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

[Image of an owl]
Lecture Overview

- **visual acuity**: 20/20 is ~1 arc min
- visual acuity varies over retina: can exploit via **foveated rendering**
- **field of view**: ~190° monocular, ~120° binocular, ~135° vertical
- **temporal resolution**: ~60 Hz (depends on contrast, luminance)
- **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

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

- **Dorsal Stream:**
  - Spatial awareness

**Primary Visual Cortex**

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

**Dorsal Stream:**
- Spatial awareness
Overview

- Lateral geniculate nucleus
- Optic chiasm
- Superior colliculus
- Optic nerve
- Optic tract
- Retina
- Visual cortex
- Cortical cells
photoreceptors: 3 types of cones (color vision), rods (luminance only, night vision)
Color Perception - Sensitivity of Cones

The diagram illustrates the absorbance of different cone types across various wavelengths. The absorbance is measured along the y-axis, and the wavelength (nm) is shown on the x-axis. The curves indicate the sensitivity of three types of cones:

- **Short**: Peaked around 400 nm, indicating sensitivity to short wavelengths and high frequencies.
- **Medium**: Peaked around 550 nm, indicating sensitivity to medium wavelengths.
- **Long**: Peaked around 600 nm, indicating sensitivity to long wavelengths and low frequencies.

The gradient at the bottom of the diagram corresponds to the color spectrum, with short wavelengths (high frequency) at the blue end and long wavelengths (low frequency) at the red end.
Visual Field / Field of View

monocular visual field

binocular visual field

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

each photorecepter

\[ \sim 1 \text{ arc min} \ (1/60 \text{ of a degree}) \]
Visual Acuity

characters are 5 arc min, need to resolve 1 arc min to read
Retina VR Display – What does it Take?

need per eye:

150° x 135° with pixels covering 1 arc min
= 9000 x 8100 pixels (probably 2-3x in practice)

biggest challenge: bandwidth

• capture or render stereo panoramas or images at that resolution
• compress and transmit huge amount of data
• drive and operate display pixels
Relative Acuity Over Retina

The diagram shows the relative acuity over the retina as eccentricity increases. The peak acuity is at the fovea, the central part of the retina where vision is sharpest. As eccentricity increases, acuity decreases, reaching a blind spot beyond 20° eccentricity.
Density of Photoreceptors on Retina

![Graph showing density of different types of photoreceptors against eccentricity.]

- **Rods**
- **Cones**
- **Ganglion Cells**

Density (per mm²)

Eccentricity (degrees)

Patney et al. 2016

Superior, Inferior, Nasal, Temporal
Density of Photoreceptors on Retina

- **Fovea**: 1-5°

**Density (per mm²)**

- Rods
- Cones
- Ganglion Cells

**Eccentricity (degrees)**

*Patney et al. 2016*
MAR / Acuity Over Retina

acuity falls off due to:

• reduced receptor and ganglion cell density
• reduced optical nerve “bandwidth”
• reduced “processing” devoted to periphery in the visual cortex

Guenter et al. 2016
acuity falls off due to:

- reduced receptor and ganglion cell density
- reduced optical nerve “bandwidth”
- reduced “processing” devoted to periphery in the visual cortex

MAR: minimum angle of resolution in deg/cycle

\[ \omega = me + \omega_0 \]

- \( me \): eccentricity in degrees
- \( \omega_0 \): smallest resolvable angle at fovea in deg/cycle
MAR / Acuity Over Retina

acuity falls off due to:

• reduced receptor and ganglion cell density
• reduced optical nerve “bandwidth”
• reduced “processing” devoted to periphery in the visual cortex

MAR: minimum angle of resolution in deg/cycle

\[
\omega = me + \omega_0
\]

eccentricity in degrees

\[
\omega_0 = \left(\frac{1}{48}\right) \text{°}
\]
somewhere between 20/20 (30 cycles per degree) and 20/10 (60 cycles per degree)

\[
m = 0.022 - 0.034
\]
acceptable – equivalent for observed image quality

Guenter et al. 2016
MAR / Acuity Over Retina

\[ \omega = me + \omega_0 \]

MAR (degrees/cycle)

Acuity (1/MAR) (cycles/degree)

Guenter et al. 2016

MAR (degrees/cycle)

eccentricity (degrees)

Acuity (cycles/degree)

eccentricity (degrees)

MAR = smallest resolvable angle at fovea in deg/cycle
me = eccentricity in degrees
\omega = slope
\omega_0 = smallest resolvable angle at fovea in deg/cycle
Foveated Rendering

• Guenter et al. 2016: split image into $n$ layers, e.g. inner (foveal, 1), middle (2), outer (3)
• render image in each zone with progressively lower resolution
• goal: save computation!
Foveated Rendering

- Guenter et al. 2016: split image into \( n \) layers, e.g. inner (foveal, 1), middle (2), outer (3)

\[
e_i = \frac{i}{n} \cdot \frac{\text{fov}}{2}
\]

\[
e_1 = \frac{\text{fov}}{6}
\]

\[
e_2 = \frac{\text{fov}}{3}
\]

\[
e_3 = \frac{\text{fov}}{2}
\]
Foveated Rendering

$\omega_1$ is best the display can do!

unit of $\omega_1$: $\frac{\text{degrees}}{\text{cycle}} = \frac{\text{degrees}}{2 \cdot \text{pixel}_{\text{size}}}$
Foveated Rendering

ω₁ is best the display can do!

unit of \( \omega_1 \): \[
\frac{\text{degrees}}{\text{cycle}} = \frac{\text{degrees}}{2 \cdot \text{pixel}_\text{size}}
\]

\[
\omega_1 = 2 \tan^{-1}\left(\frac{\text{screen}_\text{size}}{\text{screen}_\text{resolution} \cdot \text{viewer}_\text{distance}}\right) \cdot \frac{360}{2\pi}
\]
Foveated Rendering

\[ \omega_1 = 2 \tan^{-1} \left( \frac{\text{screen}_\text{size}}{\text{screen}_\text{resolution} \cdot \text{viewer}_\text{distance}} \right) \cdot \frac{360}{2\pi} \]

\[ \omega_2 = m\omega_2 + \omega_0 \]

\[ \omega_3 = m\omega_3 + \omega_0 \]
Foveated Rendering

- convert MAR (in degrees/cycle) to pixels

\[ \text{blur\_radius\_in\_px} = \text{viewer\_distance} \cdot \tan\left( \frac{\omega}{2} \cdot \frac{2\pi}{360} \right) \]
Foveated Rendering – Performance Gain

\[ m = 0.028 \]

\[ m = 0.022 \]

\( n \) is number of layers

\( speedup \) is total number of display pixels / number of pixels in all layers combined

**Conclusion:** For large fov & high-res displays, we need to shade much fewer pixels!
Depth Perception
Vergence & Accommodation

Stereopsis (Binocular)

Focus Cues (Monocular)

Oculomotor Cue

extraocular muscles

Vergence

relaxed

contracted

Visual Cue

Binocular Disparity

Retinal Blur
Vergence & Accommodation

Stereopsis (Binocular)

Focus Cues (Monocular)

Oculomotor Cue

Vergence

extraocular muscles

relaxed

contracted

Accommodation

Visual Cue

Binocular Disparity

Retinal Blur
Vergence & Accommodation

Stereopsis (Binocular)

Focus Cues (Monocular)

Oculomotor Cue

Vergence

extraocular muscles

ciliary muscles

relaxed contracted

Visual Cue

Binocular Disparity

Retinal Blur
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
Depth Perception

Cutting & Vishton, 1995
Stereoscopic Displays


Stereoscopic Displays
Stereoscopic Displays

176 years later

Charles Wheatstone 1838

stereoscopic displays
A Brief History of Virtual Reality

1838
- Stereoscopes
  - Wheatstone, Brewster, …

1968
- VR, AR,
  - Ivan Sutherland

2012-2015
- VR explosion
  - Oculus, Sony, Valve, MS, …

Next-generation VR Displays
Focus Cues
Oculumotor Processes

16 years: ~8cm to ∞
50 years: ~50cm to ∞ (mostly irrelevant)
Focus Cues Degrade With Age - Presbyopia

Nearest focus distance

0D (∞cm)
4D (25cm)
8D (12.5cm)
12D (8cm)
16D (6cm)

Age (years)

Duane, 1912

Bifocals
Blur Affects Relative Object Size!

Held et al., 2006, ACM SIGGRAPH
Accommodation and Retinal Blur

Conventional Display

0.25m (4D)  0.3m (3.33D)  0.35m (2.86D)  0.5m (2D)  0.7m (1.43D)  1 m  2m (0.5D)  ∞ (0D)
Accommodation and Retinal Blur

Conventional Display

- 0.25m (4D)
- 0.3m (3.33D)
- 0.35m (2.86D)
- 0.5m (2D)
- 0.7m (1.43D)
- 1 m
- 2m (0.5D)
- ∞ (0D)

virtual image of screen
Accommodation and Retinal Blur

Conventional Display

- 0.25m (4D)
- 0.3m (3.33D)
- 0.35m (2.86D)
- 0.5m (2D)
- 0.7m (1.43D)
- 1m
- 2m (0.5D)
- ∞ (0D)
Accommodation and Retinal Blur

Conventional Display

virtual image of screen

- 0.25m (4D)
- 0.3m (3.33D)
- 0.35m (2.86D)
- 0.5m (2D)
- 0.7m (1.43D)
- 1m
- 2m (0.5D)
- ∞ (0D)
Accommodation and Retinal Blur

Conventional Display

![Illustration of virtual image of screen with distances marked: 0.25m (4D), 0.3m (3.33D), 0.35m (2.86D), 0.5m (2D), 0.7m (1.43D), 1m, 2m (0.5D), ∞ (0D).]
Accommodation and Retinal Blur

Conventional Display
Accommodation and Retinal Blur

Conventional Display

Accommodation-dependent Point Spread Functions

![An image showing accommodation and retinal blur with a virtual image of screen.]
Real World:

Vergence & Accommodation Match!
Stereo Displays Today:

Vergence-Accommodation **Mismatch!**
Vergence-Accommodation Conflict

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

Marty Banks, UC Berkeley
Zone of Comfort

Shibata et al., 2011, Journal of Vision
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
References and Further Reading

interesting textbooks on perception:

foveated rendering:

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, visual acuity, visual field
- Snellen chart: https://en.wikipedia.org/wiki/Snellen_chart
- Ruch and Fulton, Medical physiology and biophysics, 1960

contrast sensitivity function & hybrid images: