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

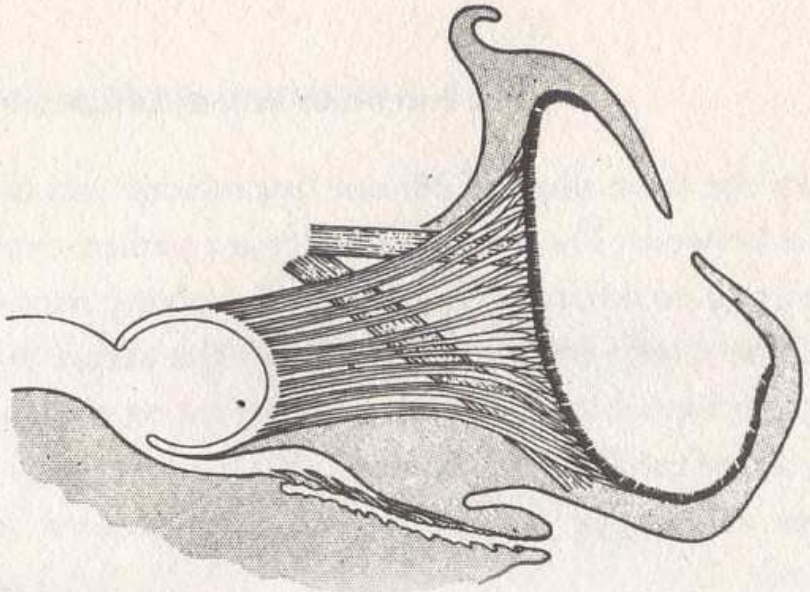
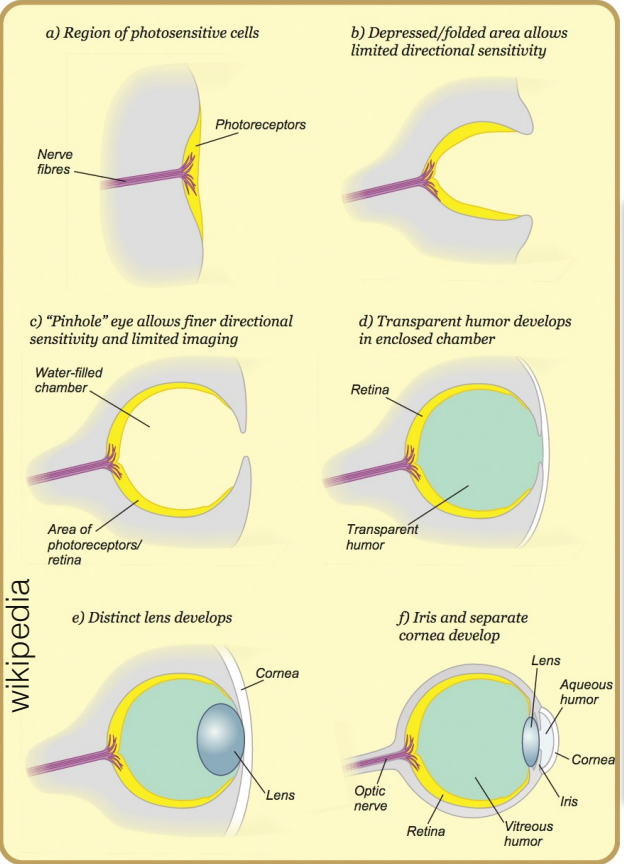



**Figure 5.8** (opposite) A range of invertebrate eyes that illustrate approaches to the formation of crude but effective images: (a) *Nautilus*'s pinhole eye; (b) marine snail; (c) bivalve mollusc; (d) abalone; (e) ragworm.

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

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

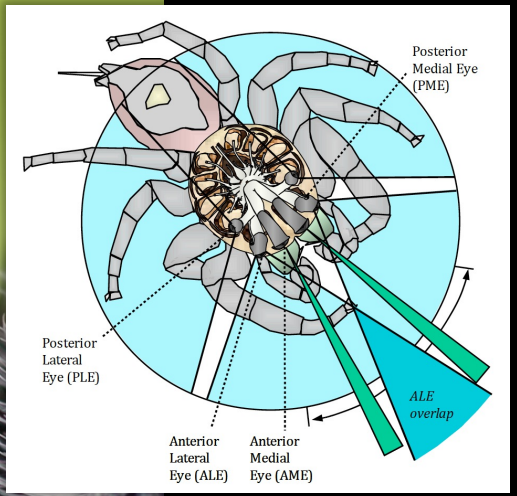
# Evolution of the Eye




wikipedia

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

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



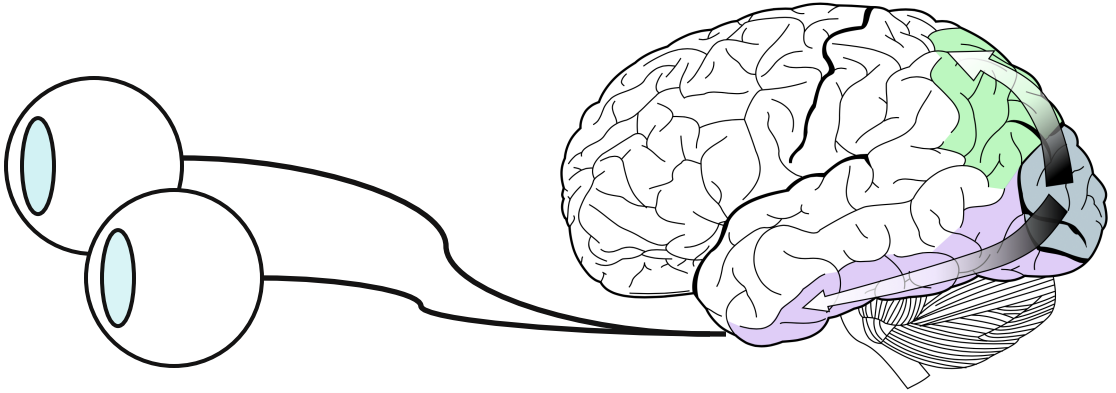

jumping spider, wikipedia

national geographics

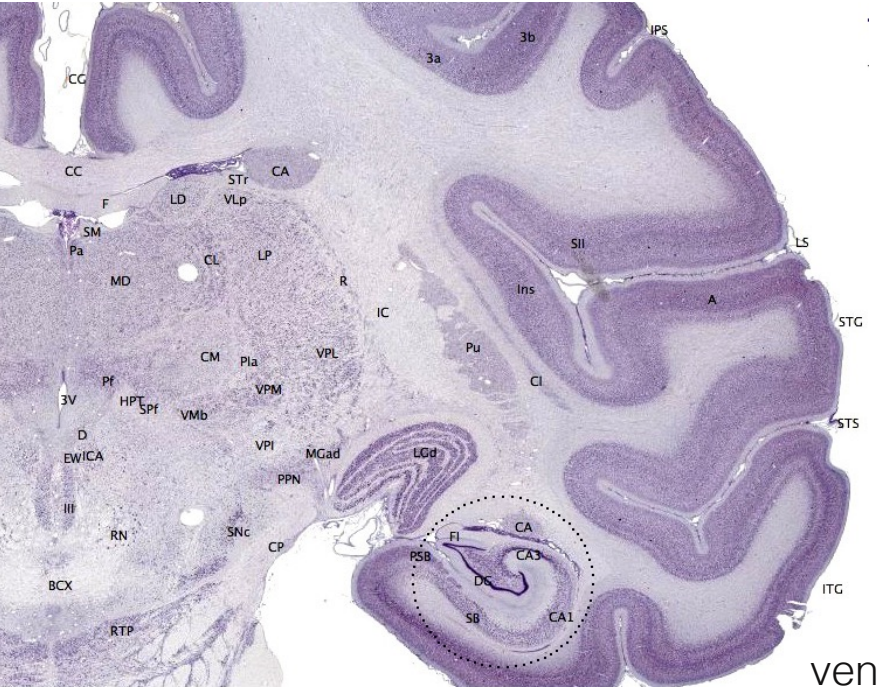
# Summary of Human Visual System (HVS)

- 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

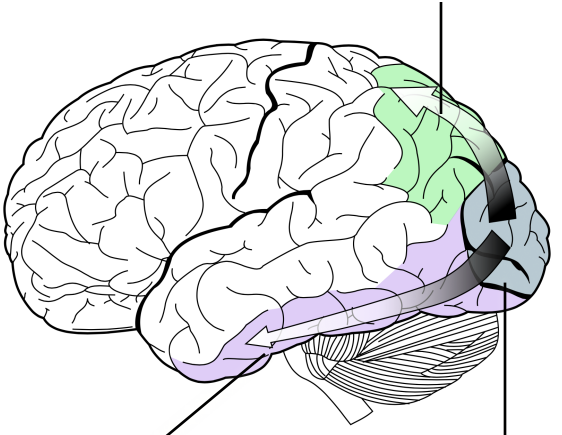
# Overview


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

# Overview




dorsal stream: spatial awareness

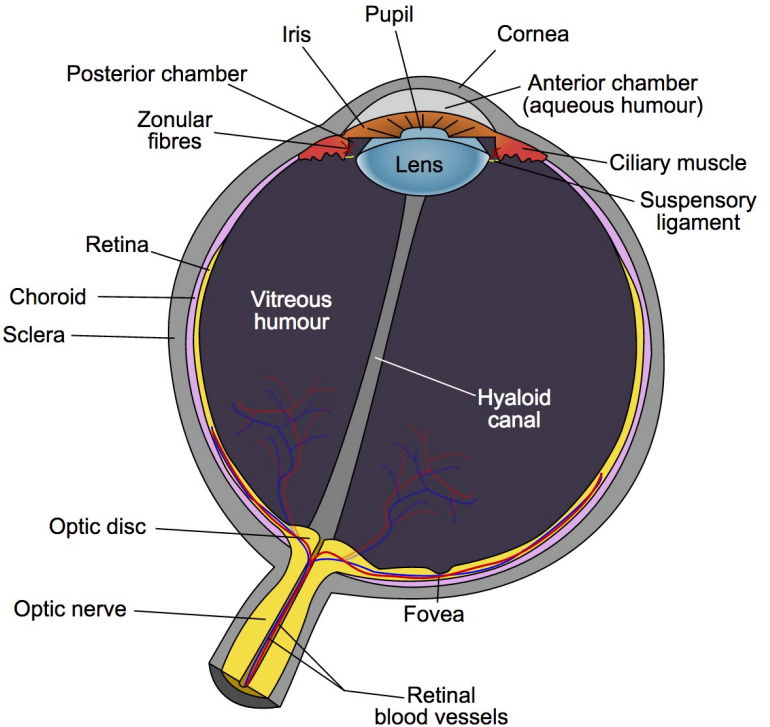


wikipedia

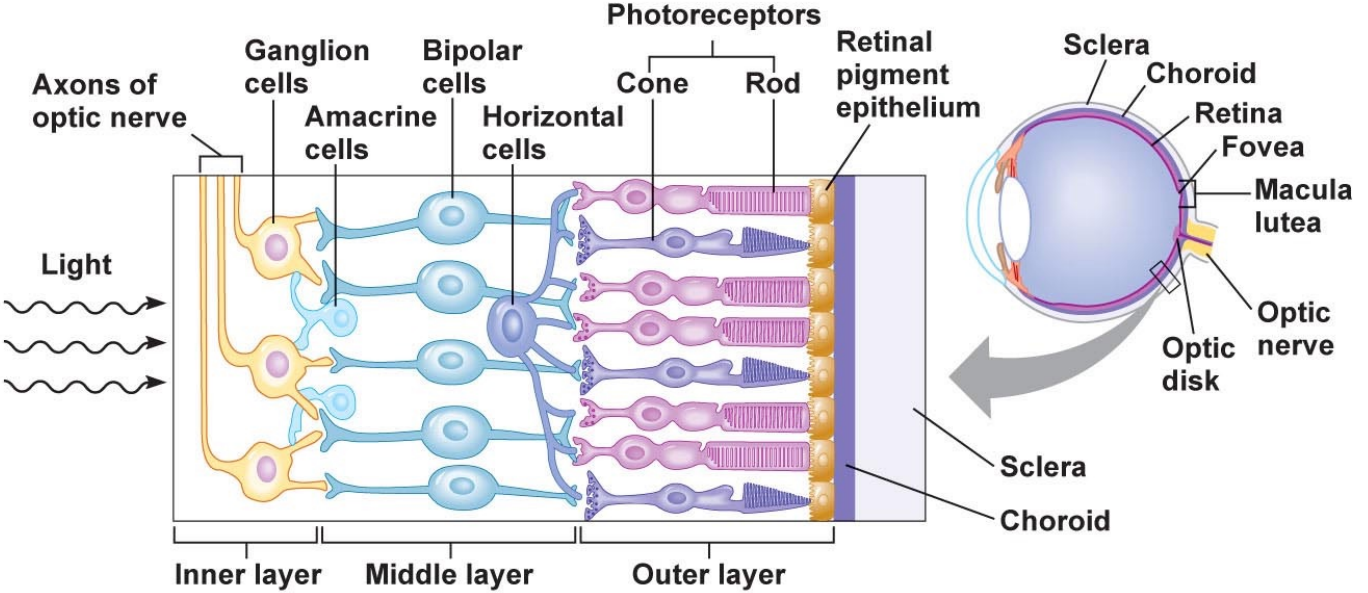
primary visual cortex

ventral stream:
recognition, object identification

# Anatomy of the Human Eye

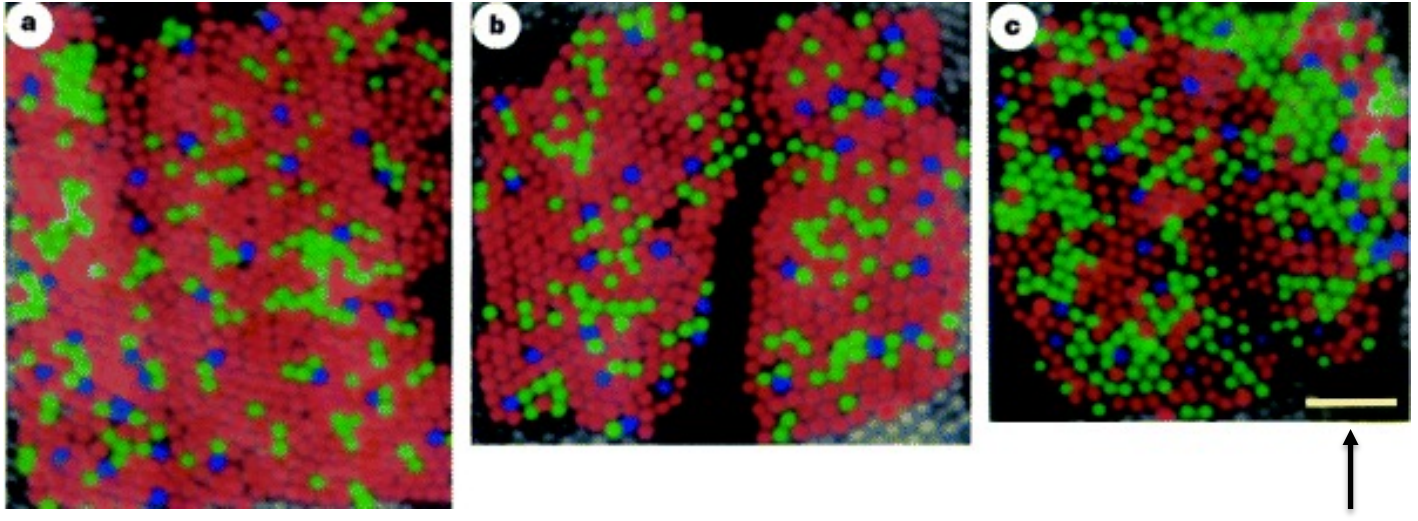


# The Retina




© 2011 Pearson Education, Inc.

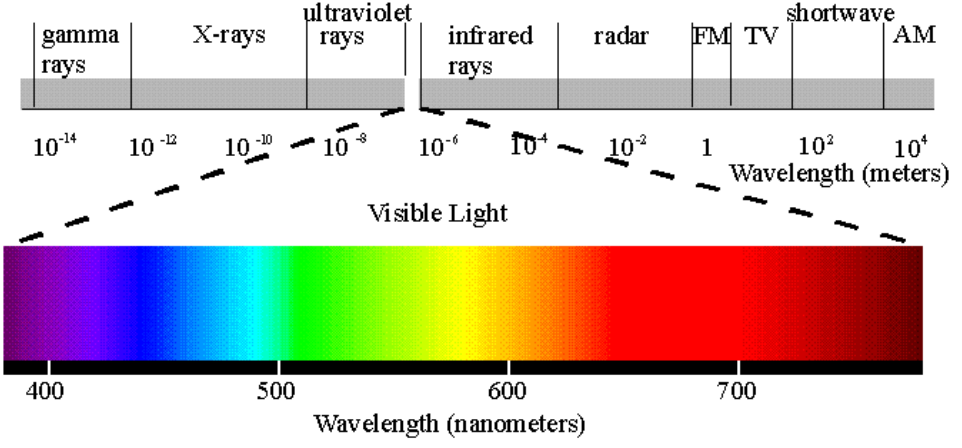
# The Retina



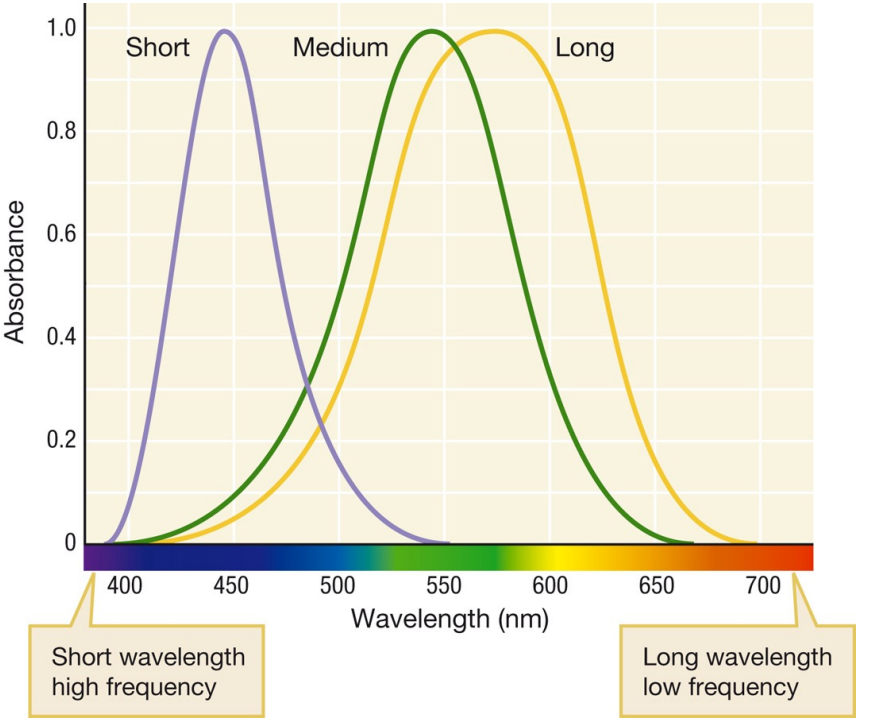

5 arcmin visual angle

Roorda & Williams, 1999, Nature

# Color Perception



# Color Perception - Sensitivity of Cones



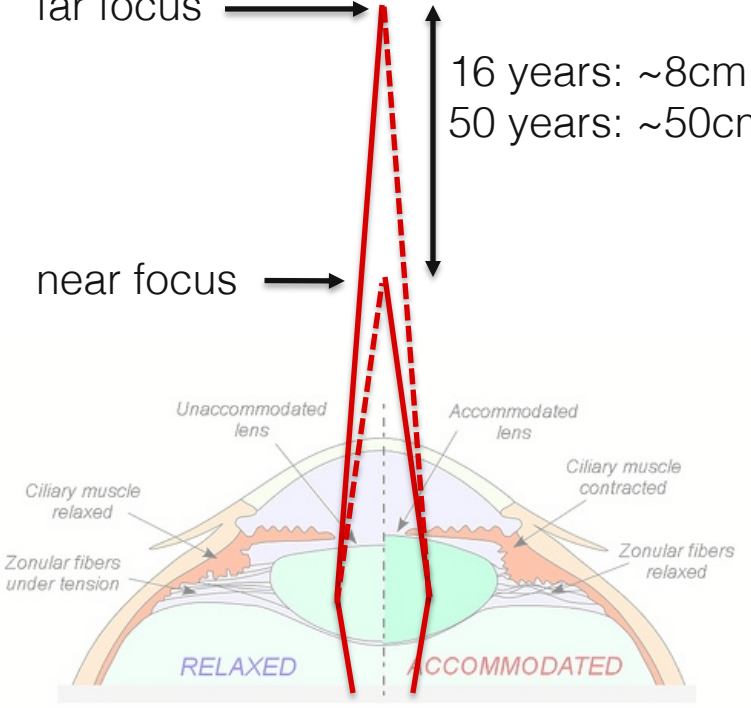

reddit.com

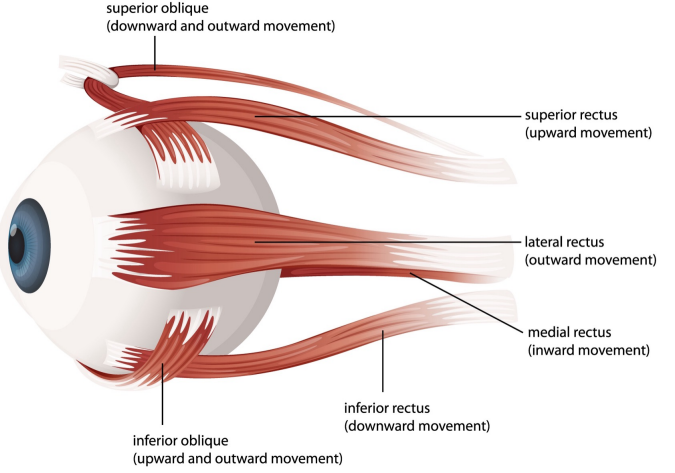
# Oculumotor Processes

far focus

near focus

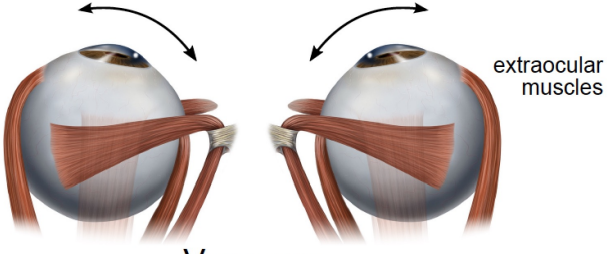
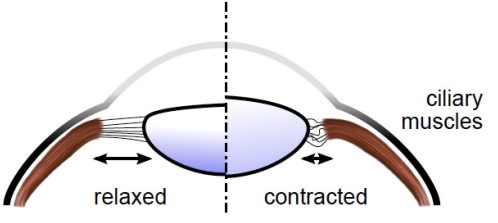
16 years: ~8cm to ∞
50 years: ~50cm to ∞ (mostly irrelevant)




adithyakiran.wordpress.com

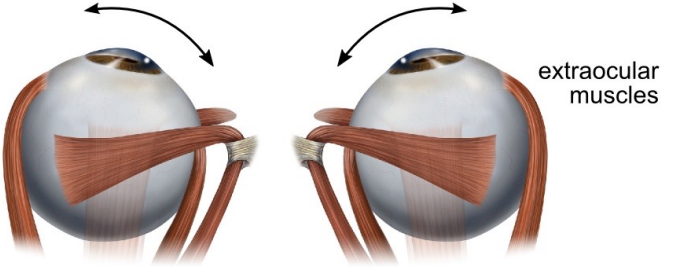
# Oculumotor Processes + Visual Cues

| | Stereopsis (Binocular) | Focus Cues (Monocular) |
|---|---|---|
| **Oculomotor Cue** |   Vergence |   Accommodation |
| **Visual Cue** | Binocular Disparity | Retinal Blur |

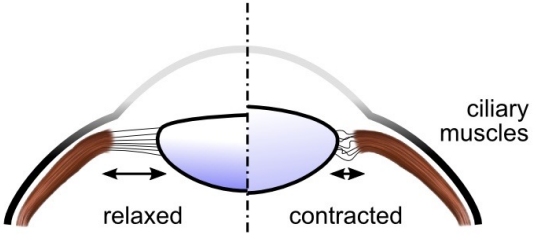
## Stereopsis (Binocular)

## Focus Cues (Monocular)

**Oculomotor Cue**




Vergence




Accommodation

**Visual Cue**

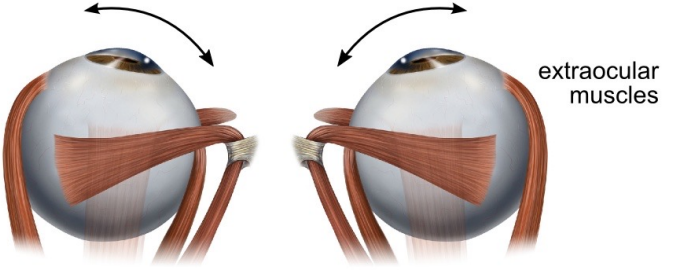
Binocular Disparity

Retinal Blur

## Stereopsis (Binocular)

## Focus Cues (Monocular)

**Oculomotor Cue**




Vergence




Accommodation

**Visual Cue**



Binocular Disparity

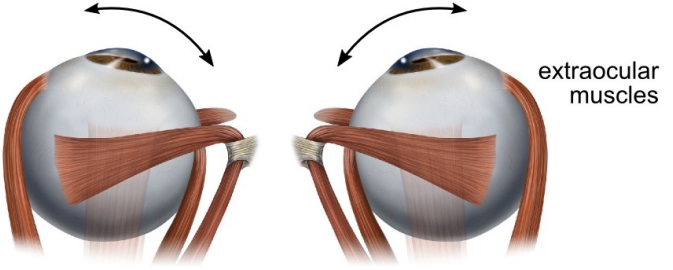


Retinal Blur

## Stereopsis (Binocular)

## Focus Cues (Monocular)

**Oculomotor Cue**




Vergence




Accommodation

**Visual Cue**

Binocular Disparity



Retinal Blur

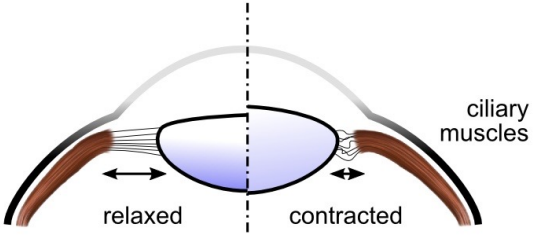
## Stereopsis (Binocular)

## Focus Cues (Monocular)

**Oculomotor Cue**




Vergence




Accommodation

**Visual Cue**



Binocular Disparity



Retinal Blur

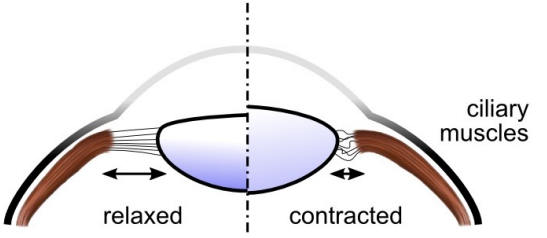
## Stereopsis (Binocular)

## Focus Cues (Monocular)

**Oculomotor Cue**




Vergence



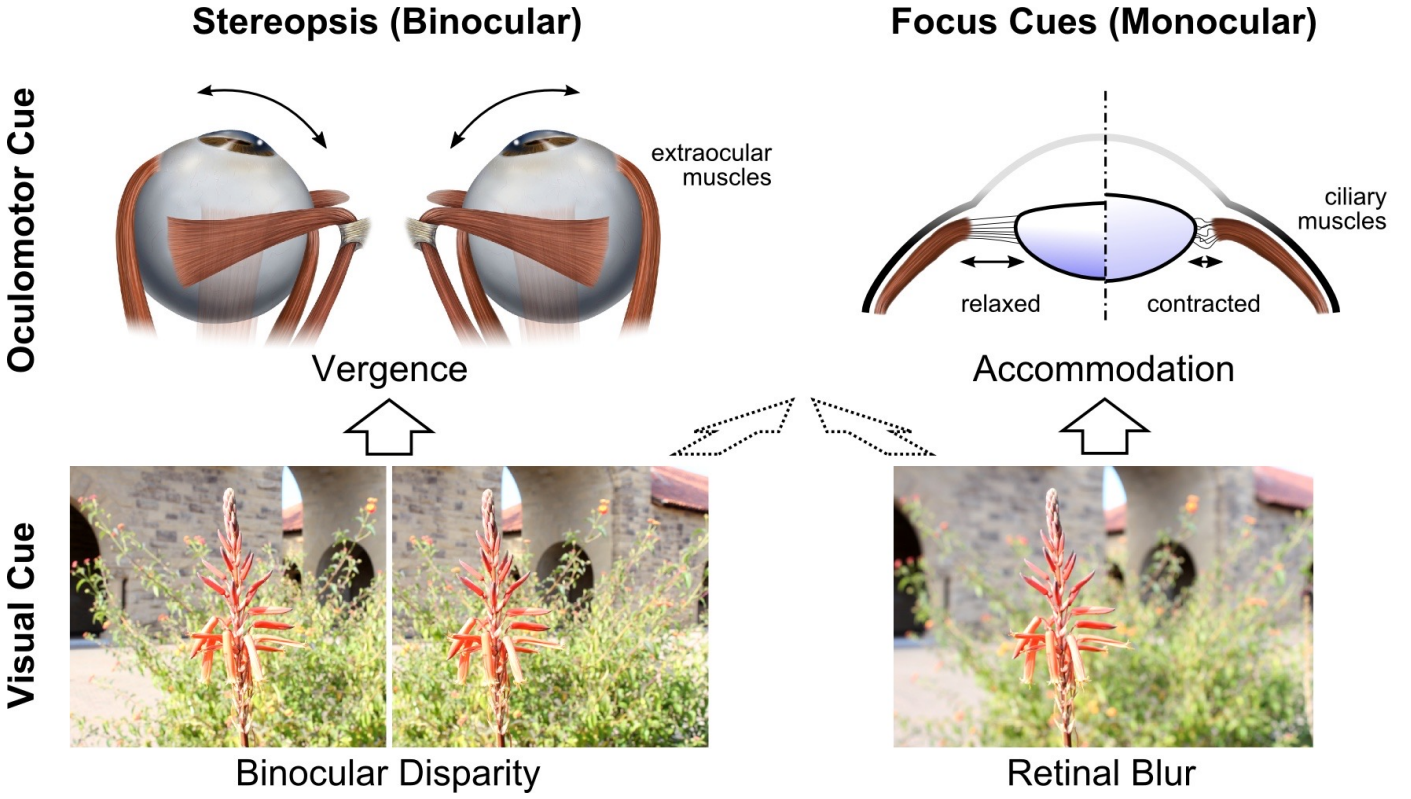

Accommodation

**Visual Cue**

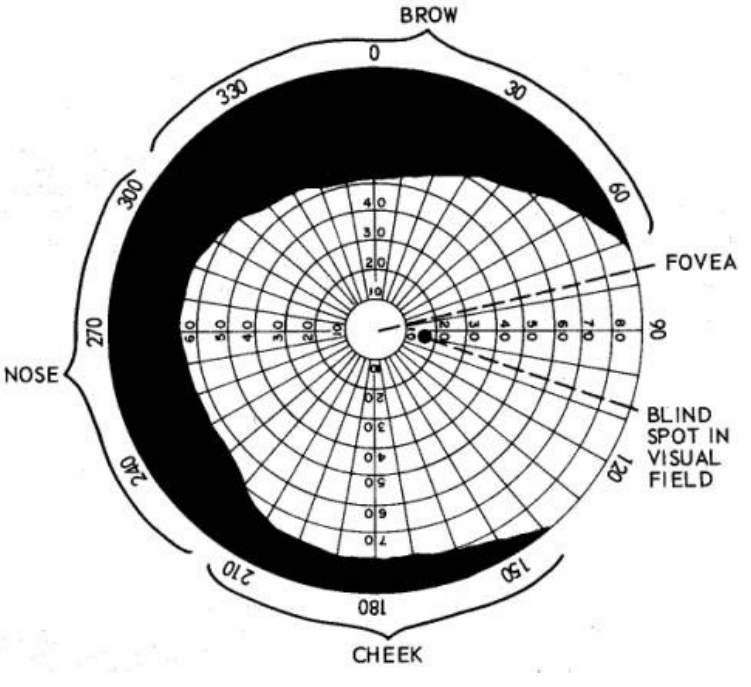


Binocular Disparity

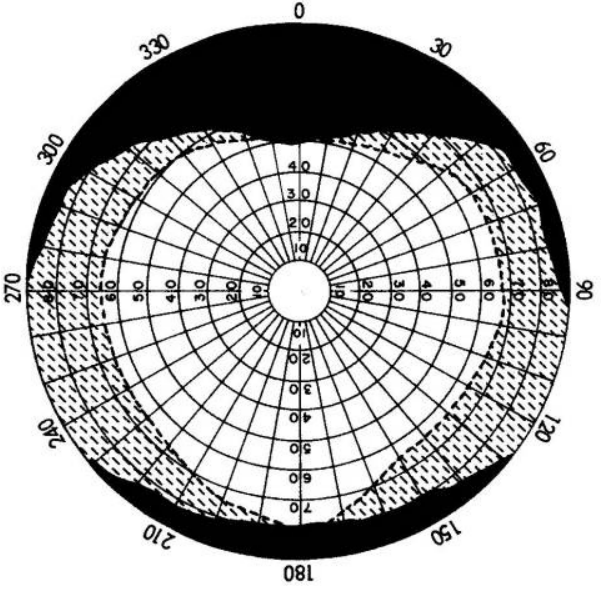
Retinal Blur


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

# Visual Field / Field of View



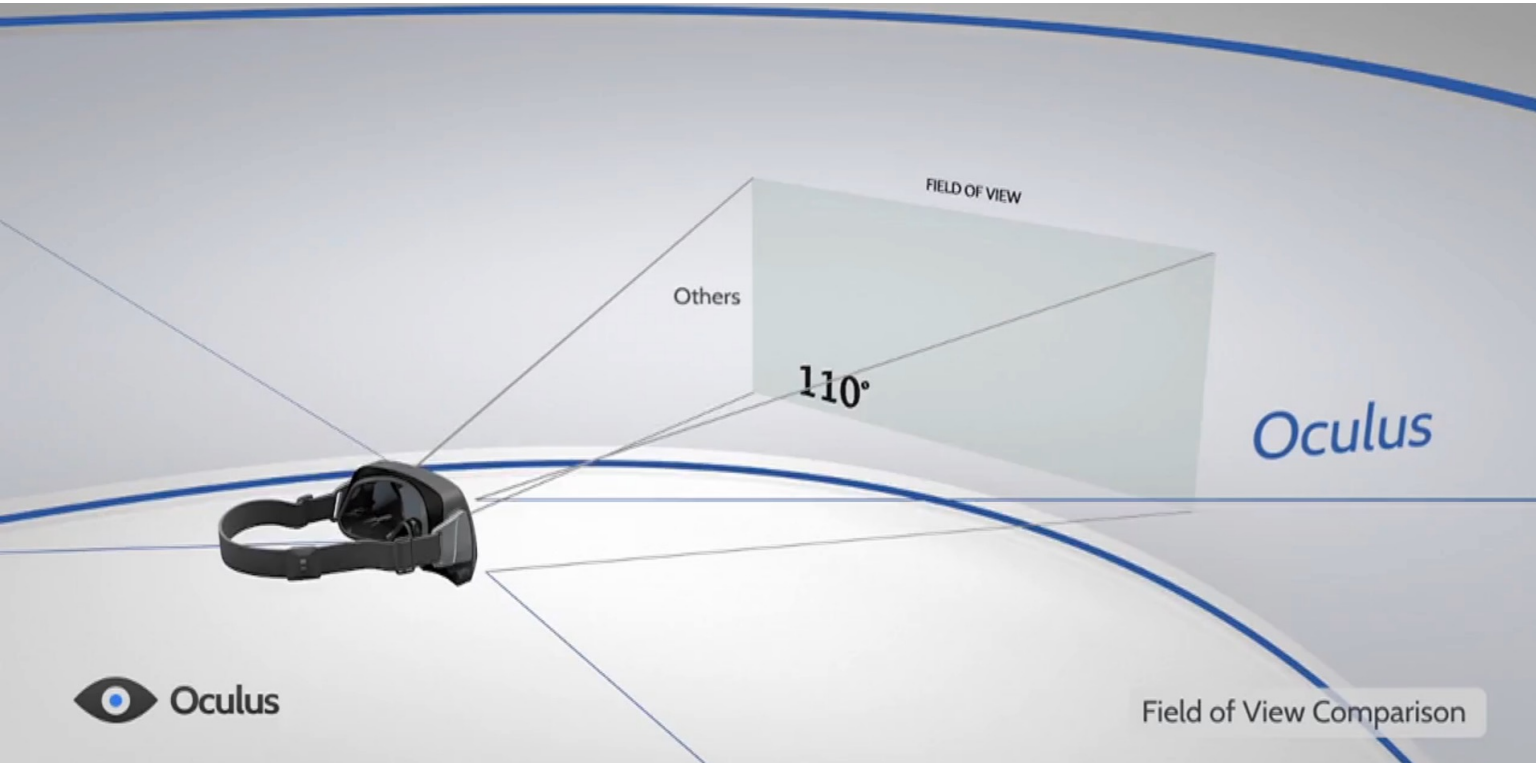

monocular visual field




binocular visual field

Ruch & Fulton, 1960

# Immersive VR – How Important is the FOV?



# Visual Acuity

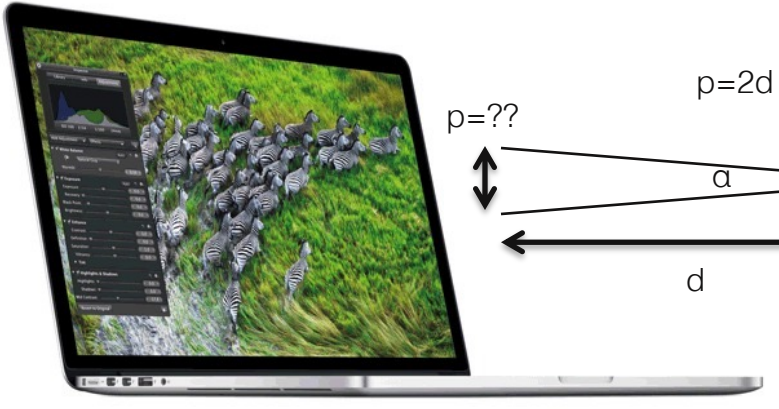
Snellen chart

| | | |
|---|---|---|
| 1 | 20/200 | |
| 2 | 20/100 | |
| 3 | 20/70 | |
| 4 | 20/50 | |
| 5 | 20/40 | |
| 6 | 20/30 | |
| 7 | 20/25 | |
| 8 | 20/20 | ← characters are 5 arc min, need to resolve 1 arc min to read |
| 9 | | |
| 10 | | |
| 11 | | |

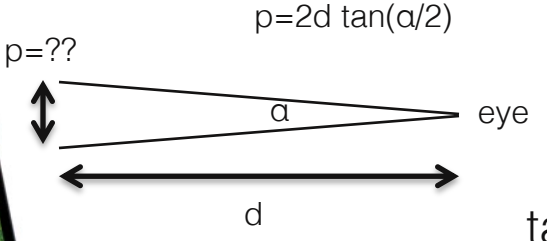
# Retina Displays

Steve Jobs: 300 dpi is retina resolution

our math: ~286 dpi



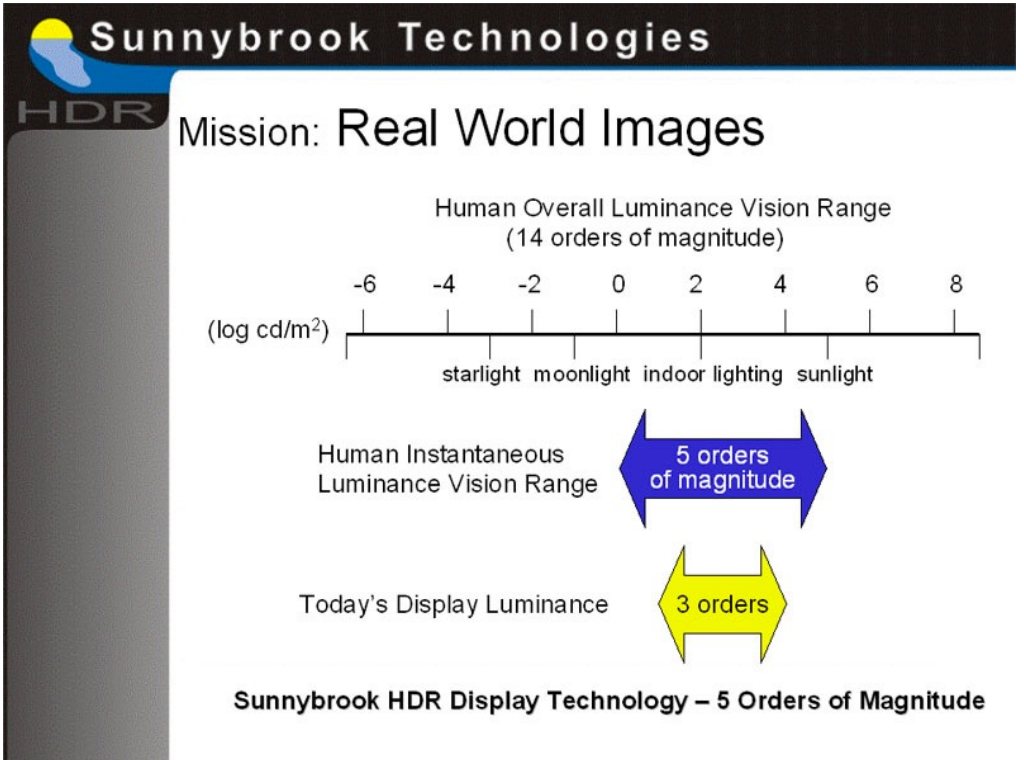
Apple Inc.



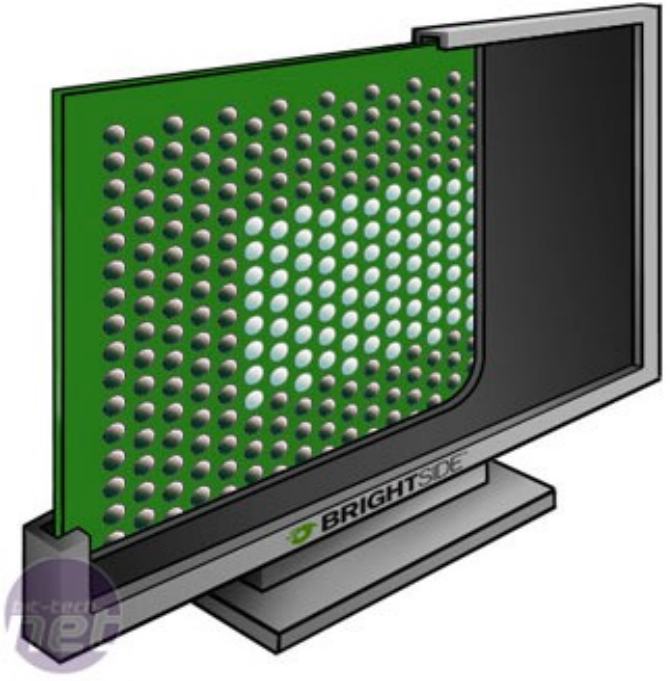

tablet, 12” away,
resolvable pixel:

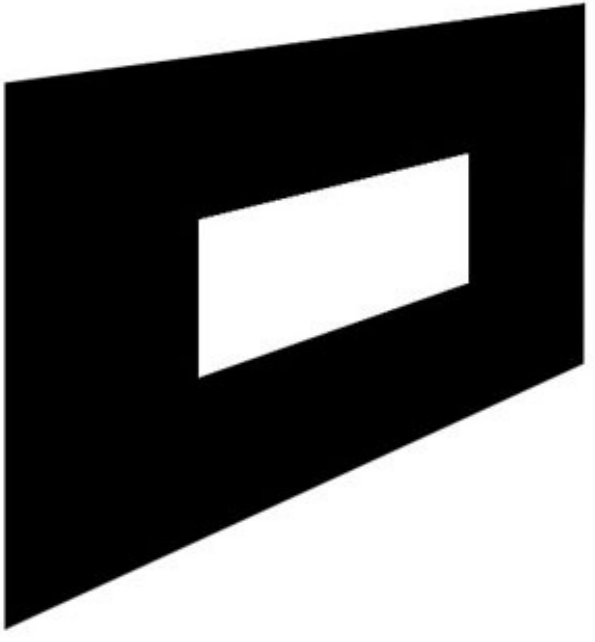
p=2*12”*tan(1 arc min /2)=0.0035”

# Dynamic Range

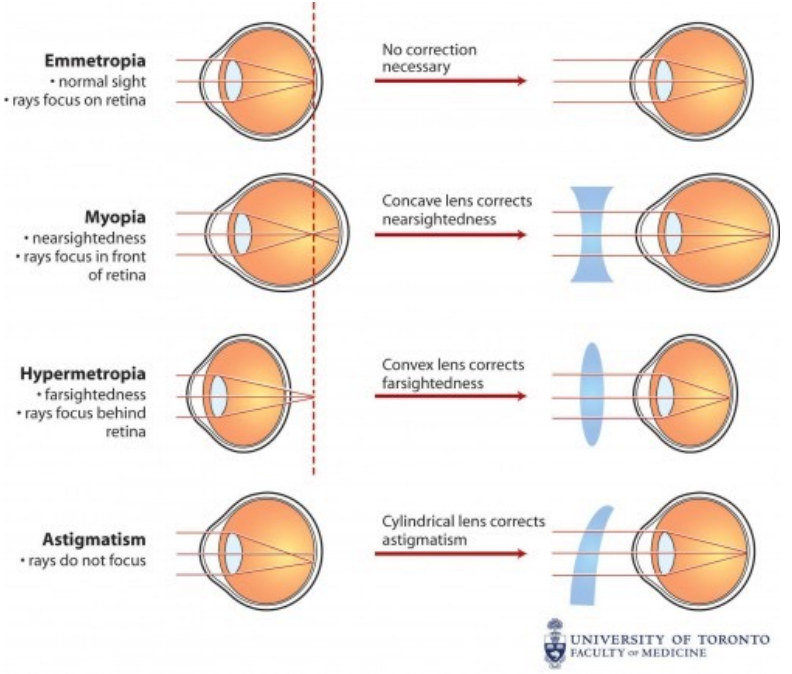


# High Dynamic Range Displays



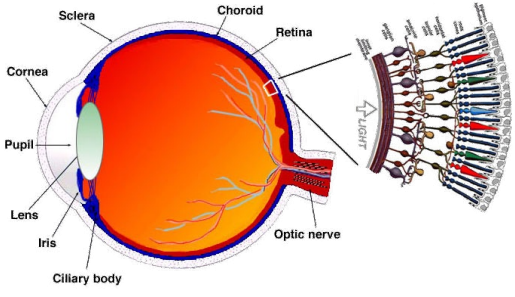
# Refractive Errors

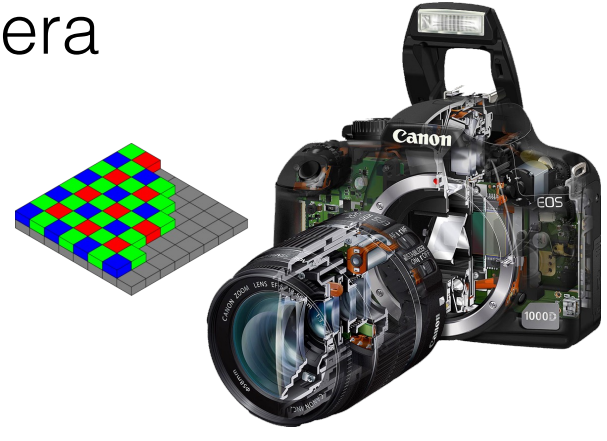


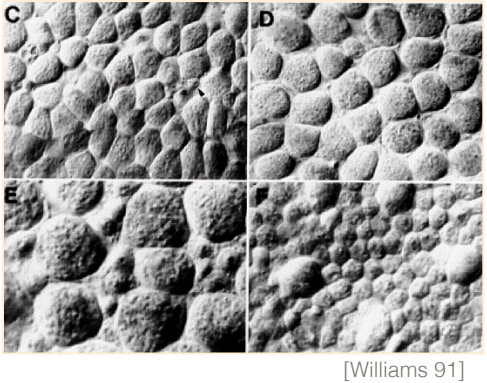
# Vision-Correcting Displays

300 dpi or higher

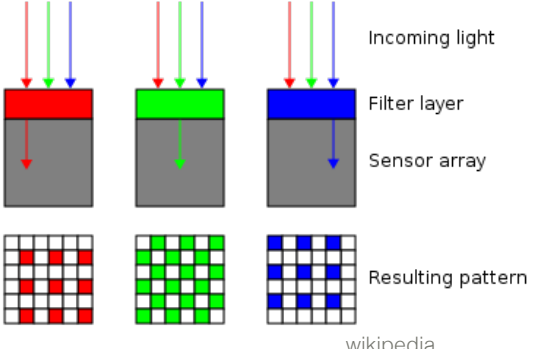
# Eye vs Camera



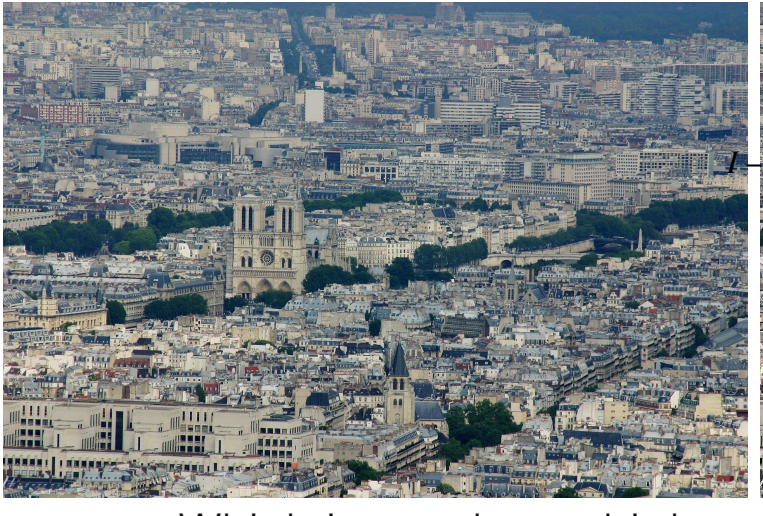



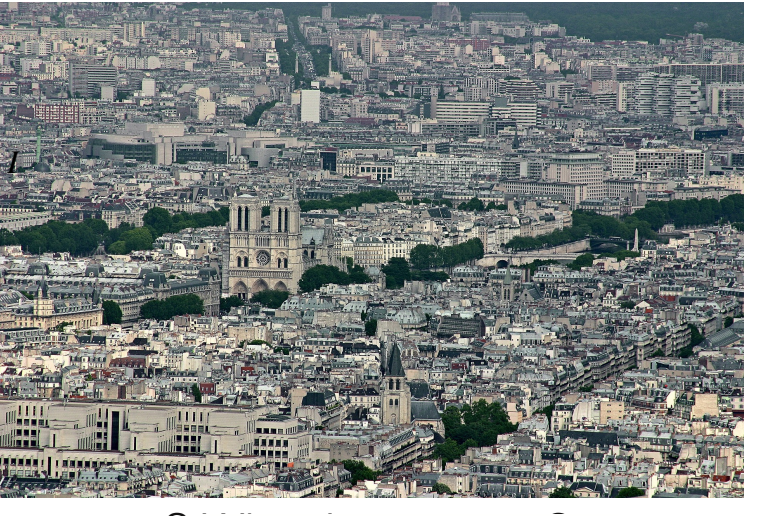

[Williams 91]




wikipedia

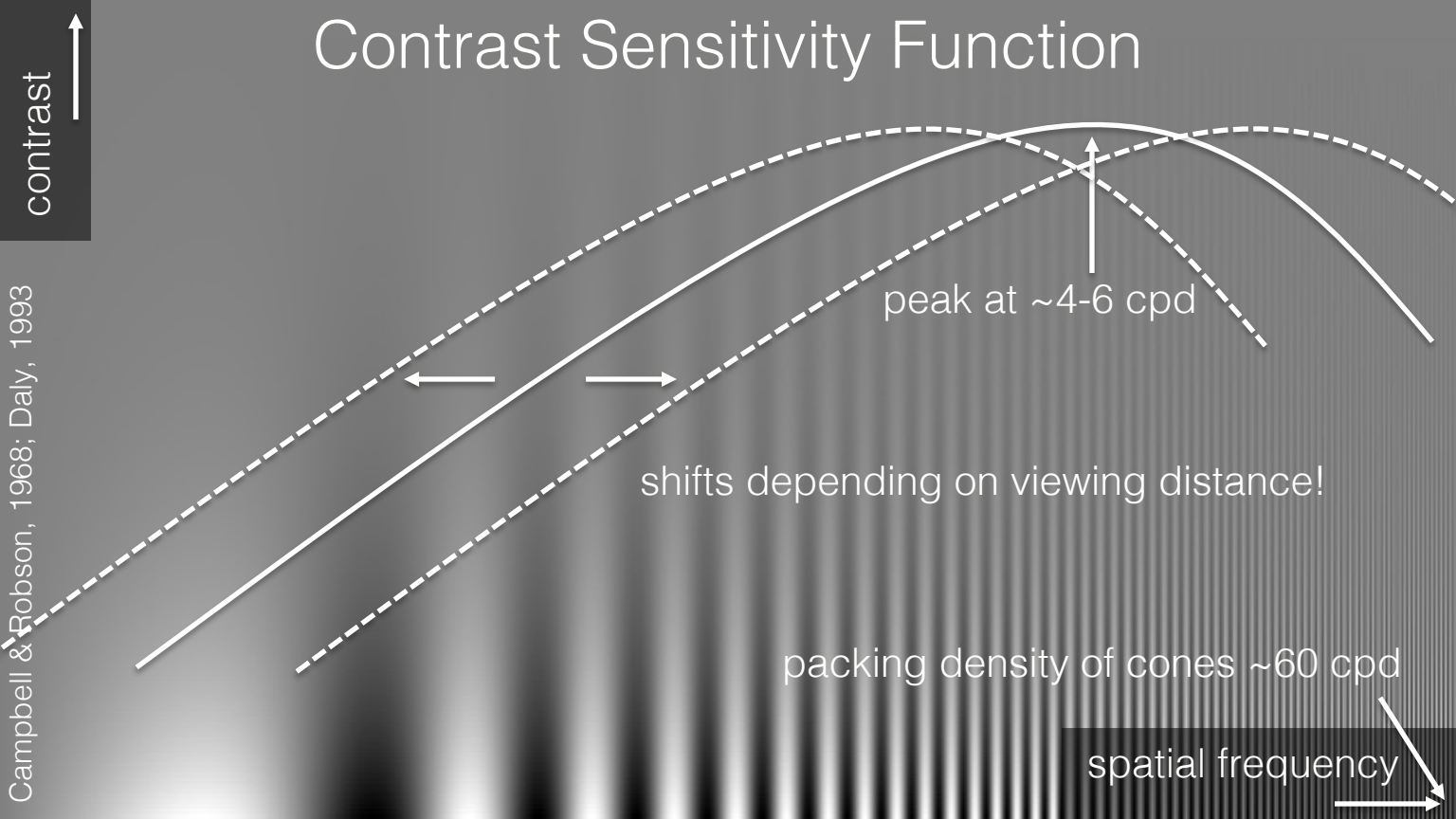
# Contrast





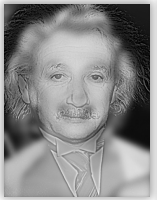
Which image has a higher contrast?

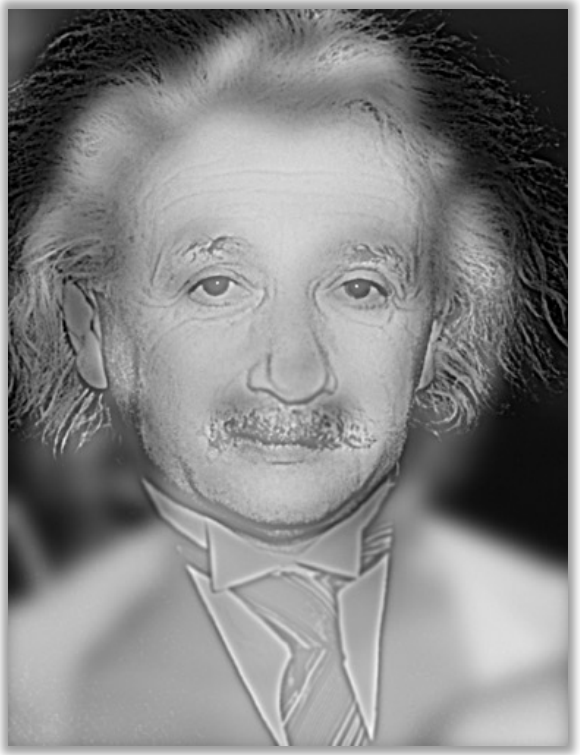
# Contrast Sensitivity Function




Campbell & Robson, 1968; Daly, 1993

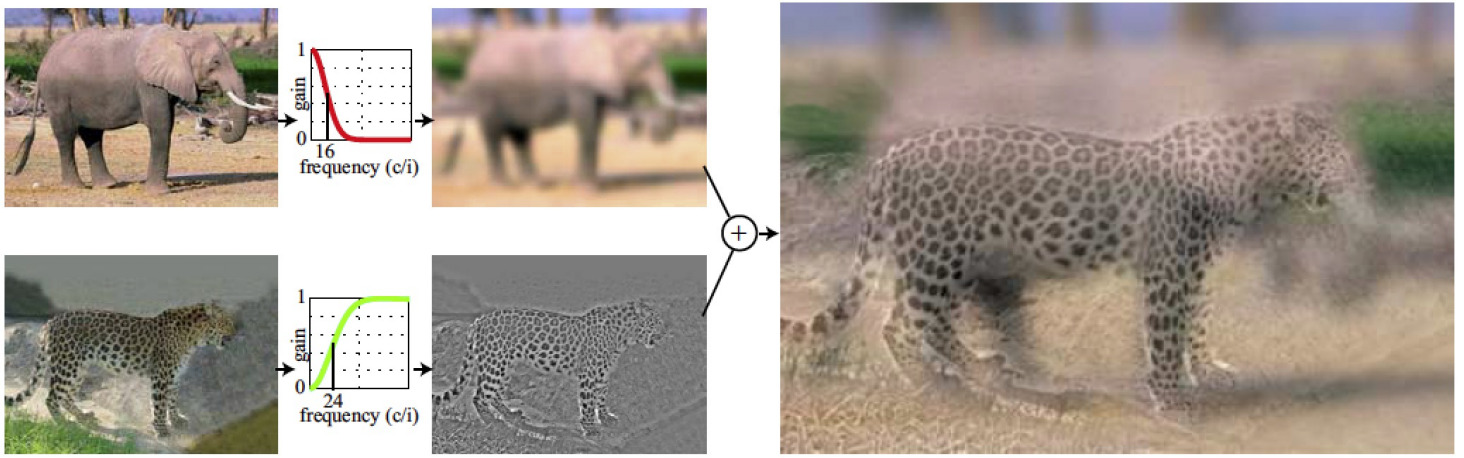
# Hybrid Images





Oliva, Torralba, & Schyns, 2006, ACM SIGGRAPH

# Hybrid Images




Oliva, Torralba, & Schyns, 2006, ACM SIGGRAPH

# Depth Perception

wikipedia

# Depth Perception

wikipedia

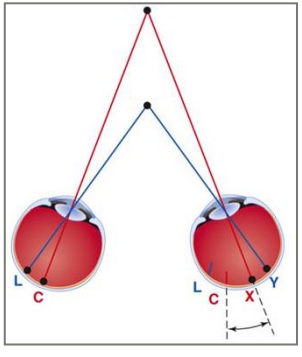
monocular cues

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

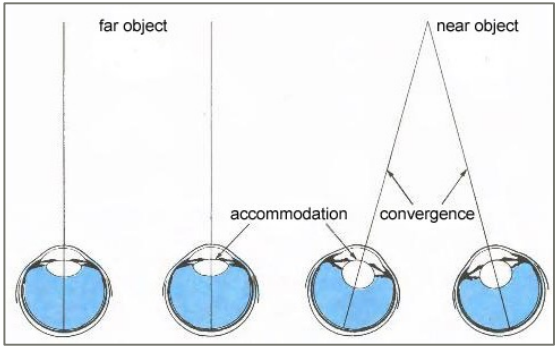
binocular cues

- (con)vergence
- disparity / parallax
- …

# Depth Perception

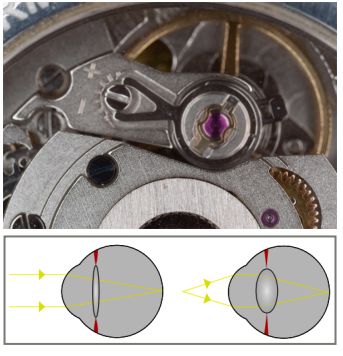



binocular disparity




convergence

motion parallax



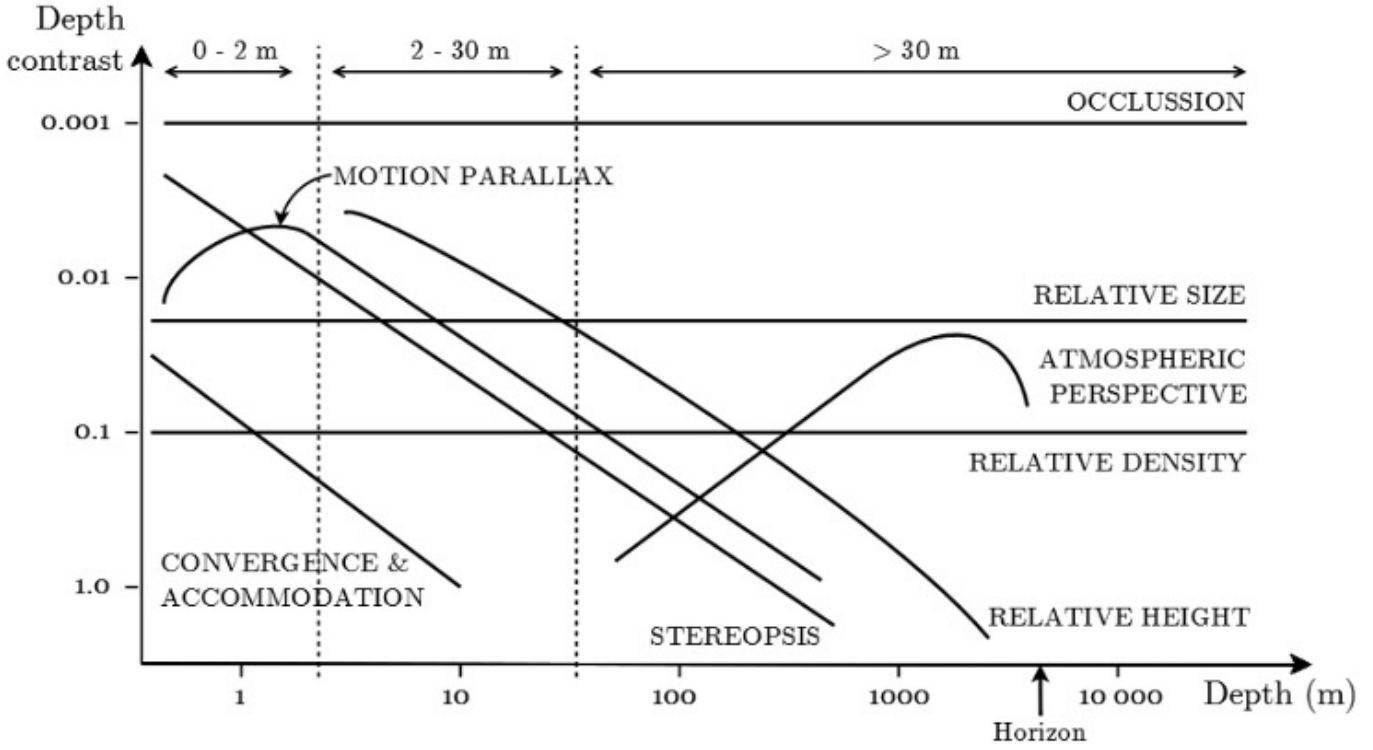
accommodation/blur

current glasses-based (stereoscopic) displays

near-term: light field displays

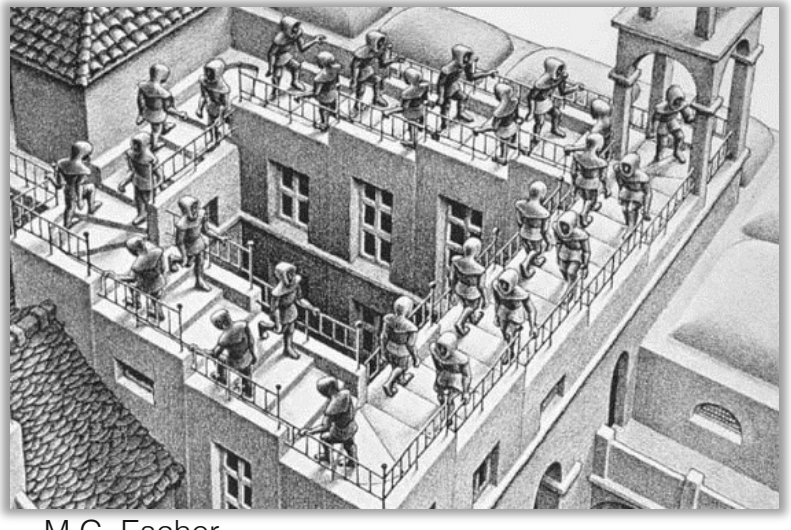
longer-term: holographic displays

# Depth Perception

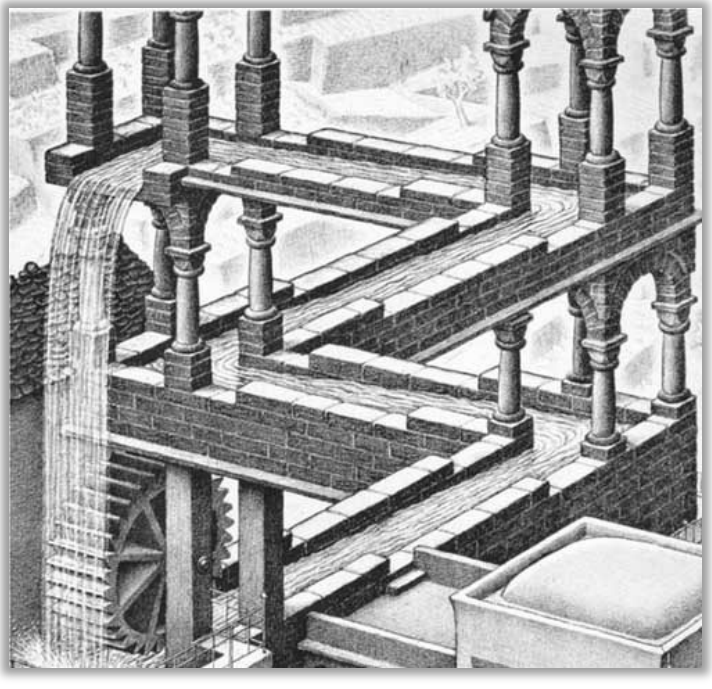


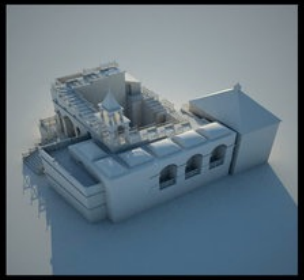

Cutting & Vishton, 1995

# Visual Illusions – Perspective, Occlusion, Size



M.C. Escher

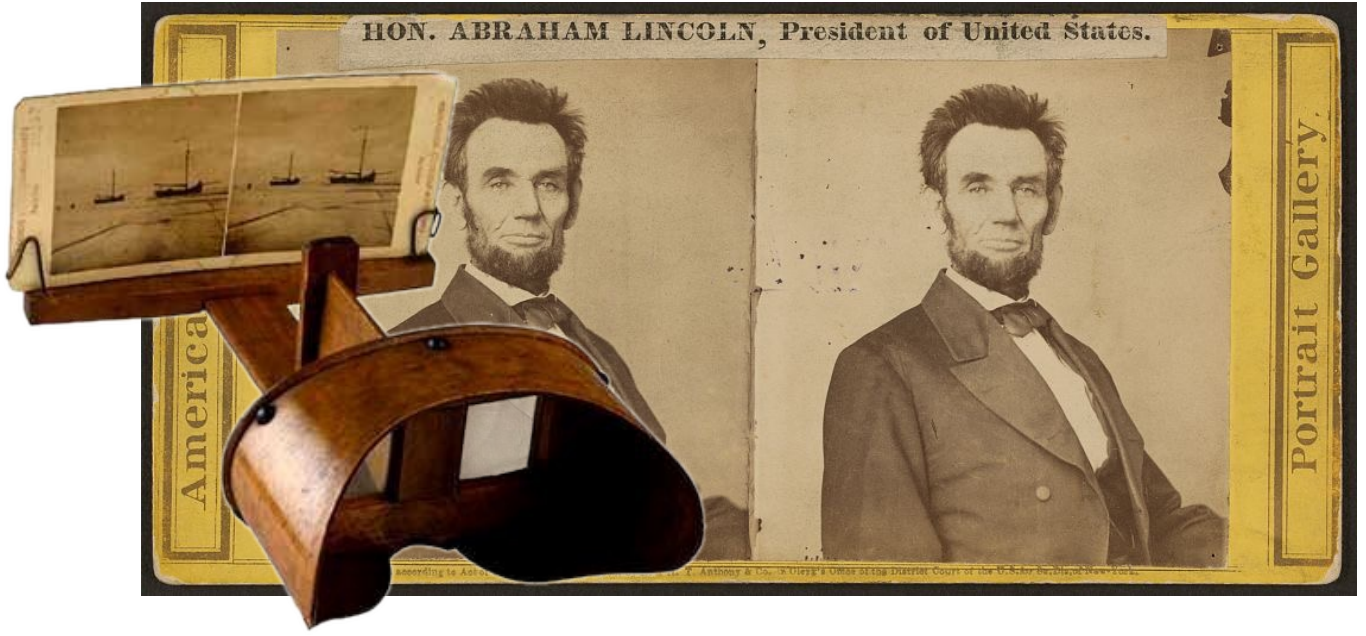




# Visual Illusions – Which Cues are These?

Held et al., 2006, ACM SIGGRAPH

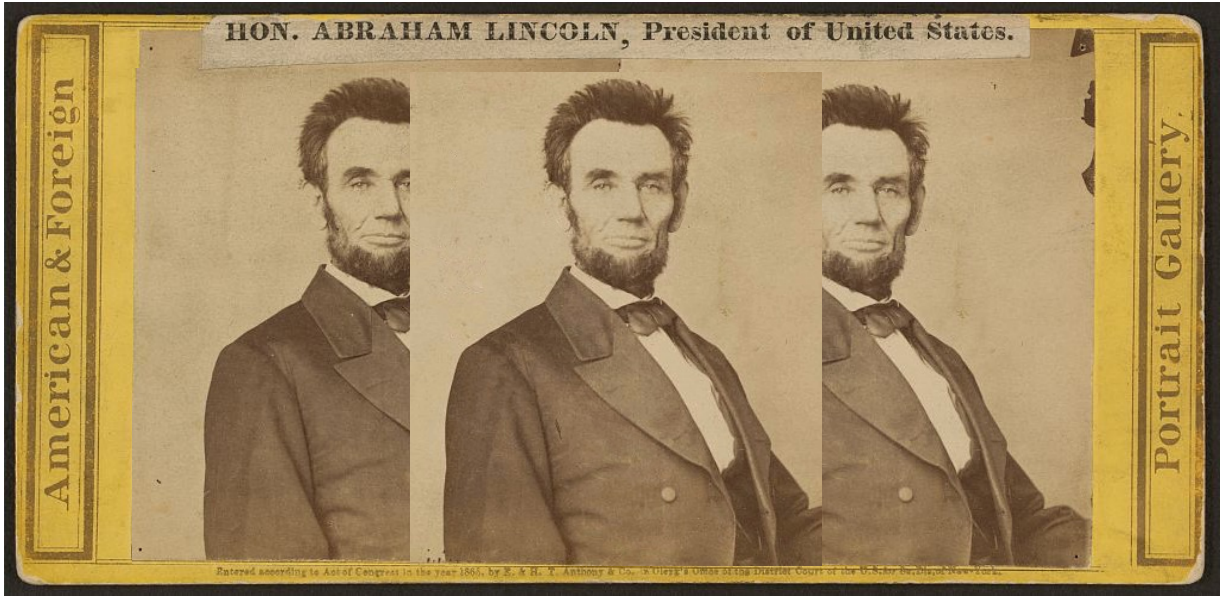
# Stereoscopic Displays




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

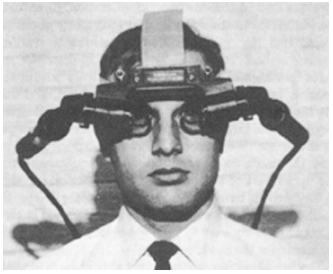
176 years later

stereoscopic displays

# A Brief History of Virtual Reality

Stereoscopes
Wheatstone, Brewster, …

VR, AR,
Ivan Sutherland



VR explosion
Meta, Apple, Sony, …

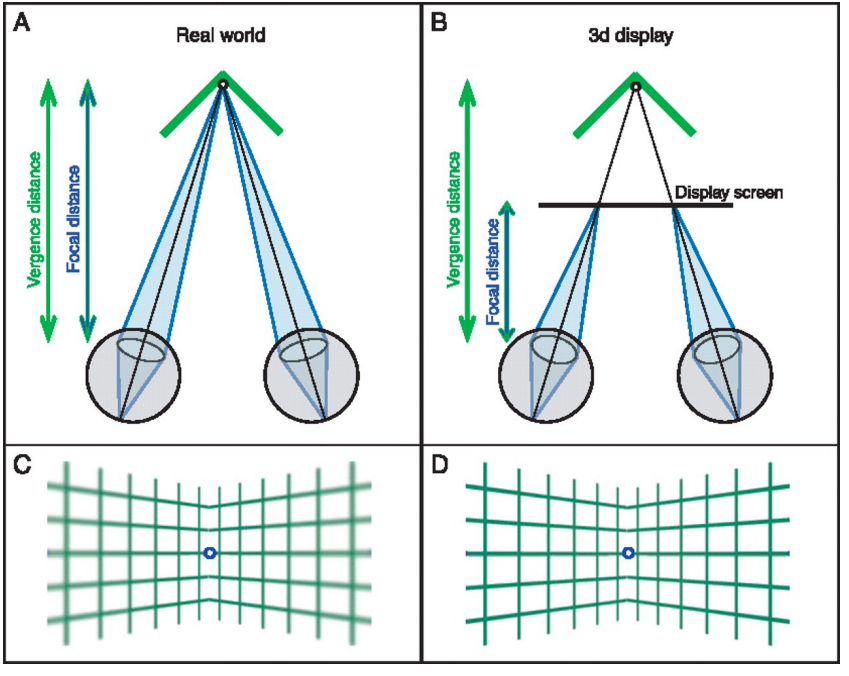
1838

1968

2012-now

Next-generation VR/AR Displays

# Vergence-Accommodation Conflict



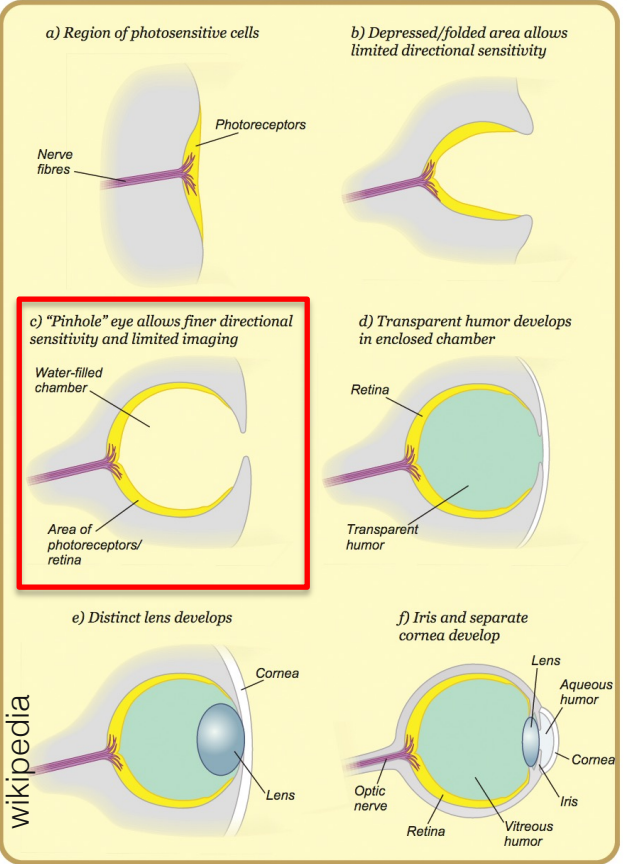

effects

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

Marty Banks, UC Berkeley

# Summary

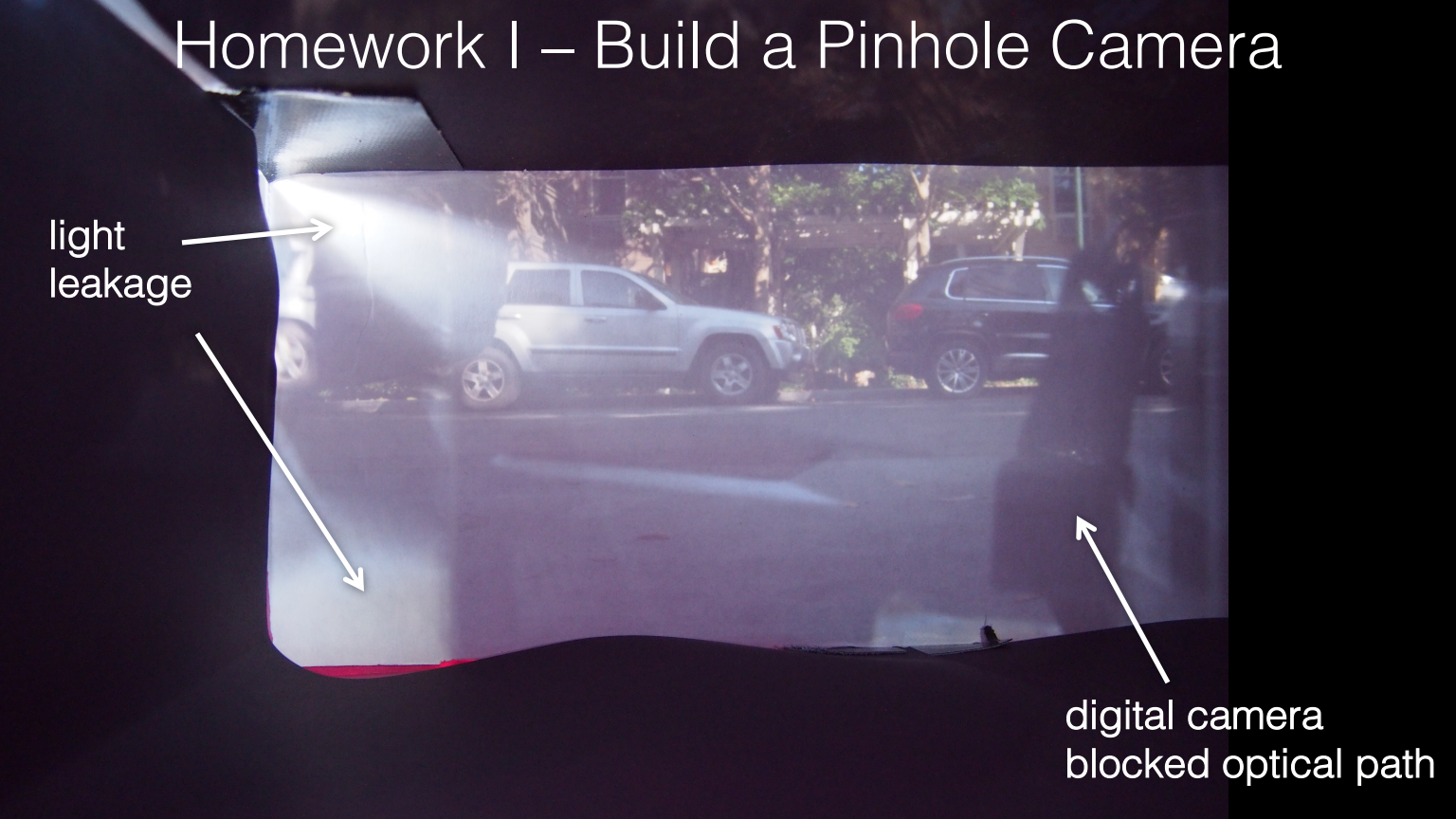
- visual acuity: 20/20 is ~1 arc min
- field of view: ~190° monocular, ~120° binocular, ~135° vertical
- temporal resolution: ~60 Hz (depends on contrast, luminance)
- dynamic range: instantaneous 6.5 f-stops, adapt to 46.5 f-stops
- color: everything in the CIE xy diagram; distances are linear in CIE Lab
- depth cues in 3D displays: vergence, focus, conflicts, (dis)comfort
- accommodation range: ~8cm to ∞, degrades with age




# 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
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the retina and visual acuity:

- Roorda, Williams, “The arrangement of the three cone classes in the living human eye”, Nature, Vol 397, 1999
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the visual field:

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contrast sensitivity function & hybrid images:

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- Spatio-temporal CSF: Kelly, Motion and Vision. II. Stabilized spatio-temporal threshold surface, Journal of the Optical Society of America,1979
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