Physiological optics and the photoreceptor mosaic

Andrew Stockman

NEUR 3045
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

An inverted image is formed on the retina

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
Visual optics

The retina is carpeted with light-sensitive rods and cones.

An inverted image is formed on the retina by the cornea and lens.

Jim Bowmaker dissecting an eye...

Cornea

Crystalline lens

Jim Schwiegerling

BBC Horizon: Light Fantastic (2006)
Accommodation to Target Distance

Distant target, relaxed ciliary muscles

Near target, accommodated eye, constricted ciliary muscles.

Relaxed ciliary muscle pulls zonules taut and flattens crystalline lens.

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

Image quality
Point spread function

Optical systems are rarely ideal.

scene → Optical System → image

Point spread function of Human Eyes

δ(x) → Optical System → PSF(x)

point source → point spread function

Input

PSF

The Point Spread Function (PSF) characterizes the optical performance of the eye.

Measuring image quality “psychophysically”

1. Visual acuity measures
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. Detection acuity

Can the subject see two lines or points rather than one?

**2-line resolution**

**2-point resolution**

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

<table>
<thead>
<tr>
<th>Snellen</th>
<th>Metric Snellen</th>
<th>MAR in arc minutes</th>
<th>Log MAR</th>
<th>Decimal</th>
<th>Grating VA c/deg</th>
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<tr>
<td>20/10</td>
<td>6/3</td>
<td>0.5</td>
<td>-0.3</td>
<td>2.0</td>
<td>60</td>
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<td>20/15</td>
<td>6/4.5</td>
<td>0.75</td>
<td>-1.2</td>
<td>1.33</td>
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<td>20/20</td>
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<td>1.5</td>
<td>0.18</td>
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<td>0.3</td>
<td>0.5</td>
<td>15</td>
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<td>0.4</td>
<td>0.4</td>
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<td>20/70</td>
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<td>20/200</td>
<td>6/60</td>
<td>10.0</td>
<td>1.0</td>
<td>0.1</td>
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</tbody>
</table>

Measuring image quality psychophysically

2. Spatial contrast sensitivity measures
Spatial frequency

Harmonics of a square wave

Harmonics of a square and triangle wave

Space  Spatial Frequency

All frequencies

One frequency
What would the results for a perfect lens look like?

Spatial MTF: Spatial frequency in this image increases in the horizontal direction and modulation depth decreases in the vertical direction.

Spatial MTF: The apparent border between visible and invisible modulation corresponds to your own visual modulation transfer function.
2. Grating Contrast Sensitivity

Contrast Sensitivity Function (CSF)

Contrast Sensitivity (1/contrast threshold)

“Bandpass”

Peak CS

Peak SF

High SF cut-off

Spatial Frequency (c/deg)

Contrast Sensitivity Function (CSF)

2. Grating Contrast Sensitivity

Contrast Sensitivity Function (CSF)

Contrast Sensitivity (1/contrast threshold)

“Bandpass”

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Peak SF

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Spatial Frequency (c/deg)

Contrast Sensitivity Function (CSF)

Example of grating contrast sensitivity test using printed gratings

Increasing contrast "sensitivity"

Increasing spatial frequency

Increasing contrast

Spatial CSFs

Spatial CSFs

Fig. 84: Spatial contrast sensitivity curves at seven different retinal illuminance levels between 0.0001 and 1000 Trolands. The subject viewed the gratings through a 2 mm diameter artificial pupil. The wavelength of the light was 555 nm. Notice the loss of sensitivity for medium and high frequencies as the retinal illumination is decreased. (Adapted from Van Nes & Booman, 1967.)

Spatial CSFs

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Vision is not always 20/20!
Contrast Sensitivity is not constant!

Light Level
Photopic
Mesopic
Scotopic

Eccentricity
4deg
30deg
Foveal

20/200 20/15

What limits visual performance?

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

Consider optical limits first
Numerical approximation of diffraction pattern from a slit of width four wavelengths with an incident plane wave. The main central beam, nulls, and phase reversals are apparent (Wikipedia).

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?

Two points in visual space
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:

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

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, $\Delta \theta = 0.77$ min of arc.

The two lines (a) can be perceptually resolved, but the two lines (b) cannot and are perceived as a single line.
Normal acuity is well matched to the diffraction limited resolution for a 550 nm light and a 3 mm diameter pupil of 0.77 min of arc.

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.

So far we have been talking about foveal vision at optimal light levels with optimal refraction...
Refraction errors

**Line spread function (LSF) of two lines with varying amounts of blur. With increasing blur, the discrimination of the two lines is lost.**

From Webvision, Michael Kalloniatis

**Corrective lenses**

From Webvision, Michael Kalloniatis

**PSFs for different refractive errors**

- **Emmetropic eye**
- **Myopic eye** Nearsighted
- **Hyperopic eye** Farsighted
Focal plane

Light

Lens

Emmetropia
(normal)

Myopia
(nearsightedness)

Hyperopia
(farsightedness)

Presbyopia
(aged)

What else limits visual performance?

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.

Stages

Optical Image on Retina

Neural Retina

Cortex

Perception
Optical Image on Retina ➔ Neural Retina ➔ Sampling

Retinal sampling

False color images showing the arrangement of L (red), M (green), and S (blue) cones in the retinas of different human subjects. All images are shown to the same scale.

Hofer et al., 2005
Impact of sampling on letter visual acuity: Notice that the foveal sampling is perfectly adequate to represent a 6/6 (20/20) letter, but inadequate to represent a 6/1.5 (20/5) letter.

Andrew Stockman

Human photoreceptors

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

- **Cones**
  - Daytime, achromatic and/or 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

Central fovea is rod-free, and the very central foveola is rod- and S-cone free

Central area of the fovea lacks S-cones and is therefore “tritanopic”.

Physiological optics
In other retinal regions, the S-cone mosaic remains sparse.

Curcio et al.

S-cones form between 5 and 10% of the cone population.

Small field tritanopia

Changes with eccentricity

Arthur Bradley
Human photoreceptors

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

- **Cones**
  - Daytime, achromatic and chromatic vision
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Rod and cone distribution

0.3 mm of eccentricity is about 1 deg of visual angle
The human visual system is a foveating system

Simulation of what we see when we fixate with cone vision.

Adaptive optics: viewing the retina through the eye’s optics

Visual acuity gets much poorer with eccentricity

False color images showing the arrangement of L (red), M (green), and S (blue) cones in the retinas of different human subjects. All images are shown to the same scale.

Hofer et al., 2005
False color images showing the arrangement of L (red), M (green), and S (blue) cones in the retinas of different human subjects. All images are shown to the same scale.

Hofer et al., 2005
Chromatic aberrations

The focusing power of the eye varies with wavelength.

This phenomenon is called longitudinal (or axial) chromatic aberration (LCA).

Photos courtesy of A. Roorda, D. Williams, U. Rochester

Larry Thibos
Chromatic aberration

The retinal location of the image varies with wavelength.

Larry Thibos

Chromatic aberration

The size of the retinal image may vary with wavelength.

This phenomenon is called chromatic difference of magnification (CDM)

Larry Thibos

Effect of chromatic blur on eye chart

Jim Schwiegerling

Physiological optics
Why visual acuity should be limited by the optics and sampling

**Under sampling and Aliases**

Repetitive Grating Stimulus

If there are less than 2 samples per period of a repetitive signal, it will be undersampled by the array, and the resulting output will be indistinguishable from a lower frequency signal.

For resolution: sample separation(s) must be \( \leq \) period/2.

For human fovea: cones separated by 1/2 arc minute, thus minimum resolvable period is 1 minute, or 60 c/deg. Above 60 c/deg, see aliases if these high frequencies existed in retinal image.

The eye’s optics filters out all SF above Nyquist limit in fovea, since foveal nyquist (60 c/deg) is slightly higher than optical cut-off (about 50 c/deg). This is not so in the peripheral retina where the optical cut-off is higher than the nyquist limit, thus aliases can be seen.
Human peripheral resolution acuity matches RGC sampling density predictions

Resolution Limit (c/deg)

SFmax = 1/2S

Impact of sampling on spatial resolution: Helmholtz

Two point Resolution:

Must have sample between images of two points in order to know that there is a gap between the stimuli and thus be able to identify two points as two.

Sampling and periodic patterns.

Shannon’s sampling theorem: basically same idea as Helmholtz (need one sample between each line)

Notice that, at limit of just one sample between each bright line of grating, there will be exactly 2 samples per period of the grating.

In order to resolve a periodic pattern there must be at least 2 samples per period. Therefore, if we know the spacing between samples, we know the maximum resolvable spatial frequency = f\text{max} = 1/(2s), where s = separation between samples.
What limits resolution acuity?

Two candidate mechanisms:
- filtering (optical or neural)
- undersampling

Filtering Limit to Visual Resolution
Original
Low-pass Filtered

Sampling Limit to Visual Resolution
Original
Undersampled
Foveal VA and CS are both limited by optical and neural factors

Optical Transfer Function

Window of visibility

Neural Threshold

Spatial frequency (cycles/deg)

Image Contrast

Optical Image on Retina

Neural Retina

Cortex

Perception

Continuous

Sampled

Sampled

Continuous

Neural sampling

2-dimensional undersampling misrepresents spatial frequency and orientation of patterns

Example with less than 2 samples per period

Psychophysical acuity data and perceived aliases from normal peripheral retina.