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Interactions Between Aberrations Increase or Decrease Visual Performance

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In the interest of full disclosure I consult for:

- Alcon, Inc.
- Sarver and Associates, Inc.
- I have proprietary interests in the WAT VQ metric and VQR
To explore these interactions, one needs to consider:

- Factors that affect retinal image quality
- The neural transduction of the retinal image
- The visual task
- Individual differences
Retinal Image Quality

- Diffraction
- Aberrations
- Scatter
- Chromatic Aberration
All of these optical factors filter the spatial information contained in the retinal image.
In the spatial domain

Diffraction only

1 mm
2 mm
3 mm
4 mm

5 arc min.

5 mm
6 mm
7 mm
8 mm

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In the frequency domain

Diffraction limited MTFs for 5 pupil diameters.
Object \rightarrow \text{PSF} \rightarrow \text{Image}

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

Pupil Diameter = 8.00 mm
Defocus = 0 D; RMS WFE = 0 μm
Airy disc diameter = 5.6 μm

Pupil Diameter = 4.00 mm
Defocus = 0 D; RMS WFE = 0 μm
Airy disc diameter = 11.2 μm
Pupil Diameter = 2.00 mm
Defocus = 0 D; RMS WFE = 0 μm
Airy disc diameter = 22.4 μm

Pupil Diameter = 1.00 mm
Pupil Diameter = 0.50 mm

Defocus = 0 D; RMS WFE = 0 μm
Airy disc diameter = 44.8 μm

Airy disc diameter = 44.8 μm

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Defocus = 0 D; RMS WFE = 0 µm
Airy disc diameter = 89.6 µm

Pupil Diameter = 0.25 mm
Clinical Implications of Diffraction Include:

- Diffraction fundamentally defines the upper limits of retinal image quality.

- Diffraction effects increase as pupil size decreases making the quality of the retinal image poorer and poorer.
Retinal Image Quality

- Diffraction
- Aberrations
- Scatter
- Chromatic Aberration
The eye has higher order wave aberrations that become increasingly manifest as the pupil diameter increases.
Diffraction Limited 6mm MTF

Normal eye 6mm MTF
For many clinical eyes (ie. keratoconics), it is important to correct the higher order aberrations for most any pupil size.

For the normal eye, the gains obtained by correcting higher order aberrations are primarily for large pupil sizes and diminish as the pupil size gets small.
In the past, a patient’s eye which could not be corrected with conventional sphero-cylindrical corrections, was often dismissed with a diagnosis of irregular astigmatism.

We are now in a position to attempt to correct these eyes.
3mm pupil
Typical non-surgical eye 20/15
Best spectacle correction

HO WFE = 0.041 µm

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

HO WFE = 0.133 µm

PSF

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VisualOpticsLab
Wave 2003

1998

6mm diffraction limited

Normal

6mm

6mm

Trad. 2003

6.5mm

6.5mm

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Clinical Implications of Wave Aberrations Include:

- The adverse effects on retinal image quality of wave aberrations in the normal healthy eye increase with pupil diameter.
- The highest fidelity retinal image (normal eye) occurs at a pupil diameter around 3mm.
- The effects of diffraction cause most eyes to see the same for pupil diameters < 2mm.
- Correlations between visual performance and wavefront aberrations must be made for the same pupil size.
Retinal Image Quality

- Diffraction
- Aberrations
- Scatter
- Chromatic Aberration
Pupil

Back-scattered

Forward-scattered

Reflected

Absorbed

Refracted

Image Plane

© RAA
Clinical Implications of Scatter Include:

• Despite the availability of a surgical cure, scatter resulting from cataract is the leading cause of legal blindness in the world.

• Scatter decreases image quality by “washing out” spatial detail in the retinal image.
Retinal Image Quality

• Diffraction
• Aberrations
• Scatter
• Chromatic Aberration
Since the index of refraction is the ratio of the speed of light in a vacuum to the speed of light in the new medium, the index of refraction is greater for short wavelengths than it is for longer wavelengths.
As light enters the eye, the higher the refractive index the greater the angle of refraction as dictated by Snell’s law.

\[ n \sin i = n' \sin i' \]
The difference in longitudinal chromatic aberration between 486 and 656 nm is just over 1 D.

Adapted from Bennet & Rabbetts, 1989
Clinical Implications of Chromatic Aberration Include:

• Chromatic aberration degrades the retinal image.

• The degradation in image quality is partially offset by the spectral sensitivities of the receptors.

• Chromatic aberration is capitalized on by the duochrome test.

• The adverse effects of low to moderate levels of monochromatic aberrations are partially offset by chromatic aberration.
Diffraction, wave aberrations, chromatic aberration and scatter along with pupil diameter affect the optical quality of the retinal image.
To explore these interactions, one needs to consider:

• Factors that affect retinal image quality
• The neural transduction of the retinal image
• The visual task
• Individual differences
It simplistic to believe that retinal image quality is the only factor affecting visual performance?
What about neural processing?
Eye’s optics

Photoreceptors

Neural Processing

Visual Percept
The Mind’s Eye

Filters
Samples
Filters
Filters

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The eye’s optical system filters spatial information and the photoreceptors sample the retinal image and the neural pathways filters the optical image.
Sampling by Foveal Cones

Projected Image

20/20 letter

Sampled Image

5 arc minutes

Courtesy Austin Roorda
Sampling by Foveal Cones

Projected Image

Sampled Image

20/5 letter

5 arc minutes

Courtesy Austin Roorda
Nyquist Sampling Theorem

The maximum spatial frequency that can be detected is equal to \_

of the sampling frequency.

Translation for acuity: For the letter E, each dark stroke and white gap can be no smaller than a photoreceptor.
Applying the Nyquist limit to the sampling density of the photoreceptors will limit correct recognition (but not detection) to an acuity of around 20/8.
Neural Filtering

The neural system also filters the sampled information. The effects of neural filtering can be seen in the contrast sensitivity function.
To explore these interactions, one needs to consider:

- Factors that affect retinal image quality
- The neural transduction of the retinal image
- The visual task
- Variation across subjects
Vision is a very complex set of abilities.

- Contrast detection
- Color vision
- Motion discrimination
- Stereopsis
- Localization
- Visual field
- Peripheral vision
- Acuity, night vision, mesopic vision etc., etc., etc.
Within acuity alone there is:

- High contrast letter acuity
- Low contrast letter acuity
- Dynamic acuity
- Vernier acuity
- Grating acuity
- Mesopic acuity, Scotopic Acuity
- Etc.
This discussion will be limited to optical aberrations and foveal high contrast letter acuity.
To explore these interactions, one needs to consider:

- Factors that affect retinal image quality
- The neural transduction of the retinal image
- The visual task
- Variation across subjects
To minimize across subject variation and focus on how wave aberration affects visual performance, the Visual Optics Institute has focused its research on how a known change in wave aberration induces change in the visual performance of an individual.
Such a study allows us to focus on how changes in one variable (wave aberration) induce change in another (visual performance) while minimizing the impact of other variables by holding them constant.
\[
\text{RMS} = \frac{1}{\text{pupil area}} \int_{\text{pupil}} (w(x,y) - \overline{w})^2 \, dx \, dy^{0.5}
\]

Mean = 0
RMS = 0.25  
6mm pupil 
Equiv. D = 0.19 D 
Letter size 20/40
RMS = 0.25  
6mm pupil 
Equiv. D = 0.19 D

Mode blur matching result

(6 subjects)

Zernike modes in OSA standard

Match Value (m)

2nd  3rd  4th  5th

Courtesy of David Williams
Applegate, RA, Marsack, J., Ramos, R., Interaction Between Aberrations Can Improve or Reduce Visual Performance, J Cataract and Refractive Surgery, in press.

RMS = 0.25
Equiv. D = 0.19 D
\[ \sqrt{0.2^2} + 0.15^2 = 0.25 \mu \]

Applegate, RA, Marsack, J., Ramos, R., Interaction Between Aberrations Can Improve or Reduce Visual Performance, J Cataract and Refractive Surgery, in press.
Aberration

Angular Frequency

-4  -3  -2  -1  0  1  2  3  4

2

Astigmatism  Defocus  Astigmatism

3

Trefoil  Vertical Coma  Horizontal Coma  Trefoil

4

Tetrafoil  Secondary Astigmatism  Spherical Aberration  Secondary Astigmatism  Tetrafoil

Sine  Cosine

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Applegate, RA, Marsack, J., Ramos, R., Interaction Between Aberrations Can Improve or Reduce Visual Performance, J Cataract and Refractive Surgery, in press.
So if RMS wavefront error and equivalent diopters do not serve well to explain the variations in visual performance, is there something better?
To compare ocular aberrations to visual performance one has to select a method for expressing the magnitude of the aberration?

• In the plane of measurement?
  – e.g., RMS, or other measures of the wavefront error in the measurement plane

• In the spatial domain at the retinal level using metrics of retinal image quality?
  – PSF, OTF or derived metrics (Strehl ratio).

• Optical metrics with a neural component?
It can easily be seen that this post LASIK eye aberrations are primarily dominated by coma, spherical aberration, secondary astigmatism, trefoil and a smaller amounts of defocus, astigmatism, and tetrafoil.
Spatial Domain

Object

Convolved with

Point Spread Function

Equals

Image

Frequency Domain

Object Spectrum

Fourier Transform

Optical Transfer Function

Fourier Transform

Image Spectrum

Fourier Transform

Convolved with

Squared modulus of Fourier Transform

Autocorrelation

Multiplied by

Fourier Transform

Inverse Fourier Transform

Fourier Transform

Multiplied by

Squared modulus of Fourier Transform

Equals

Modified from a slide
Courtesy of David Williams
Object

Fourier Transform

Object Spectrum

OTF

Convolve Object with PSF

Image

Inverse Fourier Transform

Image Spectrum
Figure 7-8 from MacRae, Krueger and Applegate, *Customized Corneal Ablation: The Quest for Super Vision*, Slack, Inc. 2001.
Take the modulation

Take the phase

From Robin Owens web page
Answering this question has become a collaborative effort of the laboratories of:

Larry Thibos – Indiana University
David Williams – University of Rochester
Ray Applegate – University of Houston
We have explored single value metrics of optical performance:

• In the pupil plane
• In the image plane (retinal plane)
• Metrics weighted for the neural transfer function
Percent of pupil having a wavefront error of less than a fixed criterion

Whole pupil fraction =

\[
\frac{\text{Total area below a fixed criterion (blue)}}{\text{Total Pupil Area}}
\]
Letters read on aberrated chart - Letters read on unaberrated chart

$y = -12.373 + 10.318x$  \( R^2 = 0.21391 \)

Whole Pupil Fraction
y = -10.779 + 6.8812x \quad R^2 = 0.64301


Letters read on aberrated chart –
Letters read on unaberrated chart

\[ y = -12.684 + 20.513x \quad R^2 = 0.80928 \]

SD \quad 1.083475
Minimum \quad -2.50526
Maximum \quad 1.924988
In Conclusion

• Including the neural transfer function improves the predictive power of single value metrics based on measures of the WFE.