Human eye

http://www.ai.rug.nl/~lambert/projects/BCI/literature/misc
Anatomy of the human eye

Retina is a 3D structure!

From Hubel - Eye, Brain & Vision
Optics of the eye: The Cornea

2/3 of total eye power
Optics of the eye: The Pupil

The Pupil is affected by:

light conditions
attention
emotion
age

Function:

govern image quality
depth of focus
control light level?
Optics of the Eye: The Crystalline Lens

Gradient index of refraction
n = 1.385 at surfaces
n = 1.375 at the equator
n ~= 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 ~= 21 D

Optical power in diopters ≡ 1 / focal length in meters
Optics of the Eye: The Retina

Images are sampled by rods (>100 million) and cones (~6 million).
The retina is a thick-multilayered structure.
Spatial Distribution of Rods and Cones

Osterberg, Acta Ophthalmologica, 6:1-103, 1935

How bad is 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.
How bad is the eye?

This is how a point source appears for a perfect eye
How bad is the eye?

This is how the same point source appears for a typical human eye
How bad is the eye?
And how to correct it with AO

- **Static Aberrations**
  - statistics on human eye aberrations are used to determine the spatial density of actuators, maximum stroke etc.

- **Dynamic Aberrations**
  - statistics on human eye aberration dynamics are used to determine AO closed-loop frequency requirements
Point Spread Function vs. Pupil Size

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

Perfect Eye

Typical Eye

C. of Austin Roorda
Every eye has a different pattern of high order aberrations

Wave Aberration

Perfect eye (diffraction limited)

MRB

GYY

MAK

5.7 mm pupil

Pointspread Function

Retinal Image

0.5 deg
How can we use AO to improve
the quality of vision?
the resolution of retinal images?
AO for astronomy and vision science are fundamentally similar, but face different challenges.
Sources of Retinal Image Blur

- Diffraction
- Aberrations
- Light Scatter
AO for Astronomy

wavefront sensor

imaging

wavefront corrector

laser beacon

Sky

LGS
AO for Astronomy

Sky

wavefront sensor

laser beacon

imaging

wavefront corrector
AO for Vision Science

- Wavefront sensor
- Imaging
- Wavefront corrector
- Laser beacon
- Illumination
- Eye
AO for Vision Science

Eye

- wavefront sensor
- illumination
- laser beacon
- wavefront corrector
- imaging
AO for Vision Science

Wavefront sensing

Vision testing

Wavefront correction

Laser beacon

Eye
First demonstration of retinal imaging & vision improvement by correcting higher order aberrations

Recent instruments are compact: Roorda’s compact scanning laser ophthalmoscope

- Can be rolled from room to room
- Not only imaging, but also a scanning confocal microscope
How many lenslets do I need to adequately sample and reconstruct the wavefront?

Will depend on several factors, including the complexity of (spatial frequencies contained in) the wavefront.

 Fewer lenslets  
Poor representation of the wavefront

 More lenslets  
More precise representation of the wavefront

There is a measurable amount of aberration in normal eyes up to at least the 8\textsuperscript{th} radial order

(70 normal eyes, 7.5 mm pupil)


Typical Shack-Hartmann wavefront sensor parameters for the *normal* human eye

1. Lenslet array parameters:
   - ~200 for dilated pupil (15 x 15 to 20 x 20 arrays within 6-8 mm pupil)

2. # pixels across spot core: 4 to 14
   - Note that vision science AO systems typically use many more pixels per subaperture than astronomy systems

3. Wavelength: 633 – 850 nm

4. Other parameters to consider:
   - CCD pixel size
   - CCD frame rate (don’t need super low read noise)
How fast does my vision AO system need to go?
Temporal fluctuations exist in all of the eye’s aberrations with natural accommodation

Accommodating at 2 D
4.7-mm pupil

- artificial eye total rms wavefront error
- total rms wavefront error
- defocus
- astigmatism
- coma
- spherical aberration

A closed-loop bandwidth of 1-3 Hz can ideally correct aberrations sufficiently to achieve a Strehl > 0.8

**Example:**

40 degree fundus image would require collection of \( \pi(40^\circ/2)^2 / \pi(1^\circ/2)^2 = 1,600 \) one-degree AO images.
Adaptive optics can resolve individual photoreceptors in the living eye

Without AO (single image)  
With AO (single image)  
With AO (registered sum)  

~ 50 μm

1 deg eccentricity

Heidi Hofer, David Williams
AO can “zoom in” to see single cells
AO allows visualization of different cell types and for visual psychophysics on a cellular scale.

### Cell Types
- **Cone & rod photoreceptors**
- **Ganglion cells**
- **RPE**

### Functional Testing
- Vasculature & Blood Flow

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Applications of AO

- **Basic science imaging**
  - Properties of retinal cells
  - Color vision mechanisms

- **Clinical applications**
  - Early diagnosis of disease
  - Track disease progression, test efficacy of new drugs

- **Functional imaging**
  - Relation between structure and function
  - Study retinal circuitry

- **Vision science**
  - Vision benefits of aberration correction
  - Optical and neural limits of human vision

- **Dynamical studies**
  - Blood flow in the eye
  - Eye motion

- **Precision light delivery**
  - Stimulate single cells
  - Targeted laser treatment
Components of the human optical system

Relative Spectral Absorptance

- L cones
- M cones
- S cones
- Rods

normalized spectral absorptance vs. wavelength (nm)
All of these 12 people have normal, nearly identical color vision despite having different relative numbers of green and red cones!
Clinical application: Cone tracking to follow progression of eye disease

Cone tracking in eye disease

Baseline

21 months later

~2089 cones per deg²

~1593 cones per deg²

~24% drop in cone density from baseline

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)
Optical Coherence Tomography is an an interferometric, non-invasive optical imaging method that offers very high axial resolution.

OCT relays on white light or low coherence interferometry. The optical setup typically consists of an interferometer (typically Michelson type) with a low coherence, broad bandwidth light source. Light is split into and recombined from reference and sample arm, respectively.
Resolution of retinal imaging instruments

AO SLO = scanning laser ophthalmoscope
AO OCT = AO optical coherence tomography

Don Miller; Indiana University
3000 A-scans; x = 6mm; Δz = 3.5 μm; Δx = 10-15 μm; dx = 1.5 μm τ = 50 μs; T=150 ms;

Slices through side view of retina
Summary

• Adaptive optics for imaging the living retina has many similarities with astronomical AO
  – “Laser guide star” for wavefront sensing
  – Similar wavefront sensors and DMs

• A key difference: retina is a 3D structure
  – Need both axial and lateral resolution
  – AO Scanning Laser Ophthalmoscopes, Optical Coherence Tomography

• Applications:
  – Physiology and psychology of vision
  – Clinical and medical applications
Want to learn more about AO for vision science?

Miller DT and Roorda A. *Adaptive optics in retinal microscopy and vision*, Chapter 17.