The Human Visual System

EE367/CS448I: Computational Imaging
stanford.edu/class/ee367
Lecture 2

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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.
Evolution of the Eye

1. Region of photosensitive cells
2. Depressed/folded area allows limited directional sensitivity
3. "Pinhole" eye allows finer directional sensitivity and limited imaging
4. Transparent humor develops in enclosed chamber
5. Distinct lens develops
6. Iris and separate cornea develop

Wikipedia

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

low-level processing

network

compute

high-level processing

wikipedia
Overview

primary visual cortex

ventral stream:
recognition, object identification

dorsal stream:
spatial awareness
Anatomy of the Human Eye

- Cornea
- Pupil
- Iris
- Anterior chamber (aqueous humour)
- Zonular fibres
- Posterior chamber
- Ciliary muscle
- Suspensory ligament
- Lens
- Vitreous humour
- Optic disc
- Optic nerve
- Fovea
- Retinal blood vessels
- Choroid
- Sclera
The Retina

Roorda & Williams, 1999, Nature

5 arcmin visual angle
Color Perception

The diagram illustrates the spectrum of light and its correlation with wavelengths. The visible light spectrum is highlighted, ranging from 400 nanometers (violet) to 700 nanometers (red). The wavelength scale is also shown on a logarithmic scale, with values ranging from $10^{-14}$ to $10^4$ meters.

Key frequencies are marked:
- Gamma rays: $10^{-14}$ meters
- X-rays: $10^{-12}$ meters
- Ultraviolet rays: $10^{-10}$ meters
- Infrared rays: $10^{-4}$ meters
- Radar: $10^{-2}$ meters
- FM: 1 meter
- TV: $10^2$ meters
- Shortwave AM: $10^4$ meters

The visible light spectrum is crucial for human vision, allowing us to perceive colors from violet to red.
Color Perception - Sensitivity of Cones

The diagram shows the absorbance of light across different wavelengths. Three peaks represent the sensitivity of different types of cones:

- **Short** cones are sensitive to light with wavelengths around 400-450 nm, which correspond to high frequencies.
- **Medium** cones are sensitive to light with wavelengths around 500-550 nm, which represent medium frequencies.
- **Long** cones are sensitive to light with wavelengths around 600-700 nm, which correspond to low frequencies.

These cones are responsible for color vision in the human eye.
Oculumotor Processes

16 years: ~8cm to ∞
50 years: ~50cm to ∞ (mostly irrelevant)
Oculomotor Processes + Visual Cues

- **Stereopsis (Binocular)**
- **Focus Cues (Monocular)**

**Oculomotor Cue**
- Vergence
- extraocular muscles

**Visual Cue**
- Binocular Disparity
- Retinal Blur
Stereopsis (Binocular)

Oculomotor Cue

Vergence

extraocular muscles

Visual Cue

Binocular Disparity

Focus Cues (Monocular)

Accommodation

Ciliary muscles

relaxed

contracted

Retinal Blur
Stereopsis (Binocular)

Oculomotor Cue

Vergence

Visual Cue

Binocular Disparity

Focus Cues (Monocular)

Accommodation

Relaxed

Ciliary muscles

Contracted

Extraocular muscles
Visual Field / Field of View

monocular visual field

binocular visual field

Ruch & Fulton, 1960
Immersive VR – How Important is the FOV?
Visual Acuity

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

tablet, 12” away, resolvable pixel:
p=2*12”*tan(1 arc min /2)=0.0035”
Dynamic Range

Mission: Real World Images

Human Overall Luminance Vision Range
(14 orders of magnitude)

(log cd/m²)

starlight moonlight indoor lighting sunlight

Human Instantaneous Luminance Vision Range

5 orders of magnitude

Today's Display Luminance

3 orders

Sunnybrook HDR Display Technology – 5 Orders of Magnitude
High Dynamic Range Displays
RefRACTIVE ERRORS

Emmetropia
- Normal sight
- Rays focus on retina
- No correction necessary

Myopia
- Nearsightedness
- Rays focus in front of retina
- Concave lens corrects nearsightedness

Hypermetropia
- Farsightedness
- Rays focus behind retina
- Convex lens corrects farsightedness

Astigmatism
- Rays do not focus
- Cylindrical lens corrects astigmatism
Vision-Correcting Displays

300 dpi or higher
Eye vs Camera

[Images of eye anatomy and camera structure]

C, D, E

[Images of textured surfaces]

[Diagram showing incoming light, filter layer, sensor array, and resulting pattern]

[Williams 91]
Contrast

Which image has a higher contrast? What is contrast?

global vs. local, Weber contrast:           Michelson contrast: $I - I$
Contrast Sensitivity Function

- Peak at ~4-6 cpd
- Packing density of cones ~60 cpd
- Shifts depending on viewing distance!

Campbell & Robson, 1968; Daly, 1998
Hybrid Images

Oliva, Torralba, & Schyns, 2006, ACM SIGGRAPH
Hybrid Images

Oliva, Torralba, & Schyns, 2006, ACM SIGGRAPH
Depth Perception

monocular cues
- perspective
- relative object size
- absolute size
- occlusion
- accommodation
- retinal blur
- motion parallax
- texture gradients
- shading
- ...

binocular cues
- (con)vergence
- disparity / parallax
- ...

wikipedia
Depth Perception

- **Binocular Disparity**
- **Convergence**
- **Motion Parallax**
- **Accommodation/Blur**

- Current glasses-based (stereoscopic) displays
- Near-term: Light field displays
- Longer-term: Holographic displays
Visual Illusions – Perspective, Occlusion, Size

M.C. Escher
Visual Illusions – Which Cues are These?
Stereoscopic Displays

Charles Wheatstone, 1841. Stereoscope.

Stereoscopic Displays

HON. ABRAHAM LINCOLN, President of United States.
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, ...

Next-generation VR/AR Displays
Vergence-Accommodation Conflict

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

Near-eye Light Field Displays

Holographic Displays

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

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

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
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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

- Light leakage
- Digital camera blocked optical path
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:


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
- Snellen chart: https://en.wikipedia.org/wiki/Snellen_chart

the retina and visual acuity:

- Ruch and Fulton, Medical physiology and biophysics, 1960

contrast sensitivity function & hybrid images:

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