The Physiology of the Human Visual System

Lecture #19
November 10, 2020
Prof. Donald P. Greenberg
The goal of tone reproduction operators

Light as Rays

The concept of the picture plane may be better understood by looking through a window or other transparent plane, from a fixed viewpoint. Your lines of sight, the multitude of straight lines leading from your eye to the objects, will all intersect this plane. Therefore, if you were to sketch out with a great pencil and draw the image of the subject on this plane, you would be "taping out" the infinite number of points of generation of sight rays and planes. The result would be that you would have "reconstructed" a three-dimensional object in a two-dimensional plane.
Light as Waves
Light as Photons
Use of all Three Descriptions of Light

• We use rays to determine which cones are stimulated.
• We use wave lengths to specify which Rodopsins are chemically effected (Color SML)
• The number of photons received define the intensity of the particular cone.
Fundamentals of Human Perception

• Retina, Rods & Cones, Physiology
• Receptive Fields
• Visual Acuity of Resolution
• Field of View
• Depth Perception
• Saccades and Eye-Tracking
Cross Section of Eye & Retina
Photoreceptors

- 120 million rods
- 7-8 million cones in each eye

Light goes in this direction

Receptor Distribution
Cone Receptor Distribution of the Human Eye

Model of cone receptor distribution of the human eye

by Michael Deering
Field of View of the Human Eye

The visual system includes the retinas, the visual pathway connecting the retinas to the brain, and the visual cortex. The two eyes’ fields of view overlap (top).

Drawings of Santiago Ramon y Cajal
Rods and Cones and Neural Connections
Rods and Cones and Neural Connections

Image from “Eye, Brain, and Vision,” David Hubel, 1988
Rods and Cones and Neural Connections

Abstraction

Neurons in the Retina

Helga Kolb 2003


American Scientist, Volume 91
Mapping the Human Retina

Austin Roorda

A- areas where cones were selected.
B- green circles indicate stimulation sites.
C- enlarged field of cones from B.
D- same region with vascular structures
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Receptive Fields

Individual cone signals can either add together or be subtracted from one another.

The ability to resolve fine details depends ultimately on both the spatial mosaic of the receptors and how they interconnect.
Receptive Fields

http://droualb.faculty.mjc.edu/CourseMaterials/Physiology%20101/Chapter%20Notes/Fall%202007/figure_10_39_labeled.jpg
Receptive Fields

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Measures of Acuity

<table>
<thead>
<tr>
<th>Detection</th>
<th>Resolution</th>
<th>Localization</th>
</tr>
</thead>
<tbody>
<tr>
<td>min. detectable 0.5&quot;</td>
<td>min. resolvable 30&quot;</td>
<td>vernier 5-7&quot;</td>
</tr>
<tr>
<td>Snellen letters 30&quot;</td>
<td></td>
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Visual Acuity

- Visual acuity is defined as “1/a where a is the response in arc-minutes”.
- This acuity is usually measured by a grating test pattern and thus is defined using a line pair.
- It takes two pixels to generate a line pair (black and white).
- Based on a large number of tests, the resolution of the human eye is approximately 0.3 arc minutes.
How many megapixels are necessary to match the resolution of the human eye?
• What is the distance from the surface of the eye to the screen in VR?

• How many pixels per inch are necessary at roughly 1.25 inches?
Visual Acuity Example

Assume 120 degree x 90 degree field of view

$$120 \times 90 \times 60 \times 60 / 0.3 \times 0.3 = 432 \text{ megapixels}$$
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Field of view of the Human Eye

Horizontal - 180°-190°
Vertical - 135°
Field of View for Humans

• Humans have an almost 180 degree frontal horizontal field of view

• The vertical range of the visual field is approximately 135 degrees

• The resolution, color discrimination, and reaction times is not uniform across the field of view
Field of View of the Human Eye
Field of View of the Human Eye

The visual system includes the retinas, the visual pathway connecting the retinas to the brain, and the visual cortex. The two eyes’ fields of view overlap (top).

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Monocular Vision

- Sixty to seventy degrees have no binocular vision (because only one eye can see those portions of the visual field)
Human Depth Perception

Depth Perception

Oculomotor
- Binocular
- Monocular
  - Convergence
  - Accommodation

Visual
- Binocular
  - Stereopsis
  - Static Cues
- Monocular
  - Motion Parallax

Static Cues
- Perspective
- Familiarity, Relative Size
- Motion, Position
- Occlusion
- Texture Gradient
- Shading, Shadows, Highlights
- Atmospheric Blur
Monoscopic Depth Cues

- Perspective
- Depth from Motion, Relative Size, Position, Familiarity
- Occlusion
- Texture Gradient
- Parallax from Motion
- Shadows and Specular Highlights
- Atmospheric Blur
- Accommodation

Note change in lens shape
Accommodation

The reflex can be controlled but cannot be ‘felt’
Accommodation amplitude declines with age
Vergence

• The simultaneous movement of the pupils of the eyes toward or away from one another during focusing.

• This measure of the convergence or divergence of a pair of light rays is defined as vergence.
Vergence Accommodation Conflict

• Computer and projection displays present images on a single surface but have a focal distance (blur on the retina) which may be in front of or behind the screen

• The inability to fuse the binocular stimuli causes discomfort and fatigue to the viewer

Diagram of Vergence
Binocular Vision

• Sixty to seventy degrees have no binocular vision (because only one eye can see those portions of the visual field)

• Binocular Vision, which is the basis for stereopsis is important for depth perception and covers 114 degrees (horizontally) of the human visual field.
Ocular Motor Systems (OMS)

• With normal visual perception, the ocular motor systems control the movement of the eyes to focus on the object of interest (voluntarily controlled)

• The OMS produces adjustments in pupil size, lens refraction, and accommodation.

• Accommodation involves the convergence of the two eyes to direct their images on to the fovea.

Ocular Motor Control
Dragoi, UTexas Med School
Ciliary Muscles
Ciliary Muscles

The eye accommodates for close vision by tightening the ciliary muscles, allowing the pliable crystalline lens to become more rounded.
Ciliary Muscles
Fovea
Saccadic Motion

The eye jumps, comes to rest momentarily (producing a small dot on the record), then jumps to a new locus of interest.

Extraocular Muscles

FIGURE 6.13
The extraocular muscles. Six muscles working in three pairs allow each eye to rotate in its socket about the three possible axes (based on Walls, 1963).

Saccade Control

• Saccade control is the ability of the eye(s) to move quickly from one fixation point to another (100-300 ms)

• To obtain a complete picture, normal adults perform 3-5 saccades (“snapshots”) per second

• Fixation “restops” are ≈ 50-100 ms
Saccades

Peak Angular Velocity

Wikipedia
Saccadic Masking

- There are two major types of saccadic masking or suppression
- **Flash suppression** is the inability of the eye to see a flash of light during a saccade
- **Suppression of image displacement** is characterized by the inability to perceive whether a target has moved during a saccade.
A.L. Yarbus 1914-1986
Yarbus Experimental Apparatus  

1950-60’s
Eye Tracking

Side view of the human eye
Purkinje Reflections
Purkinje Reflections
Eye Tracking

1\textsuperscript{st} and 4\textsuperscript{th} Purkinje Reflections
The Unexpected Visitor

Ilya Repin, 1888
The Unexpected Visitor

Ilya Repin, 1888
Foveal Eye Tracking
End
The Optomotor Cycle
Yarbus Experimental Apparatus 1950-60’s
The Unexpected Visitor

Ilya Repin, 1888
Time Response of Rods

500 ms
Time Response of Cones

500 ms
Dress in shadow. The same picture of the dress as in Figure 1 cut out and pasted into in the shadow where it appears gold and white to most observers. Figure 10 shows a context in which the dress appears blue and black to most observers. To see the differences in color perception between Figure 2 and Figure 10 more clearly, they are shown at separate locations in the text. Ideally, it is best not to have previously seen the other photos. Photograph of the dress used with permission. Copyright Cecilia Bleasdale.
Dress in the sun. The same picture of the dress as in Figure 1 and Figure 2 cut out and pasted in the sun where it appears black and blue (note that it is better not to have previously seen Figure 1 and Figure 2 to see this). Showing observers one or the other disambiguated photo in Figure 2 and this figure prior to seeing the original photo in Figure 1 determines how observers see the colors of the dress in the original photo of Figure 1 (see text for detailed results). Photograph of the dress used with permission. Copyright Cecilia Bleasdale.
White/Gold Dress
White/Gold Dress
White/Gold Dress
Nvidia DGX

2018

4X Tesla V100
500 TFLOPS
20,480 CUDA Cores
256 GB memory
Fundamentals of Human Perception

- Retina, Rods & Cones, Physiology
- Receptive Fields
- Field of View
- Visual Acuity of Resolution
- Opponent Color Theory
- Compression
- Bandwidth Limitations
- Saccades
# Opponent Color Theory

<table>
<thead>
<tr>
<th>Channel</th>
<th>Combination</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>black - white</td>
<td>M + L</td>
<td>very high</td>
</tr>
<tr>
<td>Green - red</td>
<td>M – L</td>
<td>High</td>
</tr>
<tr>
<td>yellow - blue</td>
<td>M + L – S</td>
<td>low</td>
</tr>
</tbody>
</table>
There are three types of color receptive fields called *opponent channels*.

- **Black — White (luminance) channel**: \( M + L \)
- **Green — Red channel**: \( M - L \)
- **Yellow — Blue channel**: \( M + L - S \)
Cones interconnect in the retina, eventually leading to opponent-type signals.

Figure 12.9– Foundations of Sensation and Perception, George Mather
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Visual Memory and History
Yarbus Heat Maps

1965
The Unexpected Visitor

Ilya Repin, 1888
Foveal Eye Tracking
Foveal Eye Tracking
Foveal Eye Tracking

Length of absence
Saccades Motion (length of absence)
Caravaggio
Picture exploration
Card sharps
Sensing Methods: Retinal Tracking

- Hard problem with current technologies
  - Extremely difficult to illuminate
    - Must bounce light off of retina
    - Light comes back through iris
  - Light must be extremely bright
  - Too much exposure will damage retina
- Typically done in ophthalmological setting
- Presently can only detect faint images of blood vessels, companies working on it
- Very high angular resolution, but would presently require occlusion of vision
Saccadic Masking

• Visual saccadic suppression
• The brain selectively blocks visual processing during eye movements
• Neither the motion of the eye or subsequent motion blur of the image nor the time gap in visual perception is noticeable to the viewer
Picket Fence
The Nyquist sampling rate states that an object must be sampled at twice its frequency to be able to reconstruct its characteristics.
Stereoscopic Vision: At The Screen

Apparent Image Depth

Screen / Image Plane

L
R
L
R
Stereoscopic Vision: In Front Of The Screen (Convex)
Stereoscopic Vision: Behind The Screen (Concave)
Saccadic Motion

Saccadic Motion

From Real World to Display

Light as Rays, Waves and Photons
Vergence – Accommodation Conflict
Vergence – Accommodation Conflict

(a)

Real point
Left eye
Right eye

(b)

Right image
Visual point
Left image
Left cyc
Right cyc