Optics and Image Quality in the Human Eye

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All slides (in color) are available on the web at:

• **vision.berkeley.edu/ roordalab/**

• *link to courses/resources on left menubar*
Part 1 The Optics of the Eye

*(NOTE: sections 1.1 and 1.2 will not be covered in the lecture. They are included for your reference)*
Refraction and Image Formation

\[ F = \frac{-n}{f} \quad F' = \frac{n'}{f'} \quad R = \frac{1}{r} \]
Refraction and Image Formation

\[
\frac{n'}{l'} = \frac{n}{l} + \frac{n' - n}{r}
\]
\[
L = \frac{n}{l}
\]
\[
L' = L + \frac{n' - n}{r}
\]
\[
L' = \frac{n'}{l'}
\]

define:

object vergence at surface

image vergence at surface
Refraction and Image Formation

special case 1: object at infinity => \( L = 0 \) & \( L' = F' \)

\[
F' = \frac{n' - n}{r}
\]
Refraction and Image Formation

special case 2: image at infinity => $L' = 0$ & $L=-F$

$$F = \frac{n' - n}{r} = F'$$

$$L' = L + F'$$
1.2 The reduced eye

To simplify image formation in the eye we use the reduced eye. The reduced eye has a single refracting surface.

\[ F' = \frac{n'}{f'} \quad : \quad f' = 22.22 \text{ mm} \]
1.2 The reduced eye

\[ L' = L + F \]

*By definition, in the human eye*

\[ K' = K + F_e \quad \Rightarrow \quad K = K' - F_e \]

*In the reduced eye, k (far point) and k’ are measured from the refracting surface.*
1.3 Components of the human optical system

Cornea (first surface)

transition from air (n = 1) to front surface of cornea (n = 1.376)

radius of curvature = 7.7 mm

power: \[ F' = \frac{n' - n}{r} \]

\[ = \frac{1.376 - 1}{0.0077} \]

\[ = +48.83 \text{ D} \]
1.3 Components of the human optical system

Cornea (second surface)

Transition from back surface of cornea \( (n = 1.376) \) to the aqueous humor \( (n = 1.336) \)
radius of curvature = 6.8 mm

power:

\[
F' = \frac{n' - n}{r} = \frac{1.336 - 1.376}{0.0068} = -5.88 \text{ D}
\]

total power of cornea ~ +43 D
1.3 Components of the human optical system

The Pupil is affected by:

- light conditions
- attention
- emotion
- age

Function:

govern image quality
depth of focus
control light level?
1.3 Components of the human optical system

Factors affecting pupil size

- **Stimulus Variables**
  - light level
  - spectral composition
  - spatial configurations
    - field size
    - spatial structure of field
  - monocular/binocular view
  - accommodative state
  - non-visual stimuli
    - pain
    - noise

- **Observer Variables**
  - individual differences
  - age
  - day-to-day within observer variance
  - biomechanical factors
    - respiration
    - heart beat
  - cognitive factors
    - arousal, attention, fright
    - workload
    - hedonistic content

Pokorny and Smith, 1997
The pupil is perfectly located to maximize the field of view of the eye.

Recall that the $\frac{1}{2}$-illumination field of view is defined as the angle subtended from the center of the entrance pupil to the edges of the field stop.
1.3 Components of the human optical system

The range of light intensities in the environment is enormous!

rod threshold

10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10}

clear sky  snow in sunlight  solar disc

Rodieck, B. *The First Steps in Seeing*

Note: The eye perceives light on a logarithmic scale. Therefore, if a surface radiance increases by 10 times, it only appears to become twice as bright.
1.3 Components of the human optical system

Crystalline Lens

Gradient index of refraction
n = 1.385 at surfaces
n = 1.375 at the equator
n \approx 1.41 at the center

Little refraction takes place at the surface but instead the light curves as it passes through.

For a homogenous lens to have same power, the overall index would have to be greater than the peak index in the gradient.

total power of lens \approx 21 \, \text{D}
1.3 Components of the human optical system

courtesy of Adrian Glasser, PhD
1.3 Components of the human optical system

Accommodation

The **relaxed eye** is under *tension* at the equator from the ciliary body. This keeps the surfaces flat enough so that for a typical eye, distant objects focus on the retina.
1.3 Components of the human optical system

Accommodation

In the **accommodated** eye, the ciliary muscle constricts and relaxes the tension on the equator of the lens.

Surface curvature increases.

Power of the lens increases.

Power of the accommodated lens $\sim= 32.31 \text{ D}$
1.3 Components of the human optical system

Accommodation

- The eye needs ~ 60D of power to focus light from infinity onto its retina
  - \( \frac{1.33}{60} = 0.02217 \text{ m} = 22.17 \text{ mm} \)

- Any extra power offered by the lens allows the eye to focus on near objects.
  - 8 D of extra power allows the eye to focus on objects as close as \( \frac{1}{8} = 0.125 \text{ m} = 12.5 \text{ cm} \)
1.3 Components of the human optical system

Retina:

Images are sampled by millions of rods and cones.

fovea: 5 degrees from optical axis
optic disc: 15 deg from fovea, 10 deg from optical axis.
1.3 Components of the human optical system

What is Visual Angle?

It is the angle subtended at the second nodal point by the image. It is also equal to the angle subtended at the first nodal point by the object.

The nodal points are points in the optical system where the light passing through emerges at the same angle.

The second nodal point in the eye is about 16.5 mm from the retina.

Consider a 1 mm image on the retina…

\[
\tan \frac{\theta}{2} = \frac{0.5}{16.5} \Rightarrow \frac{\theta}{2} = 1.73^\circ
\]

Visual angle = \( \theta = 3.47^\circ \)

An object subtending 3.47 deg makes a 1 mm image on the retina.

An object subtending 1” makes an image that is 288 \( \mu m \) across.
1.3 Components of the human optical system

Visual Angle

- 1 radian = 57.29 degrees
- 1 degree = 0.0174 radians = 17.4 mrad
- 1 minute = 0.29 mrad
- 1 mrad = 3.44 minutes
- 1 minute = 4.8 microns (depends on axial length)
- 1 foveal cone = 2.5 microns (with intersubject variability)
1.3 Components of the human optical system

Why Radians?

Because small angle approximations require the units to be in radians.

\[
sin \theta \approx \theta \quad \text{for small angles}
\]

eg. first try using degrees..

\[
sin(1) = 0.017
\]

now try using radians...

\[
sin(0.017453) = 0.017452
\]
1.3 Components of the human optical system

Visual Angle

• 1 foveal cone = \( \sim 2.5 \) microns = \( \sim 0.5 \) minutes of arc

• letters on an acuity chart are defined by the angles they subtend

\[
\begin{align*}
20/20 & \quad 20/10 \\
\text{5 minutes} & \quad \text{2.5 minutes} \\
\text{1 minute} & \quad 0.5 \\
\text{foveal cones} &
\end{align*}
\]
1.3 Components of the human optical system

Visual Angle

1 foveal cone
= ~2.5 microns
= ~0.5 arcmin

1 deg = ~288 microns
1.3 Components of the human optical system

Visual Angle

1 foveal cone
= ~2.5 microns
= ~0.5 arcmin

20/20 letter
= 5 arcmin
1.3 Components of the human optical system

Visual Angle

- 1 foveal cone = ~2.5 microns = ~0.5 arcmin
- 20/10 letter = 2.5 arcmin
1.3 Components of the human optical system

Visual Angle

1 foveal cone
= ~2.5 microns
= ~0.5 arcmin

Moon
= 30 arcmin

1 deg = ~288 microns
1.3 Components of the human optical system

Axes in the Eye

- Optical axis
- Visual axis
- Pupillary axis
- Fixated object
- Centers of curvature
- Line of sight
- Axes in the Eye
- Optical axis
- Visual axis

Elements:
- \( \lambda \)
- \( \kappa \)
- \( \alpha \)
- \( H \)
- \( H' \)
- \( C_1 \)
- \( L_1 \)
- \( L_2 \)
1.3 Components of the human optical system
Axes and Angles in the Eye

- **Optical axis**: best line joining the centers of curvatures of the optical surfaces
  - Some definitions choose to weight the centers of curvature by the respective powers of the components
- **Visual axis**: line from fovea through the nodal points
- **Line of sight**: line from object through center of entrance pupil that reaches the fovea (chief ray)
- **Pupillary axis**: line from center of curvature of corneal first surface with pupil center
- **Angle alpha**: angle between optical axis and visual axis
- **Angle kappa**: angle between pupillary axis and visual axis (angle kappa is easily observed as a displacement of the coaxially viewed corneal reflex from the pupil center of a fixating eye)
- **Angle lambda**: angle between pupillary axis and line of sight

*Visual axis and line of sight are often assumed to be parallel, which is only true for distant objects*
1.3 Components of the human optical system

- optic disc
- posterior pole
- fovea

10 deg
5 deg
1.3 Components of the human optical system

- Cone density peaks near fovea, decreases outward.
- Rod density increases with eccentricity.

Osterberg, Acta Ophthalmologica, 6:1-103, 1935
Curcio et al., Journal of Comparative Neurology, 292:497-523, 1990
1.3 Components of the human optical system
1.3 Components of the human optical system

Relative Spectral Absorptance

<table>
<thead>
<tr>
<th>wavelength (nm)</th>
<th>normalized spectral absorptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>1.00</td>
</tr>
<tr>
<td>450</td>
<td>1.00</td>
</tr>
<tr>
<td>500</td>
<td>1.00</td>
</tr>
<tr>
<td>550</td>
<td>1.00</td>
</tr>
<tr>
<td>600</td>
<td>1.00</td>
</tr>
<tr>
<td>650</td>
<td>1.00</td>
</tr>
<tr>
<td>700</td>
<td>1.00</td>
</tr>
</tbody>
</table>

- **L cones**
- **M cones**
- **S cones**
- **rods**
1.4 Transmission of the Ocular Media

Total transmittance at the various anterior surfaces:
1. Aqueous
2. Lens
3. Vitreous
4. Retina

Boettner and Wolter, 1962
1.4 Transmission of the Ocular Media

Lens Optical Density Increases with Age

Fig. 2(2.4.6). Spectral density curves of the human eye lens determined for the living eye by an objective method. Data for English observers of different ages (ages are shown against the curves; from Said and Weale, 1959). The crosses refer to mean data for two eyes (ages 48 and 53) obtained, after their removal in operations, by a different method (Weale, 1954).

figure from Wyszecki and Stiles, 1982
Part 2 Image Quality in the Eye

“Now, it is not too much to say that if an optician wanted to sell me an instrument which had all these defects, I should think myself quite justified in blaming his carelessness in the strongest terms and giving him back his instrument”

Helmholtz (1881) on the eye’s optics.
2.1 Depth of focus is a function of pupil size

<table>
<thead>
<tr>
<th>2 mm</th>
<th>4 mm</th>
<th>6 mm</th>
</tr>
</thead>
</table>

- For a 2 mm pupil, the depth of focus is limited, with a narrow range of focused light.
- For a 4 mm pupil, the depth of focus is moderately wide, allowing more light to be focused.
- For a 6 mm pupil, the depth of focus is the widest, allowing even more light to be focused.

This diagram illustrates how the depth of focus increases with pupil size.
2.1 Depth of focus is a function of pupil size

Focused behind retina

In focus

Focused in front of retina

2 mm 4 mm 6 mm
2.1 Depth of focus is a function of pupil size

Computation of Geometric Blur Size

\[ \text{blur}[\text{mrad}] = D \times \text{pupil size}[\text{mm}] \]
\[ \text{blur}[\text{minutes}] = 3.44 \times D \times \text{pupil size}[\text{mm}] \]

where D is the defocus in diopters
2.1 Depth of focus is a function of pupil size

Derivation of Geometric Blur Size Eqn.

By similar triangles...

\[
\frac{W}{l-x} = \frac{b}{x}
\]

use small angle approximation to get...

\[
\frac{W}{l-x} = \frac{l\theta}{x}
\]

\[
\theta = \frac{Wx}{l^2 - lx} = W \left( \frac{x-l+l}{l(l-x)} \right) = W \left( \frac{l}{l(l-x)} - \frac{l-x}{l(l-x)} \right) = W \left( \frac{1}{l-x} - \frac{1}{l} \right) = WD
\]

where \(D\) is defocus in diopters
2.1 Depth of focus is a function of pupil size

Application of Blur Equation

- 1 D defocus, 8 mm pupil produces 27.52 minute blur size ~ 0.5 degrees
2.1 Depth of focus is a function of pupil size

Draw a cross like this one on a page. Hold it so close that it is completely out of focus, then squint. You should see the horizontal line become clear. The line becomes clear because you have used your eyelids to make your effective pupil size smaller, thereby reducing the blur due to defocus on the retina image. Only the horizontal line appears clear because you have only reduced the blur in the horizontal direction.
2.1 Depth of focus is a function of pupil size
2.2 Diffraction and Interference

“Any deviation of light rays from a rectilinear path which cannot be interpreted as reflection or refraction”

Sommerfeld, ~ 1894
2.2 Diffraction and Interference

• diffraction causes light to bend perpendicular to the direction of the diffracting edge

• interference causes the diffracted light to have peaks and valleys
2.2 Diffraction and Interference

Fraunhofer Diffraction

• Also called *far-field* diffraction
• Occurs when the screen is held far from the aperture.
• *Occurs at the focal point of a lens!*
2.2 Diffraction and Interference
Fraunhofer Diffraction

rectangular aperture

square aperture

(c)

(d)
2.2 Diffraction and Interference

circular aperture

Airy Disc

Sir George Biddel Airy: Inventor of spectacles for astigmatism
2.3 The Point Spread Function

The Point Spread Function, or PSF, is the image that an optical system forms of a point source.

The point source is the most fundamental object, and forms the basis for any complex object.

The PSF is analogous to the Impulse Response Function in electronics.
2.3 The Point Spread Function

The PSF for a perfect optical system is the Airy disc, which is the Fraunhofer diffraction pattern for a circular pupil.
2.3 The Point Spread Function

The Airy Disc

\[ \theta = \frac{1.22 \cdot \lambda}{a} \]

\( \theta \equiv \) angle subtended at the nodal point
\( \lambda \equiv \) wavelength of the light
\( a \equiv \) pupil diameter
2.3 The Point Spread Function

The Airy Disc

\[ \theta = \frac{1.22 \cdot \lambda}{a} \]

\( \theta \equiv \) angle between peak and first minimum (in radians!)

\( \lambda \equiv \) wavelength of the light

\( a \equiv \) pupil diameter

\[ 1 \text{ radian} = \frac{180}{\pi} \text{ degrees} \]

1 degree = 60 minutes of arc

1 minute of arc = 60 seconds of arc
2.3 The Point Spread Function

PSF vs. Pupil Size: Perfect Eye

1 mm  2 mm  3 mm  4 mm  5 mm  6 mm  7 mm

Diffraction-limited Eye
2.4 Resolution

Unresolved point sources

Rayleigh resolution limit

Resolved
2.4 Resolution

\[ \theta_{\text{min}} = \frac{1.22 \cdot \lambda}{a} \]

- \( \theta_{\text{min}} \equiv \) angle subtended at the nodal point
- \( \lambda \equiv \) wavelength of the light
- \( a \equiv \) pupil diameter
2.4 Resolution

\[ \theta_{\text{min}} = 60 \times \frac{180}{\pi} \times \frac{1.22 \cdot \lambda}{a} \]

\[ \theta_{\text{min}} \equiv \text{angle subtended at the nodal point} \]

20/20 20/10
diffraction limited PSF
2 mm pupil @ 550 nm
Keck telescope:
(10 m reflector)

\[ \theta_{\text{min}} = \frac{1.22 \cdot \lambda}{\alpha} = \frac{1.22 \cdot 900 \times 10^{-9}}{10} = 109.8 \text{ nanoradians} = 0.023 \text{ seconds of arc} > 2500 \text{ times better than the eye!} \]
2.5 Light scatter in the human eye

slides courtesy of
Thomas J. T. P. van den Berg
The Netherlands Ophthalmic Research Institute of the Royal Netherlands Academy of Arts and Sciences,
Amsterdam, The Netherlands;

Published in:
Primary sources of scattered light

Cornea  Iris/Sclera  Lens

fundus

Tom van den Berg
Ciliary corona

Actual subjective appearance of straylight: a pattern of very fine streaks, not at all like the circularly uniform (Airy disc-like) scattering pattern of particles of approximate wavelength size
Central diffraction pattern from 2, 3, 4, 50 randomly placed particles
Diffraction pattern for 1000 particles, as a function of wavelength, including spectral luminosity effect.
2.5 Straylight (Glare) Equation

\[ I = \frac{AE}{\theta^n} \]

where \( I \) is the retinal illuminance at the distance \( \theta \) from the glare source of illuminance \( E \). \( A \) is a scaling constant. \( n \) is usually calculated to be 2.

Equation applies outside of about 1 degree from the glare source. Although 1% at 1 degree seems small, the total flux in the annulus outside of 1 degree can amount to 10% or more.
2.6 Chromatic Aberration

Longitudinal Chromatic Aberration

Blue focus

Red focus
2.6 Chromatic Aberration
2.6 Chromatic Aberration

Fig. 1. Chromatic difference of refraction from three experimental studies\textsuperscript{2–4} in the visible spectrum and best-fit Cauchy equation (5a), Cornu’s equation (5c), and Herzberger’s equation to the combined studies. All data were set to be zero at 590 nm. Results of three studies\textsuperscript{6–8} with measurements in the infrared are also shown; we moved the data from these studies studies to coincide with Eq. (5a) at the lower wavelength (543 nm, Refs. 6 and 7) or at the lowest wavelength (700 nm, Ref. 8). Where shown, error bars indicate standard deviations.
2.6 Chromatic Aberration

Figure 3. The significance of chromatic defocus depends on luminance. The solid curve shows the luminance spectrum of white-light emitted by the P4 phosphor of cathode ray tubes and arrows mark the amount of defocus if the eye accommodates for 550 nm. When the peak of the luminance spectrum is in focus, most of the light is less than 0.25 D out of focus.

Thibos, Bradley & Zhang, 1989
2.7 Monochromatic Aberrations

Perfect Eye
(limited only by diffraction)
2.7 Monochromatic Aberrations

Aberrated Eye
2.8 The Total Aberrations of the Eye

“I have never experienced any inconvenience from this imperfection, nor did I ever discover it till I made these experiments; and I believe I can examine minute objects with as much accuracy as most of those whose eyes are differently formed”

Thomas Young (1801) on his own aberrations.
2.8 The Total Aberrations of the Eye

Change in the line spread function with pupil size

Fig. 10. Optical linespread functions of the human eye. Each curve represents the normalized distribution of illuminance occurring on the fundus for a thin line source of light. Dots occur at 0.1 min increments. Narrower curve indicates the diffraction image of a line at the given pupil diameter.

Campbell & Gubisch, 1966
2.8 The Total Aberrations of the Eye

Perfect Eye

Typical Eye
Observe your own point spread function
2.9 The Modulation Transfer Function, or MTF
object: 100% contrast

image

spatial frequency

contrast
2.9 The Modulation Transfer Function

3D MTF

vertical spatial frequency (c/d)

horizontal spatial frequency (c/d)
2.9 The Modulation Transfer Function

Michelson Contrast = \frac{\text{max} - \text{min}}{\text{max} + \text{min}}
The modulation transfer function (MTF) indicates the ability of an optical system to reproduce (transfer) various levels of detail (spatial frequencies) from the object to the image.

- Its units are the ratio of image contrast over the object contrast as a function of spatial frequency.
- It is the optical contribution to the contrast sensitivity function (CSF).
2.9 The Modulation Transfer Function

Change in MTF with pupil size

Rule of thumb: cutoff frequency increases by ~30 c/d for each mm increase in pupil size
2.9 The Modulation Transfer Function

PSFs for the same eye

1 2 3 4 5 6 7 8
Spatial frequency

20/20

5 arcmin

50 cyc/deg

20/10

2.5 arcmin

60 cyc/deg
2.10 The Phase Transfer Function, or PTF
No AO
rms: 0.29 µm

AO corrected
rms: 0.09 µm
2.11 Measurement of the wave aberrations of the eye
2.11.1 What is the Wavefront?

- Parallel beam = plane wavefront
- Converging beam = spherical wavefront
2.11.1 What is the Wavefront?

parallel beam = plane wavefront

ideal wavefront
defocused wavefront
2.11.1 What is the Wavefront?

- Parallel beam = plane wavefront
- Ideal wavefront
- Aberrated beam = irregular wavefront
2.11.1 What is the Wavefront?

- **diverging beam** = spherical wavefront
- **aberrated beam** = irregular wavefront
- **ideal wavefront**
2.11.2 What is the Wave Aberration?

diverging beam = spherical wavefront
2.11.2 What is the Wave Aberration?

Wave Aberration of a Surface

Wavefront Aberration

Wavefront Aberration

Wavefront Aberration

Wavefront Aberration

Wavefront Aberration

Wavefront Aberration
What are Zernike Polynomials?

- set of basic shapes that are used to fit the wavefront
- analogous to the parabolic $x^2$ shape that can be used to fit 2D data
Zernike Polynomials

1st order

2nd order

low order aberrations

3rd order

4th order

high order aberrations

5th order
Properties of Zernike Polynomials

• orthogonal
  - terms are not similar in any way, so the weighting of one term does not depend on whether or not other terms are being fit also

• normalized
  - the RMS wave aberration can be simply calculated as the vector of all or a subset of coefficients

• efficient
  - Zernike shapes are very similar to typical aberrations found in the eye
2.11.3 Relationships Between Wave Aberration, PSF and MTF
The reason we measure the wave aberration

Image Quality Metrics

PSF
(point spread function)

OTF
(optical transfer function)

PTF (phase)  MTF (contrast)
The PSF is the Fourier Transform (FT) of the pupil function

\[ PSF \left( x_i, y_i \right) = FT \left\{ P(x, y) e^{-i \frac{2\pi}{\lambda} W(x, y)} \right\} \]

The MTF is the amplitude component of the FT of the PSF

\[ MTF \left( f_x, f_y \right) = Amplitude \left[ FT \left\{ PSF(x_i, y_i) \right\} \right] \]

The PTF is the phase component of the FT of the PSF

\[ PTF \left( f_x, f_y \right) = Phase \left[ FT \left\{ PSF(x_i, y_i) \right\} \right] \]
2.11.4 Principles of the Shack-Hartmann Wavefront Sensor

Perfect Eye

Aberrated Eye
2.11.4 Principles of the Shack-Hartmann Wavefront Sensor
2.11.4 Principles of the Shack-Hartmann Wavefront Sensor

Wavefront → Lens Array → CCD Array

Perfect eye

Aberrated (typical) eye
2.11.4 Principles of the Shack-Hartmann Wavefront Sensor

Fitting the Wavefront

• The local slope (or the first derivative) of the wavefront is determined at each lenslet location.

• The corresponding wavefront is determined by a least squares fitting of the slopes to the derivative of a polynomial selected to fit the wavefront.

• Zernike polynomial is the most commonly used.
2.11.4 Principles of the Shack-Hartmann Wavefront Sensor: The Lenslet Array
2.11.4 Principles of the Shack-Hartmann Wavefront Sensor

Shack-Hartmann Images

BD  KW  SM
2.11.4 Principles of the Shack-Hartmann Wavefront Sensor

Wavefront Maps
(at best focal plane)

BD

KW

SM

0.33 DS
-0.17 DC X 87

6.42 DS
-0.6 DC X 126

0 DS
-1 DC X 3
2.11.4 Principles of the Shack-Hartmann Wavefront Sensor

Aberrations of an RK patient
2.11.4 Principles of the Shack-Hartmann Wavefront Sensor

Aberrations of a LASIK patient
2.11.4 Principles of the Shack-Hartmann Wavefront Sensor

Post - RK

Post - LASIK
2.11.4 Principles of the Shack-Hartmann Wavefront Sensor

Keratoconus

Brian Barsky
right eye
9 Aug 2001
2.11.5 Metrics to Define Image Quality
2.11.5 Metrics to Define Image Quality

Wave Aberration Contour Map
2.11.5 Metrics to Define Image Quality

Breakdown of Zernike Terms

Coefficient value (microns)

-0.5 0 0.5 1 1.5 2

Zernike term

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

- astig. defocus
- astig.
- trefoil
- coma
- coma
- trefoil

spherical aberration

2\textsuperscript{nd} order
3\textsuperscript{rd} order
4\textsuperscript{th} order
5\textsuperscript{th} order
2.11.5 Metrics to Define Image Quality

Root Mean Square Wave Aberration

$$RMS = \sqrt{\frac{1}{A} \iint (W(x,y) - \overline{W(x,y)})^2 \, dx \, dy}$$

$A$ – pupil area

$W(x,y)$ – wave aberration

$\overline{W(x,y)}$ – average wave aberration
Include the terms for which you want to determine their impact (e.g., defocus and astigmatism only, third order terms or high order terms etc.).
2.11.5 Metrics to Define Image Quality

Point Spread Function
2.11.5 Metrics to Define Image Quality

Strehl Ratio

\[
\text{Strehl Ratio} = \frac{H_{\text{eye}}}{H_{\text{dl}}}
\]
2.11.5 Metrics to Define Image Quality

Modulation Transfer Function

Area under the MTF

Contrast vs. spatial frequency (c/deg)
2.11.5 Metrics to Define Image Quality

Convolution

\[ PSF(x, y) \otimes O(x, y) = I(x, y) \]
2.11.5 Metrics to Define Image Quality

20/20 letters

20/40 letters
Typical Values for Wave Aberration

**Strehl Ratio**

- Strehl ratios are about 5% for a 5 mm pupil that has been corrected for defocus and astigmatism.

- Strehl ratios for small (~ 1 mm) pupils approach 1, but the image quality is poor due to diffraction.
How bad is the eye? Static Aberrations

This metastudy compiles population statistics of over 1300 eyes collected from 10 different labs
For the most part, aberrations in the eye are random. When you average enough eyes together, most terms are no different from zero. The only high order aberrations that is non-zero is spherical aberration, which averages to a small positive value.

Salmon & van de Pol, J Cataract Ref Surg, 2006
How bad is the eye?: Static Aberrations

A population average of the magnitude of the Zernike terms shows that high order aberrations are dominated by 3\textsuperscript{rd} order and spherical aberration.

Salmon & van de Pol, J Cataract Ref Surg, 2006
Like most optical systems, the aberrations diminish as the aperture is reduced.

But unlike turbulence from a telescope, the paraxial regions of the eye have lower aberrations than marginal locations (i.e., Fried’s parameter is not constant).

Salmon & van de Pol, J Cataract Ref Surg, 2006
Overall, the eye’s high order aberrations reduce with pupil size. The dashed line indicates the effective diffraction limit, according to Marachel’s criterion ($\text{RMS} < \frac{\lambda}{14}$) for 550 nm light.

Salmon & van de Pol, J Cataract Ref Surg, 2006
How bad is the eye?: Dynamic Aberrations

Fig. 2. Dynamics of ocular aberrations. (a) Wavefront rms measured at 240 Hz over approximately 4 s. (b) Power spectrum of the signal in (a) showing dynamic behaviour in excess of 30 Hz.

2.12 Typical Values for Wave Aberration

- Dynamic Changes in the wave aberrations are caused by
  - accommodation
  - eye movement
  - eye translation
  - tear film
Monochromatic Aberrations as a Function of Age, from Childhood to Advanced Age

Isabelle Brunette,¹ Juan M. Bueno,² Mireille Parent,¹,³ Habib Hamam,³ and Pierre Simonet³

2.12 Typical Values for Wave Aberration Change in aberrations with age
3. Applications

• Many ophthalmic applications benefit from knowledge of the optics of the eye.
3. Applications

Adaptive Optics Phoropter

New intra-ocular lens (Tecnis IOL, Advanced Medical Optics) is designed with negative spherical aberration to counteract the positive spherical aberration of the cornea.

Tecnis Lens Is First to Claim Reduction of Aberrations and Improved Night Driving Simulator Performance

PEAPACK, N.J., May 2004 — The FDA approved new labeling for the Tecnis intraocular lens that says it can reduce postoperative spherical aberrations and improve night driving simulator performance. Since drivers over 65 are more likely to be involved in car crashes than people in their 30s, 40s, and 50s, manufacturer Pfizer Inc. considers this label change significant.

www.allaboutvision.com
3. Applications
Wavefront Correcting Refractive Surgery

Laser refractive surgery to compensate the aberrations of the eye is booming. All major companies have custom surgery systems and results are promising.
3. Applications
Adaptive Optics Phoropter

Currently, an accurate refraction requires a lengthy, subjective procedure...

... but systems that use wavefront sensing are be able to measure it instantly, and systems that use adaptive optics can be used to demonstrate the benefit of a correction.
The second time's a charm for the Light-adjustable Lens from Calhoun Vision (Pasadena, Calif.). Though the LAL had something of a false start when first implanted in human eyes several months ago, the company appears to have addressed the problems that occurred then, and a surgeon has now implanted the lens successfully in eight patients. If it proves to be effective, it could be a boon to post-refractive patients who happen to need cataract surgery, due to its ability to be customized. Here's an update on this innovative device.
3. Applications
Accommodating Intraocular Lens

Crystalens has the first FDA approved accommodating IOL. Many companies, like Abbot, are investing millions to develop their own devices.

Visiogen (now owned by Abbot)
3. Applications
Contact Lenses for Keratoconus

unaided eye
custom contact lens
3. Applications

PSFs (for 5 mm pupil)

**unaided eye**

- $\text{rms} = 4.16$
- $\text{strehl ratio} = 0.0008$

**custom contact lens**

- $\text{rms} = 1.48$
- $\text{strehl ratio} = 0.004$
3. Applications

Presbyopia Relief

Is a good multifocal or bifocal contact lens correction precluded by the presence of aberrations?

“Bifocal lenses do not always provide bifocal vision”

Does the emmetropization process extend to aberrations beyond defocus?

Constant pupil size = 5 mm

Higher order aberrations decrease with age
3. Applications

Adaptive Optics
3. Applications
Adaptive Optics Flattens the Wave Aberration

AO OFF

AO ON
3. Applications

Real-time AO at the University of Rochester

Wave Aberration

PSF

movies

Hofer, Chen, Yoon, Singer, Yamauchi, Williams, Optics Express, 2001
3. Applications

Adaptive Optics

- **Basic Science Imaging Applications**
  - reveal properties of single cells in living eyes
  - correlate properties of cellular structure in living eyes with visual performance
  - nonlinear imaging of structure and function

- **Pre-clinical applications**
  - facilitate longitudinal tests on animal models
  - test outcomes of drugs and treatments for eye disease
  - correlate phenotypes with genotypes

- **Clinical Imaging Applications**
  - provide early diagnosis for retinal or other systemic diseases
  - better understand the etiology of retinal disease for which little is known
  - discover more sensitive biomarkers for retinal disease
  - track progression of eye disease
  - measure response at a cellular level to therapies that treat disease
  - preselect patients or diseases that may benefit best from therapies or treatments

- **Functional Imaging Applications**
  - facilitate better relationships between structure and function
  - reveal properties of cell networks in living eyes (i.e., retinal circuitry)

- **Vision Applications**
  - pre-test the benefits of aberration correction on vision
  - develop optimal aberration profiles for long depth of focus
  - test possible signals that drive accommodation and/or eye growth
  - reveal the optical retinal and neural limits of human vision

- **Dynamic Applications**
  - measure properties of blood flow in small capillaries
  - measure scattering changes in response to light stimulation
  - measure eye motion with high accuracy and frequency

- **Light delivery applications**
  - track and stimulate single cells or networks of cells for electrophysiology expts
  - microperimetry
  - targeted laser treatment (photocoagulation, or uncaging drugs)
  - track eye movement responses to stimulation
  - study role of eye movements for vision
3. Applications

AO Improvement in Vision

Wave aberration

Monochromatic retinal image

White Light Retinal Image

Without AO

With AO

6.8 mm pupil
3. Applications

Visual Acuity with AO Correction

![Graph showing MAR (arc seconds) for different subjects and AO corrections.]
3. Applications

Correcting aberrations improves retinal image quality

![Image with captions: single image uncompensated, single image with adaptive compensation, registered sum of 61 images with adaptive compensation]
Applications of AO

• Basic Science Imaging Applications
  - reveal properties of single cells in living eyes
  - correlate properties of cellular structure in living eyes with visual performance
  - nonlinear imaging of structure and function
University of Rochester

Heidi Hofer, David Williams, U Rochester

* Roorda and Williams, Nature, 1999
Two-photon image of Monkey Retina

Two Photon Image

100 microns
Applications of AO

• Pre-clinical applications
  – facilitate longitudinal tests on animal models
  – test outcomes of drugs and treatments for eye disease
  – correlate phenotypes with genotypes in animal models of eye disease
Use of extrinsic fluorescent agents facilitates *in vivo* microscopic imaging of potentially any cell class.

*macaque ganglion cells*

**in vivo**  
**ex vivo confocal**

Gray et al, IOVS 2008
Applications of AO

- **Clinical Imaging Applications**
  - provide early diagnosis for retinal or other systemic diseases
  - better understand the etiology of retinal disease for which little is known
  - discover more sensitive biomarkers for retinal disease
  - track progression of eye disease
  - measure response at a cellular levels to therapies that treat disease
  - preselect patients or diseases that may benefit best from therapies or treatments
In a typical healthy eye, it is easy to track individual cones over time. The cones in this pair of images, taken over 4 years apart, remain virtually unchanged. Toggle this image back and forth to appreciate the overlay. Intensity changes reflect normal physiological variations in cone reflectivity (Pallikaris, A., Williams, D.R., & Hofer, H. Invest Ophthalmol. Vis. Sci. 44, 4580-4592. (2003).
Cone tracking in eye disease

In a diseased eye (retinitis pigmentosa illustrated here), we can monitor changes in cone density over time.

Talcott et al, submitted (2010) (also 2010 ARVO abstract)
Applications of AO

• Functional Imaging Applications
  - facilitate better relationships between structure and function
  - reveal properties of cell networks in living eyes (ie retinal circuitry)
Representative video showing cone scintillation after a single brief stimulus of 8 ms. Center panel shows a registered cone mosaic video of 90 frames (.45 s), with 20 frames before stimulus and 70 frames after stimulus. Delivery of stimulus flash to the right half of the patch is depicted by a white flash in the background of the right half of the video. Left panel displays ten cones with highest time-RMS from the unstimulated left half of the video. Right panel shows ten cones with the highest time-RMS in the stimulated right half. The center panel shows cone scintillation is present after the flash in the stimulated half and largely absent in the unstimulated half.

Applications of AO

• Vision Applications
  – pre-test the benefits of aberration correction on vision
  – develop optimal aberration profiles for long depth of focus
  – test possible signals that drive accommodation and/or eye growth
  – reveal the optical retinal and neural limits of human vision
Depth of focus is reduced with aberration correction.

Guo et al, Vision Research, 2008
Applications of AO

• Light delivery applications
  – track and stimulate single cells or networks of cells for electrophysiology expts
  – microperimetry
  – targeted laser treatment (photocoagulation, or uncaging drugs)
  – track eye movement responses to stimulation
  – study role of eye movements for vision
Combined Stimulus Delivery and Electrophysiology

imaging: 840 nm
stimulus: 680 nm
Localizing the Receptive Field

*the black spot indicates where a dim red laser has been turned on*

Sincich et al, Nature Neuroscience, 2009
Summary

- geometrical optics
- physical optics
- optical quality in the eye
- metrics for determining visual image quality
- measurement of optical quality in the eye
- applications
Thank You