**Retinal Photoreceptors**

**Rods** -
- Low illumination levels (Scotopic vision).
- Highly sensitive (respond to a single photon).
- 100 million rods in each eye.
- No rods in fovea.

**Cones** -
- High illumination levels (Photopic vision).
- Less sensitive than rods.
- 5 million cones in each eye.
- Only cones in fovea (approx. 50,000).
- Density decreases with distance from fovea.

**Calculating the viewing angle of a single cone in the fovea:**

\[
\tan(\theta) = \frac{2.5 \times 10^{-6}}{1.7 \times 10^{-6}} = 1.47 \times 10^4
\]

\[
\theta = 0.0084 \text{ deg} \approx 0.5' \text{ (arcmin)}
\]

**Cones** -
- 2.3 µ - width
- 2.5 µ - inter-cone distance
- 0.5' - field of view
Cone Mosaic

- Cone Mosaic at Fovea
- Cone Mosaic in periphery

Retinal Photoreceptors

**Cones** -
- High illumination levels (Photopic vision)
- Less sensitive than rods.
- 5 million cones in each eye.
- Only cones in fovea (approx. 50,000).
- Density decreases with distance from fovea.
- 3 cone types differing in their spectral sensitivity: L, M, and S cones.

Cone Spectral Sensitivity

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Relative sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>0</td>
</tr>
<tr>
<td>500</td>
<td>0.25</td>
</tr>
<tr>
<td>600</td>
<td>0.5</td>
</tr>
<tr>
<td>700</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Cone Receptor Mosaic

- S cone Sampling Mosaic

L-cones  M-cones  S-cones

S cone Sampling Mosaic

Foveal Periphery

- rods
- S - Cones
- L/M - Cones
What is the quality of the optics of the human eye?

Put a piece of film in front of an object.

Add a barrier to block off most of the rays.
- It reduces blurring
- The pinhole is known as the aperture
- The image is inverted

Why not create the aperture as small as possible?
- Less light gets through
- Diffraction effect

source: Yung-Yu Chuang

source: Yung-Yu Chuang
**Lensmaker's Equation**

\[ \frac{1}{d_s} + \frac{1}{d_i} = \frac{1}{f} \]

- \(d_s\) = source dist
- \(d_i\) = image dist
- \(f\) = focal length

**Optical power and object distance**

Source at infinity → Focal length

Lens power (diopters) = \( \frac{1}{\text{Focal length (m)}} \)

**Encoding Characteristics - Line spread**

Line spread defines the optical quality of the eye

**Light Scattered From The Retina**

Is Used To Estimate Optical Quality

(e.g., Campbell and Gubisch)

**Double Pass Method**
Image formation is a linear system

A system is linear if it satisfies superposition:

- **Homogeneity**: \( f(ka) = kf(a) = kb \)
- **Additivity**: \( f(a_1 + a_2) = f(a_1) + f(a_2) = b_1 + b_2 \)

A finite dimensional linear system can be written as a matrix equation:

\[
\begin{align*}
\mathbf{b} &= \mathbf{R}\mathbf{a} \\
\end{align*}
\]

where \( \mathbf{R} \) is the system matrix.

**Image Formation is a Linear System**

\[
\begin{align*}
in & \quad \text{System} \quad \text{out} \\
a & \quad f(a) = b \\
\end{align*}
\]

**Image formation is a Shift Invariant linear system**

A shifted input produces a shifted output:
Scene:

Retinal Image:

Modeling Image Formation (Westheimer)

The Human Linespread Function

The Human Modulation Transfer Function

The Pointspread Function

The pointspread function is a generalization of the linespread function.

Astigmatism Measures the Asymmetry and Orientation of the Pointspread Function
Visual Acuity

Cones at fovea are 2.5µ apart corresponding to 0.5’ (arc min).

Typical acuity targets:

- Vernier Acuity
- Landolt C
- Resolution acuity
- Grating acuity
- Snellen Letter

Expected acuity is size of cone or visual angle of cone.

Actual acuity ≈ 5’’ (arc seconds) = Hyperacuity

Visual Acuity

Do to linespread, movement of stimulus by less than receptor width causes change in receptor response:

Acuity is affected by retinal position and illumination:

Visual Acuity Test

K B X M P A S
+ + + + + + +
50 40 30 20 10 5 0

Electromagnetic Radiation - Spectrum

Gamma X rays Ultra-violet Infrared Radar FM TV wave AM electricity

Visible light

Wavelength in nanometers (1nm=10⁻⁹ m)

400 nm 500 nm 600 nm 700 nm

Wavelength in meters (m)
**Spectral Power Distribution**

The **Spectral Power Distribution** (SPD) of a light is a function $f(\lambda)$ which defines the energy at each wavelength.

![Graph of Spectral Power Distribution](image)

**Examples of Spectral Power Distributions**

- **Blue Skylight**
- **Tungsten bulb**
- **Red monitor phosphor**
- **Monochromatic light**

**Multispectral Images**

![Multispectral Images](image)

**Chromatic Aberration**

Different wavelengths bending at lens, focus at different distances.

![Graph of Chromatic Aberration](image)
Chromatic Aberration

Chromatic Aberration Measures Differences in Optical Focus Across Wavelength

Chromatic Aberration affects the MTF

Blue vs Green Modulation Transfer Function

Sampling rate of Blue vs Green is in accord with Nyquist Theorem
Chromatic Linespread Function

Some Animals Have Non-Circular Pupils

Cat Eye