Retinal Image Quality
and Visual Performance

Larry N. Thibos
School of Optometry, Indiana University,
Bloomington, IN 47405
thibos@indiana.edu  www.opt.indiana.edu

Slideshow in public domain at http://research.opt.indiana.edu/
• What is image quality (IQ)

• How is IQ measured?

• How well do metrics of IQ account for optical effects on visual performance and the quality of our visual experience?
Q1: what is image quality?

Image quality appears to be an elusive topic, like art:

• obviously very important,
• hard to define,
• difficult to measure,
• but easily recognizable

If IQ is self-evident, then we can answer the question "which image has better quality?" just by looking. Let intuition decide.
Paradigm for determining perceived quality

If you could keep just one of these photos, which would you choose?
Method for determining a metric of perceived IQ

Object

Filter #1

Filter #2

Image #1

Image #2

Observer decides

Internal criterion

What measure of these filters predicts results?
Using their intuitive sense of image quality,

- Observers prefer images with the largest number of perceived gray levels (JNDs, just-noticeable differences)
  - Granger & Cupery (1972, at Kodak, Inc. with photographic prints)
  - Barten (1987, at Phillips, Inc. with video displays)

- Number of gray levels can be predicted from optical characteristics of the system that produced the image.

- Optical characteristics can be summarized by simple measures of the MTF
  - SQF, subjective quality factor (Granger & Cupery)
  - SQRI, square root integral (Barten)
Objective prediction of perceived image quality


Area = SQF

Area = SQRI
Using perceptual data collected by Higgens (1977) for 22 MTFs and 4 stock images, Barten (1999) showed that SQRI accounted almost perfectly for perceived quality (R>0.99).
Perceived image quality is not necessarily related to visual performance for at least 3 reasons:

1. Perception & performance may emphasize different ranges of spatial frequencies and be affected differently by phase shifts in the image.

2. Performance is task-dependent (image may be good for one purpose, bad for another), whereas perceived quality is task-independent.

3. Perception depends strongly on past experience.
High subjective quality may not maximize performance

$C^0_2 = -0.35 \mu, C^0_4 = +0.1 \mu$

$C^0_2 = +0.6 \mu, C^0_4 = +0.1 \mu$
Perceived quality depends on previous experience

Blurred image looks best if observer adapts to blurry image

Sharp image looks best if observer adapts to sharp image

Webster, et al, 2002
• Perceived image quality is well accounted for by the objective quality of the optical system that produced the image.

• The best measure of optical quality for this purpose is SQRI (the area under the MTF*CSF curve plotted on log x-axis and sqrt y-axis).

• Performance IQ is different from perceived IQ in several ways and therefore we also need metrics of image quality that predict visual performance.
Equal performance $\iff$ equal image quality

If two retinal images yield equal visual performance, then (by definition) they have equal quality.

If two images have equal quality, then the optical filters that produced the images have an equivalent effect on image quality.

This logic leads us to measure performance IQ using metrics of the quality of the filters that produced the images, rather than the images \textit{per se}. 
A performance-based method for assessing IQ

Equal performance => equal image quality

What measure of these filters reveals their equality?
Specifying optical filters

Aberration map (pupil plane)

Point-spread Function

Optical Transfer Function

\[ c_2^0 = c_3^{-1} = 0.25 \mu m \]
In what way are these two filters the same?
Image quality is quantified by size of blur circle.
Effect of defocus on visual acuity

\[ \text{Blur ratio} = \frac{\beta}{w} \]

= size of blur circle relative to spatial details of object.

(Smith et al., 1989)

\[ w = \text{stroke width} \]

\[ \beta = \text{blur circle diameter} \]
Effect of defocus on visual acuity

At visual threshold for reading letters, average blur ratio $\beta / w = 4$ (range $= \pm 2$)
Generalizing blur ratio to include astigmatism

\[ M = \text{Sphere} + \text{Cyl} / 2 \quad J = -\text{Cyl} / 2 \]

\[ \beta = d \sqrt{M^2 + J^2} = d \cdot S = d \sqrt{(F_1^2 + F_2^2) / 2} \]

blur ellipse diameter = pupil diameter * blur strength

Power Cross

\[ F_2 = M - J \]

\[ F_1 = M + J \]
Blur ellipse predicts acuity when blur strength > 1D


Simple account fails when sphero-cyl blur < 1D
Current emphasis is on quasi-focussed eye

- When spherocylindrical refractive errors are small, wave-theory analysis is needed to reveal the effects of weak, higher-order aberrations and their interaction with spherical and cylindrical defocus.

- In this case, the retinal image of a point source (PSF) is NOT a uniform disk, but has a complicated shape that corresponds to contrast and phase errors in the optical transfer function (OTF).
A hierarchy of IQ metrics for visual filters

Evaluation at 3 stages of the visual pathway:

1. Quantify wavefront quality (WQ, pupil plane is surrogate for image plane)
2. Quantify image quality (IQ) for optical filter
   - Point objects (PSF)
   - Grating objects (OTF)
3. Optimize visual quality (VQ) of neuro-optical filter

Success is defined by a consistent, monotonic association between metric and performance.
Metrics of Wavefront Quality

Wavefront height => phase
  • RMS = standard deviation of height
  • Peak-to-valley = max - min heights
  • Pupil fraction (flat area/total area)

Wavefront slope => ray direction (transverse errors)
  • RMS = standard deviation of slopes
  • Pupil fraction

Wavefront curvature => focus point (longitudinal errors)
  • RMS = mean blur strength (b.s.=length of PowerVec)
  • Pupil fraction
Image Quality Metrics for Point Objects

Compact, high-contrast point image => quality optics.

Spatial Compactness
1. Area catching 50% light
2. Equivalent width
3. Second moment
4. Half-width at half-height
5. Correlation width

Image Contrast
1. Strehl ratio
2. Light in diffraction core
3. StdDev of light intensity
4. Entropy

Point image

Hi-Q

Low-Q
Image Quality Metrics for Grating Objects

1. Cutoff frequency, rMTF
2. Area between rMTF, n. thresh
3. Cutoff frequency, rOTF
4. Area between rOTF, n. thresh
5. Strehl ratio (OTF)
6. Strehl ratio (MTF)
7. OTF volume/ MTF volume

High contrast image w/o phase shifts => quality optics.
The need for Vision Quality metrics

• There is more to vision than formation of the retinal image.

• Neural processing and cognitive interpretation of the retinal image affect visual performance on tasks.

• Therefore, IQ metrics should take neural factors into account when predicting performance.
Metrics of visual quality of neural images

- Any image-plane metric can be adapted for visual quality analysis by convolving the optical PSF with a neural PSF that represents neural filtering.
- The Fourier Transform of the visual PSF is a visual transfer function of spatial frequency.

\[
\text{Optical PSF } \otimes \text{ Neural PSF} = \text{ Visual PSF} \implies \text{ Visual TF}
\]
Optical PSF

Neural weight

Visual PSF

Comparison of visual PSF to ideal case

Optical OTF

Neural Contrast sensitivity

Visual OTF

Comparison of visual OTF to ideal case

Visual Strehl Ratio: a measure of visual quality

Compare peak of visual PSF to ideal case

Compare volume of visual OTF to ideal case
Applications of visual quality (VQ) metrics

Visual quality of the retinal image in normal eyes is determined by a complex interaction between optical defocus, astigmatism, and higher-order aberrations.

Experiments have shown that metrics of visual quality account for some of these complex effects on visual performance:

- Marcos JRS (2001)
- Chen et al. OVS (2005)
- Applegate et al. OVS (2006)
- Applegate et al. JOSA (2007)
Clinically relevant applications of VQ metrics

• Wavefront refraction
• Visual acuity
Wavefront refraction

Defocus (M)  Astigmatism (J₀ or J₄₅)

Cheng et al., 2004 (J. Vision)
• computationally-blurred images, monochromatic light
• 3 levels of 3rd & 4th order Zernike aberrations
• letter size & lens power (M, J₀ or J₄₅) varied to maximize VA
Predicting visual acuity changes

Visual Quality Metric VSR = Contrast of Neural PSF

Polychromatic

Monochromatic

Journal of Vision, 4:322-328

Fall Vision Meeting

$R^2 = 0.76$

$R^2 = 0.74$
Wavefronts are a monochromatic concept

Monochromatic wavefronts predict monochromatic images
But the world is filled with color!

A wavefront method is needed for broad-spectrum sources.
Brute-force calculation of polychromatic images

Measure wavefront aberrations at multiple wavelengths

Compute monochromatic PSFs, which are then convolved with monochromatic components of the object.
Polychromatic image calculations

Not yet ready for the clinic - requires much information that is difficult to obtain:

– Wavefront aberrations at multiple wavelengths
– Knowledge of energy spectrum at every point in the object

Alternative method is to measure aberrations at just 1 wavelength and use an optical model of ocular chromatic aberration, including higher-order chromatic aberration, to simplify the predictions.

– See Sowmya Ravikumar's presentation on Saturday
Polychromatic PSF as a metric of IQ

Polychromatic PSF = \( \sum \) monoPSFs*Source Luminance

Combine monochromatic PSFs into a polychromatic luminance PSF that can be reduced to a single number using the same methods developed for monochromatic PSFs.
Summary

• What is image quality (IQ)?
  – Perceived IQ (subjective, task-independent)
  – Performance IQ (objective, task-dependent)

• How is IQ measured?
  – By quantifying the quality of the optical system that produced the image
  – Metrics exist for wavefront quality (WQ), image quality (IQ), and visual quality (VQ)

• How well do metrics account for optical effects on visual performance?
  – The best metrics account for the vast majority of variance in visual performance - little room for improvement
The end

Slideshow in public domain at http://research.opt.indiana.edu/

Vision Research at

http://www.opt.indiana.edu