Use of Metrics to Understand Image Quality During Emmetropization and Lens Induction of Myopia

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Chick Model of Myopia

- The chick is commonly used as a model of ocular development
Refractive Error Measurement in Monocular Goggled Chicks

Analogous to humans: ↓ in mean ocular refraction; ↓ in range of refraction; ↓ in astigmatism

Chicks develop myopia in response to lenses
Image Quality in Emmetropization and Myopia

- Can image quality changes be explained by eye growth?
- Does the aberration contribution to image quality actively emmetropize during growth?
- Is image quality due to HOA affected in myopia?

Evidence that aberrations may be under active control: aberration structure of the crystalline lens changes with rearing conditions in fish (Kröger et al, 2001) and chicks (Priolo et al, 2000).

Will use appropriate image quality metrics to answer these questions.
Aberrations are a possible signal to eye growth.

- Direction of defocus is detectable in an individual’s PSF (Wilson et al, 2002; King et al, 2001).
Scaled Eye Growth

*Increase by a factor of $m$, magnification
Pupil size also increases by a similar factor*

Most elements increase in size with similar exponentials with time.
Schematic Hartmann-Shack Apparatus
Angular PSF: HOA as a Function of Age and Goggling with increasing pupil size

Use metrics to quantify image quality changes

- small changes due to aberrations during normal and abnormal growth
- interested in asymmetry
PSF: HOA, Defocus & Astigmatism as a Function of Age and Goggling

243.6 arcmin

Control

Day 0  Day 2  Day 4  Day 7  Day 9  Day 10  Day 14

Goggle

Use metrics to quantify image quality changes
• small changes due to aberrations during normal and abnormal growth
• larger changes due primarily to defocus in goggled eyes
Analysis

- Image quality metrics calculated from PSFs & OTFs
- Normal vision and that through the goggles
- Examined both overall quality & higher-order aberrations only (3rd & 4th order Zernikes)
- Metrics analyzed for experimental data and compared with predictions of models of eye growth
Point Spread Functions with Pupil Size

Diffraction-Limited PSF

- Large Pupil PSF
- Small Pupil PSF
Image Quality Metrics

Relative
- Compare with the diffraction limit
- Strehl Ratio and Correlation with perfect eye

Absolute
- With increasing pupil diffraction limited PSF improves
- Entropy and Square-root of 2nd Moment
Predictions of Scaled, Passive Growth

Increase by a factor of $m$

$RMSA \propto m \quad EB = constant$

Most elements increase in size with $m$ changing exponentially with time
Predictions of a Feedback Model
Maintaining Constant Linear Blur

Relative metrics = constant
RMSA = constant

Absolute metrics → $EB \propto \frac{1}{m}$
$PSF \propto \frac{1}{m^2}$
$OTF \propto m^2$
Results suggest aberrations under active control
Are metrics of image quality on the retina in normal growth & lens-induced myopia consistent with this?
Relative Image Quality Metrics:
Strehl Ratio

Passive model predicts decreasing Strehl
Feedback model predicts constancy
Improvement seen implies increasing retinal sensitivity
Absolute Image Quality Metrics: Equivalent Blur due to HOA

\[ \frac{4\sqrt{3}}{r_{\text{rms}}} \]

Equivalent Blur

Experimental Results
Passive Prediction
Active Prediction

Age (days)

Reference Sphere
Wavefront
Equivalent defocus (D)
Equivalent blur
Image Plane
Absolute Image Quality Metrics: MTF Entropy

Image quality is improving faster than predicted by feedback or passive models.
Linear sensitivity on the retina is increasing?
Signals to Defocus Direction with 15 D Defocus

<table>
<thead>
<tr>
<th>Eye 1</th>
<th>Eye 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hyperopic Viewing</td>
<td>Hyperopic Viewing</td>
</tr>
<tr>
<td>Myopic Viewing</td>
<td>Myopic Viewing</td>
</tr>
</tbody>
</table>

Astigmatism & Higher-order Aberrations

Higher-order Aberrations

Aberration visible in some eyes even though amount of aberration is considerably less than that due to defocus. Needs asymmetric metrics like ferret elongation.
Conclusions

- Image plane measures differentiate changes in image quality due to higher-order aberrations & defocus with age & in myopia.
- From hatching, retinal image quality (both overall and HOA alone) improves with growth in control eyes, both relative to diffraction-limit & absolute image quality.
- In myopic eyes image quality due to HOA improves with age but remains poorer than in normal eyes.
- Reductions in defocus and higher-order aberrations in normal chicks is more rapid than predicted by scaled or feedback growth models.
Acknowledgements

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Absolute Image Quality Metrics: MTF Entropy

![Graph showing MTF Entropy over age (Days)]

- $\Delta \psi < 0.001$
- $3^{rd}$ & $4^{th}$ order
- $\Delta \psi \pi < 0.001$
- $2^{nd}$ order & up
- $\Delta \psi \pi \pi = 0.038$
Relative Image Quality Metrics: PSF Correlation

$\Delta \alpha \psi = 0.008$
$\Delta \varphi \pi = 0.041$

$3^{\text{re}} \& 4^{\text{th}} \text{ order}$
$E \psi \pi = 0.001$

$2^{\text{nd}} \text{ order} \& \upsilon$
$E \psi \pi < 0.001$

$\Phi \text{e} \delta \varepsilon \chi \mu \sigma \alpha \chi \kappa \chi \nu \phi \chi \iota \sigma \tau \alpha \nu \chi \psi$
$\Phi \text{e} \delta \varepsilon \chi \mu \sigma \alpha \chi \nu \phi \chi \iota \sigma \tau \alpha \nu \chi \psi$

$\chi \nu \tau \nu \omicron \lambda \alpha \iota \tau \rho \dagger \iota \nu \lambda \rho \iota \omicron \nu$

$\chi \nu \tau \nu \omicron \lambda \alpha \iota \tau \rho \dagger \iota \nu \lambda \rho \iota \omicron \nu$

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$\chi \nu \tau \nu \omicron \lambda \alpha \iota \tau \rho \dagger \iota \nu \lambda \rho \iota \omicron \nu$
Absolute Image Quality Metrics: PSF Entropy

Age (days): 0 2 4 6 8 10 12 14

Entropy: 0 50 100 150 200 250

Control

Google

3rd & 4th order

2nd order & up
Signals to Defocus:
Image Plane Shift

\[ \Delta k' = 0 \mu m \quad \Delta K = 0 \text{D} \]
\[ \Delta k' = 50 \mu m \quad \Delta K = 0 \text{D} \]
\[ \Delta k' = 0 \mu m \quad \Delta K = 1.15 \text{D} \]
\[ \Delta k' = 50 \mu m \quad \Delta K = 1.15 \text{D} \]
Predictions of Scaled, Passive Growth

\[ \text{InCREASEE } \psi \alpha \ \text{FACTOR } \Phi \mu \]

\[ \text{Growth} \]

\[ \Phi \text{in} \mu, \ \text{the magnification } \psi \ \omega \eta \chi \eta \ \text{the e} \psi \ \text{INCREASES } \sigma \zeta \varepsilon \ \omega \iota \eta \ \text{a} \gamma \varepsilon \ M\text{ost e} \lambda \varepsilon \varepsilon \varepsilon \ \text{INCREASES IN SI} \zeta \varepsilon \ \text{EXPONENTIAL } \omega \iota \eta \ \text{TIME} \]

\[
\text{MOR } \mu \quad 1 \quad m \\
\text{RMSA } \mu \quad m \\
\text{EB} = \text{constant}
\]
\[ EB \propto \frac{1}{m} \]

\[ EB = \text{constant}^m \]
Predictions of a Feedback Model

\[ \text{MOR} \propto \frac{1}{m^2} \quad \text{RMSA} = \text{constant} \quad \text{EB} \propto \frac{1}{m} \]
Predictions of a Feedback Model

Absolute metrics →

\[ PSF \propto \frac{1}{m^2} \]

\[ OTF \propto m^2 \]

Relative metrics = constant
Absolute Image Quality Metrics: PSF √2\textsuperscript{nd} Moment

\[ \rho_{σ\delta} \] 

\[ \rho_{Ω\delta} \] 

\[ \text{Age (days)} \]

\[ \text{PSF} \sqrt{2^{\text{nd} \text{ Moment}}} \]

\[ \text{Control} \]

\[ \text{Goggles} \]
Predictions of a Feedback Model
Maintaining

Relative metrics = constant

\[ \text{MOR} \mu \frac{1}{m^2} \quad \text{RMSA} = \text{constant} \quad \text{EB} \mu \frac{1}{m} \]