Adaptive Optics for Vision Science

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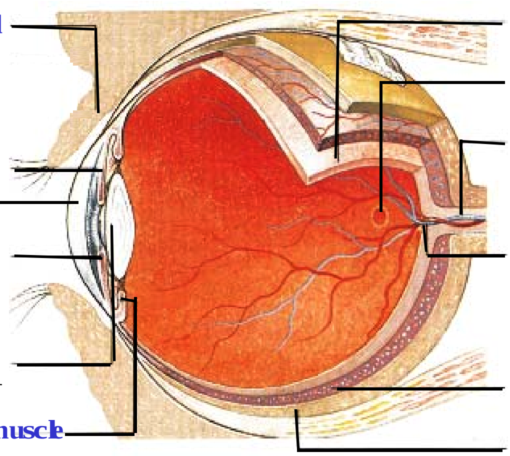
http://www.cvs.rochester.edu/williamslab/

Outline

- **Why do we need AO for vision science**
- **Rochester AO system design and performance**
- **What can AO do for vision science**
- **Summary**

Why do we need AO for vision science?

Structure of the human eye

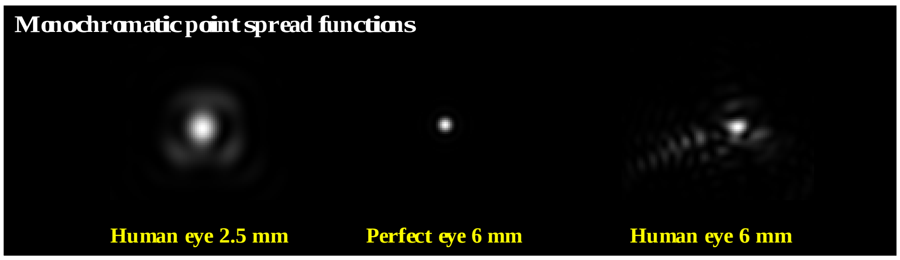


The main components of the eye's optics: the cornea, the iris and pupil, the crystalline lens, and the retina.

Defects of the eye's optics

Sources of retinal blur

- **Scattering**
- **Diffraction**
- **Aberrations**



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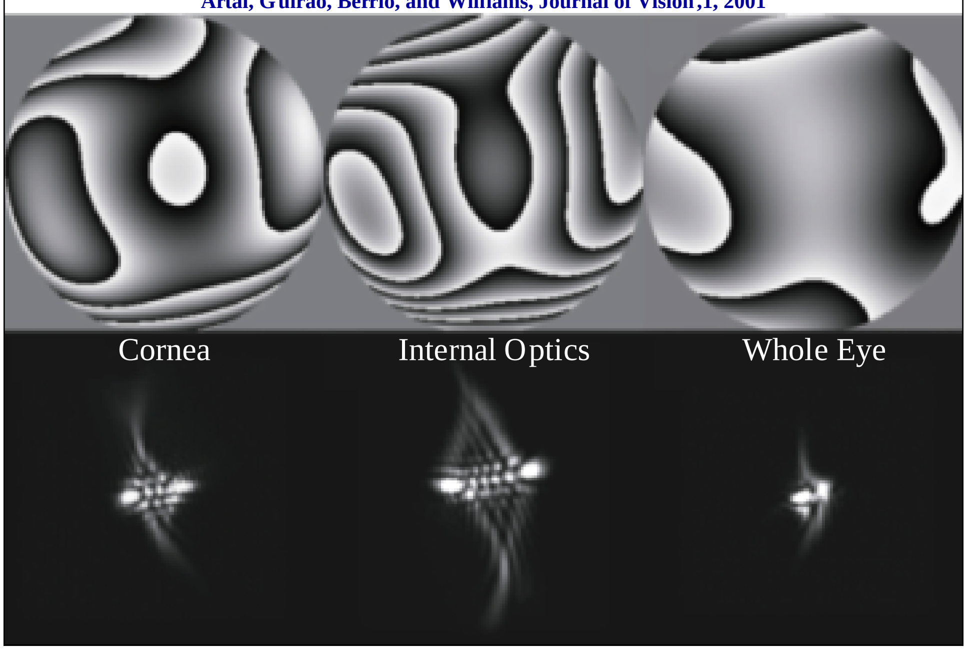
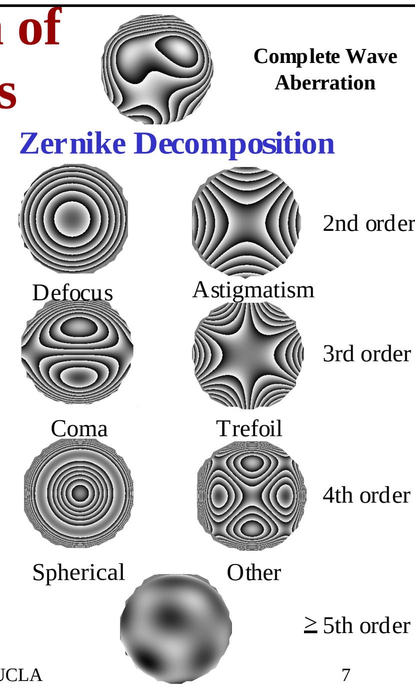
Where are aberrations from?

Artal, Guirao, Berrio, and Williams, Journal of Vision,1, 2001



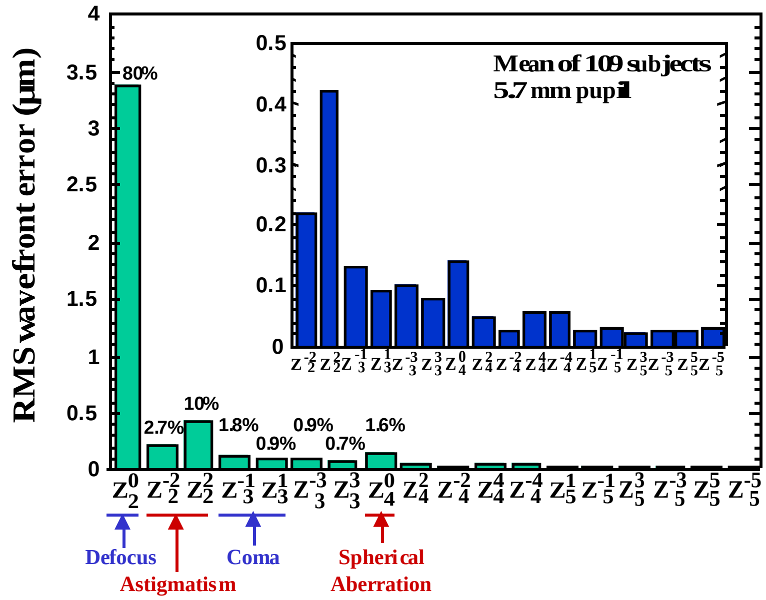
A complete description of the eye's optical defects



Low order aberrations

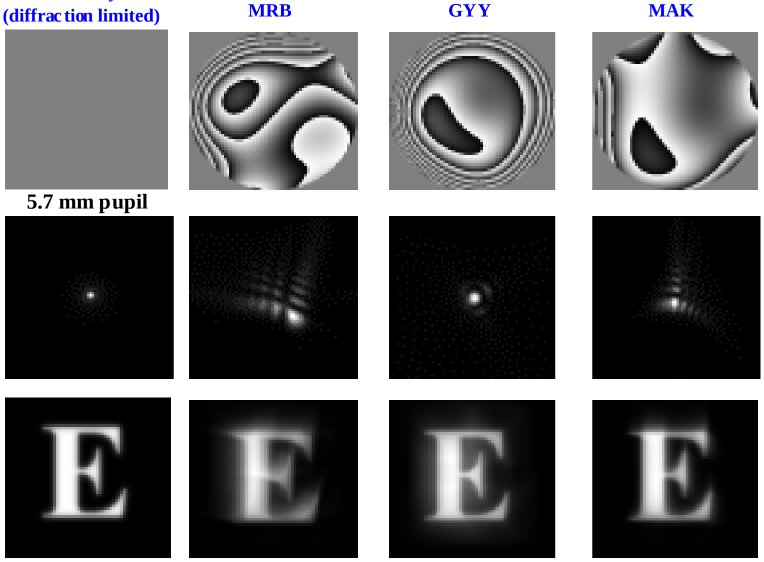
Higher order aberrations

Population Statistics of the Eye's Wave Aberration



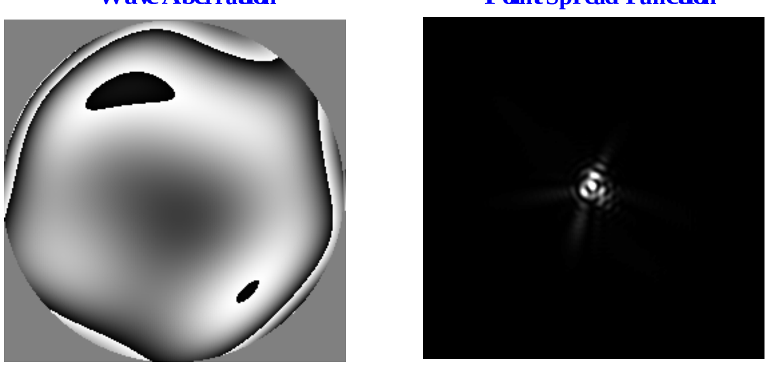
Porter et al., JOSA A, 2001

Everyone has a different pattern of aberrations



The wave aberration is not static

(HH, 5.7mm pupil, 550 nm wavelength)

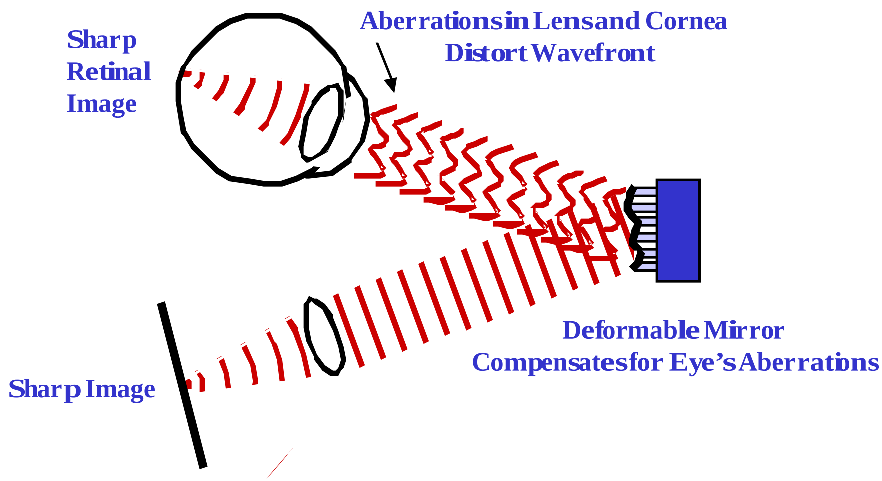


Dynamic correction can increase resolution and contrast

Dynamic range of eye's wave aberration required closed loop bandwidth 1~2 Hz to correct temporal fluctuation

Hofer, Artal, Singer, Aragon, and Williams, J. Opt. Soc. Am. A(2001)

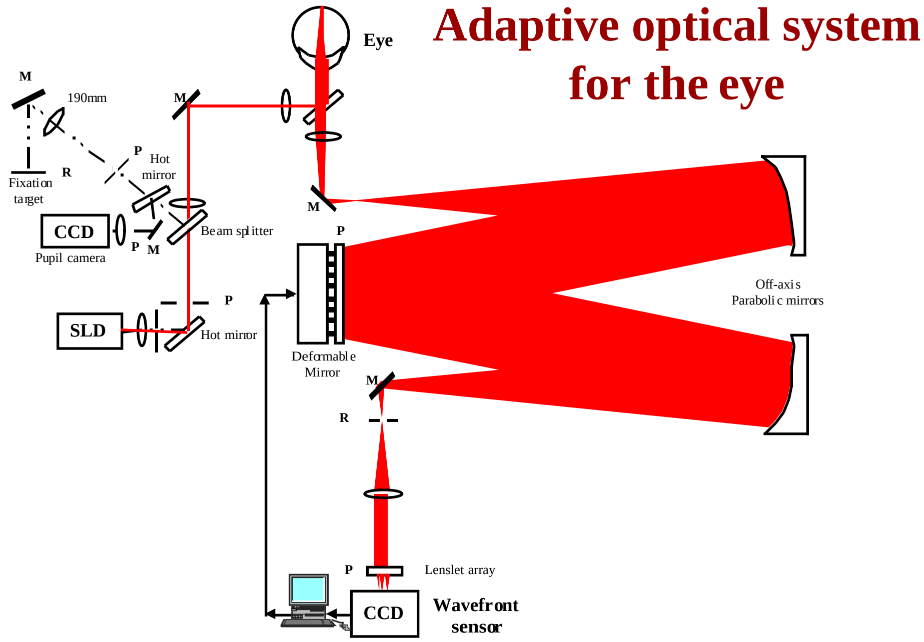
Adaptive optics can compensate for monochromatic aberrations



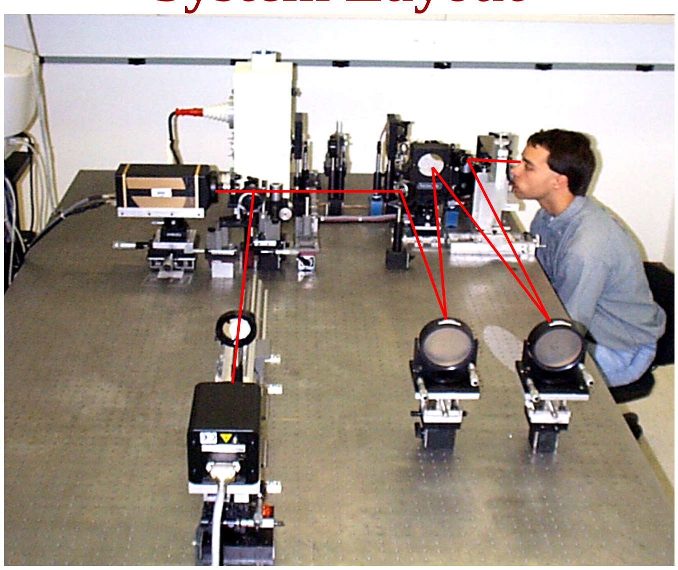
Rochester AO system

design and performance

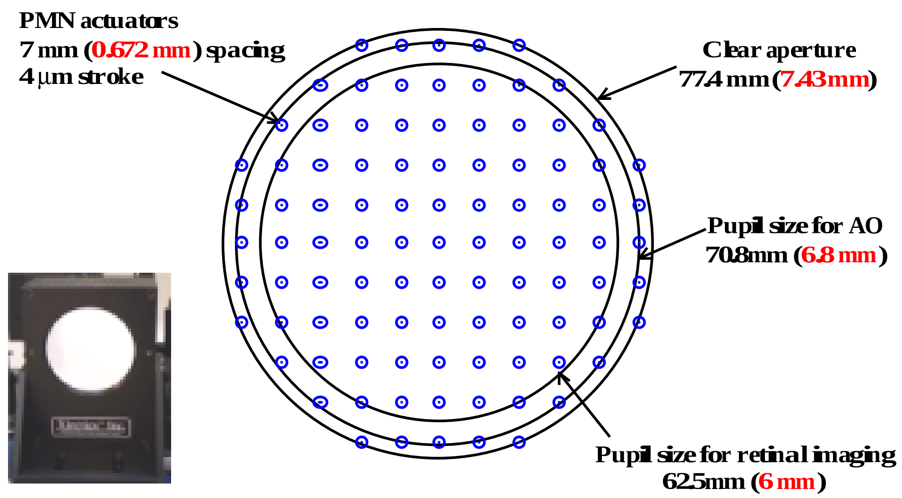
Adaptive optical system for the eye



System Layout



Wavefront correcting---Xinξtics 97 channel DM



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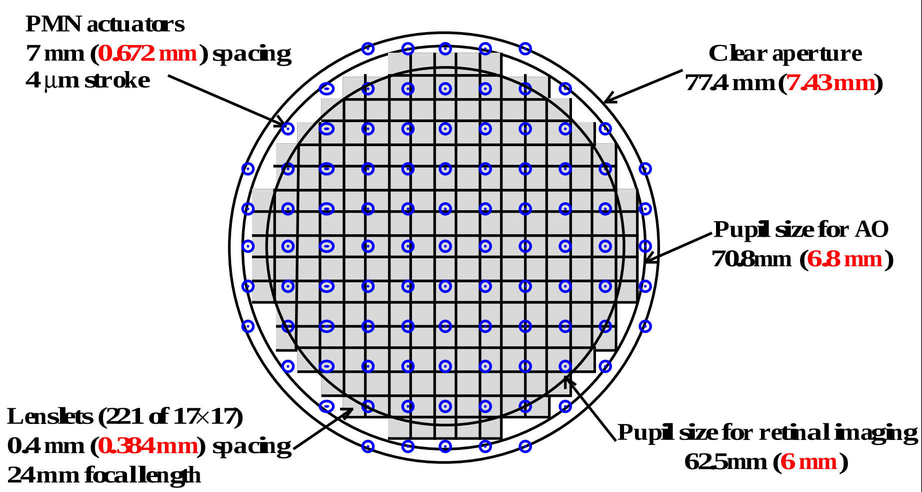
Geometry of three conjugate pupil planes



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Wavefront correcting ----Tip-tilt removed from slope vector

Original slope vector

$$S=\begin{bmatrix} s_{1_x} \\ s_{2_x} \\ \vdots \\ s_{M_x} \\ s_{1_y} \\ s_{2_y} \\ \vdots \\ s_{M_y} \end{bmatrix}$$

x-tilt component $S_x = \dfrac{\sum_{i=1}^{M} s_{i_x}}{M}$

y-tilt component $S_y = \dfrac{\sum_{i=1}^{M} s_{i_y}}{M}$

New slope vector

$$S=\begin{bmatrix} s_{1_x}-S_x \\ s_{2_x}-S_x \\ \vdots \\ s_{M_x}-S_x \\ s_{1_y}-S_y \\ s_{2_y}-S_y \\ \vdots \\ s_{M_y}-S_y \end{bmatrix}$$

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Wavefront correcting----Direct slope control algorithm

$$\boldsymbol{V} = \boldsymbol{D}^{+}\boldsymbol{S}$$

voltage to update actuators

slope influence function

slope from WFS

$$V=\begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_N \end{bmatrix}$$

$$D=\begin{bmatrix} s(1,1)_x & s(2,1)_x & \cdots & s(N,1)_x \\ s(1,2)_x & s(2,1)_x & \cdots & s(N,2)_x \\ \vdots & \vdots & \vdots & \vdots \\ s(1,M)_x & s(2,M)_x & \cdots & s(N,M)_x \\ s(1,1)_y & s(2,1)_y & \cdots & s(N,1)_y \\ s(1,2)_y & s(2,2)_y & \cdots & s(N,2)_y \\ \vdots & \vdots & \vdots & \vdots \\ s(1,M)_y & s(2,M)_y & \cdots & s(N,M)_y \end{bmatrix}_{2M\times N}$$

$$S=\begin{bmatrix} s_{1_x} \\ s_{2_x} \\ \vdots \\ s_{M_x} \\ s_{1_y} \\ s_{2_y} \\ \vdots \\ s_{M_y} \end{bmatrix}$$

M: total number of lenslets (221)
N: total number of actuators (97)

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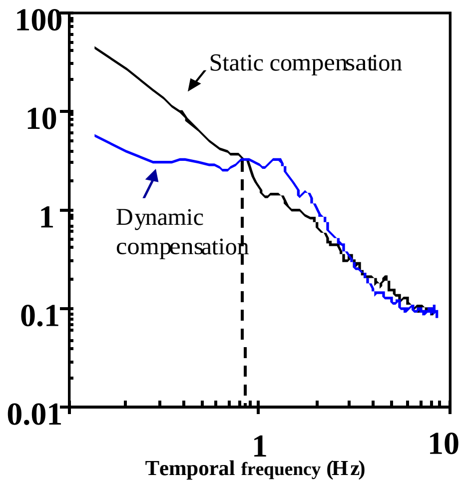
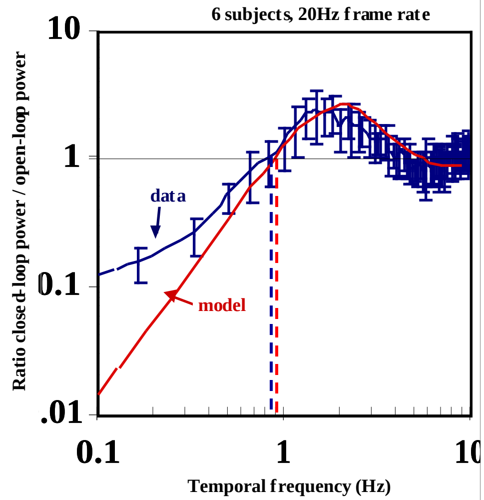
System performance---Dynamic compensation

Average wavefront power spectrum



Wavefront disturbance rejection

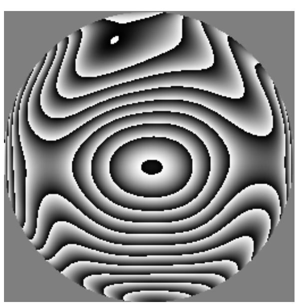


Model: 0.9Hz, Experimental data: 0.85Hz

Hofer, Chen, Yoon, Singer, Yamauchi, Williams, Optics Express, 2001

System performance---Aberration correction

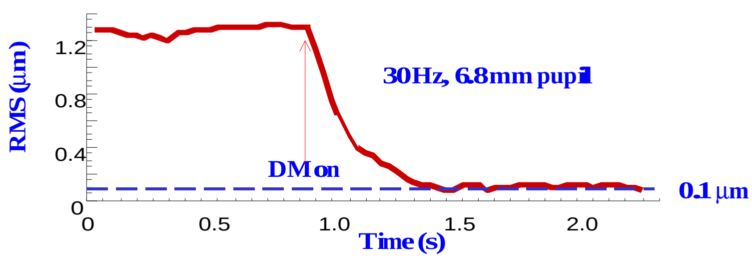
GYY, 6.8 mm pupil, 550 nm



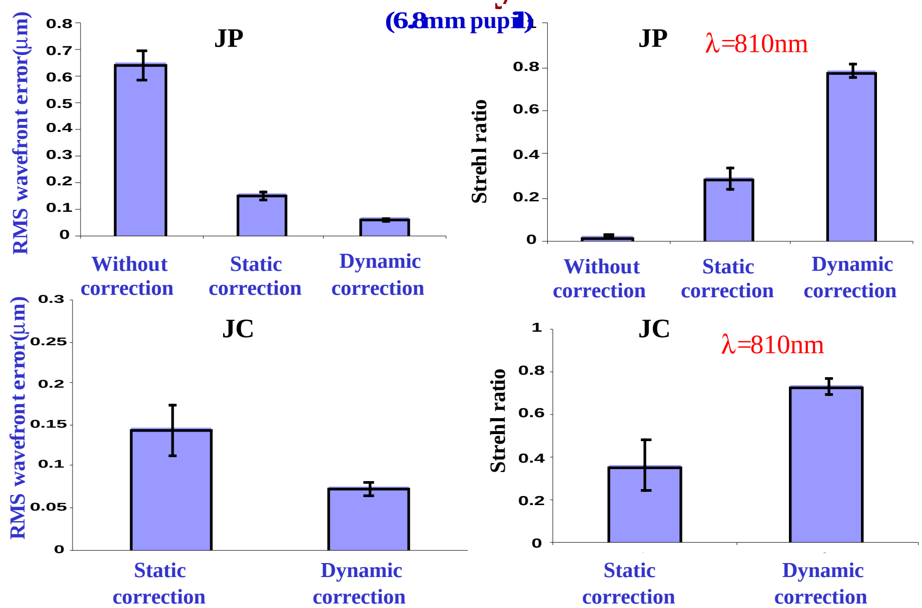
Wave aberration

GYY, 6.8 mm pupil, 550 nm

Point spread function



Static correction vs. dynamic correction



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What can AO do for vision science?

AO for imaging retina

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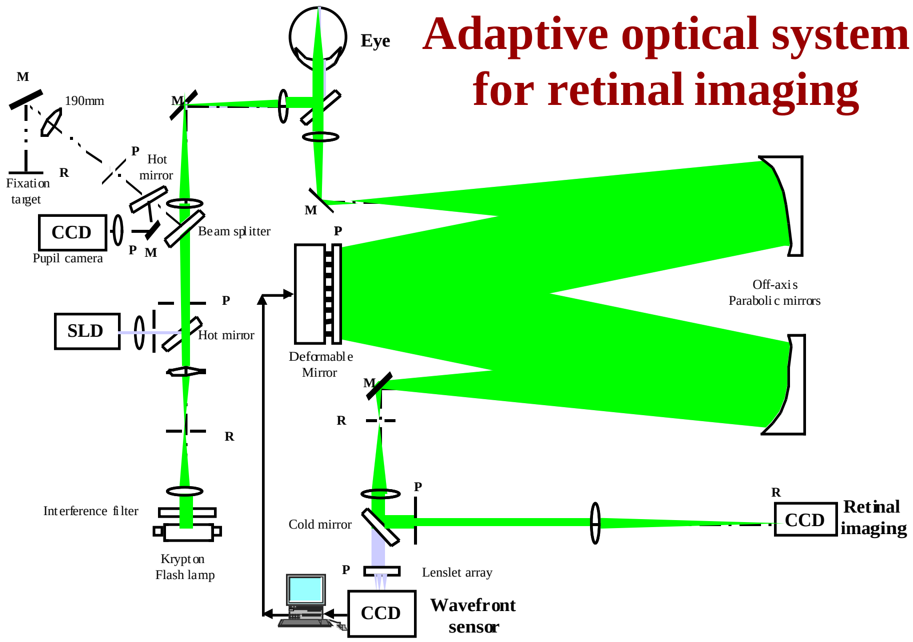
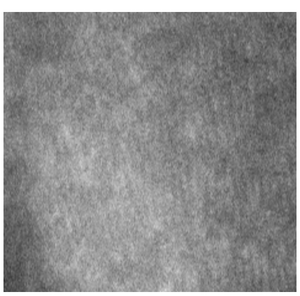
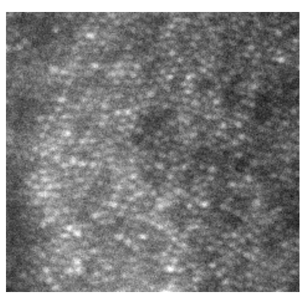
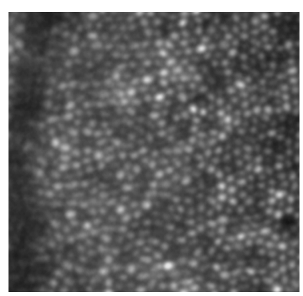
Adaptive optical system for retinal imaging

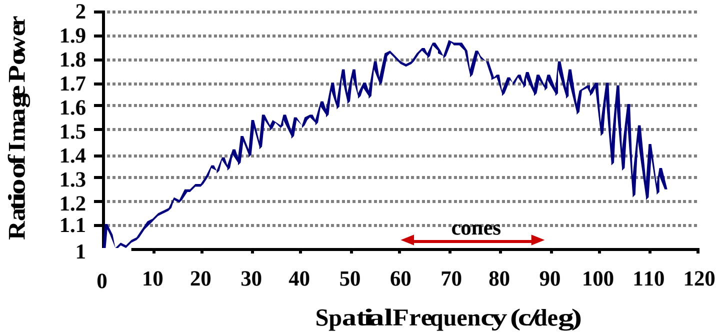


Adaptive optics enhances retinal image quality

Without adaptive optics (single image)	With adaptive optics (single image)	With adaptive optics (~10 images)
		

1 deg retinal eccentricity

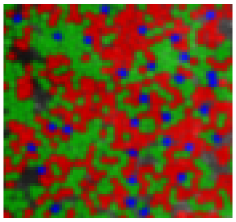
Increase in the power at the cone spatial frequencies with dynamic correction



The contrast of the cones in the retinal image increased by 30% with dynamic AO correction. This allows cone classing in the retinas of living human subjects

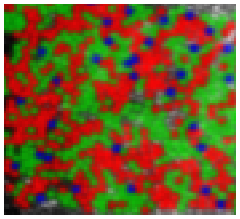
Cone classing with AO

YY, 1 deg nasal-superior



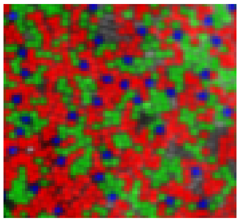
%L = 51 ± 5

AP, 1.25 deg nasal



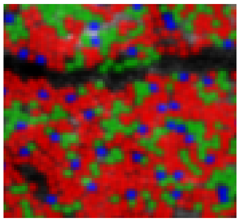
%L = 51 ± 3

MD, 1.25 deg nasal



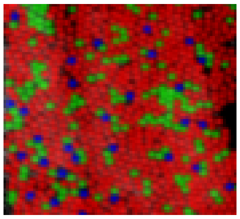
%L = 60 ± 3

JC, 1.25 deg temporal



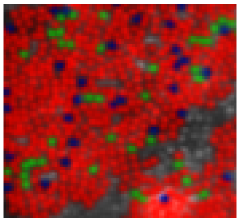
%L = 66 ± 4

JW, 1 deg temporal



%L = 80

BS, 1.25 deg nasal

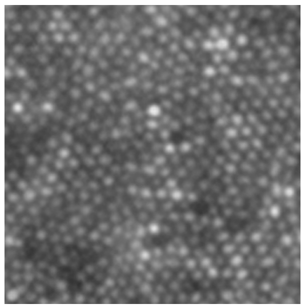


%L = 94 ± 3

Courtesy Heidi Hofer and Austin Roorda

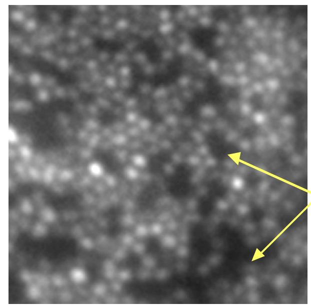
Adaptive Optics has discovered a new form of color blindness

MM – Protanope
Functional loss of L cones



Missing all L gene(s)

NC – Deuteranope
Functional and physical loss of M cones



Has "normal" gene array

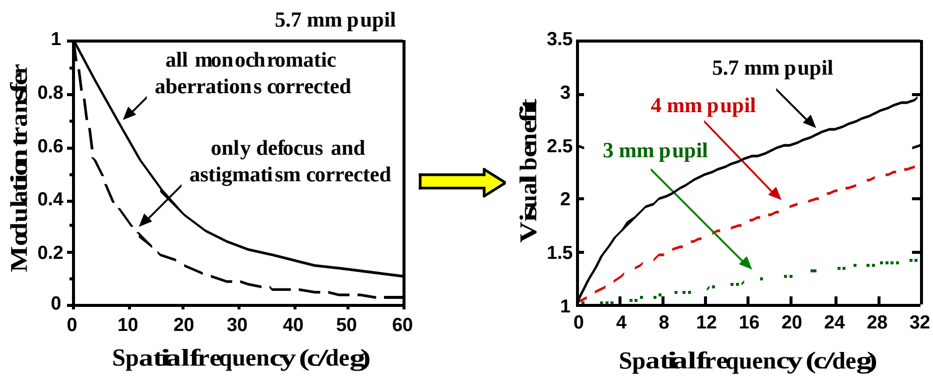
Joe Carroll, Heidi Hofer & David Williams, Rochester
Jay & Maureen Neitz, Medical College of Wisconsin

What can AO do for vision science?

AO for psychophysical experiment

Visual Benefit of correcting higher order aberrations

(Mean of 109 subjects)



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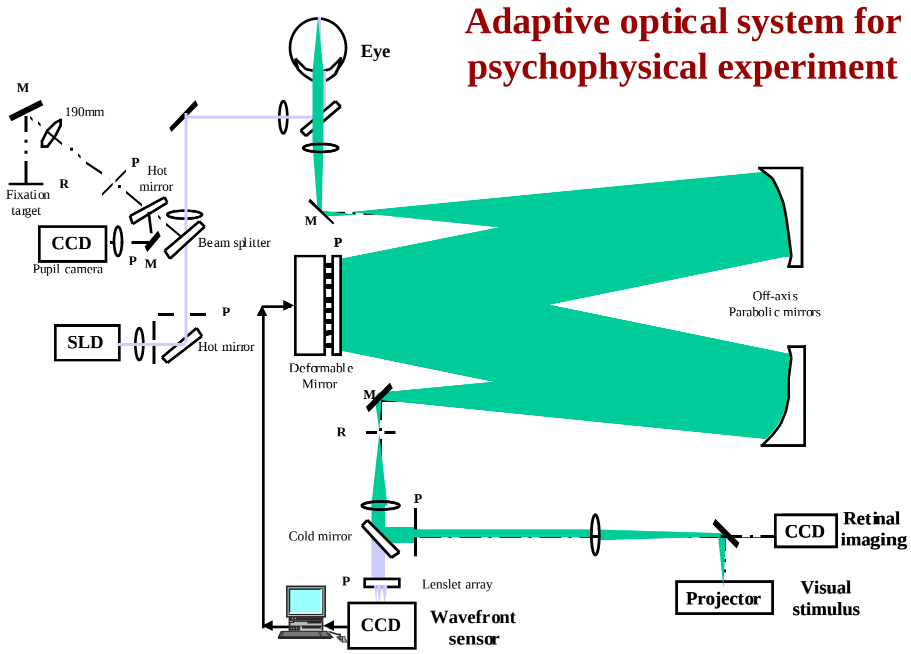
Guirao, Porter, Williams, Cox, JOSA A, 2002

Adaptive optical system for psychophysical experiment



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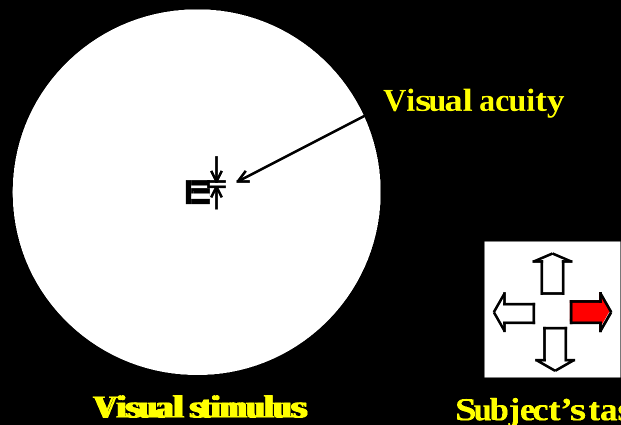
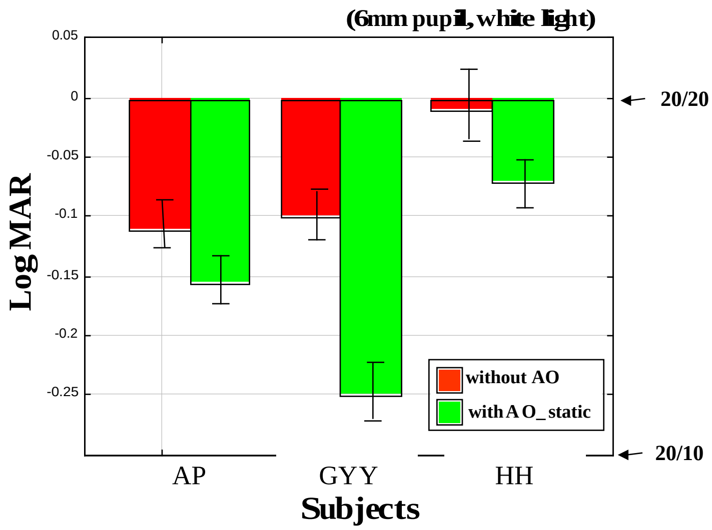
Visual acuity with letter E

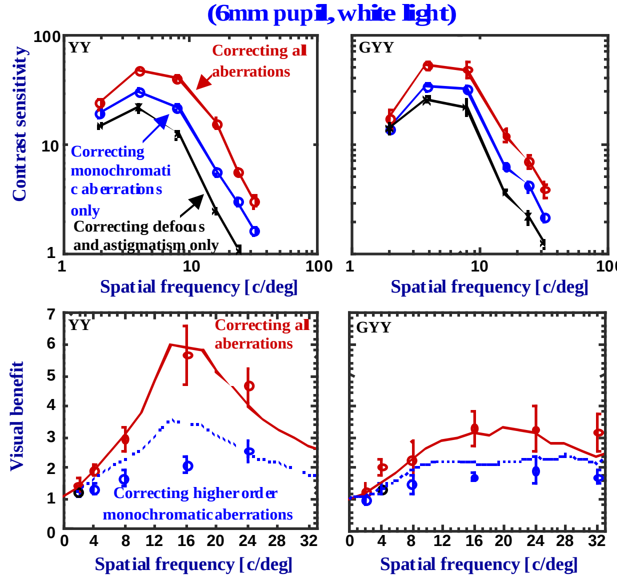


Visual acuity improved with AO



Contrast sensitivity improved with AO

(6mm pupil, white light)



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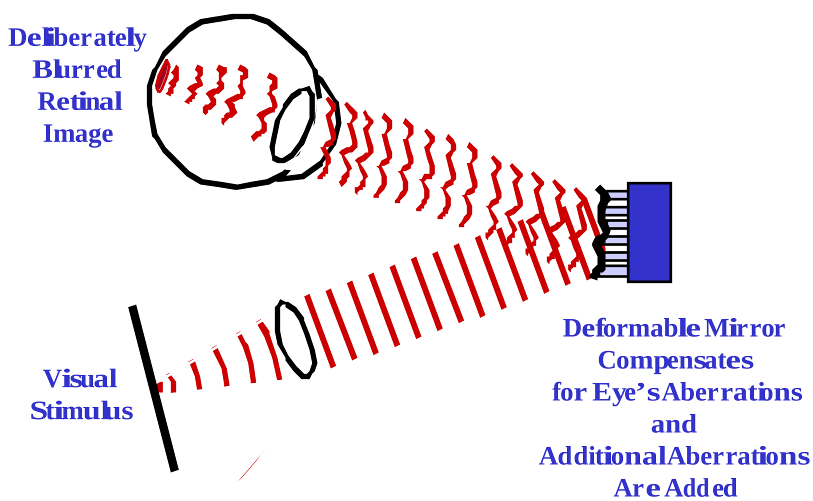
Yoon and Williams, J. Opt. Soc. Am. A, (2002)

Adaptive optics can generate aberrations



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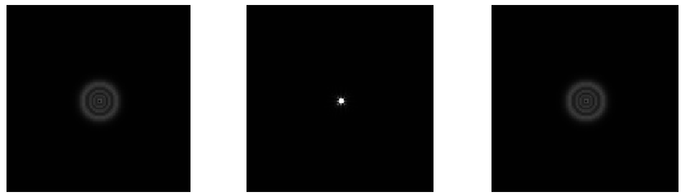
AO for accommodation experiment

Far step 0.5D	0 D	Near step -0.5D



Without higher order aberrations

With higher order aberrations

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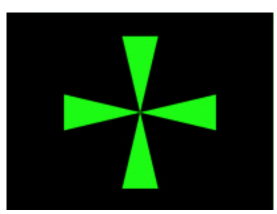
Chen L., Kruger P. and Williams D., *ARVO 2002.*

DM produces step changes in defocus without changing magnification

(Artificial eye, 6mm pupil)

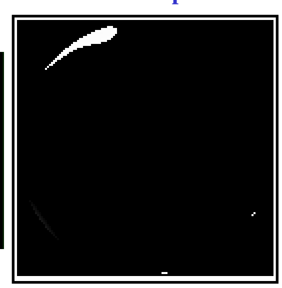
Far step

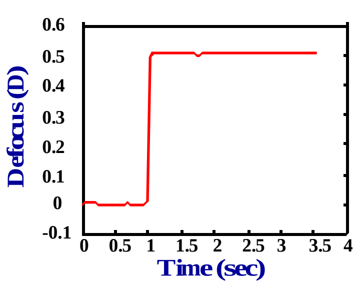
Maltese cross (550nm)



1 deg FOV

Near step





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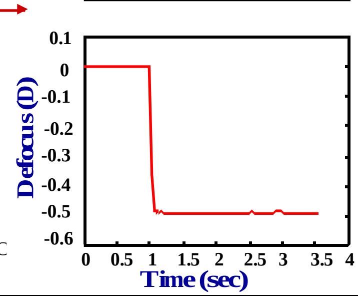

AO for image metrics to predict subjective image quality

Requires lengthy subjective procedure

Requires algorithm to transform wave aberration into optimum values for sphere, cylinder, and axis

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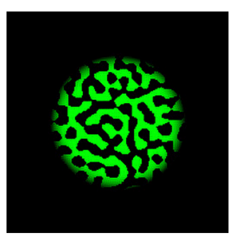
Chen L., Porter J., Singer B., Llorente L., Nagy L., and Williams D. R., *ARVO 2003*; Williams D. R., *ARVO 2002*.

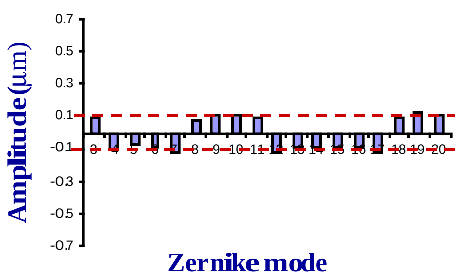
Blur matching

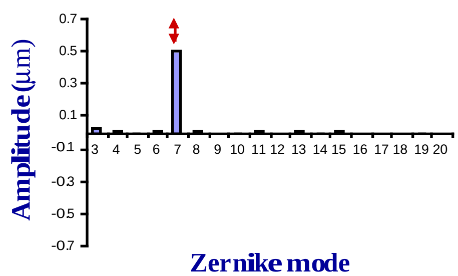
Standard Aberration



Stimulus

Test Mode





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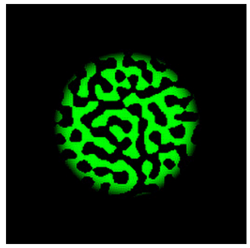
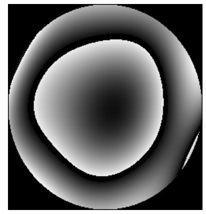
Subject Adjusts Amount of Defocus to Match the Blur from Each Patient's Wave Aberration

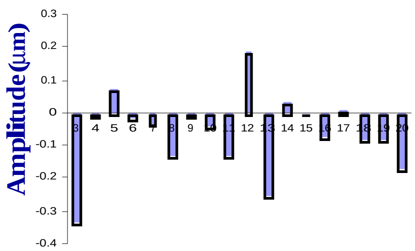
Patient wave aberration

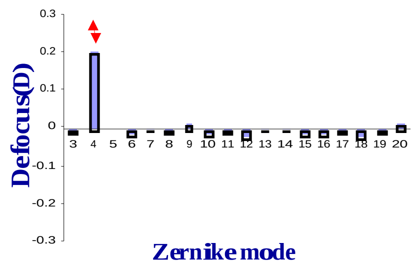


Stimulus



Defocus





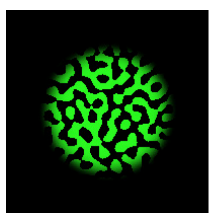
Does the brain compensate to the eye's optics defects?

Though HOA existing the eye always blur the retinal image, our subjective impression is that the vision world is always sharp and clear, suggesting that the brain might compensate their subjective blur influence.

Wave Aberration

Angle = 0 deg

Factor = 1



Stimulus

550nm wavelength

1 degree FOV

Rotated Aberration

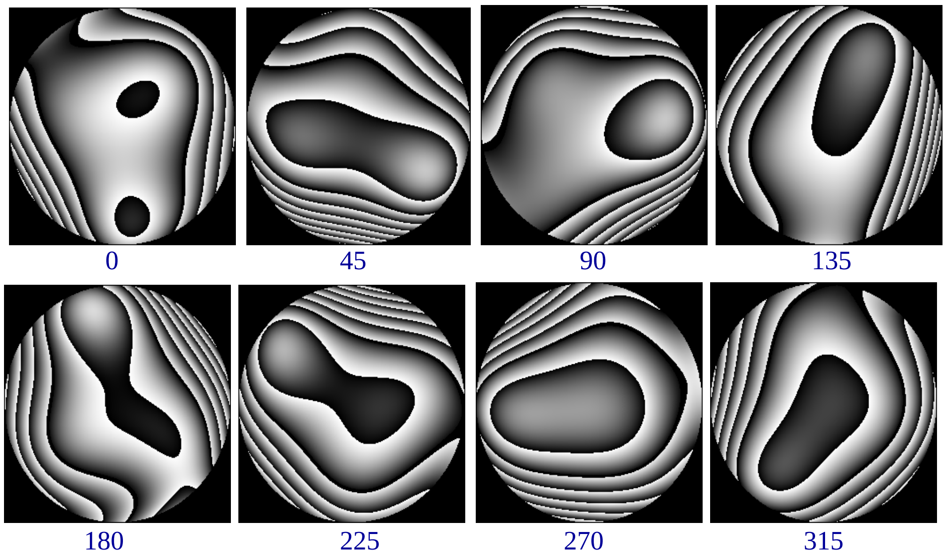
Angle = 45 deg

Factor = 0.6

Artal P., Chen L., Fernández E., Singer B., Manzanera S., and Williams D., JOV, 2004

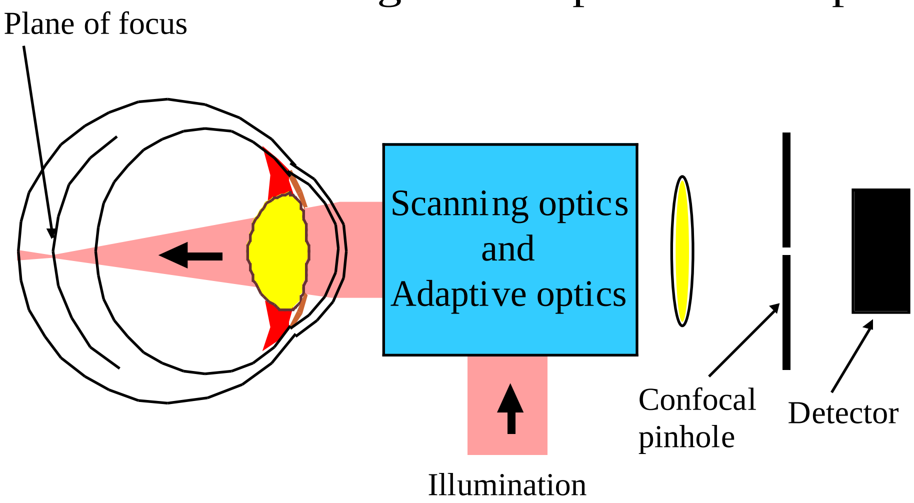
Wave aberration rotated counterclockwise

(MC, 6mm pupil)



Confocal Scanning Laser Ophthalmoscopy with Adaptive Optics

AO Scanning Laser Ophthalmoscope



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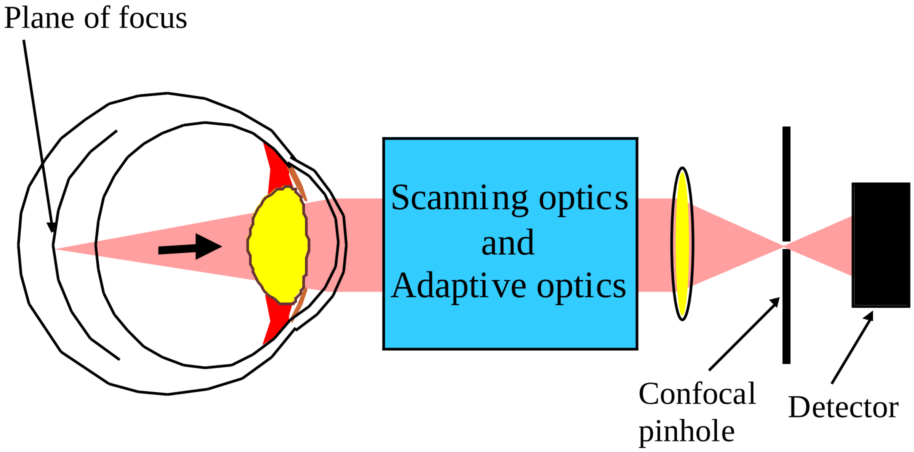
Scattered Light from the Plane of Focus



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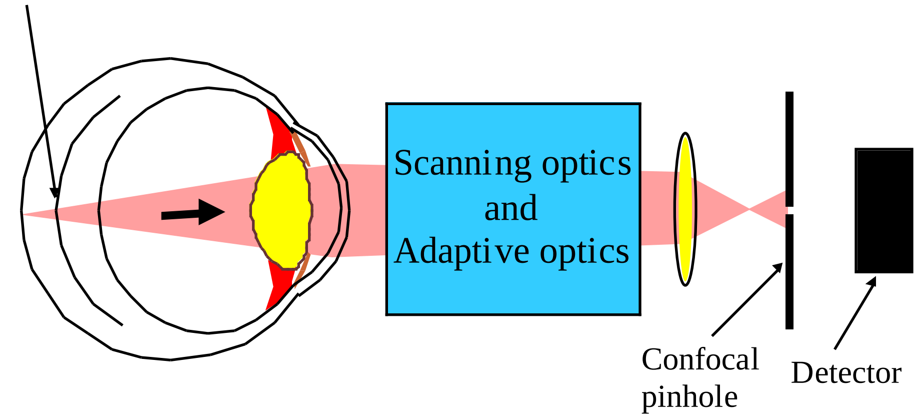
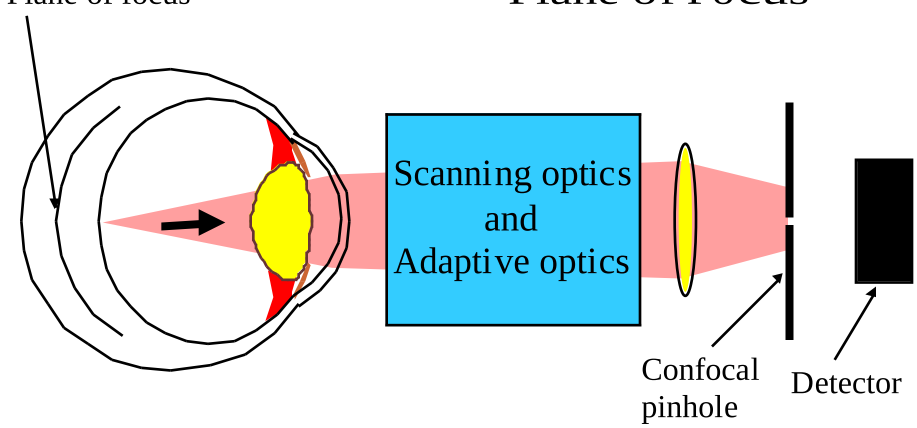
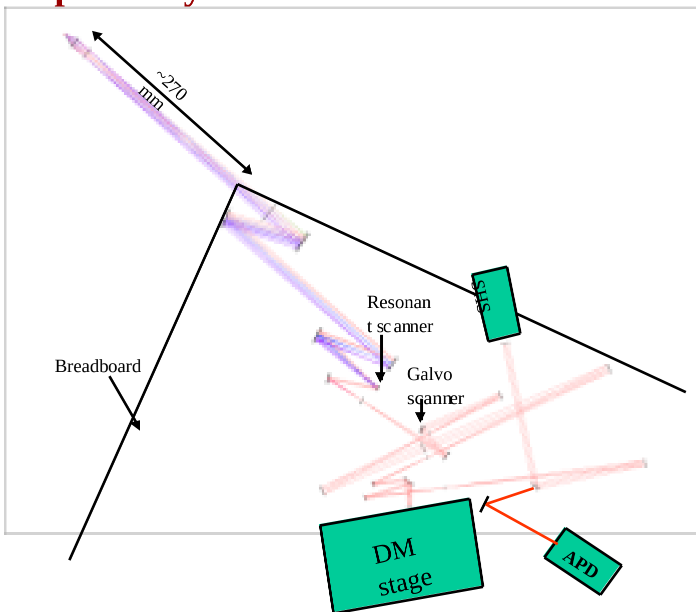
Scattered Light from *Behind* the Plane of Focus



Scattered Light from *Before* the Plane of Focus



Optical layout of Rochester SLO with AO



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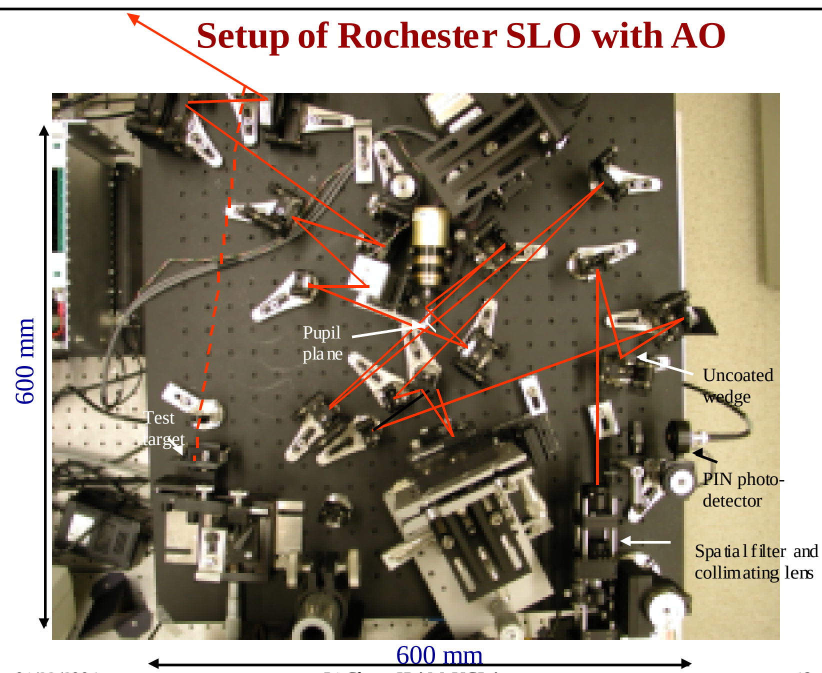
Setup of Rochester SLO with AO



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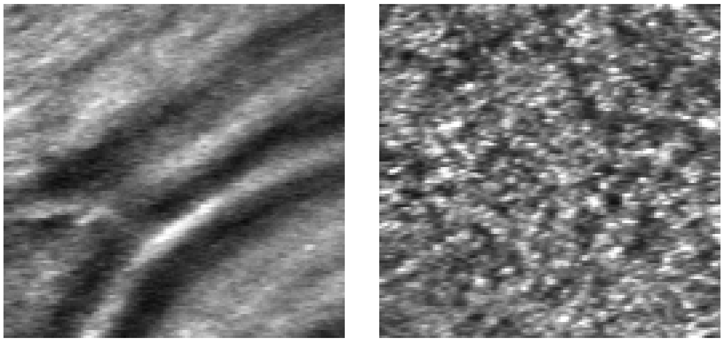
Retinal images with Rochester confocal SLO

(1.5 degree, without AO)



Summary

- **Rochester's real time AO system for vision science**
  - **97 actuator deformable mirror**
  - **221 lenslet for wavefront measurement**
  - **realtime compensation up to 30Hz**
  - **Closed loop bandwidth 0.85Hz**
- **This AO system can greatly reduce the aberrations in the eye to achieve nearly diffraction-limited performance.**
  - **High resolution retinal images can be obtained automatically and quickly**
  - **AO can improve visual performance**
  - **There are a number of applications of adaptive optics for basic science (color vision) and medical (laser refractive surgery, and diagnosis and treatment of retinal diseases).**