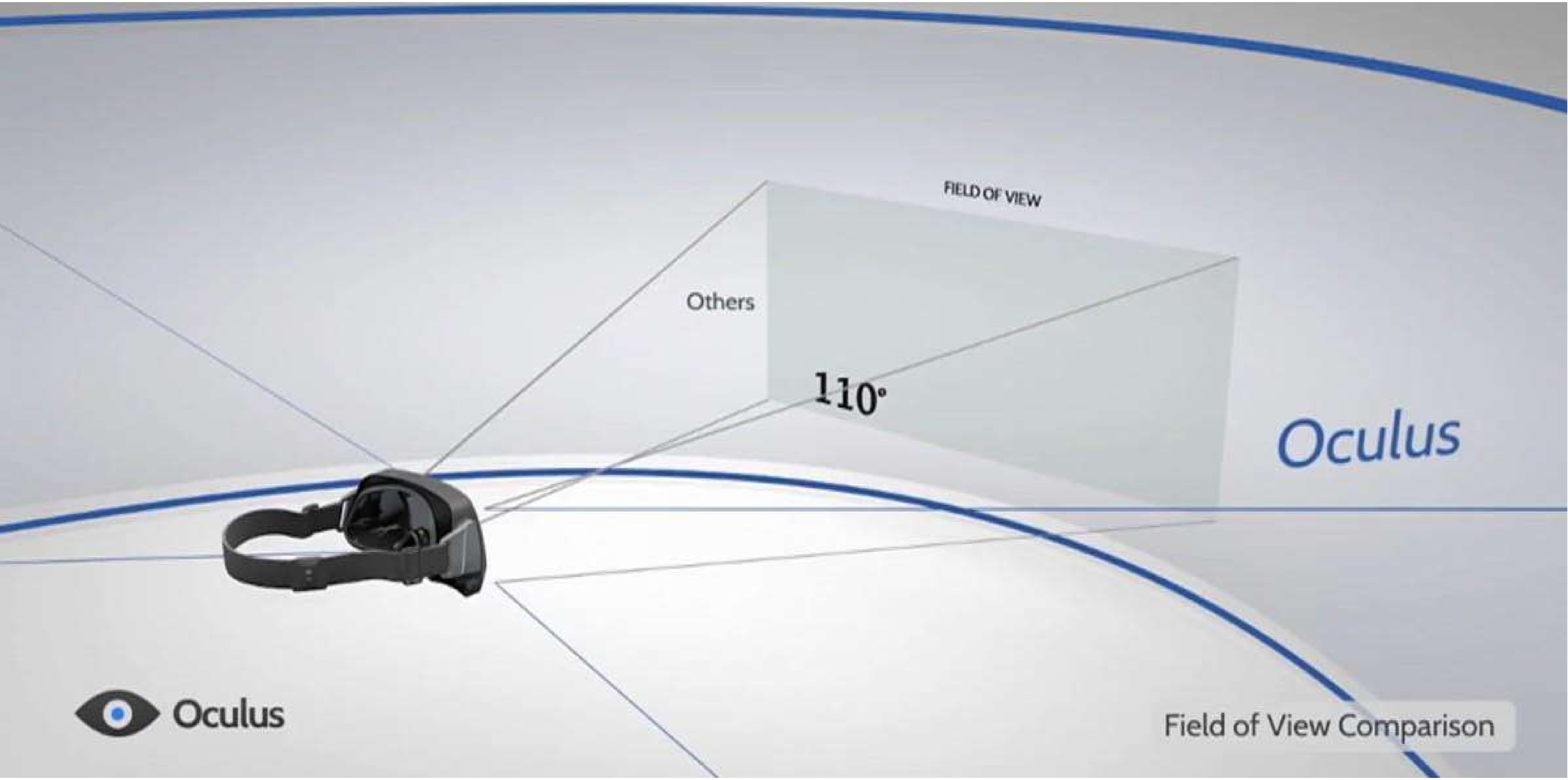


Visual Field

Field of View (FoV)



Immersive VR – How Important is the FOV?



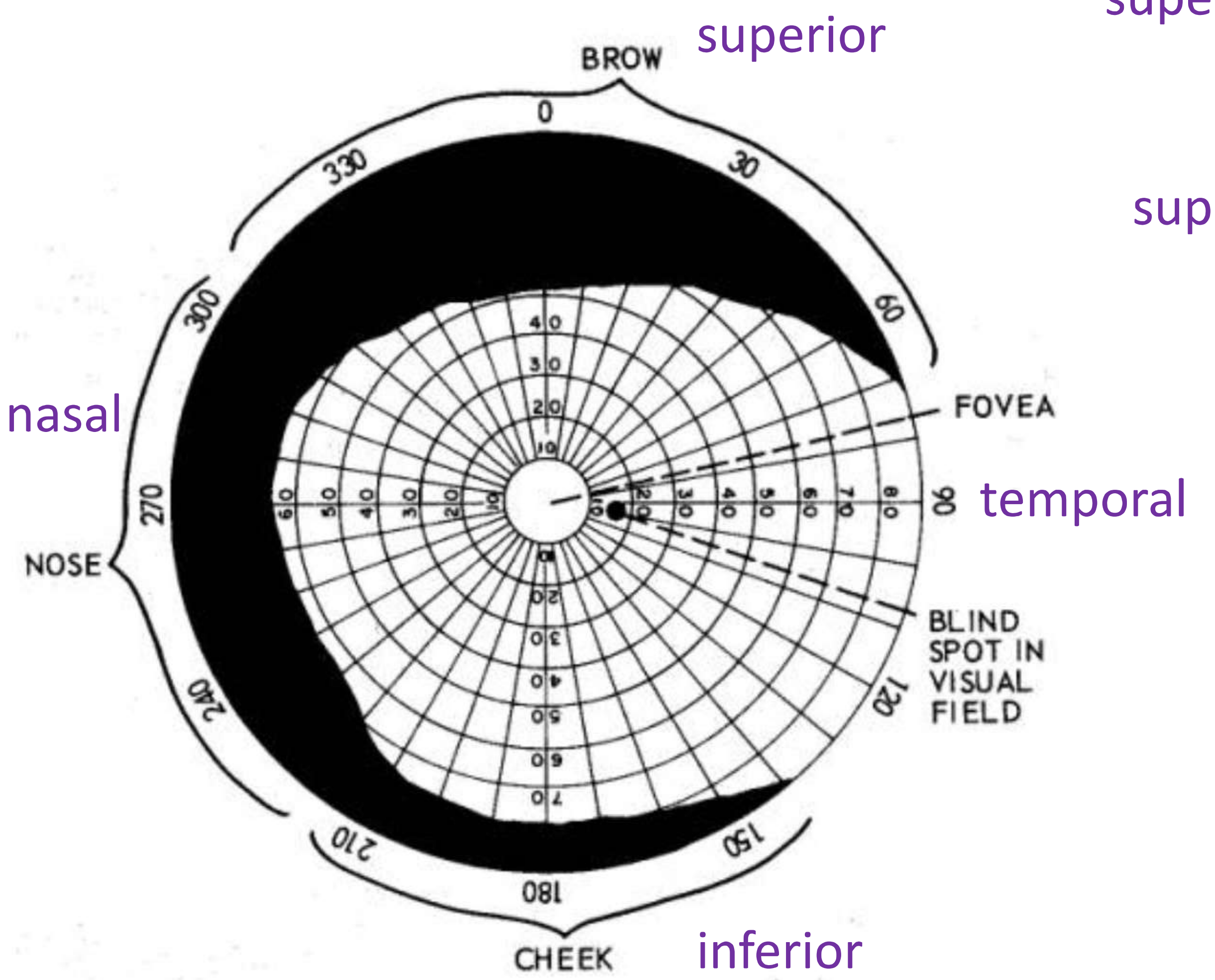
Visual Field - Terminology

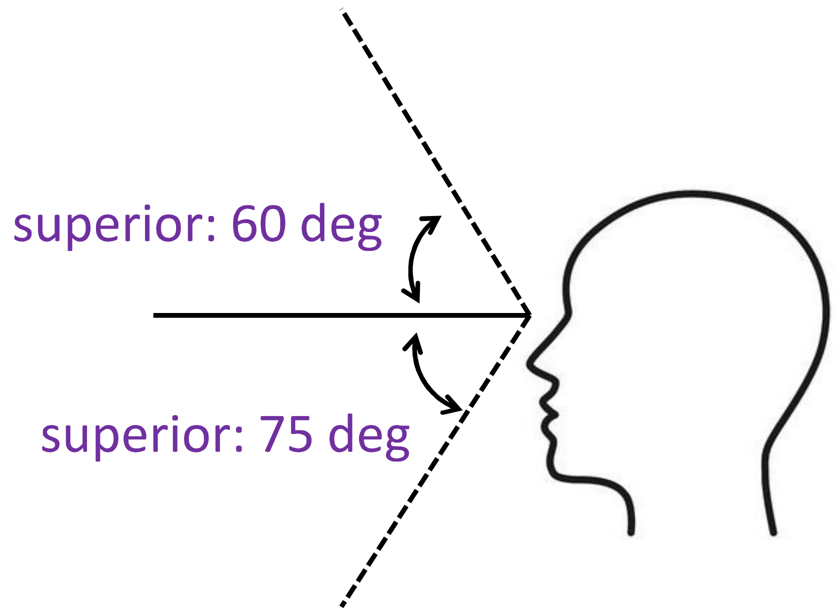
- monocular visual field: visual field of either only the left or right eye

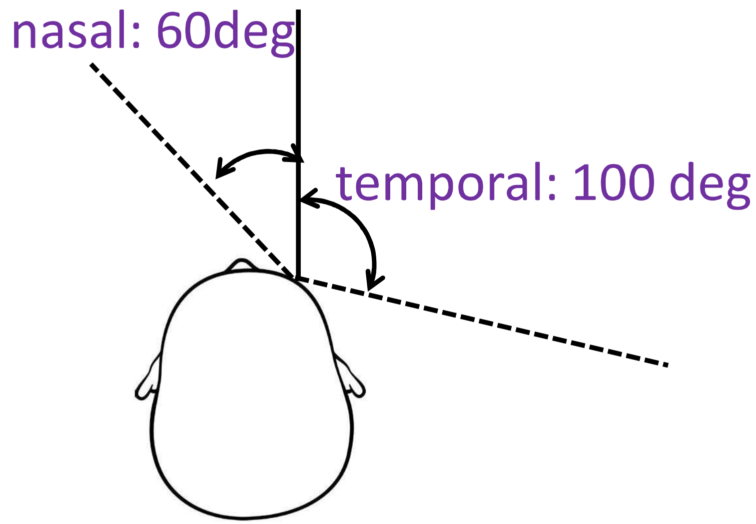
- binocular visual field or region of binocular overlap: intersection of monocular visual fields, i.e. only the overlapping part of both eyes – this is where we see stereo!

- total visual field: union of monocular visual fields, i.e. visual fields of both eyes combined – not all of this is stereo, temporal peripheries are mono!

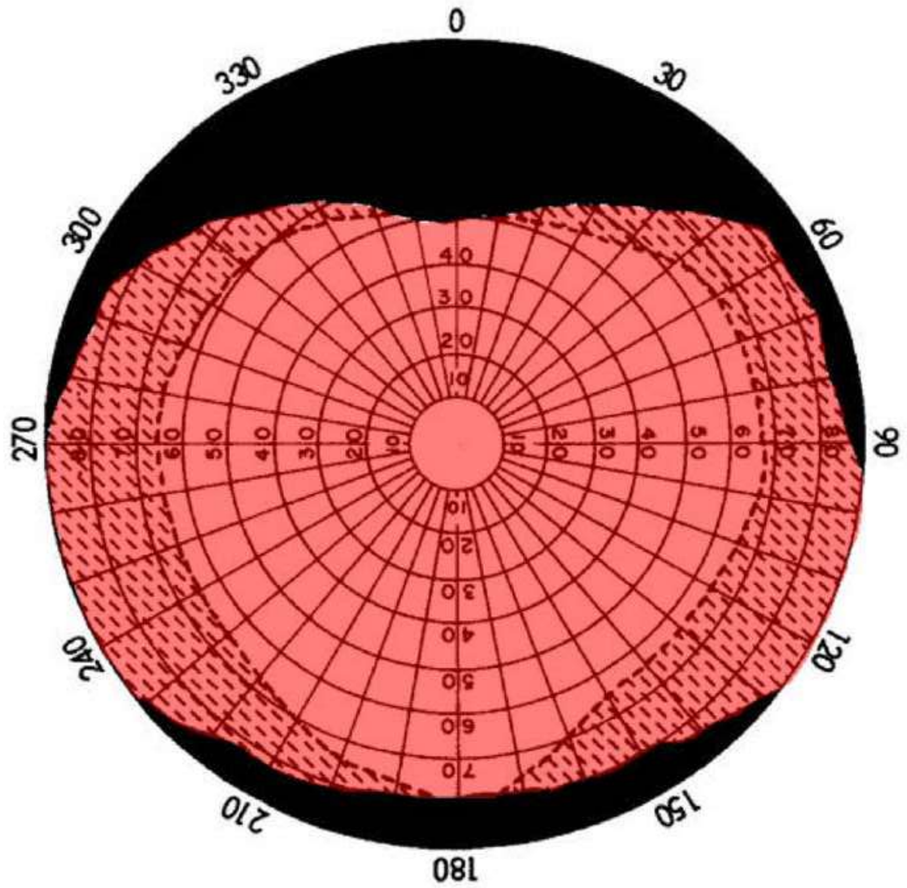
Visual Field

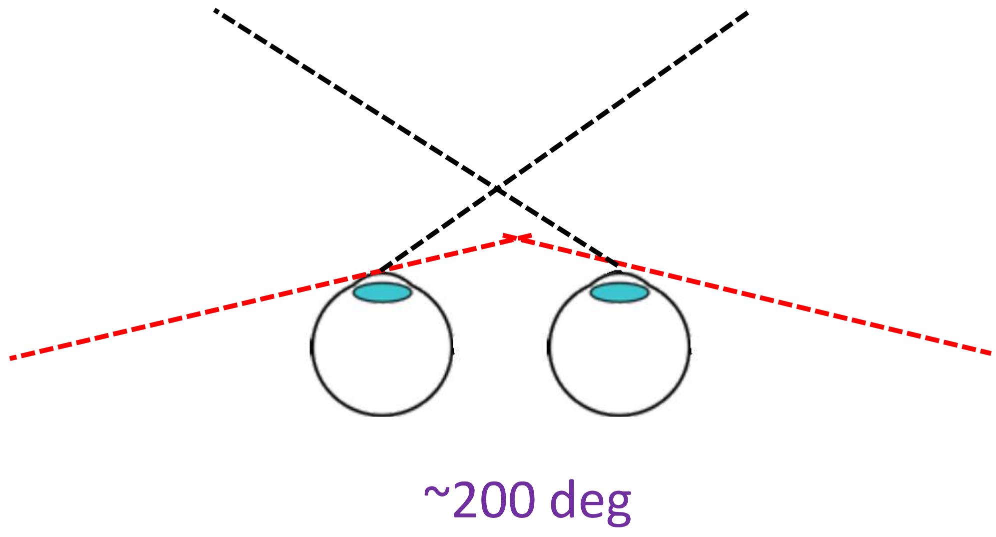




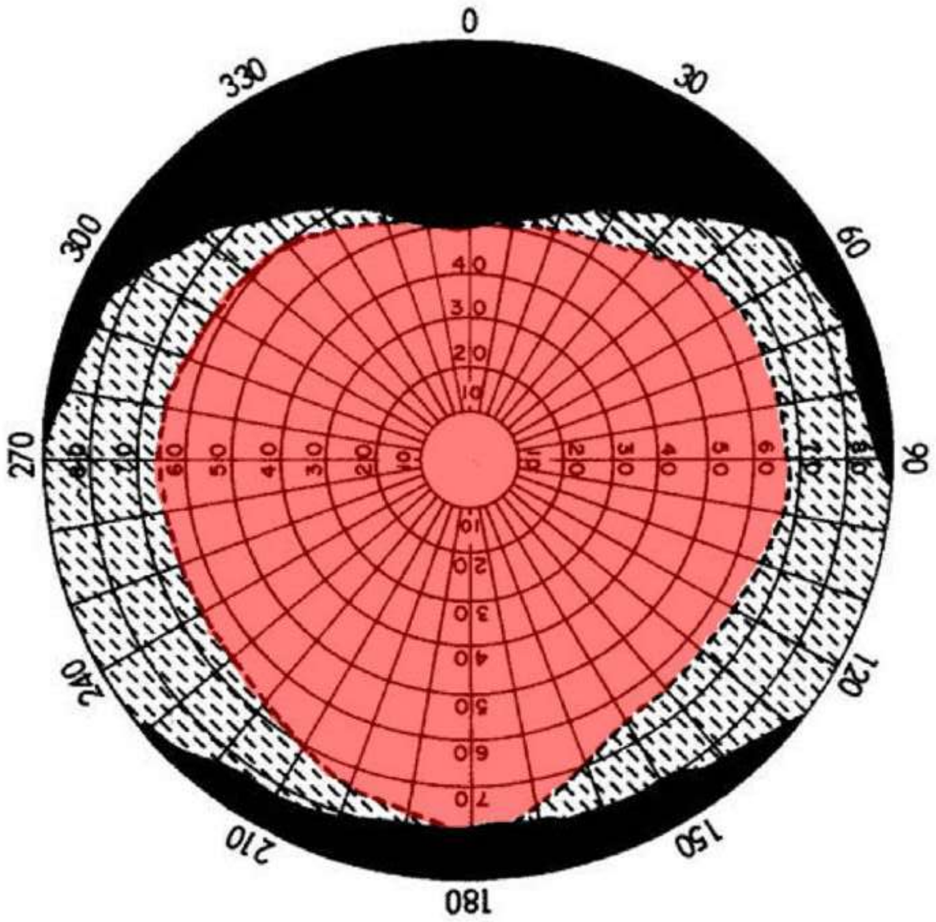


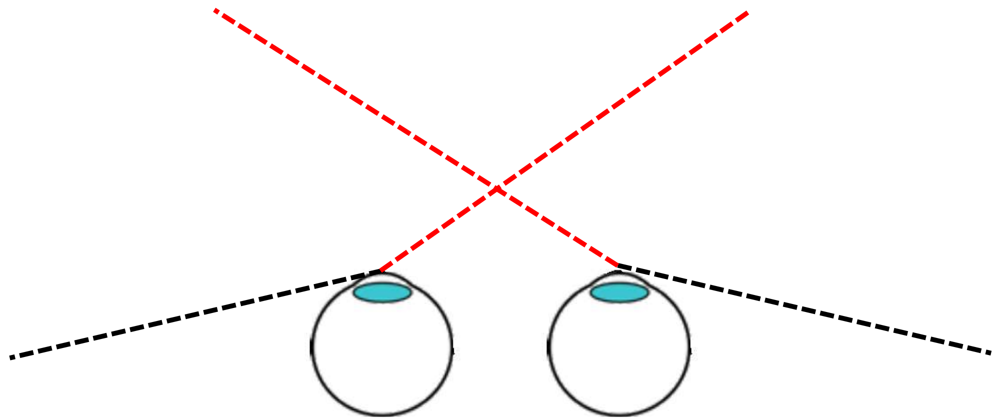
Visual Field





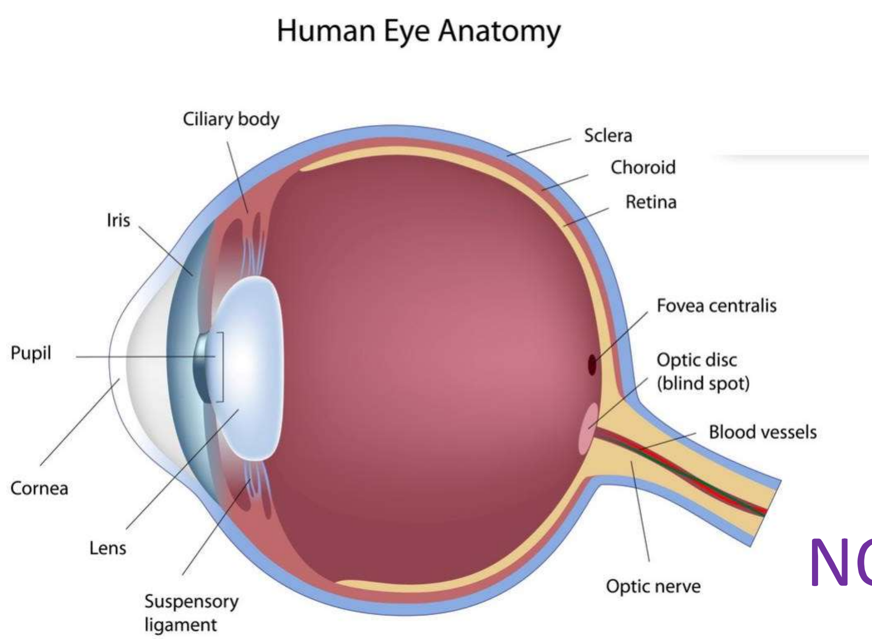
Visual Field

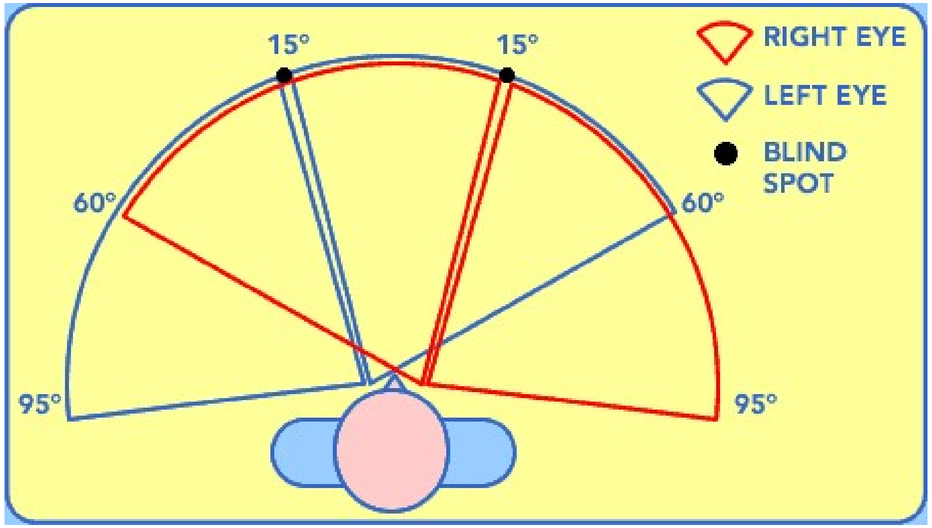




~120 deg

Visual Field





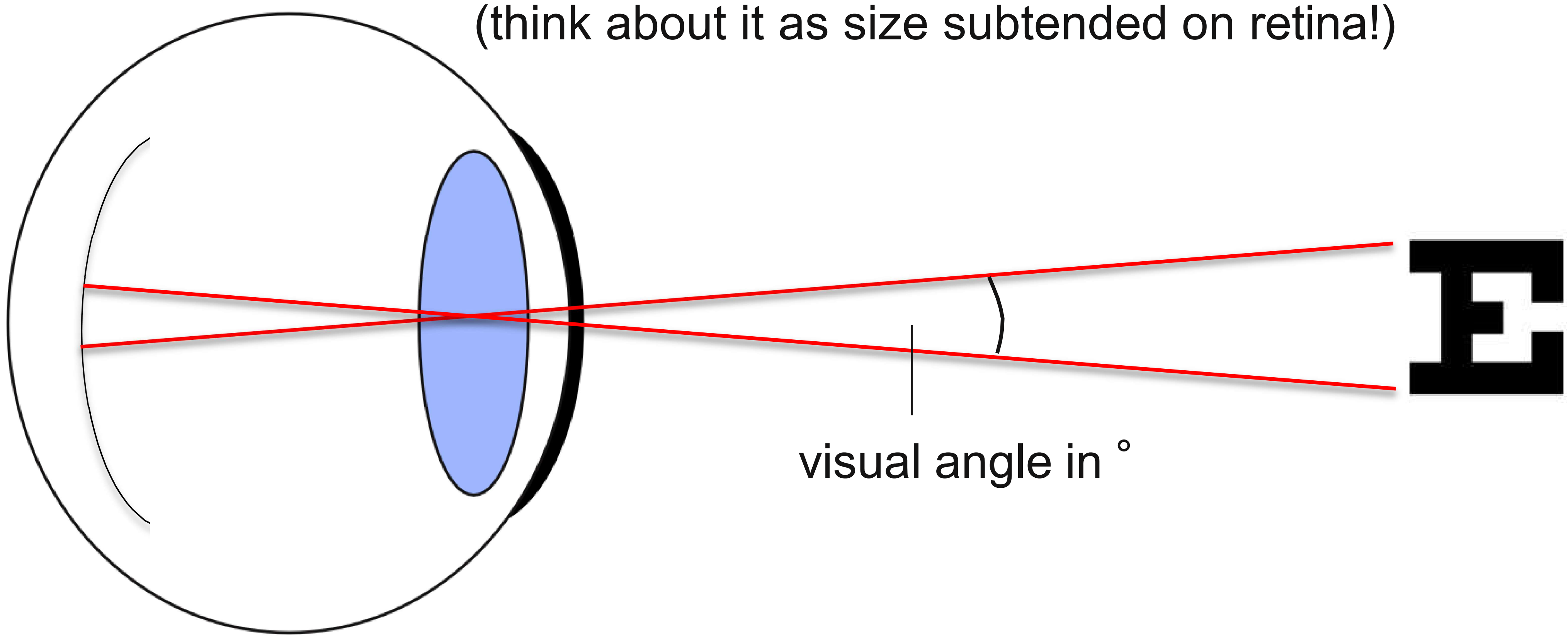
NO photoreceptor exists

https://www.vision-and-eye-health.com/

Visual Angle

- vision scientists often measure size in visual angle
- visual angle ≈ object size / object distance in degree

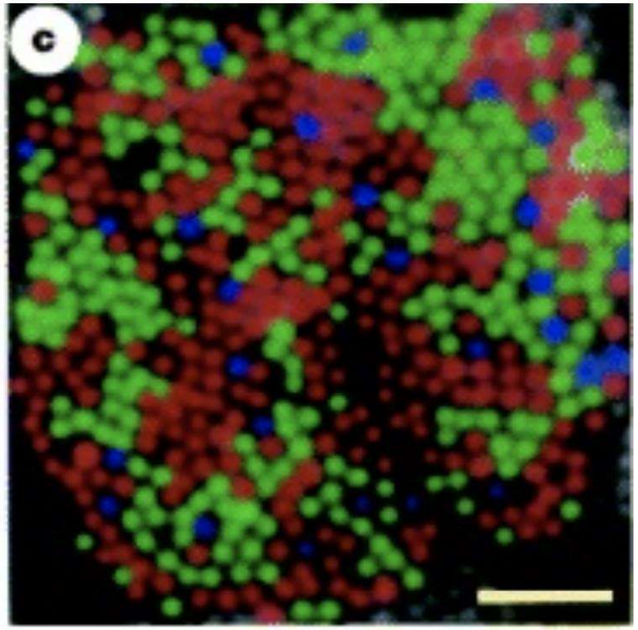
(think about it as size subtended on retina!)



Visual Acuity

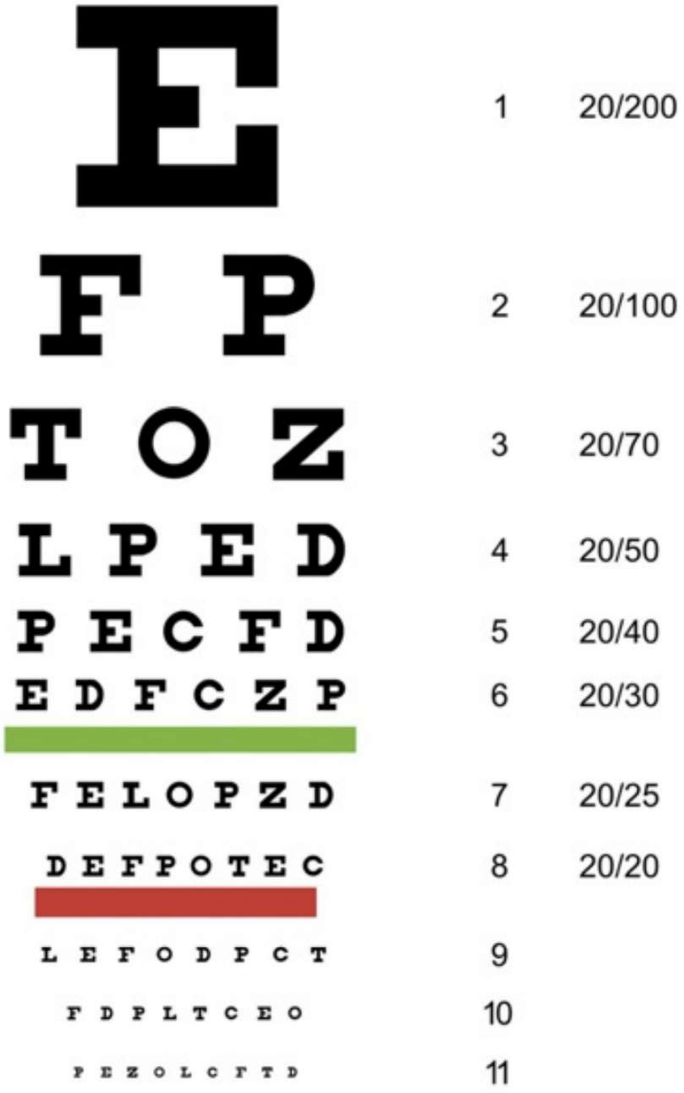
Roorda & Williams, 1999, Nature

each photorecepter
~ <u>1 arc min</u> (1/60 of a degree)
of visual angle



5 arcmin visual angle

Snellen chart



characters are 5 arc min of visual angle, need to resolve 1 arc min to read

Retina VR Display – What does it Take?

need per eye:

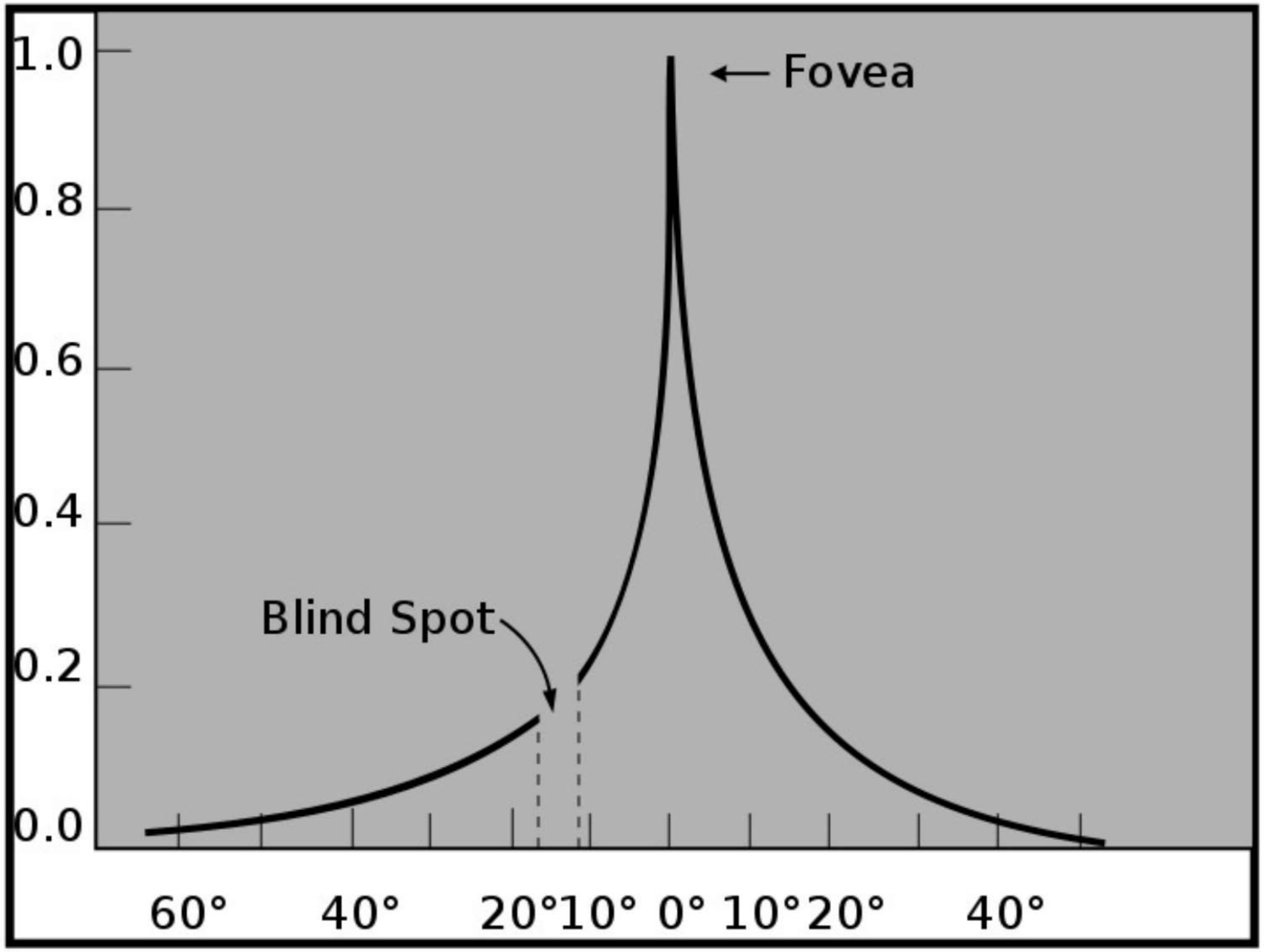
$150^\circ \times 135^\circ$ with pixels covering 1 arc min of visual angle

= 9000 x 8100 pixels (probably 2-3x of that in practice)

biggest challenge: bandwidth

- capture or render stereo panoramas or images at that resolution
- compress and transmit huge amount of data
- drive and operate display pixels

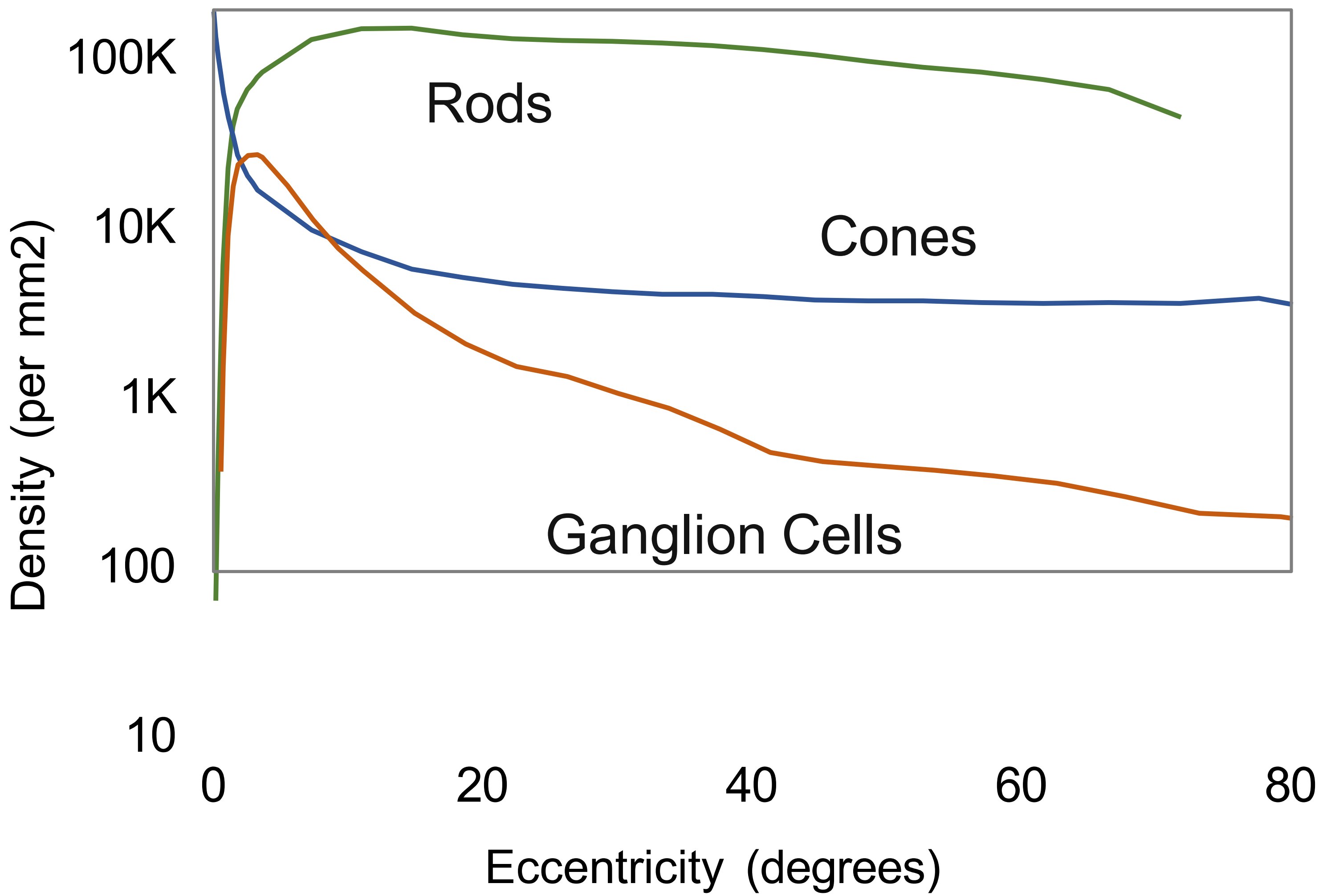
Relative Acuity Over Retina

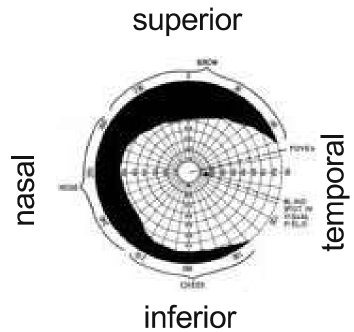


Eccentricity (i.e., distance to fovea in degrees of visual angle)

wikipedia

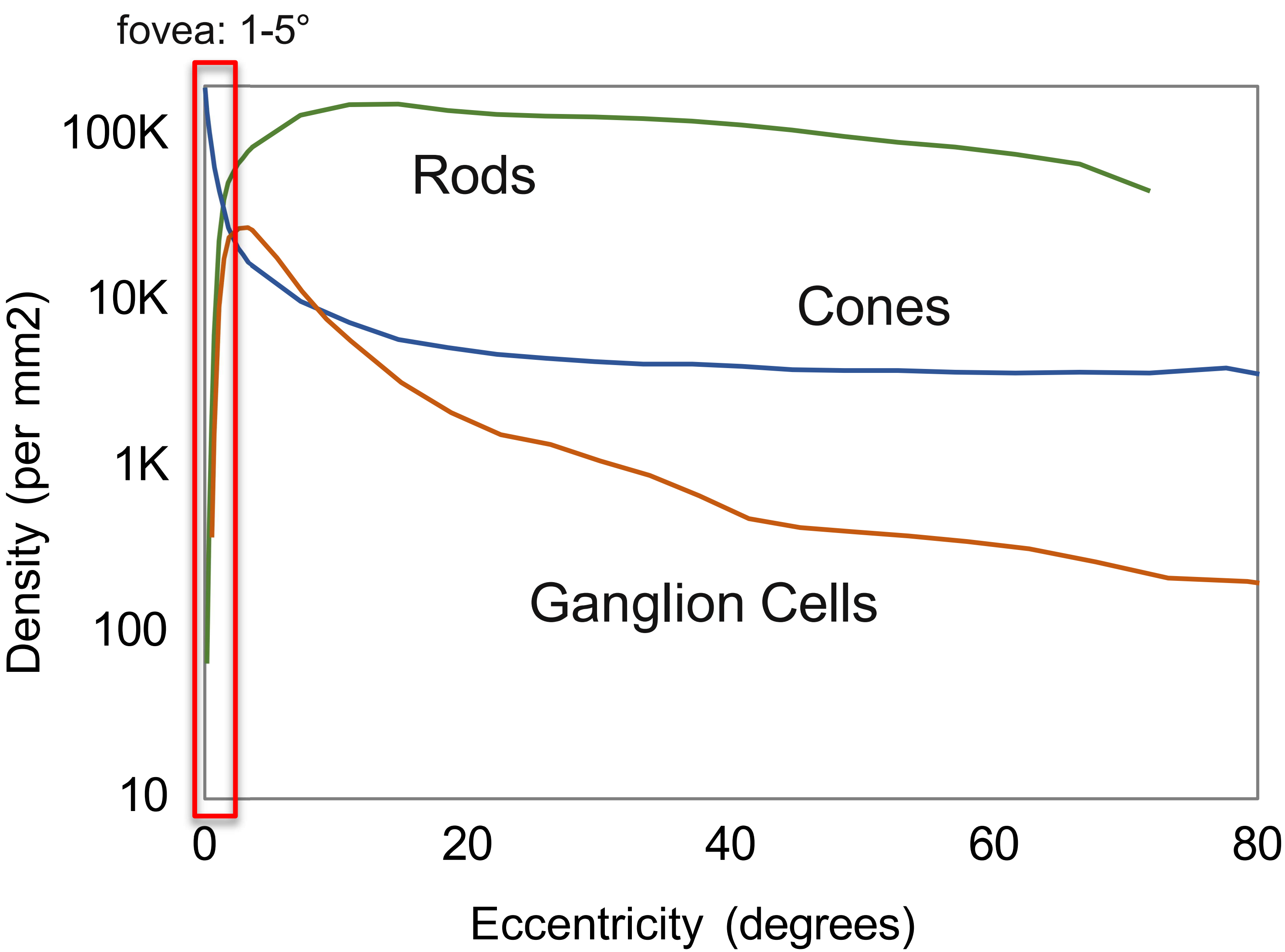
Density of Photoreceptors on Retina

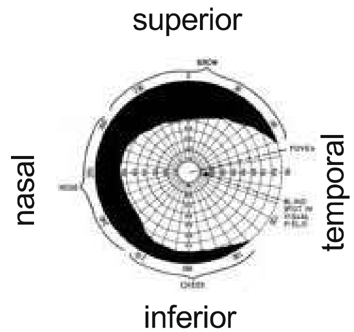




Patney et al. 2016

Density of Photoreceptors on Retina





Patney et al. 2016

Acuity Over Retina / MAR

acuity falls off due to:

- reduced receptor and ganglion cell density
- reduced optical nerve “bandwidth”
- reduced “processing” devoted to periphery in the visual cortex

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MAR: minimum angle of resolution in deg/cycle

slope

$$\omega = me + \omega_0$$

eccentricity in degrees

smallest resolvable angle at fovea in deg/cycle

$$\omega_0 = (1/48)^\circ$$

somewhere between 20/20 (30 cycles per degree) and 20/10 (60 cycles per degree)

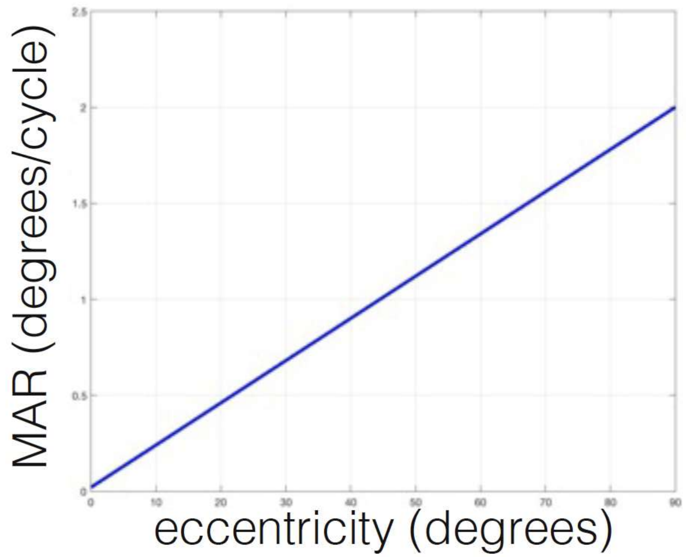
$$m = 0.022 - 0.034$$

range of acceptable – equivalent for observed image quality

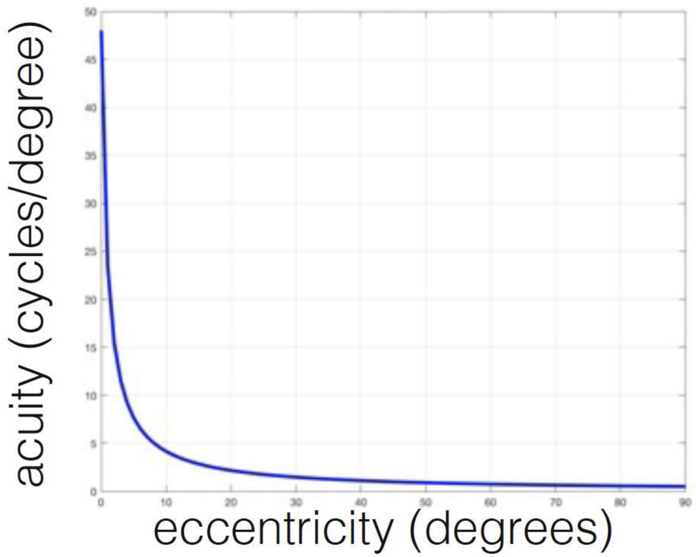
Guenter et al. 2012

Acuity Over Retina / MAR

MAR



Acuity (=1/MAR)



MAR slope

$$\omega = me + \omega_0$$

eccentricity in degrees smallest resolvable angle at fovea in deg/cycle

Guenter et al. 2012


Patney et al. 2016

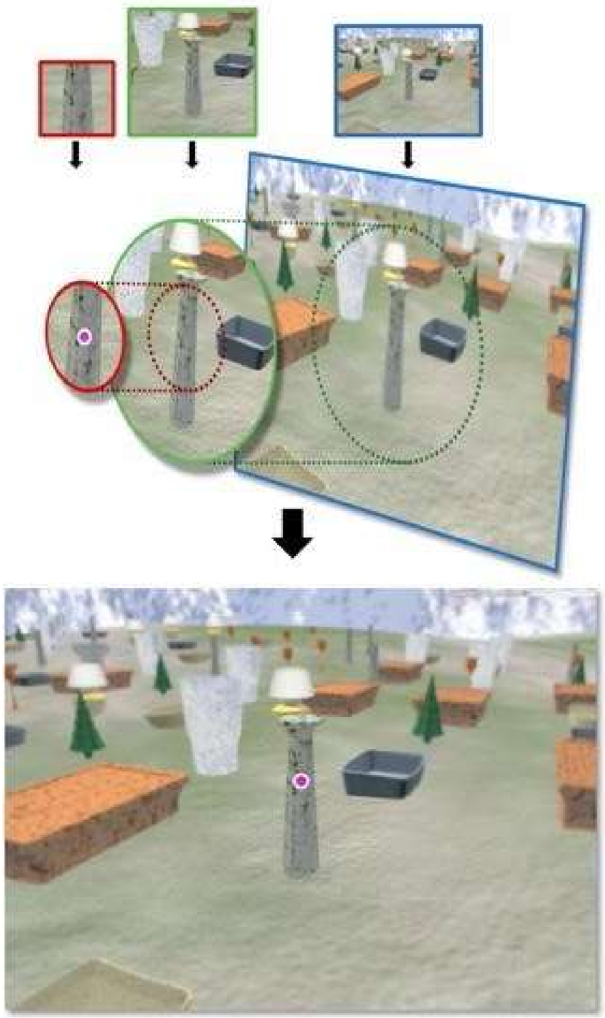
Patney et al. 2016

Reading/final project options

[1] **Foveated 3D graphics**
Guenter et al. 2012
https://dl.acm.org/doi/10.1145/2366145.2366183

[2] Towards foveated rendering for gaze-tracked virtual reality
Patney et al. ACM Trans. Graph 2016
https://dl.acm.org/doi/abs/10.1145/2980179.2980246

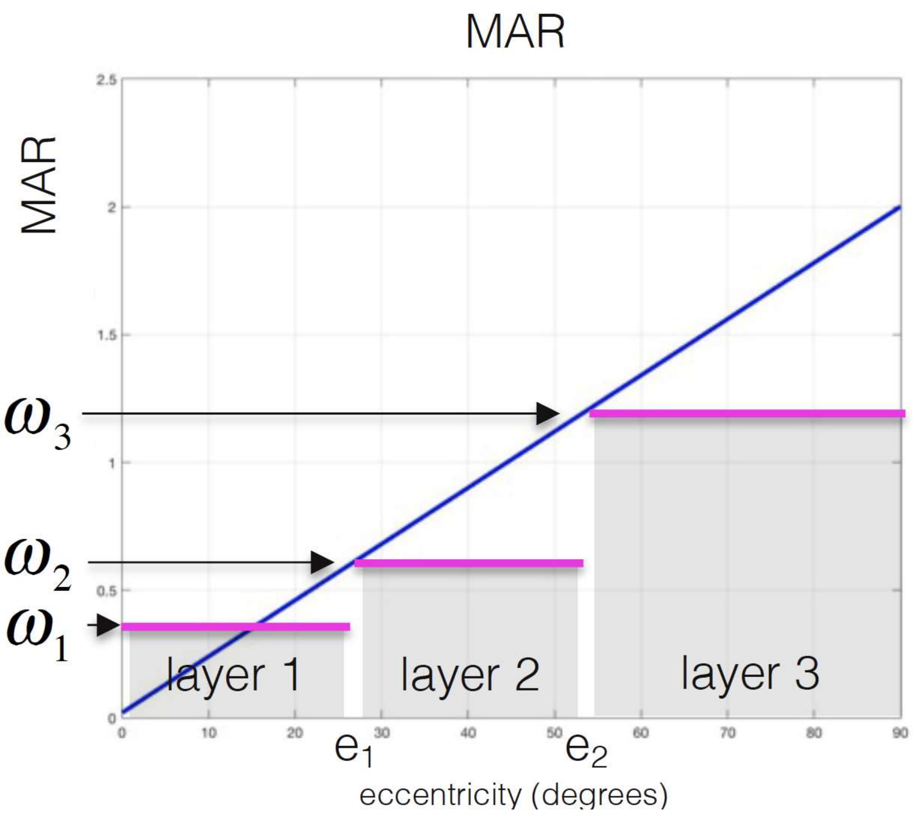
Foveated Rendering



- Guenter et al. 2012: split image into n layers, e.g. inner (foveal, 1), middle (2), outer (3)
- render image in each zone with progressively lower resolution
- goals: save computation & bandwidth!

Foveated Rendering

- Guenter et al. 2012: split image into *n* layers, e.g. inner (foveal, 1), middle (2), outer (3)

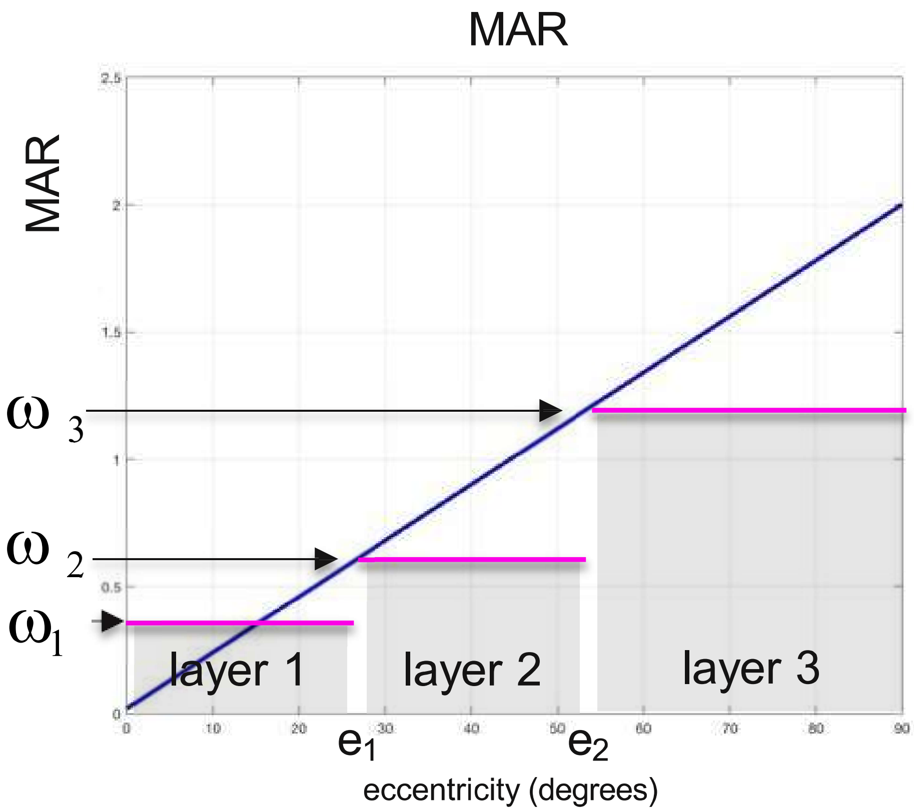


$$e_i = \frac{i}{n} \cdot \frac{fov}{2}$$

$$e_1 = \frac{fov}{6}$$

$$e_2 = \frac{fov}{3}$$

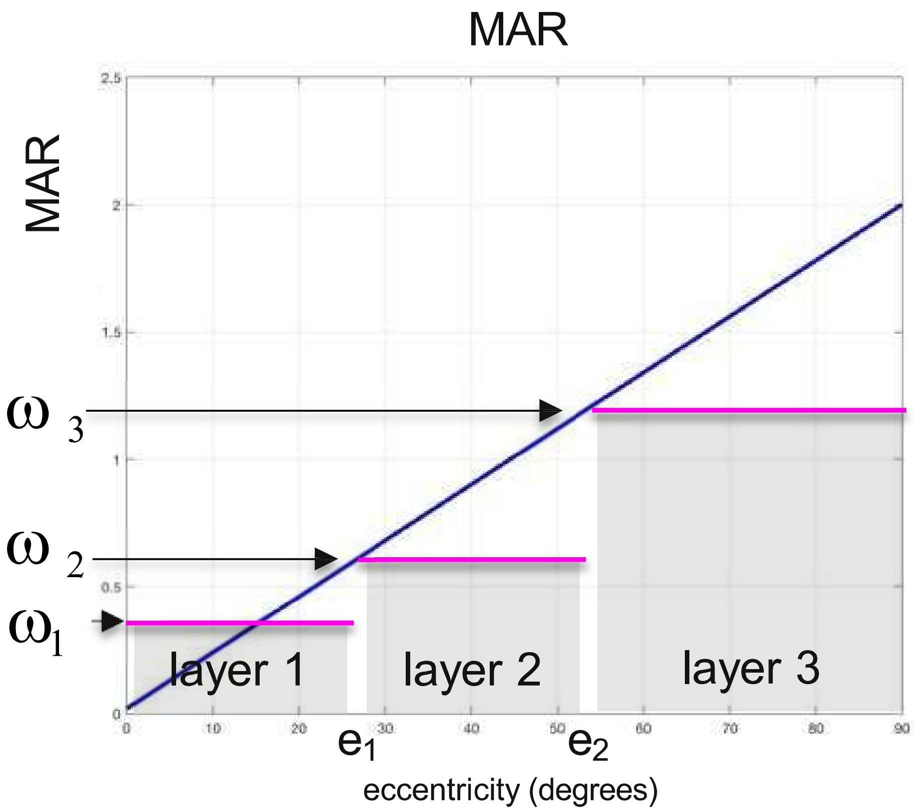
Foveated Rendering



ω_1 is best the display can do!

unit of ω_1: $\frac{degrees}{cycle} = \frac{degrees}{2 \cdot pixel\_size}$

Foveated Rendering



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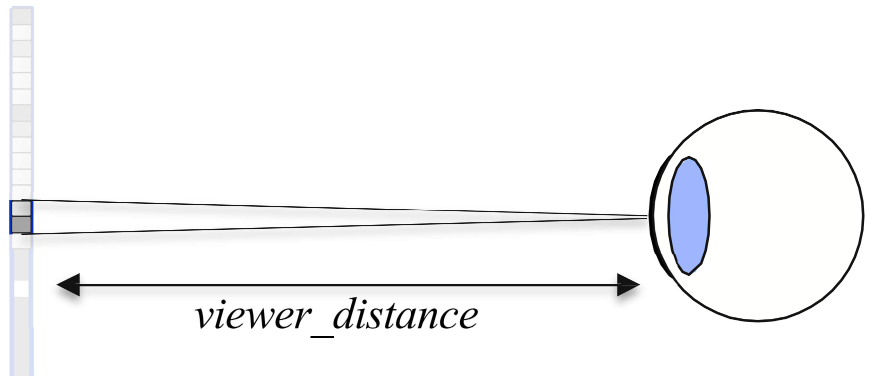
$$\omega_1 = 2\tan^{-1}\left(\frac{screen\_size}{screen\_resolution \cdot viewer\_distance}\right) \cdot \frac{360}{2\pi}$$



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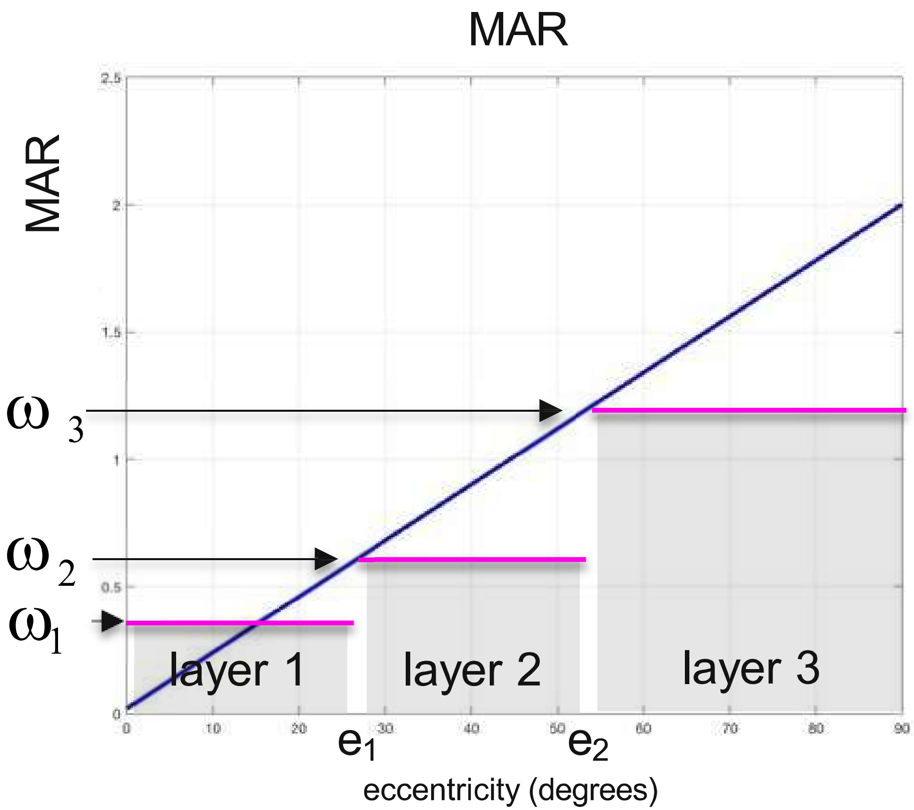

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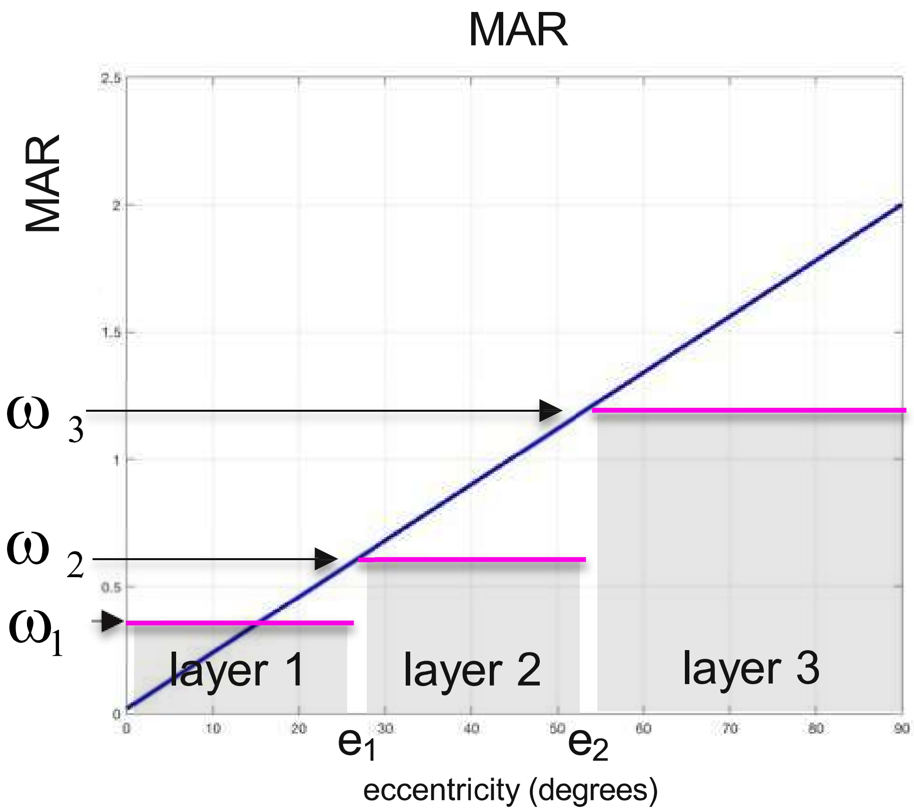
$$\omega_1 = 2\tan^{-1}\left(\frac{screen\_size}{screen\_resolution \cdot viewer\_distance}\right) \cdot \frac{360}{2\pi}$$

$screen\_size$ is either screen width or height (same units as viewer_distance)

$screen\_resolution$ is either number of horizontal pixels or vertical pixels of the screen (same dimension as screen_size)

Foveated Rendering



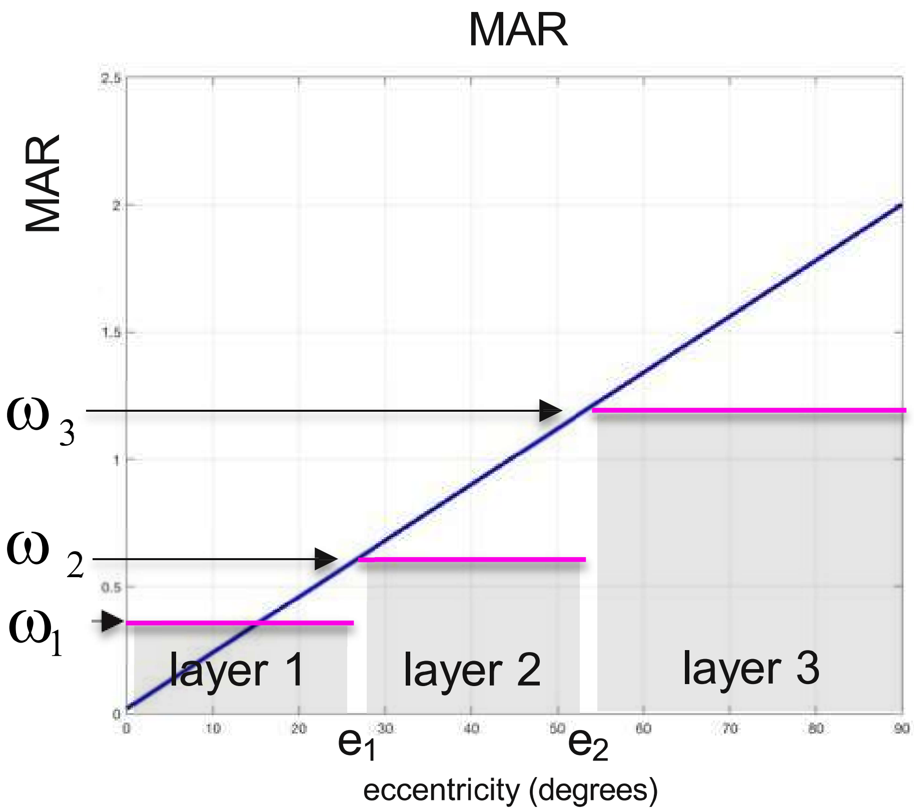
$$\omega_1 = 2\tan^{-1}\left(\frac{screen\_size}{screen\_resolution \cdot viewer\_distance}\right)\cdot\frac{360}{2\pi}$$

$$\omega_2 = me_2 + \omega_0$$

$$\omega_3 = me_3 + \omega_0$$

Foveated Rendering

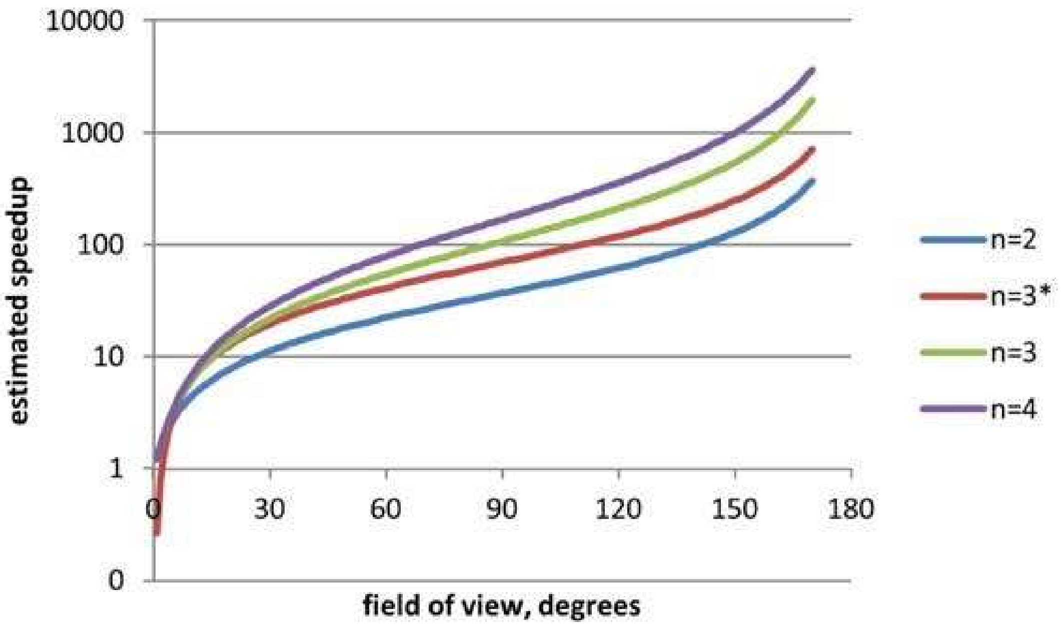
- convert MAR (in degrees/cycle) to pixels



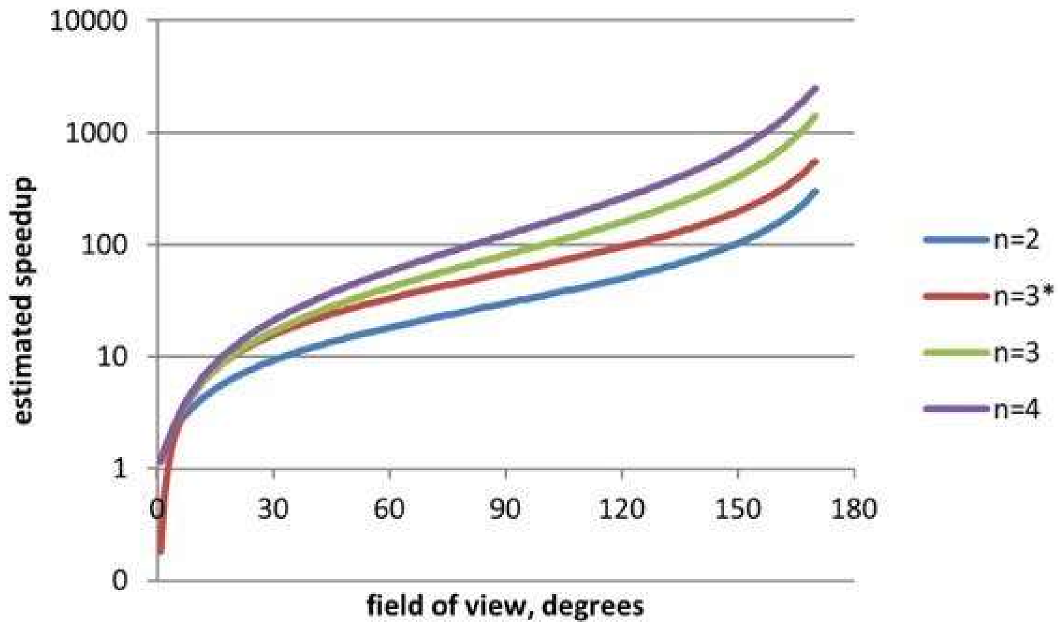
$$blur\_radius\_in\_px = viewer\_distance \cdot \tan\left(\frac{\omega}{2} \cdot \frac{2\pi}{360}\right)$$

Foveated Rendering – Performance Gain

$m = 0.028$



$m = 0.022$

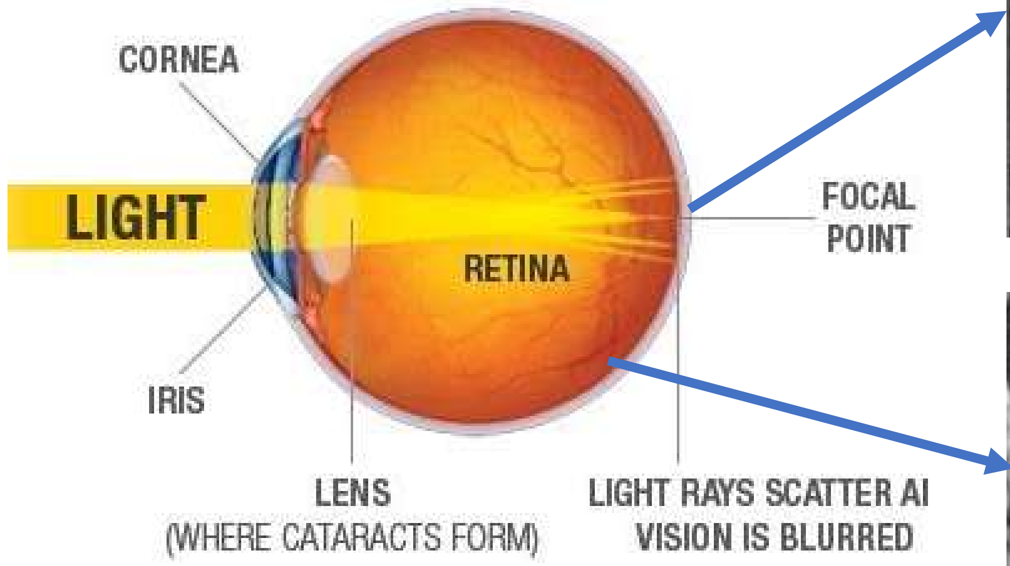


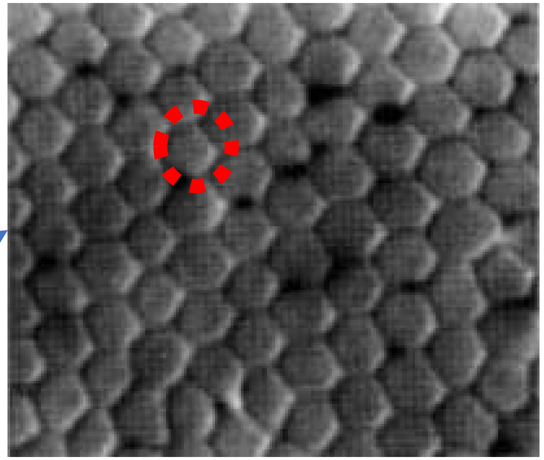
n is number of layers

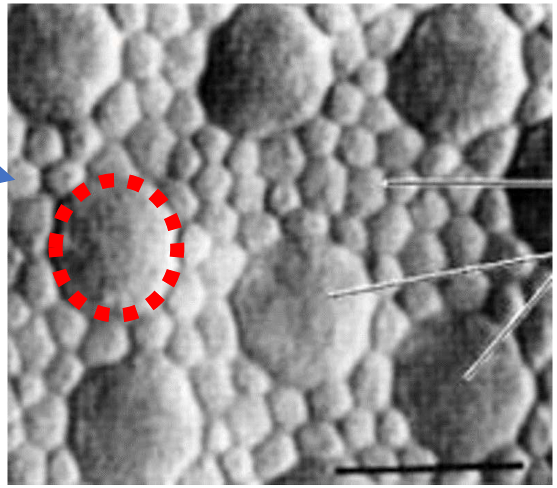
speedup is total number of display pixels / number of pixels in all layers combined

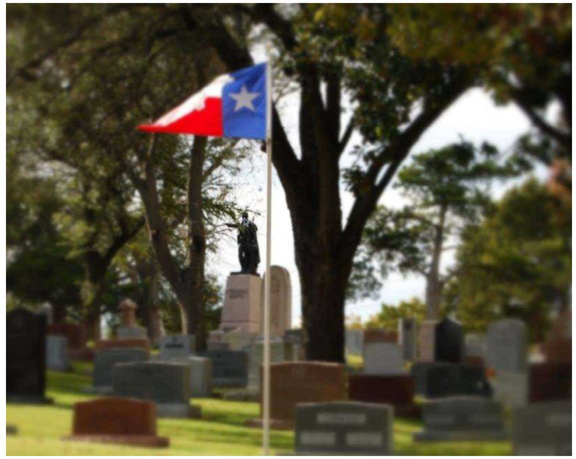
<u>conclusion</u>: for large fov & high-res displays, we need to shade much fewer pixels!

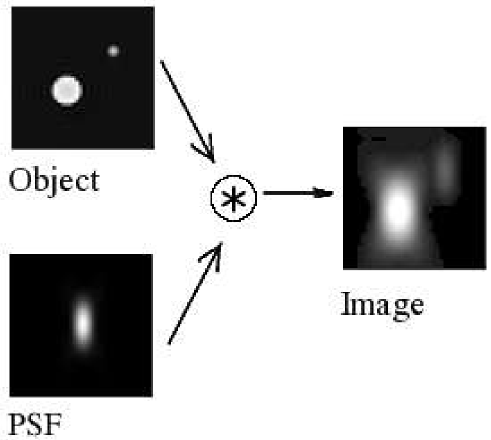
Visual Acuity





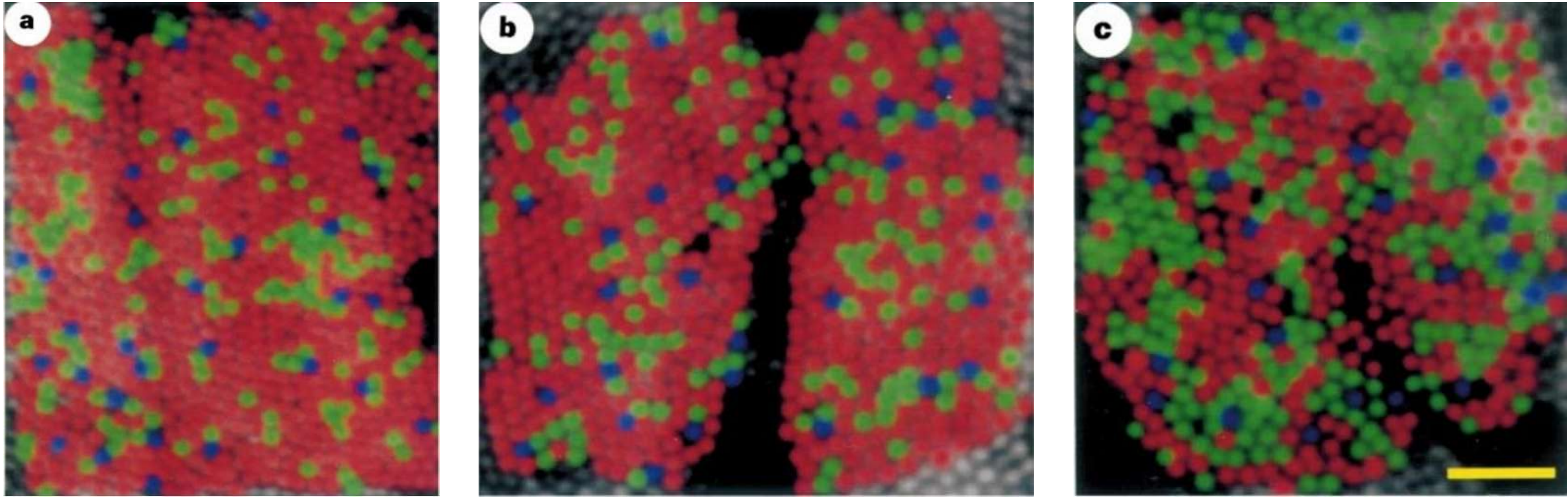






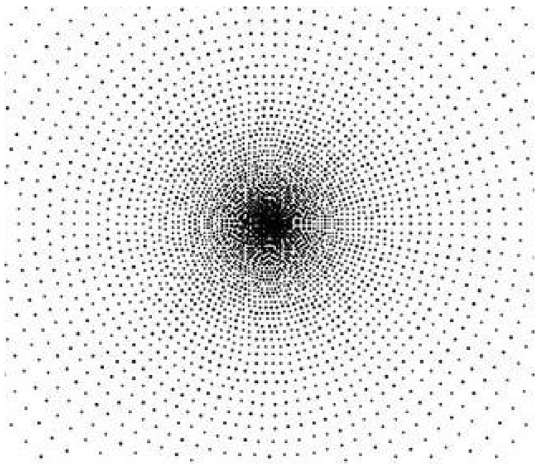
Source: Mango Optics

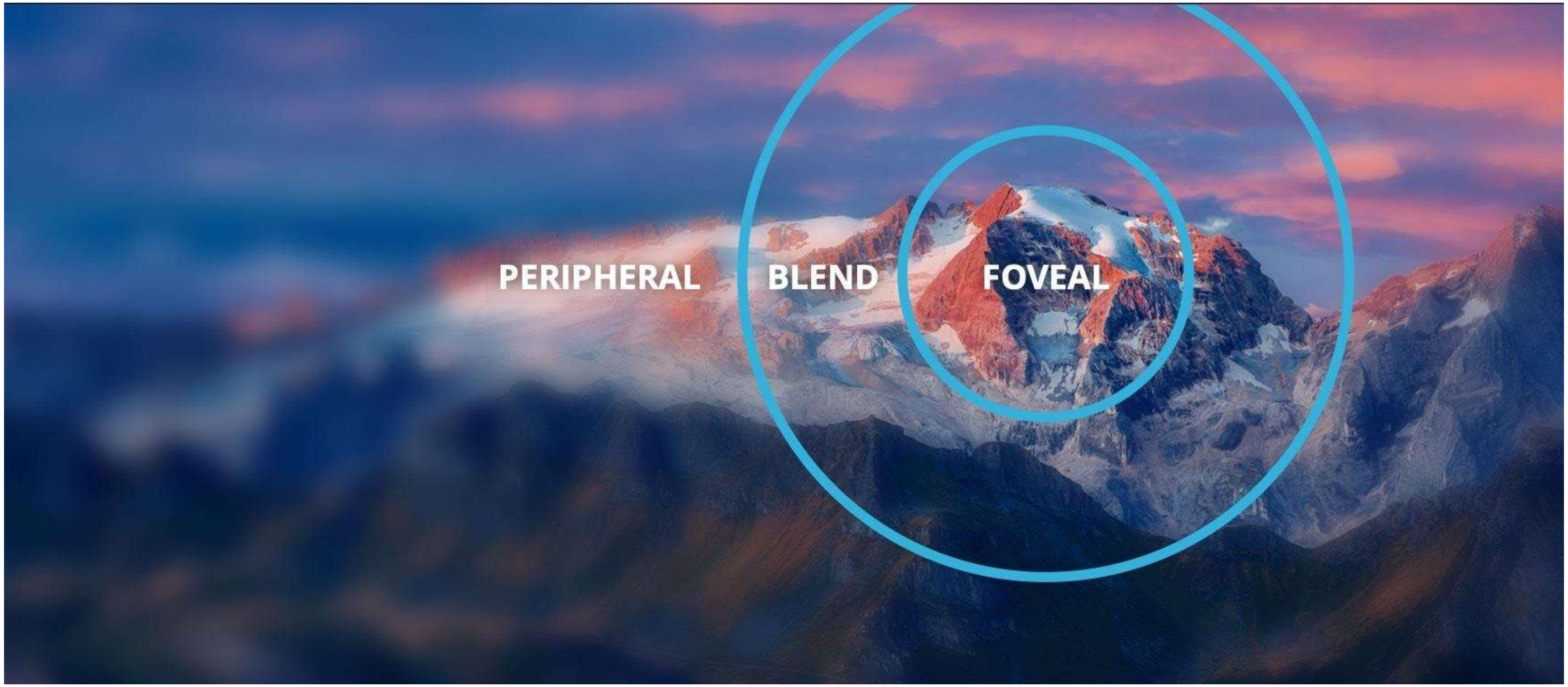
Visual Acuity



The arrangement of the three cone classes in the living human eye,
Roorda and Williams, Nature 1999

Visual Acuity





Visual Field – Find Your Own Blind Spot!

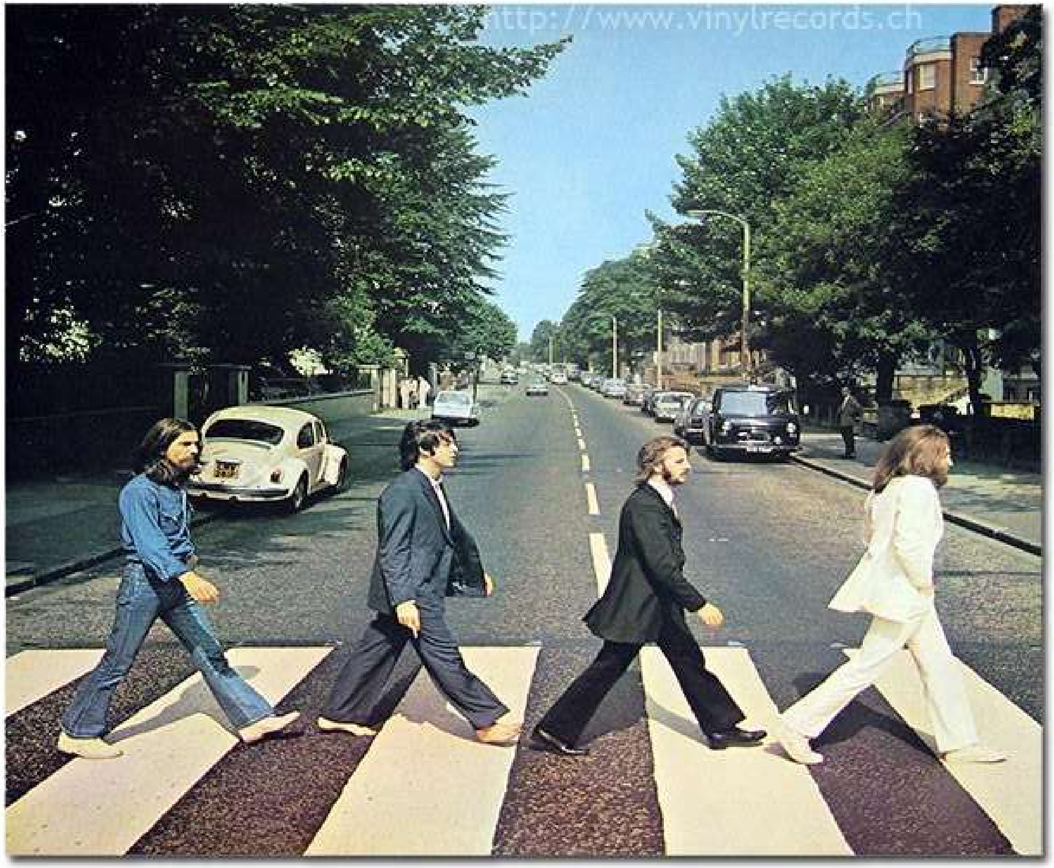
shorturl.at/fgiX5

Depth Cues

3D Depth Cues

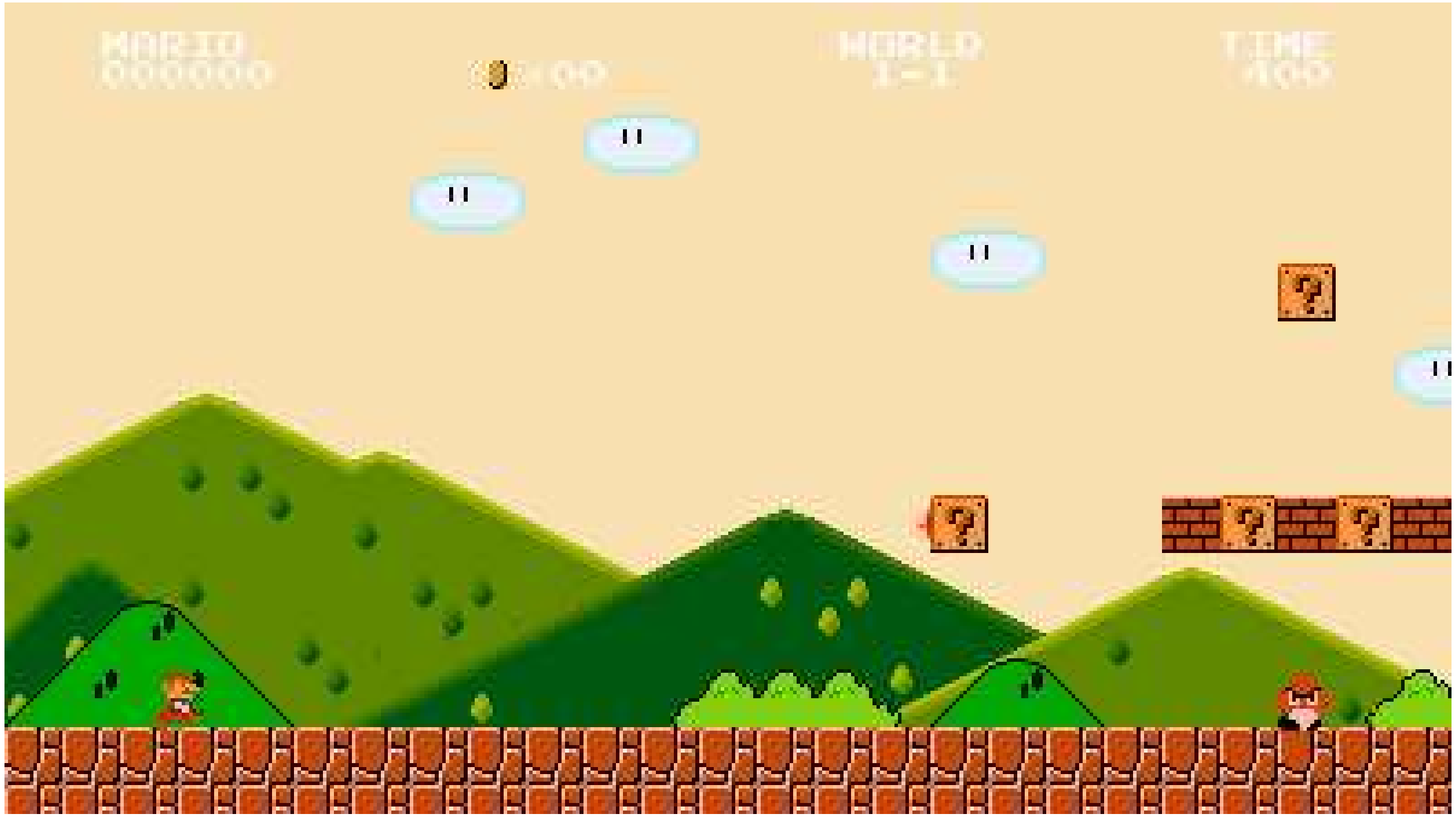
- Monocular vision

- Binocular vision



[The Beatles, Abbey Road]

Monocular Cues – Motion Parallax

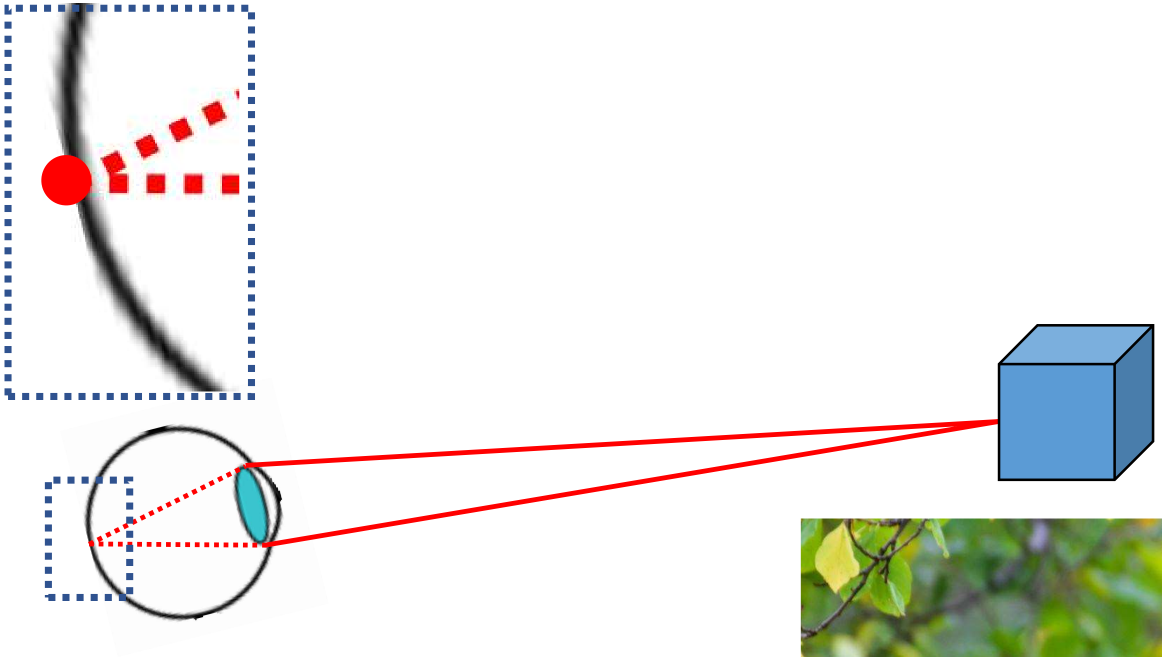


Monocular Cues – Perspective Projection

https://en.wikipedia.org/wiki/Depth_perception#/media/File:08913-Perspective_Run.jpg

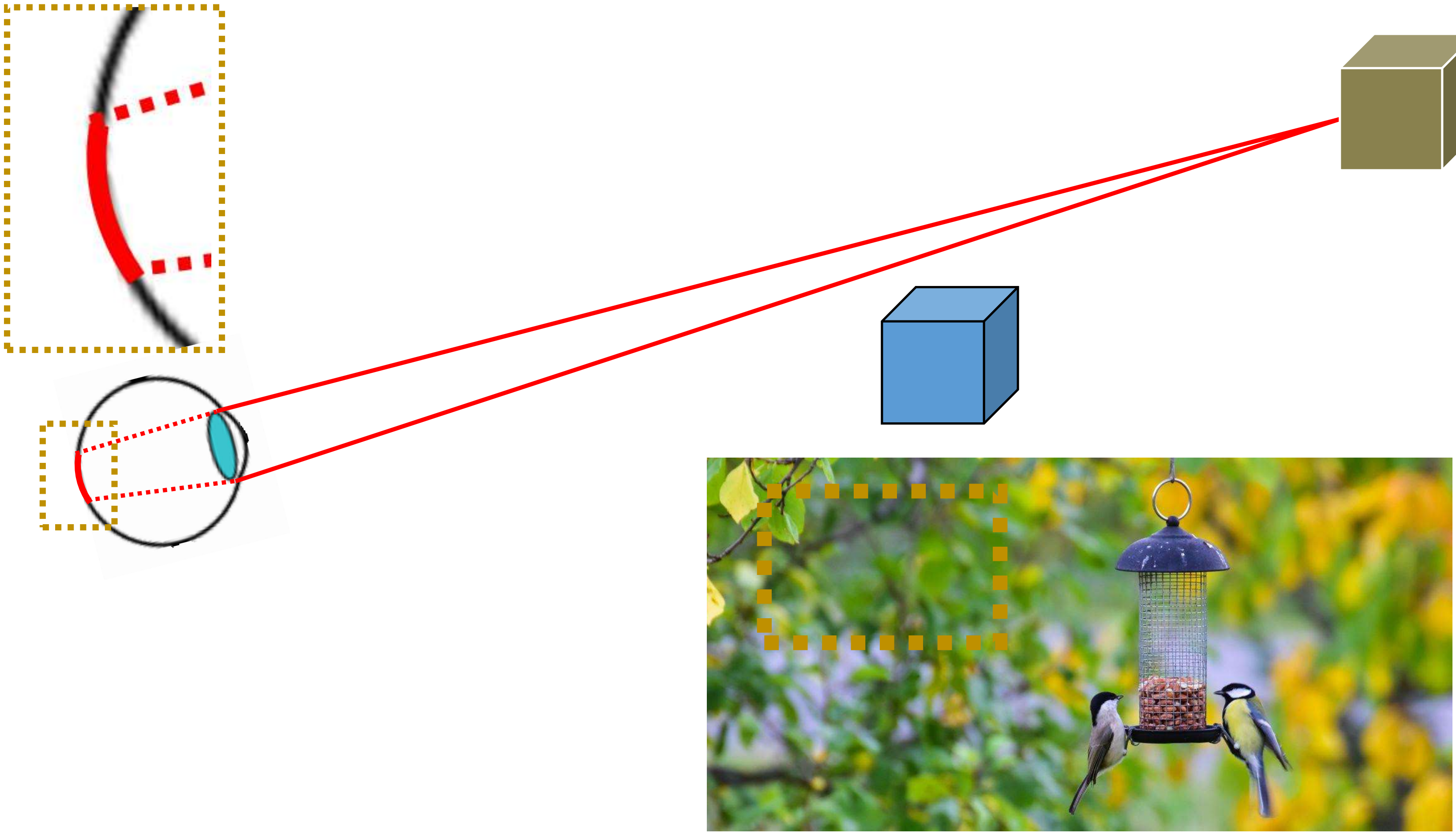
Monocular Cues – Occlusion

Monocular Cues – Accommodation

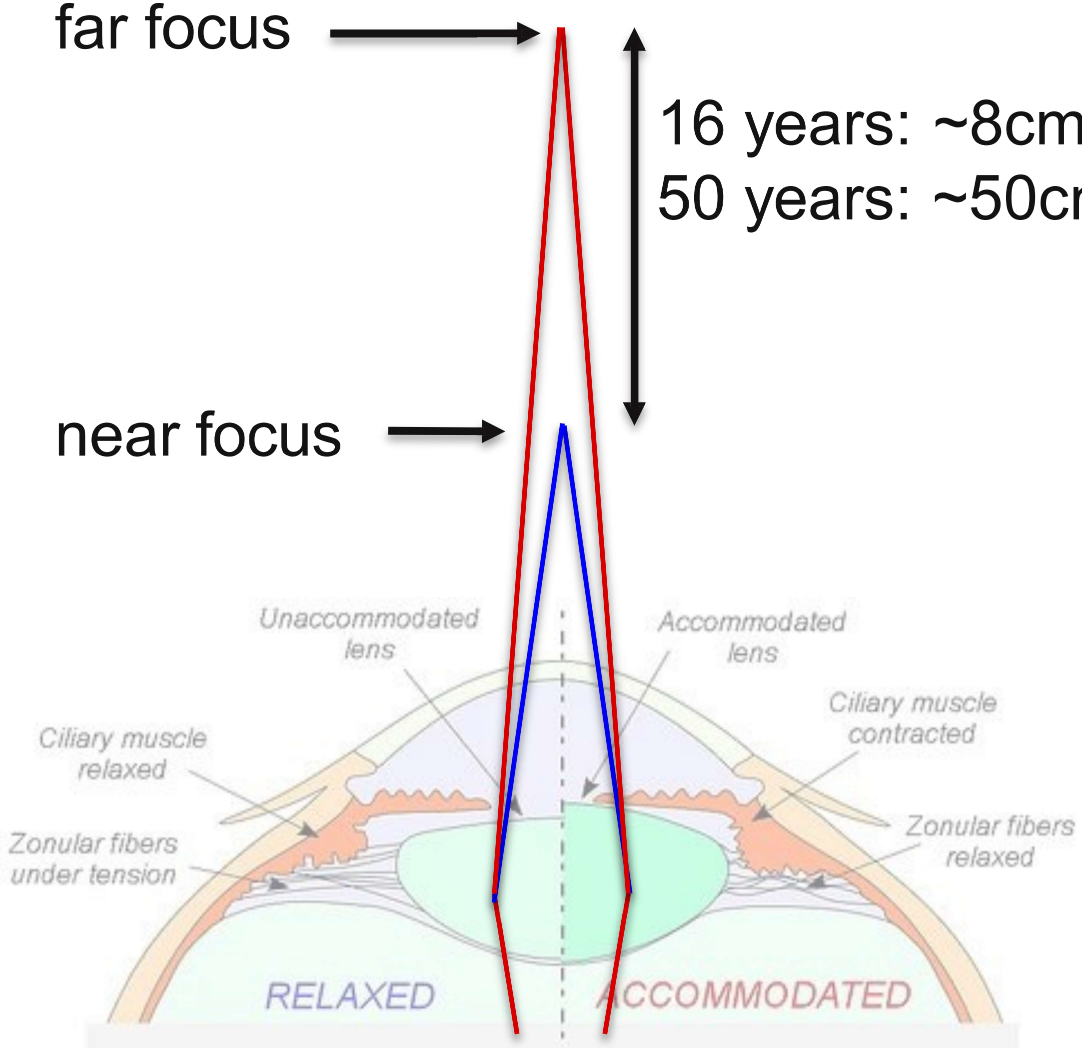


https://www.housebeautiful.com/lifestyle/gardening/g30613155/squirrel-proof-bird-feeder/

Monocular Cues – Accommodation

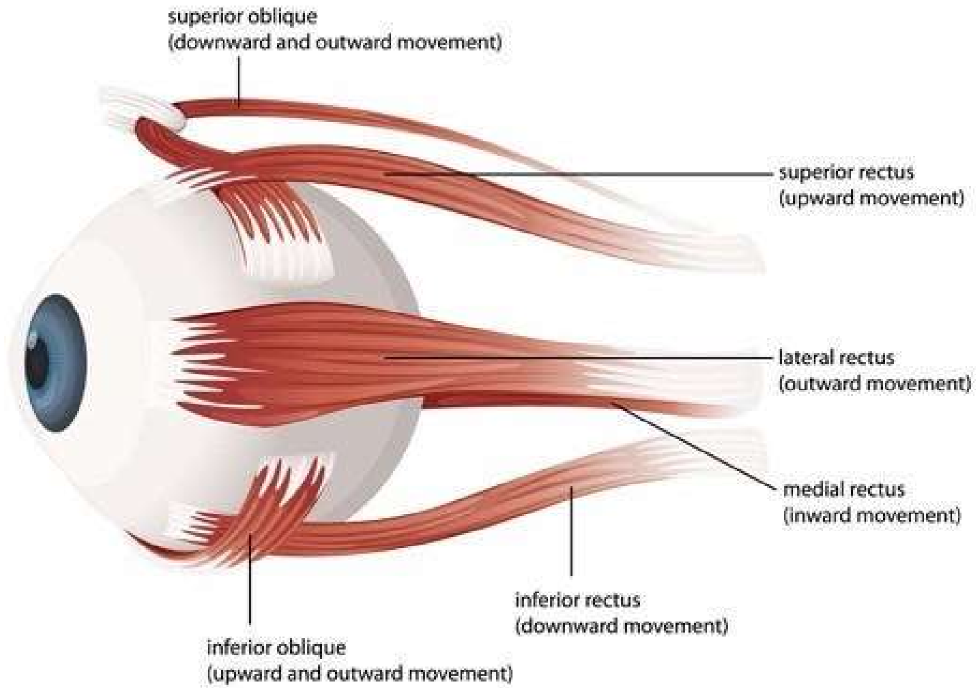


Oculumotor Processes



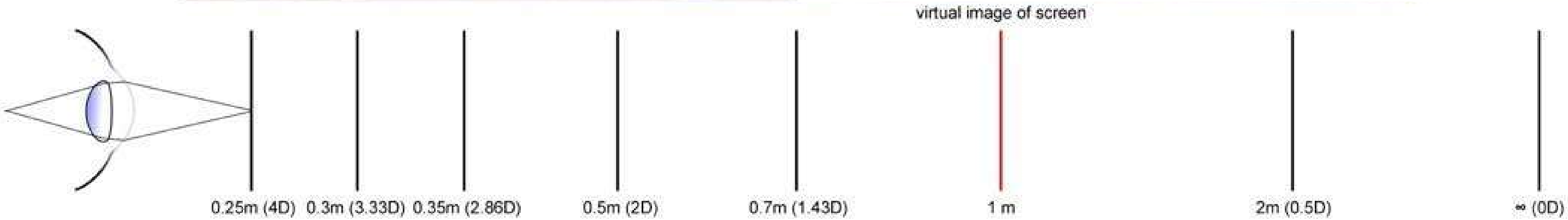
adithyakiran.wordpress.com

16 years: ~8cm to ∞
50 years: ~50cm to ∞ (mostly irrelevant)



Accommodation and Retinal Blur

Conventional Display

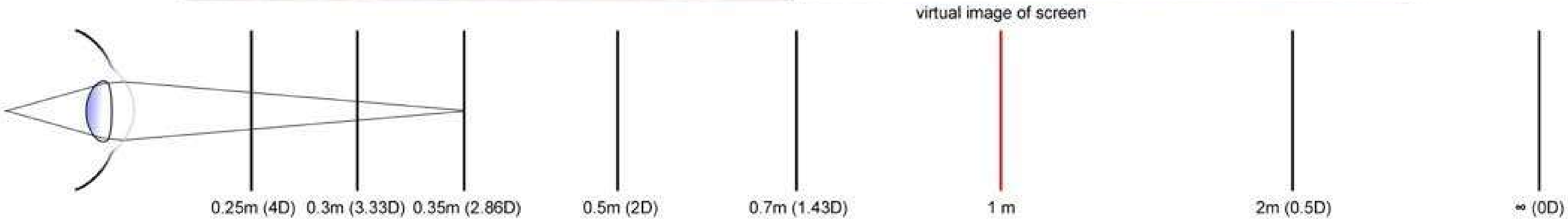


Accommodation and Retinal Blur

Conventional Display

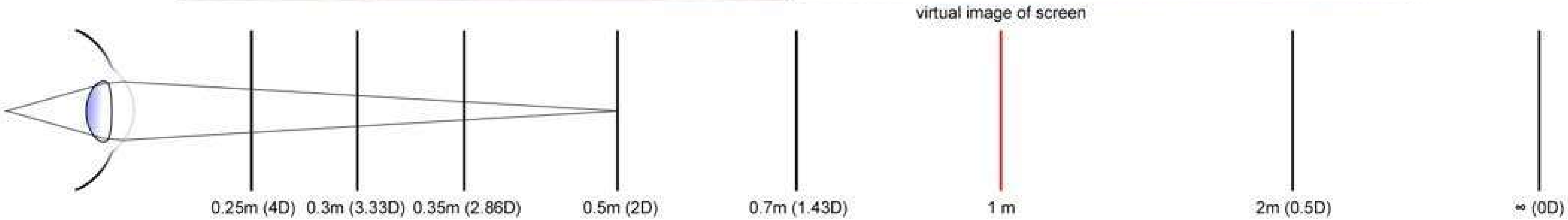
Accommodation and Retinal Blur

Conventional Display



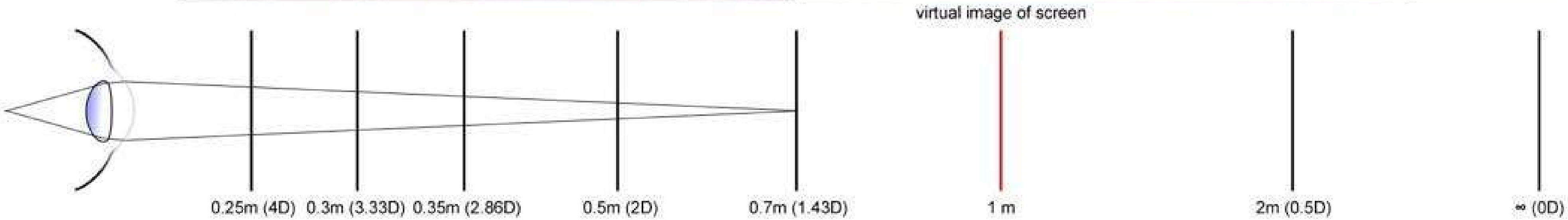
Accommodation and Retinal Blur

Conventional Display



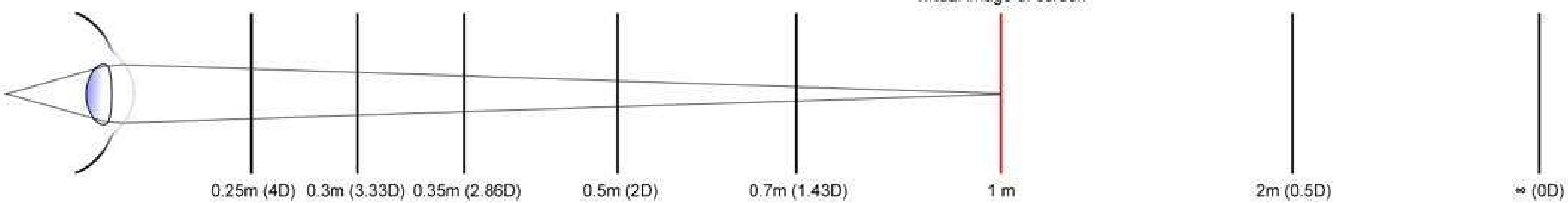
Accommodation and Retinal Blur

Conventional Display



Accommodation and Retinal Blur

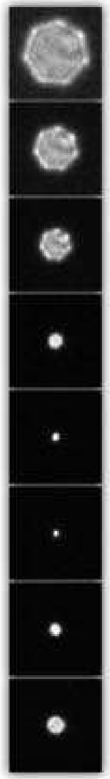
Conventional Display

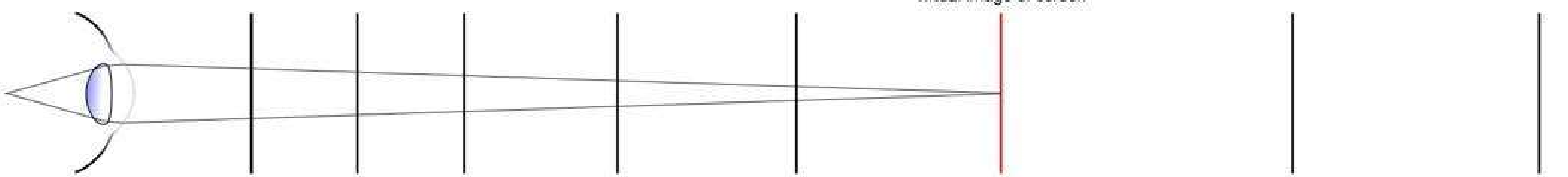


Accommodation and Retinal Blur

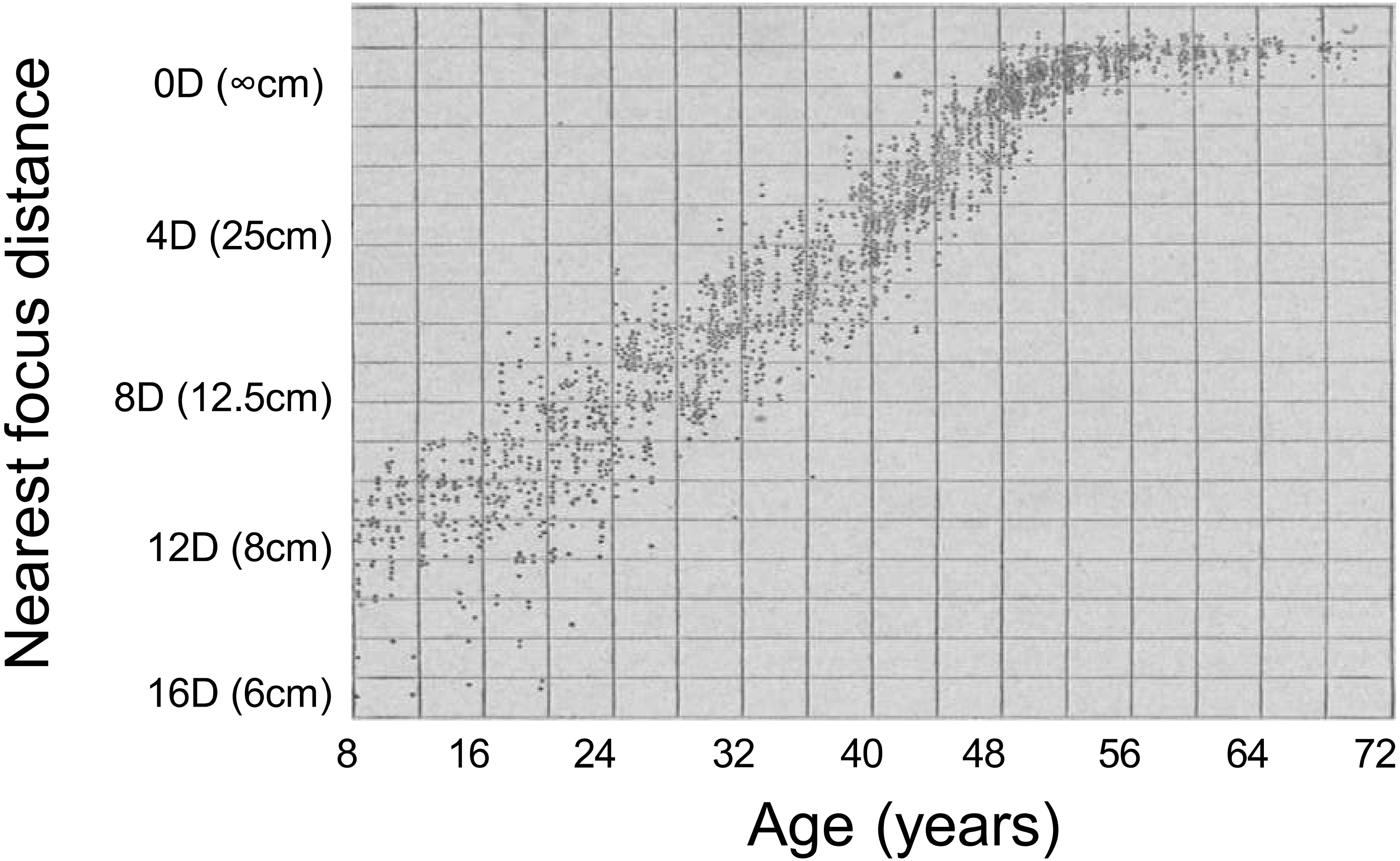
Conventional Display

Accommodation-dependent Point Spread Functions





Focusing Ability Degrades With Age - Presbyopia

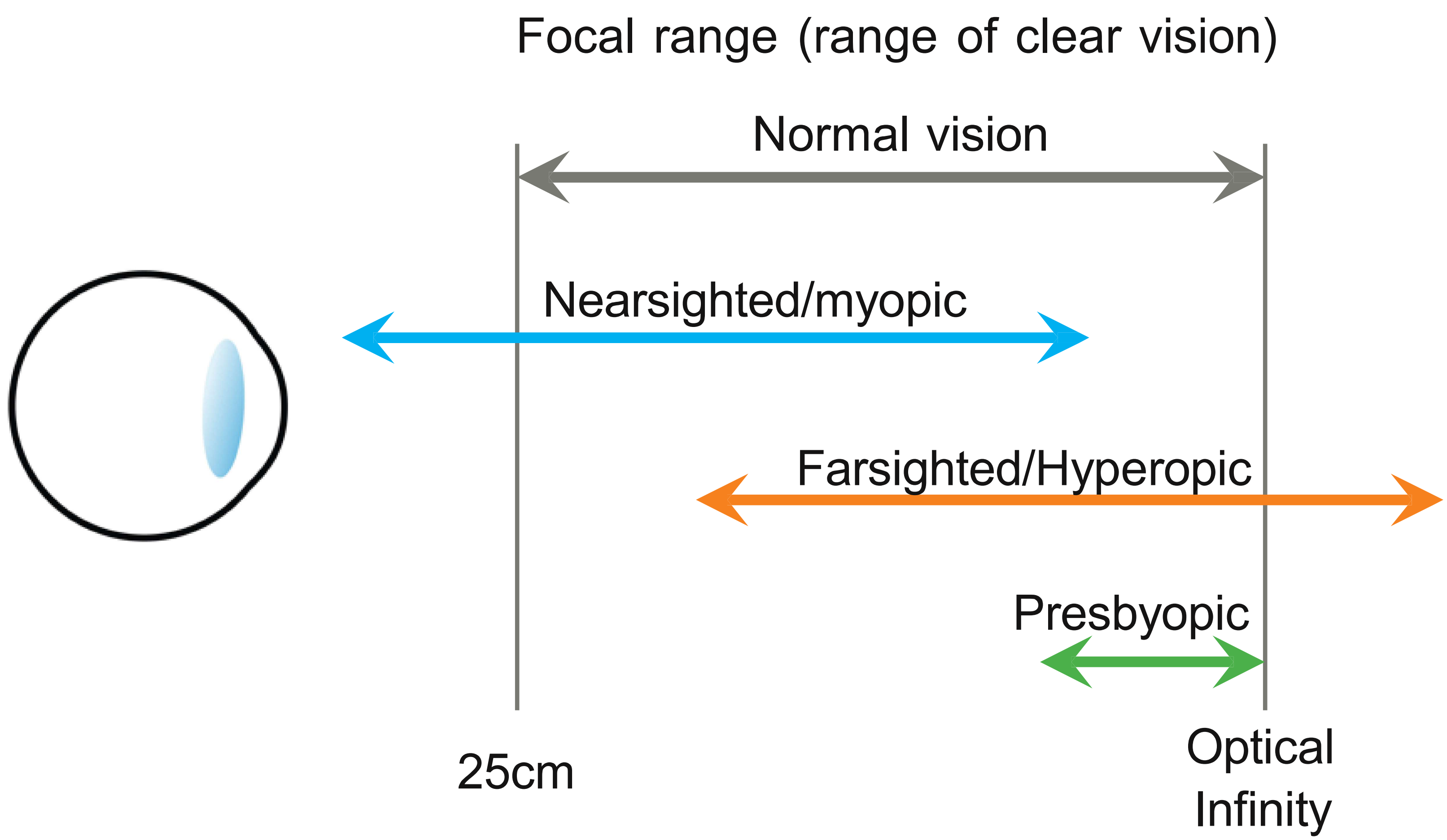


Duane, 1912

Bifocals

https://c1.staticflickr.com/1/77/173805491_4e4d77fa71_b.jpg

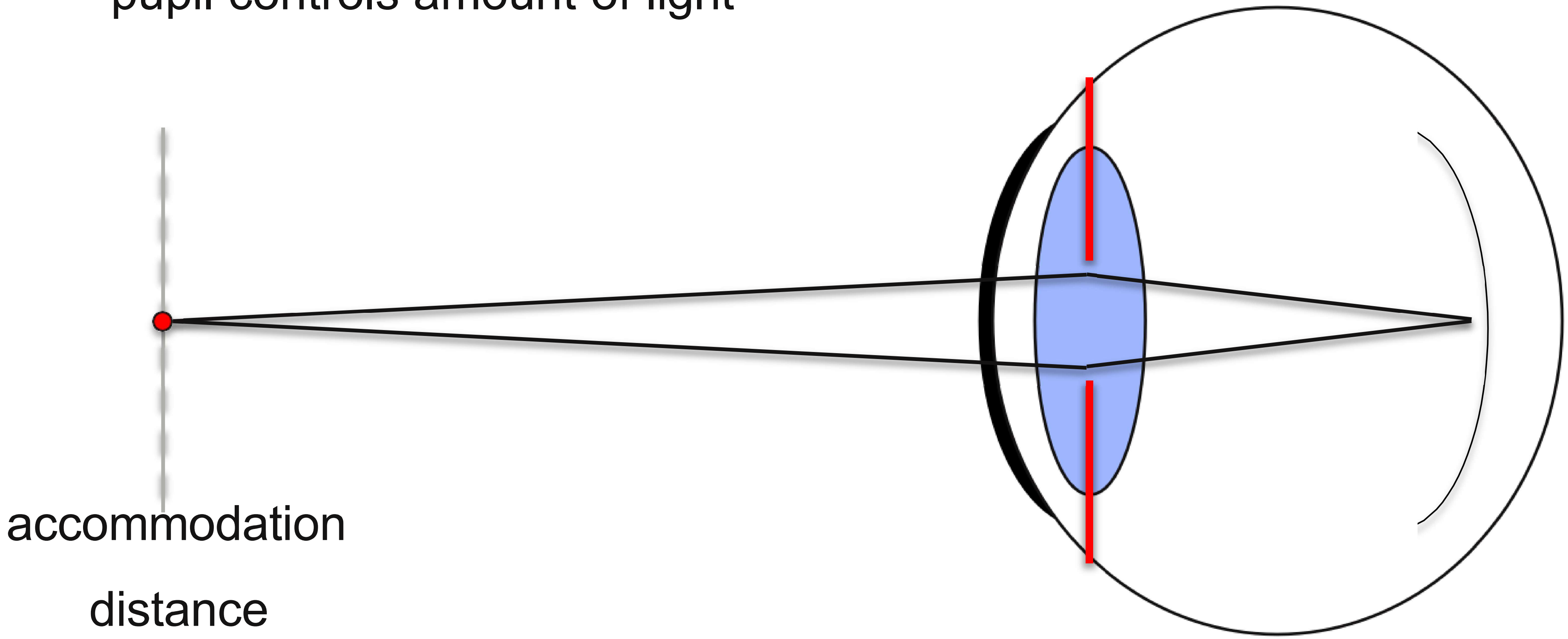
Myopia, Hyperopia, Presbyopia



Modified from Pamplona et al. SIGGRAPH 2010

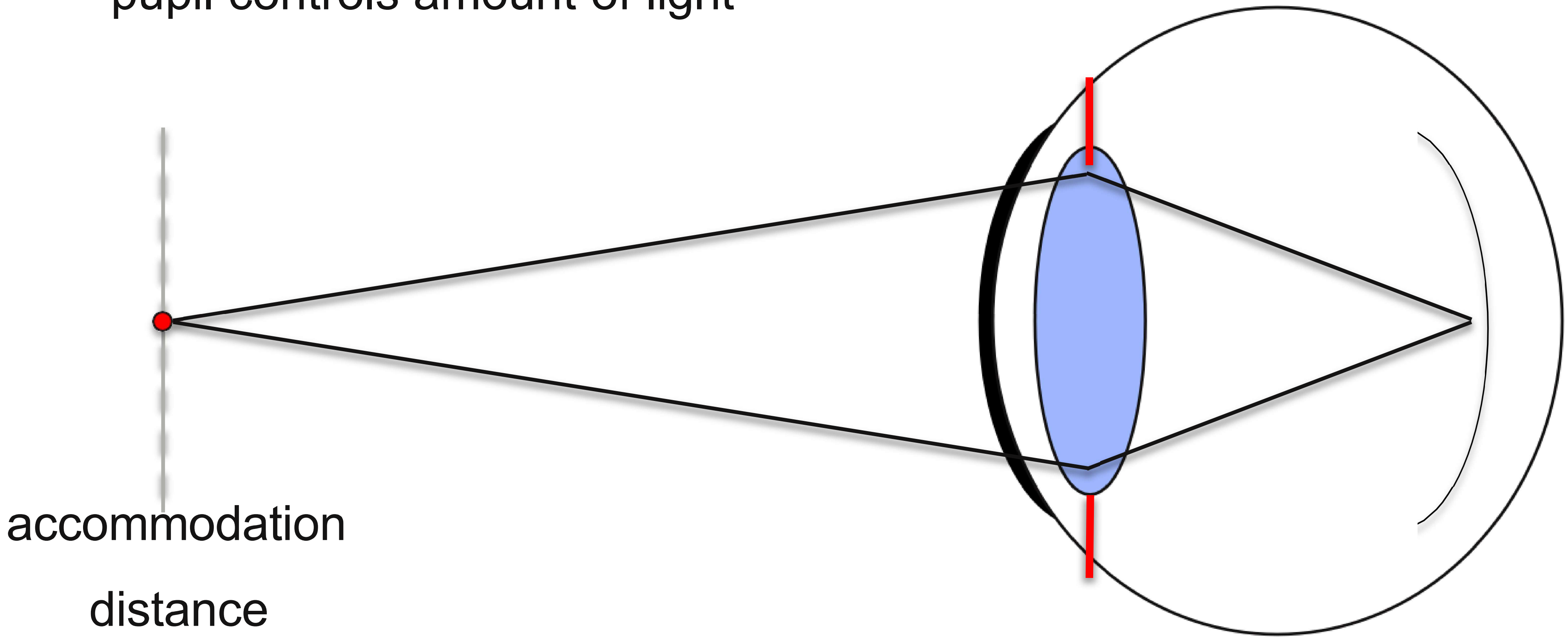
Retinal Blur

- pupil controls amount of light



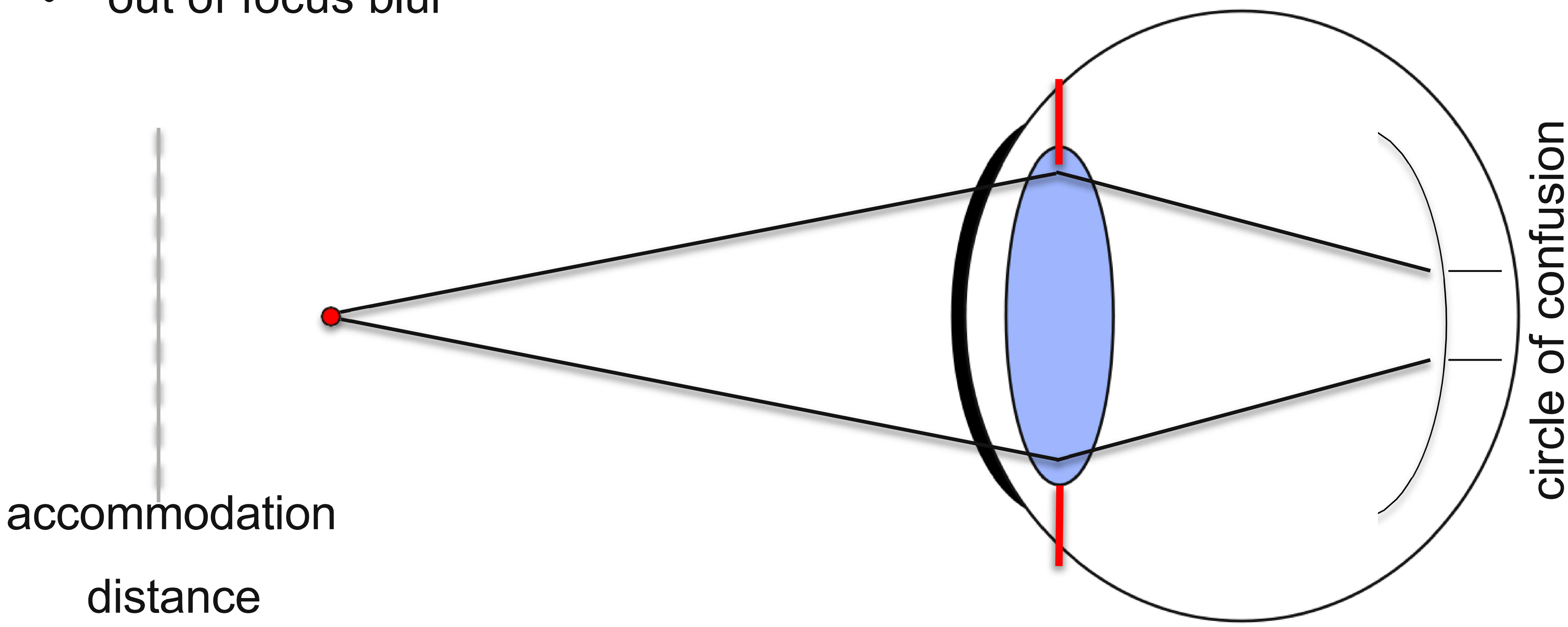
Retinal Blur

- pupil controls amount of light



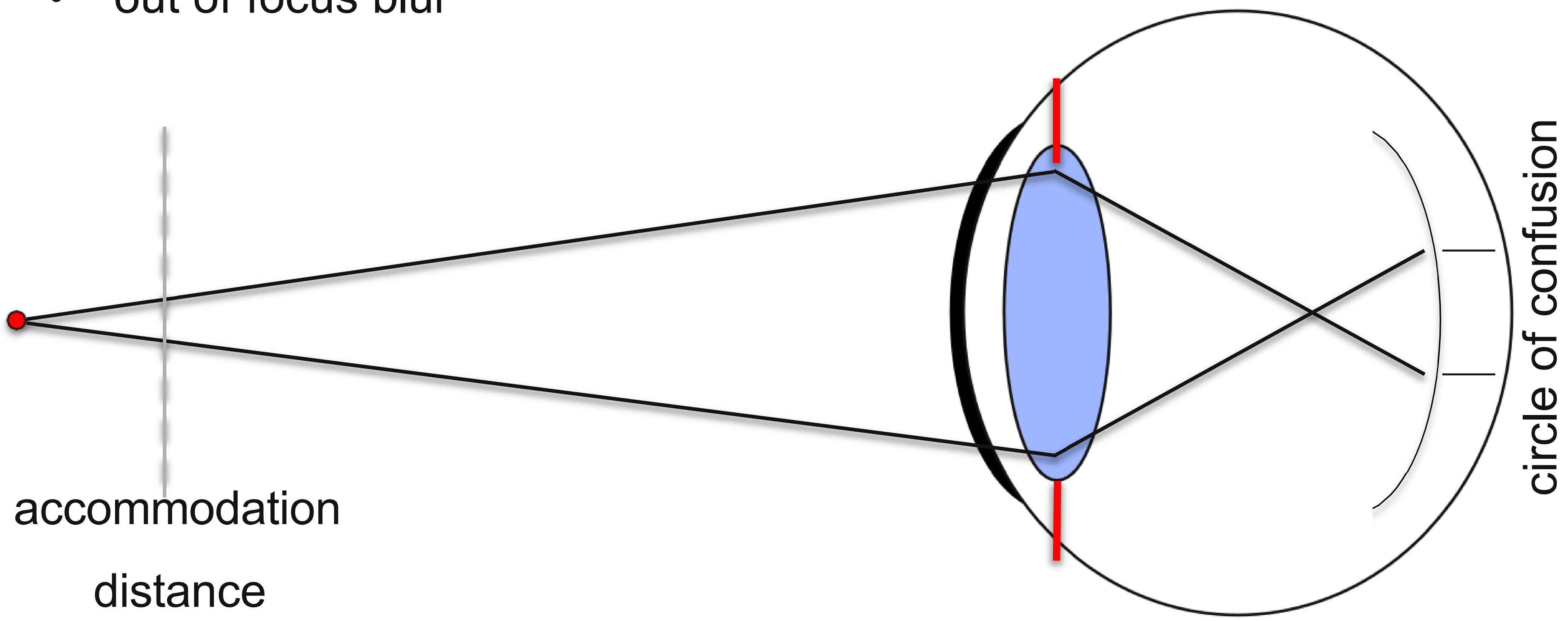
Retinal Blur

- out of focus blur



Retinal Blur

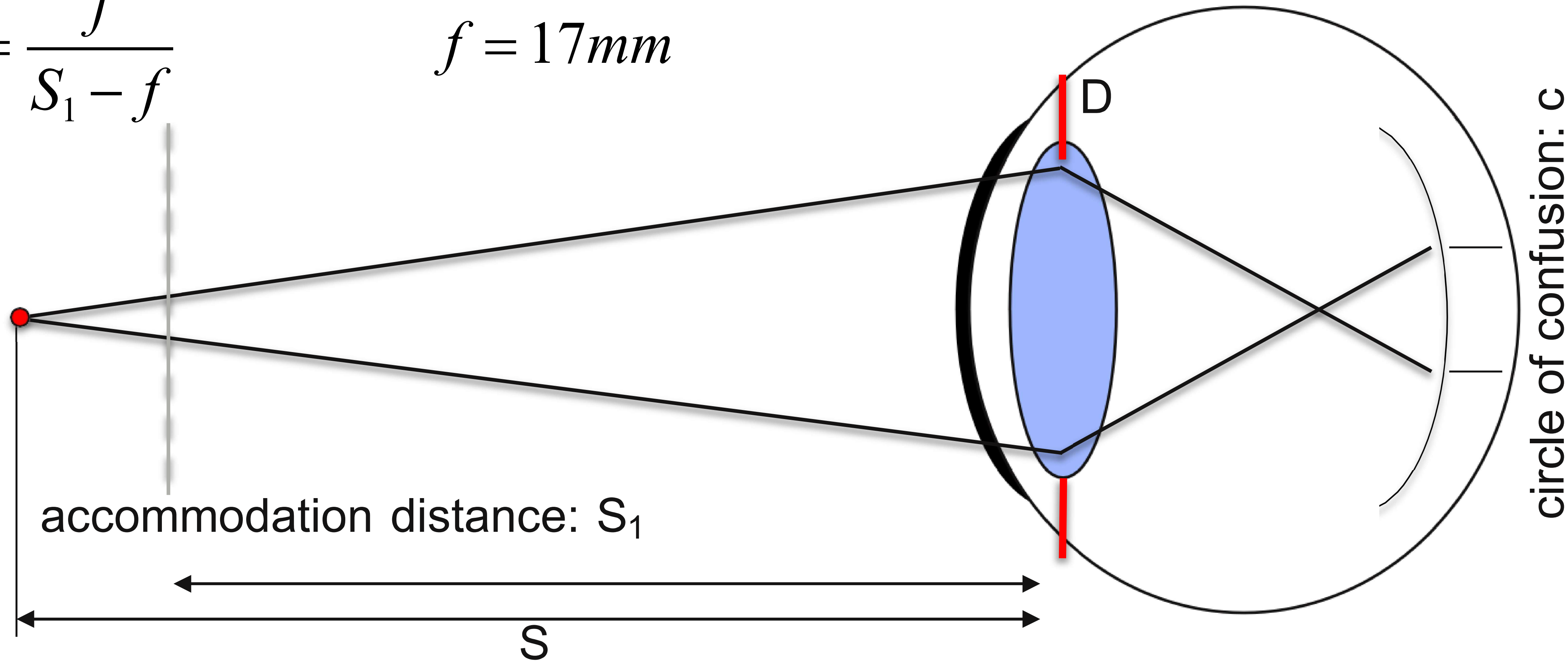
- out of focus blur



Retinal Blur / Depth of Field Rendering

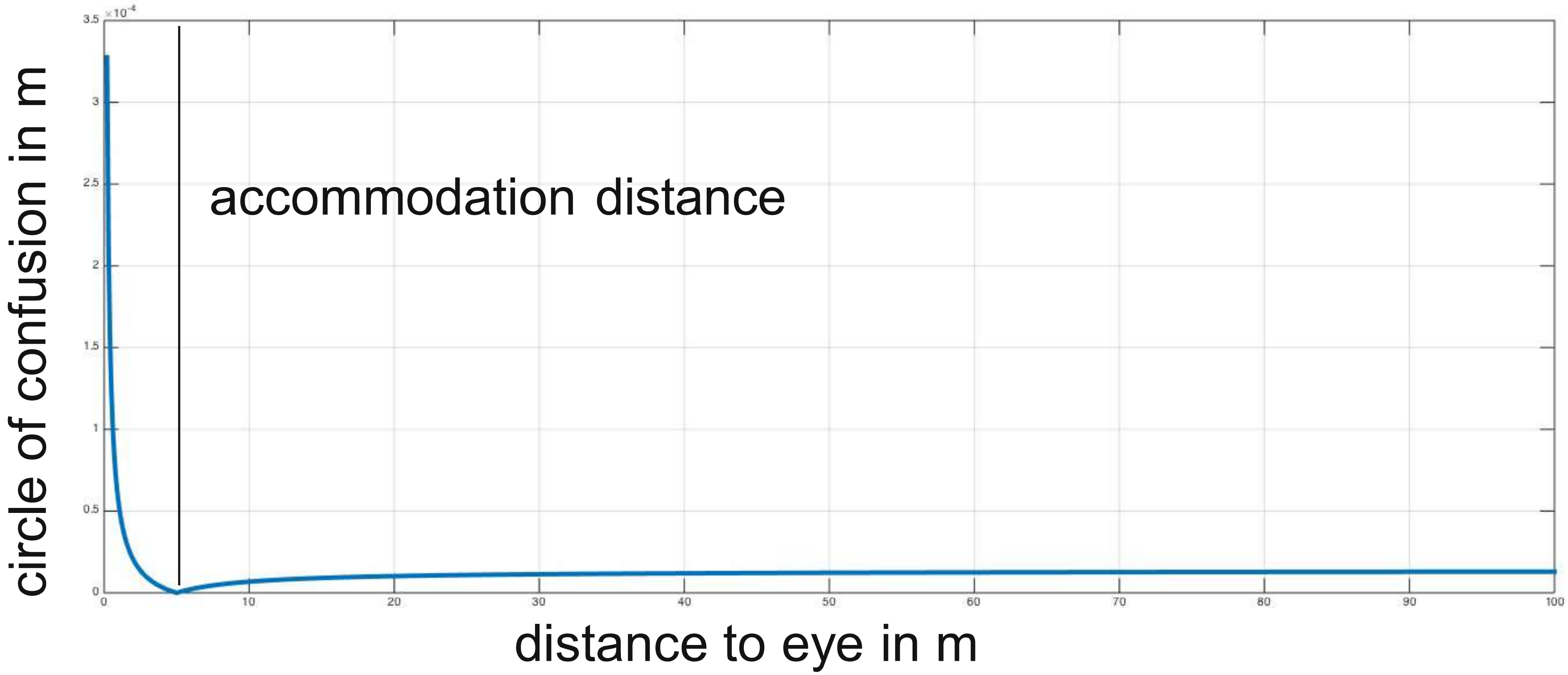
$$c = M \cdot D \cdot \frac{|S - S_1|}{S}$$

$$M = \frac{f}{S_1 - f} \qquad f = 17mm$$



Circle of Confusion

$$c = M \cdot D \cdot \frac{|S - S_1|}{S}$$



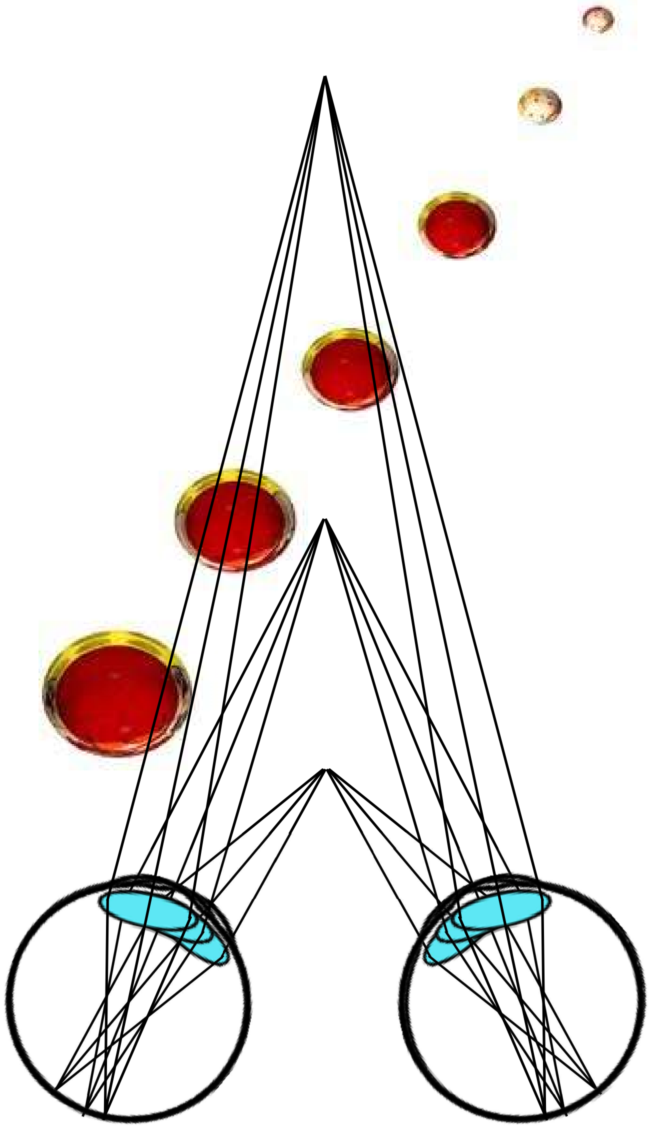
Blur Affects Relative Object Size!

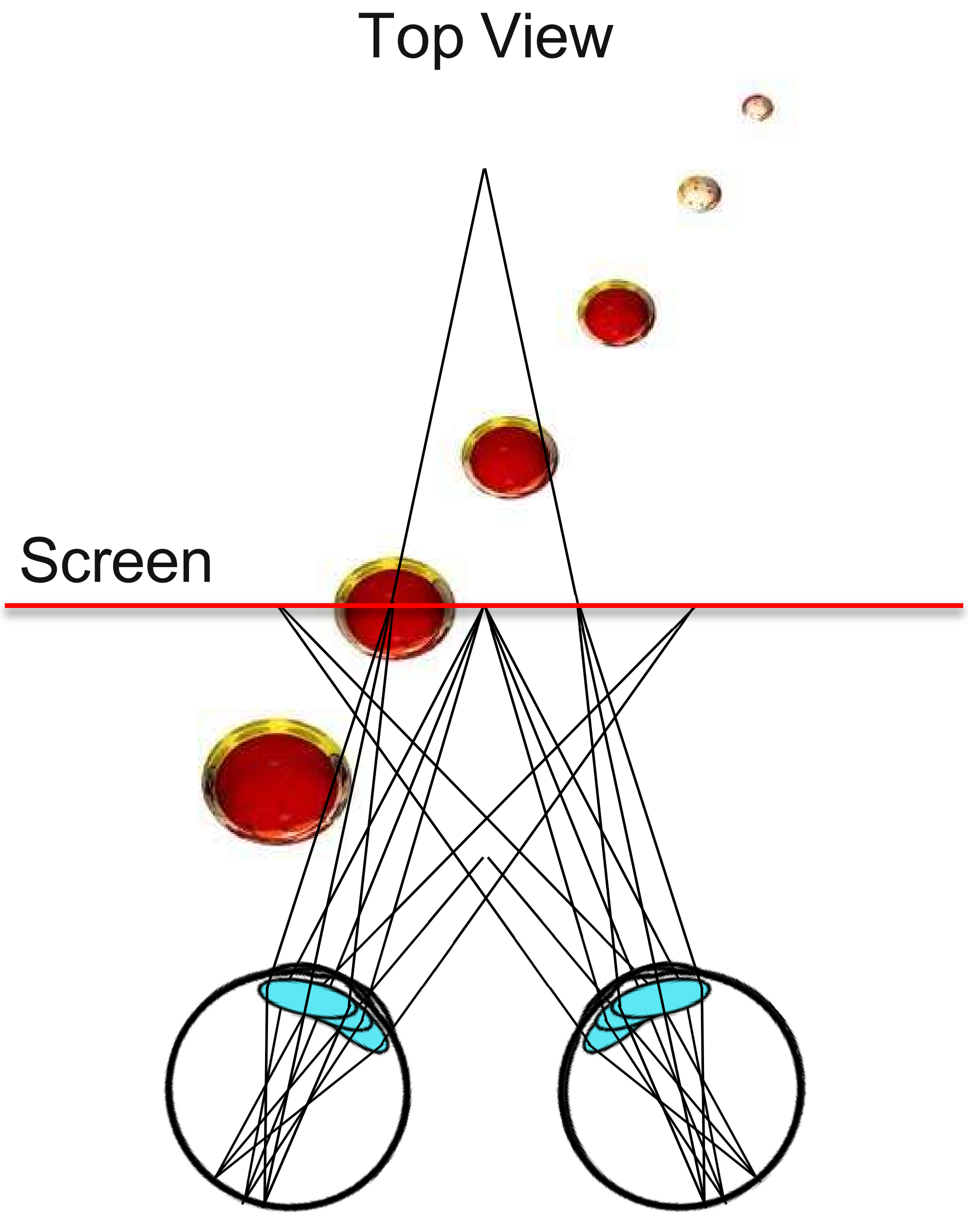
Held et al., 2006, ACM SIGGRAPH

Real World:

Vergence & Accommodation Match!

Top View



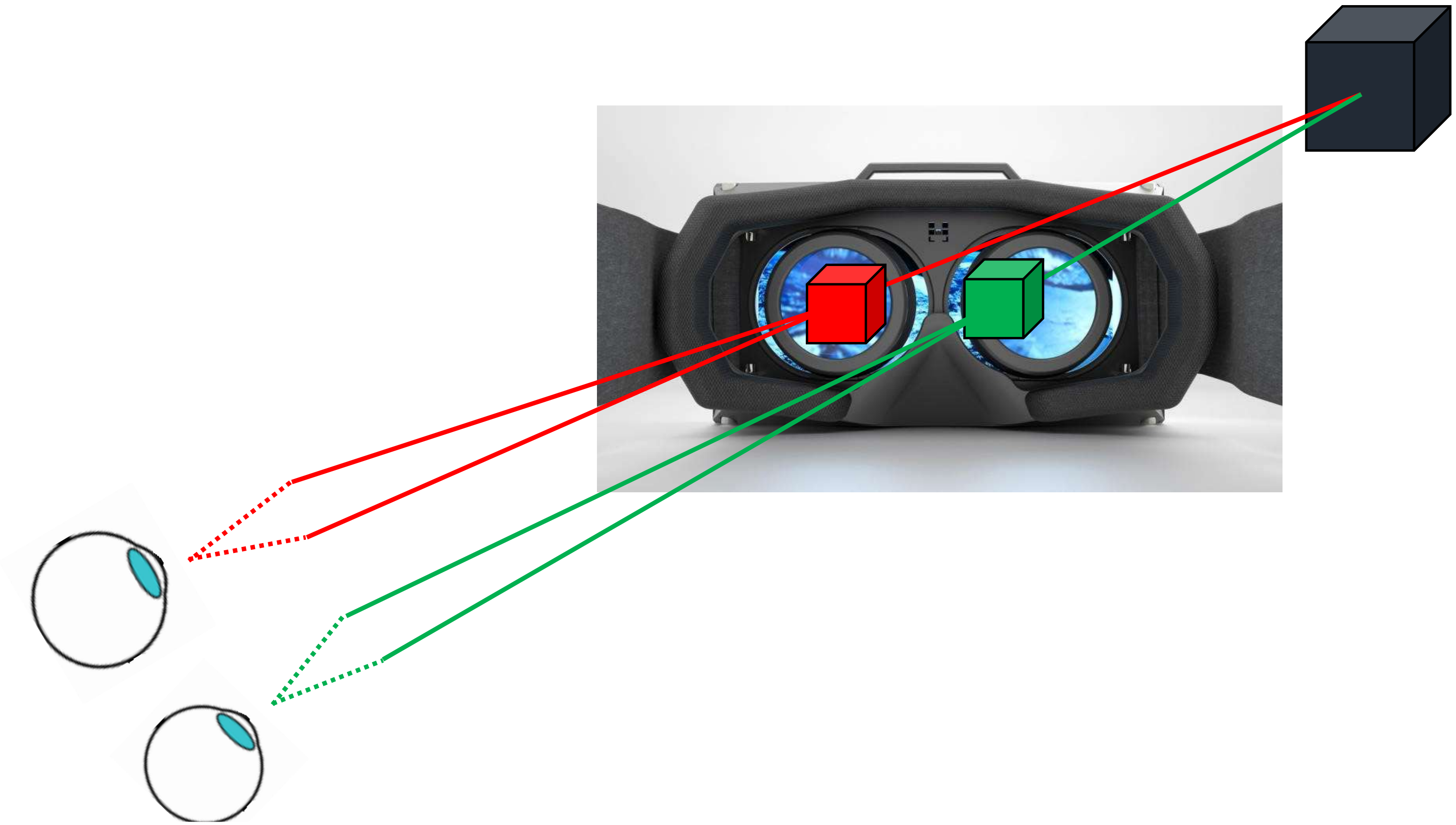


Stereo Displays Today:

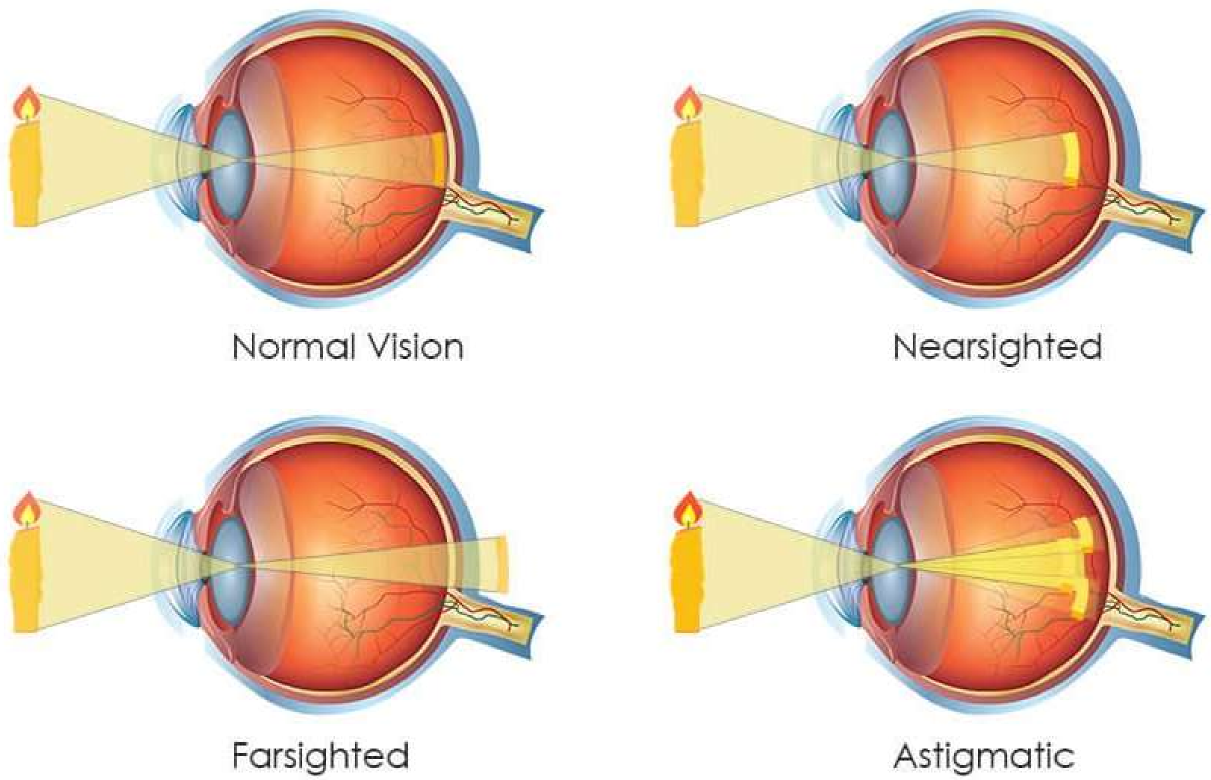
Vergence-Accommodation Mismatch!

Vergence-Accommodation Conflict

What visual/displays suffice for Vergence? Accommodation?

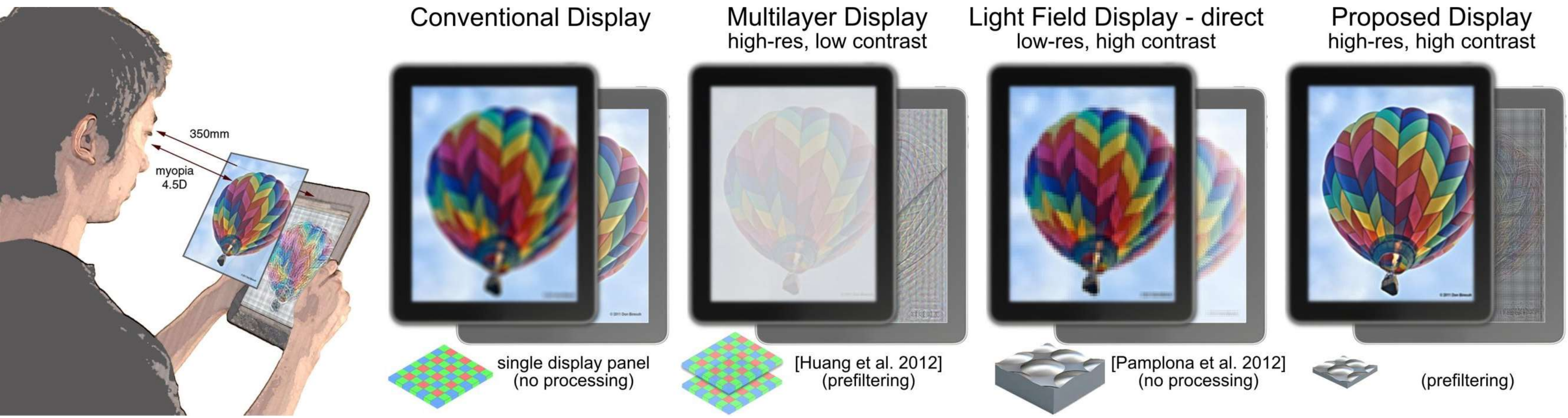


Myopia/near-sighted vs. hyperopia/far-sighted



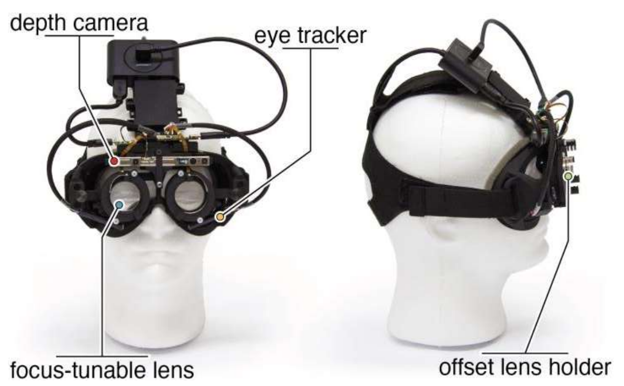
https://en.wikipedia.org/wiki/Depth_perception#/media/File:08913-Perspective_Run.jpg

Myopia/near-sighted vs. hyperopia/far-sighted



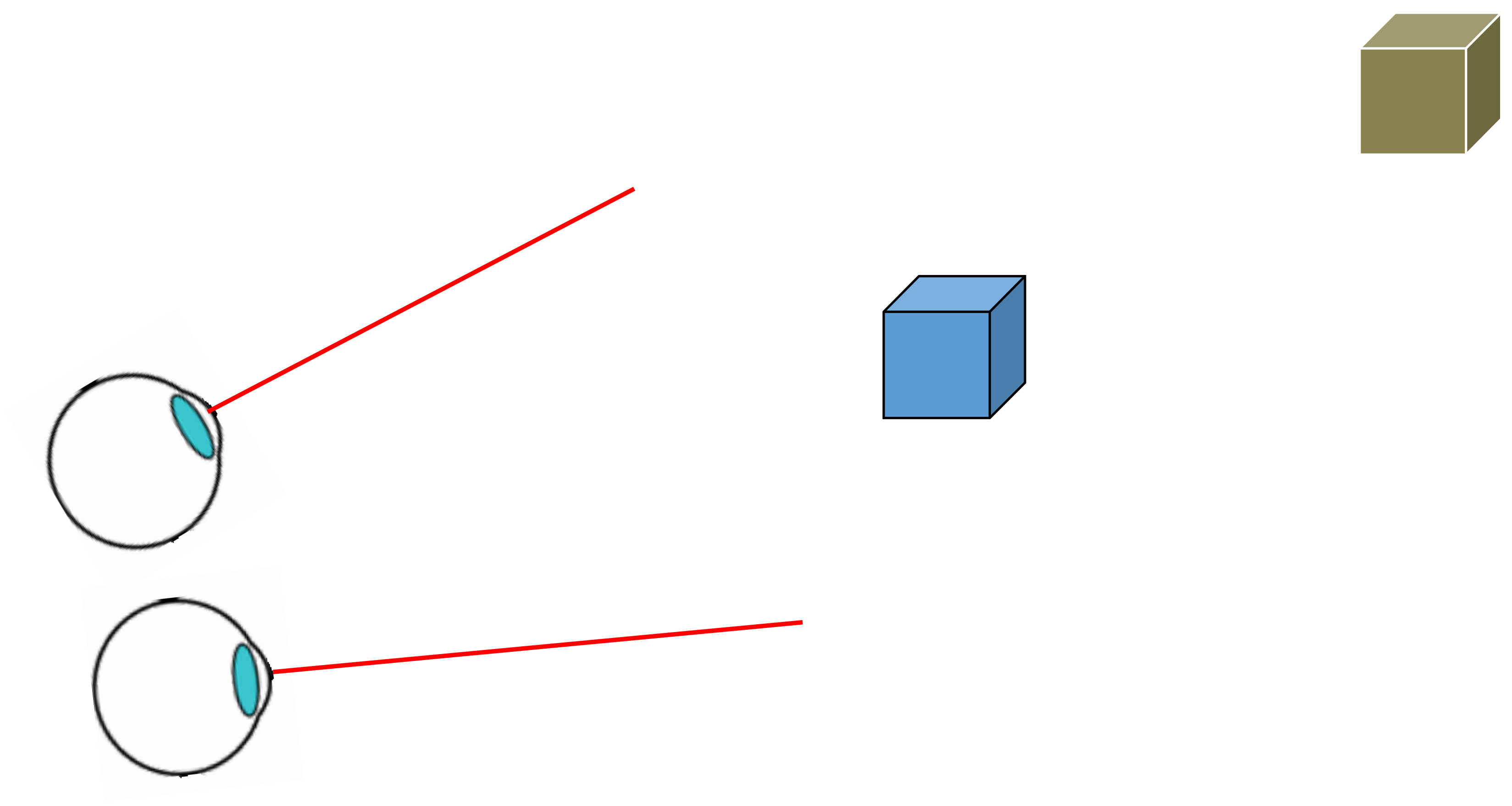
[Huang 2014 SIGGRAPH]

Myopia/near-sighted vs. hyperopia/far-sighted

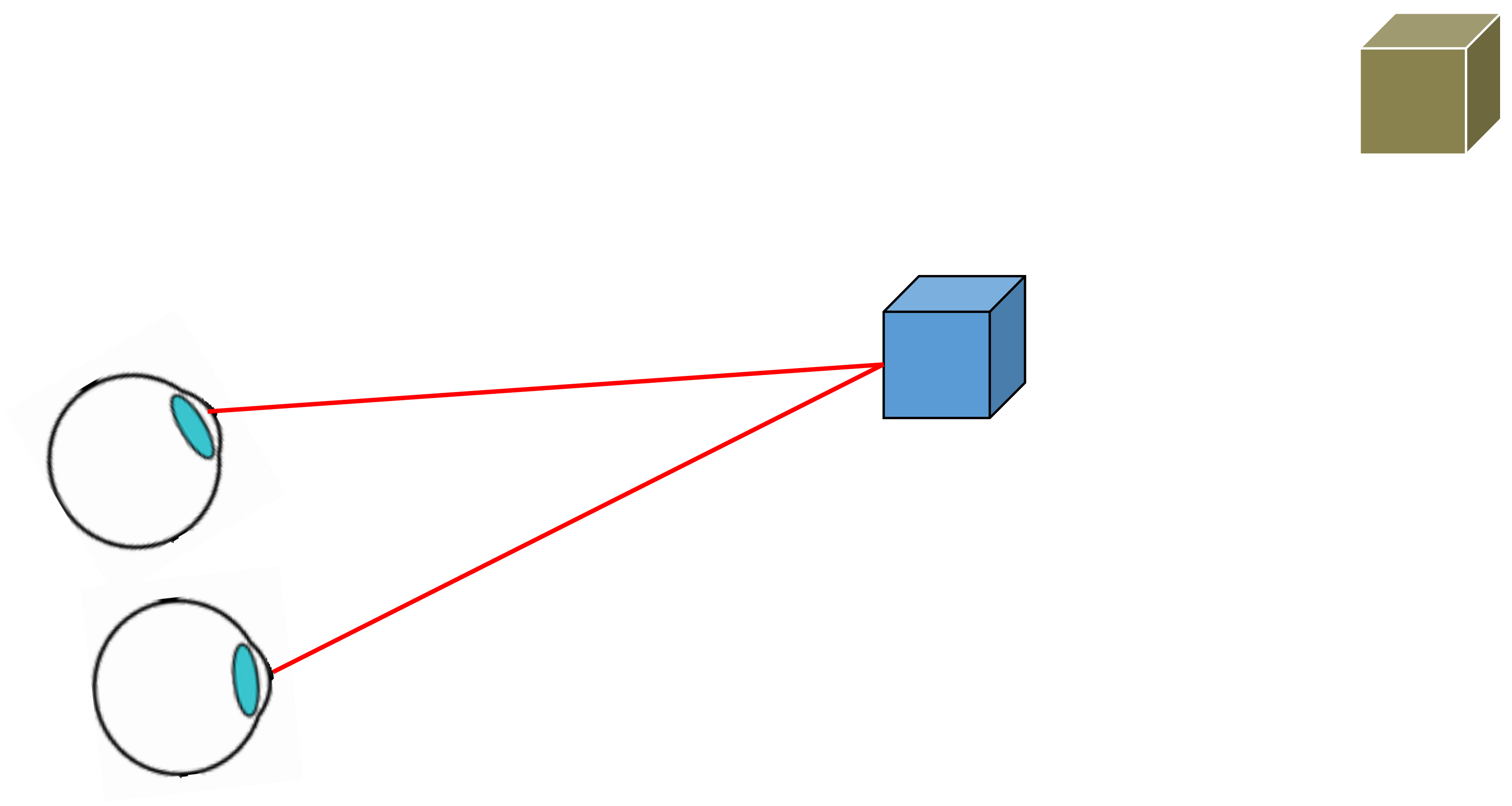


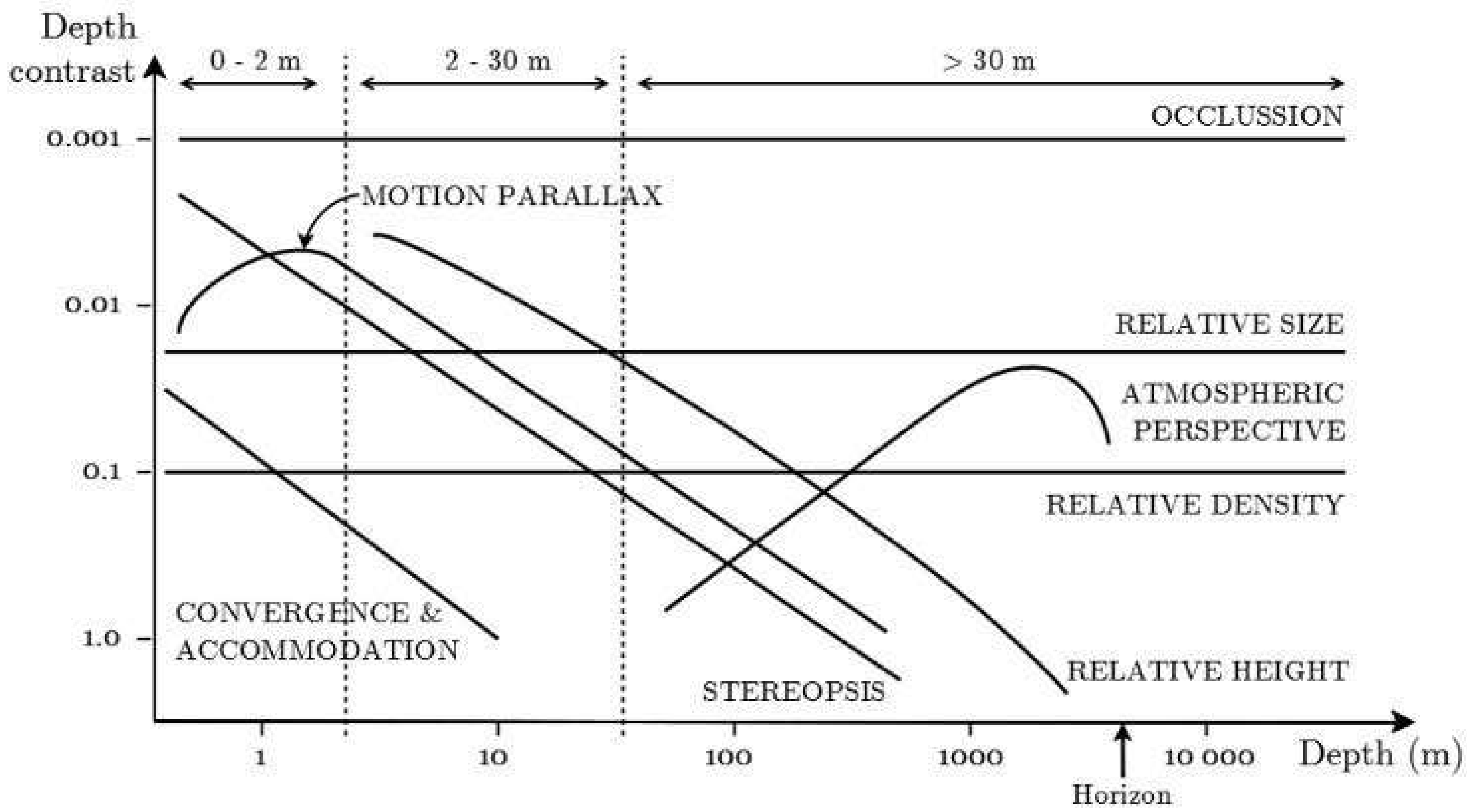
[Padmanaban 2019. Science Advances]

Binocular Cues – Vergence



Binocular Cues – Vergence





Cutting & Vishton, 1995

Temporal Behaviors

Temporal Behaviors

vergence

saccade

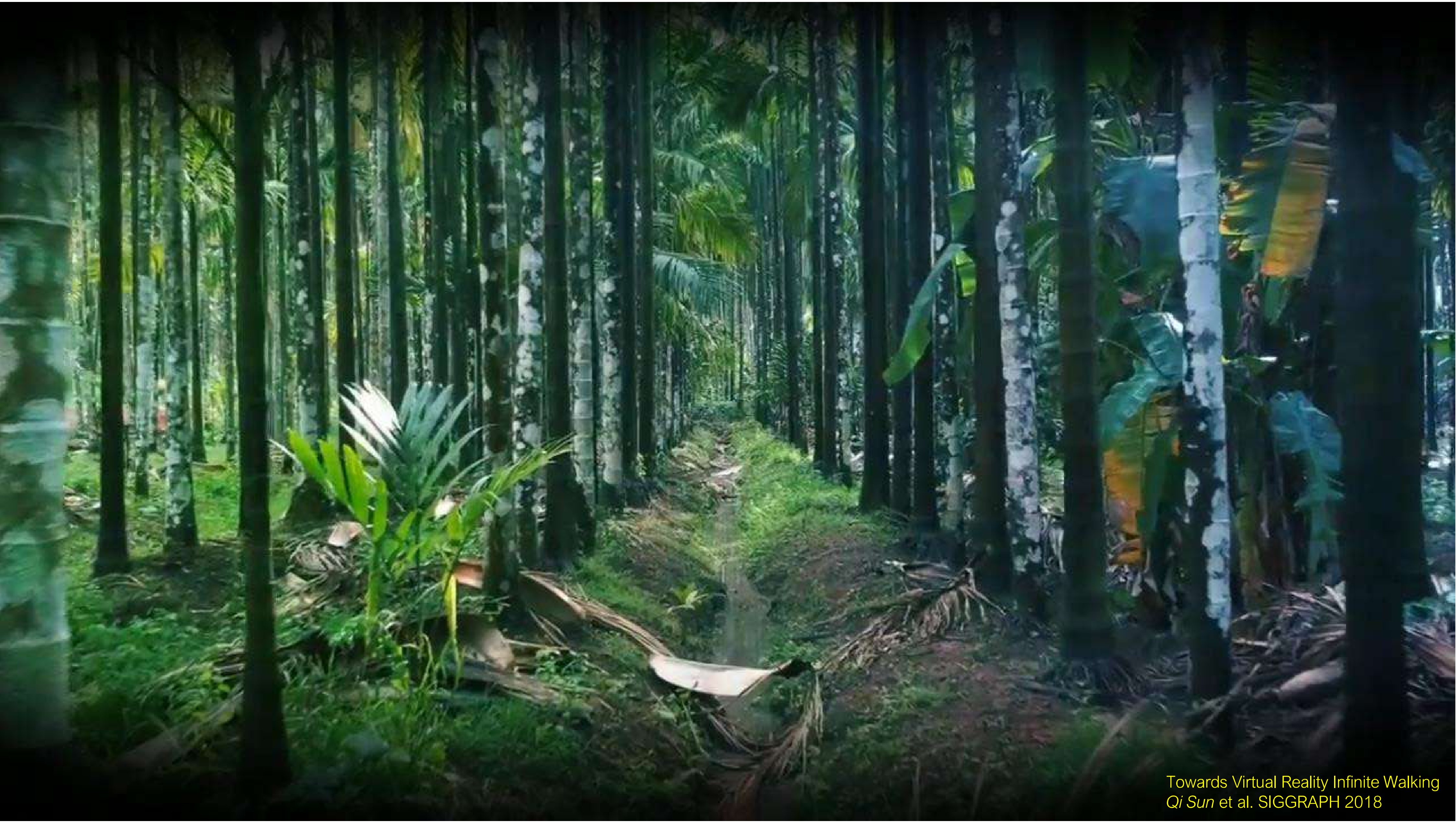
vestibulo–ocular reflex

Temporal Behaviors – Saccade (fast movement)

You are UNABLE to move slowly

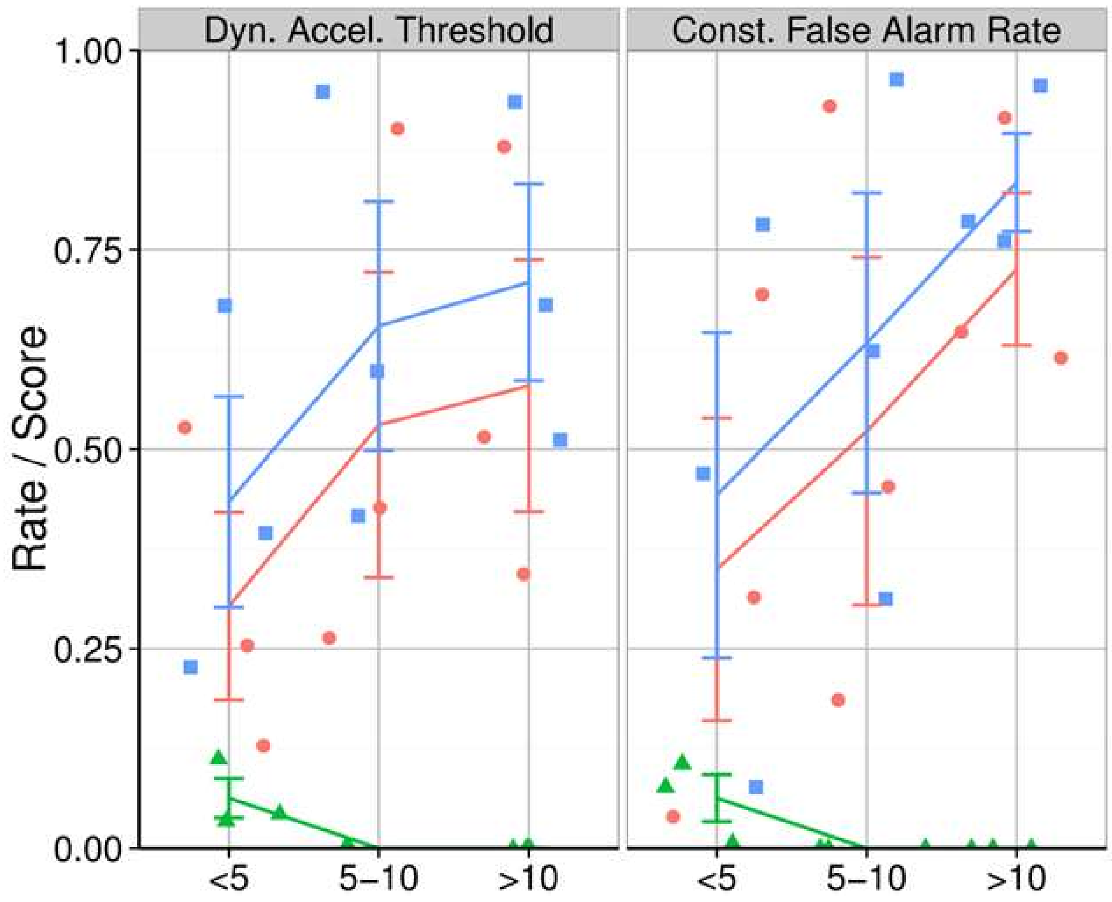
Spider Saccade

image courtesy: reddit user forte2


Towards Virtual Reality Infinite Walking
Qi Sun et al. SIGGRAPH 2018

Stopped Clock Effect

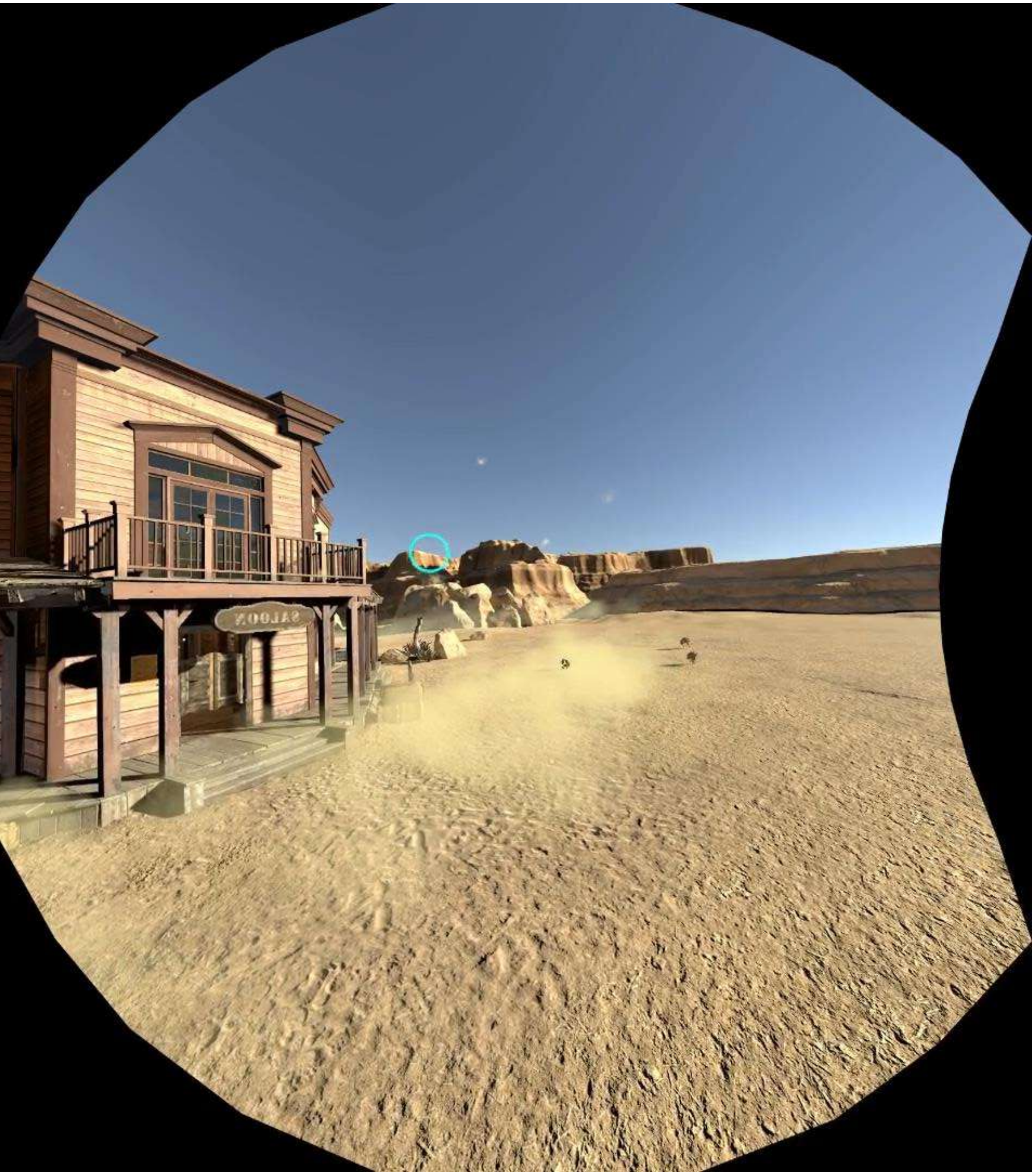
Imperceptible Angular Rotation

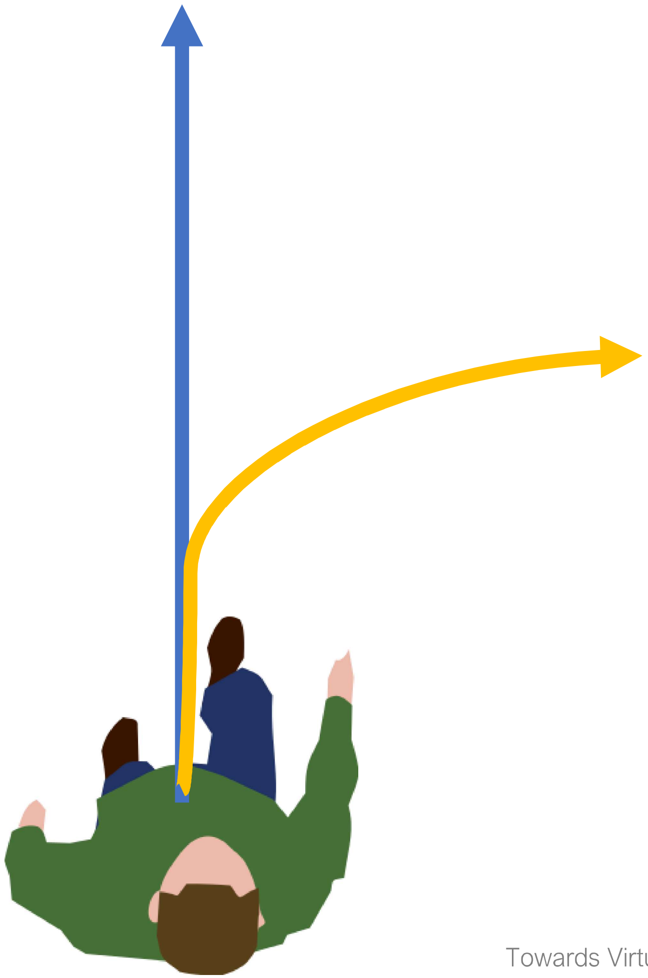


12.6 deg/sec

[Bolte et al., TVCG 2015]

Saccadic Redirection

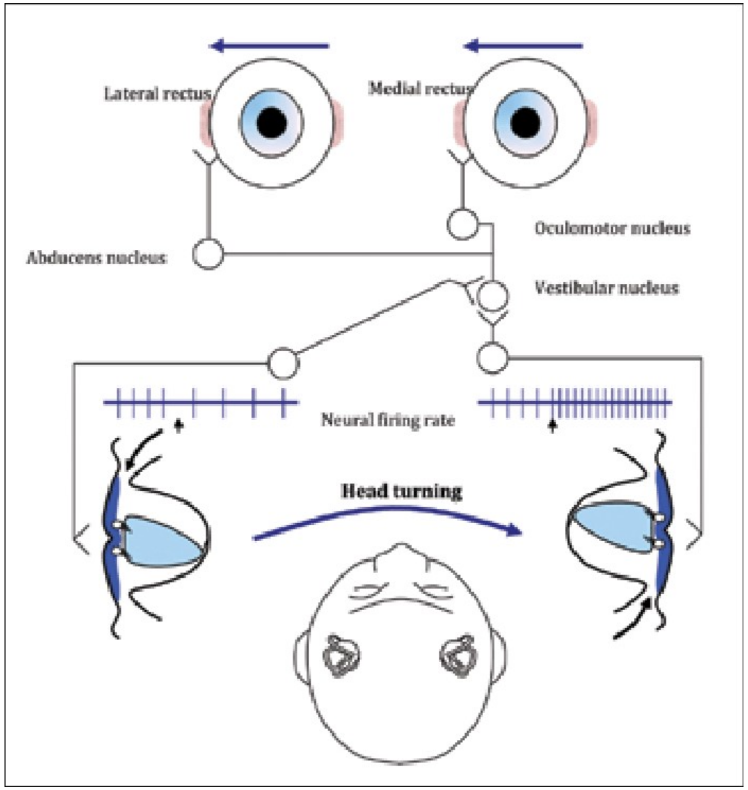




Towards Virtual Reality Infinite Walking
Qi Sun et al. SIGGRAPH 2018


SACCADIC REDIRECTED
BEYOND ROOM SCALE: EXPLOITING GAZE TO MAKE LARGER
NVIDIA RESEARCH AND ADOBE RESEARCH

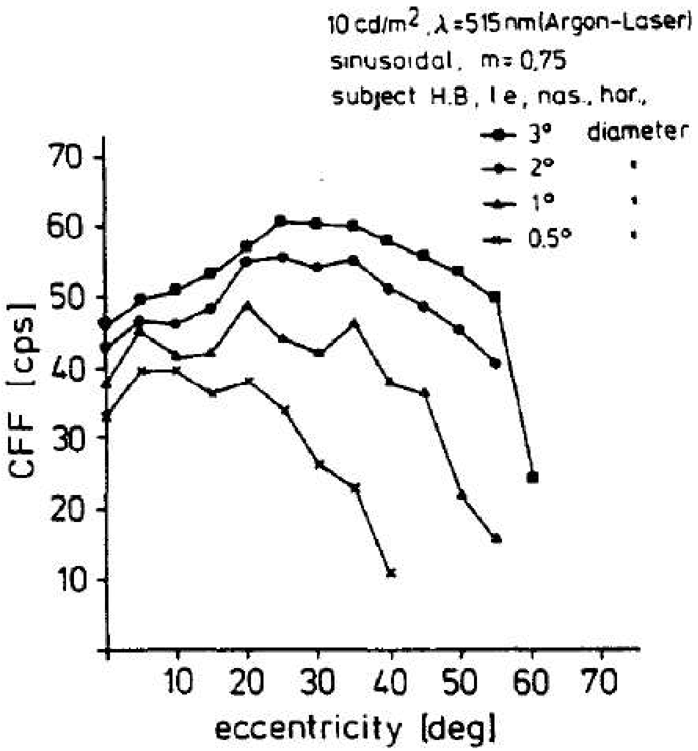
Temporal Behaviors – Vestibular-Ocular Reflex

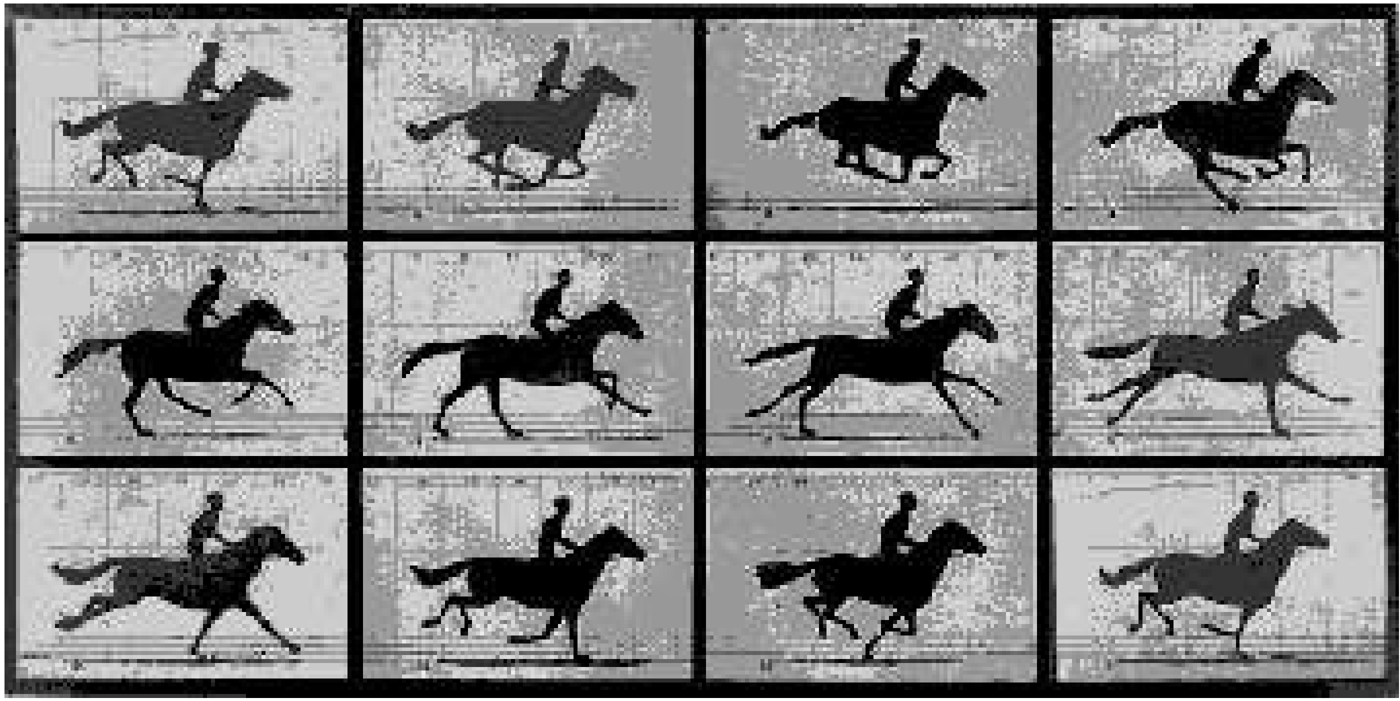


https://www.youtube.com/watch?v=6RCOEElKj6c&t=6s

Temporal Model: Our Eyes Sample@30FPS

Persistence of vision/Flicker Fusion





[Hartman et al.. 1978]