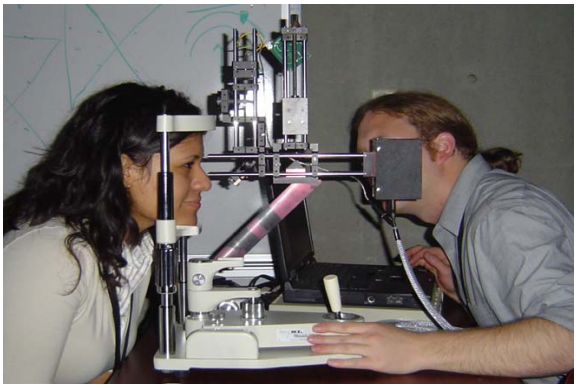
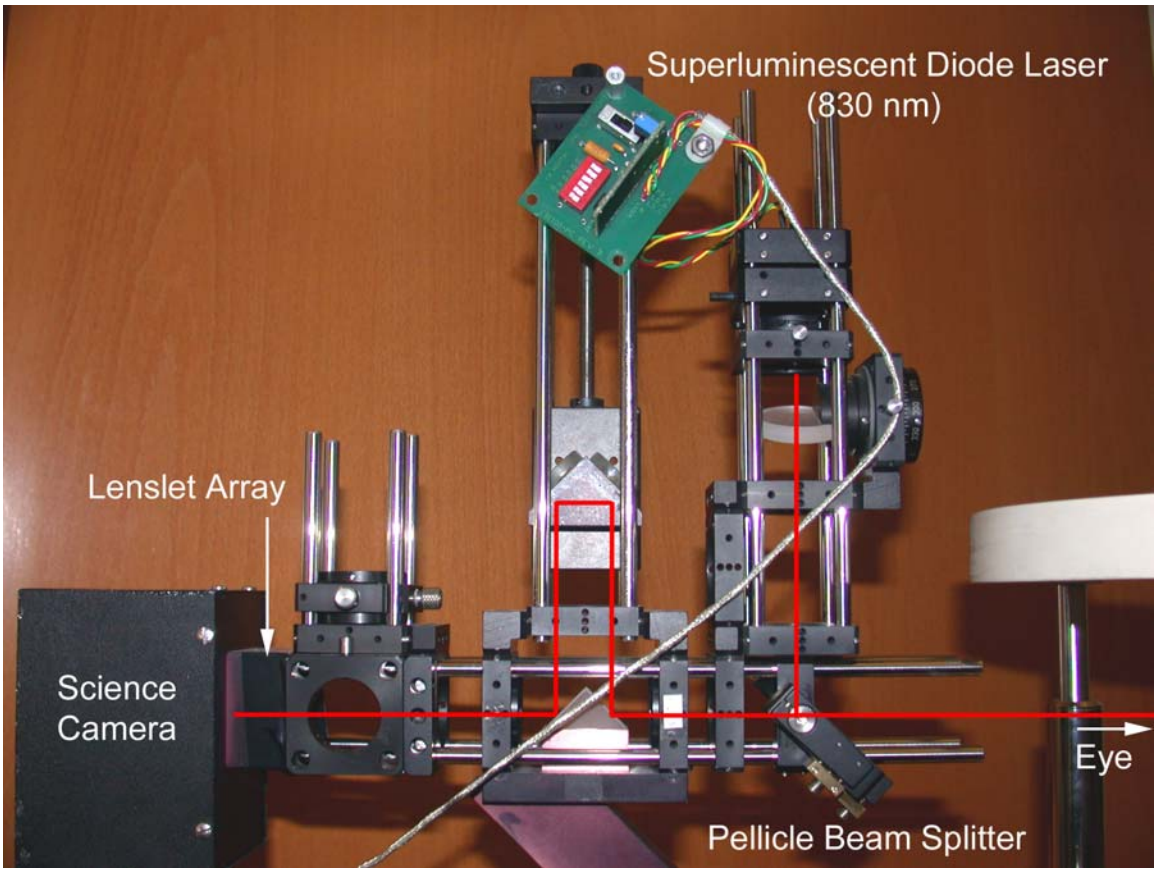
CfAO Summer School
Vision Science Activity



Vision Science Wavefront Sensor:
A Shack-Hartman wavefront sensor designed for clinical measurement of the aberrations of the human eye.

Components:
Laser: 830 nm superluminescent diode (Hamamatsu L8414-04)
Lenslet Array: 7.6 mm focal length, 330 micron diameter
Camera: PixeLINK 1024x1280 (1.3 megapixel) CCD w/ Firewire interface



Wavefront Aberrations

- In the eye, the wavefront aberrations are described by Zernike polynomials.

$$W(\rho,\theta)=\sum_n\sum_m C_n^m N_n^m Z_n^m$$

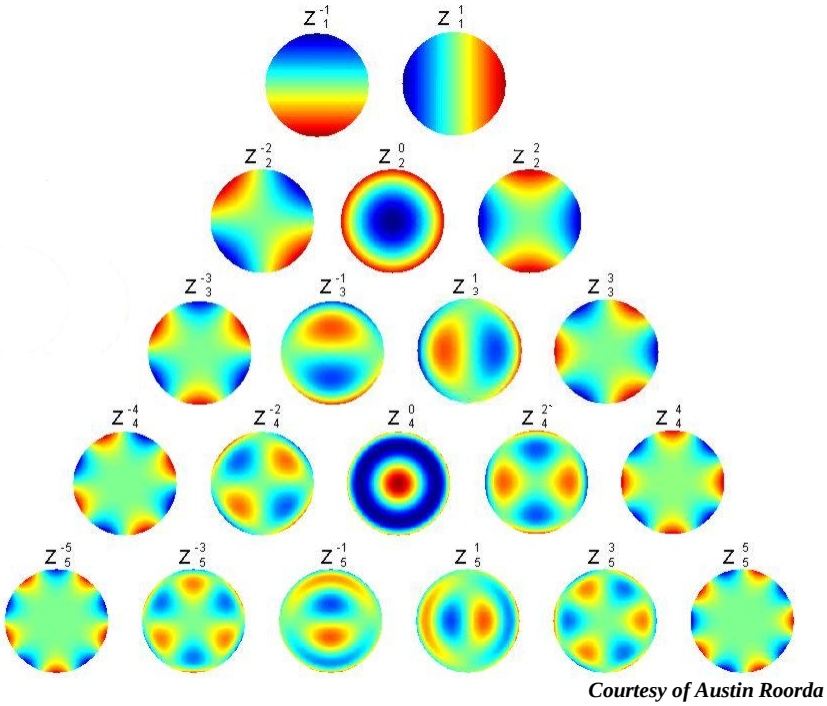
where ρ and θ describe the pupil position in normalized polar co-ordinates, C_n^m is the coefficient

$$Z_n^m=\begin{Bmatrix} R_n^{|m|}\cos m\theta & m\geq 0 \\ R_n^{|m|}\sin m\theta & m<0 \end{Bmatrix}$$

$$R_n^{|m|}=\sum_{s=0}^{\frac{n-|m|}{2}}(-1)^s\frac{(n-s)!}{s!\left(\frac{n+|m|}{2}-s\right)!\left(\frac{n-|m|}{2}-s\right)!}\rho^{n-2s}$$

$$N_n^m=\sqrt{\frac{2(n+1)}{1+\delta_{m0}}}$$

- *n* is the radial order & *m* is the meridional frequency
- The root-mean-square wavefront aberration gives a general indication as to the quality of the optical system.
- The value of the coefficient for each individual Zernike term is the root-mean-square for that aberration type.

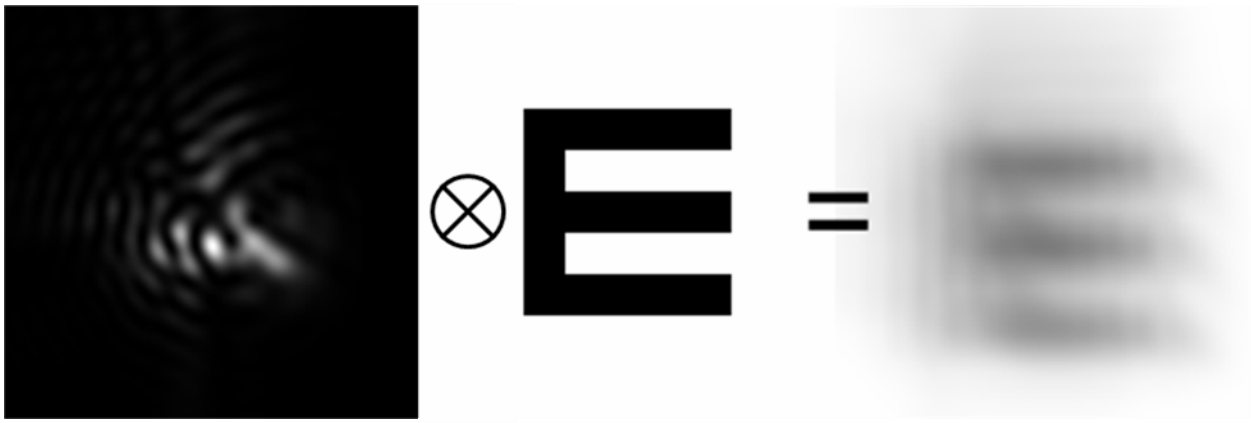


Courtesy of Austin Roorda

n	*m*	N_n^m	Z_n^m	**Aberration Type**
0	0	1	1	Piston
1	-1	2	$\rho\sin\theta$	Tip
1	1	2	$\rho\cos\theta$	Tilt
2	-2	$\sqrt{6}$	$\rho^2\sin 2\theta$	Astigmatism, axis ±45°
2	0	$\sqrt{3}$	$2\rho^2-1$	Defocus
2	2	$\sqrt{6}$	$\rho^2\cos 2\theta$	Astigmatism, axis 0° & 90°
3	-3	$2\sqrt{2}$	$\rho^3\sin 3\theta$	Trefoil
3	-1	$2\sqrt{2}$	$(3\rho^3-2\rho)\sin\theta$	3rd order Vertical Coma
3	1	$2\sqrt{2}$	$(3\rho^3-2\rho)\cos\theta$	3rd order Horizontal Coma
3	3	$2\sqrt{2}$	$\rho^3\cos 3\theta$	Trefoil
4	-4	$\sqrt{10}$	$\rho^4\sin 4\theta$	Quadrafoil
4	-2	$\sqrt{10}$	$(4\rho^4-3\rho^2)\sin 2\theta$	2nd order Astigmatism
4	0	$\sqrt{5}$	$6\rho^4-6\rho^2+1$	3rd order Spherical
4	2	$\sqrt{10}$	$(4\rho^4-3\rho^2)\cos 2\theta$	2nd order Astigmatism
4	4	$\sqrt{10}$	$\rho^4\cos 4\theta$	Quadrafoil

Point Spread Function and Optical Transfer Function

- The image of any given incoherent object produced by an optical system may be fully described with knowledge of the object and the pupil function.



- In the Fraunhofer limit, the pupil function is given by the equation.

$$\mathrm{P}(x,y) = P(x,y)e^{-\frac{2\pi i}{\lambda}W(x,y)}$$

where λ is the wavelength of light passing through the optical system, $P(x,y)$ describes the shape and intensity transmission of the pupil, and $W(x,y)$ describes any aberrations of the wavefront in the pupil plane.

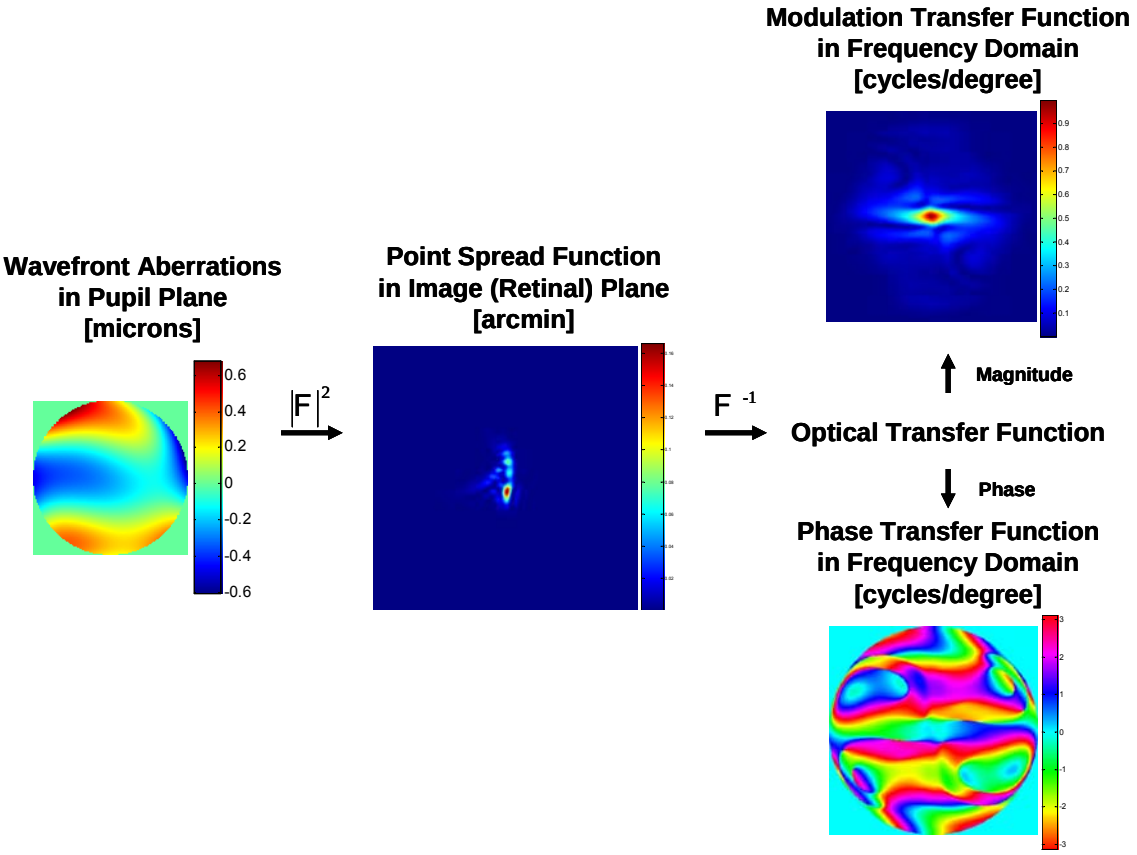
- For a clear aperture, $P(x,y)$ is 1 inside the pupil and 0 outside of the pupil. In the eye, it may also be described by a Gaussian to model the Stiles-Crawford effect (directional sensitivity of cone photoreceptors).
- The point spread function (PSF) is the image of a point source as imaged through the optics of the eye. It is affected by diffraction, scatter and aberrations. Neglecting scatter,

$$PSF = \left|\mathrm{F}\{\mathrm{P}(x,y)\}\right|^2$$

- The optical transfer function (OTF) gives an indication of the image quality in the spatial frequency domain.

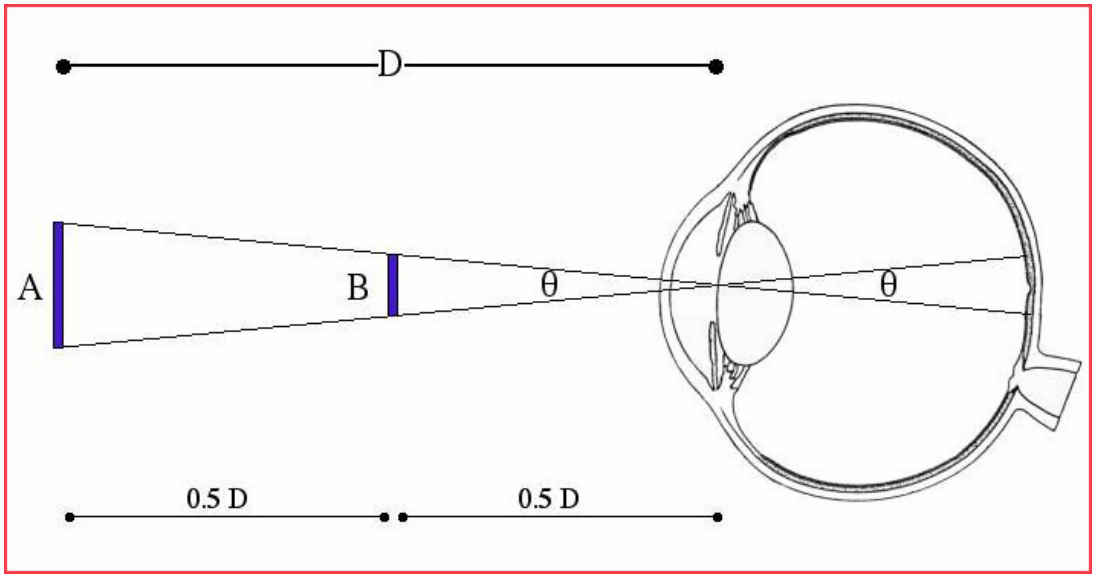
$$OTF = \mathrm{P}(x,y) * \mathrm{P}^*(x,y) = \frac{\mathrm{F}^{-1}\{PSF\}}{\mathrm{F}^{-1}\{PSF\}\Big|_{Fx=0,Fy=0}} = MTFe^{iPTF}$$

- The modulation transfer function (MTF) is the modulus of the complex OTF.
- The phase transfer function (PTF) is the phase portion of the complex OTF.



Visual angle

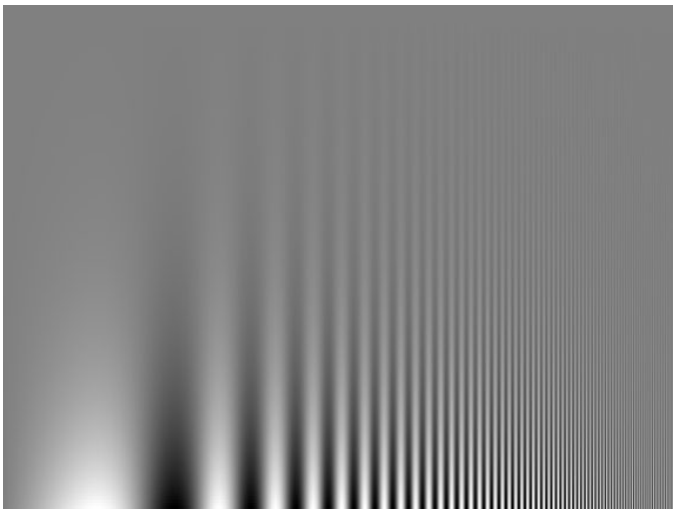
- Minimum separation between pattern features.
- Visual angle: for small angles $\theta = \frac{A}{D}$

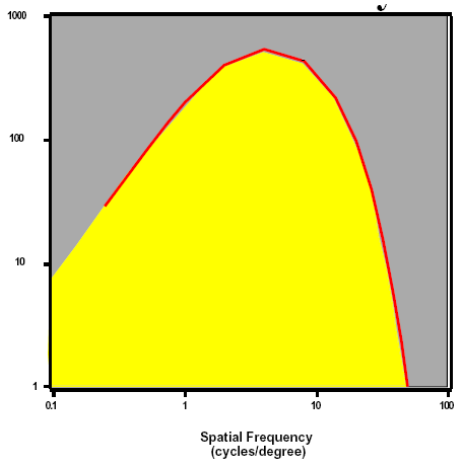


- Under ideal conditions, humans can resolve gratings (multiple cycles that include a light and a dark bar) where one cycle subtends an angle of ~1 minute of arc on the retina (a 60 cycles per degree grating).
- This is one of the fundamental limits of vision.

Contrast Sensitivity Function

- Contrast sensitivity is obtained by measuring the smallest amount of contrast needed to detect the target (the contrast threshold), and sensitivity is defined as the reciprocal of the threshold contrast.
- The high frequency cut-off of the CSF is about 60 cycles per degree, at which point 100% contrast is needed to detect the target.





Refractive Error

- Emmetropia: light rays from infinity come to a focus on the retina.
- Myopia (nearsightedness): light from infinity focuses in front of the retina, corrected with negative lenses.
- Hyperopia (farsightedness): light from infinity comes to a focus behind the retina, corrected with positive lenses.
- Astigmatism: an eye has unequal surface curvatures creating differing powers along principle meridians, corrected with the use of toric lenses.
- The spectacle prescription or refractive error is usually described in negative cylinder form as

$$S - C \times \theta$$

where S is the spherical correction required, C is the toric correction and θ is the angle of the astigmatic correction. These can be calculated from the coefficients of the Zernike wavefront polynomial.

$$S = \frac{-4\sqrt{3}C_2^0 + 2\sqrt{6}\sqrt{\left(C_2^{-2}\right)^2 + \left(C_2^2\right)^2}}{r^2}$$

$$C = \frac{-4\sqrt{6}\sqrt{\left(C_2^{-2}\right)^2 + \left(C_2^2\right)^2}}{r^2}$$

$$\theta = \frac{1}{2}\tan^{-1}\left(\frac{C_2^{-2}}{C_2^2}\right)$$

First Exploration Questions

- How does pupil size affect vision? How does vision/environment affect pupil size?
- What is your depth of focus? How does refractive error and pupil size affect depth of focus?
- What is accommodation? What is your amplitude of accommodation? Does accommodation change with age?
- What is refractive error? What is my refractive error? What does 20/20 mean? What is it like to be nearsighted or farsighted?
- What is astigmatism and how does it affect vision? How is astigmatism corrected?
- Is there a relationship between vision and spatial frequency or contrast? How does refractive error affect low vs. high contrast vision? What is the cut-off spatial frequency of my vision?
- Why is my vision worse at night?
- How can you quantify quality of vision?

Second Exploration Questions

- What is it about my vision that makes it unique (different from other people)?
- Is there a relationship between the aberrations of my right & left eyes?
- How do different aberrations affect my vision quality? Do some aberrations affect my vision quality more than others? Is there a relationship between ocular aberrations or vision quality and the Zernike pyramid?
- How does vision quality change with pupil size? What happens to my vision if I correct defocus? Astigmatism? High-order aberrations?
- Are aberrations and vision quality affected by age? Gender? Prescription? Refractive surgery? Disease? Species? Development? Other? (2 groups)
- Is there a relationship between a Zernike term's root-mean-square and its radial order?
- How do different aberrations interact with one another? Do they add together or can they cancel each other out?

Activity Timeline

5 minutes	Introduction
20 minutes	Wavefront Sensor Demo
15 minutes	Starter & Choose 1st Question
30 minutes	Focused investigation & wavefront measurements
20 minutes	Introduction to Zernike Software & Choose 2nd Question

BREAK

50 minutes	Focused Investigation
10 minutes	Make a poster to answer your question
20 minutes	Sharing out: each group will have 2 minutes to present
10 minutes	Synthesis