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

Lower Order Aberrations

Higher Order Aberrations

astigmatism
defocus
astigmatism

trefoil
coma
coma
trefoil

trefoil
coma
coma
trefoil

quadrafoil
secondary astigmatism
spherical
secondary astigmatism
quadrafoil

pentafoil
secondary trefoil
secondary coma
secondary coma
secondary trefoil
pentafoil

Higher Order Aberrations

radial order
2nd

3rd

4th

5th

Lower Order Aberrations

Higher Order Aberrations

astigmatism
defocus
astigmatism

trefoil
coma
coma
trefoil

quadrafoil
secondary astigmatism
spherical
secondary astigmatism
quadrafoil

pentafoil
secondary trefoil
secondary coma
secondary coma
secondary trefoil
pentafoil
Zernike Modes

radial order
2nd
defocus astigmatism

3rd
trefoil coma coma trefoil

4th
quadrafoil secondary astigmatism spherical secondary astigmatism quadrafoil

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

Use Retinal Image Quality, Not the Wave Aberration

Wave Aberration

Point Spread Function
Aberrations in Lens and Cornea Distort Wave front

Principle of Adaptive Optics

Deformable Mirror Corrects Wave front

Sharp Image in Camera

Wave front Sensor Measures Wave front
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  Zernike mode

QuickTime™ and a Photo - JPEG decompressor are needed to see this picture.
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)
RMS Metric

\[ R^2 = 0.462 \]
Strehl Ratio of Point Spread Function

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

Diffraction-limited PSF (Perfect Eye)

Actual PSF (Aberrated Eye)

C. of Austin Roorda
Strehl Ratio Metric

\[ R^2 = 0.490 \]

![Graph showing the relationship between metric matches (D) and subject matches (D) with an R^2 value of 0.490.](Image)
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

\[ R^2 = 0.703 \]
Wavefront RMS

Metric Matches (D)

\[ R^2 = 0.462 \]

Subject Matches (D)

\[ R^2 = 0.703 \]

Neural Sharpness
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