### Visual Performance

<table>
<thead>
<tr>
<th>Aspects</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution Limit</td>
<td>Illumination</td>
</tr>
<tr>
<td>Pattern Detection</td>
<td>Monocular vs. Binocular</td>
</tr>
<tr>
<td>Pattern Recognition</td>
<td>Distance</td>
</tr>
<tr>
<td>Contrast Level</td>
<td>On-axis vs. Off-axis</td>
</tr>
<tr>
<td>Color</td>
<td>Single or multiple targets</td>
</tr>
<tr>
<td>Temporal Response</td>
<td>Literacy &amp; Verbal ability</td>
</tr>
</tbody>
</table>

#### Theoretical Limit of Resolution

\[
\theta = \frac{1.22\lambda}{D} \text{ radians}
\]

For \( \lambda = 587.6 \text{ nm} \)

- \( D \) ranges from 2 – 8 mm
- \( 0.090 \leq \theta \leq 0.358 \text{ mrad} \)
- \( 0.3 \leq \theta \leq 1.23 \text{ minutes of arc} \)
Rayleigh Criteria

![Graph showing Rayleigh Criteria][1]

1.6 mm Pupil
Contrast 14%

Visual Acuity

Visual Acuity is a measure of the smallest detail that can be resolved by the visual system. There are different types of acuity measures.

Point Acuity – “Binary Star” test – typically 1 arcmin resolution

Vernier Acuity – Two lines slightly offset from each other. Finds smallest detectable offset – typically 10 seconds of arc

[1]: https://example.com/rayleigh_criteria_graph.png
Visual Acuity

**Grating Acuity** – Sinusoidal or Square wave gratings are used to determine the smallest separation between peaks that can be resolved. Typically 2 arcmin.

![Grating Acuity Image]

**Letter Acuity** – Different Letters or Symbols need to be recognized. Typically 5 arcmin.

![Letter Acuity Image]
Visual Acuity & Pupil Size

Visual Acuity Charts are designed so the 20/20 line subtends 5 arcmin. 20/40 subtends 10 arcmin. 20/10 subtends 2.5 arcmin.
Stereo Acuity

Given one object slightly closer than the other, find the smallest separation that is resolvable.
Typically - 5 seconds of arc

Modulation Transfer Function (MTF)

The MTF measures the loss in contrast in the image of a sinusoidal target. It is the ratio of the object contrast and the image contrast.

\[ MTF = \frac{0.55}{1.00} = 0.55 \]
Contrast

Contrast Sensitivity CS is the reciprocal of the minimum value of C that is detectable.

\[ CS = \frac{1}{C_{\text{min}}} \]

Contrast C = \( \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \)
Spatial Frequency

7.5 cycles

Spatial frequency is the number of cycles (1 black bar plus 1 white bar equals 1 cycle) subtending 1 degree.

Arden Grating
Spatial Frequency

20/20 Letter

\[
\begin{align*}
\text{E} & \quad 5 \text{ arcmin} \\
\quad \text{or} & \quad 25 \mu m
\end{align*}
\]

\[
\frac{1 \text{ cycle}}{10 \mu m} \left( \frac{1000 \mu m}{1 \text{ mm}} \right) = 100 \frac{\text{cycles}}{\text{mm}} \text{ (on retina)}
\]

\[
\frac{1 \text{ cycle}}{2 \text{ arcmin}} \left( \frac{60 \text{ arcmin}}{1 \text{ deg}} \right) = 30 \frac{\text{cycles}}{\text{deg}}
\]

Aberrations & Contrast Sensitivity

\[
\begin{array}{cccccc}
m=98\% & m=85\% & m=70\% & m=55\% & m=40\% \\
\includegraphics[width=0.2\textwidth]{image1} & \includegraphics[width=0.2\textwidth]{image2} & \includegraphics[width=0.2\textwidth]{image3} & \includegraphics[width=0.2\textwidth]{image4} & \includegraphics[width=0.2\textwidth]{image5} \\
m=25\% & m=10\% \\
\includegraphics[width=0.2\textwidth]{image6} & \includegraphics[width=0.2\textwidth]{image7}
\end{array}
\]
Point Spread Function

The Point Spread Function (PSF) is the image of a point source of light formed on the retina. It has a finite size due to aberrations and diffraction.

Optical Transfer Function (OTF)

The OTF is a complex function that measures the loss in contrast in the image of a sinusoidal target, as well as any phase shifts. The MTF is the amplitude (i.e. $\text{MTF} = |\text{OTF}|$) and the Phase Transfer Function (PTF) is the phase portion of the OTF.
Fourier Theory

Object → Convolution → PSF → Image
Padding → FT
Object Spectrum → Multiplication → OTF → Image Spectrum

\[ |FT\{P(x,y)\exp(i2\pi(Wavefront\ Error))\}|^2 = PSF \]
\[ FT\{PSF\} = OTF \]

Effects of Refractive Surgery

No Surgery  -2.75 D PRK  -7.00 D PRK
Retinal Image Quality

- Ideally, if the optics of the eye are known, then we can determine the quality of the image falling onto the retina.
- Need to measure the aberrations of the eye.
- Would like to measure wavefront error directly, but this has only recently become feasible.
- Early researchers settled for MTF (no phase information).
- More recently, the PSF was measured directly.

Campbell & Green Experiment

- First, perform contrast sensitivity
- Second, perform contrast sensitivity when bypassing the optics of the eye.
Campbell and Green Experiment

MTF & Contrast Sensitivity

MTF = \frac{C_{\text{ret}}}{C_{\text{ext}}} \Rightarrow \frac{C_{\text{ret}}}{C_{\text{ret, min}}} = \frac{C_{\text{ext}}}{C_{\text{ext, min}}}

CS_{\text{ext}} = \frac{1}{C_{\text{ext, min}}}

Define CS_{\text{ret}} = \frac{1}{C_{\text{ret, min}}}

MTF = \frac{CS_{\text{ext}}}{CS_{\text{ret}}}

Contrast Sensitivity

Spatial Frequency (cyc/deg)
Campbell and Green Experiment

Improving Vision

$$\text{MTF} = \frac{\text{CS}_{\text{ext}}}{\text{CS}_{\text{ret}}}$$

$$\Delta \text{MTF} = [C_{\text{ret min}}] \Delta \text{CS}_{\text{ext}}$$

Changes to Optical System

Modulation Threshold
Under a given illumination, this is fixed by the retina & brain

Changes to Visual Performance
Van Nes & Bouman Experiment
- Measured Modulation Threshold for different illumination levels.

Higher contrast objects are needed for darker conditions
High spatial frequencies cannot be seen under dark conditions

Mitchell et al. Experiment
- Found modulation threshold is lowest for horizontal and vertical gratings and highest for gratings at ±45°

These gratings are easier to see…
than these gratings
Grating Acuity

Square Wave Gratings

\[ a_o + \frac{4a}{\pi} \left[ \sin x + \frac{1}{3} \sin 3x + \frac{1}{5} \sin 5x + \ldots \right] \]
If a square wave pattern is used for contrast sensitivity testing in place of a sine wave, the sensitivity is higher. For spatial frequencies higher than 1 cyc/deg, the fundamental frequency is detected. For lower spatial frequencies, the harmonics are seen.