Physiological Optics and the Photoreceptor Mosaic

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NEUR 0017
Visual Neuroscience
Outline

- The eye
- Visual optics
- Image quality
- Measuring image quality
- What limits visual performance?
- Refractive errors
- Sampling
- Why visual acuity should be limited by the optics and sampling
- Adaptive optics
- Chromatic aberrations
The retina is carpeted with light-sensitive rods and cones.

An inverted image is formed on the retina by the cornea and lens.
Cornea – Clear membrane on the front of the eye.
Crystalline Lens – Lens that can change shape to alter focus.
Retina – Photosensitive inner lining of eye
Fovea – central region of retina with sharpest vision.
Optic Nerve – bundle of nerve fibers that carry information to the brain.

Jim Schwiegerling
Eye Dissection and Part of the Eye
Visual optics
Retinal cross-section

Sclera
Choroid
Pigmented epithelium
Photoreceptor layer
Bipolar layer
Ganglion layer

LIGHT

Retina 200 ×
Accommodation to Target Distance

Distant target, relaxed ciliary muscles

Near target, accommodated eye, constricted ciliary muscles.
Accommodation

Relaxed ciliary muscle pulls zonules taut and flattens crystalline lens.

Constricted ciliary muscle releases tension on zonules and crystalline lens bulges.

Jim Schwiegerling
Presbyopia (age related far-sightedness)

Images are formed directly on the retina creating good close up vision.

The lens ages and stiffens. Images are formed behind the retina causing blurry close up vision.
PSFs for different refractive errors

(a) Emmetropic eye

(b) Myopic eye
Nearsighted

(c) Hyperopic eye
Farsighted

From Webvision, Michael Kalloniatis
Corrective lenses

Myopia

Hyperopia
Focal plane

Light

Lens

Focal plane

Emmetropia (normal)
Myopia (nearsightedness)
Hyperopia (farsightedness)
Presbyopia (aged)
Retinal Sampling and Resolution
The Point Spread Function (PSF) characterizes the optical performance of the eye.
Point Spread Function Shape vs Resolution
Optical systems are rarely ideal.

Point spread function of Human Eyes

\[ \delta(x) \rightarrow \text{Optical System} \rightarrow \text{PSF}(x) \]

Input

PSF

Minutes of arc
Point spread function (PSF)

Point in visual space

From Webvision, Michael Kalloniatis
Measuring Image Quality Psychophysically

1. Visual acuity measures
   - Review methods for measurement in the clinic/trial setting
   - What do these measures represent

2. Spatial contrast sensitivity measures
   - Review methods for measurement in the clinic/trial setting
   - How does this represent our vision
Smallest resolvable black and white target. Many different types of tests are available, but the letter chart introduced by Snellen in 1862 is the most common.
Snellen defined “standard vision” as the ability to recognize one of his optotypes when it subtended 5 minutes of arc. Thus, the optotype can only be recognized if the person viewing it can discriminate a spatial pattern separated by a visual angle of 1 minute of arc.

A Snellen chart is placed at a standard distance, twenty feet in the US (6 metres in Europe). At this distance, the symbols on the line representing "normal" acuity subtend an angle of five minutes of arc, and the thickness of the lines and of the spaces between the lines subtends one minute of arc. This line, designated 20/20, is the smallest line that a person with normal acuity can read at a distance of twenty feet.

The letters on the 20/40 line are twice as large. A person with normal acuity could be expected to read these letters at a distance of forty feet. This line is designated by the ratio 20/40. If this is the smallest line a person can read, the person's acuity is "20/40."
Visual Acuity: four standard methods

- **Letter acuity (Snellen)**: Can the subject correctly identify the letter or the letter orientation?
- **Grating acuity**: Orientation resolution acuity
  - vs.
- **2-line resolution**: Can the subject see two lines or points rather than one?
- **2-point resolution**: Detection acuity

Borrowed from Arthur Bradley
MAR = Minimum Angle of Resolution

MAR is the smallest gap between letter strokes or grating bars that can be detected/resolved.

6/6 (20/20) letter: bar/stroke width = 1 arc minute, letter height = 5 min
Grating period = 2 arc minute (1/30 degree) when bar = 1 min, and grating SF = 1/period = 30 c/deg,
Comparison of seven different visual acuity measures

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<tr>
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<td>10</td>
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<td>0.1</td>
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Arthur Bradley
Vision is not always 6/6!
1. Visual acuity measures
   - Review methods for measurement in the clinic/trial setting
   - What do these measures represent
2. Spatial contrast sensitivity measures
   - Review methods for measurement in the clinic/trial setting
   - How does this represent our vision
What would the results for a perfect lens look like?
Spatial Frequency Gratings

Increasing spatial frequency

Increasing contrast
Spatial MTF

Spatial frequency in this image increases in the horizontal direction and modulation depth decreases in the vertical direction.
The apparent border between visible and invisible modulation corresponds to your own visual modulation transfer function.
2. Grating Contrast Sensitivity

Contrast Sensitivity Function (CSF)

“Bandpass”

Peak CS

Peak SF

High SF cut-off

Contrast Sensitivity (1/contrast threshold)

Spatial Frequency (c/deg)

low medium high

Arthur Bradley
Example of grating contrast sensitivity test using printed gratings

Increasing contrast sensitivity

Increasing spatial frequency

Increasing contrast

Arthur Bradley
Spatial CSFs

Fig. 8.4. Spatial contrast sensitivity curves at seven different retinal illuminance levels between 0.0009 and 900 trolands. The subject viewed the gratings through a 2 mm diameter artificial pupil. The wavelength of the light was 525 nm. Notice the loss of sensitivity for medium and high frequencies as the retinal illumination is decreased. (Adapted from Van Nes & Bouman, 1967.)
Contrast sensitivity varies!

Light Level
- Scotopic
- Mesopic
- Photopic

Eccentricity
- Foveal
- 4deg
- 30deg

20/200 20/15

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What limits visual performance?
Imaging Resolution

- Poor Optical Resolution
- Poor Sensor Resolution
- Good Optical and Sensor Resolution
Stages

Optical Image on Retina → Neural Retina → Cortex → Perception
Optical Image on Retina

Consider optical limits first
For a diffraction-limited image an Airy disk pattern is formed on the retina from a point source due to the diffraction at the pupil.
How does this affect spatial resolution?

Airy disc (PSF)

Perception

2D profile

From Webvision, Michael Kalloniatis
Overlapping point spread functions (PSF)

Two points in visual space

From Webvision, Michael Kalloniatis
The Rayleigh criterion for resolving two point sources of equal brightness is when the peak of one diffraction pattern lies upon the first minimum of the other. This yields a theoretical maximum angular resolution referred to as *diffraction-limited resolution* given by:

$$\Delta \theta = 1.22 \frac{\lambda}{D}$$

where $\Delta \theta$ is in radians, $D$ is the diameter of the aperture (i.e. the pupil in this case) in the same units as the wavelength $\lambda$ of the light.
So, for a 550 nm light and a 3 mm diameter pupil, \( \Delta \theta = 0.77 \text{ min of arc} \).
The two lines (a) can be perceptually resolved, but the two lines (b) cannot and are perceived as a single line.

From Webvision, Michael Kalloniatis
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Arthur Bradley
Effect of Aperture: Pupil size

The size of the pupil is an important factor affecting visual acuity.

A large pupil allows more light to reach the retina and reduces diffraction but resolution is reduced because the optical aberrations are greater (a greater area of the lens and cornea are used and they are imperfect).

A small pupil reduces optical aberrations but resolution is then diffraction limited.

A mid-size pupil of about 3 mm to 5 mm represents a compromise between the diffraction and aberration limits.
Aberrations of the Eye

Perfect optics

Imperfect optics

Larry Thibos
Removing Atmospheric Blur....
Adaptive Optical Systems
The Human Eye is Highly Aberrated

Wave Aberration (High order)

Perfect eye (diffraction-limited)

MRB

GYY

MAK

5.7-mm pupil

Courtesy: Jason Porter
The Human Eye is Highly Aberrated

Ideal, Diffraction-Limited Eye

Normal, Aberrated Eye

\[
\frac{\partial W(x,y)}{\partial x} = \frac{\Delta d_x}{f}
\]
Principle of Adaptive Optics Retinal Imaging

Principle of Adaptive Optics Retinal Imaging

Supernormal vision and high-resolution retinal imaging through adaptive optics

Junzhong Liang, David R. Williams, and Donald T. Miller

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Adaptive optics scanning laser ophthalmoscopy

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Melanie C.W. Campbell
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The relationship between visual resolution and cone spacing in the human fovea

Ethan A Rossi¹ & Austin Roorda¹,²

Visual resolution decreases rapidly outside of the foveal center. The anatomical and physiological basis for this reduction is unclear. We used simultaneous adaptive optics imaging and psychophysical testing to measure cone spacing and resolution across the fovea, and found that resolution was limited by cone spacing only at the foveal center. Immediately outside of the center, resolution was worse than cone spacing predicted and better matched the sampling limit of midget retinal ganglion cells.
Cone Inputs and Visual Sensation
Cone Stimulation Map
Chromatic aberrations
Chromatic aberration

Base picture: Digital camera world
Effect of chromatic blur on eye chart
Ray Tracing: Light to Image
Ray Tracing: Light to Image

Ophthalmoscope  Eye
Ray Tracing: Light to Image

Ophthalmoscope

Eye
Ray Tracing: Light to Image

Ophthalmoscope

Eye

Sensor/Camera
Ray Tracing: Light to Image
Changes with eccentricity
**Human photoreceptors**

- **Rods**
  - Achromatic night vision
  - 1 type

- **Cones**
  - Daytime, achromatic and chromatic vision
  - 3 types
    - Long-wavelength-sensitive (L) or “red” cone
    - Middle-wavelength-sensitive (M) or “green” cone
    - Short-wavelength-sensitive (S) or “blue” cone
0.3 mm of eccentricity is about 1 deg of visual angle.
Cone distribution and photoreceptor mosaics

after Østerberg, 1935; as modified by Rodieck 1988; micrographs from Curcio et al., 1990
The human visual system is a foveating system

Simulation of what we see when we fixate with cone vision.
Visual acuity gets much poorer with eccentricity.
Conclusions

• Light can function as both a particle and a wave, these are important properties to understand how light interacts with the environment to permit vision

• Light passes through the cornea, where refractive index changes cause aberrated focusing

• Fixation is dependent on a cone rich foveal region that provides high acuity and colour vision, outside this region is rod rich, very light sensitive but lacks acuity or colour discrimination
Interested in learning more?

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