Theoretical and Experimental Evaluation of Depth of Focus and Blur Perception

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Any talk on DoF should begin with a definition of the term

- Depth-of-focus: a range of spherical defocus over which there is no appreciable change in image quality

- Surely Atchison will say*: “define appreciable”
  - Just noticeable ← Today’s choice
  - Troublesome
  - Objectionable
  - Intolerable
  - Bloody horrible!!

- Criterion matters, especially when judging success of extended depth-of-focus treatments.

*Atchison DA, Fisher SW, Pedersen CA, Ridall PG. Noticeable, troublesome and objectionable limits of blur. Vision Res. 2005;45(15):1967-74.

The “Optical Syllogism”

A guiding principle for studies of blurred vision:

1. If an eye is aberrated, then the retinal image will be degraded.
2. If the retinal image is degraded, then visual performance will suffer.
3. Therefore, it is logical to conclude that if an eye is aberrated, then visual performance will suffer.

George Smith's quantification* of the optical syllogism

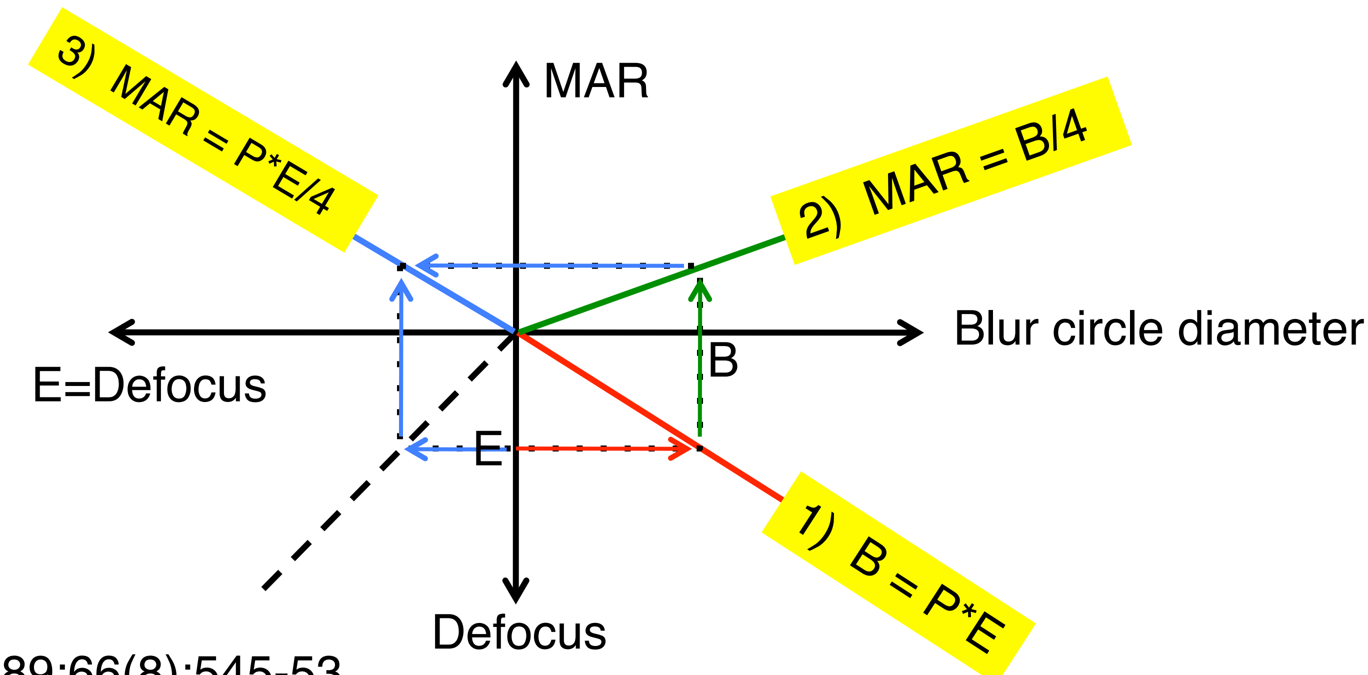
A geometrical optics analysis of an aberration-free eye:

1) Theoretically, if an eye with pupil diameter P is defocused by amount E, then the diameter of the retinal blur circle B = P*E.

2) Empirically, a retinal blur circle of diameter B will result in a minimum angle of resolution (MAR) = B/4 (on average).

3) Therefore, it is logical to conclude that if an eye is defocused, then visual acuity MAR = P*E/4.

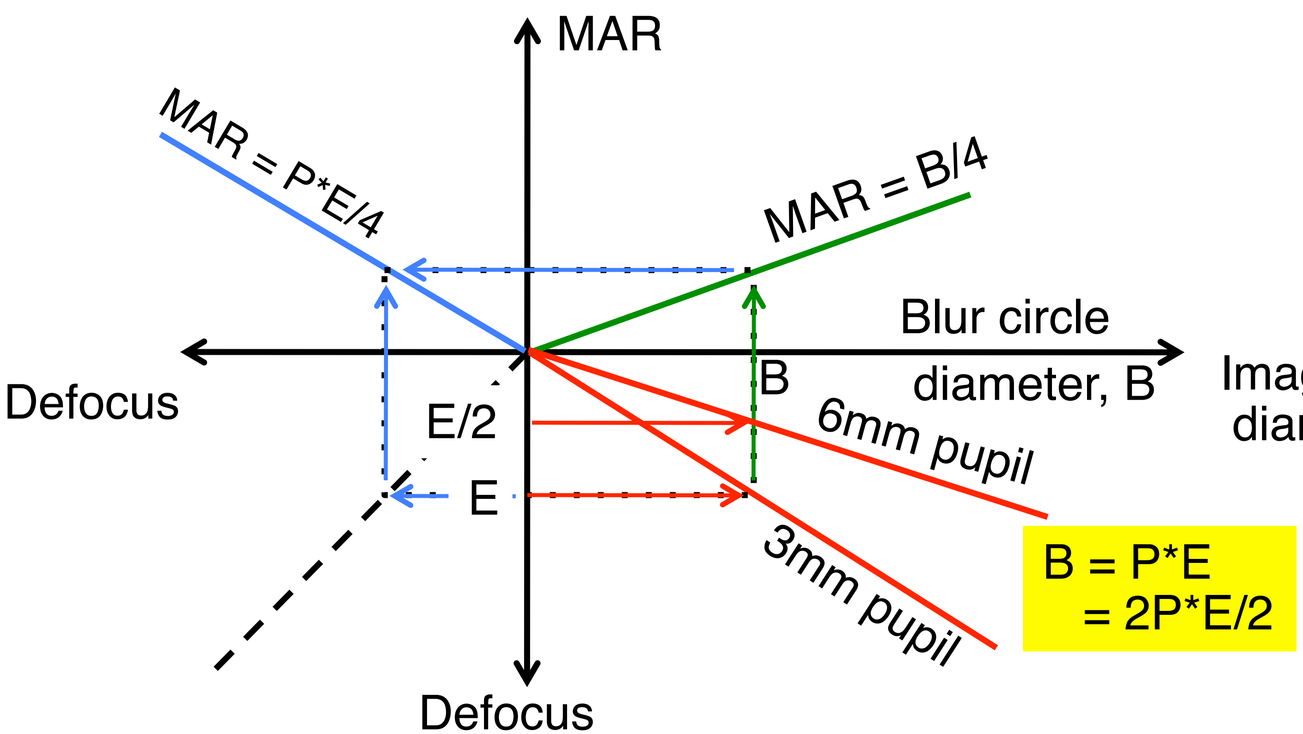
Graphical depiction of the optical syllogism.



*Optom Vis Sci. 1989;66(8):545-53

Predicting the effect of pupil size on depth-of-focus (DoF)

According to Smith's simplified model, *doubling* pupil diameter P and *halving* the amount of defocus E will produce the same blur circle diameter B and therefore increase MAR by the same criterion amount.



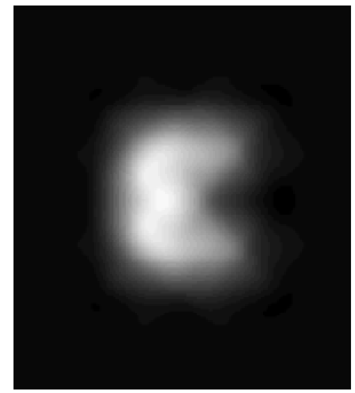


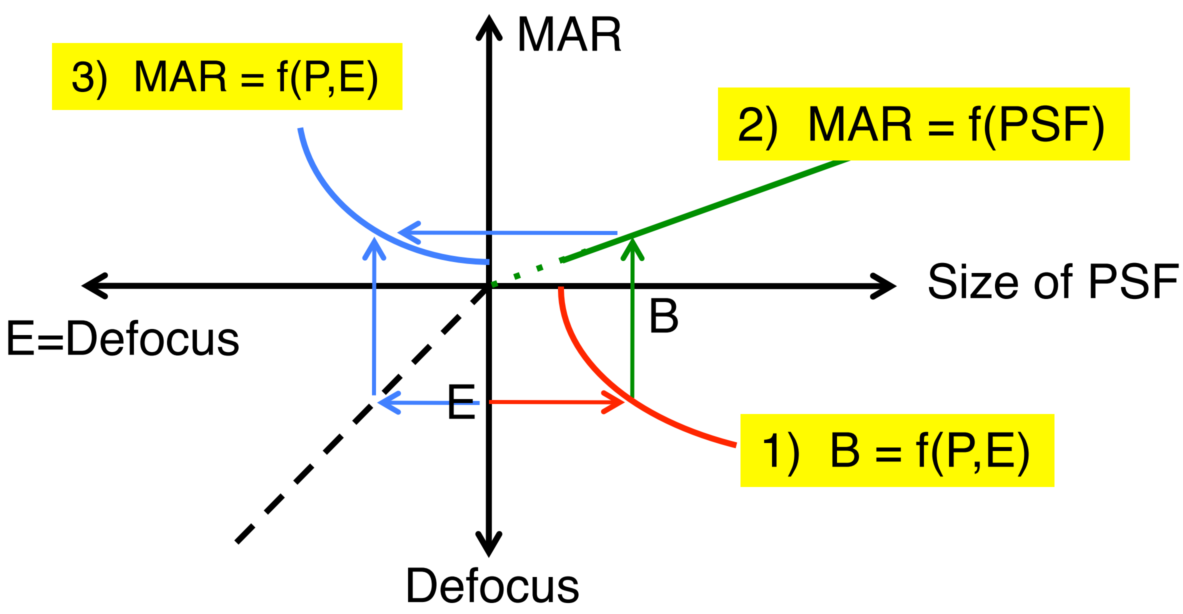
Image of E when blur circle diameter = 4x stroke width

Limitations of Smith's analysis

Although Smith's analysis is valid for large amounts of defocus, it fails for DoF studies using a JND criterion where small amounts of defocus are added to a well-focused eye.

Three reasons for failure:

1. For small pupils, diffraction sets a lower limit to MAR
2. For large pupils, aberrations set a lower limit to MAR
3. In an aberrated eye, the image of a point (PSF) is not a uniform disk of light.

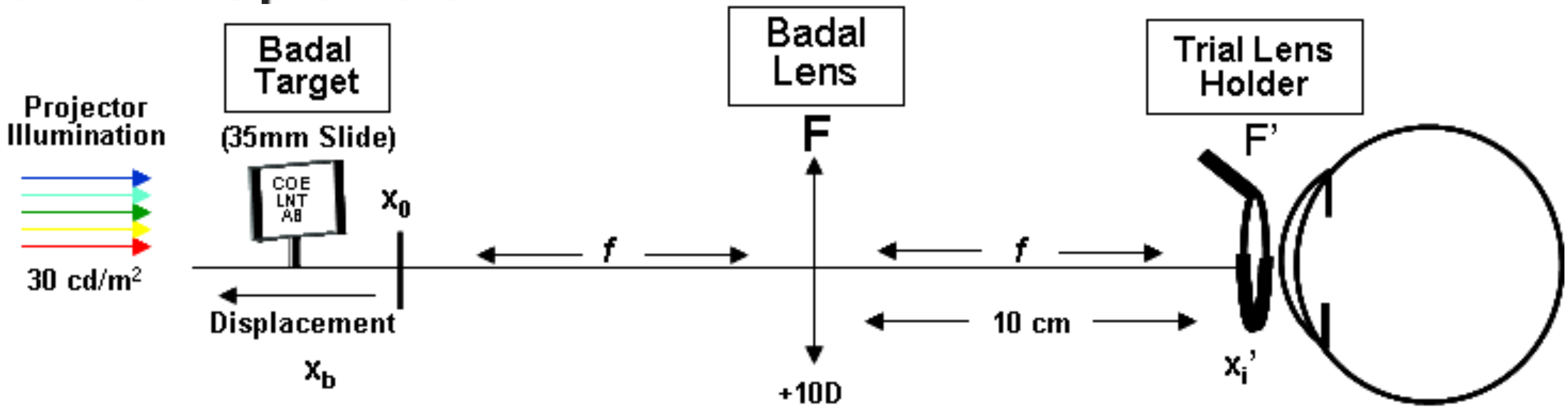


New experiments (PhD thesis of Charles Coe, OD,PhD)

- Aim: to quantify the relationship between just-noticeable amounts of defocus, retinal image quality, and visual acuity in aberrated eyes.
- Wavefront aberrometry was used to compute the eye's polychromatic point-spread-function (PSF).
- Retinal image quality was quantified by PSF metric "D50"
  - D50 = diameter of a circular area centered on PSF peak which captures 50% of the light energy (arcmin)
  - D50 ignores the PSF tails, which are more relevant to veiling glare and overall contrast than to image formation.
- Depth of focus was measured for two pupil sizes
  - Small 3mm pupil, minimizes effect of aberrations
  - Large 8mm pupil, emphasizes effect of aberrations

Method for Psychophysical Measurement of the DoF

The Badal Optometer:



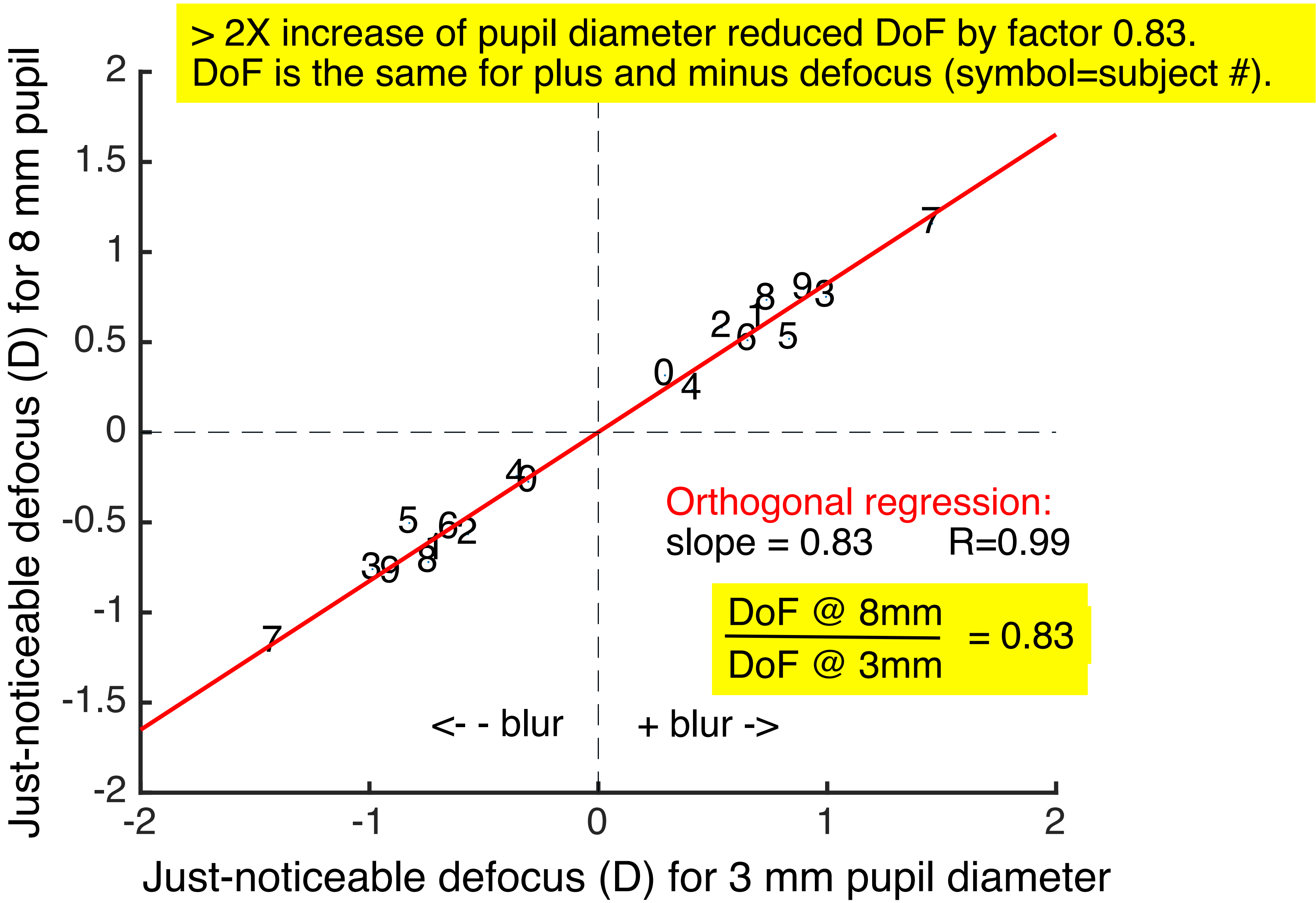
The Badal Optometer (resolution of 0.01D)

- Target = 35mm slide of a high contrast VA chart, back illuminated by monochromatic or white light (30 cd/m^2)
- DoF determined by method-of-limits paradigm for "Just Noticeable Blur" of smallest resolvable letters
- 5 measurements each of optimum focus, - defocus, and + defocus

Subjects (N=10, age range 20-60)

- Accommodation paralyzed, clinical Rx corrected with trial lenses.
- Pupil diameter = ~8mm (dilated) or 3mm (aperture in trial lens holder)

DoF is only slightly smaller for 8mm pupil compared to 3mm



Computed image quality metric D50 as a function of defocus

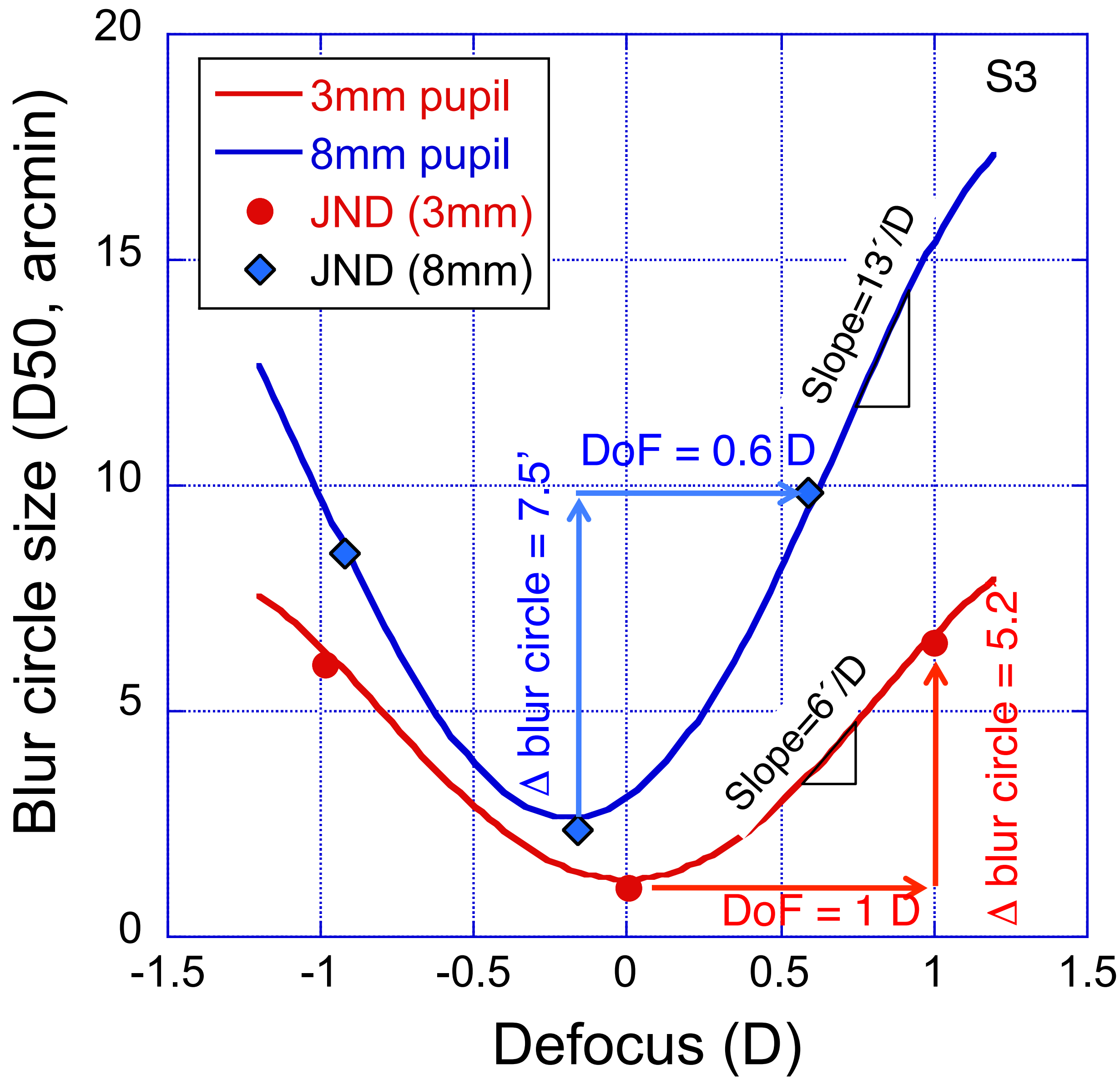
For this subject (S3), DoF=1D for 3mm pupil, which increased blur circle diameter by 5.2'

Increasing pupil to 8mm
- changed best focus
- increased D50 min.
- reduced DoF to 0.6D
- increased D50 by 7.5'

Conclusions:

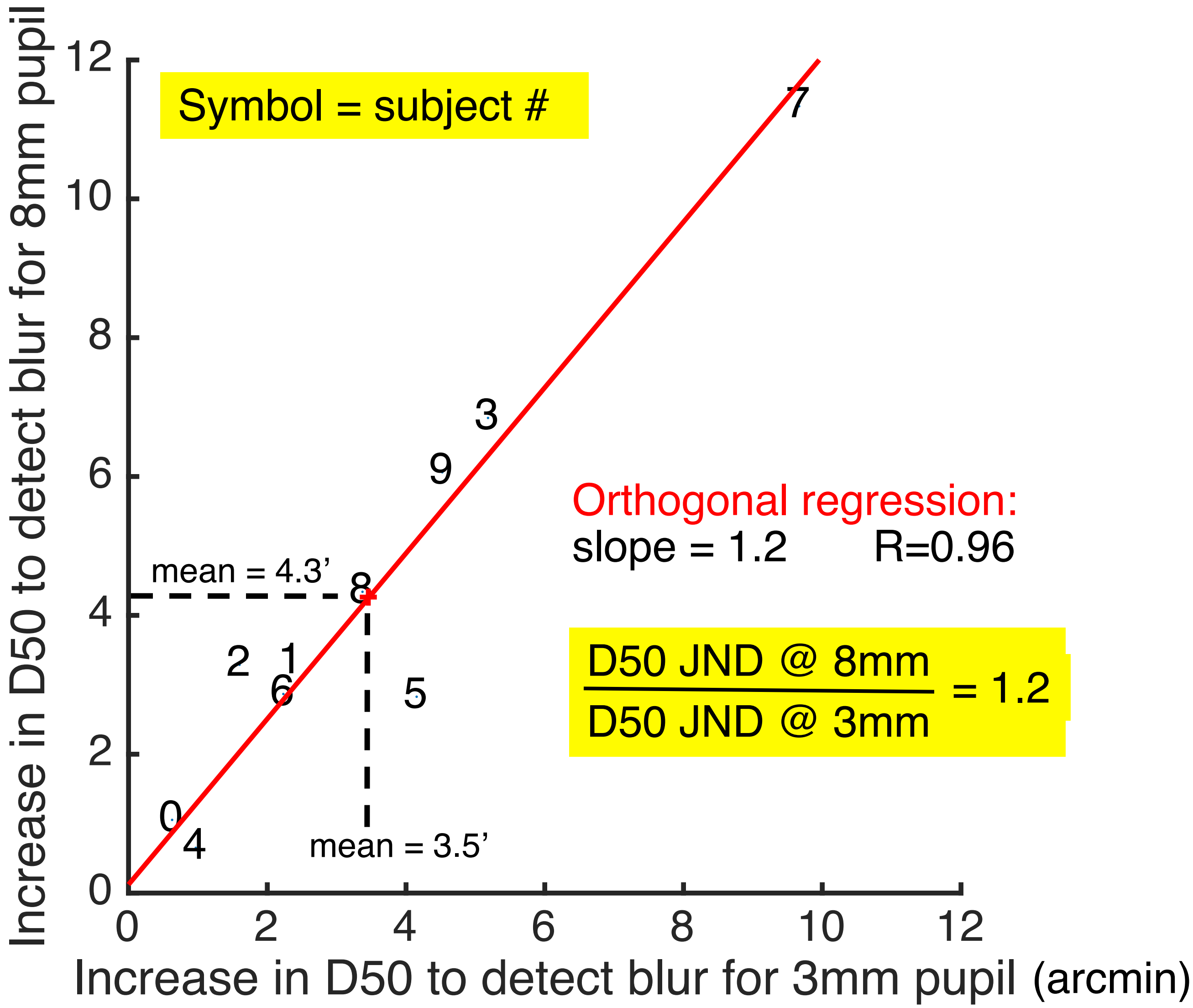
For best-focused case, image quality is worse when pupil is larger (curve shifts up).

Rate of blur circle enlargement with defocus increases 2.1x when pupil size increases 2.7x (curve gets steeper).



JND for D50 is larger when best-focused D50 is larger

For our study population of 10 individuals, the just-noticeable increase in blur circle diameter was slightly greater for large pupils compared to small pupils.

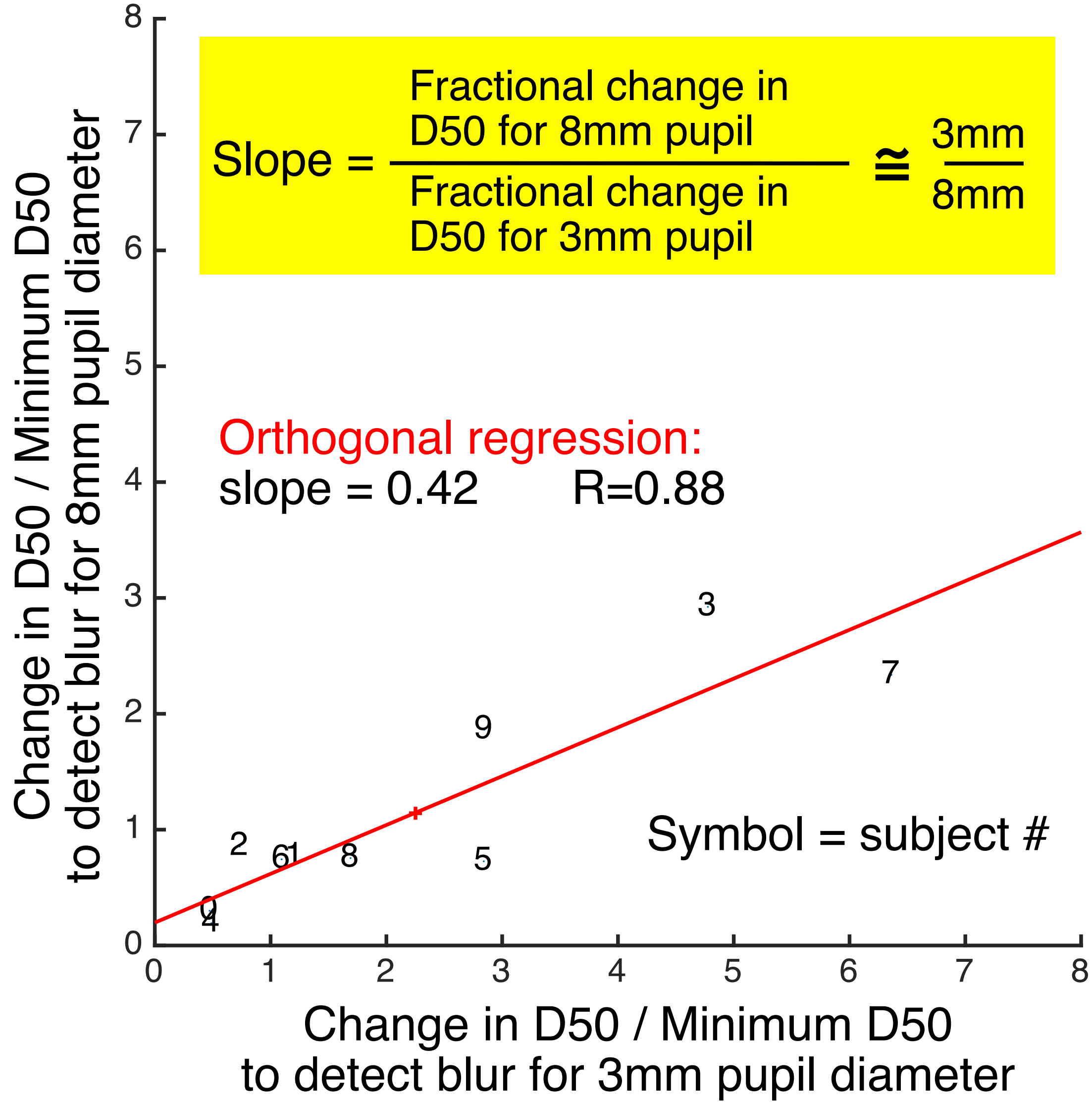


Relative changes in D50 is inversely related to pupil sizes

Minimum blur circle size at best-focus is larger in 8mm pupils than for 3mm pupils (because of aberrations)

Therefore, a certain increase in blur disk size represents a smaller fractional increase for larger pupils compared to smaller pupils.

Ratio of fractional changes in D50 is approximately equal to ratio of pupil sizes.



Summary of results

1. A just-noticeable degradation of retinal image quality from “best focused” requires a slightly greater increase in blur-circle size when the pupil is large compared to when it is small:

   D50 JND @ 8mm = 1.2 * D50 JND @ 3mm

2. Depth of focus for a “just-noticeable” criterion is slightly smaller (in diopters) for large pupils compared to small:

   DoF @ 8mm = 0.8 * DoF @ 3mm

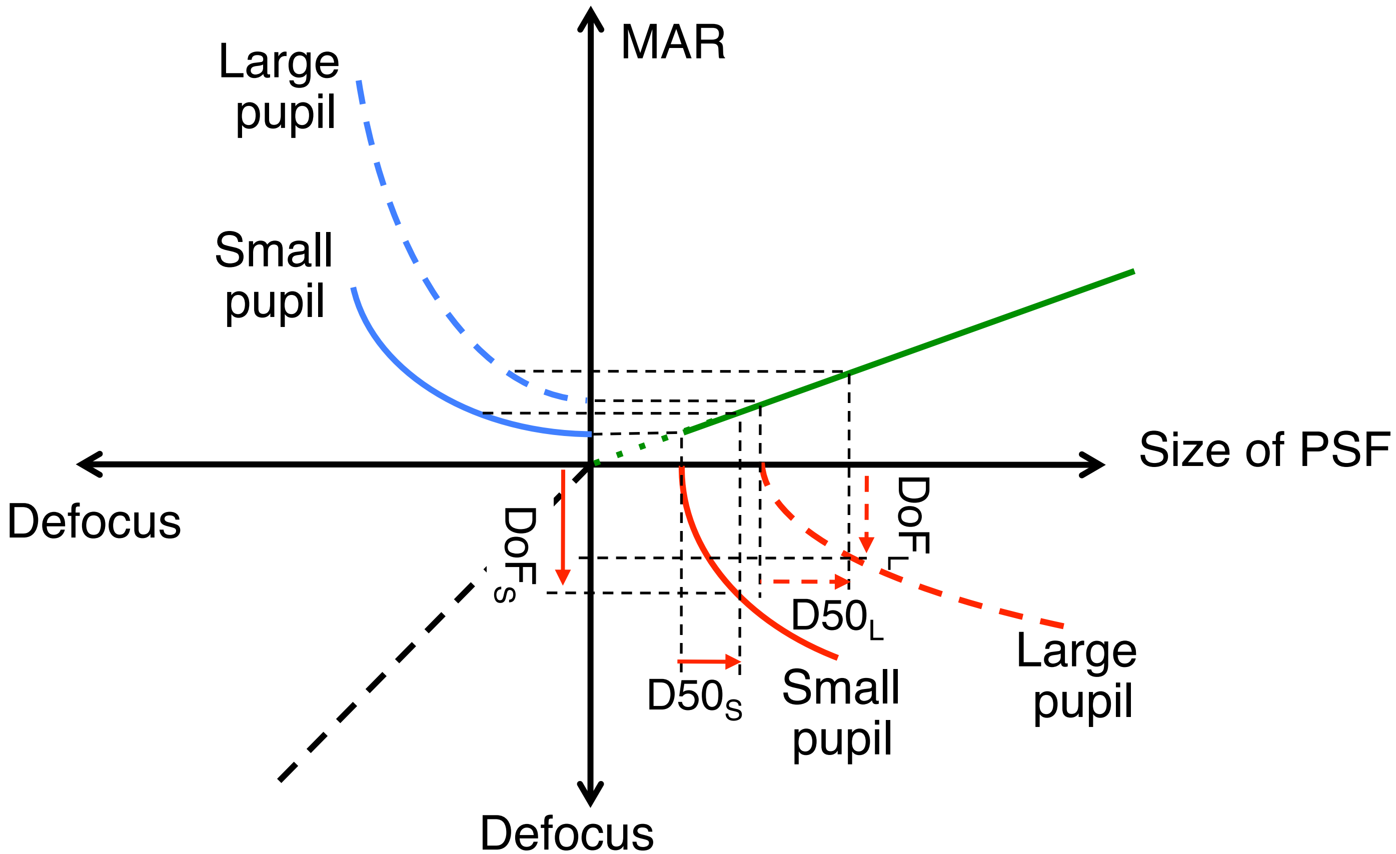
3. The ratio of these two equations shown above indicates the slope of the blur-circle size vs. defocus relationship is steeper for larger pupils, but not as steep as in an aberration-free model:

$$\frac{\text{Change in D50}}{\text{Change in Defocus}} \text{ @ 8 mm} = 1.5 * \frac{\text{Change in D50}}{\text{in Defocus}} \text{ @ 3 mm}$$

Conclusion: the Optical Syllogism for aberrated eyes

The functional relationship between PSF size and defocus is steeper for large pupils for aberrated eyes, but not as steep as for un-aberrated eyes.

Additional experiments are needed to determine if the relationship between PSF size and MAR is fixed (green line), or varies with pupil size.



Conclusions, in plain English

- Increasing pupil size degrades a well-focused image because the blurring effect of aberrations is greater.
- Defocusing an eye by a small amount degrades image quality more for large pupils than for small pupils.
  - This is true for an aberration-free eye (Smith, 1986)
  - This is also true for normally aberrated eyes (our results).
- Depth-of-focus F is smaller when pupil is larger (and therefore aberrations have a greater blurring effect), but this pupil effect is not as dramatic as for Smith's model of the aberration-free eye.

Implications for extended DoF lenses

- We increased the effects of defocus and other aberrations on image quality by increasing pupil size.
- However, extended DoF lenses increase the effect of aberrations by making the magnitude of aberrations greater for the same pupil size.
- Our finding that the rate of increase of blur circle size with defocus is less influenced by pupil size when aberrations are present supports the rationale of extended DoF treatments.
- Increasing ocular aberrations will cause the same amount of defocus to have less impact on visual acuity, which is the aim of extended DoF treatments.

The end