an engineering-focused introduction to

The Human Visual System

EE367/CS448I: Computational Imaging and Display
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

- Region of photosensitive cells
- Depressed/folded area allows limited directional sensitivity
- “Hole” eye allows finer directional sensitivity and limited imaging
- Transparent humor develops in enclosed chamber
- Distinct lens develops
- Iris and separate cornea develop

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

- **Primary Visual Cortex**
  - **Ventral Stream:** Recognition, object identification
  - **Dorsal Stream:** Spatial awareness

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**Image Descriptions**

- **Ventral Stream:** Recognition, object identification
- **Dorsal Stream:** Spatial awareness

**Wikipedia**
The Retina
The Retina

Roorda & Williams, 1999, Nature

5 arcmin visual angle
Anatomy of the Human Eye

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

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

**Stereopsis (Binocular)**

- Extracocular muscles
- Vergence

**Focus Cues (Monocular)**

- Ciliary muscles
- 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

Characters are 5 arc min, need to resolve 1 arc min to read.
Retina Displays

Steve Jobs: 300 dpi is retina resolution
our math: ~573 dpi (Shannon!)

p=2d tan(α/2)

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)

-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

*Image source: University of Toronto Faculty of Medicine*
Vision-Correcting Displays

300 dpi or higher
Eye vs Camera

[Williams 91]

In addition to the visual information, the diagram on the left shows the layers of the eye: Ciliary body, Cornea, Lens, Choroid, Retina, and Optic nerve. The diagram on the right illustrates the light path through a camera's filter layer and sensor array, resulting in different patterns. The Wikipedia logo is also present, indicating the source of the visual content.
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
Sensitivity of Cones

![Graph showing the sensitivity of cones across different wavelengths. The graph illustrates the absorbance of light at various wavelengths, with peaks at different wavelengths for short, medium, and long wavelengths. The short wavelength cone has its peak at around 450 nm, the medium wavelength cone at around 550 nm, and the long wavelength cone at around 650 nm. The graph also notes that short wavelength light has a high frequency, while long wavelength light has a low frequency.](reddit.com)
CIE XYZ Color Space

\[
X = \int_{380}^{780} I(\lambda) \bar{x}(\lambda) \, d\lambda
\]

\[
Y = \int_{380}^{780} I(\lambda) \bar{y}(\lambda) \, d\lambda
\]

\[
Z = \int_{380}^{780} I(\lambda) \bar{z}(\lambda) \, d\lambda
\]

CIE xy chromaticity diagram

\[
x = \frac{X}{X + Y + Z} \quad y = \frac{Y}{X + Y + Z}
\]
Display Gamut

REC 709
(HDTV Standard)

Typical LCD
(DP6, TVLogic 5.6, Ikan D5W)

DP7-OLED
(Native Color Gamut)

my gamut – how did I do that?

CIE 1931 color space
CIE XYZ – Distances are Nonlinear!

MacAdam ellipses
CIE LAB Color Space

lightness

$$L^* = 116 f(Y/Y_n) - 16$$

color-opponent pairs

$$a^* = 500 \left[ f(X/X_n) - f(Y/Y_n) \right]$$

$$b^* = 200 \left[ f(Y/Y_n) - f(Z/Z_n) \right]$$

$$f(t) = \begin{cases} 
  t^{1/3} & \text{if } t > \left( \frac{6}{29} \right)^3 \\
  \frac{1}{3} \left( \frac{29}{6} \right)^2 t + \frac{4}{29} & \text{otherwise}
\end{cases}$$
CIE LAB Color Space

https://www.colorcodehex.com/color-model.html
Depth Perception
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?

(a) (b)
Stereoscopic Displays

Charles Wheatstone, 1841. Stereoscope.

Stereoscopic Displays
Stereoscopic Displays

Charles Wheatstone 1838

176 years later

stereoscopic displays
A Brief History of Virtual Reality

- **1838**: Stereoscopes by Wheatstone and Brewster
- **1968**: Ivan Sutherland's groundbreaking work on virtual reality
- **2012-2015**: VR explosion with companies like Oculus, Sony, Valve, and Microsoft

Next-generation VR 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

A

B

Viewing Distance (D)

Viewing Distance (m)

Vergence Distance (D)

Vergence Distance (m)

mobile

near

desktop

cinema

television

far
The Light Field Stereoscope

Technical Paper
& E-Tech Demo
with NVIDIA Research

ACM SIGGRAPH 2015

www.computationalimaging.org
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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:
• 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
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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
• 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