Aberrations and Visual Performance: Part I: How aberrations affect vision

Raymond A. Applegate, OD, Ph.D.
Professor and Borish Chair of Optometry
University of Houston
Houston, TX, USA
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Diffraction, Aberrations and Visual Performance
I will:

- Discuss the optical factors influencing image quality and their calculation
- Discuss metrics of image quality
- Demonstrate how various aberrations affect visual acuity
- Demonstrate that aberrations interact to increase or decrease acuity
- Discuss progress in determining metrics predictive of visual performance
The optics of the eye is the first stage of vision. It is an extremely important stage but not the only stage.
The optical quality of the retinal image is defined by:

- Diffraction
- Pupil size
- Optical Aberrations
- Scatter
To understand diffraction, we need to understand the behavior of a wavefront as it passes through an aperture or by edge.
Wavefronts connect points having the same phase.

Figure 5-1 from MacRae, Krueger and Applegate, *Customized Corneal Ablation: The Quest for Super Vision*, Slack, Inc. 2001.
Rays of light are perpendicular to the wavefront.
If light traveled like bullets along the path of a ray, then an eye could not see a point source unless a ray from the point source passed through the aperture and into the eye.
This eye can see the light.
But not seen if viewed from here.
But the light can be dimly seen. Light is apparently bent by the aperture.
How can this be explained?
Huygens postulated that every point on a wavefront was the source of a secondary wavefront.
For an unbounded wave, the effect of the wavelets cancels except in the original direction where the effect is identical to the original wave motion.
However, for a bounded wavefront, the effects do not cancel.
Thus, light from the wavelets can reach the eye even though a straight line from the eye to the point source does not pass through the aperture.
Further, because the wavefront has been bounded with an aperture, the wavelets interact. The interaction has been described by Fresnel and is termed Fresnel diffraction.
A special and particularly interesting case of Fresnel diffraction, called Fraunhofer diffraction, occurs in the focal plane of aberration-free or nearly aberration-free imaging systems.
The Fraunhofer diffraction pattern of an axial point source defines the appearance of the point source in the image plane.
More importantly, Fraunhofer diffraction in an aberration-free imaging system defines the resolution limit of the system.
In a aberration-free system with a circular aperture the Fraunhofer diffraction pattern is circular with a central bright spot referred to as an Airy disc.
Fraunhofer diffraction defines the diffraction limited point spread function (PSF).

Airy disc
The diameter of the Airy disc varies with pupil diameter.
The radius of the Airy disc increases as pupil size decreases.

\[ r = 1.22\lambda \ (F\#) \]
That is, the diameter of the best possible image of a point varies inversely with pupil diameter.
Diffraction only

1 mm         2 mm         3 mm         4 mm

5 arc min.

5 mm        6 mm        7 mm        8 mm

5 arc min.
Consequently, the best resolution in an aberration-free optical system occur when the aperture is the largest.
Now let’s see what happens to images in an aberration-free optical system as pupil size decreases increasing the Airy disc size.
We can explore the impact of diffraction on the retinal image by convolving an object with the PSF of the optical system to generate a simulation of the retinal image.
Object \hspace{1cm} PSF \hspace{1cm} Image

\textbf{Convolution}
Defocus = 0 D; RMS WFE = 0 μm
Airy disc diameter = 2.8 μm

Image Simulation
View D: 4.0000 ft, Height: 0.8437 in, Angle: 1.0070 deg

Pupil Diameter = 8.00 mm

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Defocus = 0 D; RMS WFE = 0 µm
Airy disc diameter = 5.6 µm

Image Simulation

View D: 4.0000 ft, Height: 0.8437 in, Angle: 1.0070 deg

Pupil Diameter = 4.00 mm
Defocus = 0 D; RMS WFE = 0 μm
Airy disc diameter = 11.2 μm

Image Simulation
View D: 4.0000 ft, Height: 0.8437 in, Angle: 1.0070 deg

5 arc min.

Pupil Diameter = 2.00 mm

© RAA
Defocus = 0 D; RMS WFE = 0 µm
Airy disc diameter = 22.4 µm

Image Simulation
View D: 4.0000 ft, Height: 0.8437 in, Angle: 1.0070 deg

Pupil Diameter = 1.00 mm

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Defocus = 0 D; RMS WFE = 0 \( \mu \text{m} \)
Airy disc diameter = 44.8 \( \mu \text{m} \)

Image Simulation
View D: 4.0000 ft, Height: 0.8437 in, Angle: 1.0070 deg

Pupil Diameter = 0.50 mm
Defocus = 0 D; RMS WFE = 0 \, \mu m
Airy disc diameter = 89.6 \, \mu m

Image Simulation
View D: 4.0000 ft, Height: 0.8437 in, Angle: 1.0070 deg

Pupil Diameter = 0.25 mm
How does a normal eye’s higher order aberrations affect the PSF?
Normal eye with sph. and cyl. corrected

1 mm  2 mm  3 mm  4 mm

5 arc min.

5 mm  6 mm  7 mm  8 mm
The point spread gets larger in a best spectacle corrected normal eye as the pupil enlarges due to ocular optical aberrations that can not be corrected with spherocylindrical lenses.
A typical normal eye best image quality is achieved when the PSF is the smallest. This occurs when the pupil is about 3mm.
Goal of an ideal correction

8mm normal eye
sph. and cyl.
corrected

8mm normal eye
Sph. and cyl. and
hi order aberrations
corrected
In the normal eye for pupil diameters less than 3mm, diffraction limits image quality. For pupil diameters greater than 3mm, optical aberrations limit image quality.
The optical quality of the retinal image is defined by:

- Diffraction
- Pupil size
- Optical Aberrations
- Scatter
The reality is not as simple as we tell our patients.
That is, the eye has higher order aberrations that become increasingly manifest as the pupil diameter increases.
Before diving into aberrations I thought you might want to know why Texans are so tough.
Why Texans are SO tough...
Object $\Rightarrow$ Fourier Transform $\Rightarrow$ Object Spectrum $\times$ OTF $\Rightarrow$ Image Spectrum

Convolve Object with PSF $\Rightarrow$ Image

Inverse Fourier Transform $\Rightarrow$ Image Spectrum
What is an object spectrum?
Fig. 12.1 (a) The stripe pattern is called a square-wave grating. Its intensity distribution is plotted next to it. (b) This grating is called a sine-wave grating, because the intensity is a sinusoidal function of location.
Fig. 12.2 The sine-wave grating in (b) has twice the spatial frequency of the grating in (a). When the two light distributions are added together, the distribution in (c) results. The intensity at each point in (c) is simply the sum of the intensities in the corresponding points in (a) and (b).
The addition of sine waves to synthesize a square wave. When the frequencies or the sine waves are $f$, $3f$, $5f$..., and the amplitudes are $A$, $1/3A$, $1/5A$..., the sum of an infinite series is a square wave.
Any object can be broken into an object spectrum.
Object

Fourier Transform

Object Spectrum

Con

XX

OTF

Image Spectrum

Image

Inverse Fourier Transform

Convolve Object with PSF

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The OTF is comprised of:

• The modulation transfer function (MTF)
• The phase transfer function (PTF)
What is the modulation transfer function (MTF)?
The MTF defines how much contrast as a function of spatial frequency is transferred by the optical system to the image plane.
Plotting contrast as a function of spatial frequency (MTF) for several pupil diameters for an aberration free eye clearly reveals how pupil size influences contrast as a function of spatial frequency.
Diffraction limited MTFs for 5 pupil diameters.

Nyquest Limit

20/20
20/8

MTF

Frequency (cycles/degree)

1mm 3mm 5mm 7mm 9mm

0 50 100 150 200 250

MTF

0.2 0.4 0.6 0.8 1
Diffraction Limited
6mm MTF
Diffraction Limited 6mm MTF

Normal eye 6mm MTF
Wave Trad.

1998

6mm

6.5mm 6mm

6mm diffraction limited

Normal

6mm

6mm Wave

6mm

6.5mm
Spatial Location

Figure 7-2 from MacRae, Krueger and Applegate, *Customized Corneal Ablation: The Quest for Super Vision*, Slack, Inc. 2001.
Figure 7-8 from MacRae, Krueger and Applegate, *Customized Corneal Ablation: The Quest for Super Vision*, Slack, Inc. 2001.
Now we have looked at two routes to the image.

- Convolution with the PSF
- Multiplication with the OTF
How is the OTF or PSF determined?
Spatial Domain

Object

Generalized Pupil Function

Point Spread Function

Image

Frequency Domain

Object Spectrum

Optical Transfer Function

Image Spectrum

Fourier Transform

Equals

Squared modulus of Fourier Transform

Convolved with

Autocorrelation

Inverse Fourier Transform

Multipled by

Courtesy of David Williams, University of Rochester
$P(x, y) = A(x, y)e^{-2\pi i \frac{w(x, y)}{\lambda}}$
Wavefront Error and Visual Performance

Raymond A. Applegate, OD, Ph.D.
Professor and Borish Chair of Optometry
University of Houston
Houston, TX, USA
Once the wavefront error is determined, image quality is defined.
To understand wavefront error it is useful to change our thinking from rays of light to waves of light.
Rays
Wavefronts
Rays

Wavefront after refraction
Waves and Rays

Ideal

Aberrated
Waves and Rays

Ideal

Aberrated
A particularly useful representation of wavefront error is to fit the error between the actual wavefront and the ideal wavefront with a Zernike expansion.
Fitting the error data with a Zernike expansion parcels the error into unique building blocks.
\[ Z(r^n, f \theta) = Z_n^m \]

- \( n \) = radial order
- \( m \) = angular frequency

Sine phase → Cosine phase
$$Z(r^n, f\theta) = Z_n^m$$

$n =$ radial order

$m =$ angular frequency

sine phase $\rightarrow$ cosine phase
Each weighted Zernike mode when added together form a representation of the actual WFE.
Machines to measure wavefront error are available today from a variety of sources and generally look very much like corneal topography units.
Wavefront error degrades the optical image it cannot improve image quality above the diffraction limit.
3mm pupil
Typical non-surgical eye
Best spectacle correction

WFE = 0.041 µm

3mm pupil Post LASIK >1yr
Happy patient 20/15 acuity
Best spectacle correction

WFE = 0.133 µm
Wavefront error defines the ideal compensating optic.
WFE specifies how much tissue or material to remove at every location across the pupil.
WFE specifies how much tissue or material to remove at every location across the pupil.

Wavefront retarded: Remove more material
WFE specifies how much tissue or material to remove at every location across the pupil.

Wavefront advanced:
Remove less material
Amount of material to remove = \( \frac{C + WFE}{n' - n} \)

Where:
- \( C \) = minimum amount of tissue to be removed
- \( WFE \) = wavefront error
- \( n' \) = optical index of the material light is entering
- \( n \) = optical index of the material light is leaving
But do higher order aberrations really matter?

- It depends on their magnitude.
- It depends on the pupil size
- It depends on our neural transfer function
- It depends on the visual task
- It depends on the object
Magnitude

For many clinical eyes that we have thrown into the garbage bag of irregular astigmatism, it is very important.
Pupil Size

For normal eyes the potential gains are significant for large pupil sizes and diminish as the pupil size gets small.
To understand impact of aberrations on visual performance, it is very helpful to know which aberrations are particularly bad and how they interact with each other.
Equally important to researchers and clinicians alike is the development of single value metrics of optical quality capable of predicting visual performance.
An important feature of the normalized Zernike expansion is that the magnitude of the coefficient for each mode reflects its relative contribution to the total wavefront error.
JH 09/28/00 6mm pupil Post LASIK >1yr

Wavefront Zernikes
Wavefront Zernikes

JH 09/28/00 6mm pupil Post LASIK >1yr
Just because the magnitude of the coefficient reflects its relative contribution to the total wavefront RMS error does not mean that the largest Zernike coefficient will affect vision the most.
Different modes of the Zernike expansion affect vision more than others.
Further, modes can combine to lessen the adverse visual effects or combine to further worsen visual performance.
Wavefront error fundamentally defines the optical properties of the eye and can be used to calculate other metrics of optical quality.
Higher-order aberrations

- Sph: 0.74 D
- Cyl: -0.63 D
- Axis: 8°
- LO RMS: 0.35 μm
- HO RMS: 0.24 μm
- TOT RMS: 0.43 μm
- Pupil: 4.00 mm
- Wavelength: 546 nm

Wavefront error

PSF

Fourier Transform

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Fourier Transform

Convolution

Image Simulation

View D: 4.000 ft, Height: 0.8437 in, Angle: 1.0070 deg
Such a transformation is a powerful tool for visualizing and quantifying the impact of aberrations on visual performance.
Notice in the following simulations that as the pupil size decreases WFE decreases despite the fact that the dioptic defocus remains constant.
Further, notice in the simulations that measuring wavefront error for a large pupil and comparing it to visual performance measured through a smaller pupil leads to erroneous conclusion.
To determine how ocular wavefront error affects visual performance one must measure both at the same pupil size.
Defocus = 0.25 D; RMS WFE = .58 $\mu$m

Image Simulation

View D: 4.0000 ft, Height: 0.8437 in, Angle: 1.0070 deg

Pupil Diameter = 8.00 mm
Defocus = 0.25 D; RMS WFE = 0.32 µm

Image Simulation

View D: 4.0000 ft, Height: 0.8437 in, Angle: 1.0070 deg

Pupil Diameter = 6.00 mm
Defocus = 0.25 D; RMS WFE = 0.14 µm

Pupil Diameter = 4.00 mm

Image Simulation
View D: 4.0000 ft, Height: 0.8437 in, Angle: 1.0070 deg
Defocus = 0.25 D; RMS WFE = 0.036 µm

Image Simulation
View D: 4.0000 ft, Height: 0.8437 in, Angle: 1.0070 deg

Pupil Diameter = 2.00 mm
Wavefront error tells us that the image is getting better. Dioptric error does not.
While we have demonstrated that visual acuity decreases with increasing wavefront error for any single mode...
we have also reported that all aberrations are not equal...

and that aberrations interact to increase or decrease visual performance.
\[ Z(r^n, f \theta) = Z_n^m \]

- \( n = \text{radial order} \)
- \( m = \text{angular frequency} \)

\( n = 2 \): Images 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14

\( m = -4 \to -3 \to -2 \to -1 \to 0 \to 1 \to 2 \to 3 \to 4 \)

Sine phase: Images 2, 3, 4, 5

Cosine phase: Images 6, 7, 8, 9

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Predicted Letters Gained or Lost

Zernike Coefficient

-12 -10 -8 -6 -4 -2 0 2 3 4 5 6 7 8 9 10 11 12 13 14

2nd Order 3rd Order 4th Order Sphere & Cylinder

HC Letters Gained or Lost

2nd Order

3rd Order

4th Order

Sphere & Cylinder

Zernike Coefficient

© RAA
Equivalent Diopters = 0.19 D
Equivalent Diopters = 0.19 D
Zernike terms interact to affect visual performance.
\[ Z(r^n, f \theta) = Z_n^m \]

- \( n = \text{radial order} \)
- \( m = \text{angular frequency} \)

Diagram:
- Sine phase
- Cosine phase

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\[
\sqrt{0.2^2 + 0.15^2} = 0.25 \quad \text{RMS in } \mu
\]
The SSCP Matrix is singular.
So if wavefront error and equivalent diopters do not serve well to explain the variations in visual performance, is there something better?
Regression Plot

Inclusion criteria: Total RMS is .25 from Metrics Data.svd

\[ Y = -12.764 + 12.029 \times X; \quad R^2 = .263 \]
Regression Plot
Inclusion criteria: Total RMS is .25 from Metrics Data.svd

Y = -9.887 + 6.031 * X; R^2 = .494
In addressing this question, it is important to remember that retinal image quality is the first step in the visual process.
Camera optics

Film

Developing

Enlarging Optics and Printing

Eye’s optics

Photoreceptors

Neural Processing

Visual Percept

The Mind’s Eye

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Camera optics

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Eye’s optics

Photoreceptors

Neural Processing

Visual Percept

The Mind’s Eye
The measurement of the wavefront error of the eye provides the best possible assessment of the retinal image quality.
It does not tell us how the brain transfers the image into a visual percept.
None-the-less, we do have good estimates of the neural transfer function in the typical normal eye.
Figure 7-9 from MacRae, Krueger and Applegate, *Customized Corneal Ablation: The Quest for Super Vision*, Slack, Inc. 2001.
Dioptric equivalent of 0.19 D

Regression Plot

Inclusion criteria: Total RMS is .25 from Metrics Data.svd

\[ Y = -12.107 + 19.827 \times X; \quad R^2 = .719 \]
Regression Plot
Inclusion criteria: Total RMS is .25 from Metrics Data.svd

Y = -12.107 + 19.827 * X; R^2 = .719
Finally, it is wise to remember that even if we know the optical and neural transfer functions of the eye we do not always know how the mind’s eye will interpret the information.
All is Vanity, By Gilbert
In Summary

• New clinically viable aberrometers are changing the way we correct the refractive errors of the normal and clinical eye.
• Zernike modes interact to increase or decrease visual perception.
• Pupil size plays an important role in visual perception.
• To compare the affects of aberrations on visual performance both have to be measured at the same pupil size.
In Summary

• The best visual image and best visual perception occurs when aberrations are minimized.

• New single parameter metrics calculated from wavefront error can be used to predict visual performance measures like acuity.
The animation, simulations, and graphics of WFE in this presentation were generated using a program call CTView.

www.sarverassociates.com
The eye graphics in this presentation were generated using a program call EyeView.

www.sarverassociates.com
Thank you