an engineering-focused introduction to

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

- a) Region of photosensitive cells
  - Nerve fibres
  - Photoreceptors

- b) Depressed/folded area allows limited directional sensitivity
  - Water-filled chamber
  - Area of photoreceptors/retina

- c) "Pinhole" eye allows finer directional sensitivity and limited imaging
  - Transparent humor develops in enclosed chamber

- d) Distinct lens develops
  - Aqueous humor
  - Cornea
  - Ciliary muscles

- e) Iris and separate cornea develop
  - Lens
  - Optic nerve
  - Vitreous humor

- f) Iris and separate cornea develop
  - Lens
  - Aqueous humor
  - Cornea
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

high-level processing

compute

low-level processing

compute

high-level processing
Overview

**Primary visual cortex**

**Ventral stream:**
- Recognition, object identification

**Dorsal stream:**
- Spatial awareness

-wikipedia

**Primary visual cortex**

**Ventral stream:**
- Recognition, object identification

-dorsal stream: spatial awareness

-wikipedia
Anatomy of the Human Eye
The Retina

Axons of optic nerve

Ganglion cells
Amacrine cells
Bipolar cells
Horizontal cells

Photoreceptors
Cone
Rod

Retinal pigment epithelium

Sclera
Choroid
Retina
Fovea
Macula lutea
Optic nerve
Optic disk

Sclera
Choroid

Inner layer
Middle layer
Outer layer

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The Retina

Roorda & Williams, 1999, Nature

5 arcmin visual angle
Oculumotor Processes

far focus

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

near focus
Oculomotor Processes + Visual Cues

Stereopsis (Binocular)

Focus Cues (Monocular)

Vergence

Accommodation

Binocular Disparity

Retinal Blur
Stereopsis (Binocular)

Oculomotor Cue

Vergence

extraocular muscles

Visual Cue

Binocular Disparity

Focus Cues (Monocular)

Accommodation

relaxed

contracted

ciliary muscles

Retinal Blur
Stereopsis (Binocular)

Oculomotor Cue

Vergence

Visual Cue

Binocular Disparity

Focus Cues (Monocular)

Accommodation

Retinal Blur

eye muscles

ciliary muscles

relaxed

contracted
Visual Field / Field of View

monocular visual field
binocular visual field

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

Field of View Comparison

Oculus
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:

\[ p = 2d \tan(\alpha/2) \]

\[ p = 2 \times 12” \times \tan(1 \text{ arc min} / 2) = 0.0035” \]
Dynamic Range

Mission: Real World Images

Human Overall Luminance Vision Range
(14 orders of magnitude)

(log cd/m²)

-6 -4 -2 0 2 4 6 8

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 components]

[Diagram showing light filtering and sensor arrays]

[Text citation: Williams 91]
Contrast

Which image has a higher contrast? What is contrast?

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

peak at ~4-6 cpd

shifts depending on viewing distance!

packing density of cones ~60 cpd

Campbell & Robson, 1968; Daly, 1993
Hybrid Images

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

wikipedia
**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

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. Steroscope.

Stereoscopic Displays
Stereoscopic Displays

Charles Wheatstone 1838

176 years later

stereoscopic displays
A Brief History of Virtual Reality

- **1838**: Stereoscopes
  - Wheatstone, Brewster, ...

- **1968**: VR, AR,
  - Ivan Sutherland

- **2012-now**: VR explosion
  - Oculus, Sony, Valve, MS, ...

**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
• …
Real World:

Vergence & Accommodation Match!
Stereo Displays Today:

Vergence-Accommodation **Mismatch**!
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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• 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!
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

the retina and visual acuity:

- 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:

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