Subjective Image Quality Metrics from The Wave Aberration

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How Bad Is This Wave Aberration?
Goal:

To compute a number that captures the subjective effect of the eye’s wave aberration.

Uses:

Assessing severity of the wave aberration
Calculating the best correction
How Bad Is This Wave Aberration?

RMS Wavefront Error = 0.87 µm
Some Aberrations Interact Strongly in Image Blur

Defocus \( \text{rms} = 0.5 \, \mu m \)

Spherical Aberration \( \text{rms} = 0.16 \, \mu m \)

Defocus and Spherical Aberration \( \text{rms} = 0.52 \, \mu m \)
Zernike Modes

radial order
2nd

3rd

4th

5th

astigmatism
defocus
astigmatism
trefoil
coma
coma
trefoil

quadrafoil
secondary astigmatism
spherical
secondary astigmatism
quadrafoil

pentafoil
secondary trefoil
secondary coma
secondary coma
secondary trefoil
pentafoil

Lower Order Aberrations

Higher Order Aberrations

Lower Order Aberrations

Higher Order Aberrations

Z2
0
Z 2
-2
Z2
2

Z 3
-1
Z3 1
Z 3
-3
Z3 3

Z4
0
Z4
2
Z4
-2
Z4
-4

Z 5
1
Z5 1
Z 5
-1
Z5 3
Z 5
-3
Z5 5
Z 5
-5
Zernike Modes

radial order
2nd

astigmatism
defocus
astigmatism

astigmatism
defocus
astigmatism

Lower Order Aberrations

Higher Order Aberrations

3rd
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coma
coma
trefoil

4th
quadrafoil
secondary astigmatism
spherical
secondary astigmatism
quadrafoil

5th
pentafoil
secondary trefoil
secondary coma
secondary coma
secondary trefoil
pentafoil

Lower Order
Aberrations
Zernike Modes

radial order
2nd

3rd

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5th

Lower Order Aberrations

Higher Order Aberrations

astigmatism
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Lower Order Aberrations

Higher Order Aberrations

astigmatism
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trefoil
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coma
trefoil
quadrafoil
secondary astigmatism
spherical
secondary astigmatism
quadrafoil
pentafoil
secondary trefoil
secondary coma
secondary coma
secondary trefoil
pentafoil
Zernike Modes

2nd order
- 2nd radial
- Z2 0
- Z2 -2

3rd order
- Z3 3
- Z3 -3
- Z3 1
- Z3 -1

4th order
- Z4 4
- Z4 -4
- Z4 2
- Z4 -2

5th order
- Z5 5
- Z5 -5
- Z5 3
- Z5 -3

Lower Order Aberrations
- astigmatism
- defocus
- astigmatism

Higher Order Aberrations
- trefoil
- coma
- coma
There are strong interactions between Zernike Modes.

Therefore, Decomposing the wave aberration into Zernike modes is not the best way to evaluate the subjective impact of the wave aberration.
How Bad is This Wave Aberration?

Wave Aberration  Point Spread Function

Use Retinal Image Quality, Not the Wave Aberration
Principle of Adaptive Optics

Aberrations in Lens and Cornea

distort wave front

Deformable Mirror

corrects wave front

Wave front sensor

measures wave front

sharp image

in camera
Adaptive Optics Sharpens the Eye's Point Spread Function
Adaptive Optics Can Create Wave Aberrations

(Subject: ND)

Wave Aberration  After AO correction  With coma added

Convoluted retinal image
Wave aberrations from Lasik postOp patient

Wave aberrations created by adaptive optics

(With real eye, JP)
Blur Matching

Binary Noise Stimulus

- Lots of Sharp Edges
- Edges At All Orientations
- Seen Through Adaptive Optics

550 nm, 1 deg, 6 mm pupil
Blur Matching of Patient Wave Aberrations

The subject adjusted the amplitude of defocus so that the subjective blur matched that of the patient wave aberration.

Patient wave aberration  Stimulus  Defocus

Zernike mode

Amplitude (µm)

Defocus (D)

Zernike mode
Blur Matching Controls for Neural Differences between Patients

Using Multiple Subjects
Controls for Neural Adaptation
Acuity does not always capture the subjective quality of vision

Equal Acuity But Different Subjective Image Quality
Compare Subject Matches with Matches Made Using Three Different Metrics

Wavefront RMS
Strehl Ratio
Neural Sharpness
Wave Aberration RMS

Big RMS

Small RMS

Amplitude (µm)

Aperture (mm)
$R^2 = 0.4627$
Strehl Ratio of Point Spread Function

\[ \text{Strehl Ratio} = \frac{H_{\text{eye}}}{H_{dl}} \]

\(H_{dl}\)  \(H_{\text{eye}}\)

Diffraction-limited PSF (Perfect Eye)

Actual PSF (Aberrated Eye)

C. of Austin Roorda
Strehl Ratio Metric

$R^2 = 0.4902$
A Simple, Biologically-Plausible Metric for Subjective Image Quality

\[ \sum \left( \text{Point Spread Function} \times \text{Gaussian Neural Blur } \sigma = 0.8' \right) = \text{Subjective Image Quality} \]
Neural Sharpness Metric

\[ R^2 = 0.7034 \]
Wavefront RMS

R² = 0.4627

Neural Sharpness

R² = 0.7034

Subject Matches (D)
Collaboration to Identify the Optimum Image Quality Metric

Ray Applegate, University of Houston:
Effectiveness of Image Quality Metrics in Predicting Visual Acuity with Convolution Simulations

David Williams, University of Rochester
Effectiveness of Image Metrics in predicting Subjective Image Quality with Adaptive Optics

Larry Thibos, Indiana University:
Effectiveness of Image Quality Metrics in Predicting Visual Acuity in the Population
Optimizing refraction with an image quality metric

search in 3-D space

Guirao and Williams (2003)
Conclusions

- Generating blur with adaptive optics leads to a robust metric for correcting vision.

- It is hard to estimate subjective blur from the wave aberration. Zernike Decomposition doesn’t help much.

- The point spread function combined with a biologically plausible model of neural blur is better.

- Standards for optimizing correction from wavefront are in the works