an engineering-focused introduction to

The Human Visual System

EE367/CS448I: Computational Imaging

stanford.edu/class/ee367

Lecture 2

Gordon Wetzstein

Stanford University

nautilus eye, wikipedia

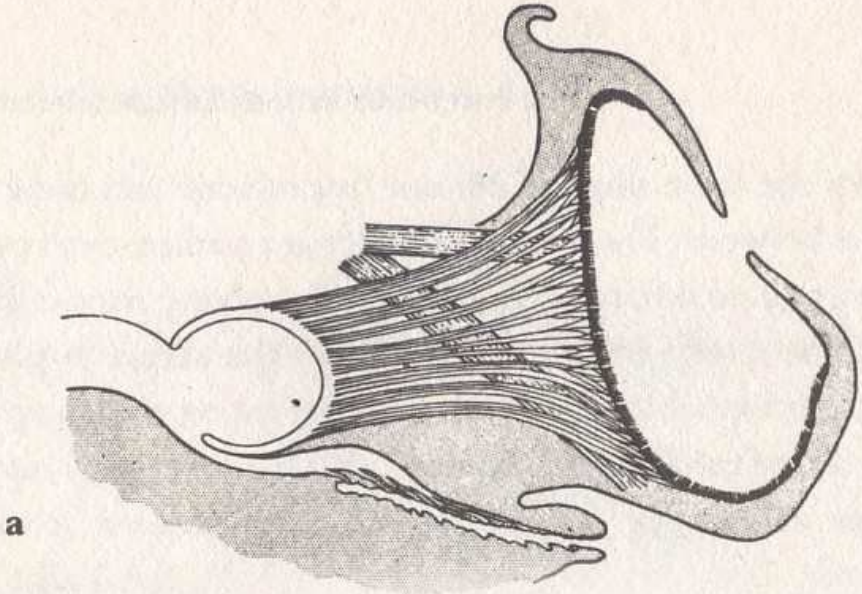
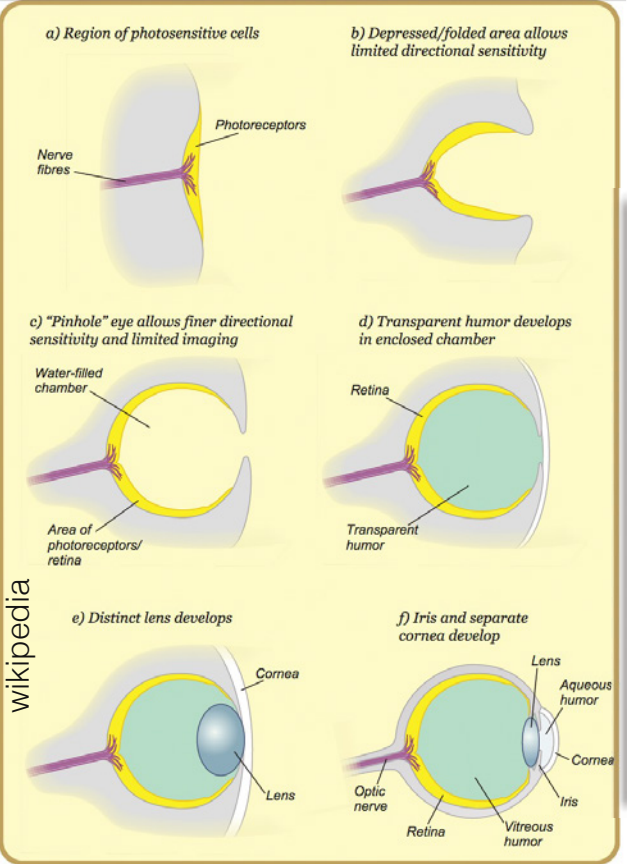


Figure 5.8 (opposite) A range of invertebrate eyes that illustrate approaches to the formation of crude but effective images: (a) *Nautilus*'s pinhole eye; (b) marine snail; (c) bivalve mollusc; (d) abalone; (e) ragworm.

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

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

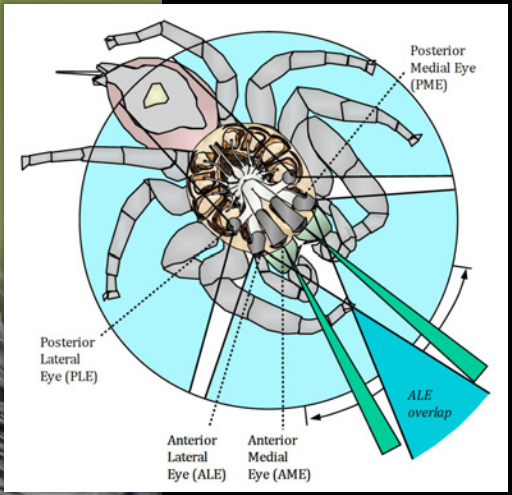
Evolution of the Eye



wikipedia

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

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



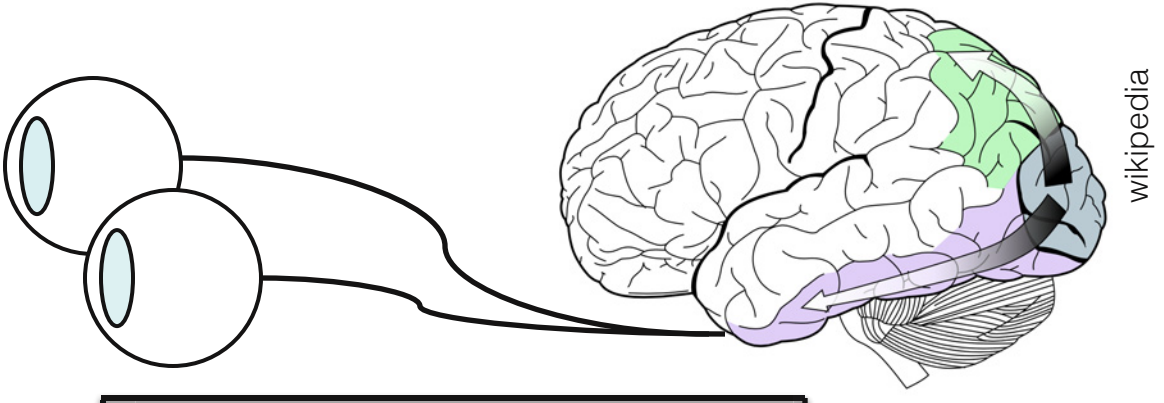
jumping spider, wikipedia

national geographics

Summary of Human Visual System (HVS)

- **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

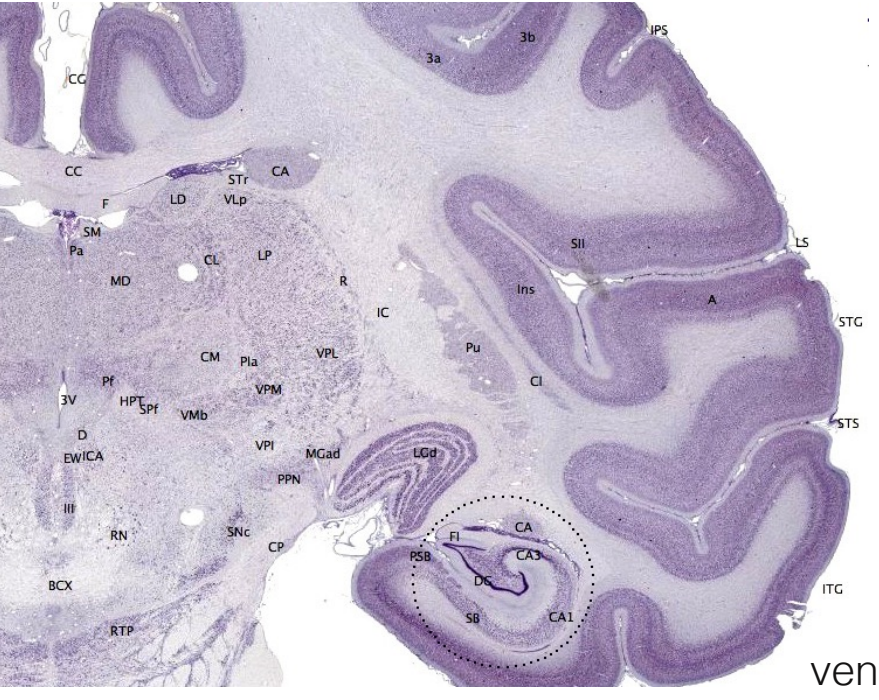
Overview



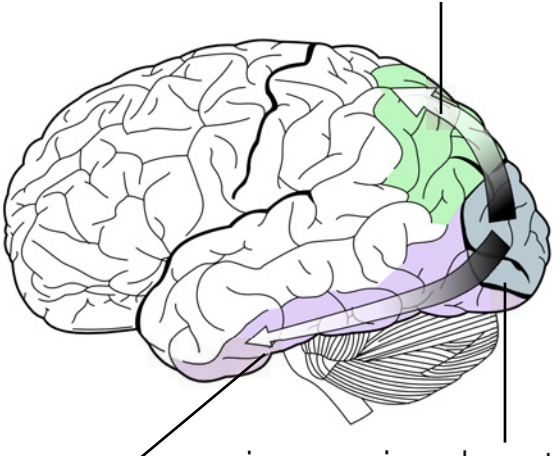
sensors → network → compute

low-level processing high-level processing

Overview



dorsal stream: spatial awareness

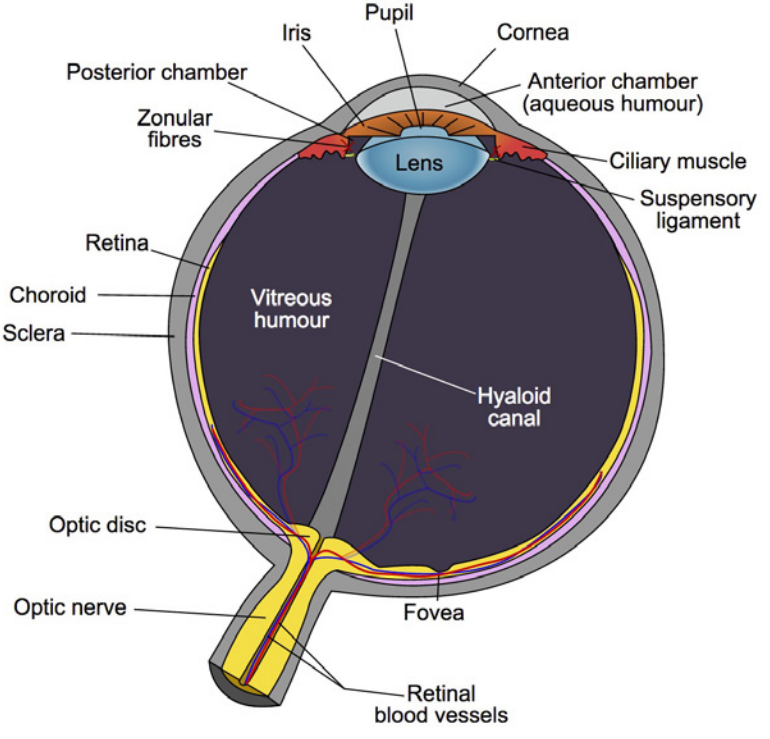


wikipedia

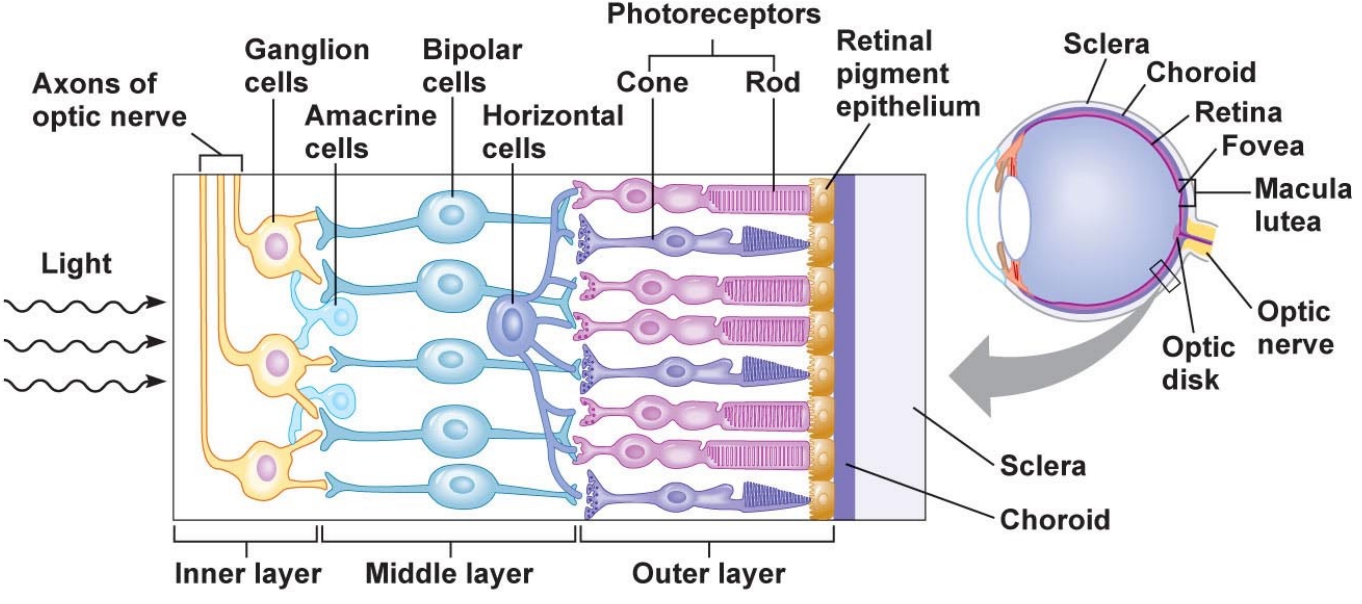
primary visual cortex

ventral stream:
recognition, object identification

Anatomy of the Human Eye

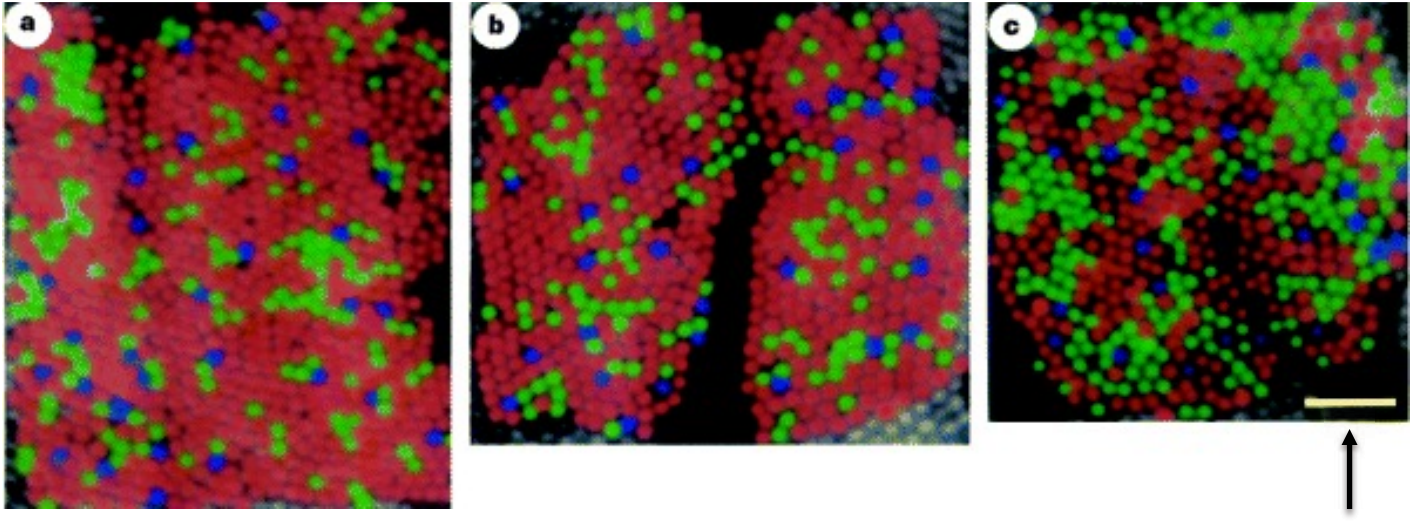


The Retina



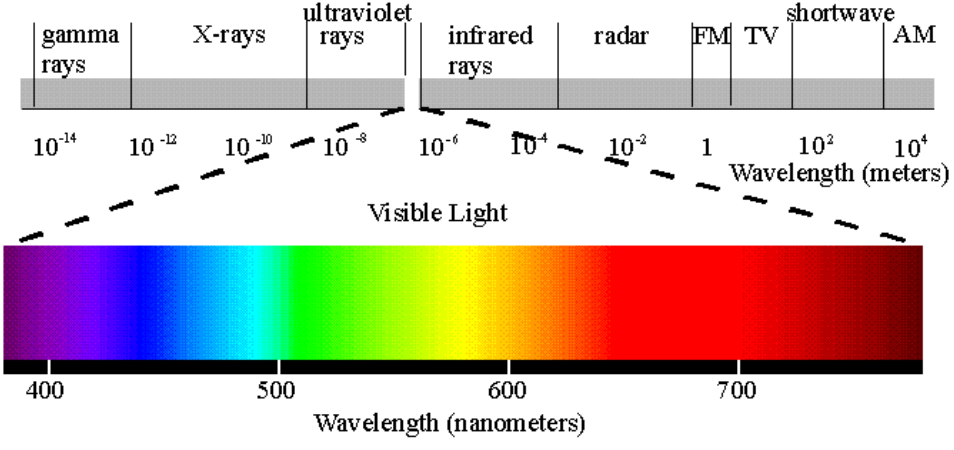
The Retina

Roorda & Williams, 1999, Nature



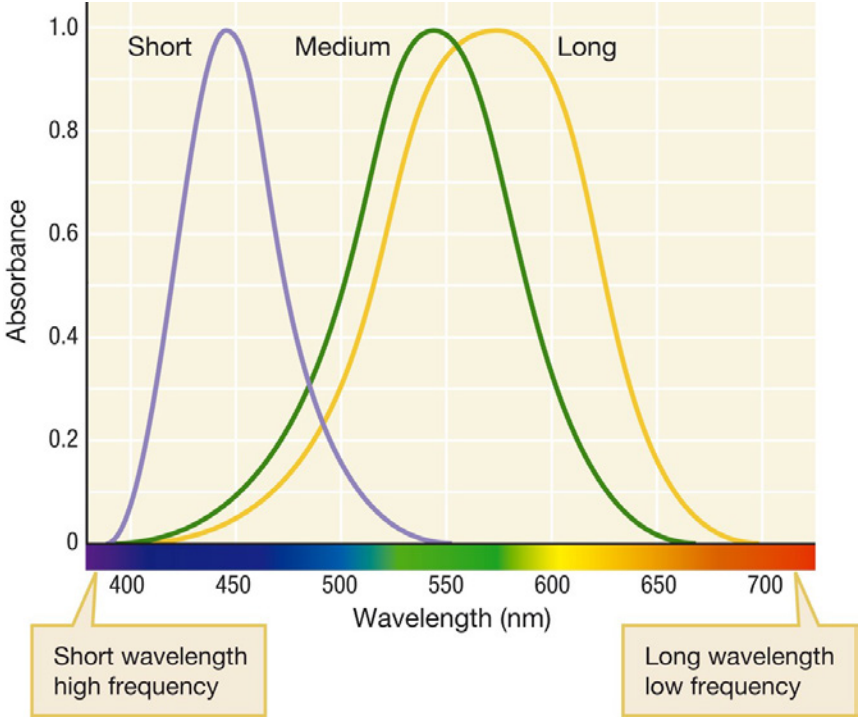
5 arcmin visual angle

Color Perception



Color Perception - Sensitivity of Cones

reddit.com

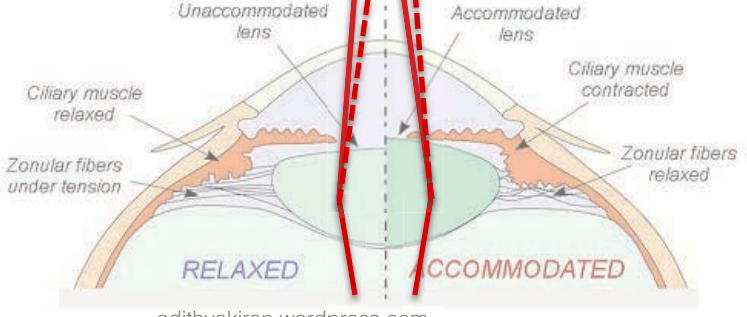


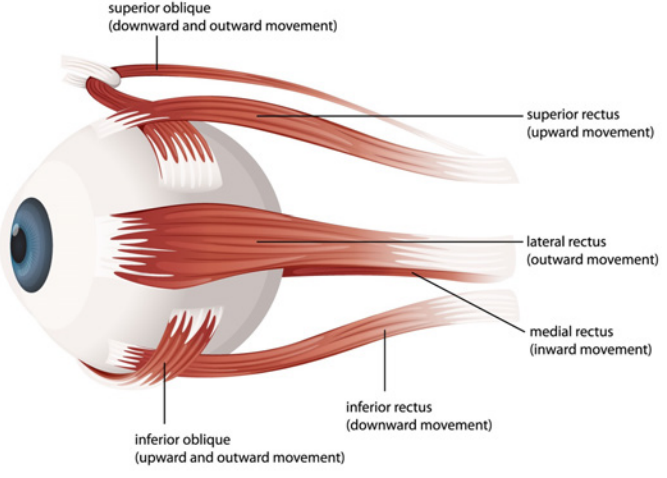
Oculumotor Processes

far focus

near focus

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





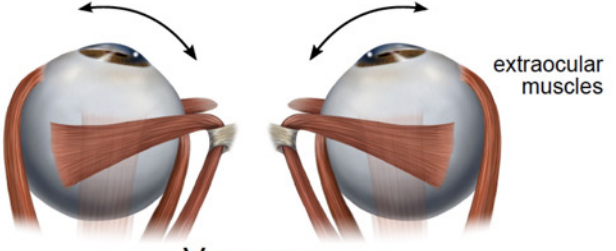
adithyakiran.wordpress.com

Oculumotor Processes + Visual Cues

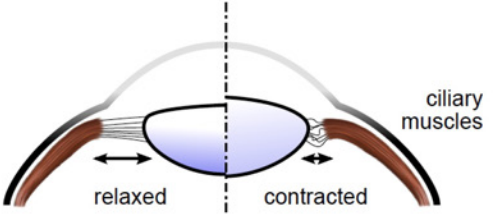
Stereopsis (Binocular)

Focus Cues (Monocular)

Oculomotor Cue



Vergence

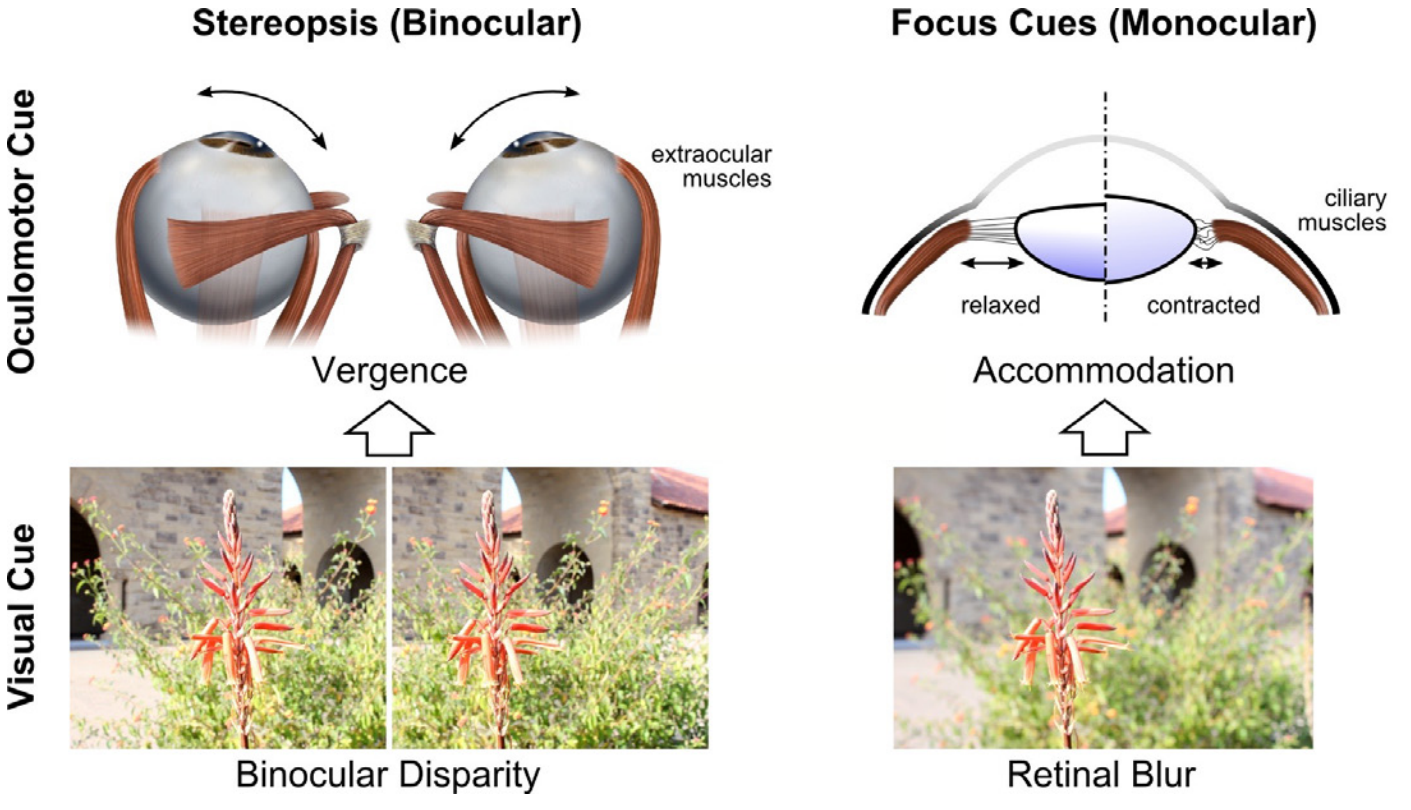


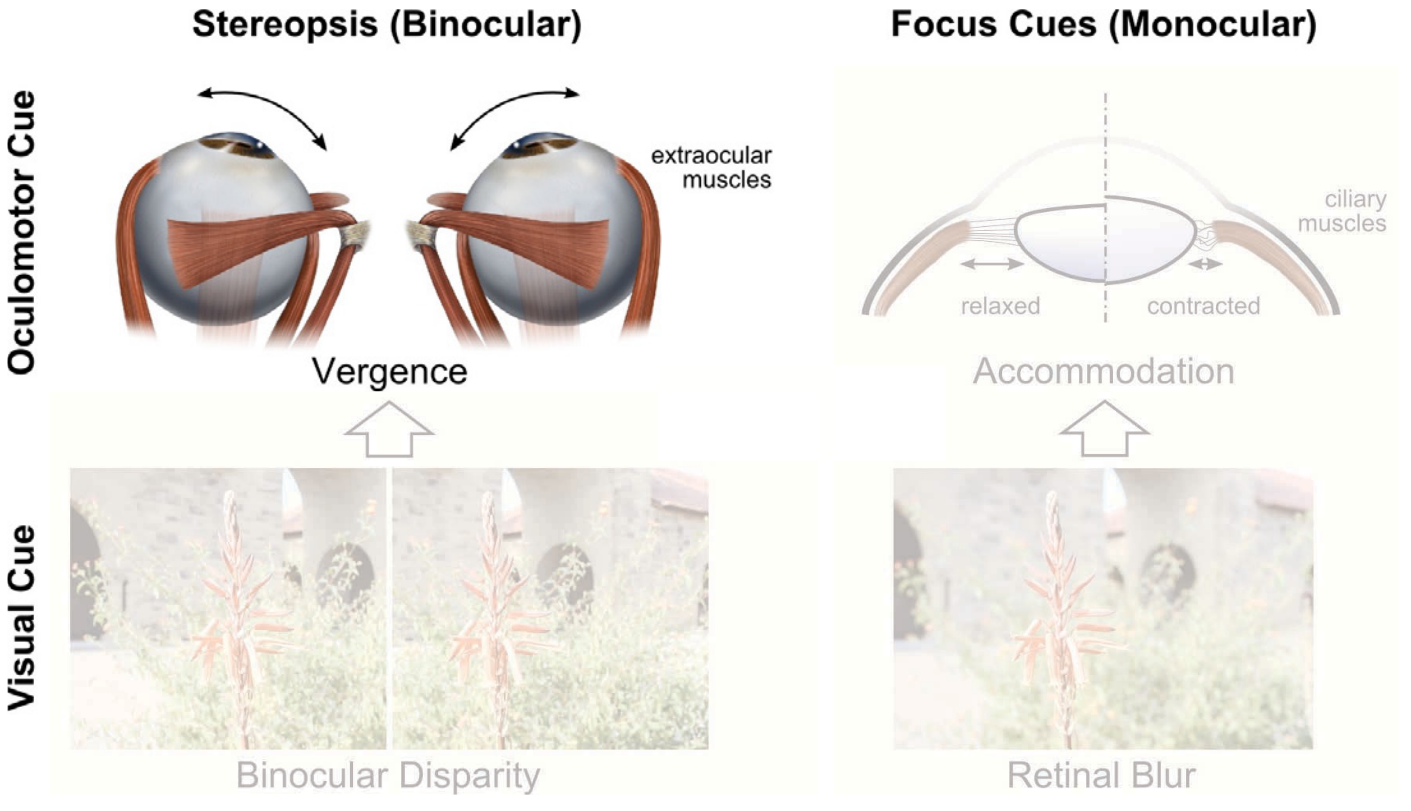
Accommodation

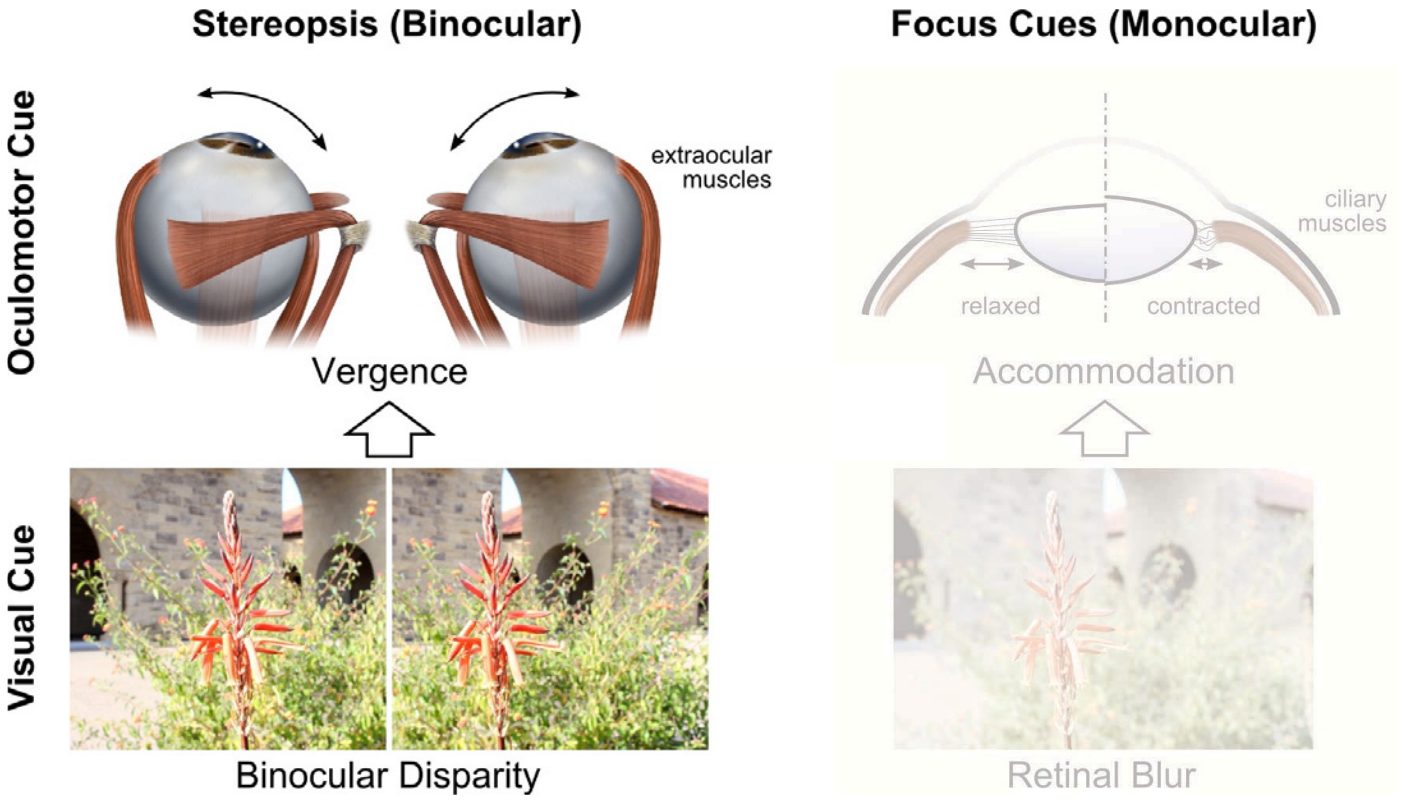
Visual Cue

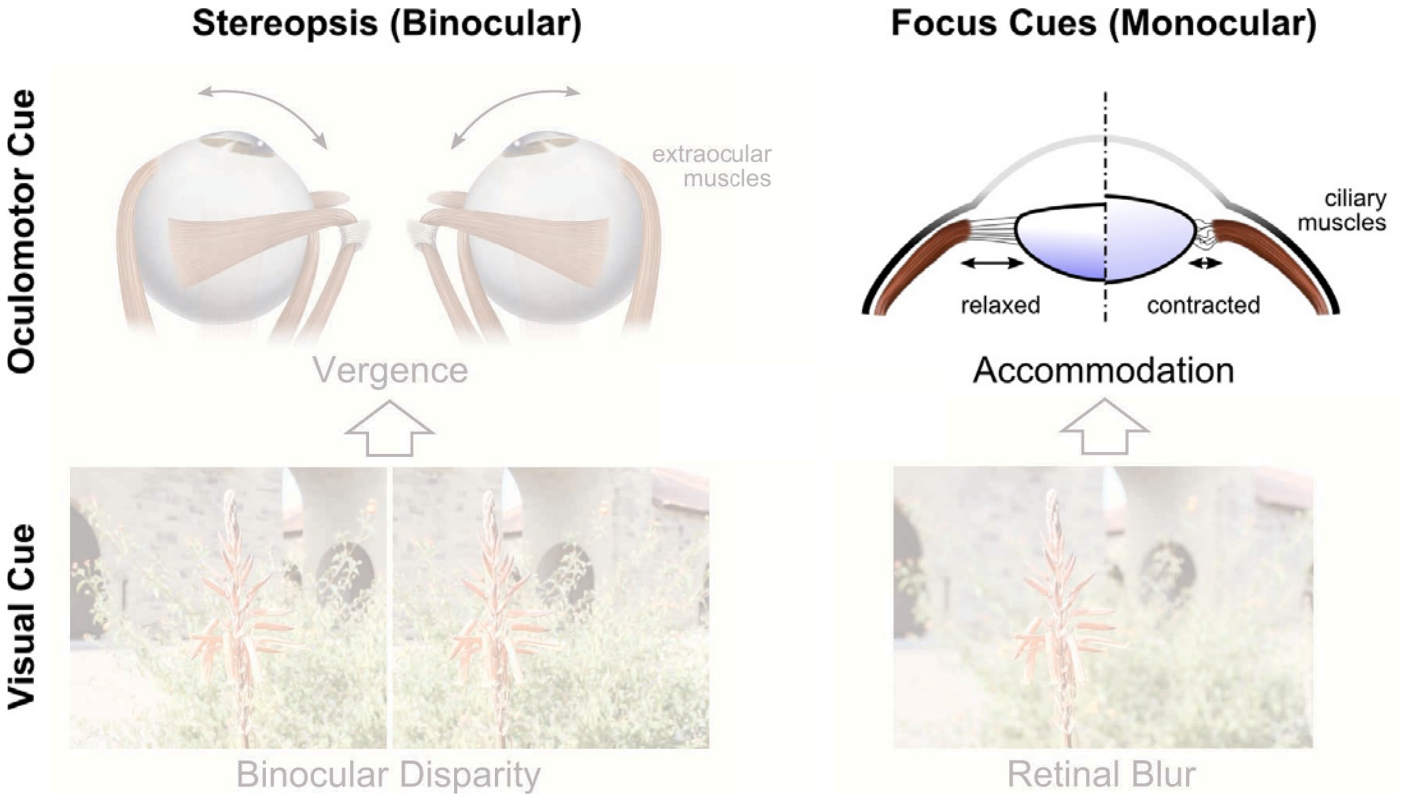
Binocular Disparity

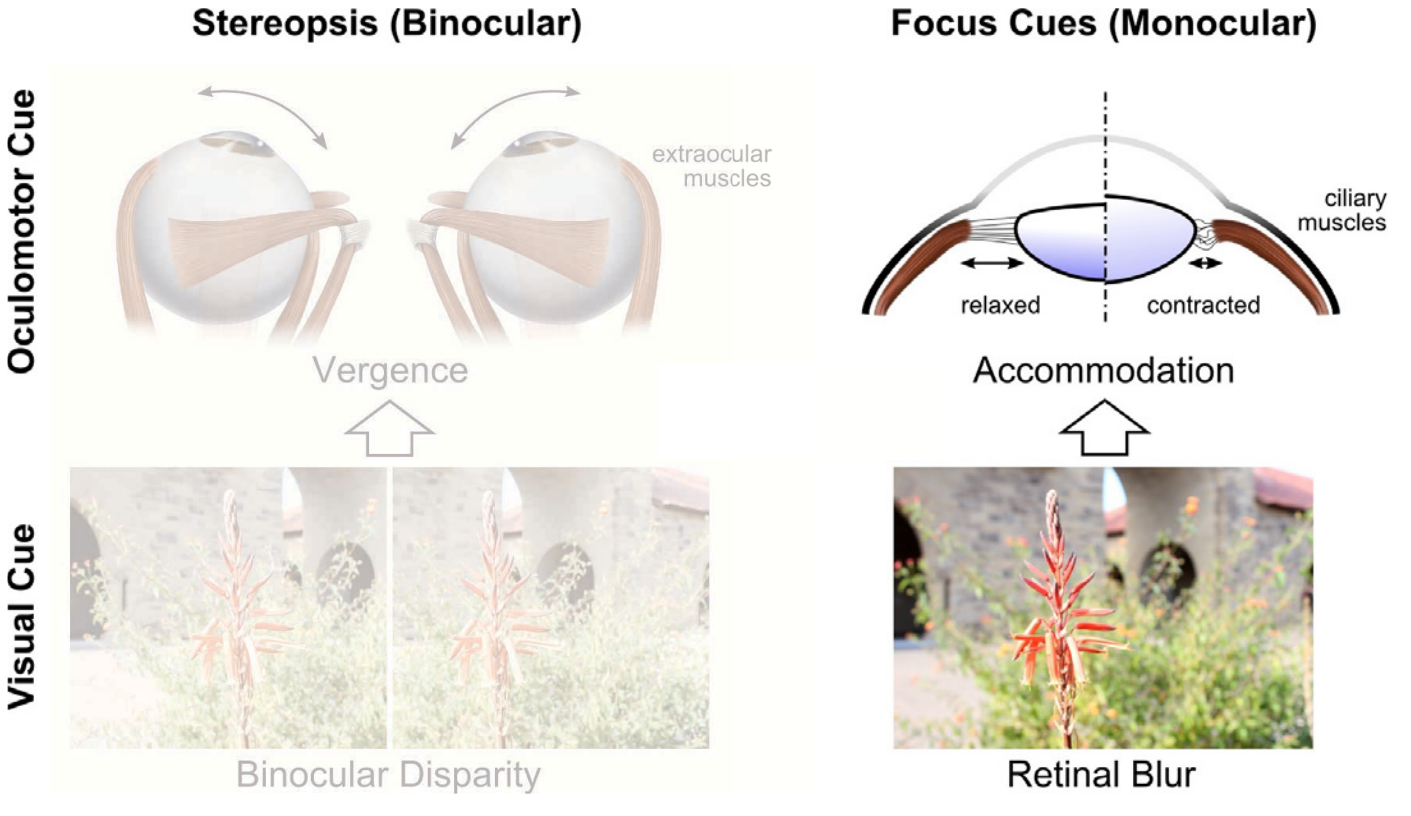
Retinal Blur

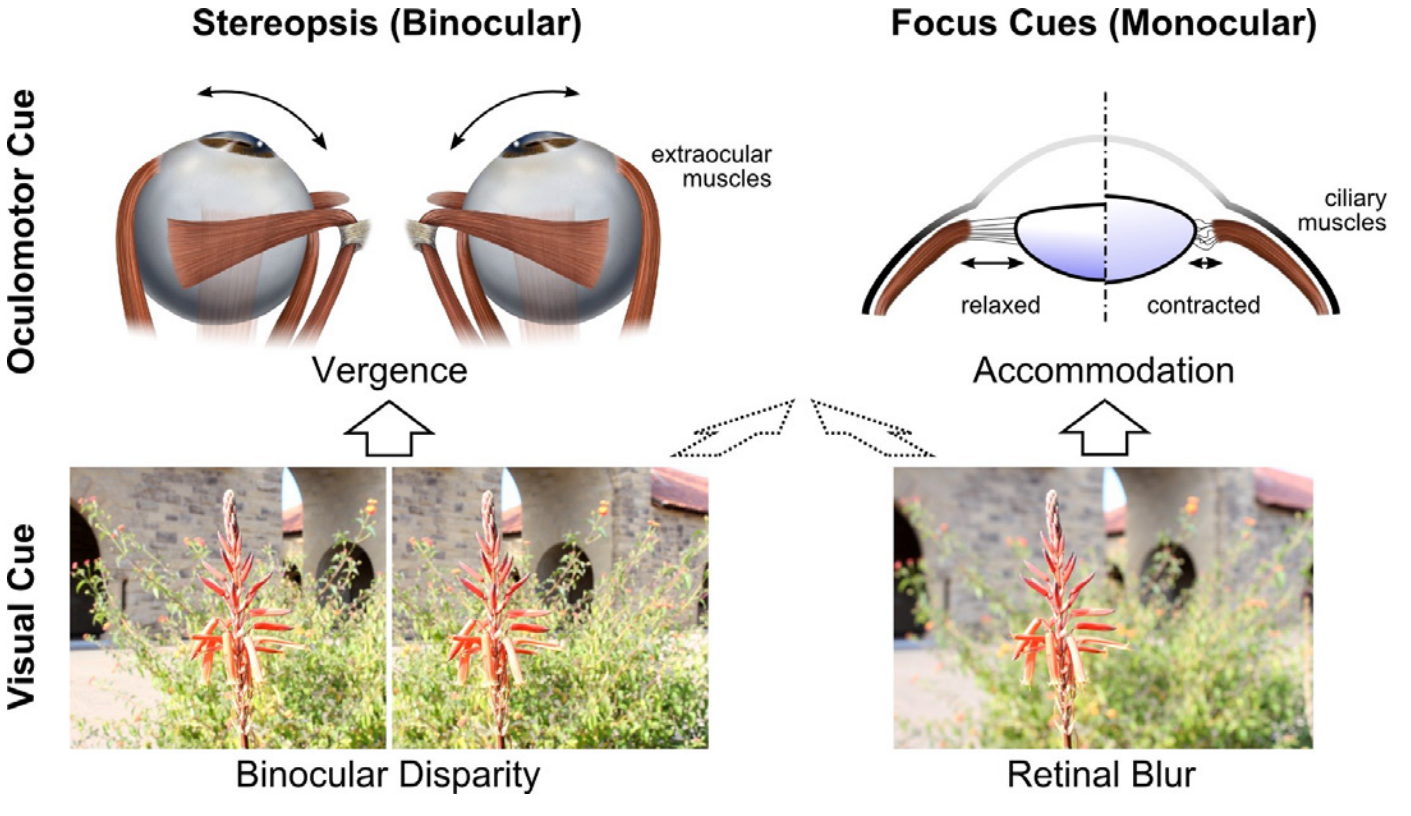

Stereopsis (Binocular)
Focus Cues (Monocular)
Oculomotor Cue
extraocular muscles
ciliary muscles
relaxed
contracted
Vergence
Accommodation
Visual Cue
Binocular Disparity
Retinal Blur


Stereopsis (Binocular)
Focus Cues (Monocular)
Oculomotor Cue
extraocular muscles
Vergence
ciliary muscles
relaxed
contracted
Accommodation
Visual Cue
Binocular Disparity
Retinal Blur


Stereopsis (Binocular)
Focus Cues (Monocular)
Oculomotor Cue
extraocular muscles
Vergence
ciliary muscles
relaxed
contracted
Accommodation
Visual Cue
Binocular Disparity
Retinal Blur

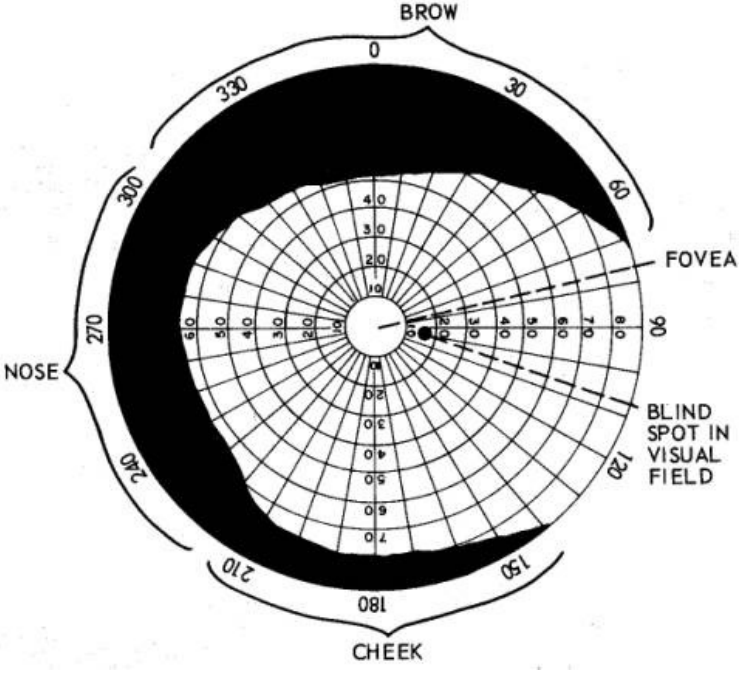

Stereopsis (Binocular)
Focus Cues (Monocular)
Oculomotor Cue
extraocular muscles
Vergence
ciliary muscles
relaxed
contracted
Accommodation
Visual Cue
Binocular Disparity
Retinal Blur


Stereopsis (Binocular)
Focus Cues (Monocular)
Oculomotor Cue
extraocular muscles
Vergence
ciliary muscles
relaxed
contracted
Accommodation
Visual Cue
Binocular Disparity
Retinal Blur

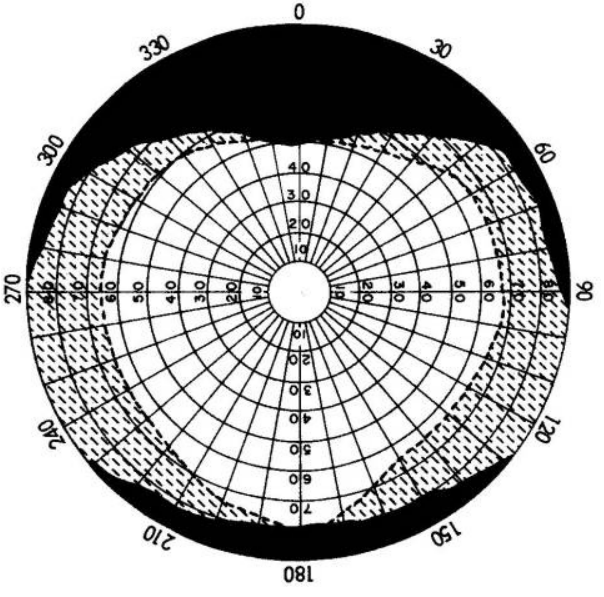

Stereopsis (Binocular)
Focus Cues (Monocular)
Oculomotor Cue
extraocular muscles
ciliary muscles
relaxed
contracted
Vergence
Accommodation
Visual Cue
Binocular Disparity
Retinal Blur

Visual Field / Field of View

Ruch & Fulton, 1960

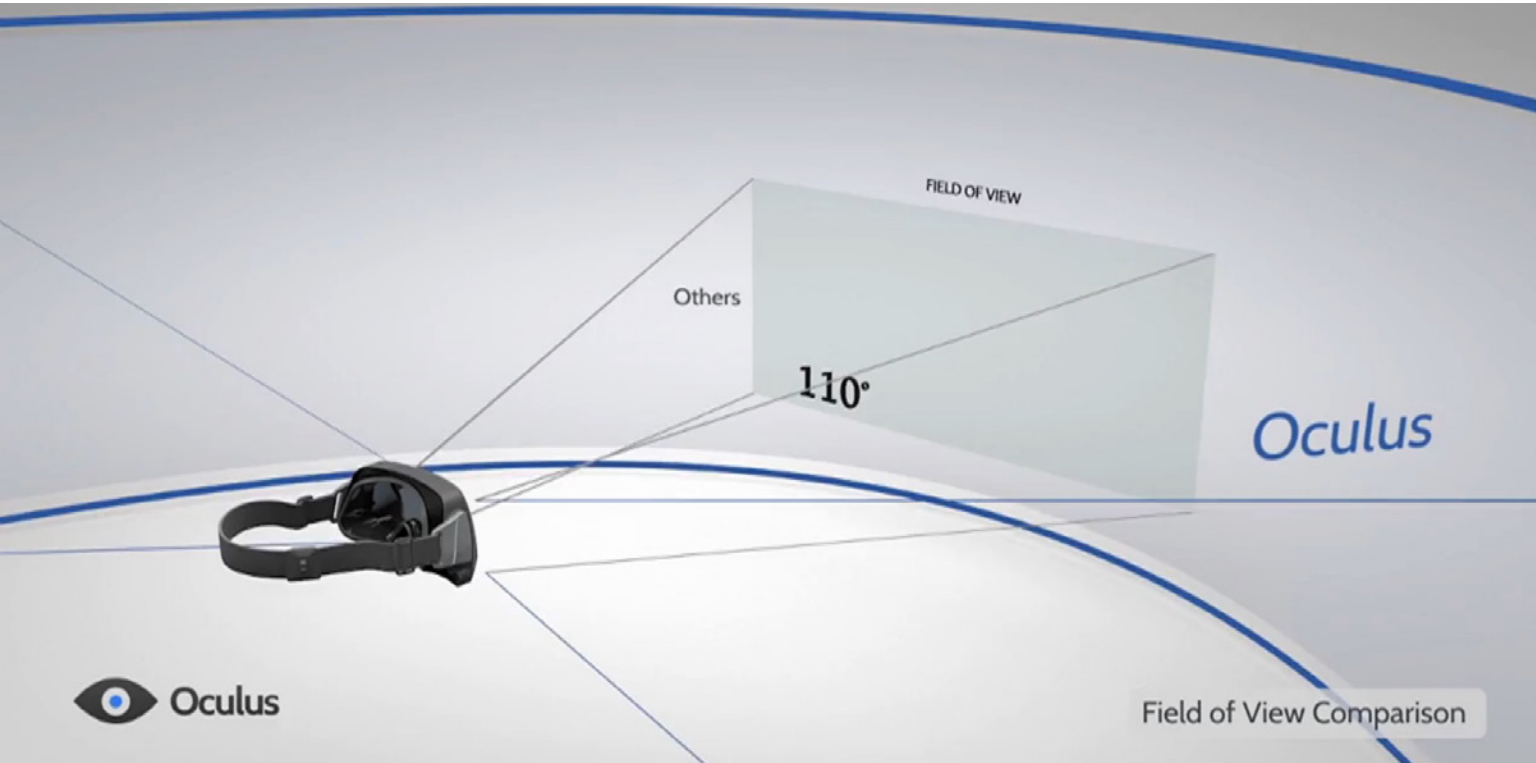


monocular visual field



binocular visual field

Immersive VR – How Important is the FOV?



Visual Acuity

Snellen chart

1	20/200
2	20/100
3	20/70
4	20/50
5	20/40
6	20/30
7	20/25
8	20/20
9	
10	
11	

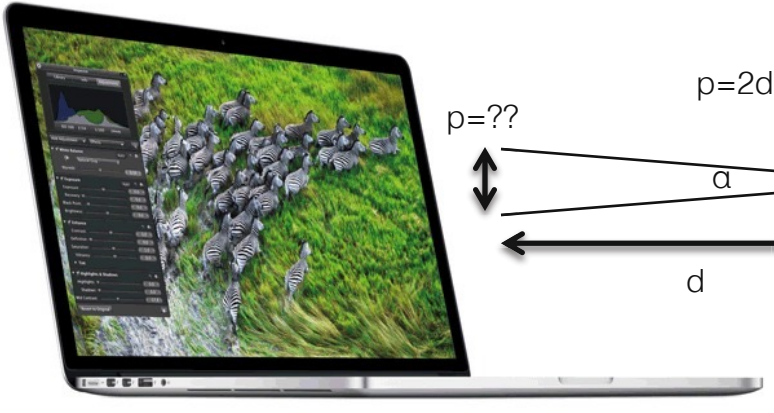
characters are 5 arc min, need to resolve 1 arc min to read

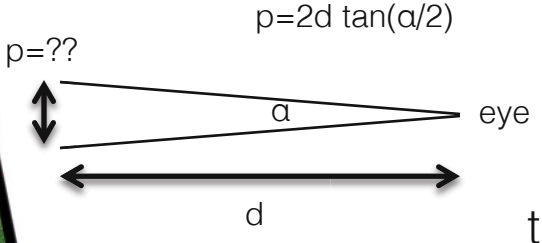
Retina Displays

Steve Jobs: 300 dpi is retina resolution

our math: ~286 dpi

Apple Inc.

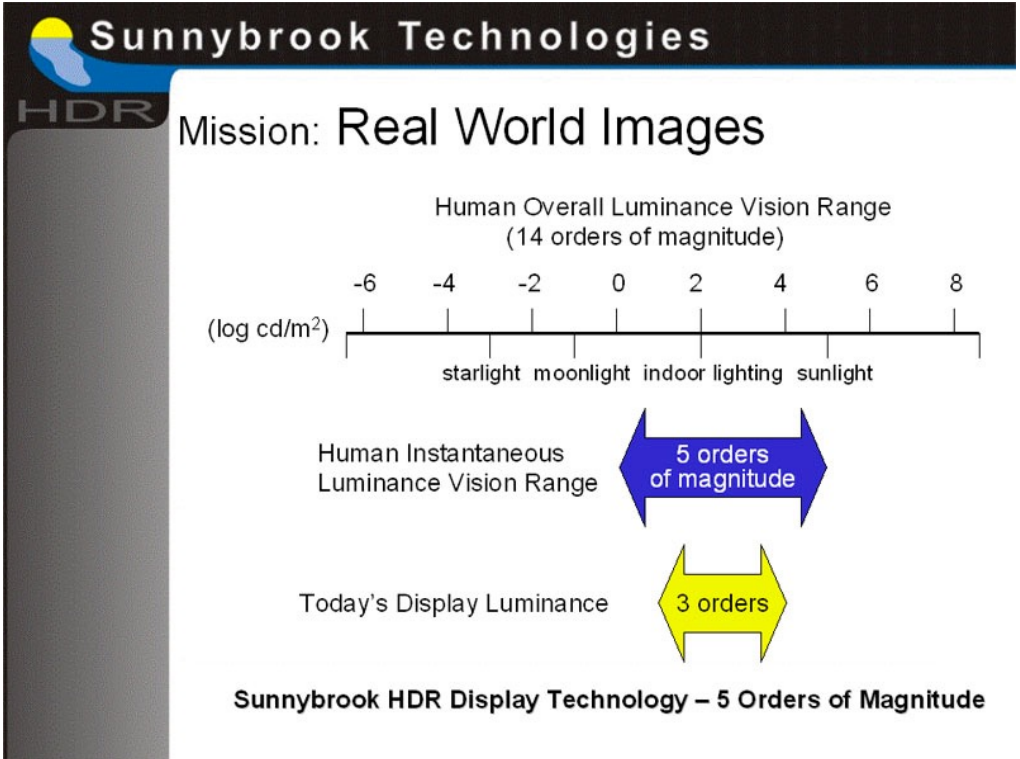




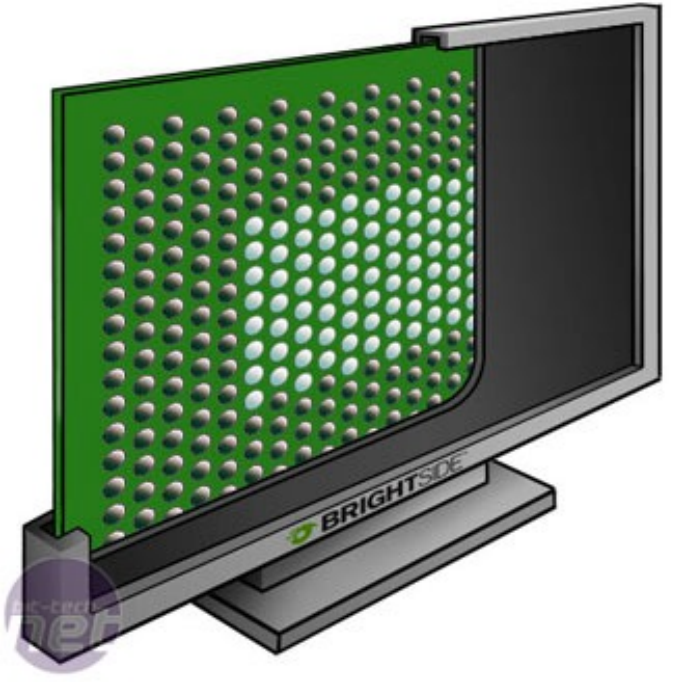
tablet, 12” away,
resolvable pixel:

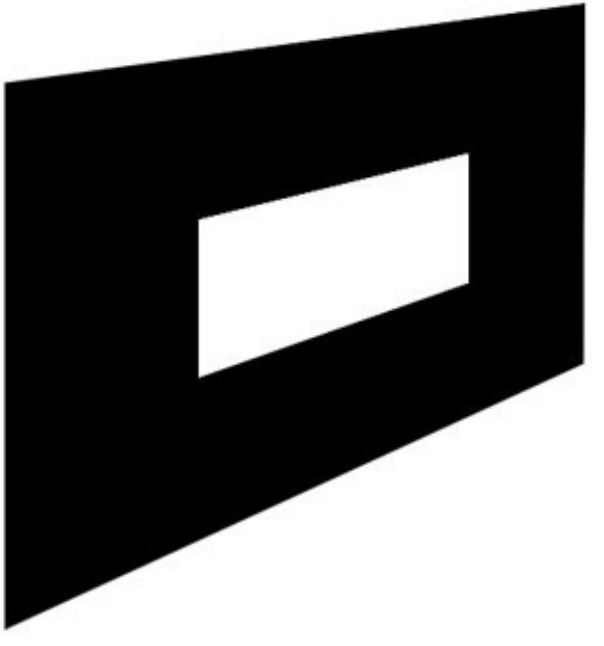
p=2*12”*tan(1 arc min /2)=0.0035”

Dynamic Range

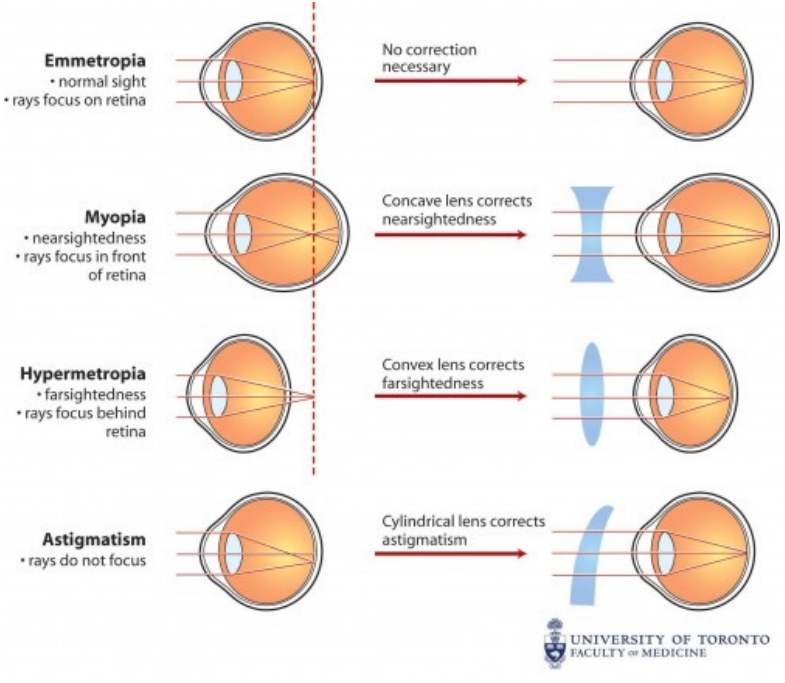


High Dynamic Range Displays





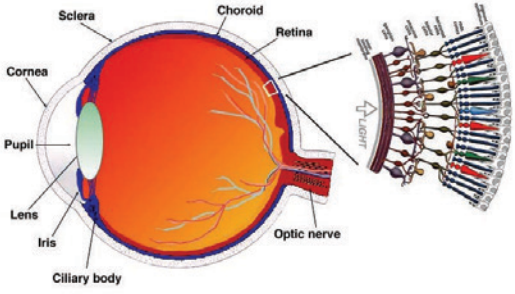
Refractive Errors

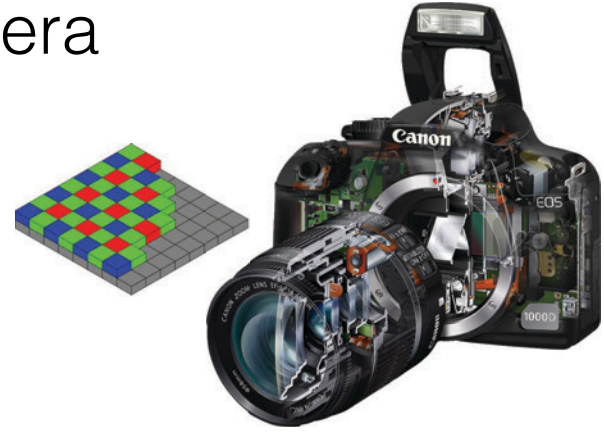


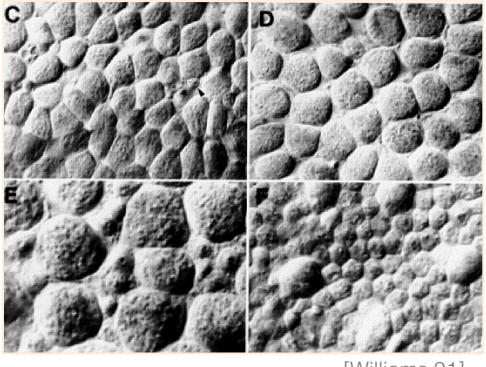
Vision-Correcting Displays

300 dpi or higher

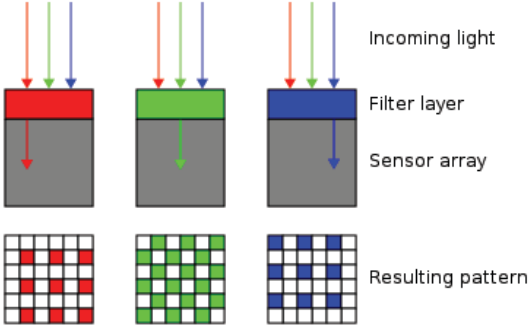
Eye vs Camera





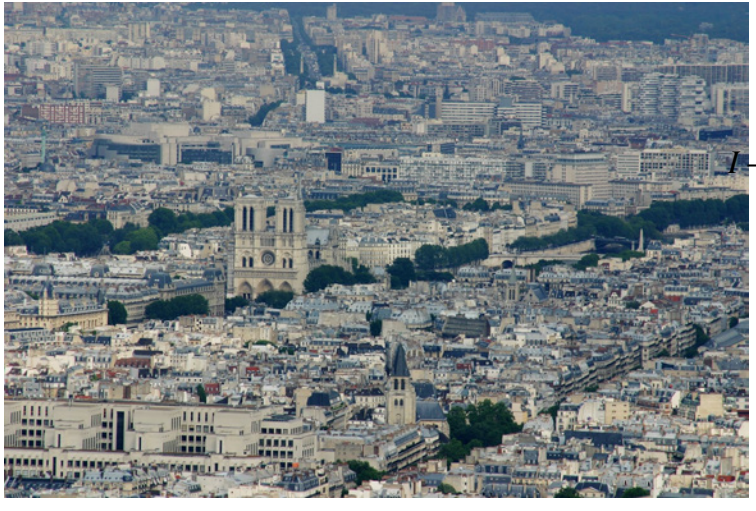


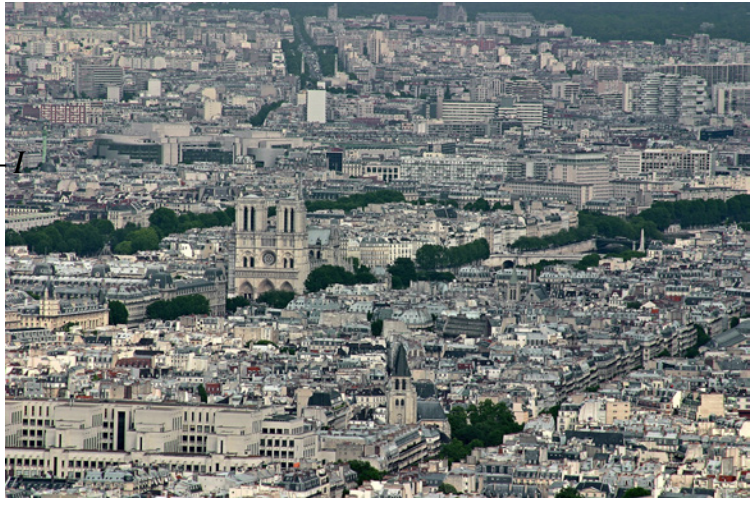
[Williams 91]



wikipedia

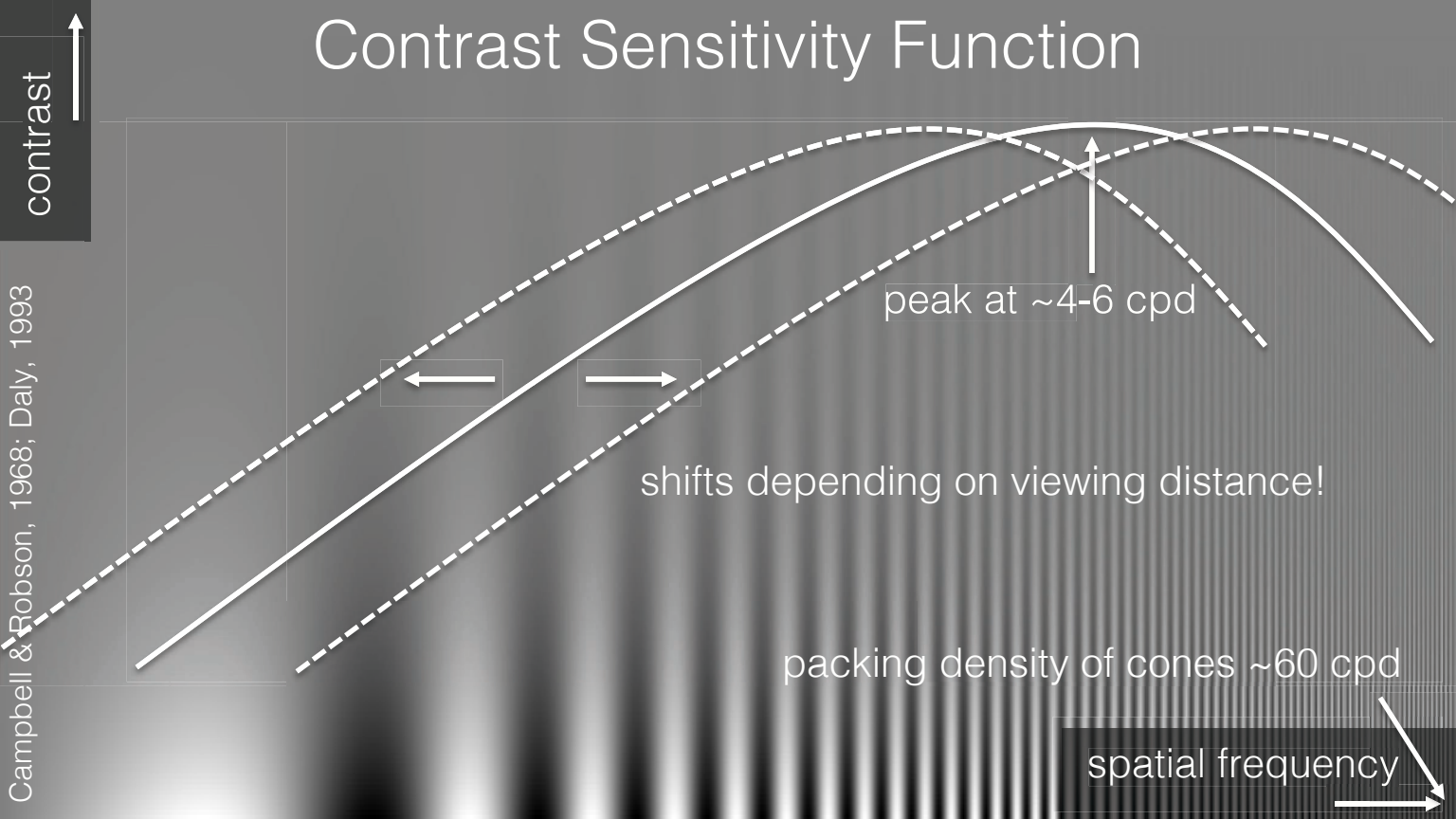
Contrast





Which image has a higher contrast?

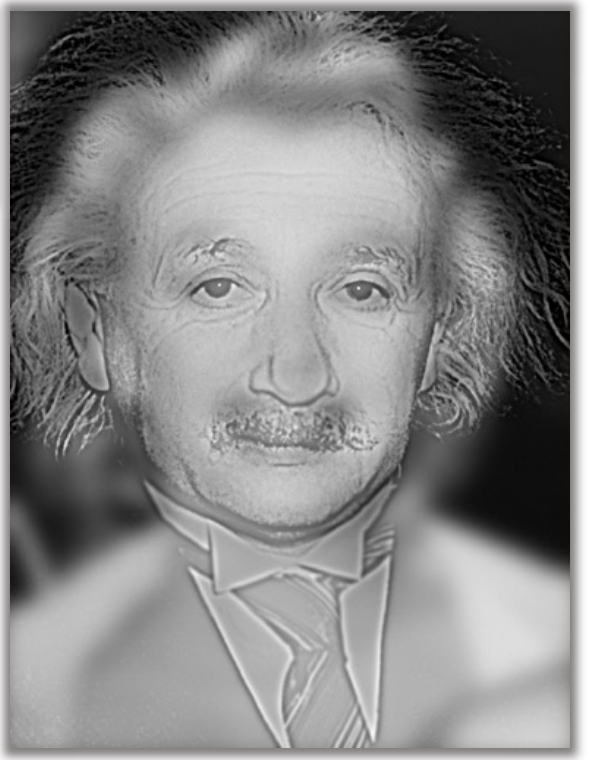
Contrast Sensitivity Function



Campbell & Robson, 1968; Daly, 1993

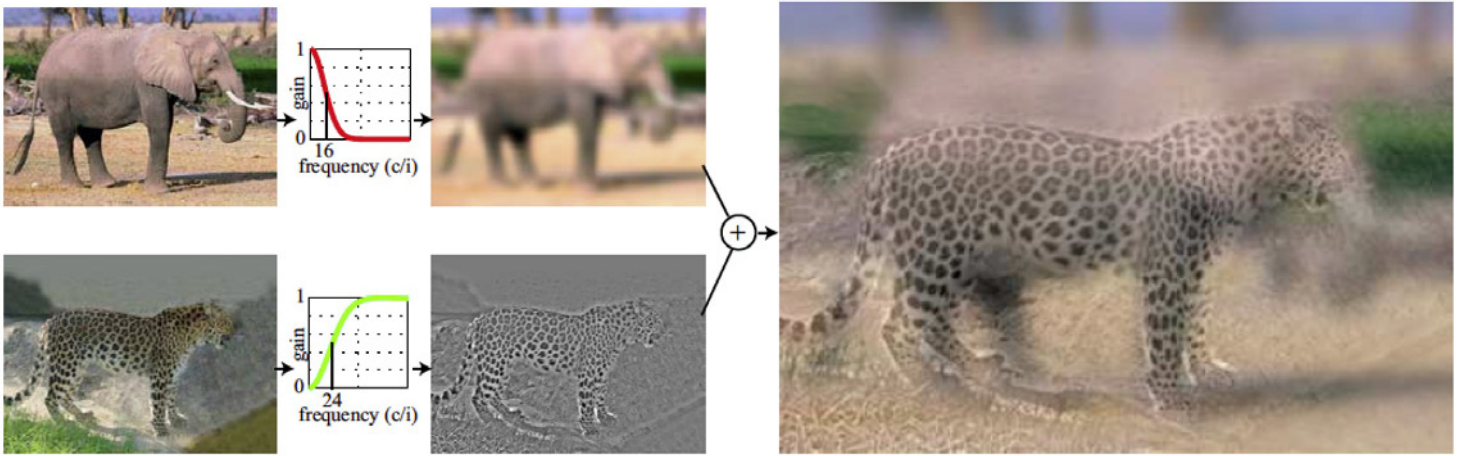
Hybrid Images

Oliva, Torralba, & Schyns, 2006, ACM SIGGRAPH



Hybrid Images

Oliva, Torralba, & Schyns, 2006, ACM SIGGRAPH



Depth Perception

wikipedia

Depth Perception

wikipedia

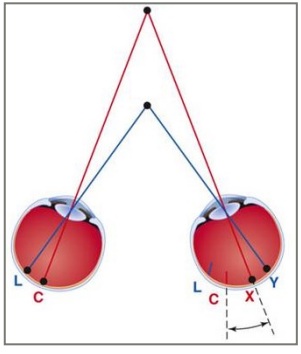
monocular cues

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

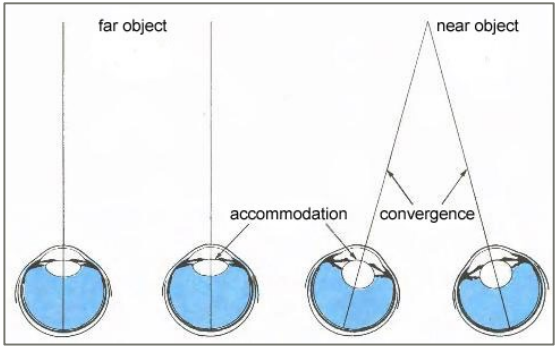
binocular cues

- (con)vergence
- disparity / parallax
- …

Depth Perception

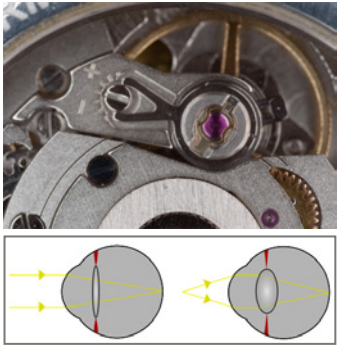


binocular disparity



convergence

motion parallax



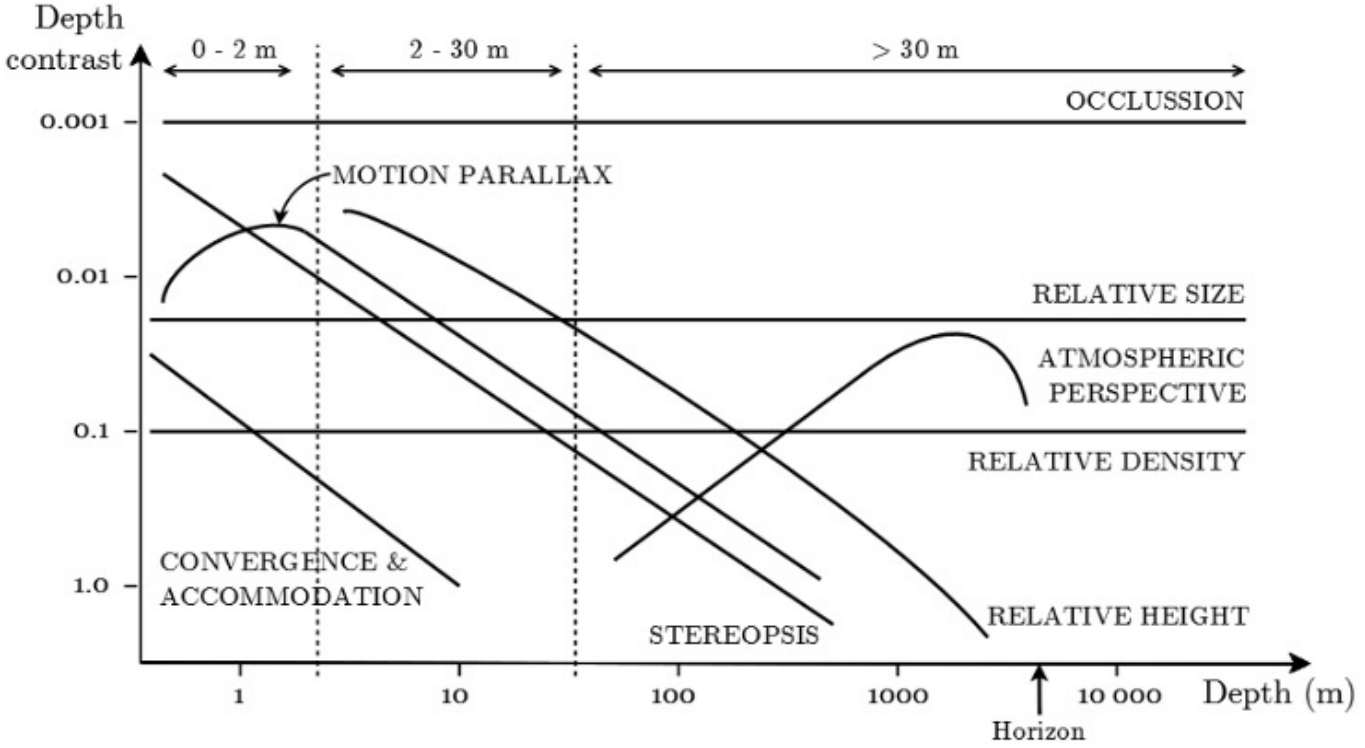
accommodation/blur

current glasses-based (stereoscopic) displays

near-term: light field displays

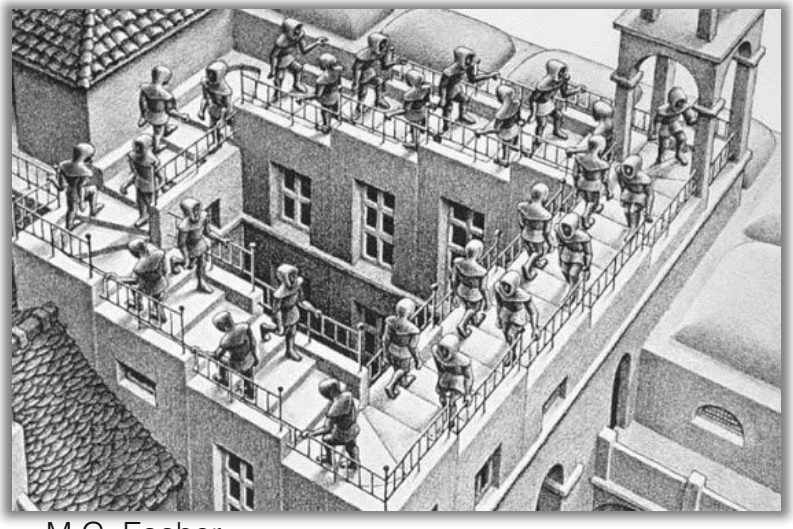
longer-term: holographic displays

Depth Perception

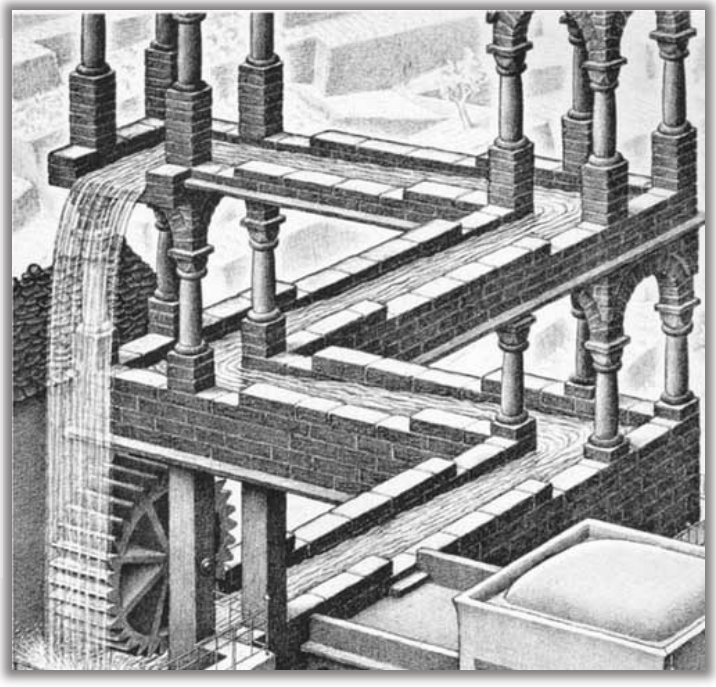


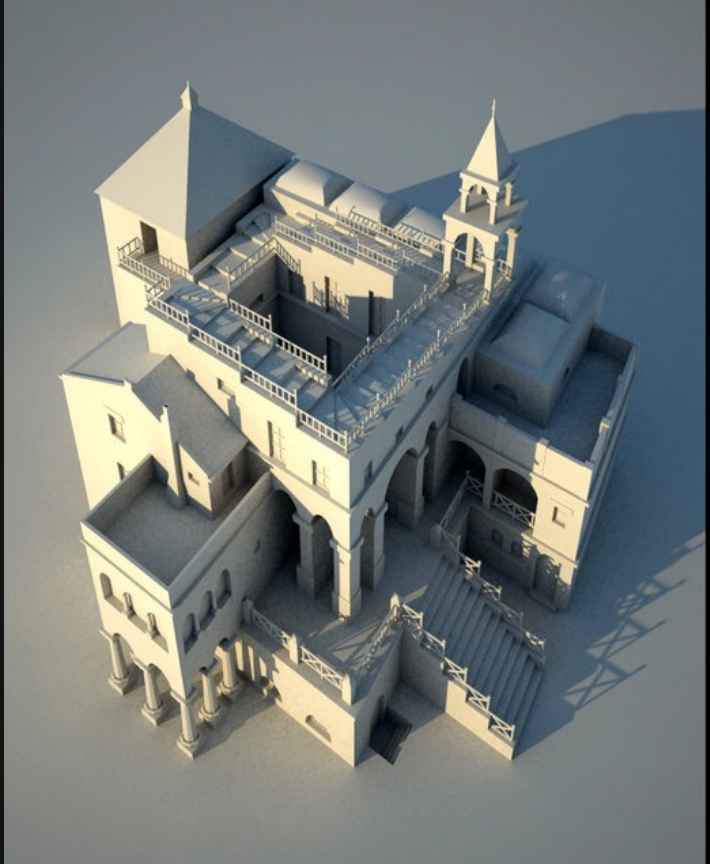
Cutting & Vishton, 1995

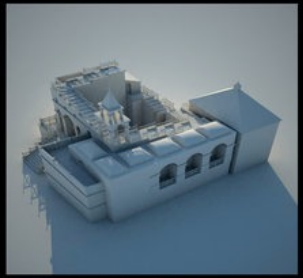
Visual Illusions – Perspective, Occlusion, Size



M.C. Escher

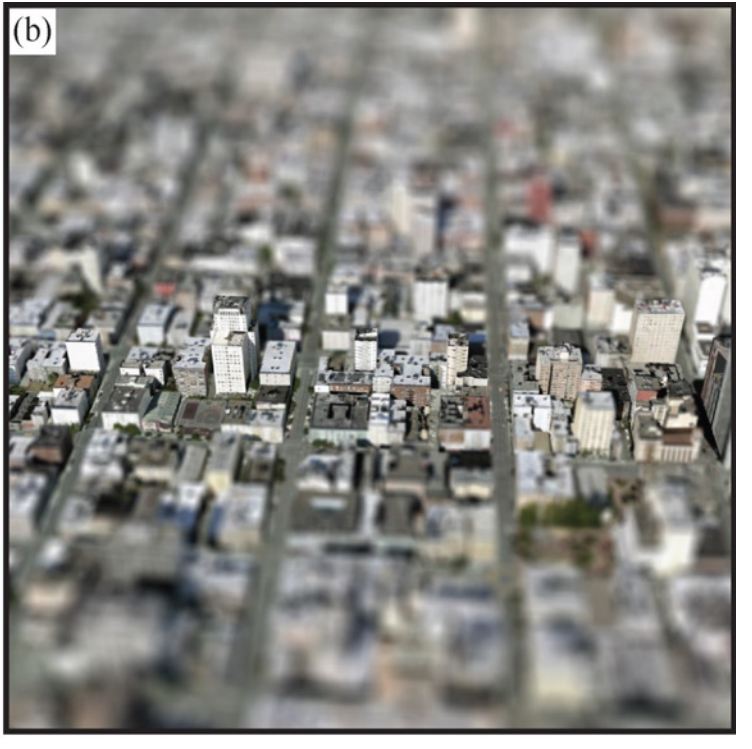






Visual Illusions – Which Cues are These?

Held et al., 2006, ACM SIGGRAPH

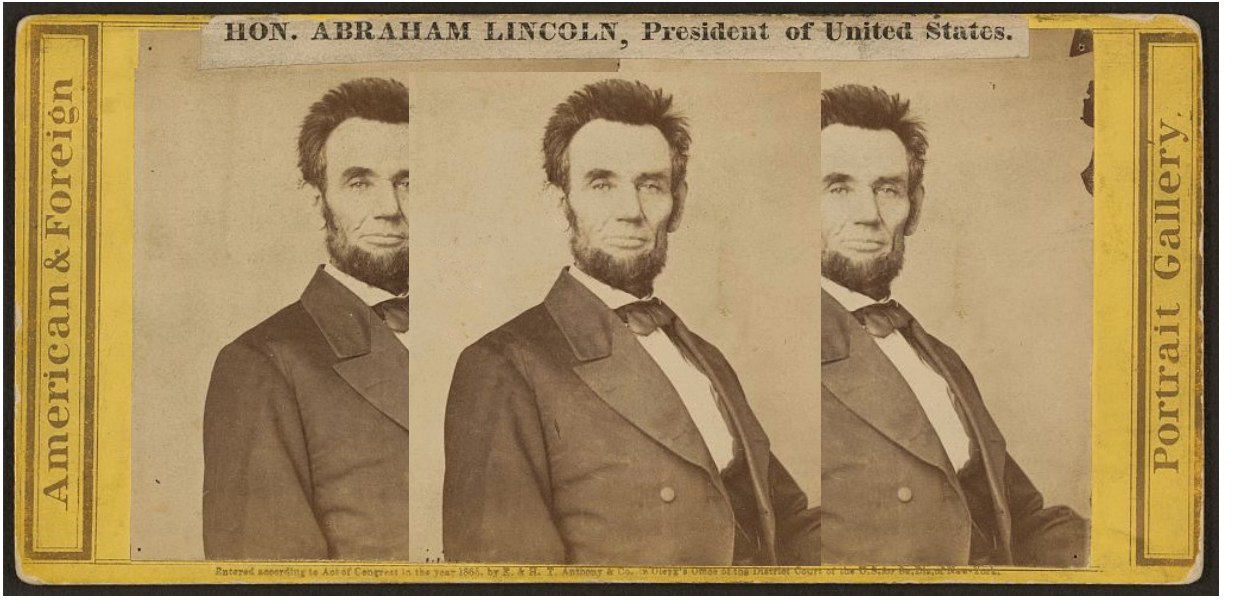


Stereoscopic Displays

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

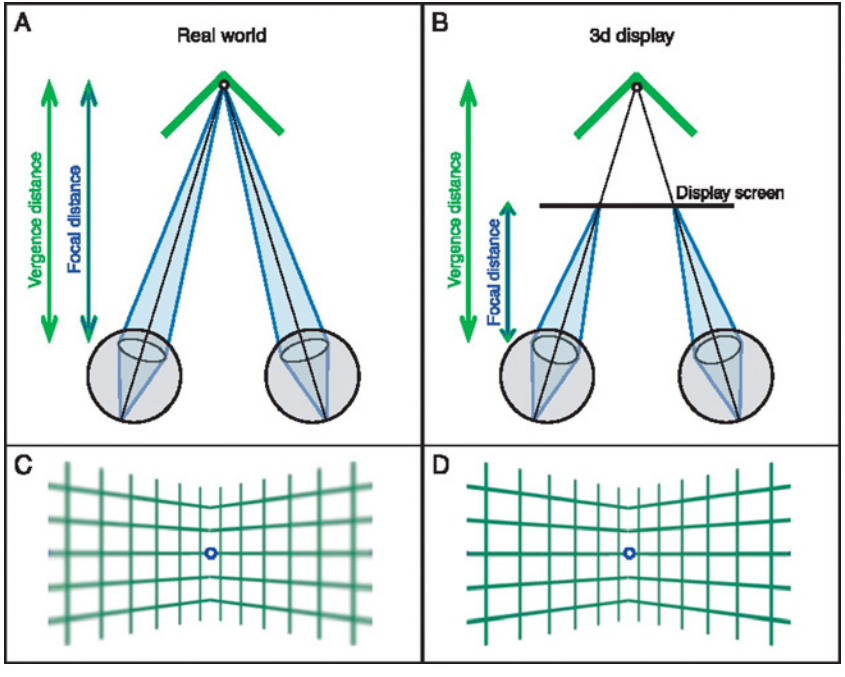
1968

2012-now

Next-generation VR/AR Displays

Vergence-Accommodation Conflict

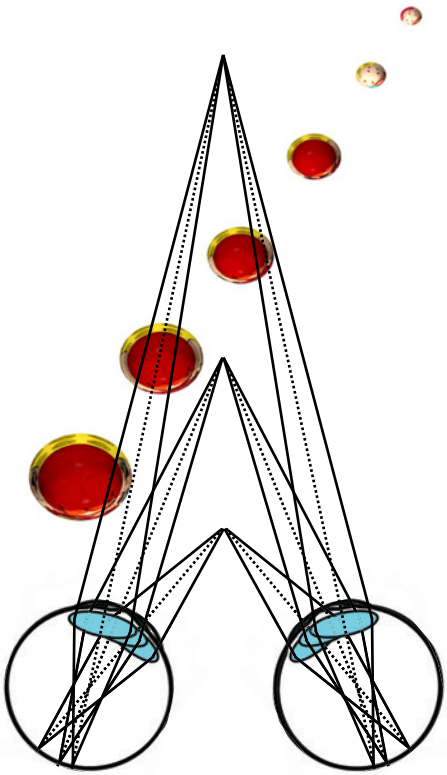
Marty Banks, UC Berkeley



effects

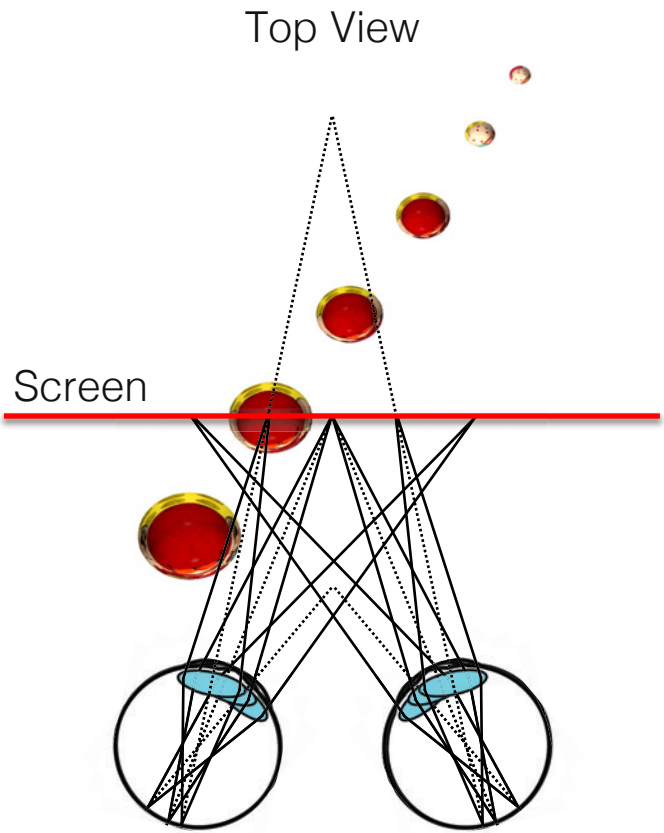
- visual discomfort
- visual fatigue
- nausea
- diplopic vision
- eyestrain
- compromised image quality
- pathologies in developing visual system
- …

Top View



Real World:

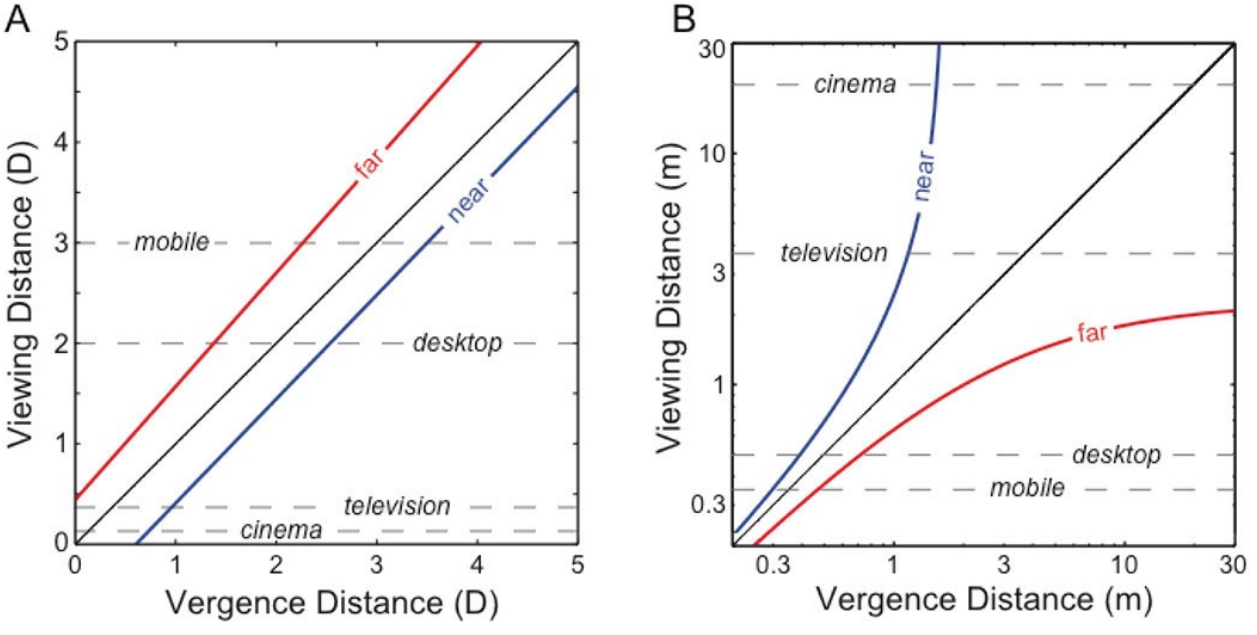
Vergence & Accommodation Match!



Stereo Displays Today:

Vergence-Accommodation **Mismatch!**

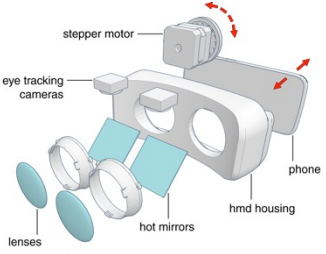
Zone of Comfort



Shibata et al, 2011, Journal of Vision

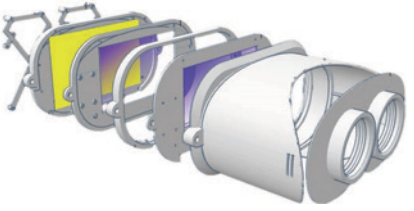
VR/AR Displays with Focus Cues

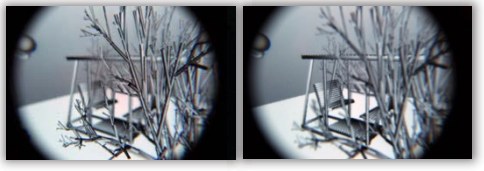
Gaze-contingent Focus Displays



Konrad et al., SIGCHI 2016;
Padmanaban et al., PNAS 2017

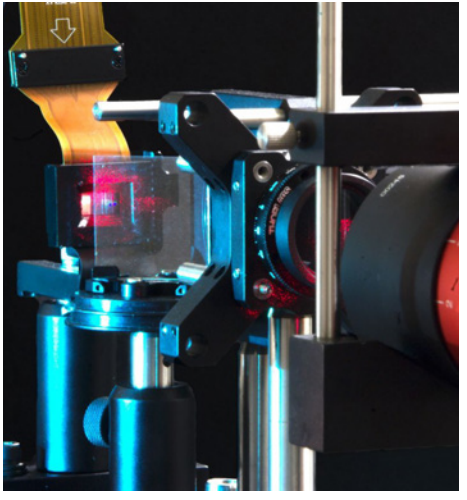
Near-eye Light Field Displays





Huang et al., SIGGRAPH 2015;
Wetzstein et al., SIGGRAPH 2011, 2012

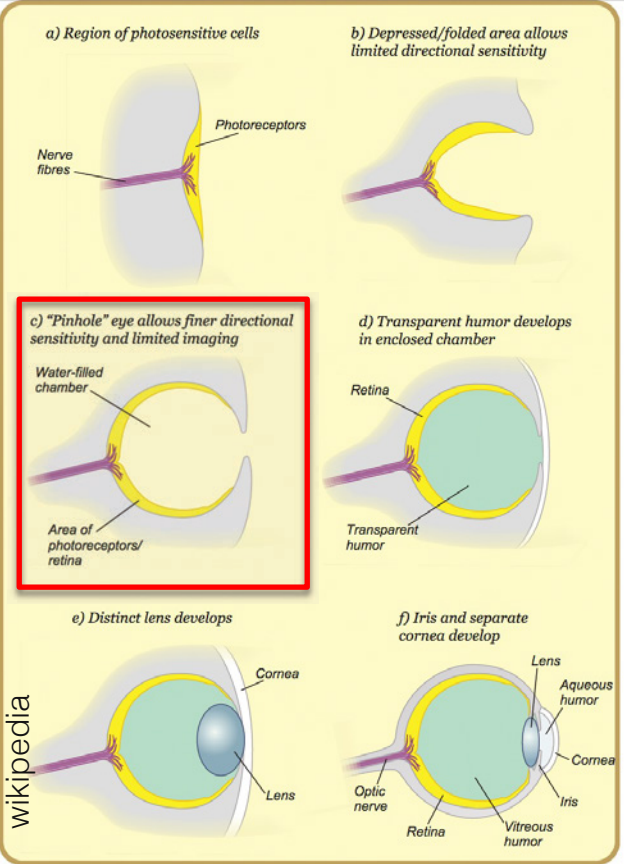
Holographic Displays



Padmanaban et al., SIGGRAPH Asia 2019
Peng et al., SIGGRAPH Asia 2020
Choi et al., Optica 2021

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

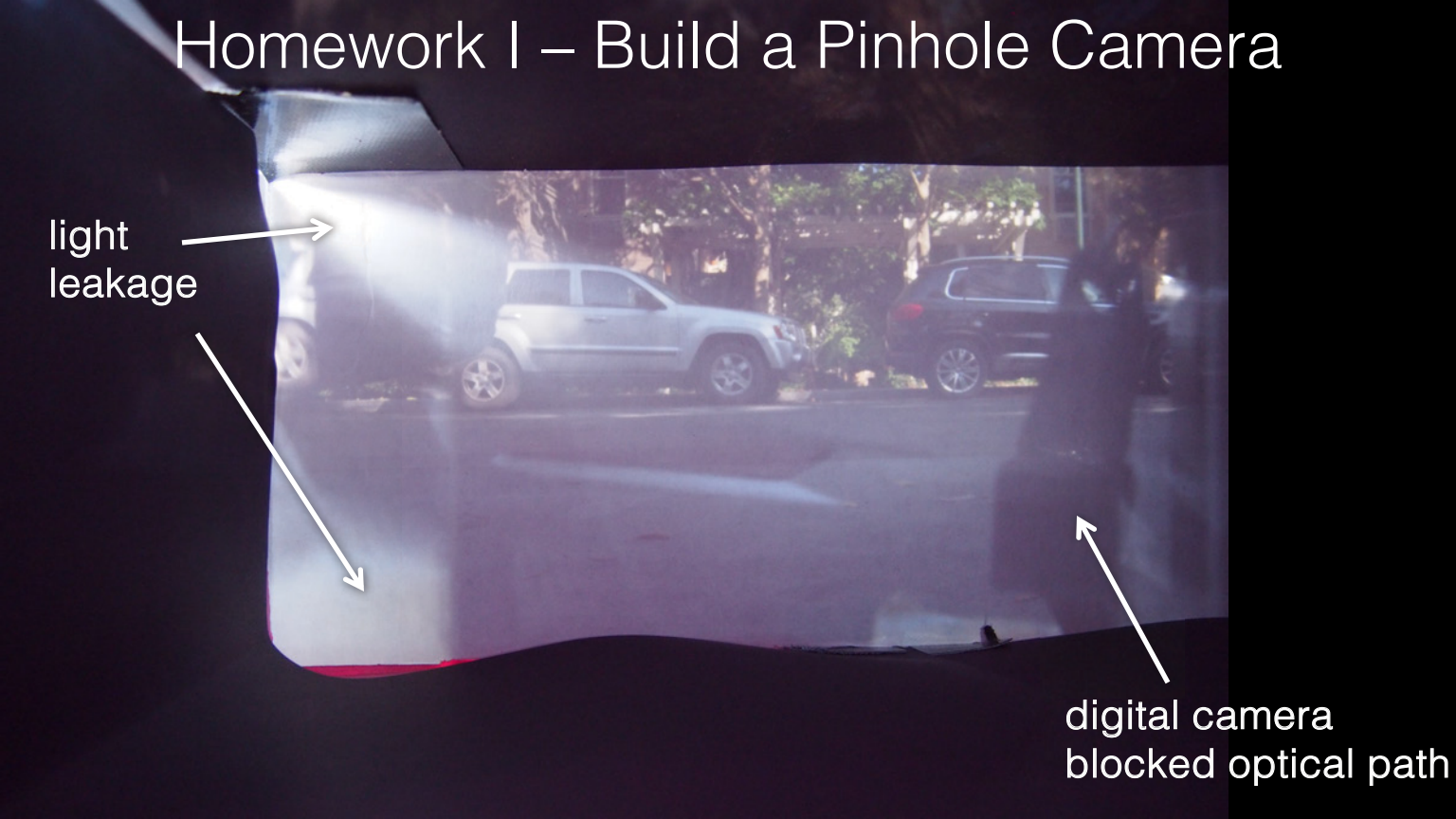


wikipedia

Homework I

- take a step back in evolution
- build a pinhole camera
- capture photos with it
- read instructions carefully!

Homework I – Build a Pinhole Camera



Next: Digital Photography I

- optics
- aperture
- depth of field
- field of view
- noise
- sensors
- color filter arrays

References and Further Reading

interesting textbooks on perception:

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

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 and visual acuity:

- 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

the visual field:

- 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
- Mantiuk, Kim, Rempel, Heidrich, “HDR-VDP-2: A calibrated visual metric for visibility and quality predictions in all luminance conditions”, SIGGRAPH 2011