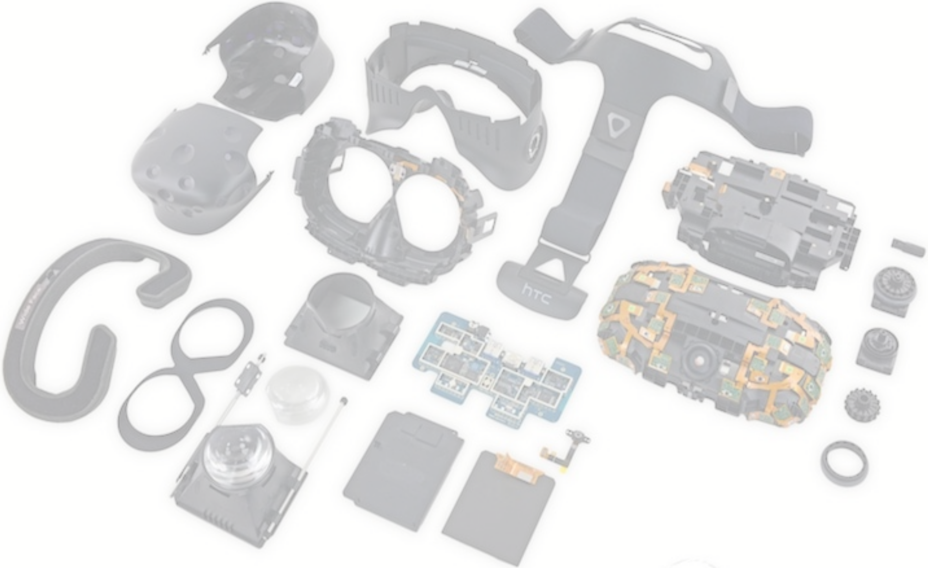
The Human Visual System



Gordon Wetzstein
Stanford University

EE 267 Virtual Reality

Lecture 5

stanford.edu/class/ee267/

nautilus eye, wikipedia

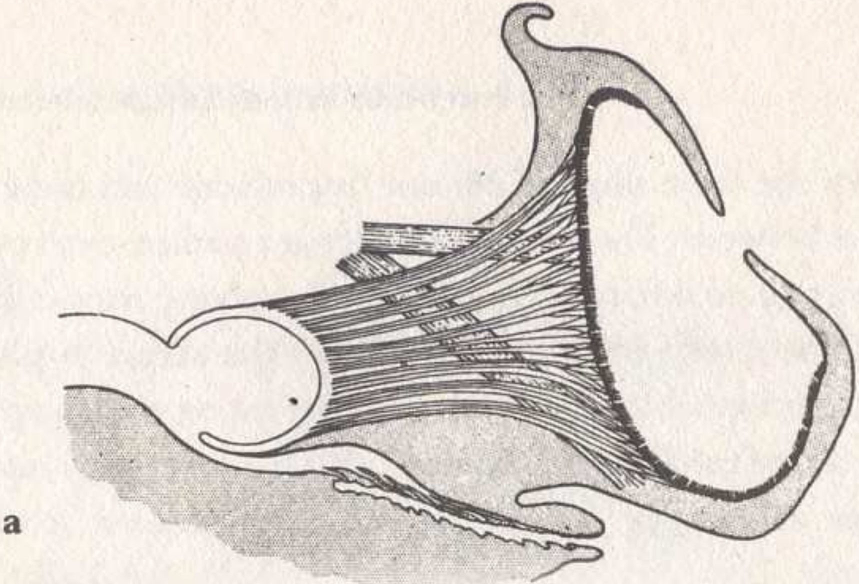
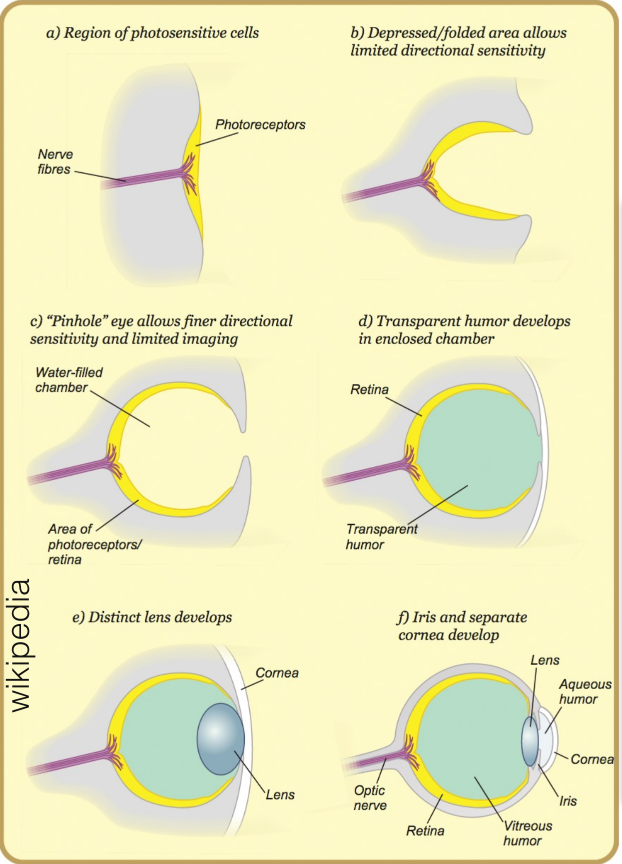


Figure 5.8 (opposite) A range of invertebrate eyes that illustrate approaches to the formation of crude but effective images: (a) *Nautilus*'s pinhole eye; (b) marine snail; (c) bivalve mollusc; (d) abalone; (e) ragworm.

Dawkins, "Climbing Mount Improbable", Norton & Company, 1997

reptile eye, http://pichost.me/1608580/

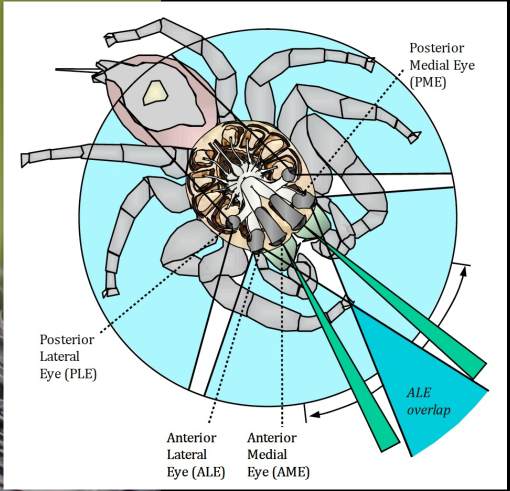
Evolution of the Eye



wikipedia

owl, https://www.pinterest.com/pin/452400725039917330/

pigeon, http://globe-views.com/dreams/pigeon.html



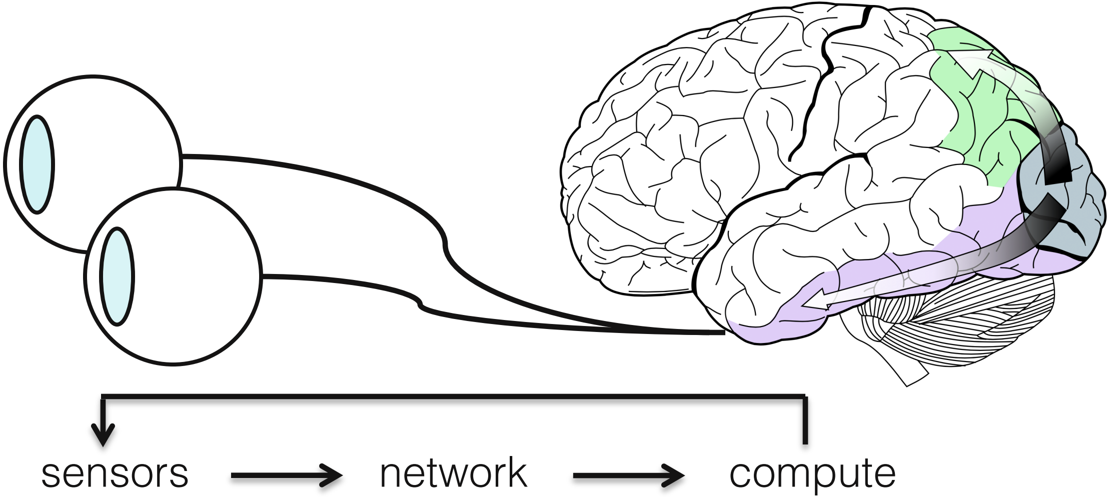
jumping spider, wikipedia

national geographics

Lecture Overview

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

Overview



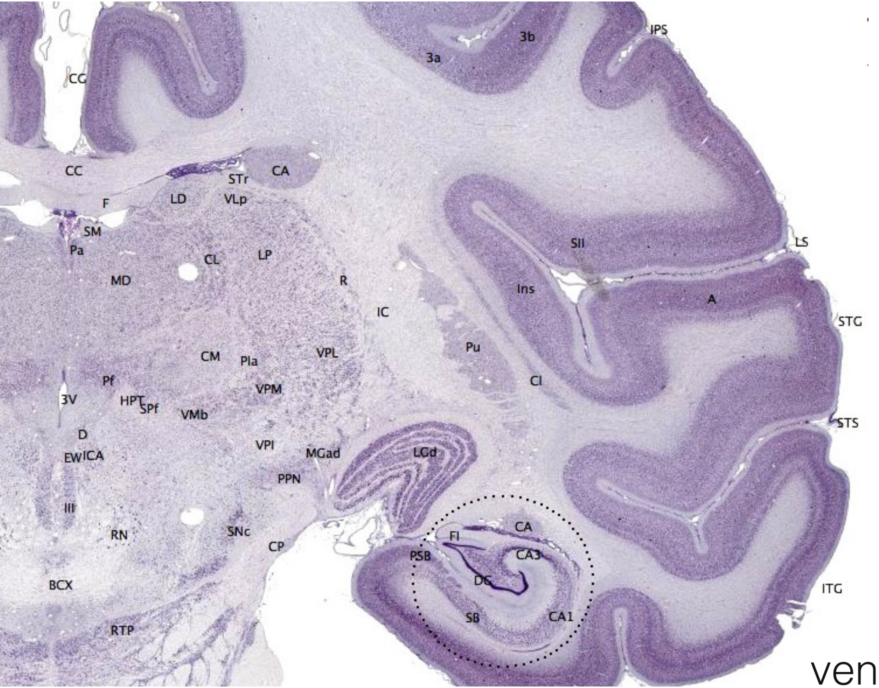
sensors → network → compute

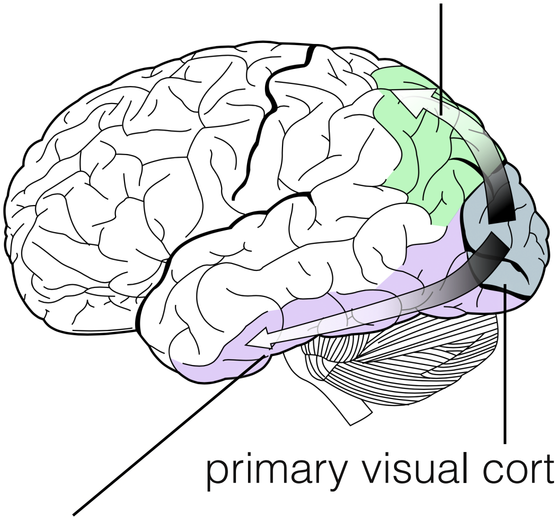
low-level processing

high-level processing

wikipedia

Overview





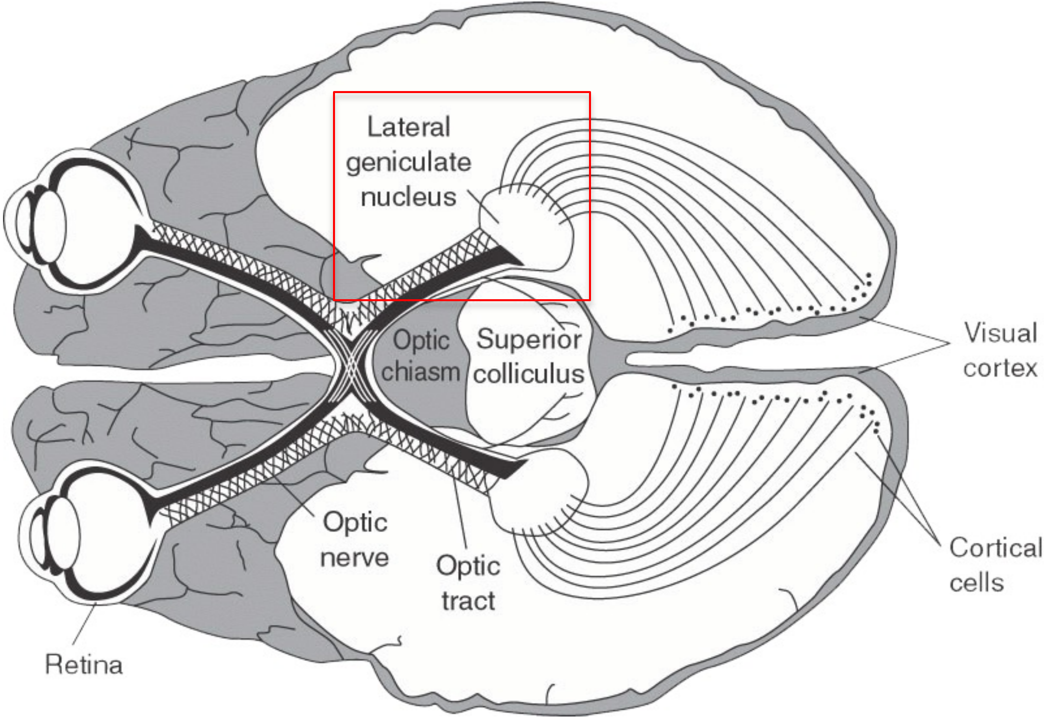
dorsal stream: spatial awareness

primary visual cortex

ventral stream:
recognition, object identification

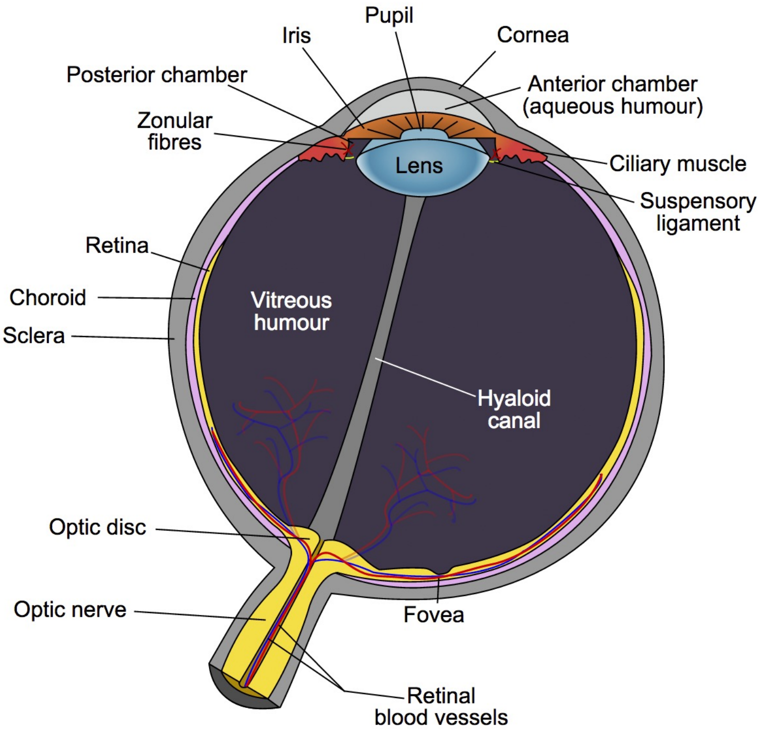
wikipedia

Overview



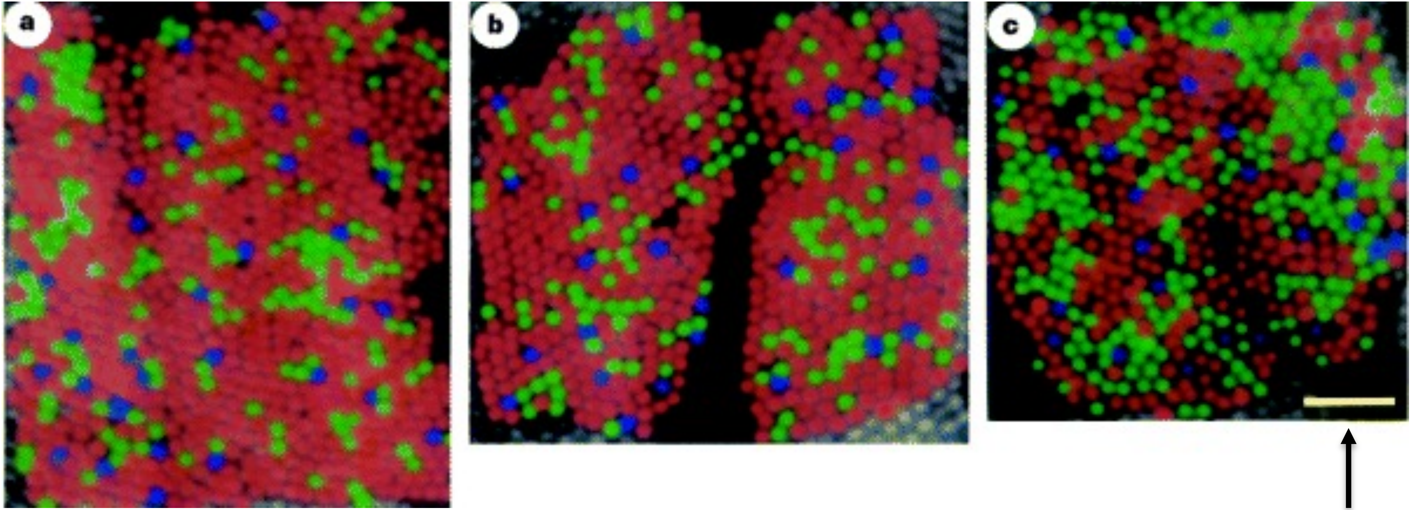
van der Helm

Anatomy of the Human Eye



The Retina

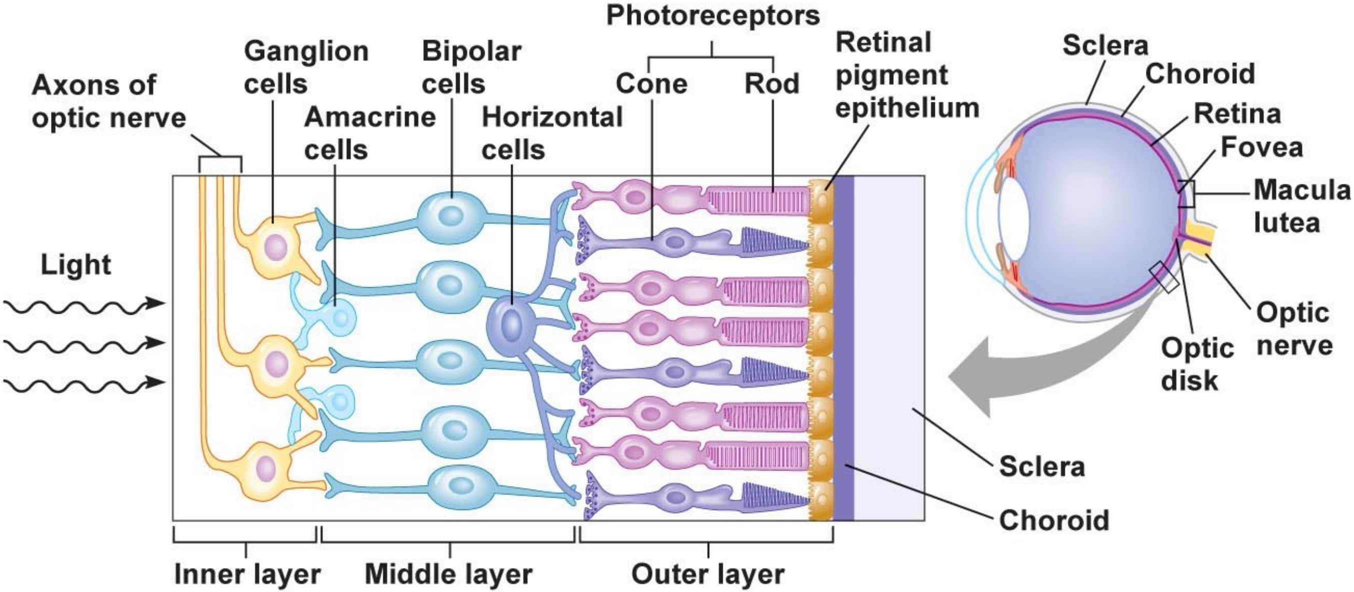
Roorda & Williams, 1999, Nature



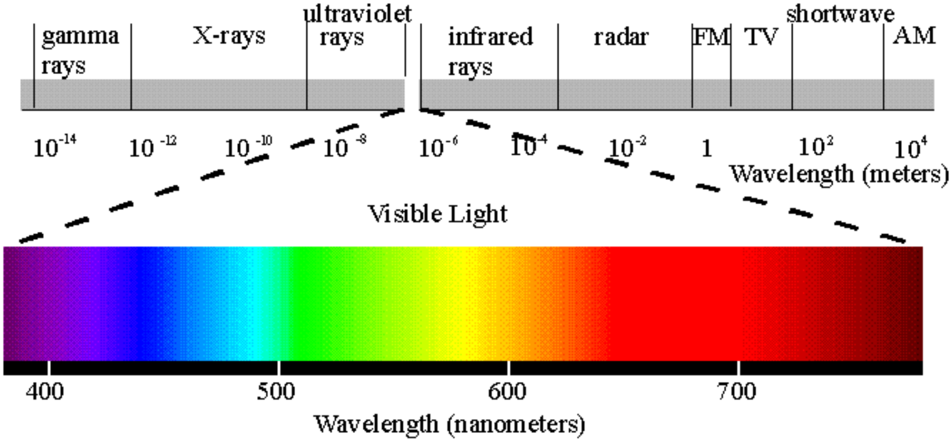
5 arcmin visual angle

photoreceptors: 3 types of cones (color vision), rods (luminance only, night vision)

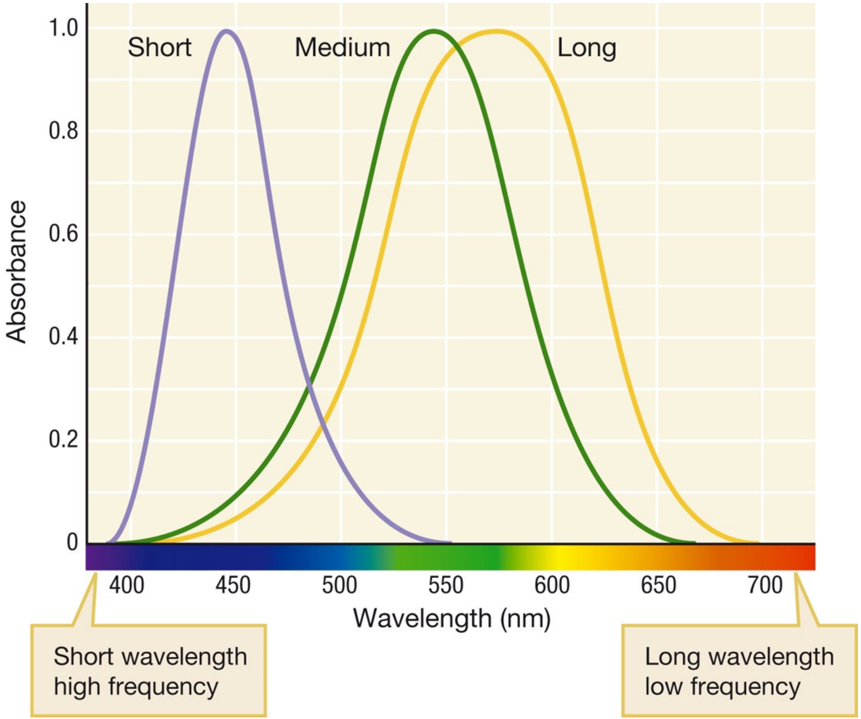
The Retina


Photoreceptors
Ganglion cells
Bipolar cells
Cone
Rod
Retinal pigment epithelium
Sclera
Choroid
Axons of optic nerve
Amacrine cells
Horizontal cells
Retina
Fovea
Macula lutea
Light
Optic nerve
Optic disk
Sclera
Choroid
Inner layer
Middle layer
Outer layer

Color Perception



Color Perception - Sensitivity of Cones

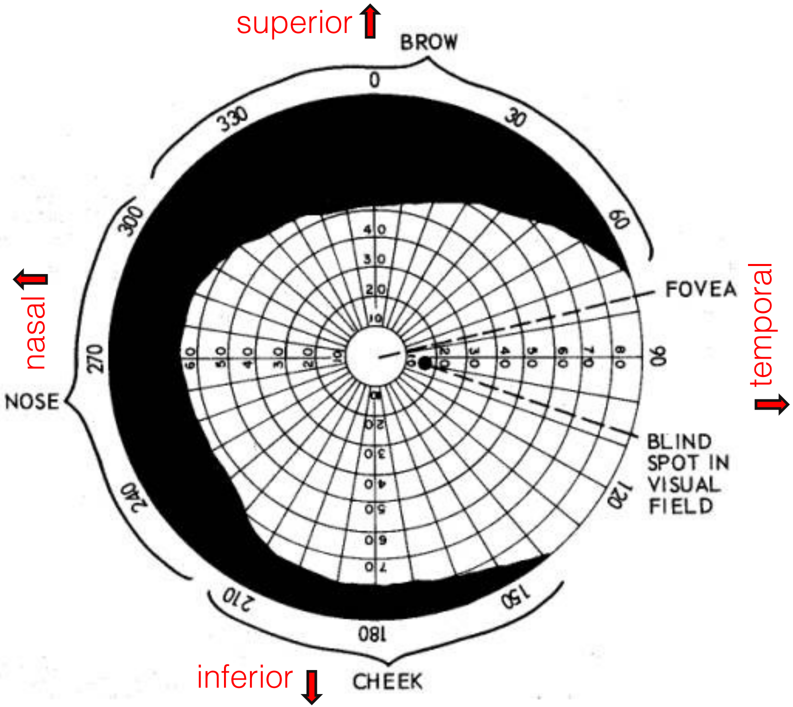


Short wavelength
high frequency

Long wavelength
low frequency

reddit.com

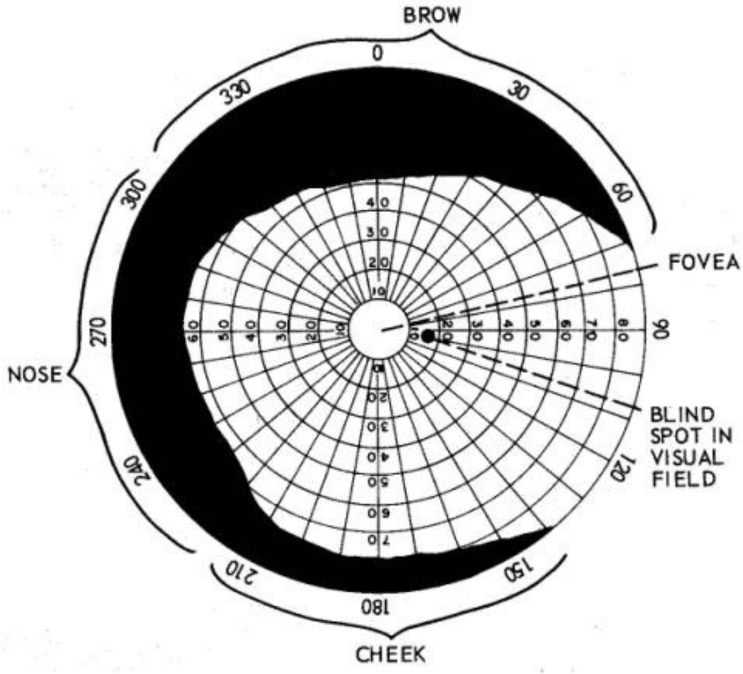
Visual Field



monocular visual field of right eye

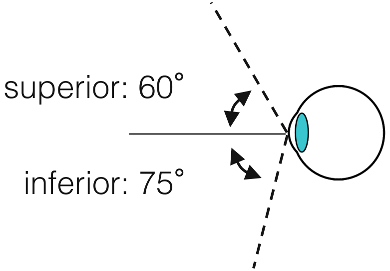
Ruch & Fulton, 1960

Visual Field



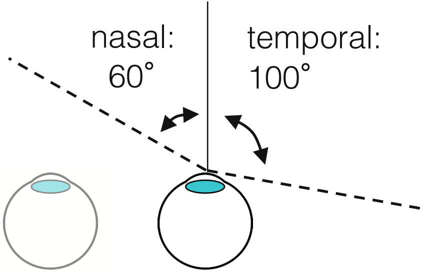
monocular visual field of right eye

Ruch & Fulton, 1960


superior: 60°

inferior: 75°

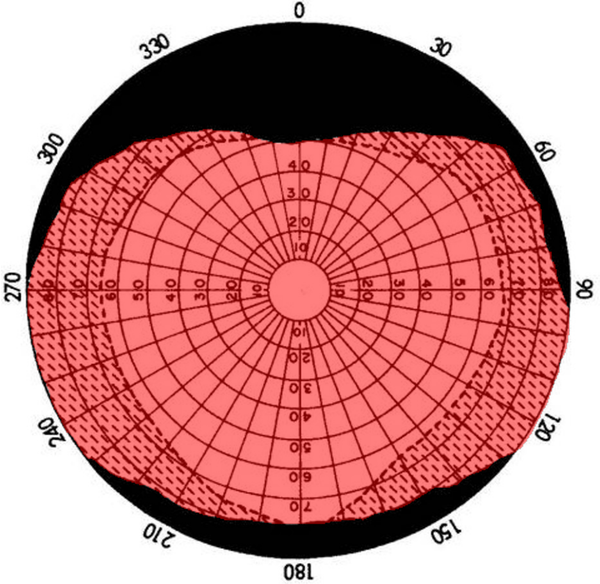
vertical (superior / inferior directions)


nasal: 60°

temporal: 100°

horizontal (nasal / temporal directions)

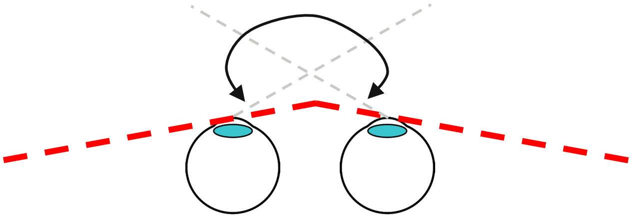
Visual Field



Ruch & Fulton, 1960

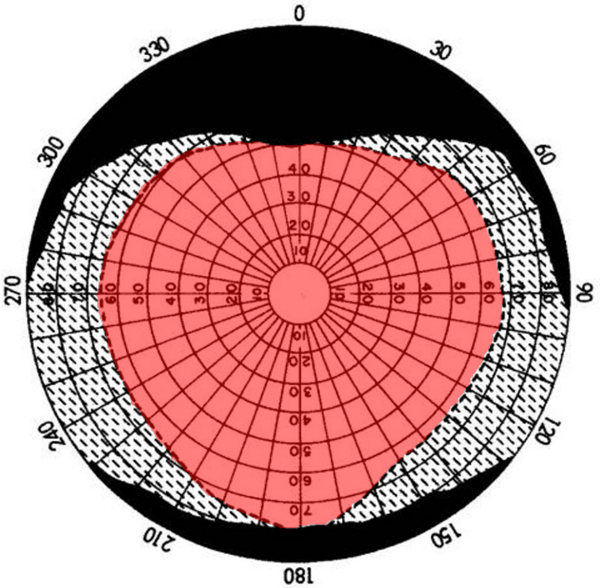
visual field of both eyes

temporal left + temporal right: 200°



total visual field of both eyes

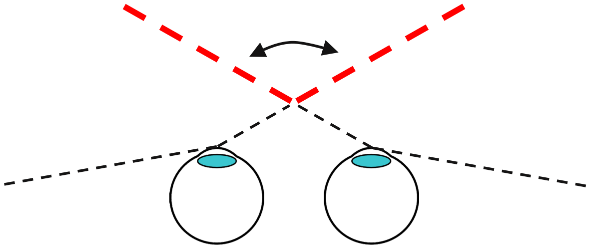
Visual Field



Ruch & Fulton, 1960

visual field of both eyes

nasal left + nasal right: 120°



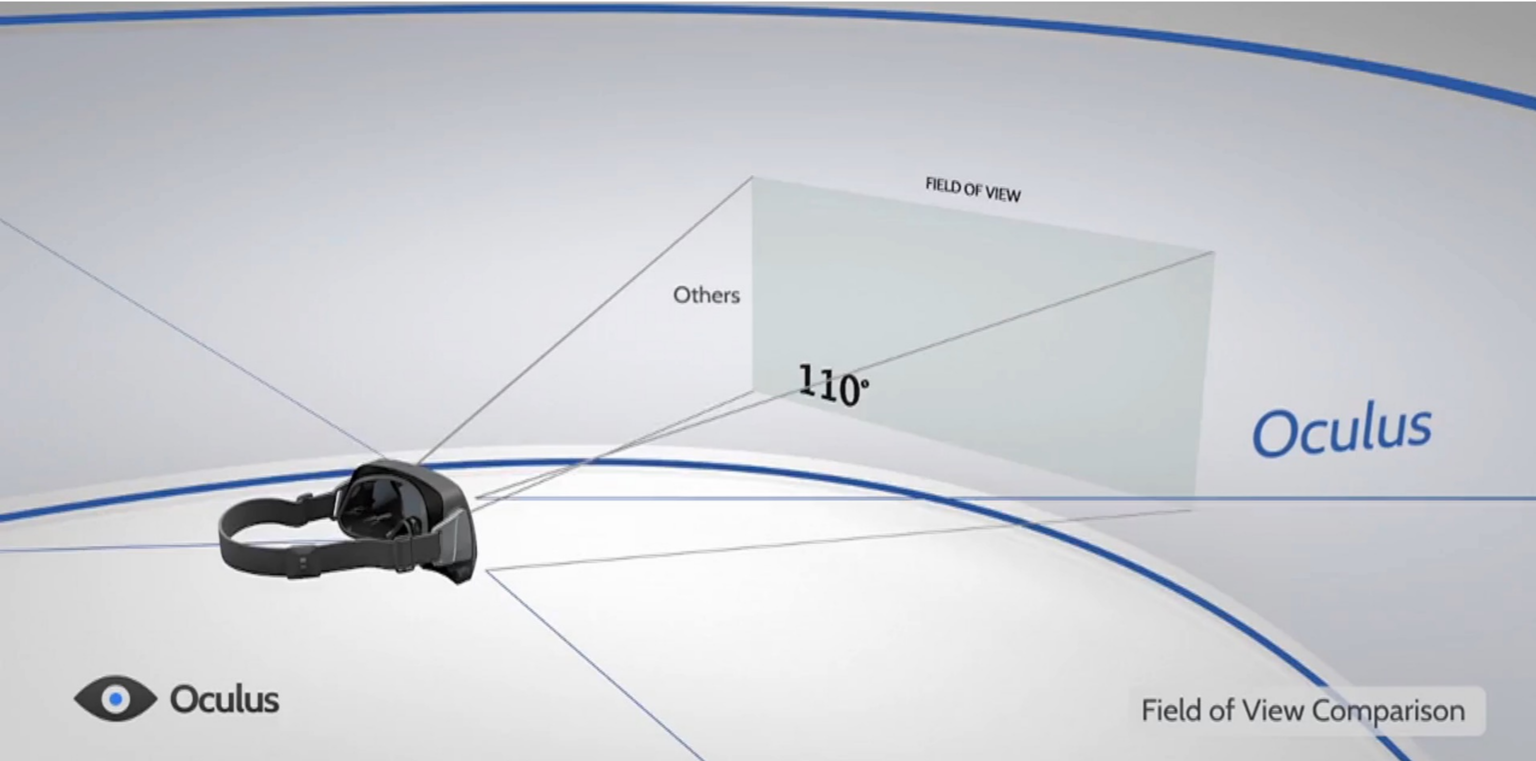
binocular visual field or region of binocular overlap

→ stereo vision

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!

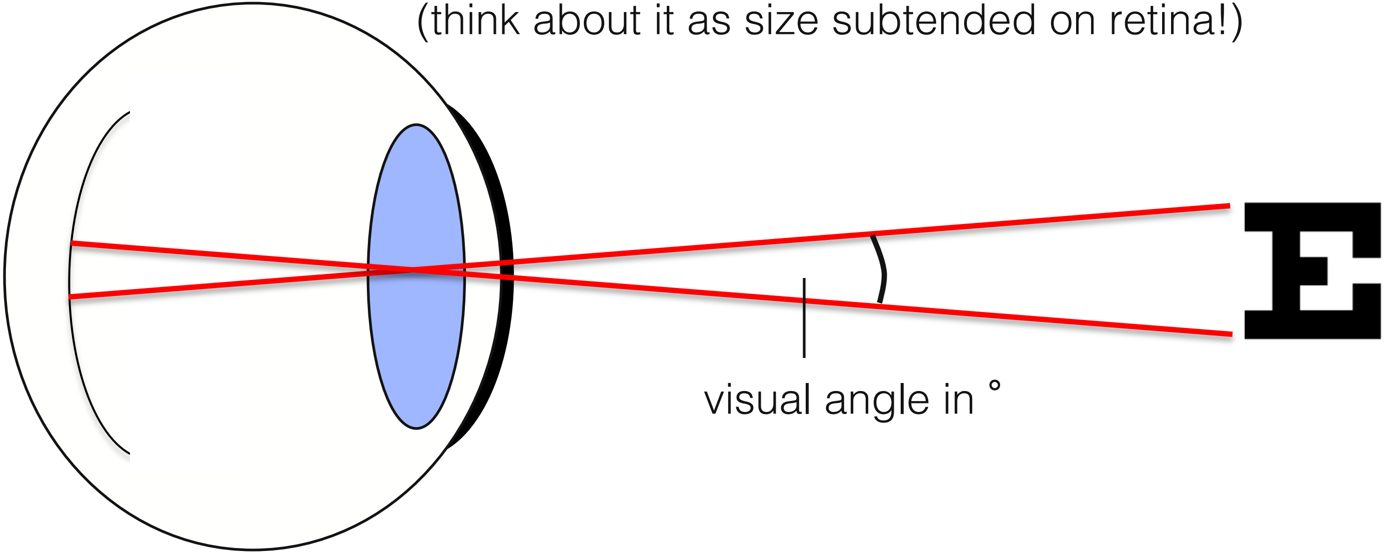
Immersive VR – How Important is the FOV?



Visual Angle

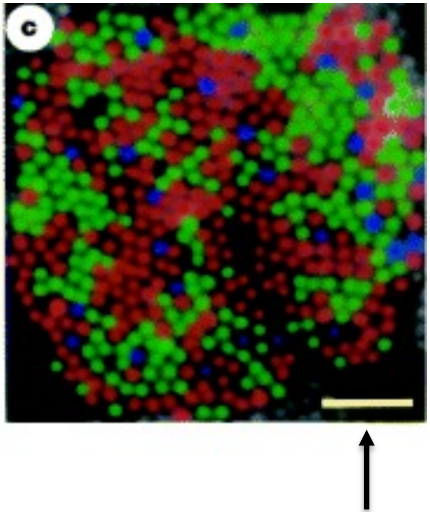
- vision scientists often measure size in visual angle
- visual angle ≈ object size / object distance in degree

(think about it as size subtended on retina!)



Visual Acuity

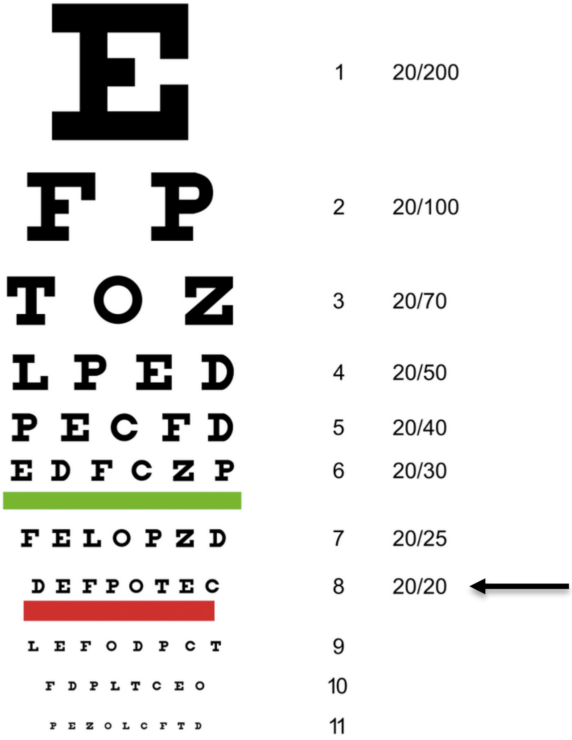
each photorecepter
~ 1 arc min (1/60 of a degree)
of visual angle



5 arcmin visual angle

Roorda & Williams, 1999, Nature

Visual Acuity



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:

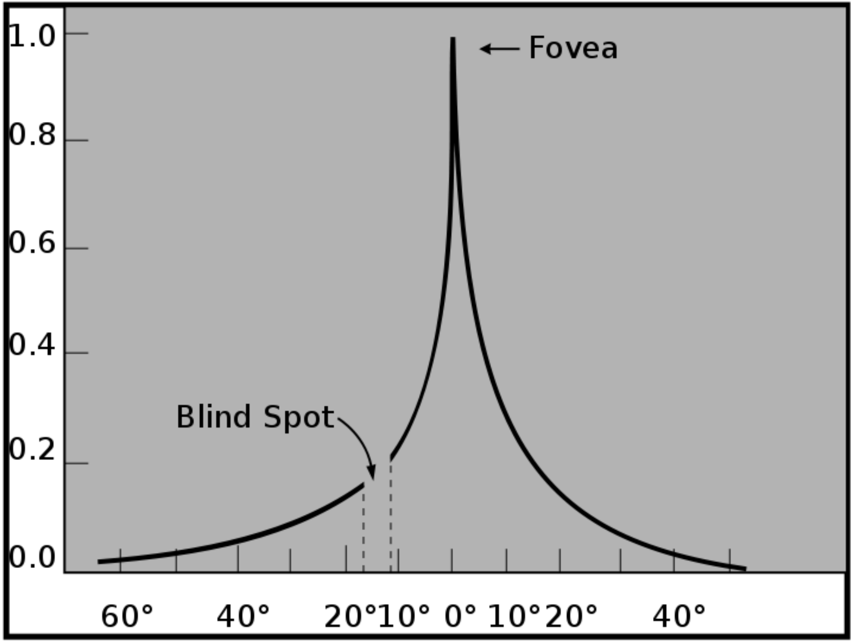
150° x 135° with pixels covering 1 arc min of visual angle

= 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

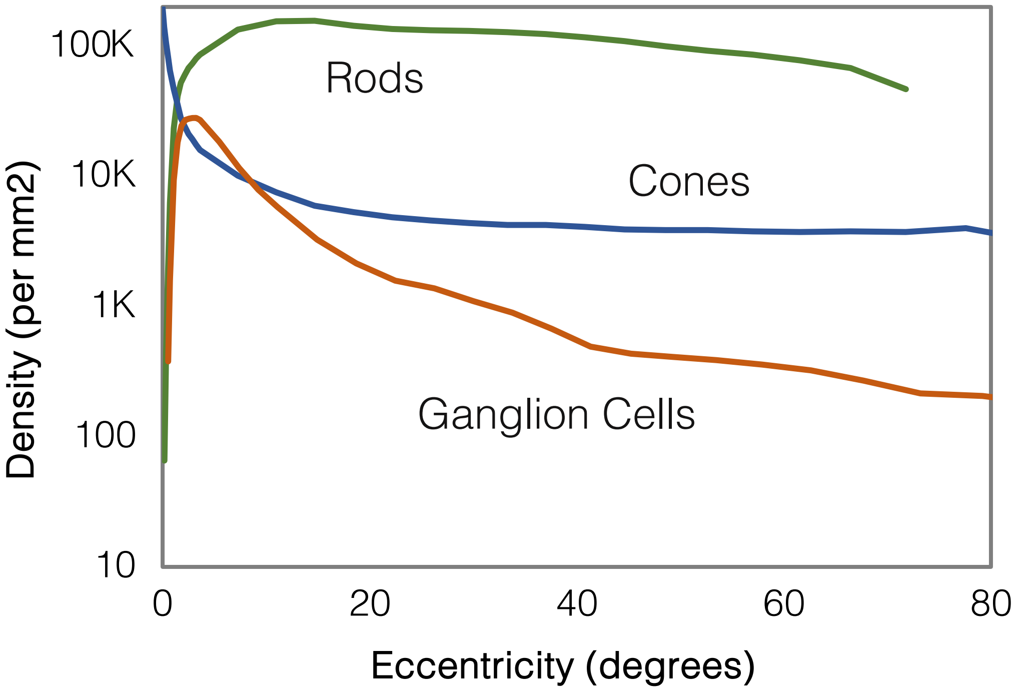
Relative Acuity Over Retina

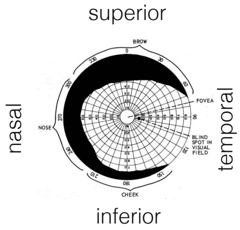


Eccentricity (i.e., distance to fovea in degrees of visual angle)

wikipedia

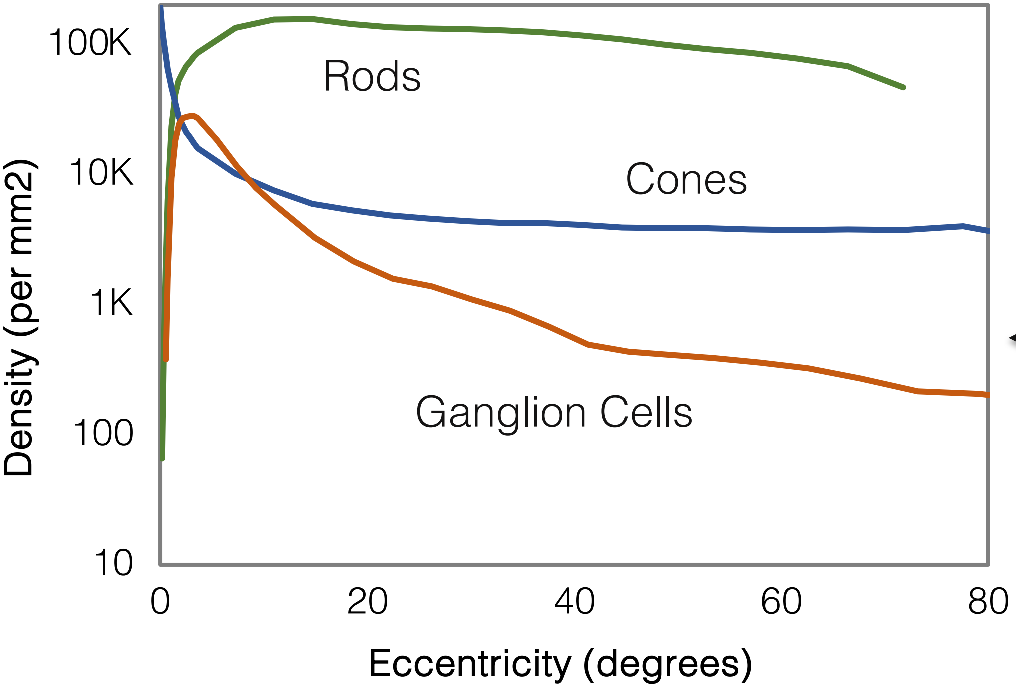
Density of Photoreceptors on Retina

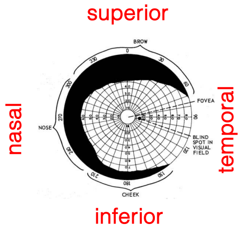




Patney et al. 2016

Density of Photoreceptors on Retina



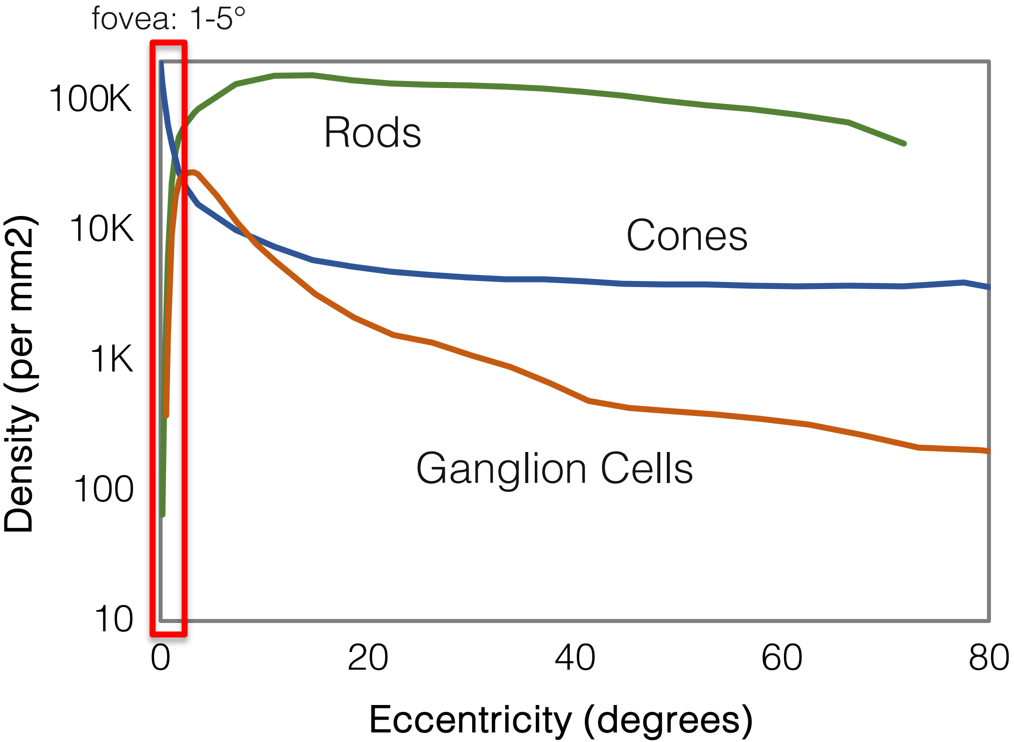


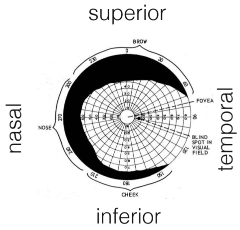
← superior, but other directions are similar

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

Acuity Over Retina / MAR

acuity falls off due to:

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

MAR: minimum angle of resolution in deg/cycle

slope

$$\omega = me + \omega_0$$

eccentricity in degrees

smallest resolvable angle at fovea in deg/cycle

Guenter et al. 2012

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

$$\overset{\substack{\text{MAR: minimum angle of}\\ \text{resolution in deg/cycle}\\ \downarrow}}{\omega} = \overset{\substack{\text{slope}\\ \downarrow}}{m}\underset{\substack{\uparrow\\ \text{eccentricity in degrees}}}{e} + \underset{\substack{\uparrow\\ \text{smallest resolvable angle at fovea in deg/cycle}}}{\omega_0}$$

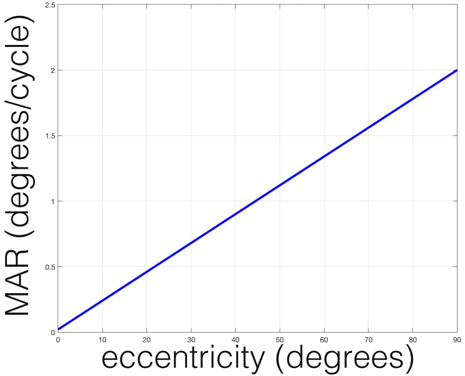
$\omega_0 = (1/48)^\circ$ somewhere between 20/20 (30 cycles per degree) and 20/10 (60 cycles per degree)

$m = 0.022 - 0.034$ range of acceptable – equivalent for observed image quality

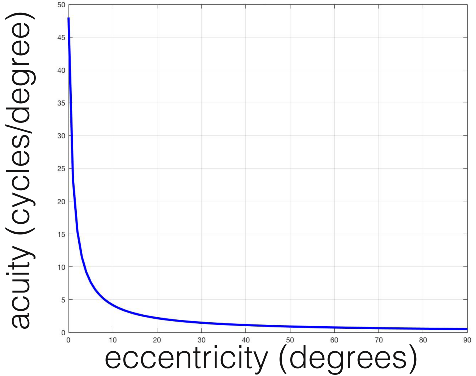
Guenter et al. 2012

Acuity Over Retina / MAR

MAR



Acuity (=1/MAR)



MAR slope

$$\omega = me + \omega_0$$

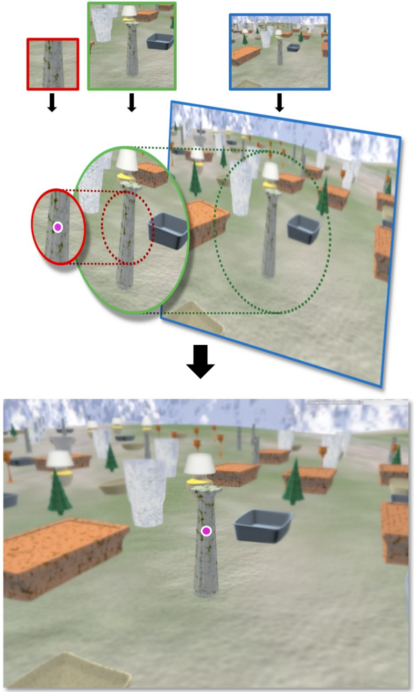
eccentricity in degrees smallest resolvable angle at fovea in deg/cycle

Guenter et al. 2012

Patney et al. 2016

Patney et al. 2016

Foveated Rendering

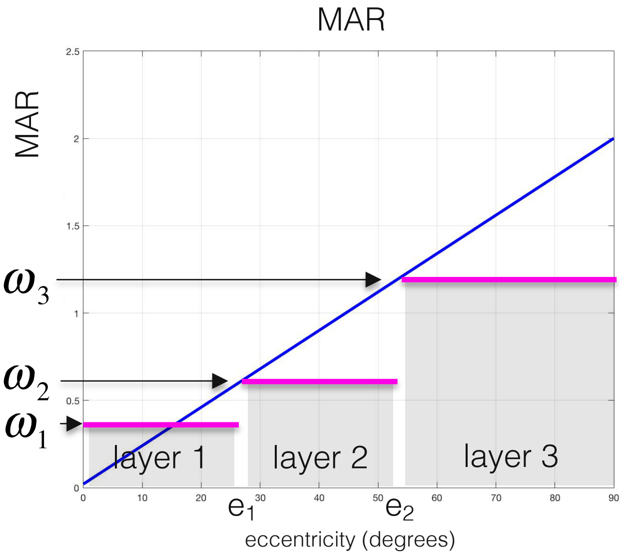


- Guenter et al. 2012: split image into *n* layers, e.g. inner (foveal, 1), middle (2), outer (3)
- render image in each zone with progressively lower resolution

- goals: save computation & bandwidth!

Foveated Rendering

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

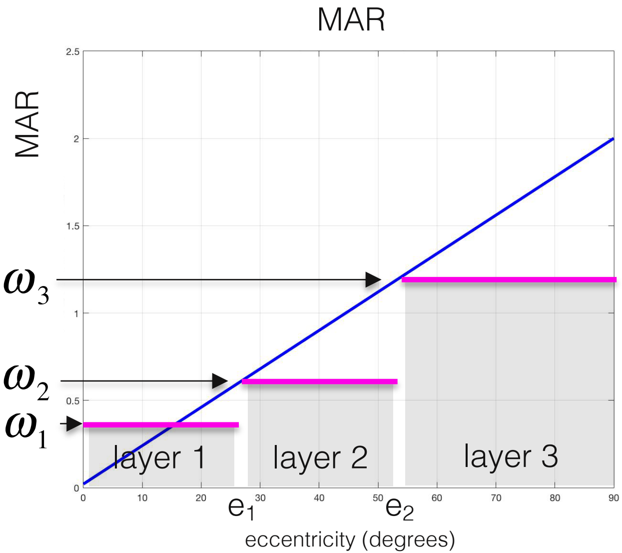


$$e_i = \frac{i}{n} \cdot \frac{fov}{2} \Rightarrow$$

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

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

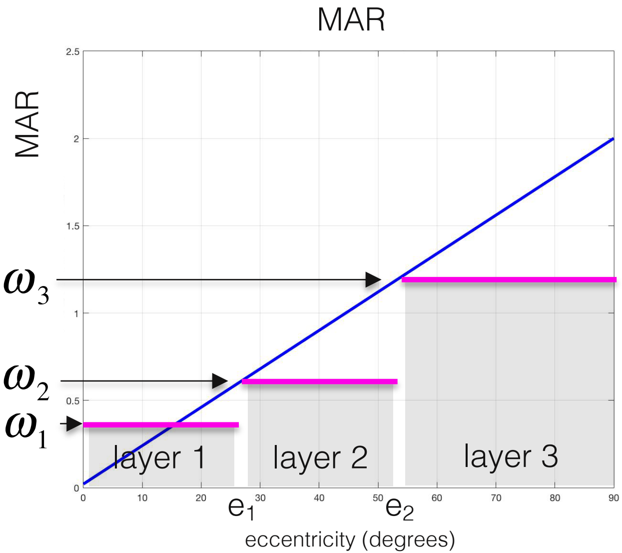
Foveated Rendering



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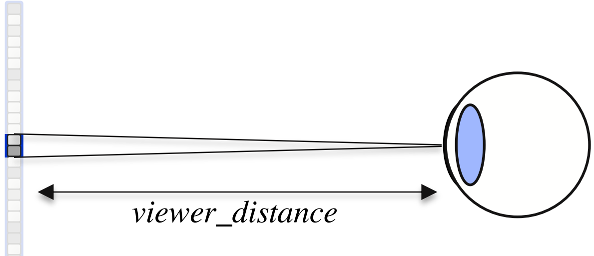
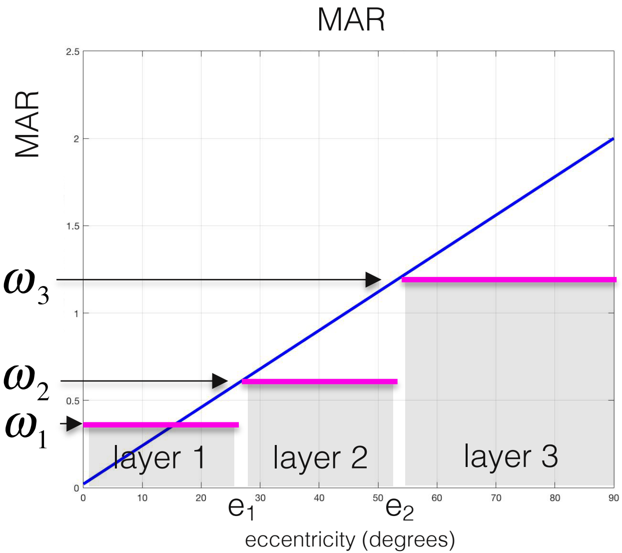
$$\omega_1 = 2\tan^{-1}\left(\frac{screen\_size}{screen\_resolution \cdot viewer\_distance}\right) \cdot \frac{360}{2\pi}$$



Foveated Rendering



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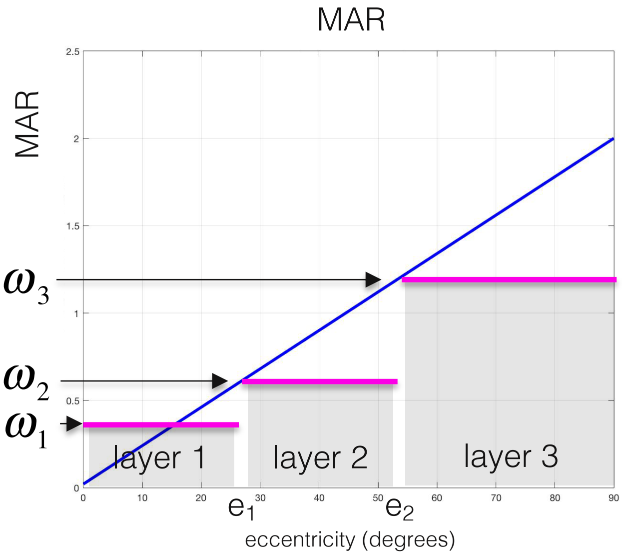
$$\omega_1 = 2\tan^{-1}\left(\frac{screen\_size}{screen\_resolution \cdot viewer\_distance}\right) \cdot \frac{360}{2\pi}$$

$screen\_size$	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



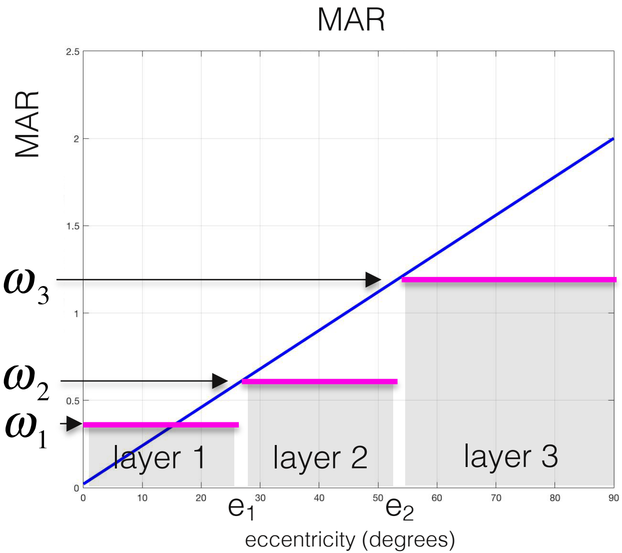
$$\omega_1 = 2\tan^{-1}\left(\frac{screen\_size}{screen\_resolution \cdot viewer\_distance}\right) \cdot \frac{360}{2\pi}$$

$$\omega_2 = m e_2 + \omega_0$$

$$\omega_3 = m e_3 + \omega_0$$

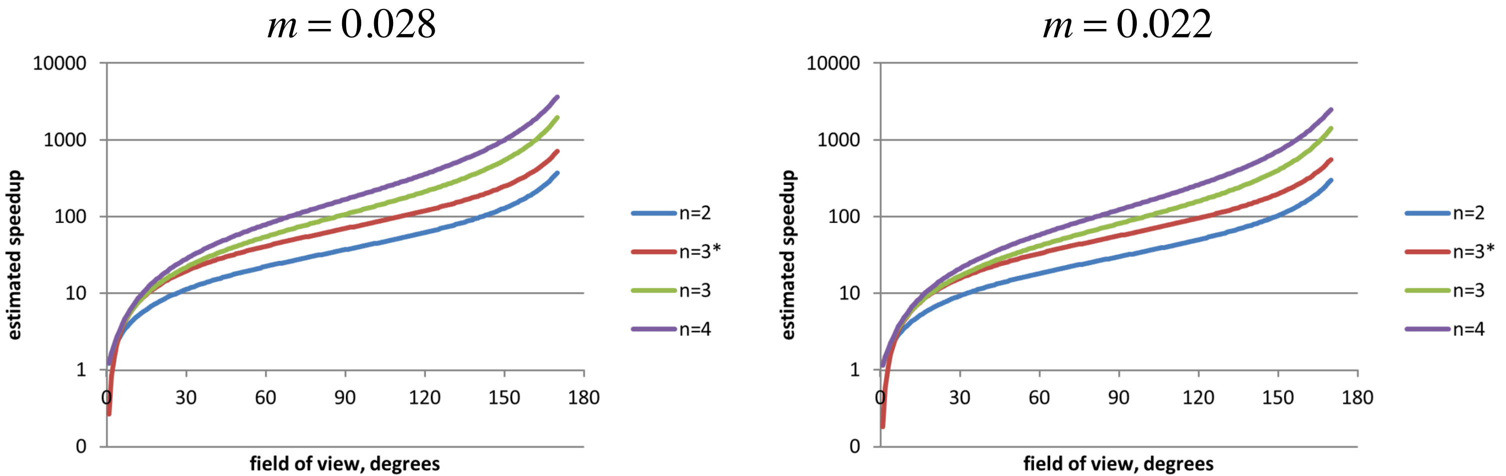
Foveated Rendering

- 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

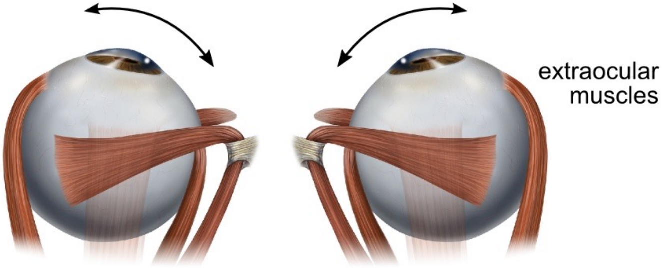
<u>conclusion</u>: for large fov & high-res displays, we need to shade much fewer pixels!

Depth Perception

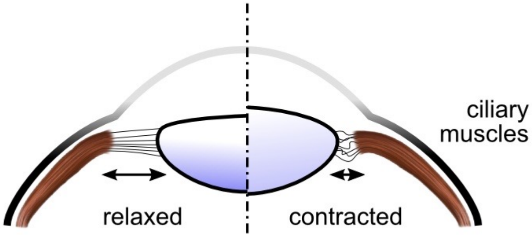
Stereopsis (Binocular)

Focus Cues (Monocular)

Oculomotor Cue



Vergence



Accommodation

Visual Cue

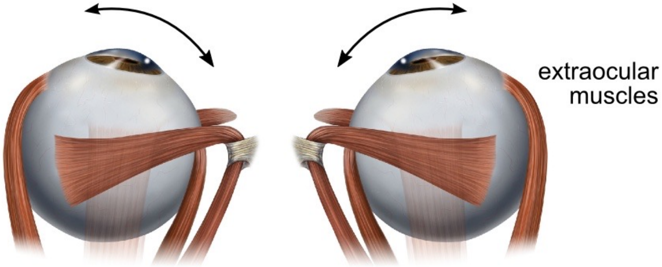
Binocular Disparity

Retinal Blur

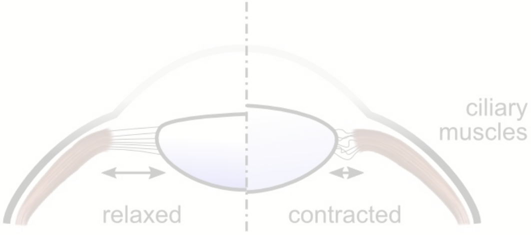
Stereopsis (Binocular)

Focus Cues (Monocular)

Oculomotor Cue



Vergence



Accommodation

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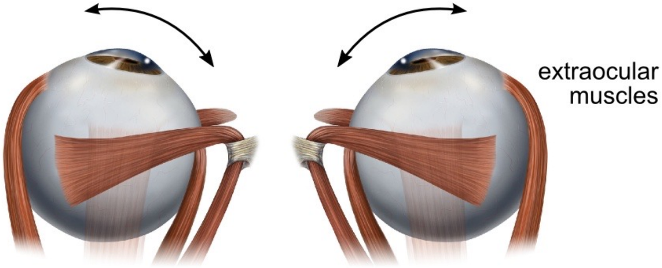
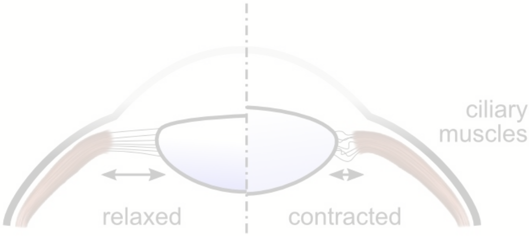


Vergence



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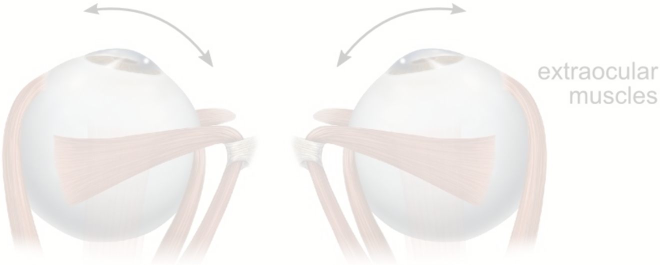
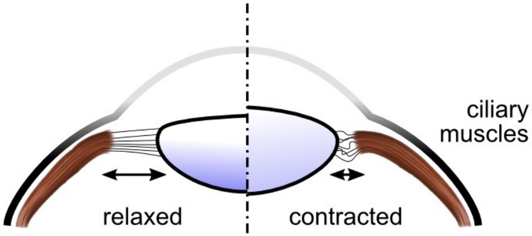


Vergence



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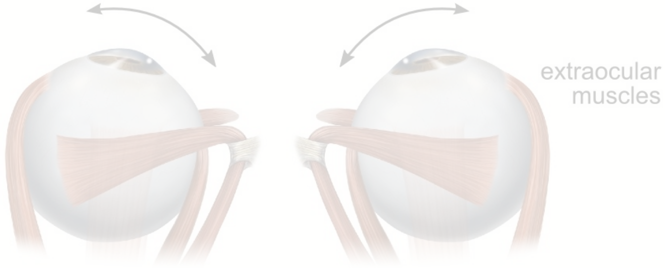
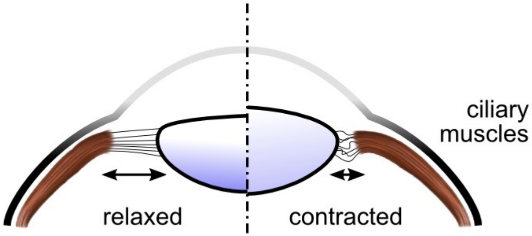


Vergence



Accommodation

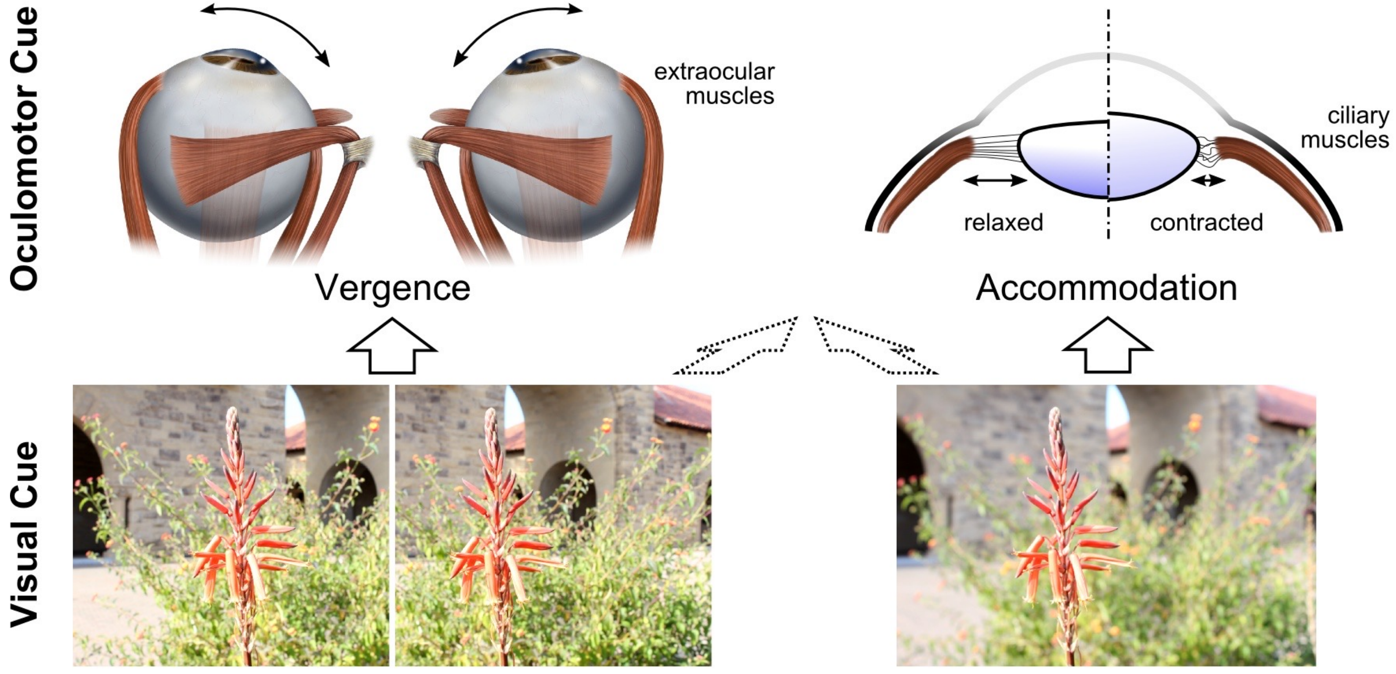
Visual Cue

Binocular Disparity

Retinal Blur

Stereopsis (Binocular)

Focus Cues (Monocular)



Oculomotor Cue

extraocular muscles

Vergence

ciliary muscles

relaxed

contracted

Accommodation

Visual Cue

Binocular Disparity

Retinal Blur

Depth Perception

wikipedia

Depth Perception


wikipedia

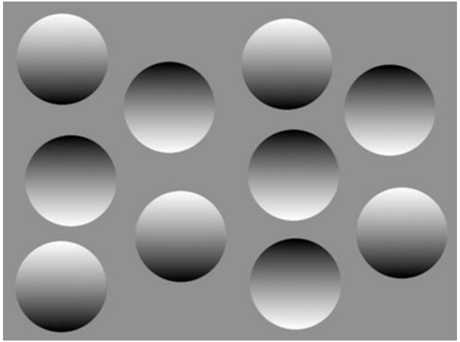
monocular cues

- perspective
- relative object size
- absolute size
- occlusion
- accommodation
- retinal blur
- motion parallax
- texture gradients
- shading
- …

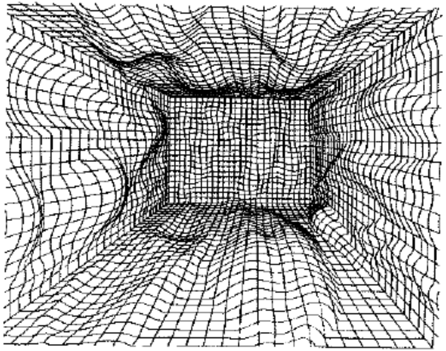
binocular cues

- (con)vergence
- disparity / parallax
- …

Depth Perception – Pictorial Cues

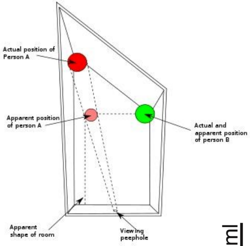


shading



Marr, “Vision”, 1982

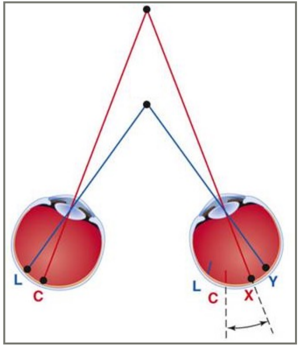
texture gradients



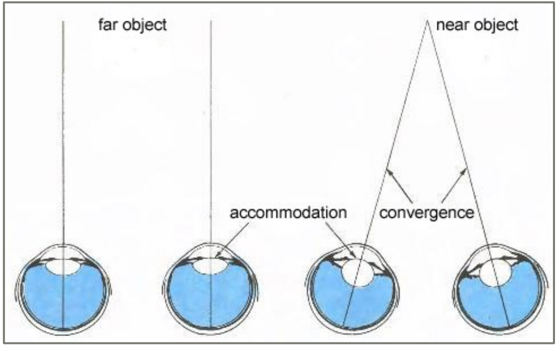
http://oceanswebsite.com/Amesroom1.html

Ames room
conflict between perspective
& relative object size

Depth Perception

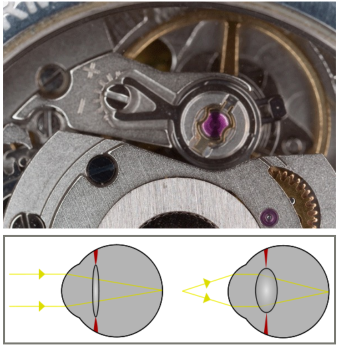


binocular disparity

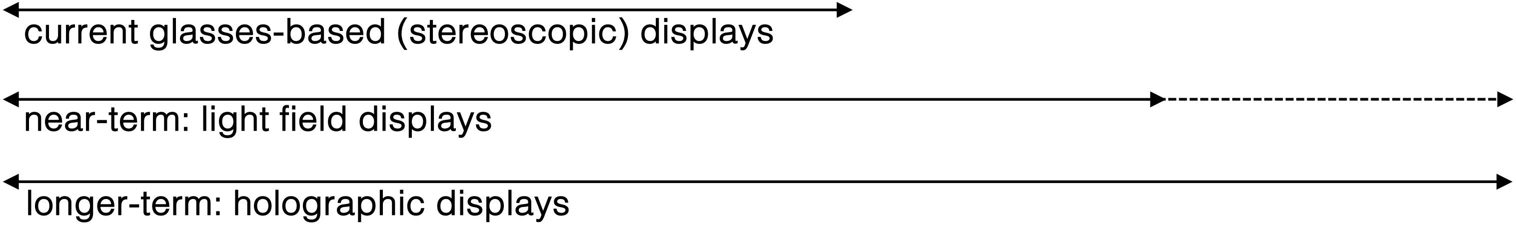


convergence

motion parallax



accommodation/blur

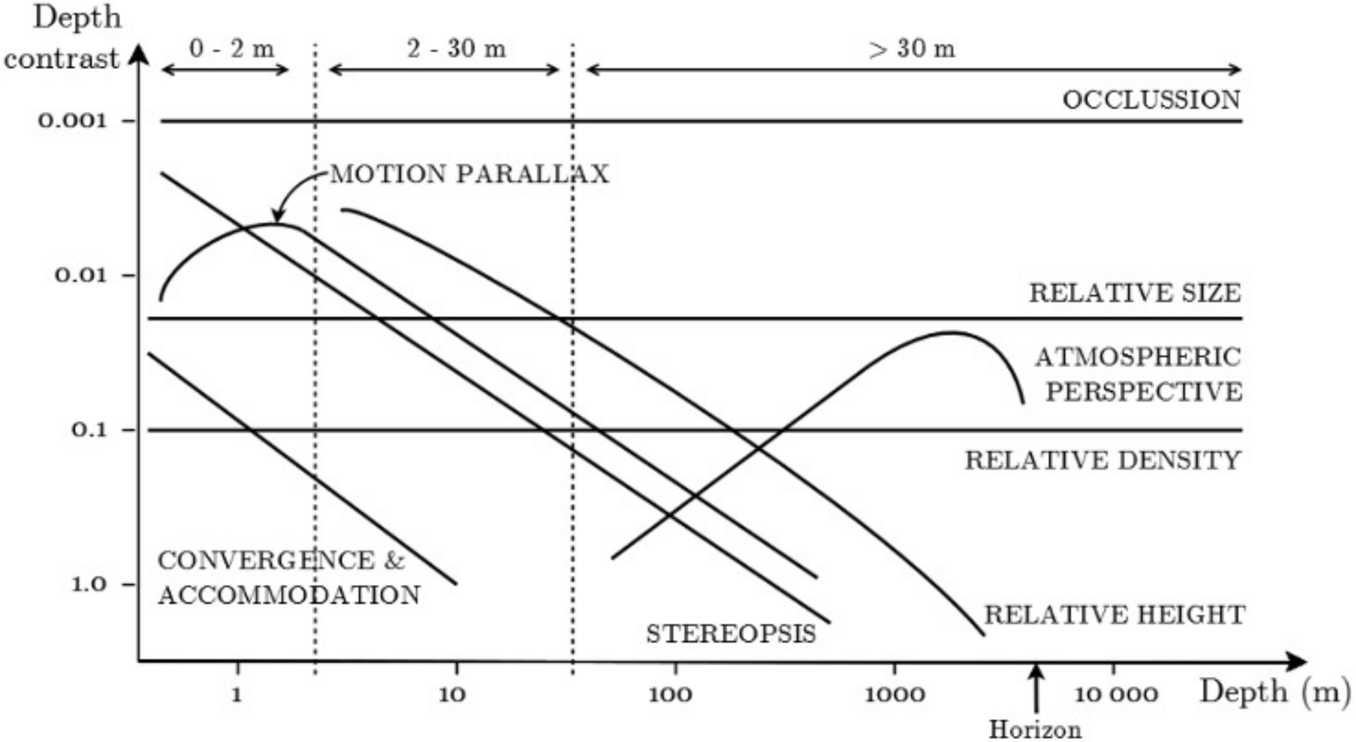


current glasses-based (stereoscopic) displays

near-term: light field displays

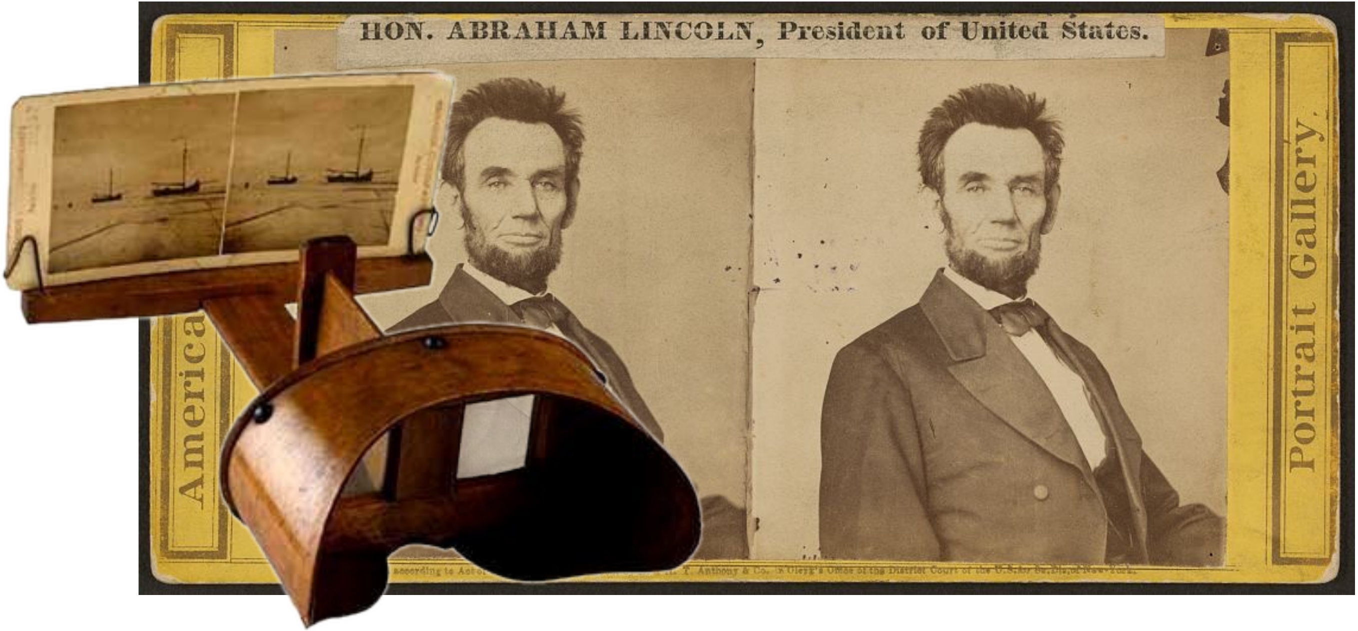
longer-term: holographic displays

Depth Perception



Cutting & Vishton, 1995

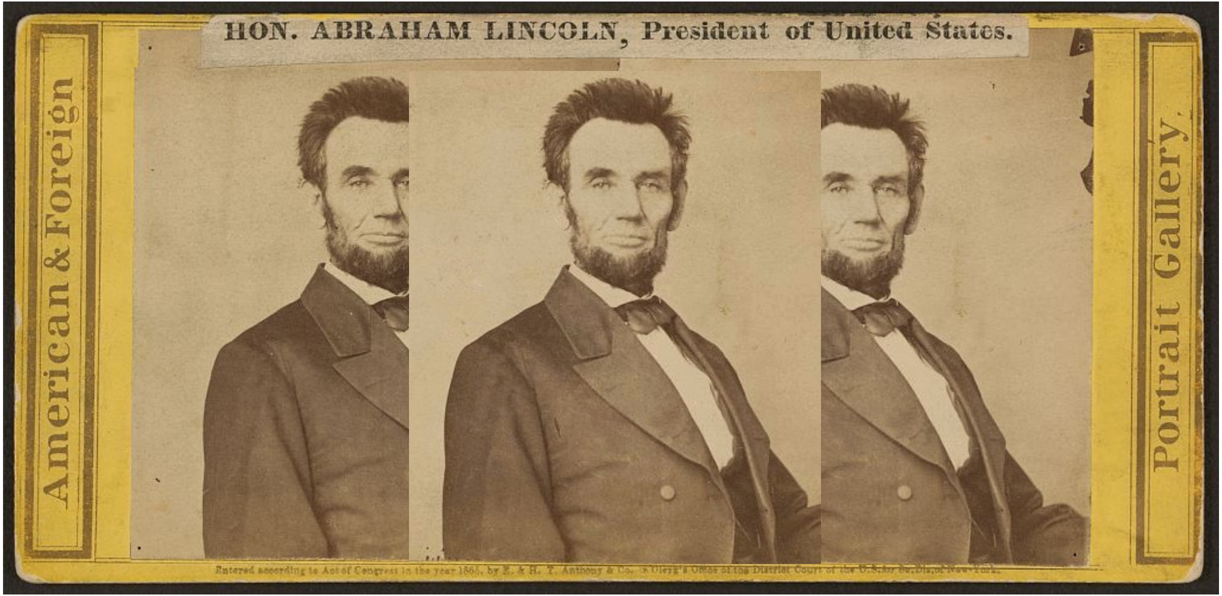
Stereoscopic Displays



Charles Wheatstone., 1841. Stereoscope.

Walker, Lewis E., 1865. Hon. Abraham Lincoln, President of the United States. Library of Congress

Stereoscopic Displays



Stereoscopic Displays

Charles Wheatstone 1838

176 years later

stereoscopic displays

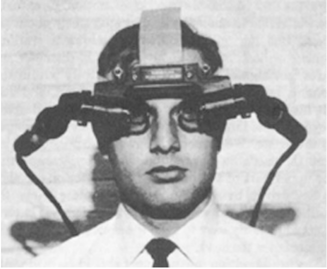
A Brief History of Virtual Reality

Stereoscopes

Wheatstone, Brewster, …

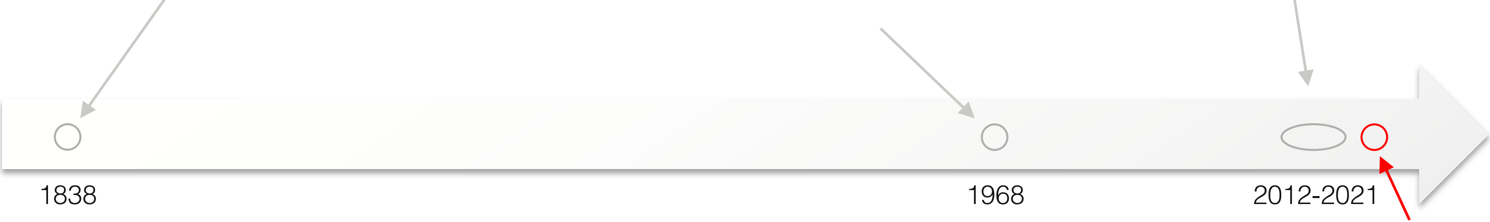
VR, AR,

Ivan Sutherland



VR explosion

Oculus, Sony, Valve, MS, …



1838

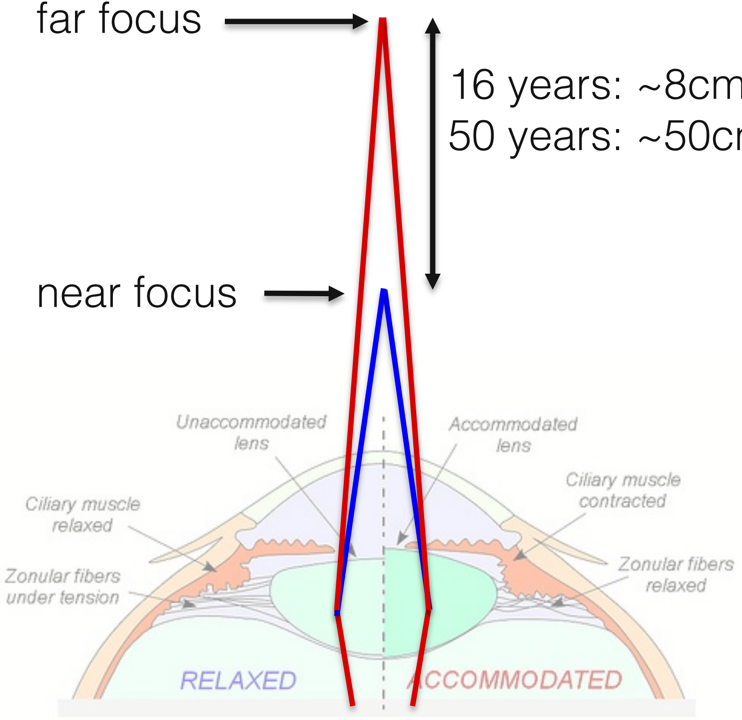
1968

2012-2021

Next-generation VR & AR Displays

Focus Cues

Oculomotor Processes



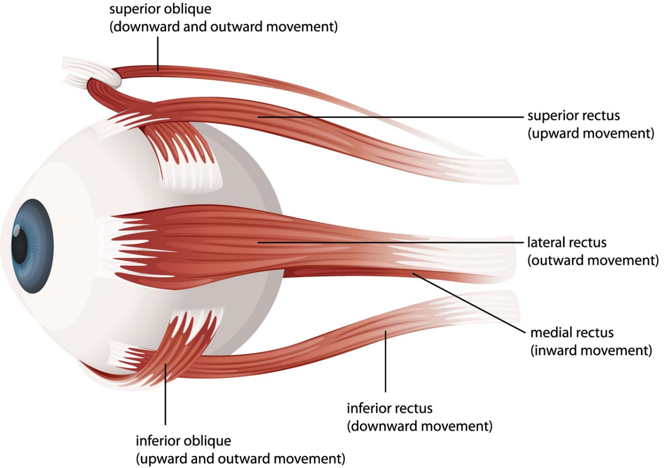
far focus

near focus

16 years: ~8cm to ∞

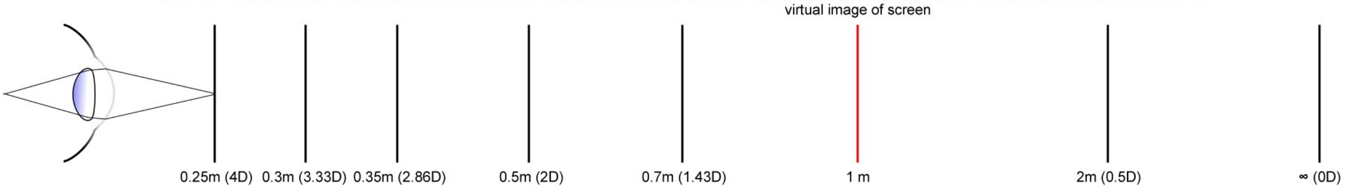
50 years: ~50cm to ∞ (mostly irrelevant)

adithyakiran.wordpress.com



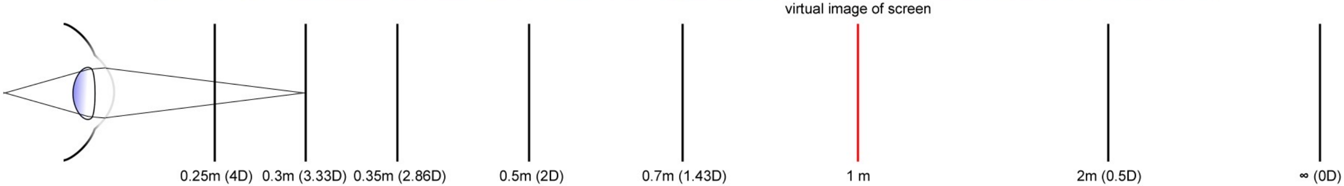
Accommodation and Retinal Blur

Conventional Display



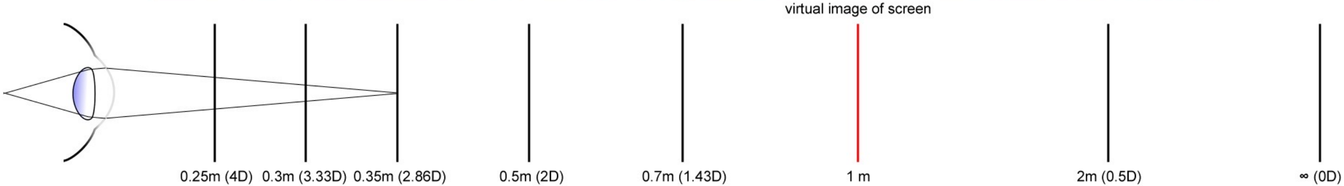
Accommodation and Retinal Blur

Conventional Display



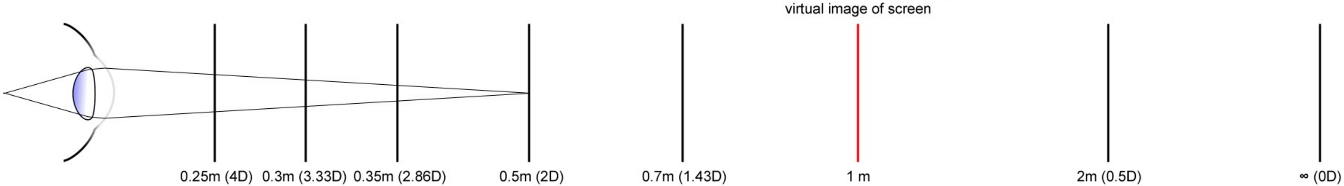
Accommodation and Retinal Blur

Conventional Display



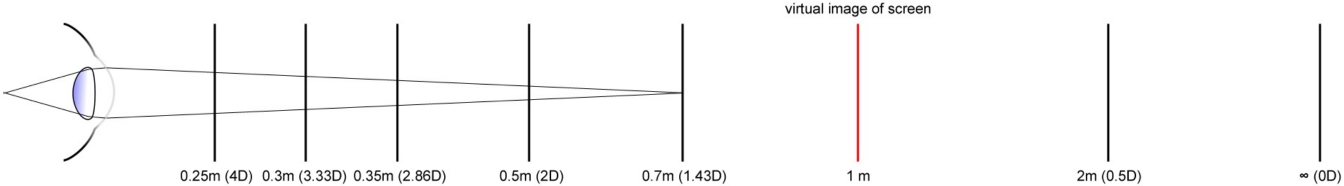
Accommodation and Retinal Blur

Conventional Display



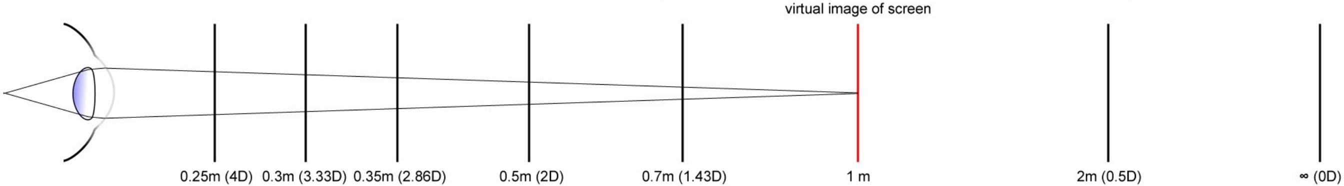
Accommodation and Retinal Blur

Conventional Display



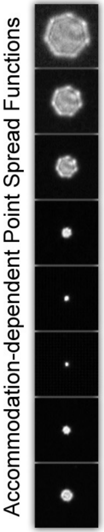
Accommodation and Retinal Blur

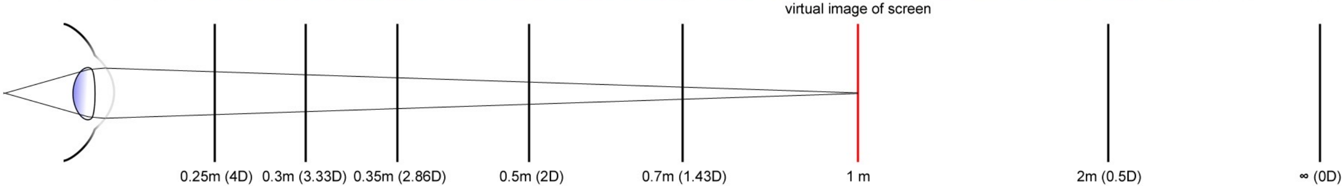
Conventional Display



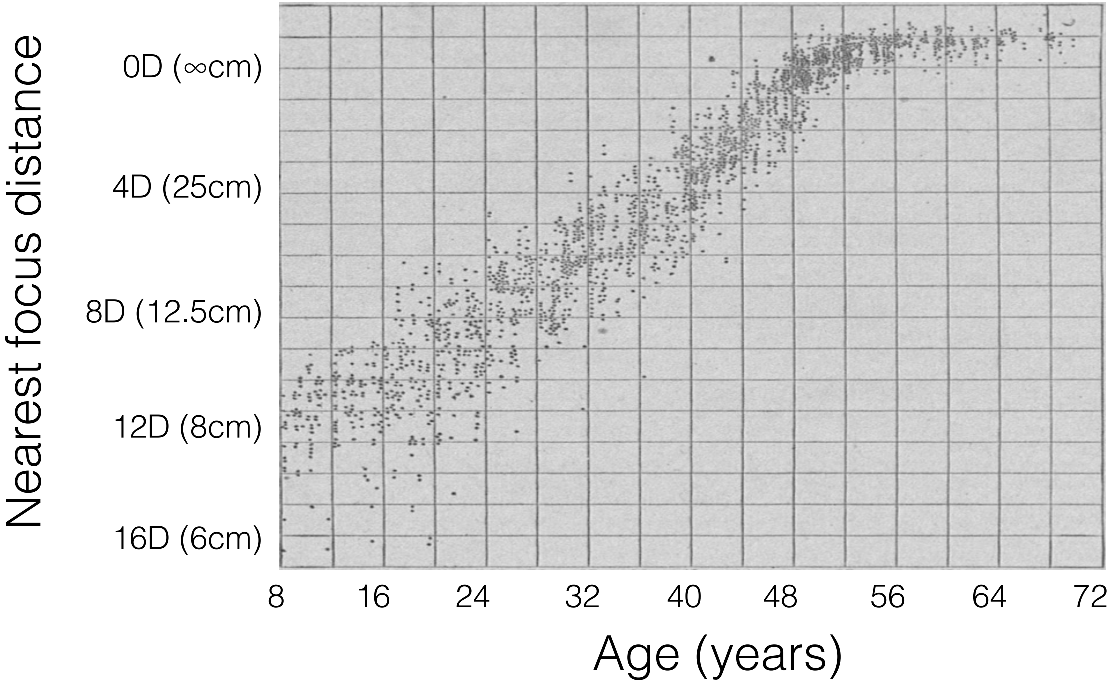
Accommodation and Retinal Blur

Conventional Display





Focusing Ability Degrades With Age - Presbyopia

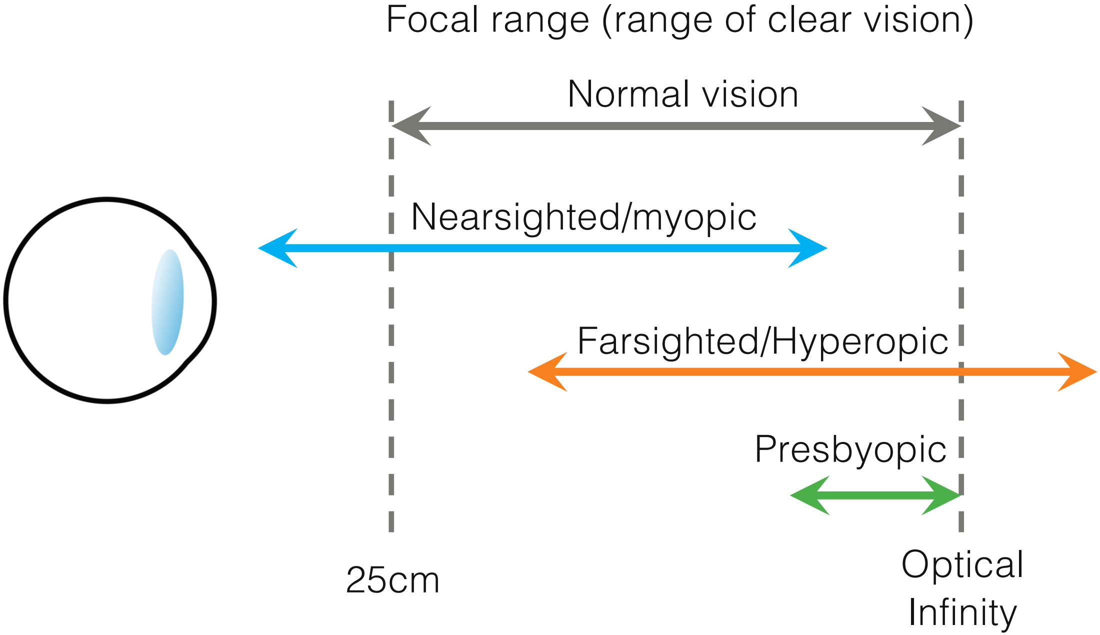


Duane, 1912

Bifocals

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

Myopia, Hyperopia, Presbyopia


Focal range (range of clear vision)

Normal vision

Nearsighted/myopic

Farsighted/Hyperopic

Presbyopic

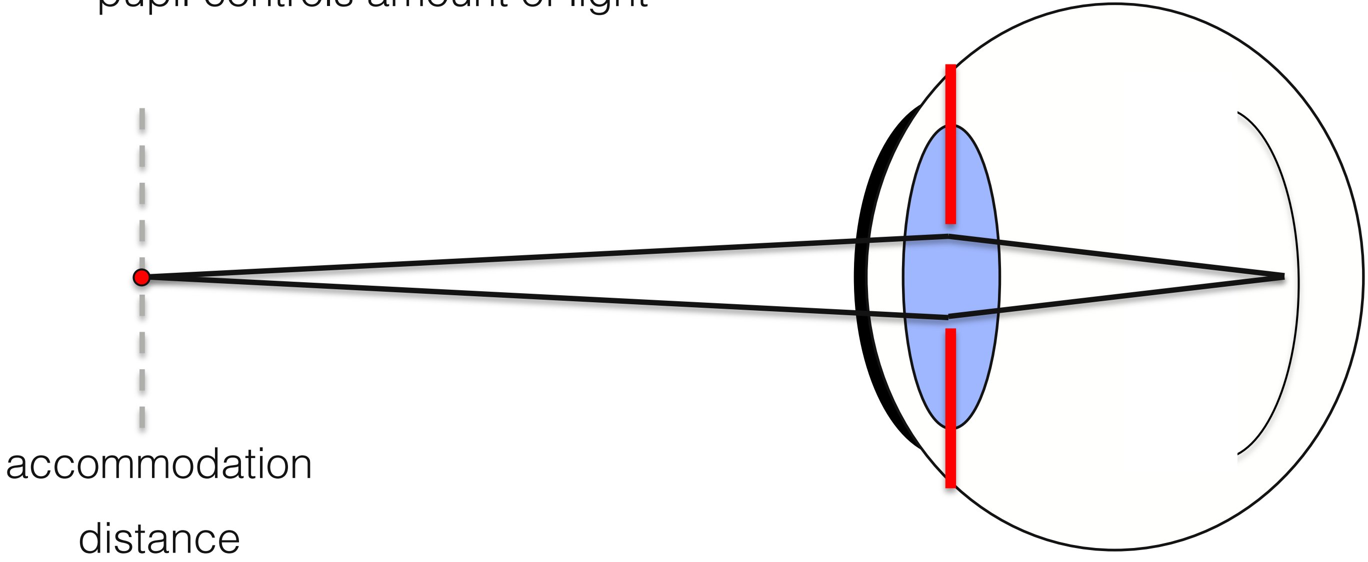
25cm

Optical Infinity

Modified from Pamplona et al. SIGGRAPH 2010

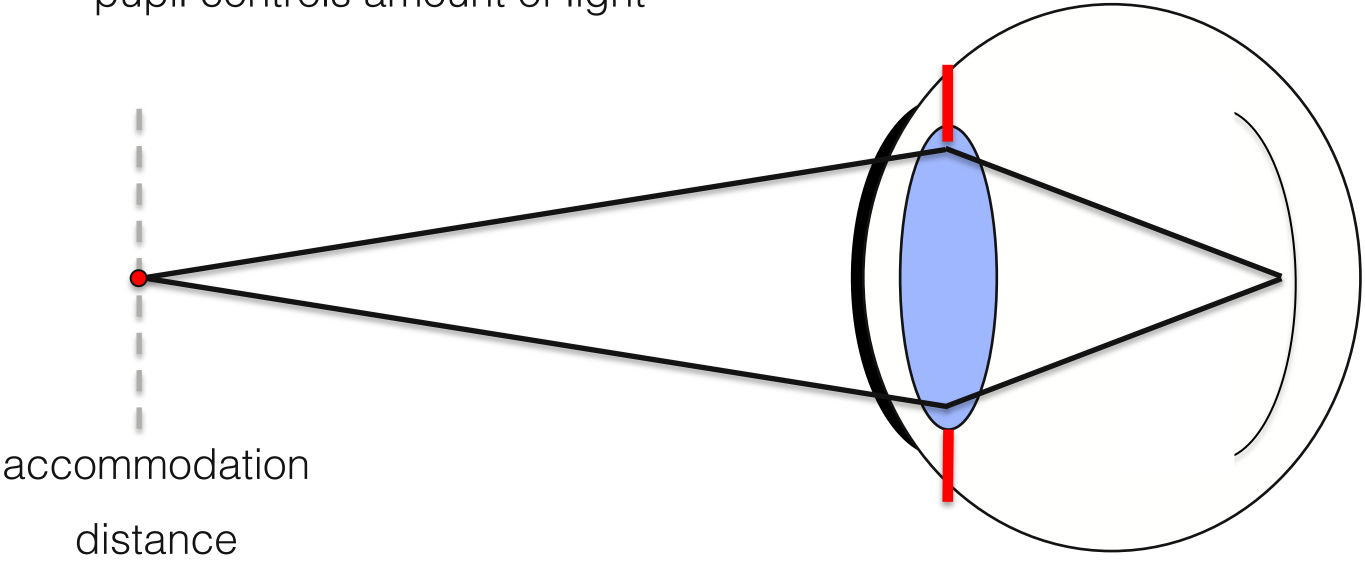
Retinal Blur

- pupil controls amount of light



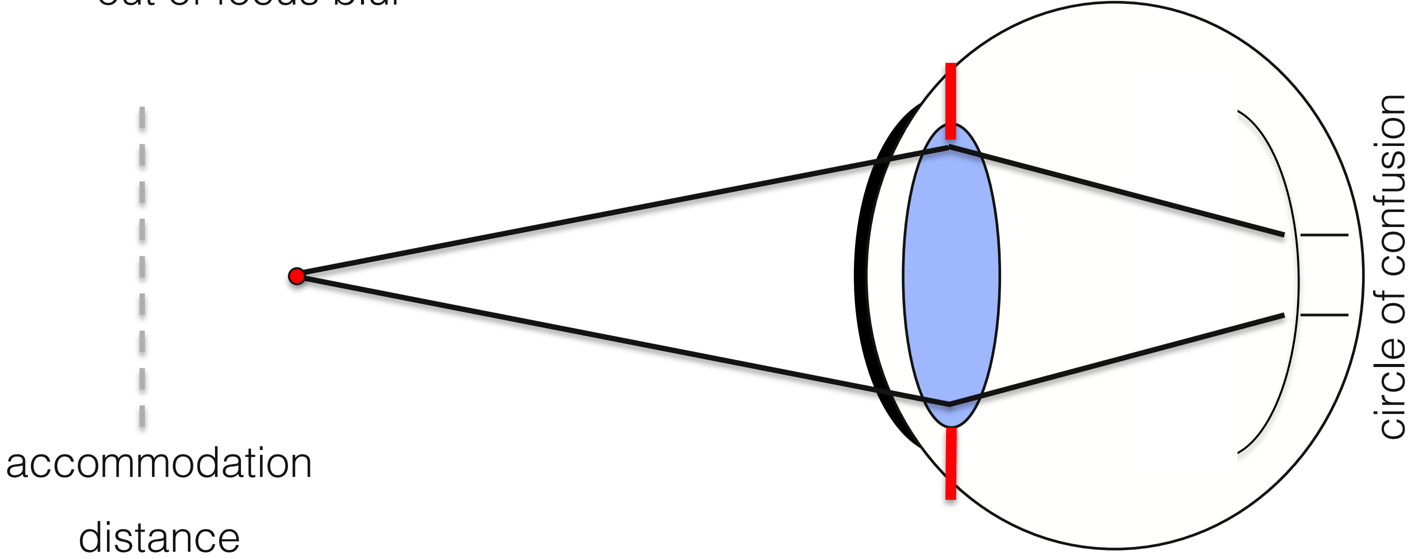
Retinal Blur

- pupil controls amount of light



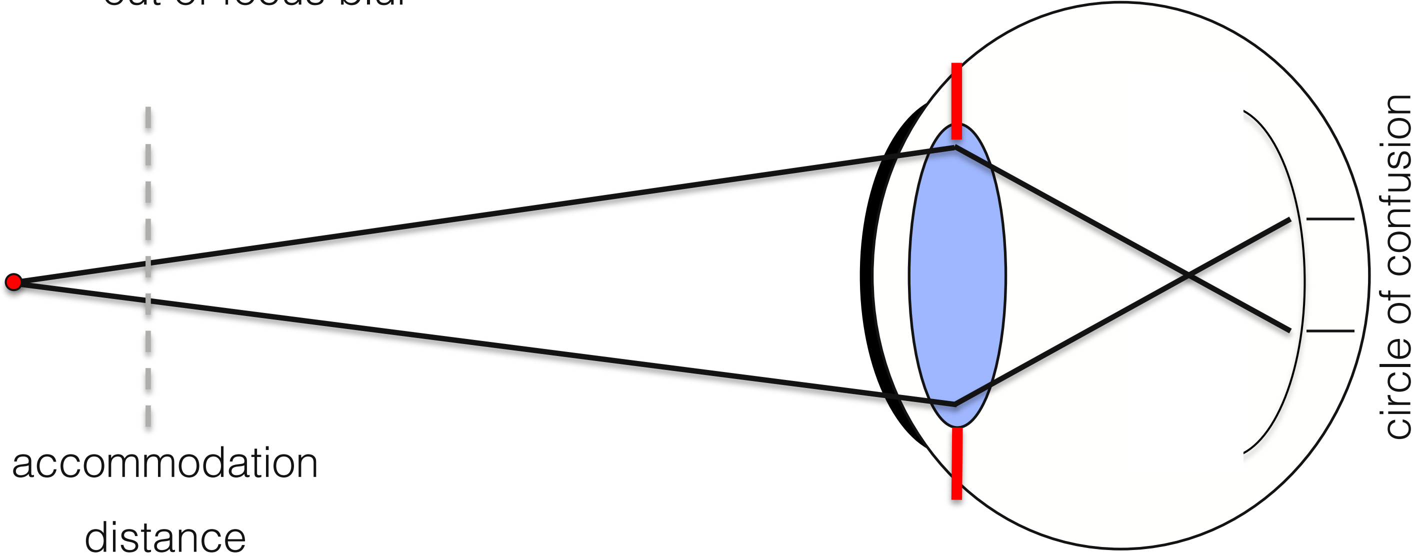
Retinal Blur

- out of focus blur



Retinal Blur

- out of focus blur

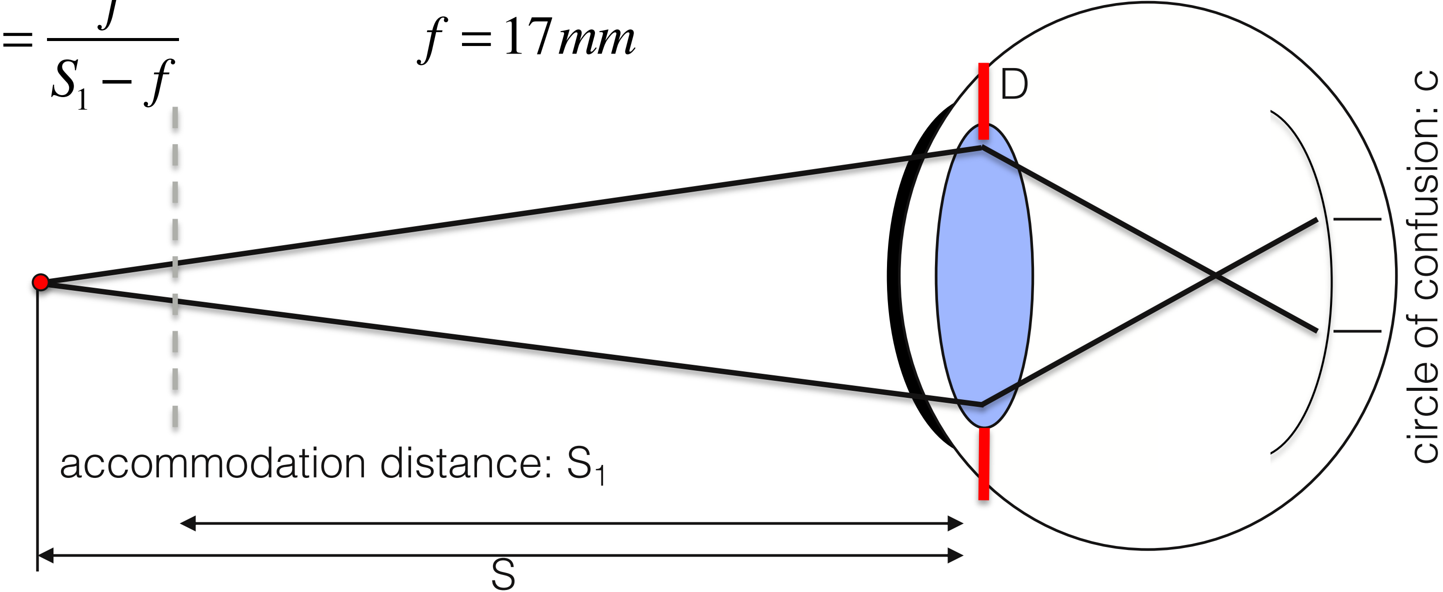


Retinal Blur / Depth of Field Rendering

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

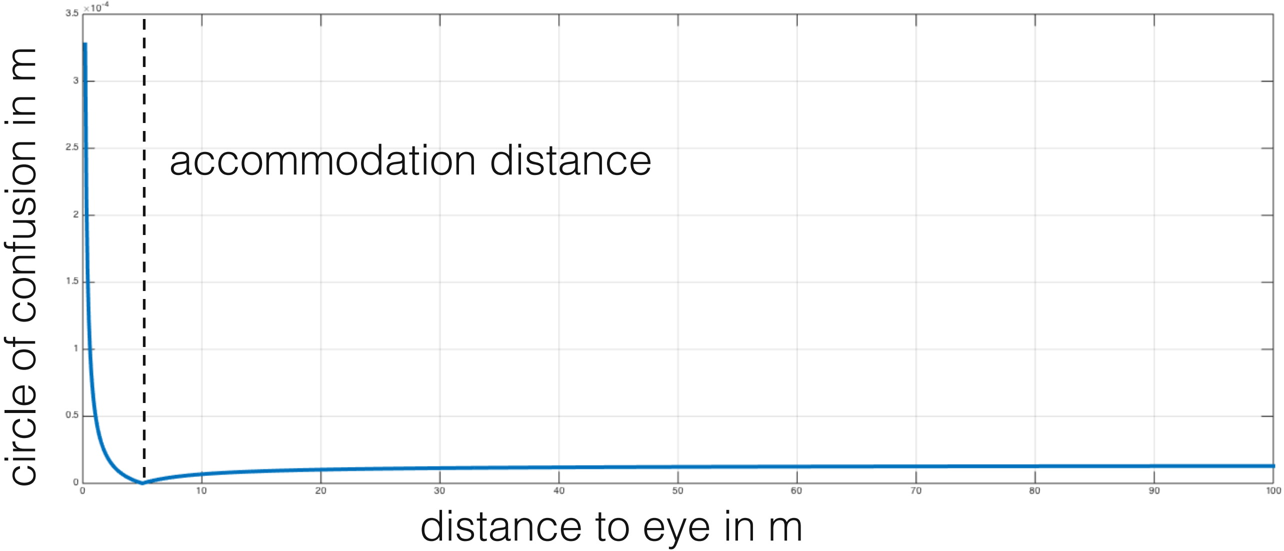
$$M = \frac{f}{S_1 - f}$$

$$f = 17mm$$



Circle of Confusion

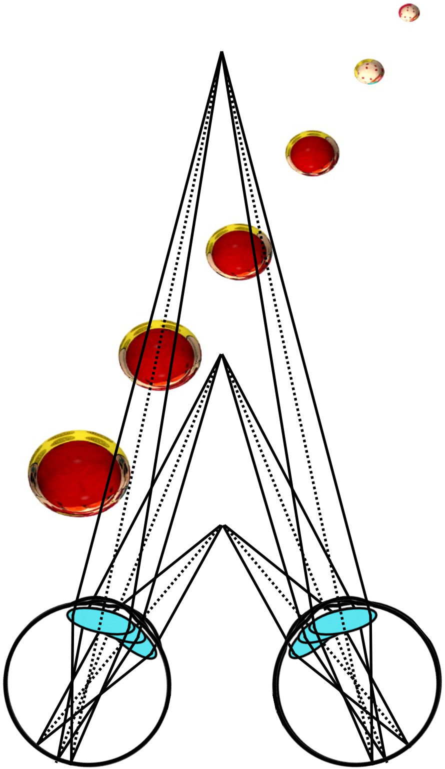
$$c = M \cdot D \cdot \frac{\left|S - S_1\right|}{S}$$



Blur Affects Relative Object Size!

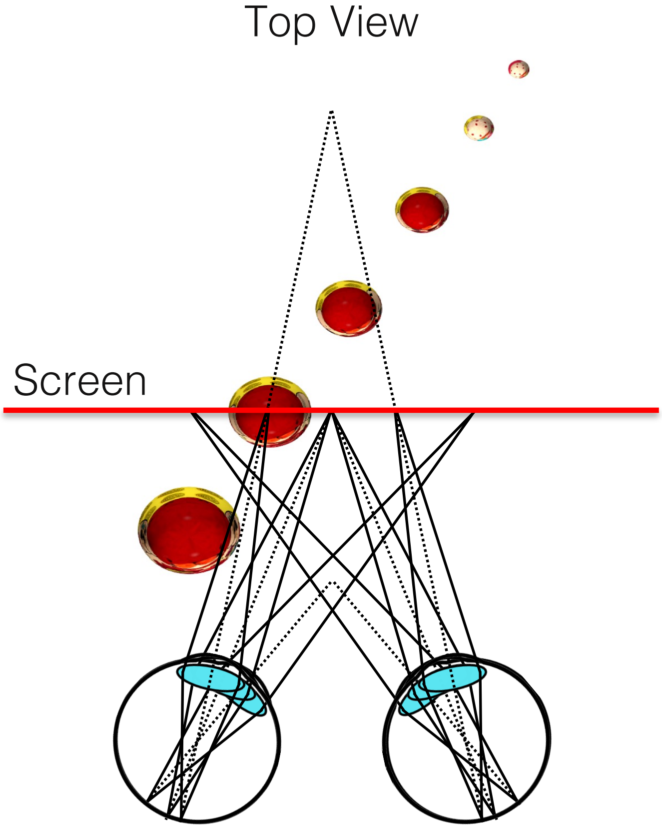
Held et al., 2006, ACM SIGGRAPH

Top View



Real World:

Vergence & Accommodation Match!

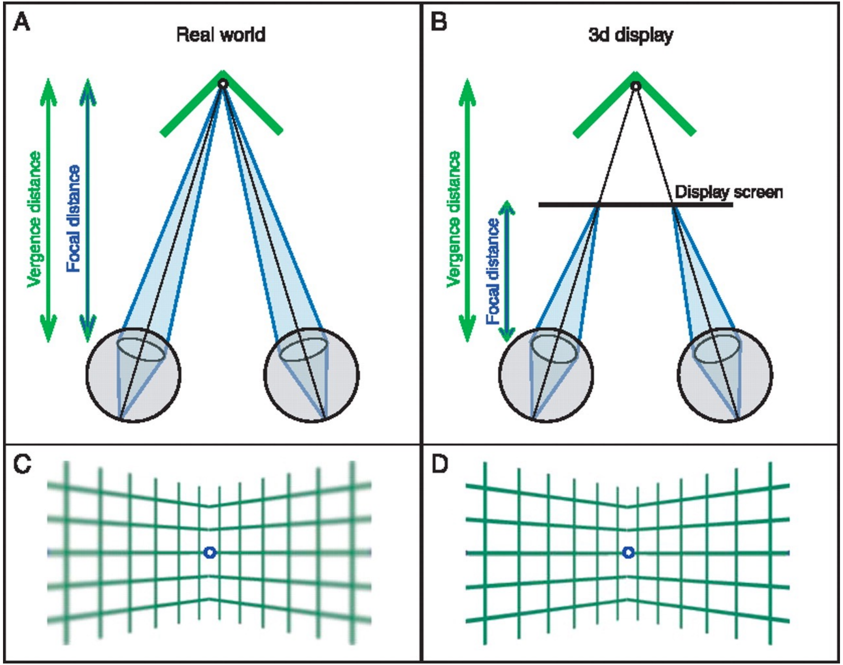


Stereo Displays Today:

Vergence-Accommodation Mismatch!

Vergence-Accommodation Conflict

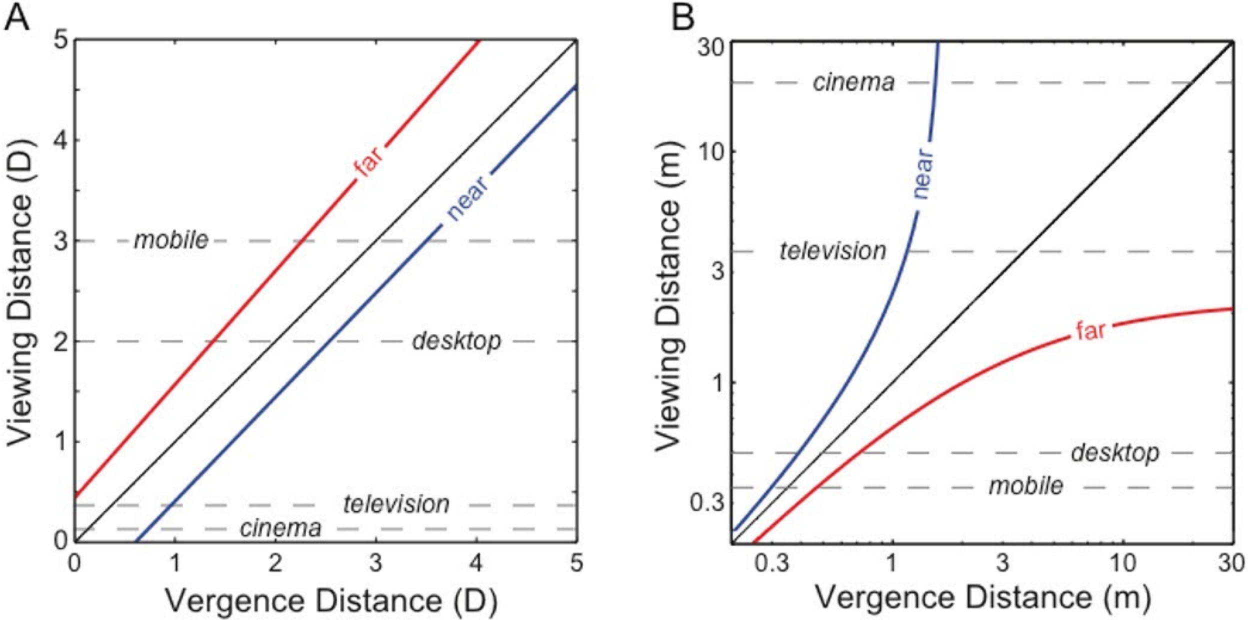
Marty Banks, UC Berkeley



effects

- visual discomfort
- visual fatigue
- nausea
- diplopic vision
- eyestrain
- compromised image quality
- pathologies in developing visual system
- …

Zone of Comfort



Shibata et al, 2011, Journal of Vision

Summary

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

References and Further Reading

interesting textbooks on perception:

- Wandell, “Foundations of Vision”, Sinauer Associates,1995
- Howard, “Perceiving in Depth”, Oxford University Press, 2012

foveated rendering:

- Guenter, Finch, Drucker, Tan, Snyder “Foveated 3D Graphics”, ACM SIGGRAPH Asia 2012
- Patney, Salvi, Kim, Kaplanyan, Wyman, Benty, Luebke, Lefohn “Towards Foveated Rendering for Gaze-Tracked Virtual Reality”, ACM SIGGRAPH Asia 2016

depth cues and more:

- Cutting & Vishton,” Perceiving layout and knowing distances: The interaction, relative potency, and contextual use of different information about depth”, Epstein and Rogers (Eds.), Perception of space and motion, 1995
- Held, Cooper, O’Brien, Banks, “Using Blur to Affect Perceived Distance and Size”, ACM Transactions on Graphics, 2010
- Hoffman and Banks, “Focus information is used to interpret binocular images”. Journal of Vision 10, 2010
- Hoffman, Girshick, Akeley, and Banks, “Vergence-accommodation conflicts hinder visual performance and cause visual fatigue”. Journal of Vision 8, 2008
- Huang, Chen, Wetzstein, “The Light Field Stereoscope”, ACM SIGGRAPH 2015

the retina, visual acuity, visual field

- Roorda, Williams, “The arrangement of the three cone classes in the living human eye”, Nature, Vol 397, 1999
- Snellen chart: https://en.wikipedia.org/wiki/Snellen_chart
- Ruch and Fulton, Medical physiology and biophysics, 1960

contrast sensitivity function & hybrid images:

- Oliva, Torralba, Schyns, “Hybrid Images”, ACM Transactions on Graphics (SIGGRAPH), 2006
- Spatio-temporal CSF: Kelly, Motion and Vision. II. Stabilized spatio-temporal threshold surface, Journal of the Optical Society of America,1979