The Human Visual System

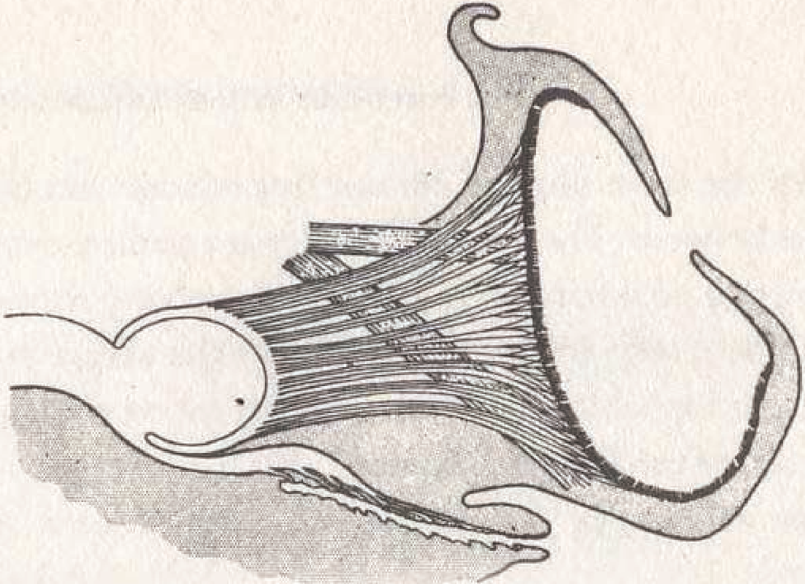
Gordon Wetzstein
Stanford University

EE 267 Virtual Reality

Lecture 5

stanford.edu/class/ee267/

nautilus eye, wikipedia



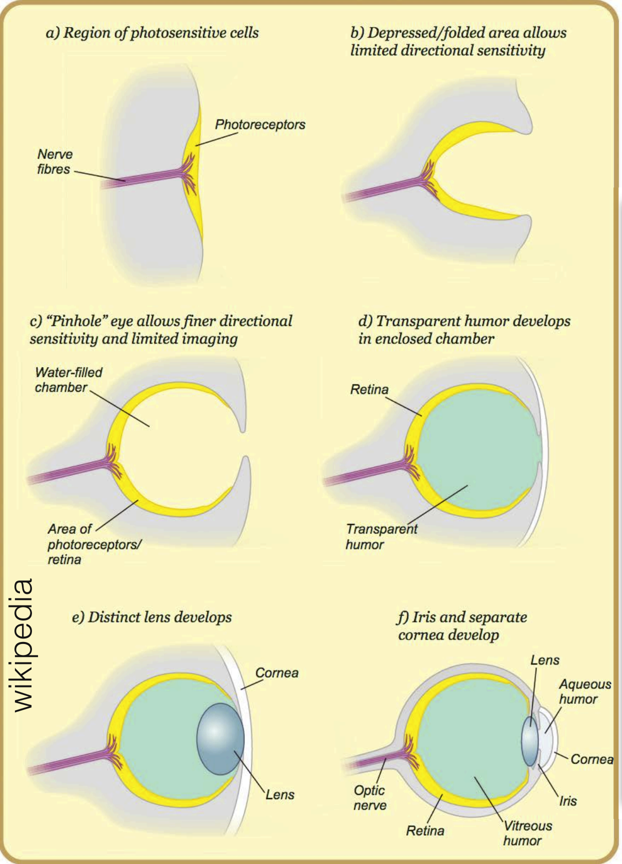
a

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/

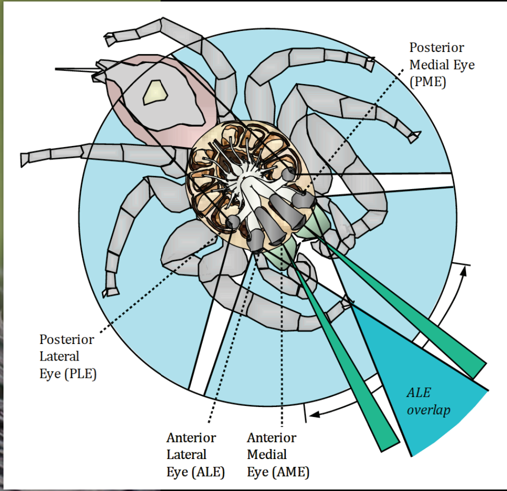
Evolution of the Eye



wikipedia

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

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



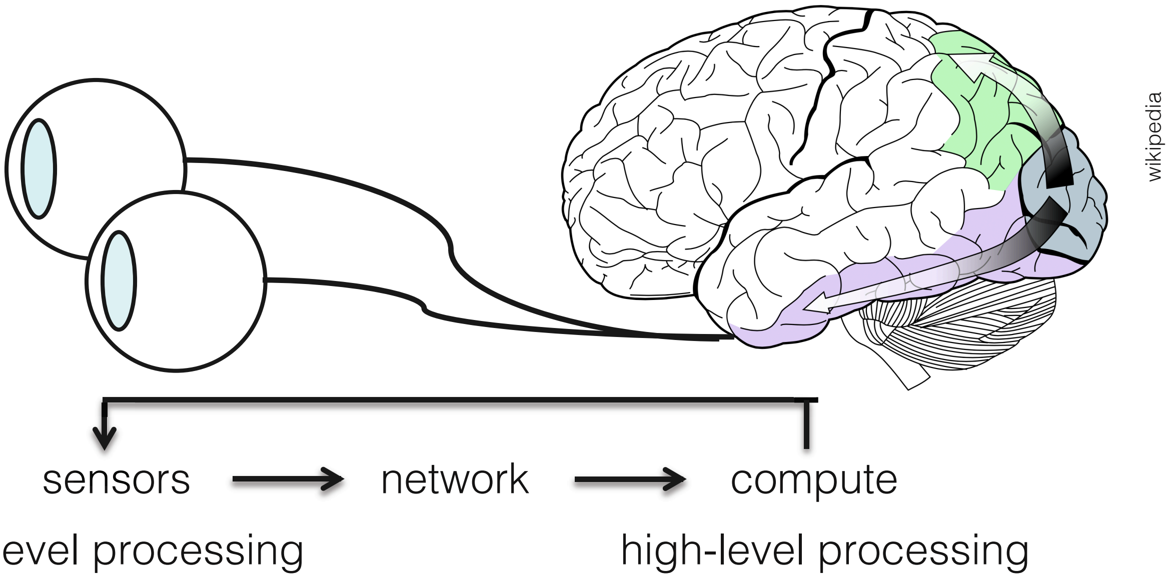
jumping spider, wikipedia

national geographics

Lecture Overview

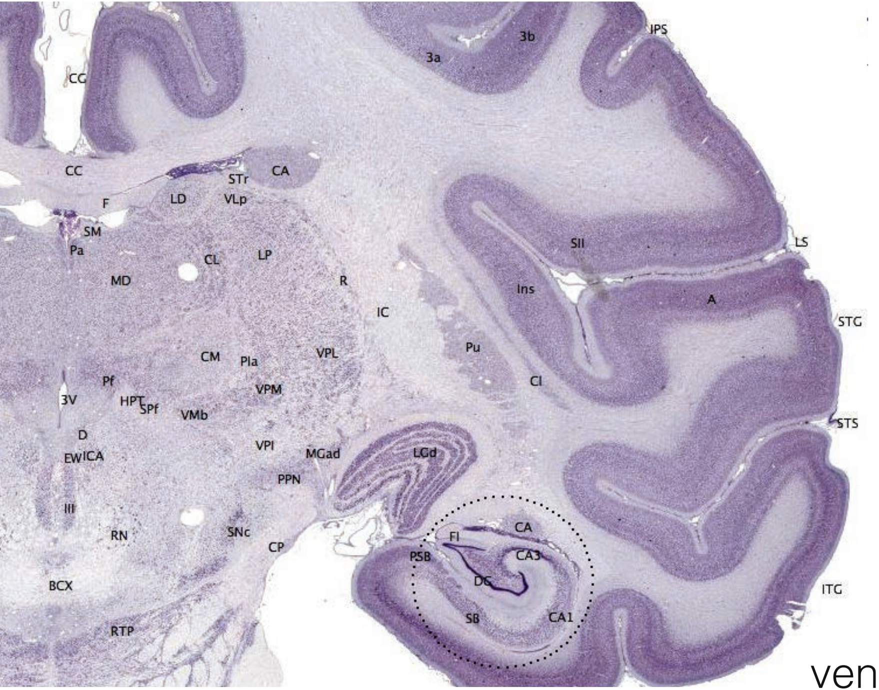
- visual acuity: 20/20 is ~1 arc min
- visual acuity varies over retina: can exploit via foveated rendering
- field of view: ~190° monocular, ~120° binocular, ~135° vertical
- temporal resolution: ~60 Hz (depends on contrast, luminance)
- depth cues in 3D displays: vergence, focus, conflicts, (dis)comfort
- accommodation range: ~8cm to ∞, degrades with age

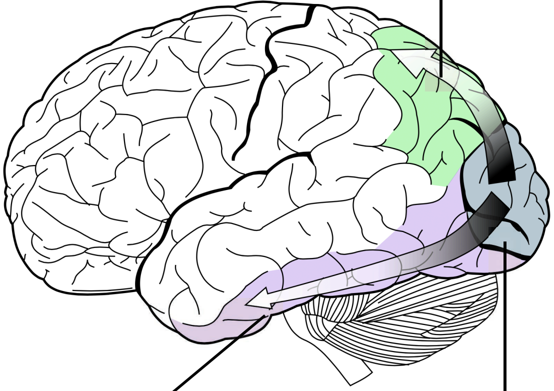
Overview



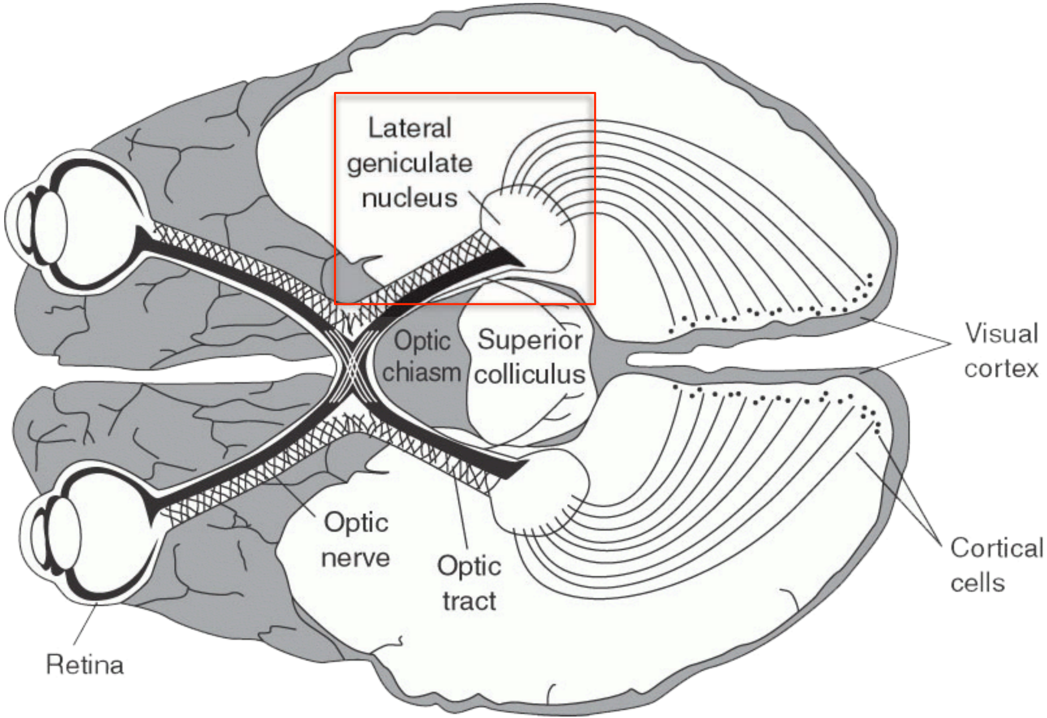
wikipedia
sensors
network
compute
low-level processing
high-level processing

Overview


CC
3a
3b
IPS
CC
CA
STr
LD
VLp
F
SM
Pa
CL
LP
MD
R
SII
LS
Ins
A
IC
STG
CM
Pla
VPL
Pu
Pf
3V
HPT
SPf
VPM
VMb
Cl
STS
D
EW
ICA
VPI
MGad
LGd
PPN
III
RN
SNc
CP
CA
Fl
PSB
CA3
DG
BCX
SB
CA1
ITG
RTP

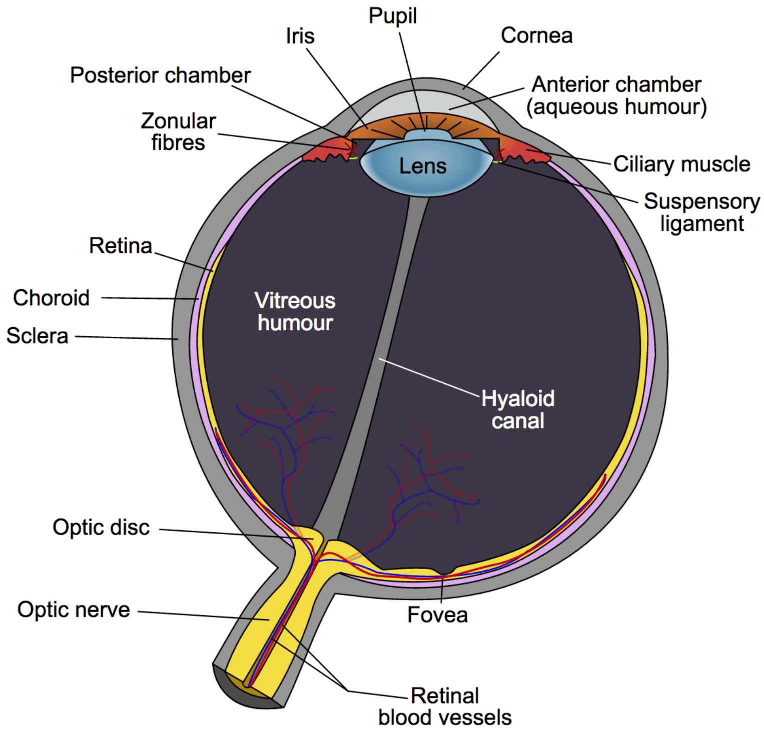

dorsal stream: spatial awareness
wikipedia
primary visual cortex
ventral stream:
recognition, object identification

Overview

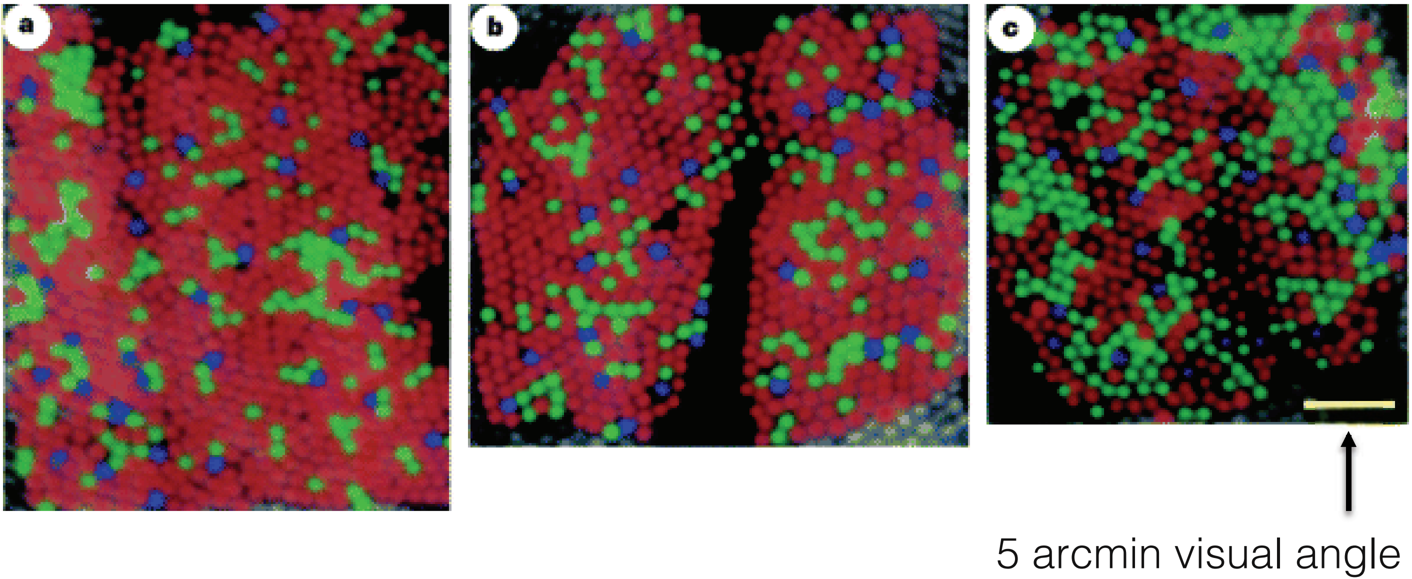


van der Helm

Anatomy of the Human Eye



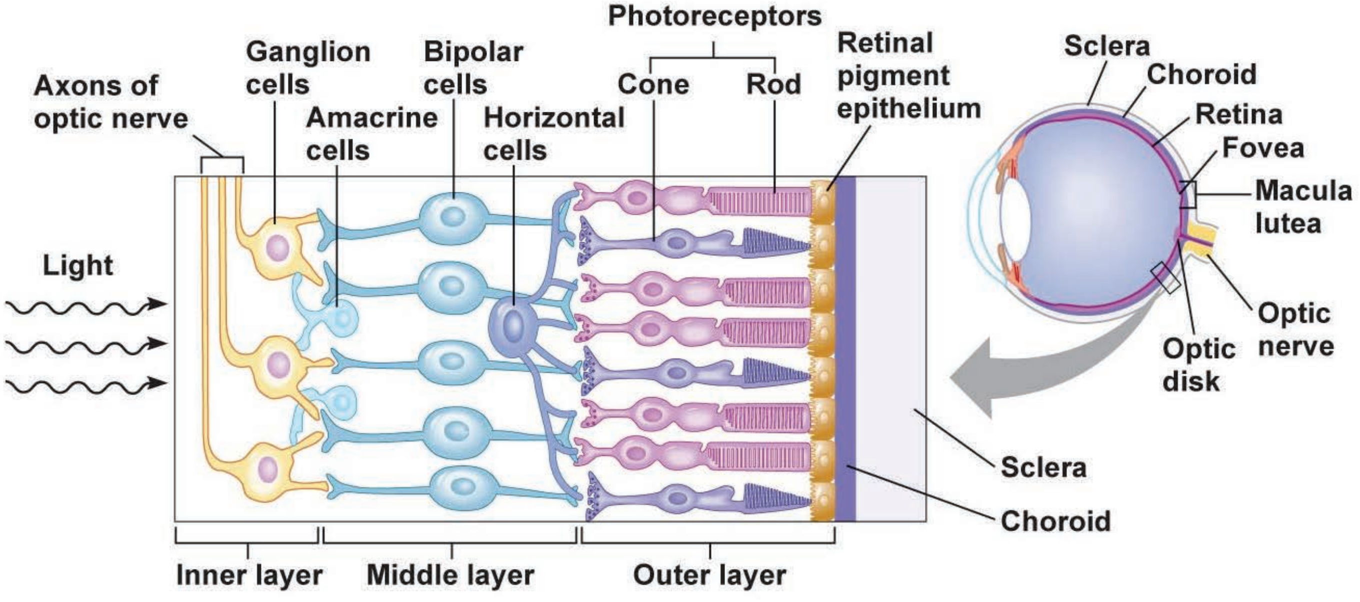
The Retina



Roorda & Williams, 1999, Nature

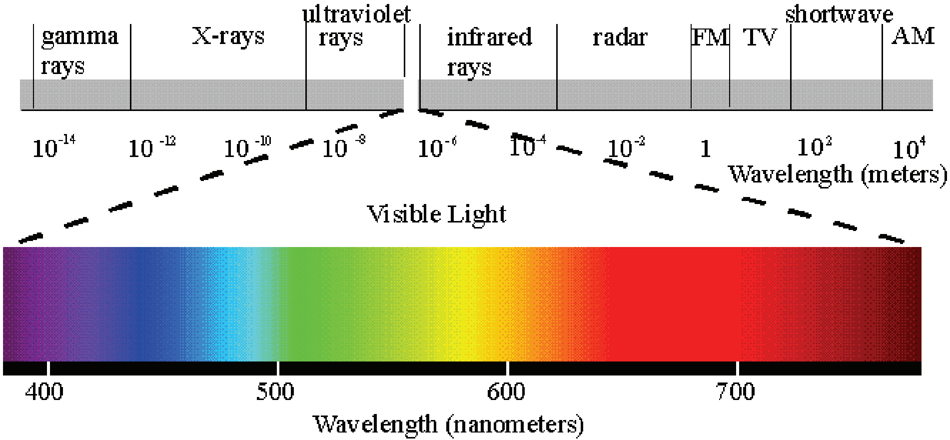
photoreceptors: 3 types of cones (color vision), rods (luminance only, night vision)

The Retina



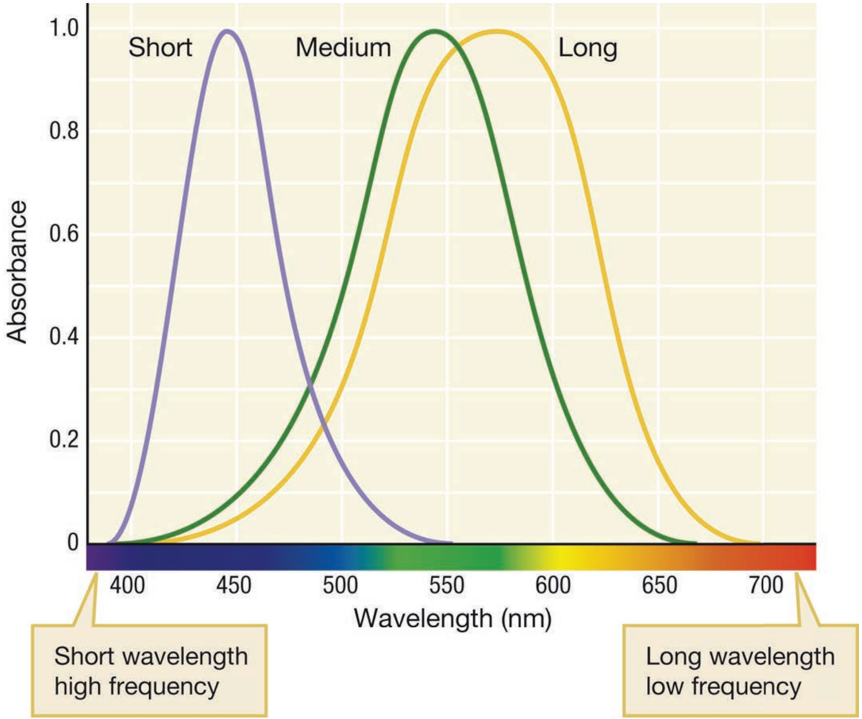
Photoreceptors
Ganglion cells
Bipolar cells
Cone
Rod
Retinal pigment epithelium
Axons of optic nerve
Amacrine cells
Horizontal cells
Light
Inner layer
Middle layer
Outer layer
Sclera
Choroid
Retina
Fovea
Macula lutea
Optic nerve
Optic disk
Sclera
Choroid

Color Perception



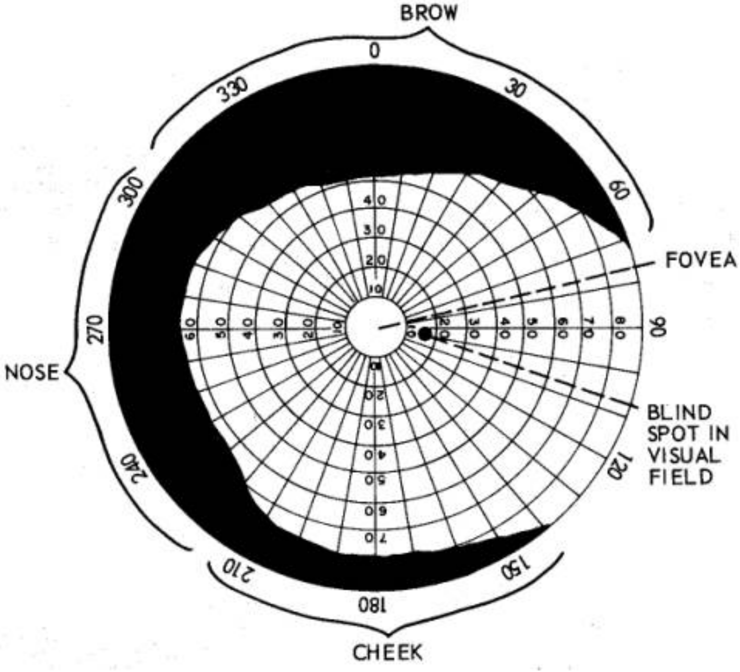
Color Perception - Sensitivity of Cones

reddit.com

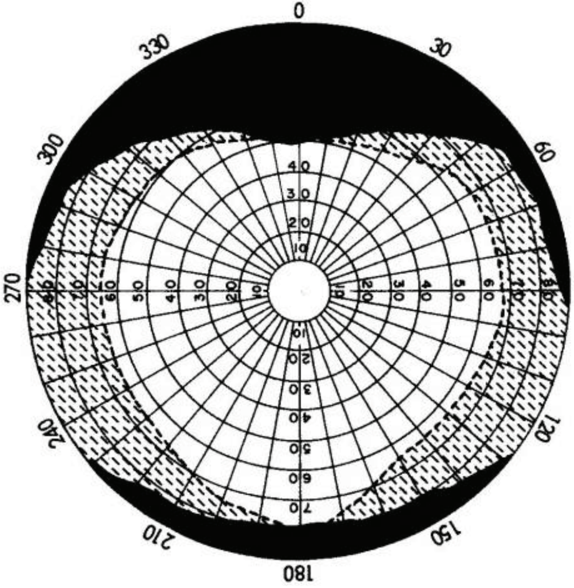


Visual Field / Field of View

Ruch & Fulton, 1960

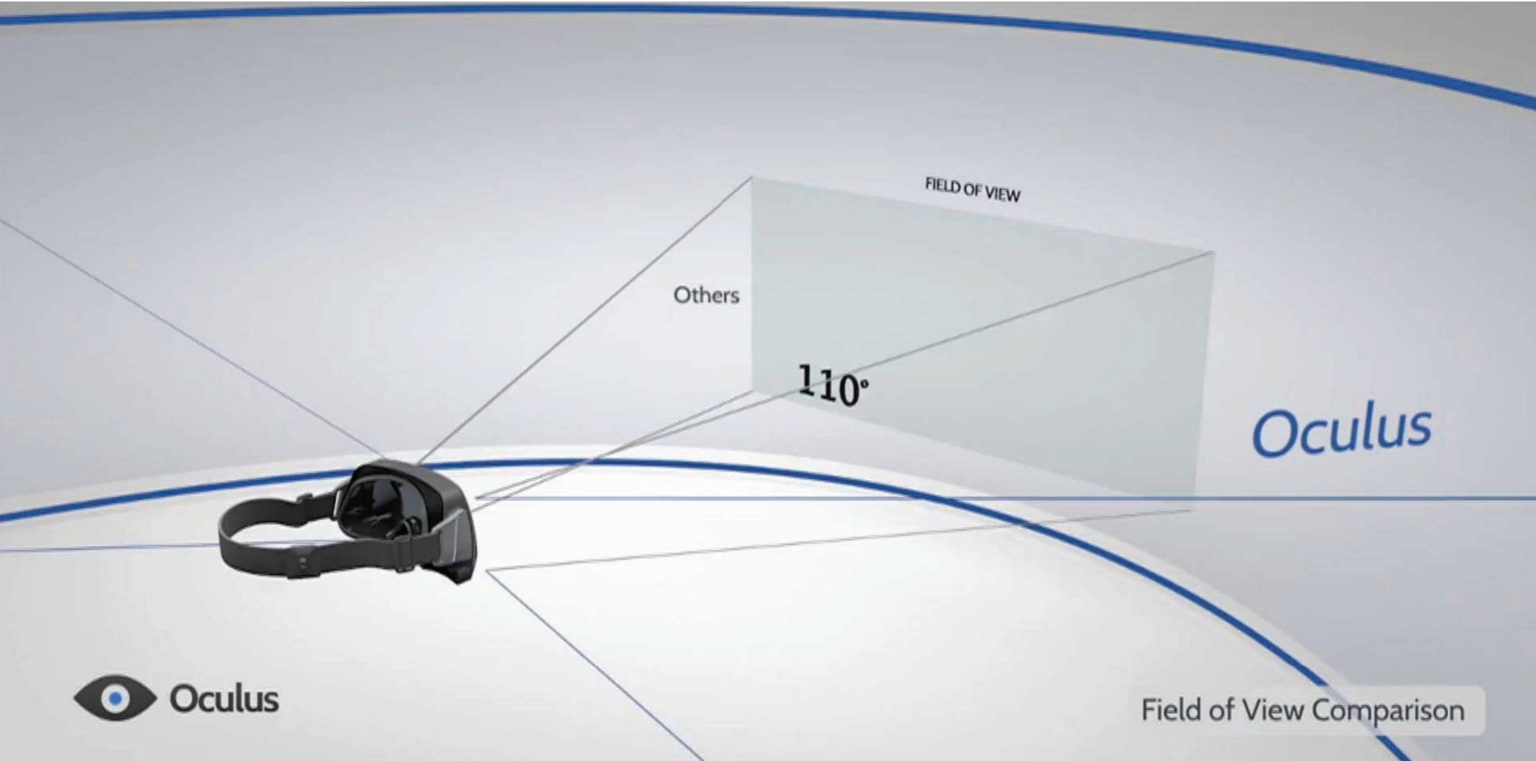


monocular visual field



binocular visual field

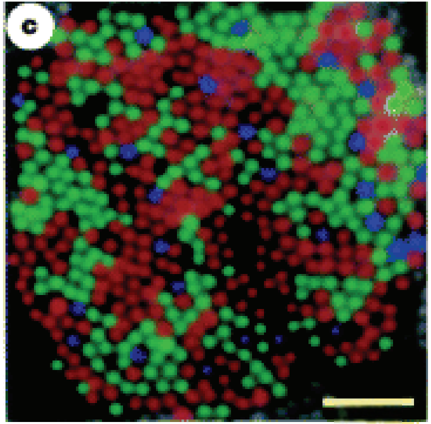
Immersive VR – How Important is the FOV?



Visual Acuity

Roorda & Williams, 1999, Nature

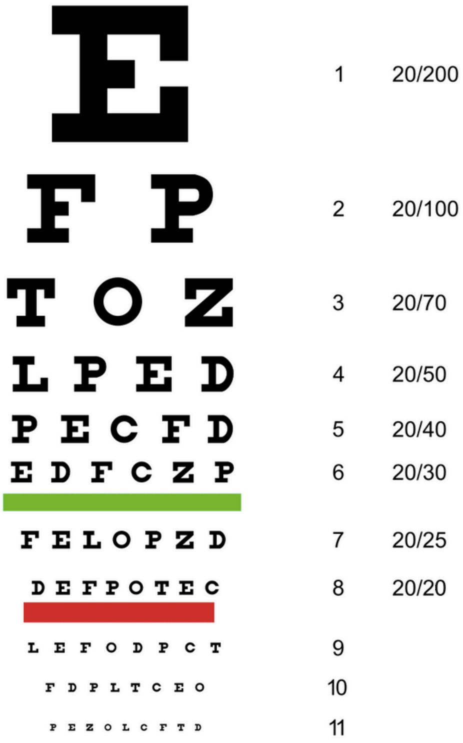
each photorecepter
~ <u>1 arc min</u> (1/60 of a degree)



5 arcmin visual angle

Visual Acuity

Snellen chart



characters are 5 arc min, need to resolve 1 arc min to read

Retina VR Display – What does it Take?

<u>need per eye</u>:

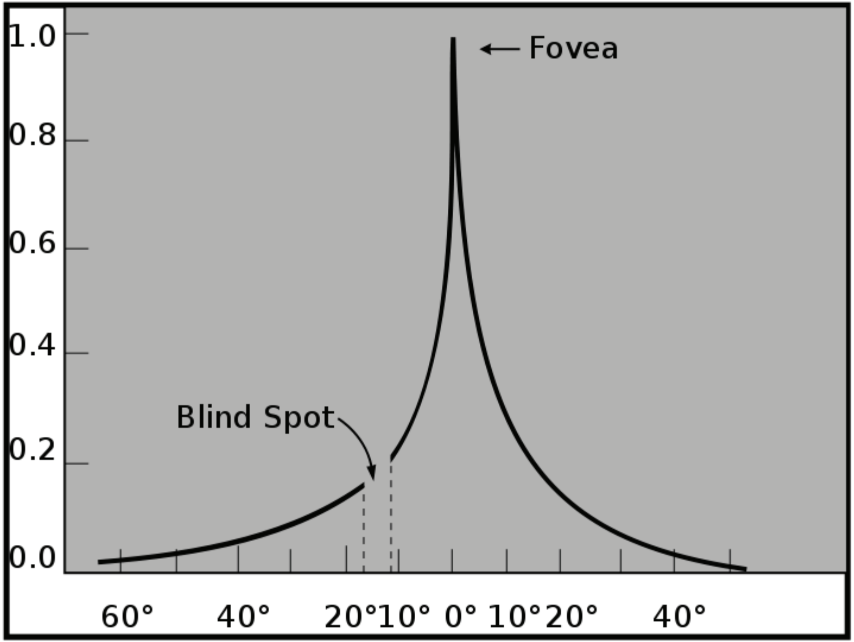
150° x 135° with pixels covering 1 arc min

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

<u>biggest challenge: bandwidth</u>

- 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

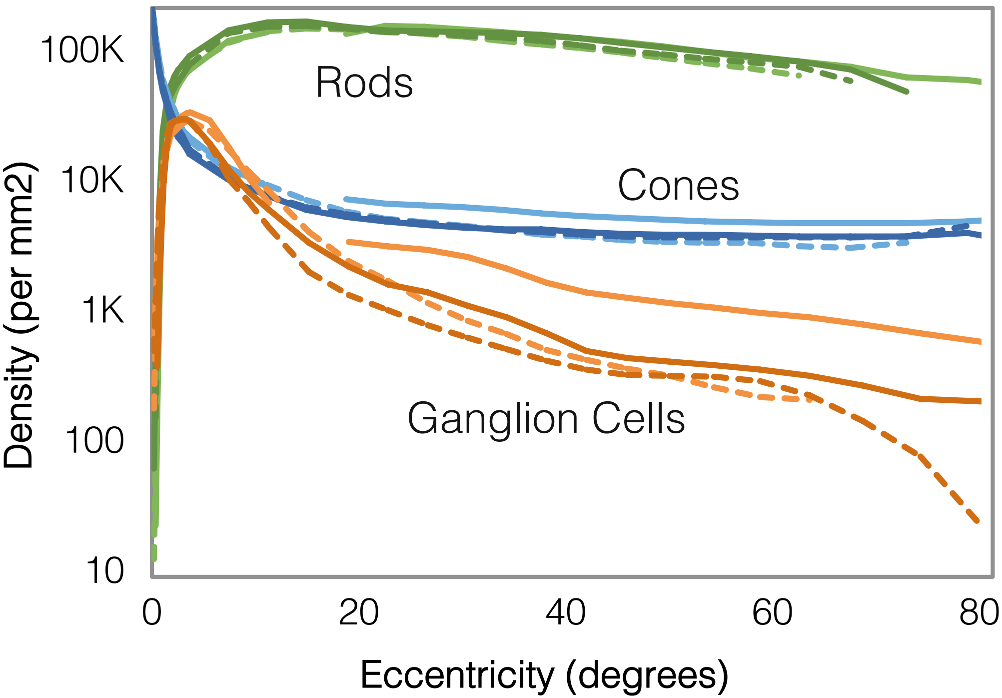


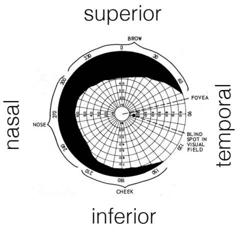
Eccentricity

wikipedia

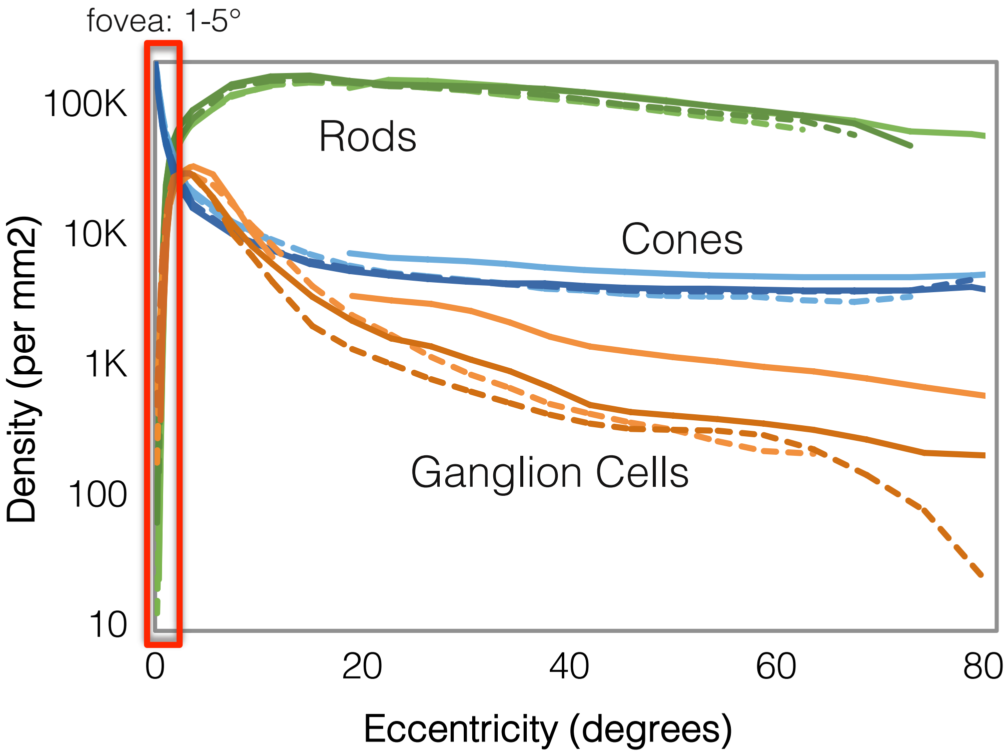
Density of Photoreceptors on Retina

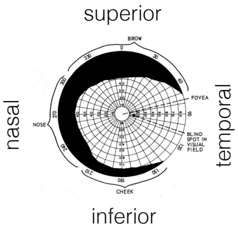
Patney et al. 2016





Density of Photoreceptors on Retina





Patney et al. 2016

MAR / Acuity Over Retina

acuity falls off due to:

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

Guenter et al. 2016

MAR / Acuity Over Retina

acuity falls off due to:

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

Guenter et al. 2016

MAR: minimum angle of resolution in deg/cycle

slope

$$\omega = me + \omega_0$$

eccentricity in degrees

smallest resolvable angle at fovea in deg/cycle

MAR / Acuity Over Retina

acuity falls off due to:

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

Guenter et al. 2016

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)

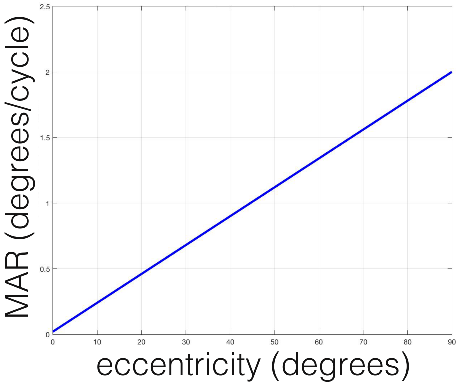
$$m = 0.022 - 0.034$$

acceptable – equivalent for observed image quality

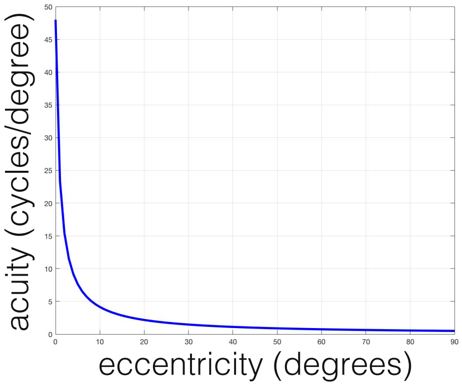
MAR / Acuity Over Retina

Guenter et al. 2016

MAR



Acuity (=1/MAR)



MAR slope

$$\omega = me + \omega_0$$

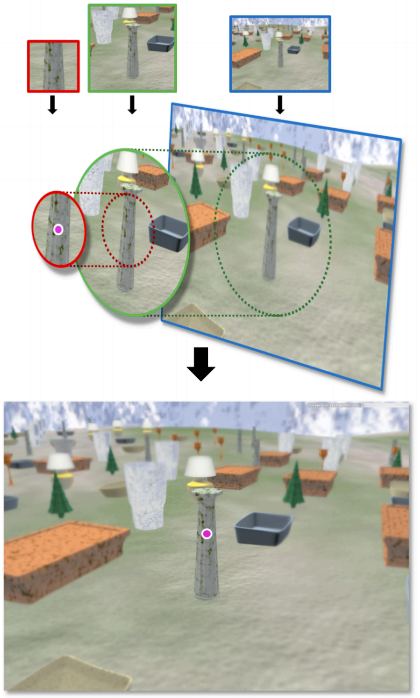
eccentricity in degrees

smallest resolvable angle at fovea in deg/cycle

Patney et al. 2016

Patney et al. 2016

Foveated Rendering

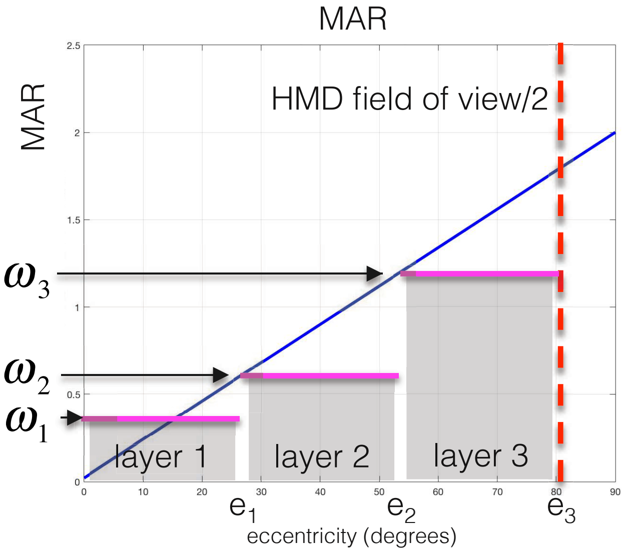


- Guenter et al. 2016: split image into *n* layers, e.g. inner (foveal, 1), middle (2), outer (3)
- render image in each zone with progressively lower resolution

- goal: save computation!

Foveated Rendering

- Guenter et al. 2016: split image into *n* layers, e.g. inner (foveal, 1), middle (2), outer (3)



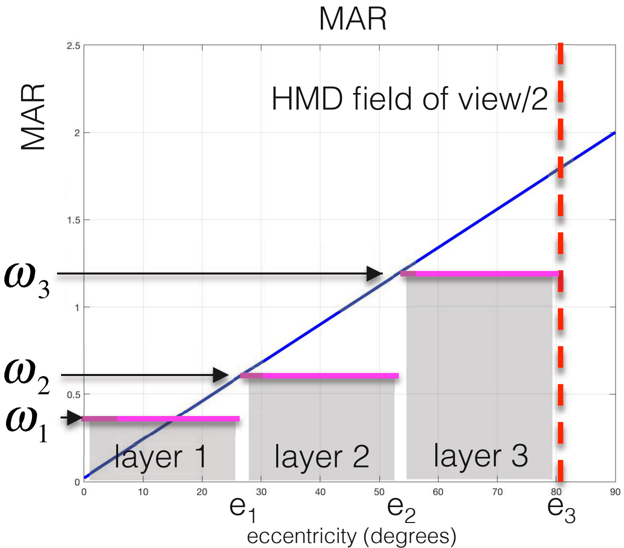
$$e_i = \frac{i}{n} \cdot \frac{fov}{2}$$

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

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

$$e_3 = \frac{fov}{2}$$

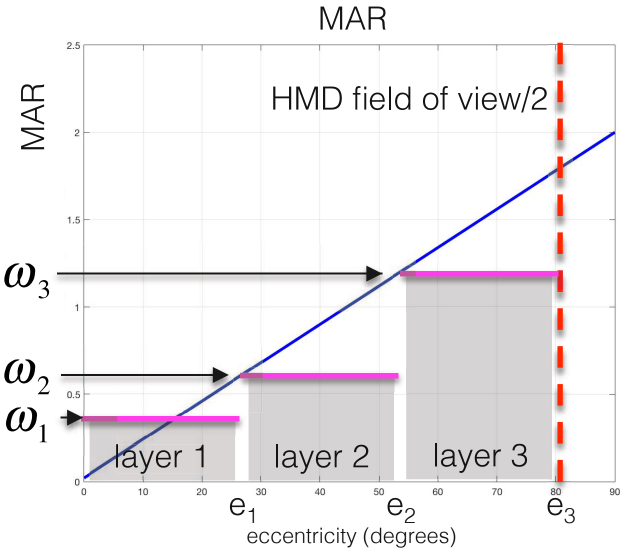
Foveated Rendering



ω_1 is best the display can do!

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

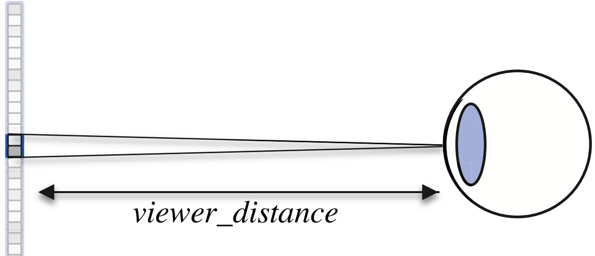
Foveated Rendering



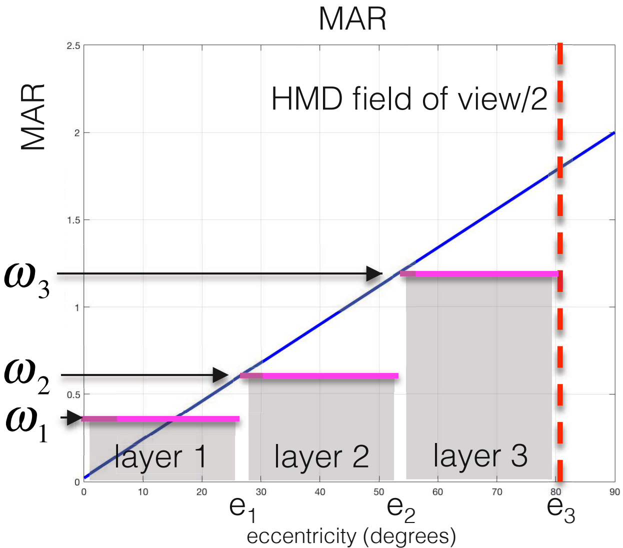
ω_1 is best the display can do!

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

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



Foveated Rendering



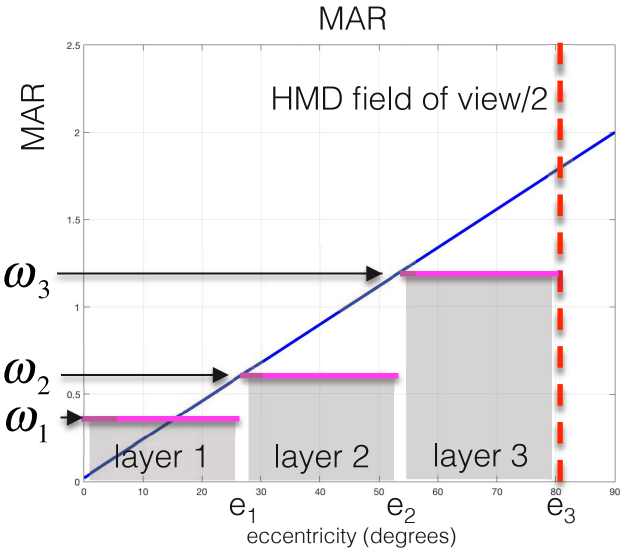
$$\omega_1 = 2\tan^{-1}\left(\frac{screen\_size}{screen\_resolution \cdot viewer\_distance}\right)\cdot\frac{360}{2\pi}$$

$$\omega_2 = me_2 + \omega_0$$

$$\omega_3 = me_3 + \omega_0$$

Foveated Rendering

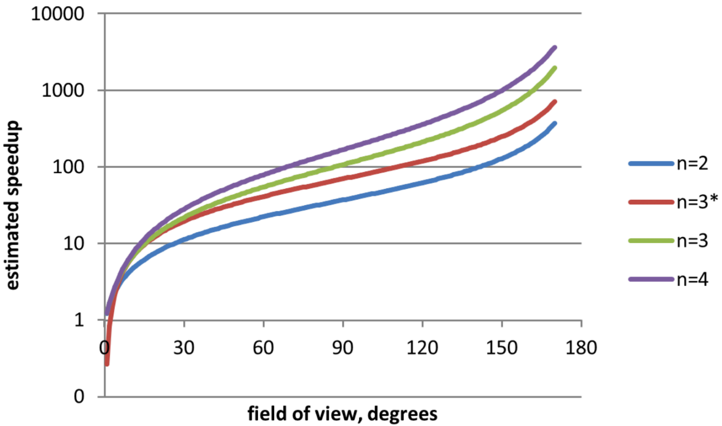
- convert MAR (in degrees/cycle) to pixels



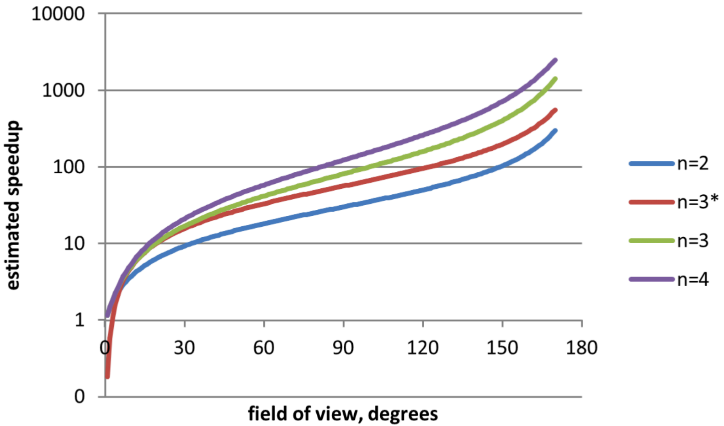
$$blur\_radius\_in\_px = viewer\_distance \cdot \tan\left(\frac{\omega}{2} \cdot \frac{2\pi}{360}\right)$$

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

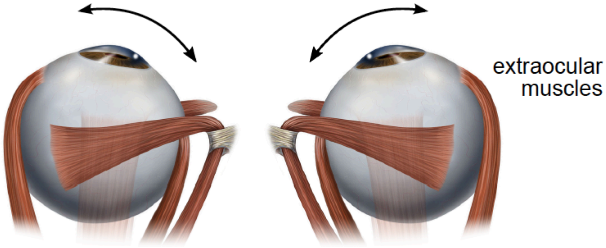
<u>conclusion</u>: for large fov & high-res displays, we need to shade much fewer pixels!

Depth Perception

Vergence & Accommodation

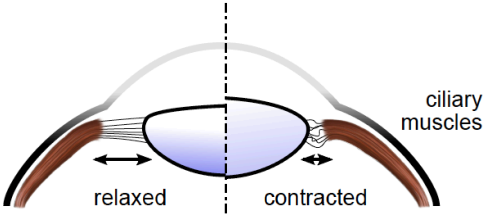
Oculomotor Cue

Stereopsis (Binocular)



Vergence

Focus Cues (Monocular)



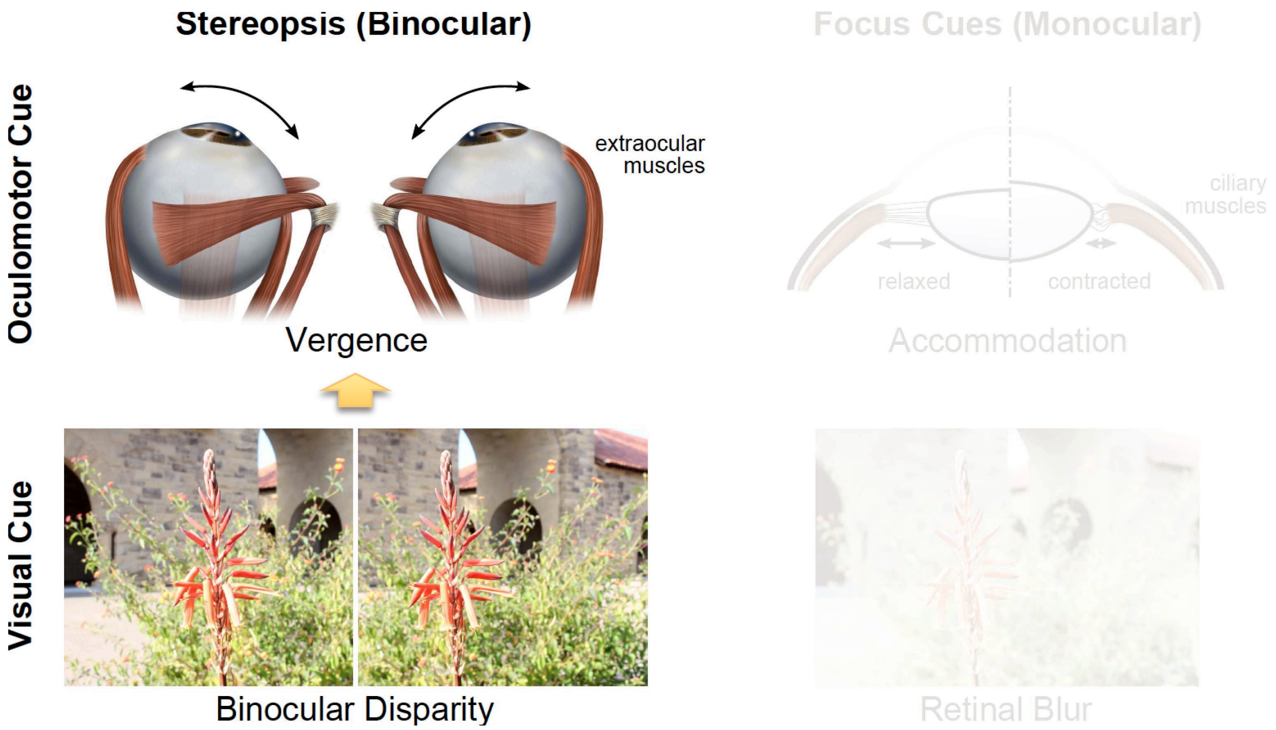
Accommodation

Visual Cue

Binocular Disparity

Retinal Blur

Vergence & Accommodation



Vergence & Accommodation

Oculomotor Cue

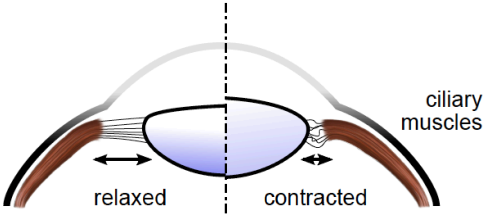
Visual Cue

Stereopsis (Binocular)

Vergence

Binocular Disparity

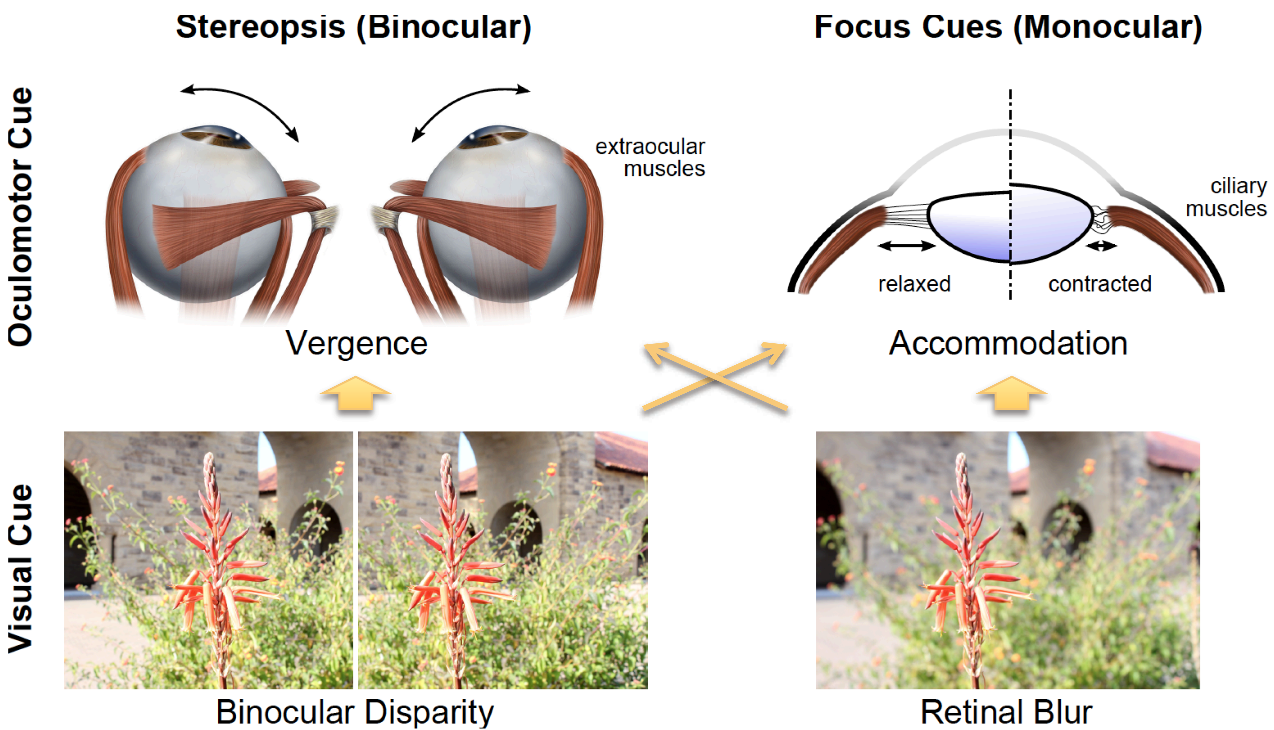
Focus Cues (Monocular)



Accommodation

Retinal Blur

Vergence & Accommodation



Depth Perception

wikipedia

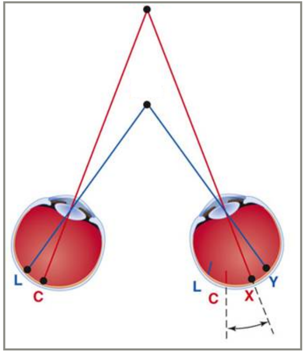
monocular cues

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

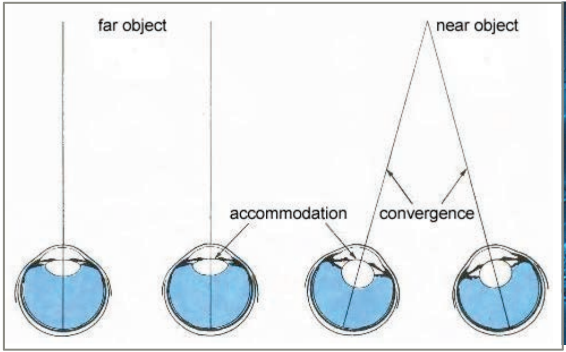
binocular cues

- (con)vergence
- disparity / parallax
- …

Depth Perception

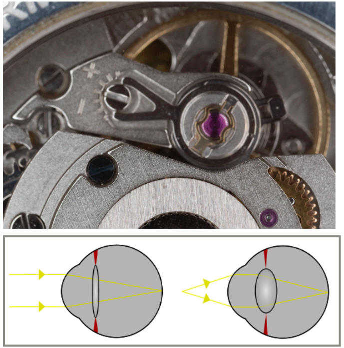


binocular disparity



convergence

motion parallax



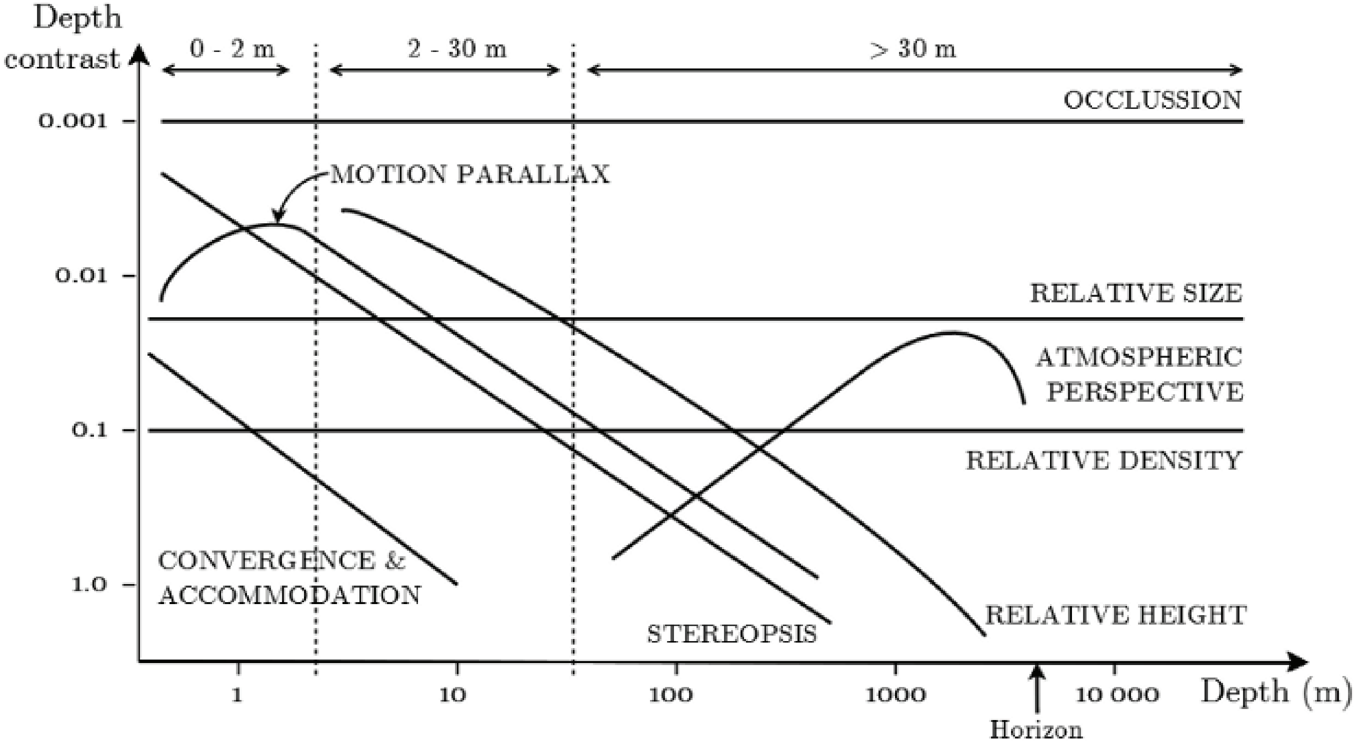
accommodation/blur

current glasses-based (stereoscopic) displays

near-term: light field displays

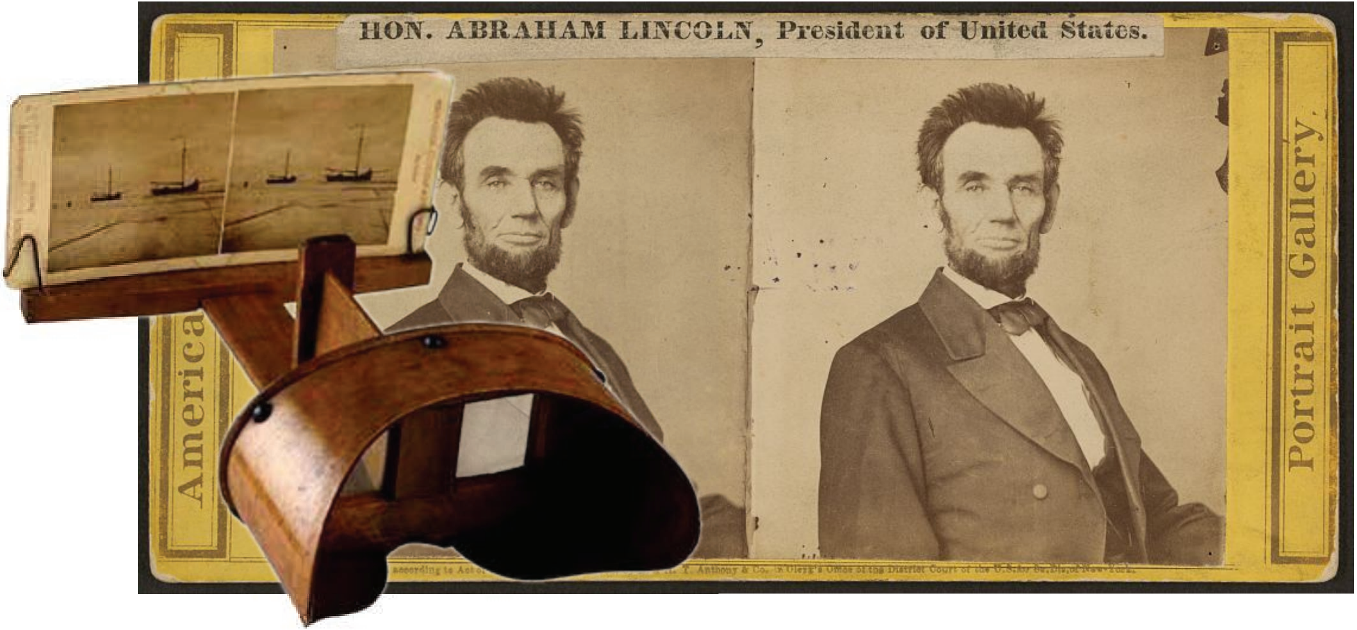
longer-term: holographic displays

Depth Perception



Cutting & Vishton, 1995

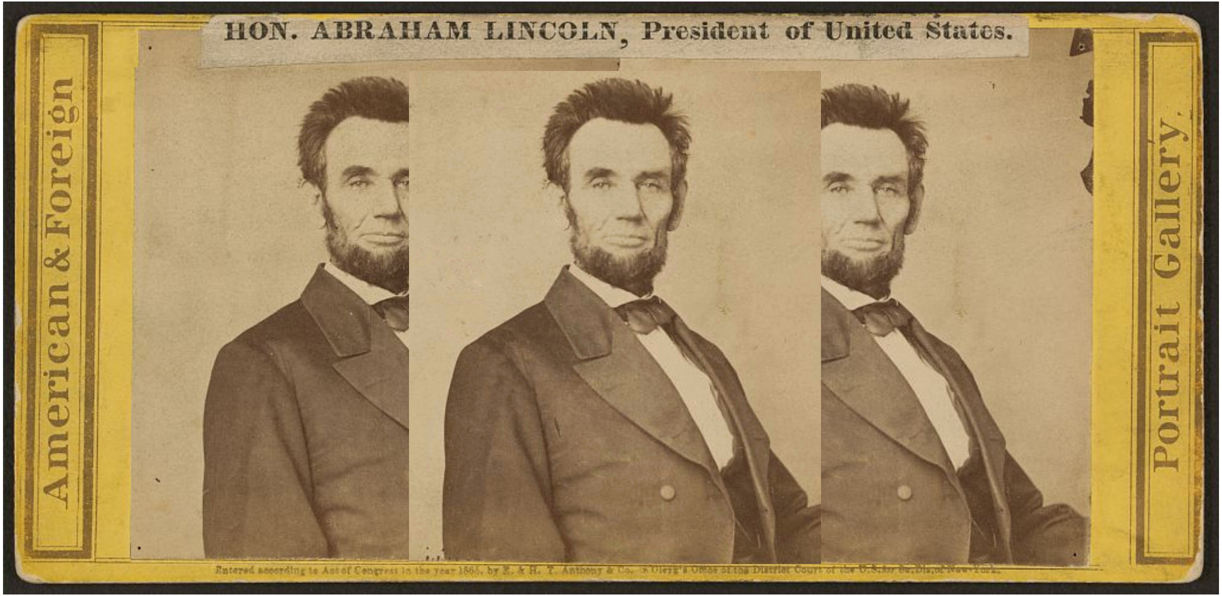
Stereoscopic Displays



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

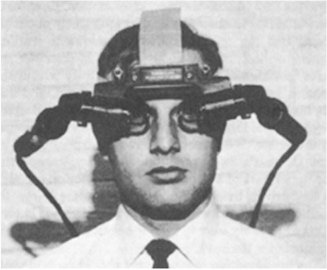
176 years later

stereoscopic displays

A Brief History of Virtual Reality

Stereoscopes
Wheatstone, Brewster, …

VR, AR,
Ivan Sutherland



VR explosion
Oculus, Sony, Valve, MS, …

1838

1968

2012-2015

Next-generation VR Displays

Focus Cues

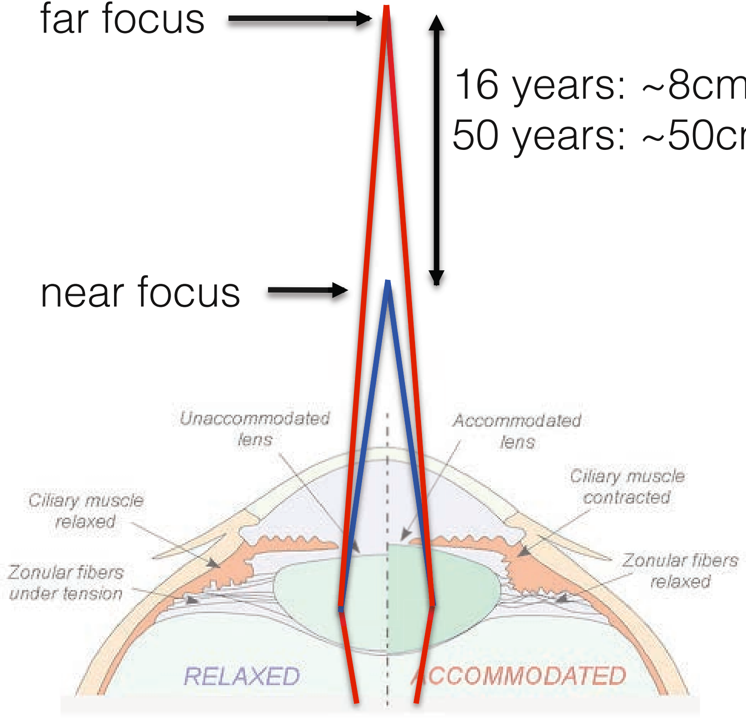
Oculomotor Processes

far focus

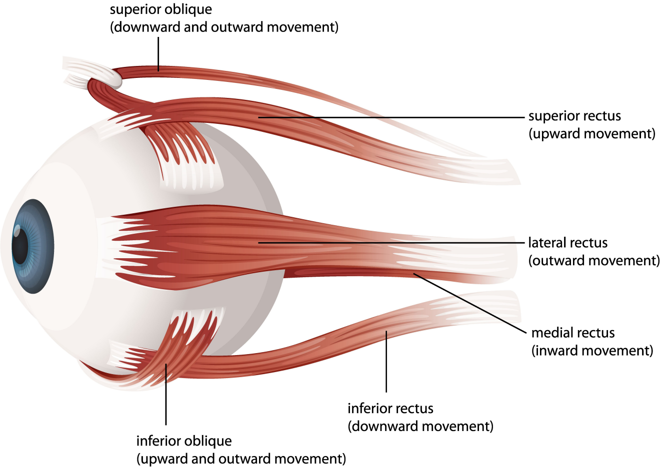
near focus

16 years: ~8cm to ∞

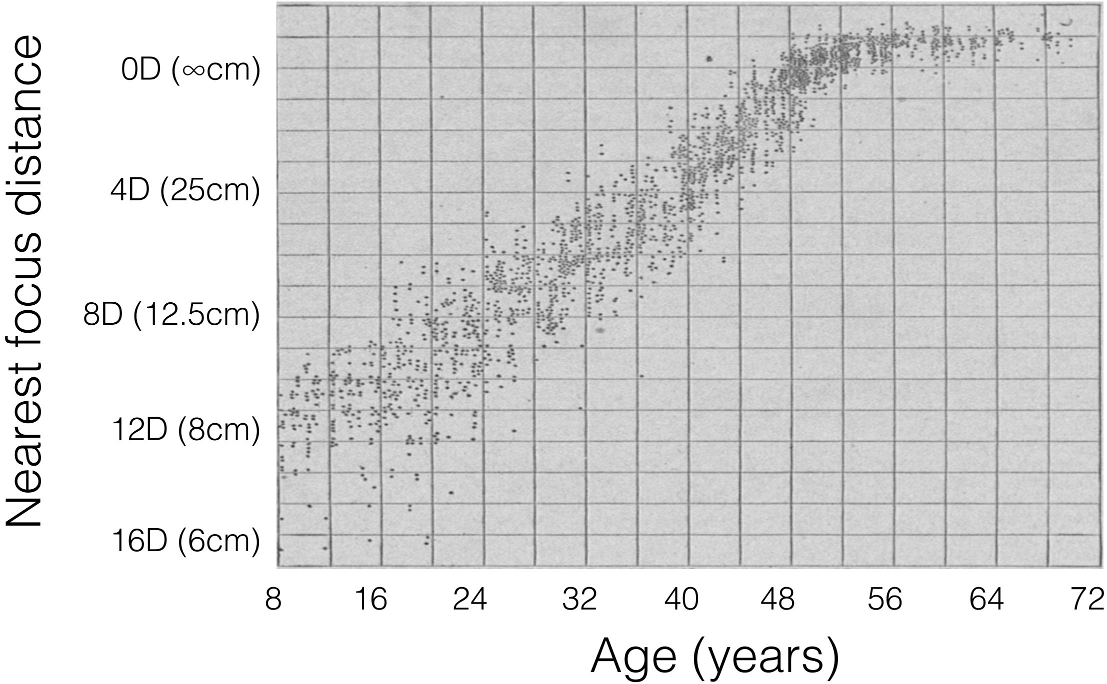
50 years: ~50cm to ∞ (mostly irrelevant)



adithyakiran.wordpress.com



Focus Cues Degrade With Age - Presbyopia



Duane, 1912

Bifocals

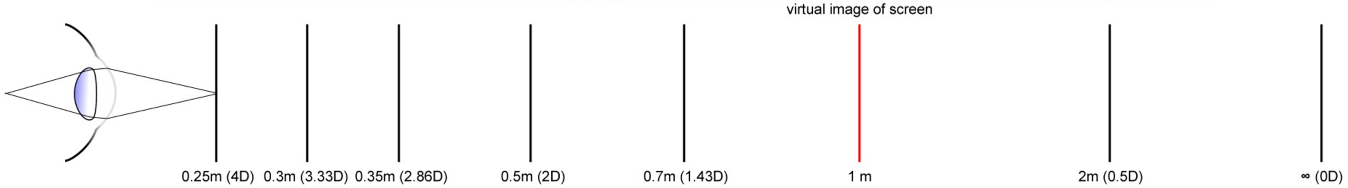
https://c1.staticflickr.com/1/77/173805491_4e4d77fa71_b.jpg

Blur Affects Relative Object Size!

Held et al., 2006, ACM SIGGRAPH

Accommodation and Retinal Blur

Conventional Display

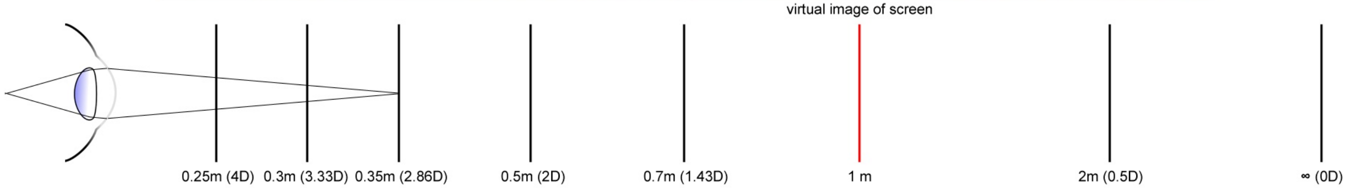


Accommodation and Retinal Blur

Conventional Display

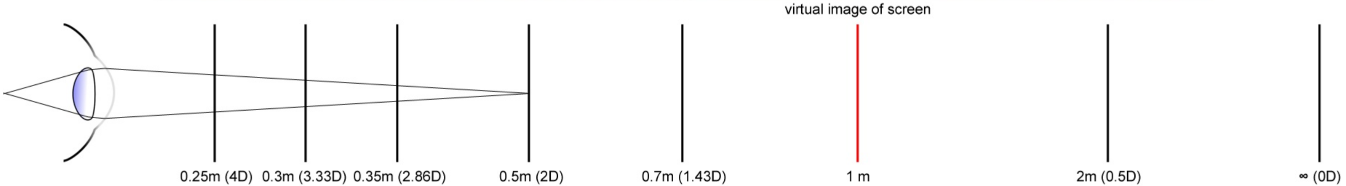
Accommodation and Retinal Blur

Conventional Display



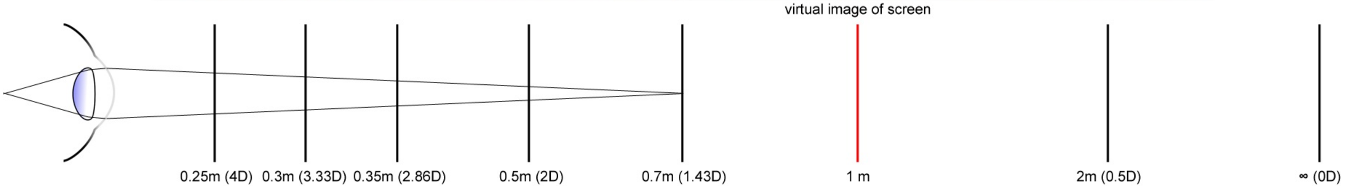
Accommodation and Retinal Blur

Conventional Display



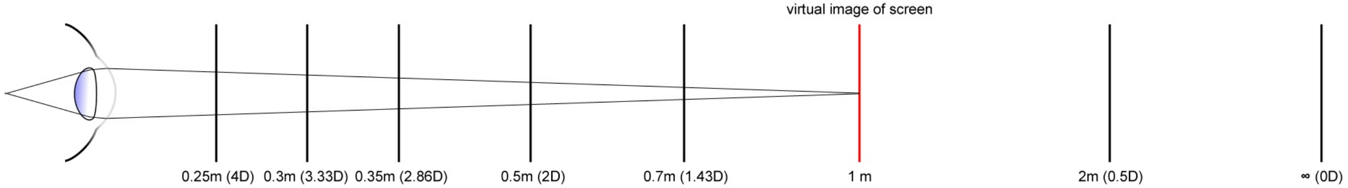
Accommodation and Retinal Blur

Conventional Display

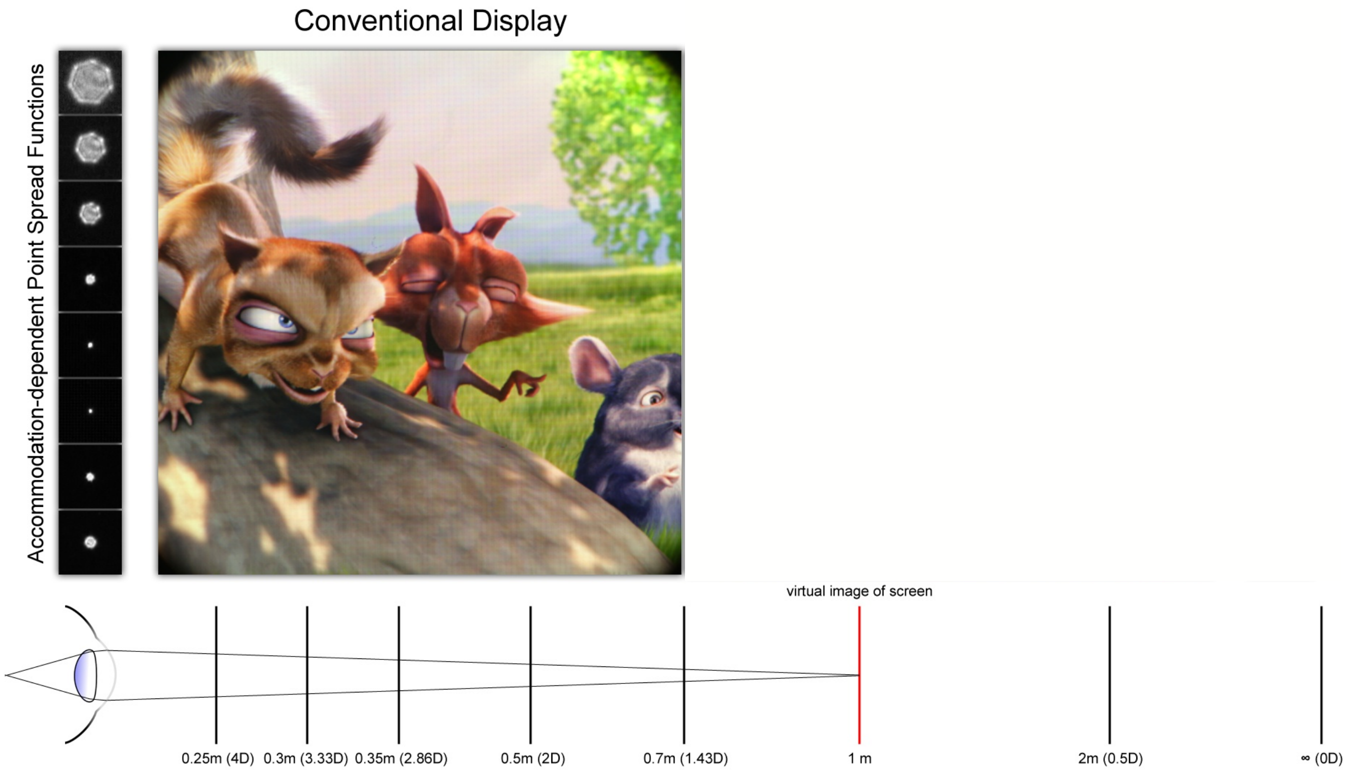


Accommodation and Retinal Blur

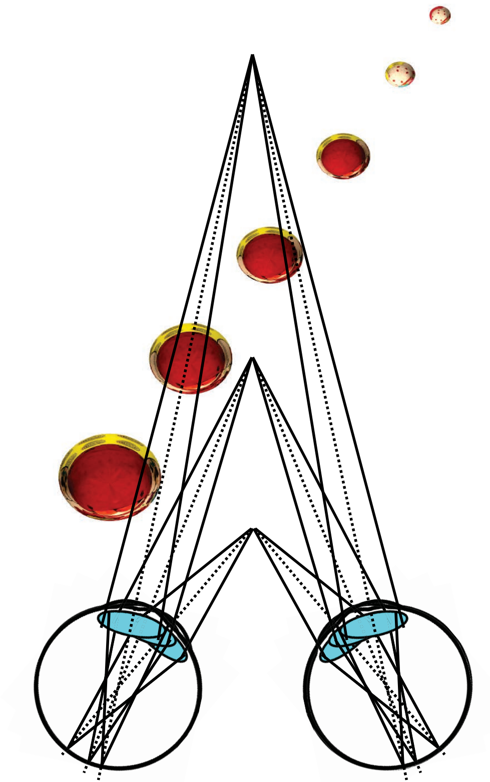
Conventional Display



Accommodation and Retinal Blur

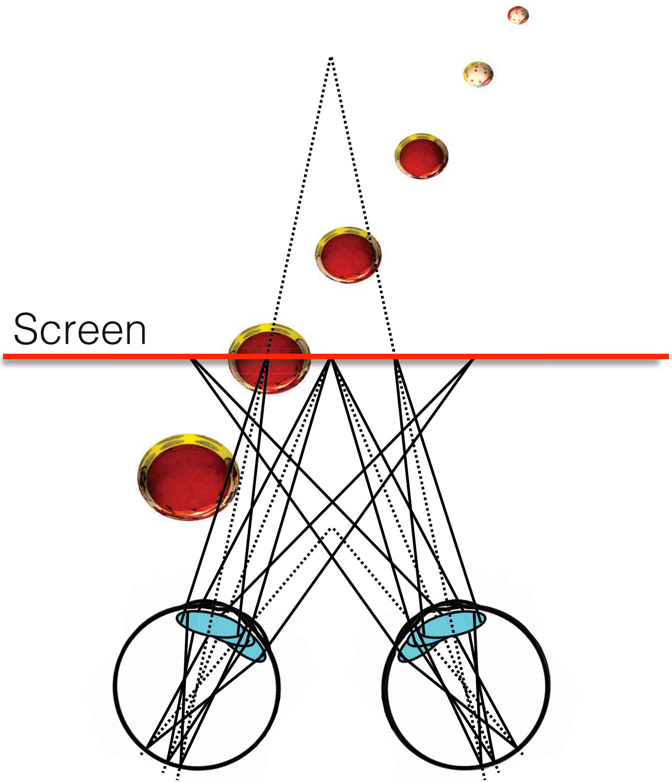


Top View



Real World:

Vergence & Accommodation Match!

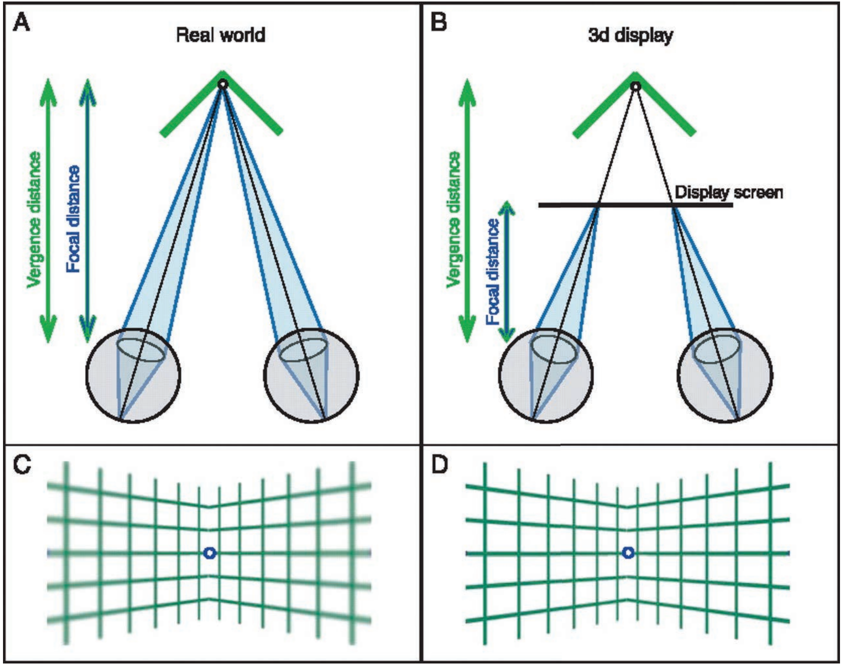


Stereo Displays Today:

Vergence-Accommodation Mismatch!

Vergence-Accommodation Conflict

Marty Banks, UC Berkeley

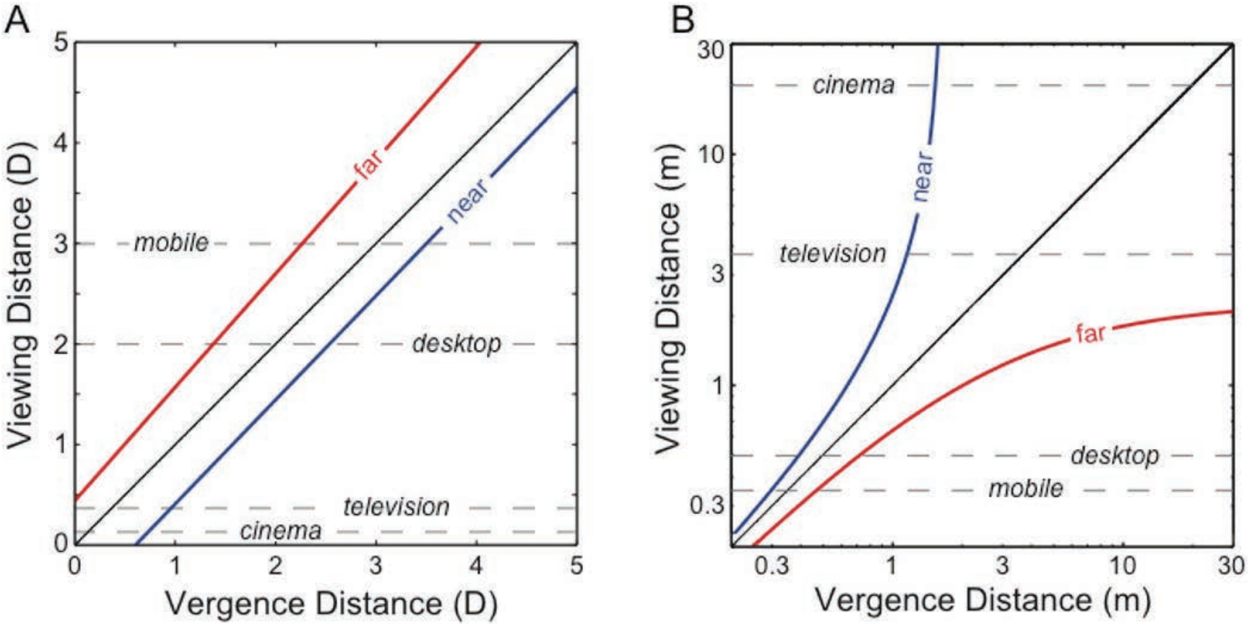


effects

- 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
- field of view: ~190° monocular, ~120° binocular, ~135° vertical
- temporal resolution: ~60 Hz (depends on contrast, luminance)
- dynamic range: instantaneous 6.5 f-stops, adapt to 46.5 f-stops
- color: everything in the CIE xy diagram; distances are linear in CIE Lab
- depth cues in 3D displays: vergence, focus, conflicts, (dis)comfort
- 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