Aberrations of the Eye: Implications to vision, eye growth, and imaging

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Waterloo

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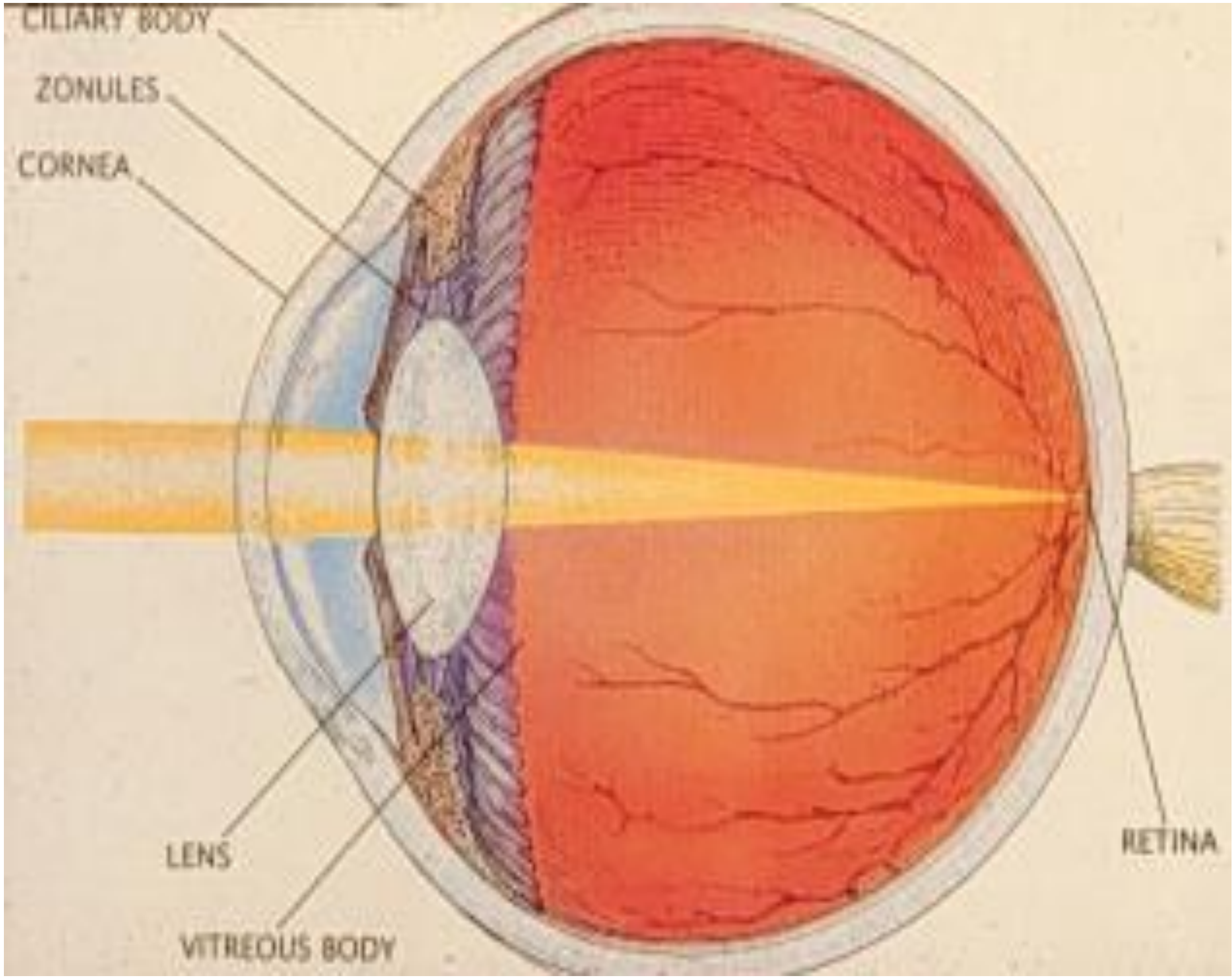
Outline

- Background optics of the eye
- Monochromatic wavefront errors (aberrations) and image quality
- Chromatic aberration in the eye
- Measurements and correction of aberrations
- Importance to vision, eye growth, high resolution imaging

Optics of the Eye



Aberrations of the Eye

- Monochromatic aberrations -
  - blur when rays away from the axis focus differently than near axial rays (*spherical aberration, coma, astigmatism*)
  - Image curvature & distortion (*field curvature and distortion*)
- Chromatic aberration
  - difference in focus of rays of different colours
  - focus differently due to $n(\lambda)$
  - Dependence of monochromatic aberrations on λ

Spherical Aberration

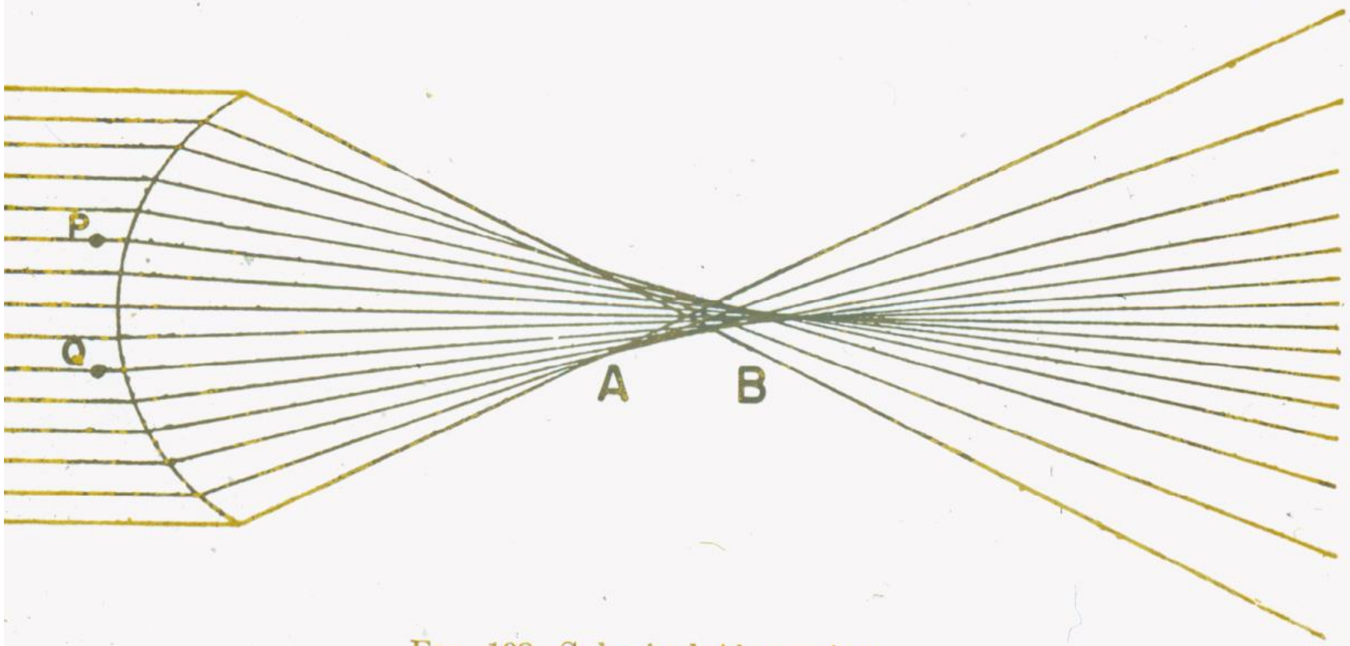
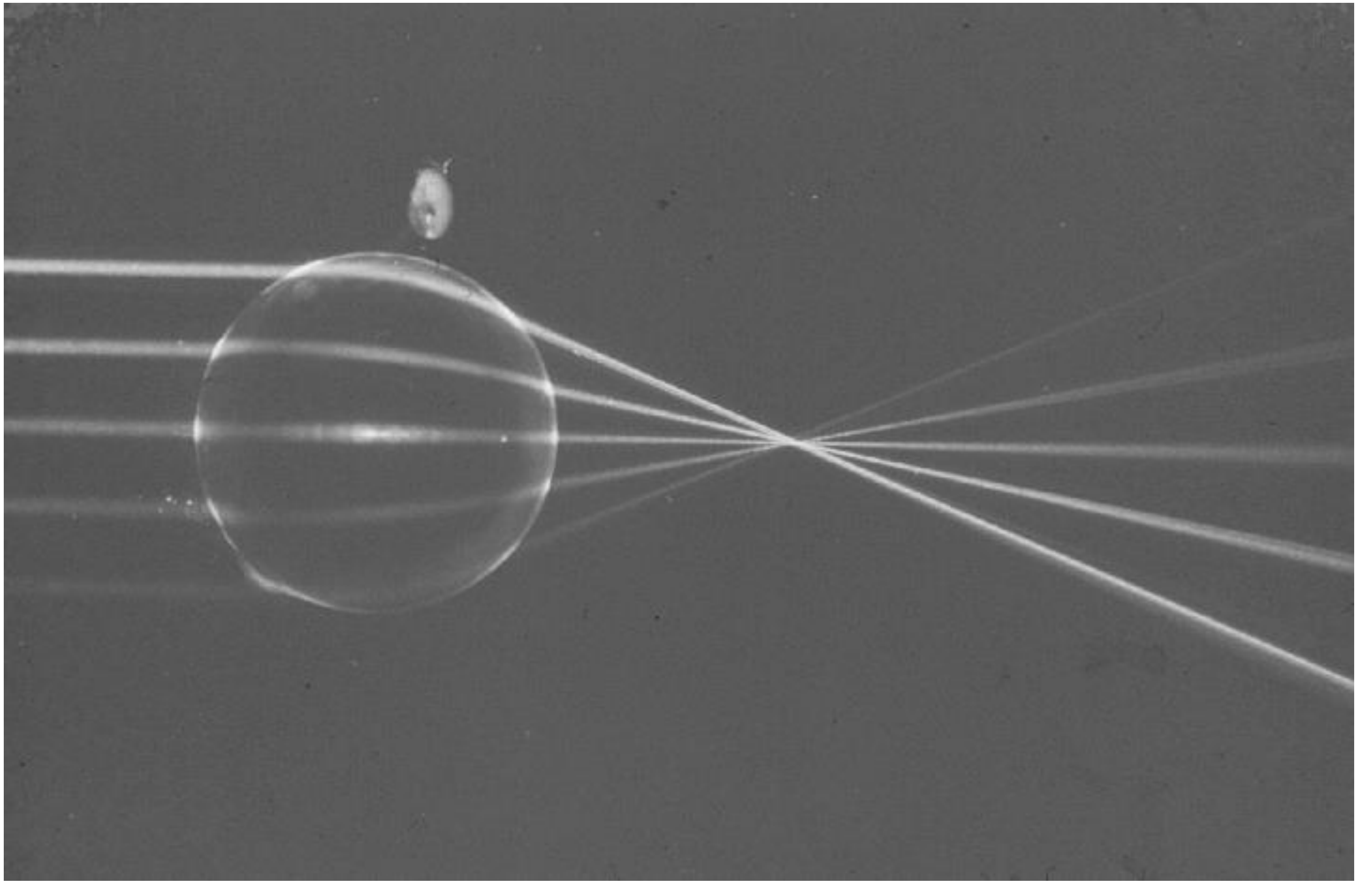


FIG. 108. Spherical Aberration

Factors Affecting the Eye's Image Quality

- GRIN of lens and aspheric surfaces
  - Age, accommodation, rearing conditions
- Misalignment of components
- Tear film
- Pupil size
- Field angle

Gradient Refractive Index Optics of the Lens of the Eye

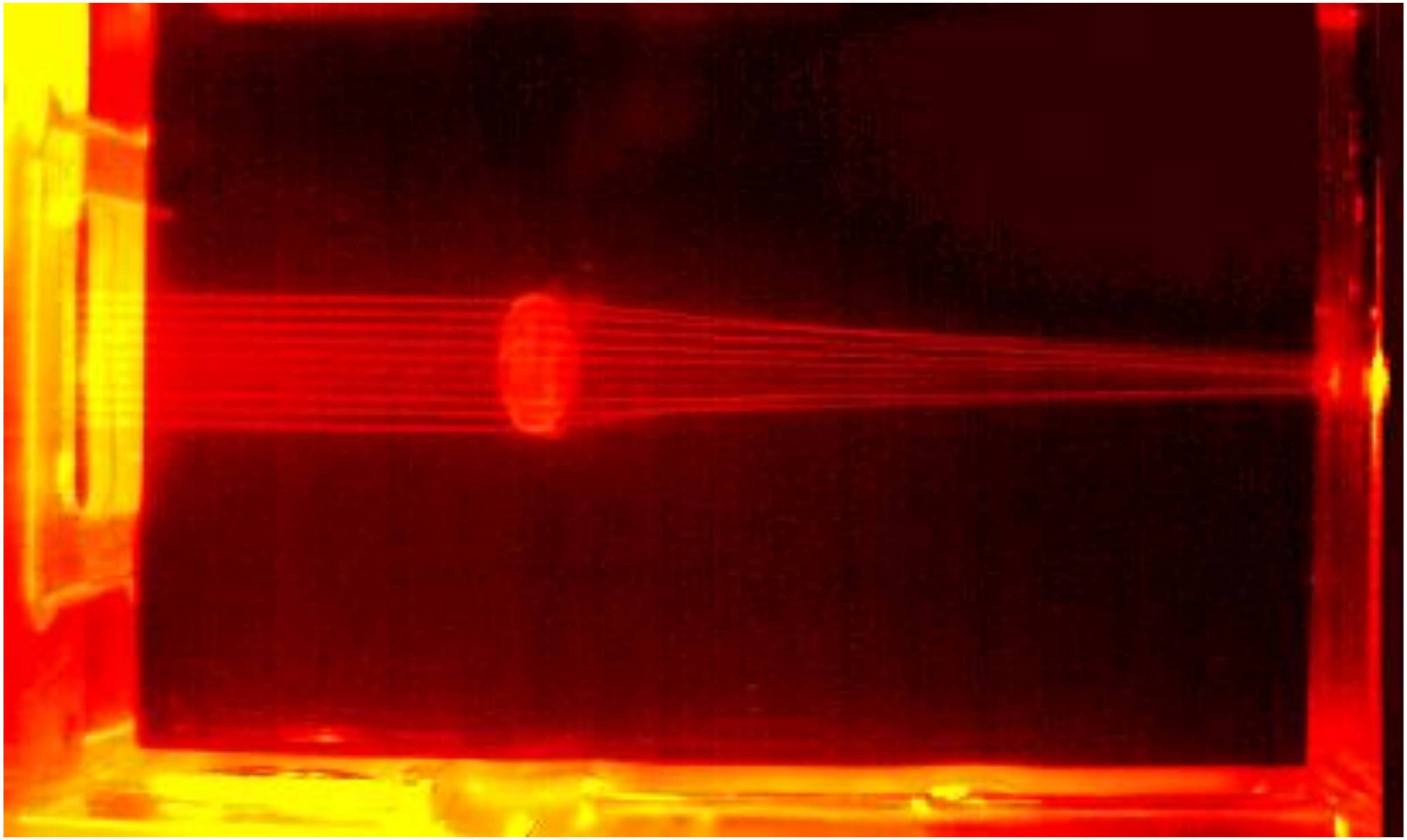


Excellent Optics: the Fish Lens

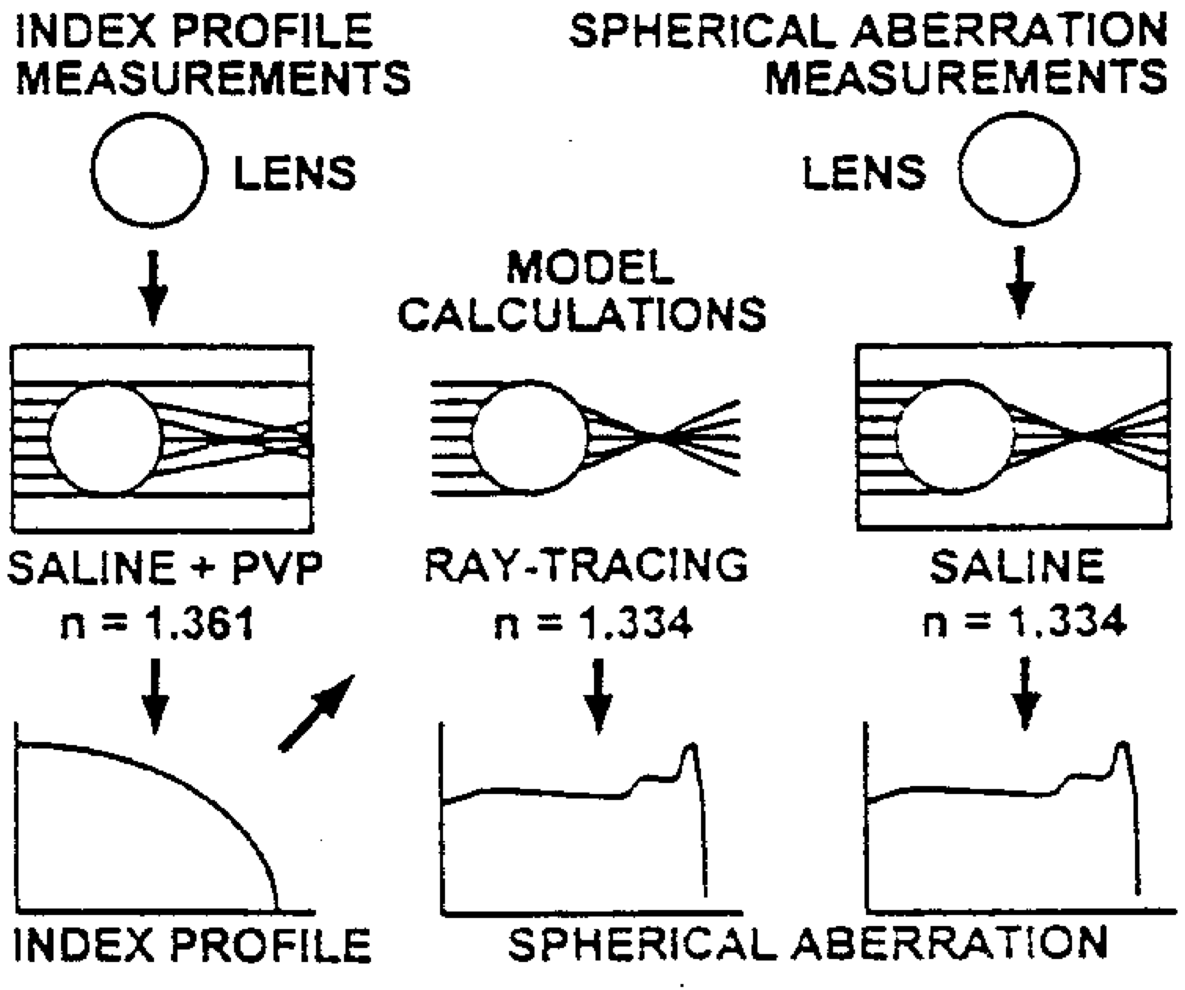
Courtesy of J. Sivak

In vitro Laser Scanning of the Crystalline Lens

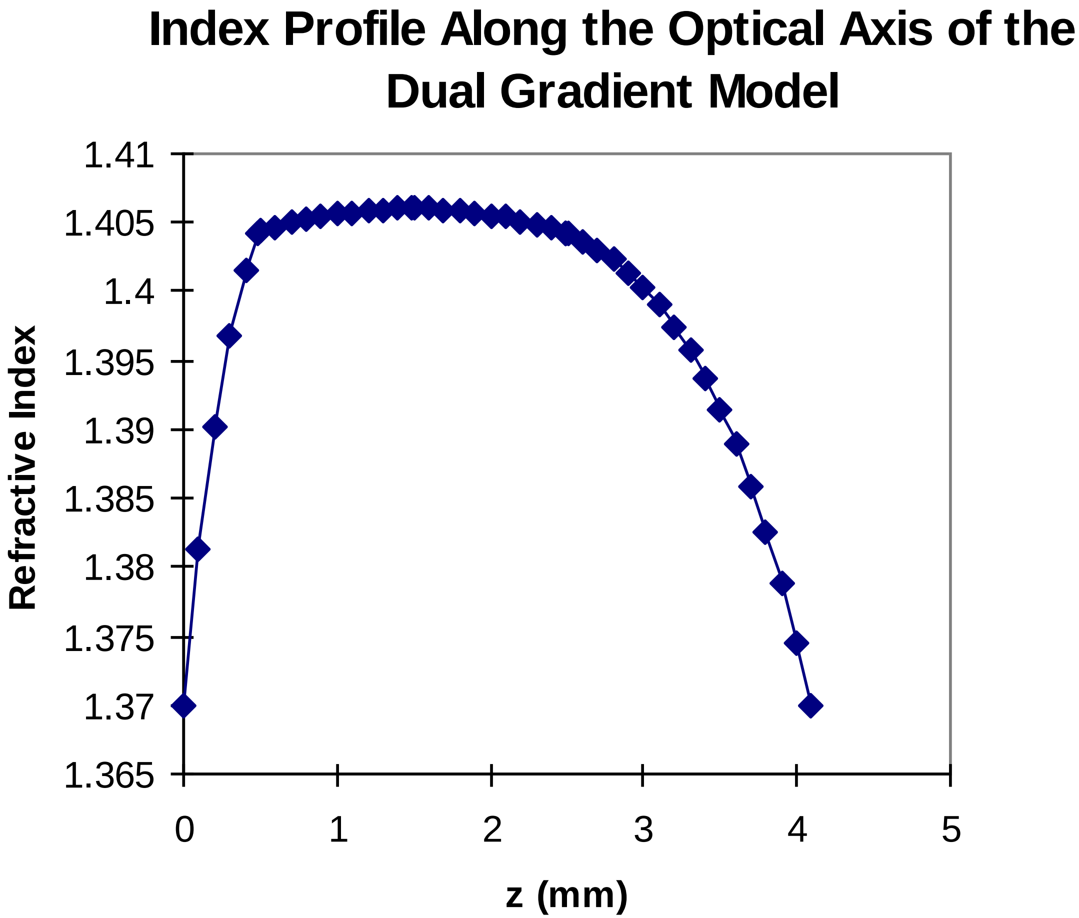
Glasser and Campbell, 1998



Methodology for Determining the GRIN Profile of the Lens



Refractive Index Profile of the Human Crystalline Lens

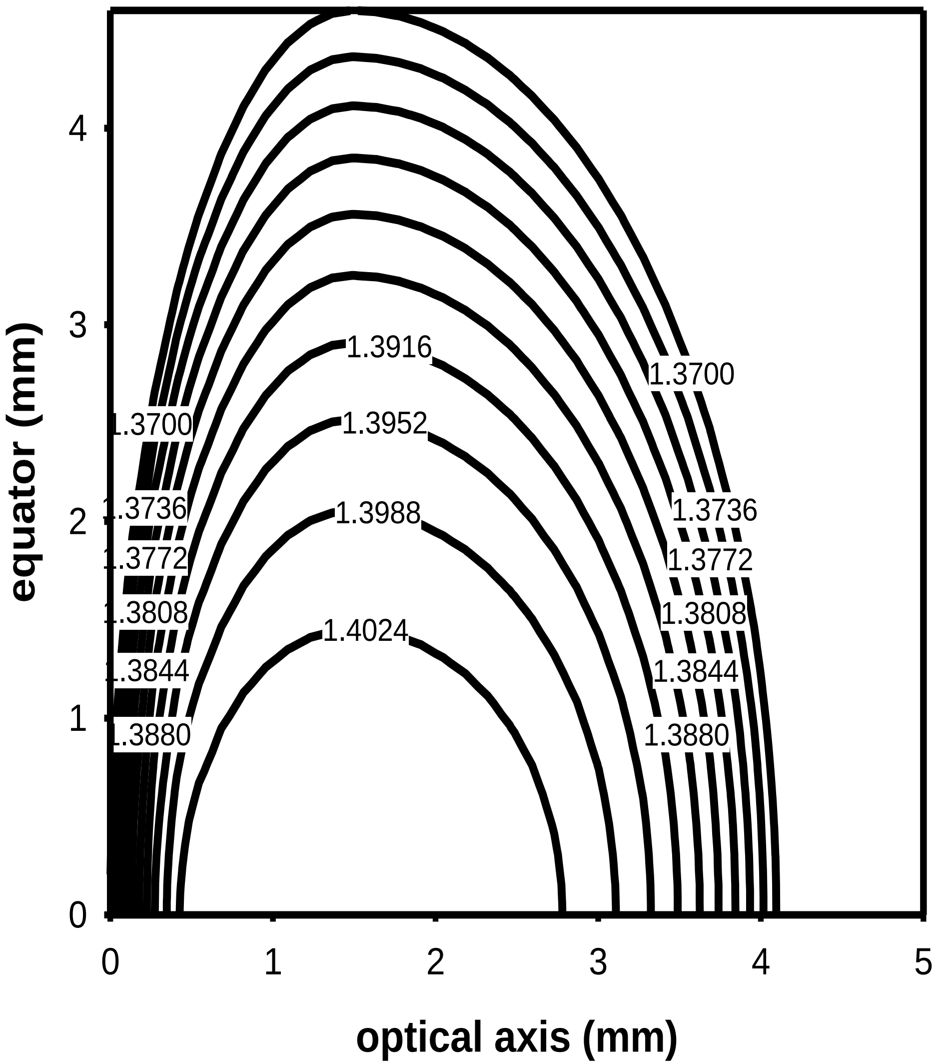


Model of Campbell and Piers

Isoindicial Surfaces of the GRIN Model

Model of

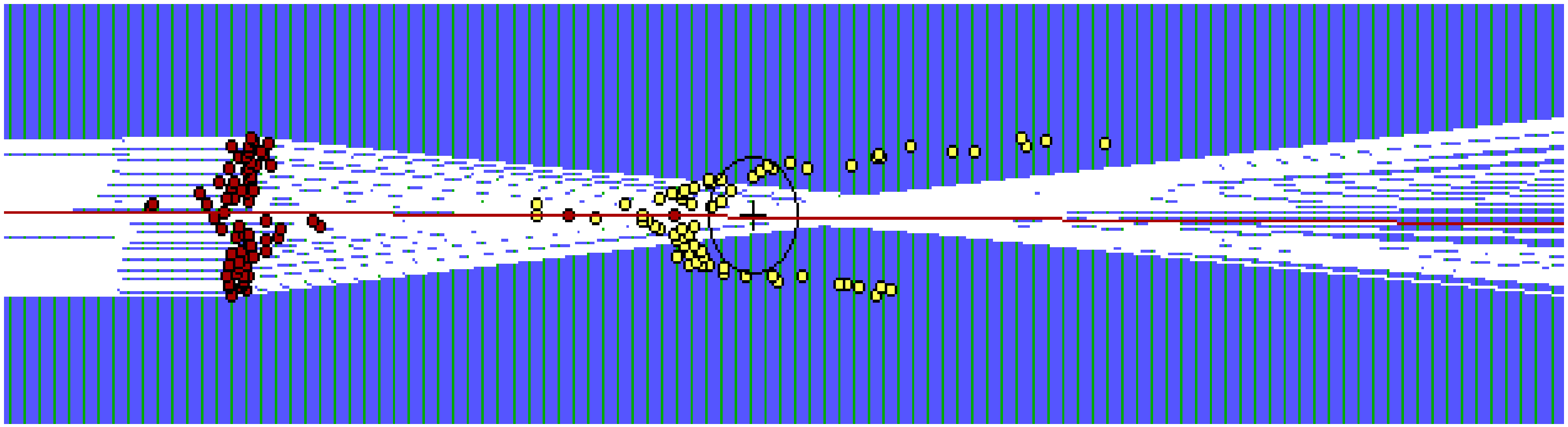
Campbell and Piers



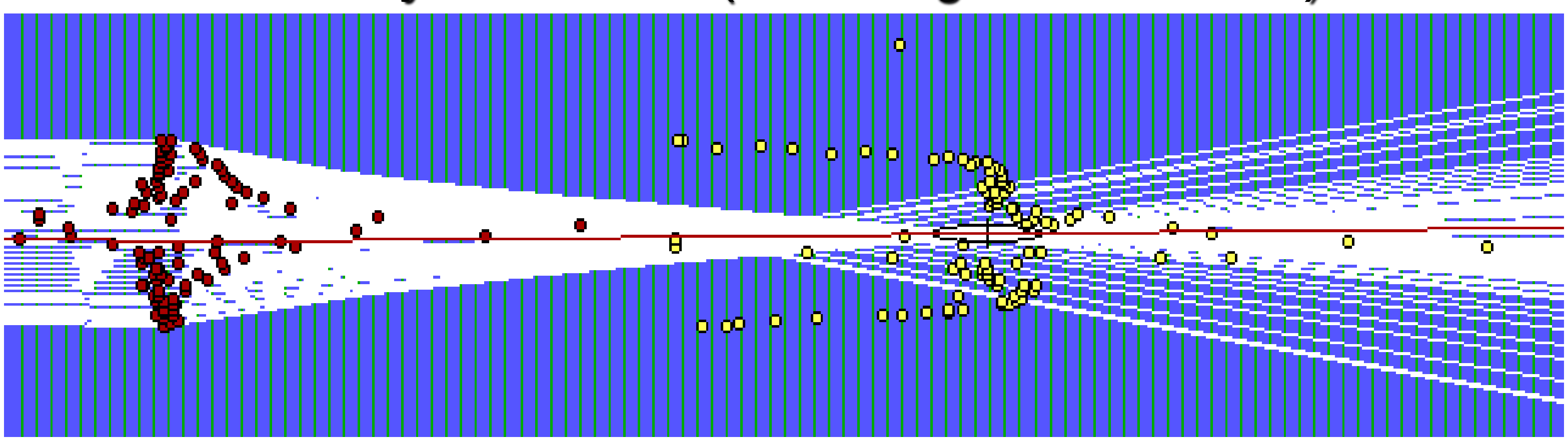
Scans of 10 and 66 Year Old Lenses

Glasser and Campbell, 1998

Unstretched 10 year old lens (focal length = 34.16 mm)

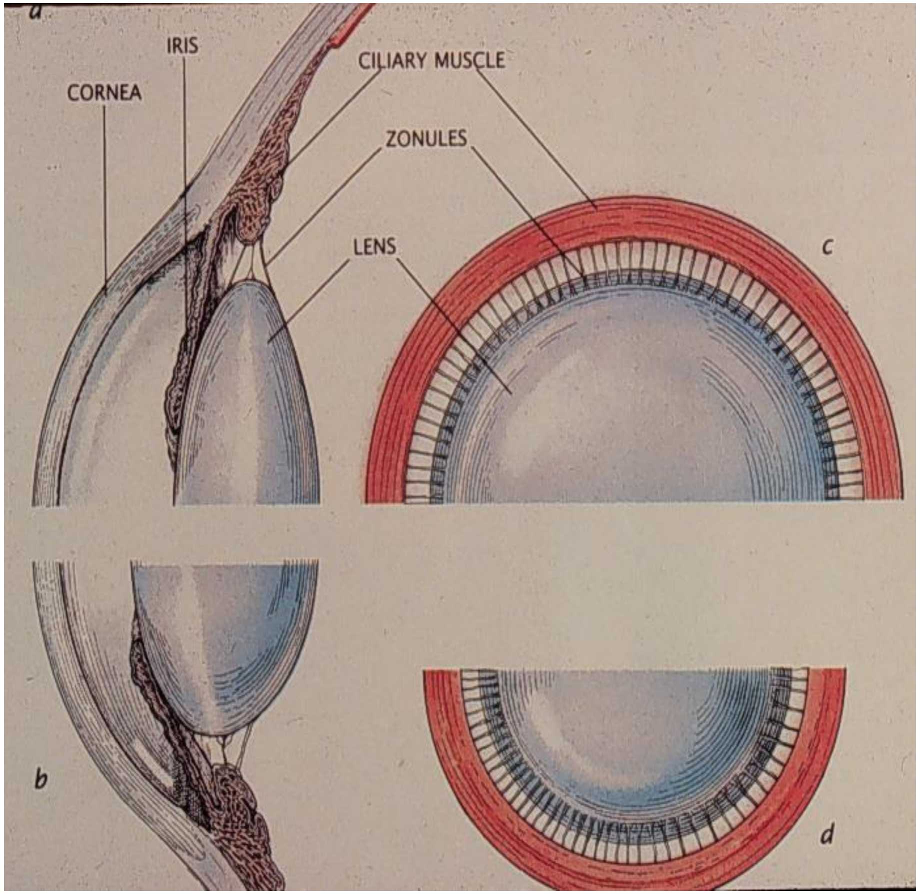


Unstretched 66 year old lens (focal length = 71.29 mm)



Focal length of the older lens is too long for near vision

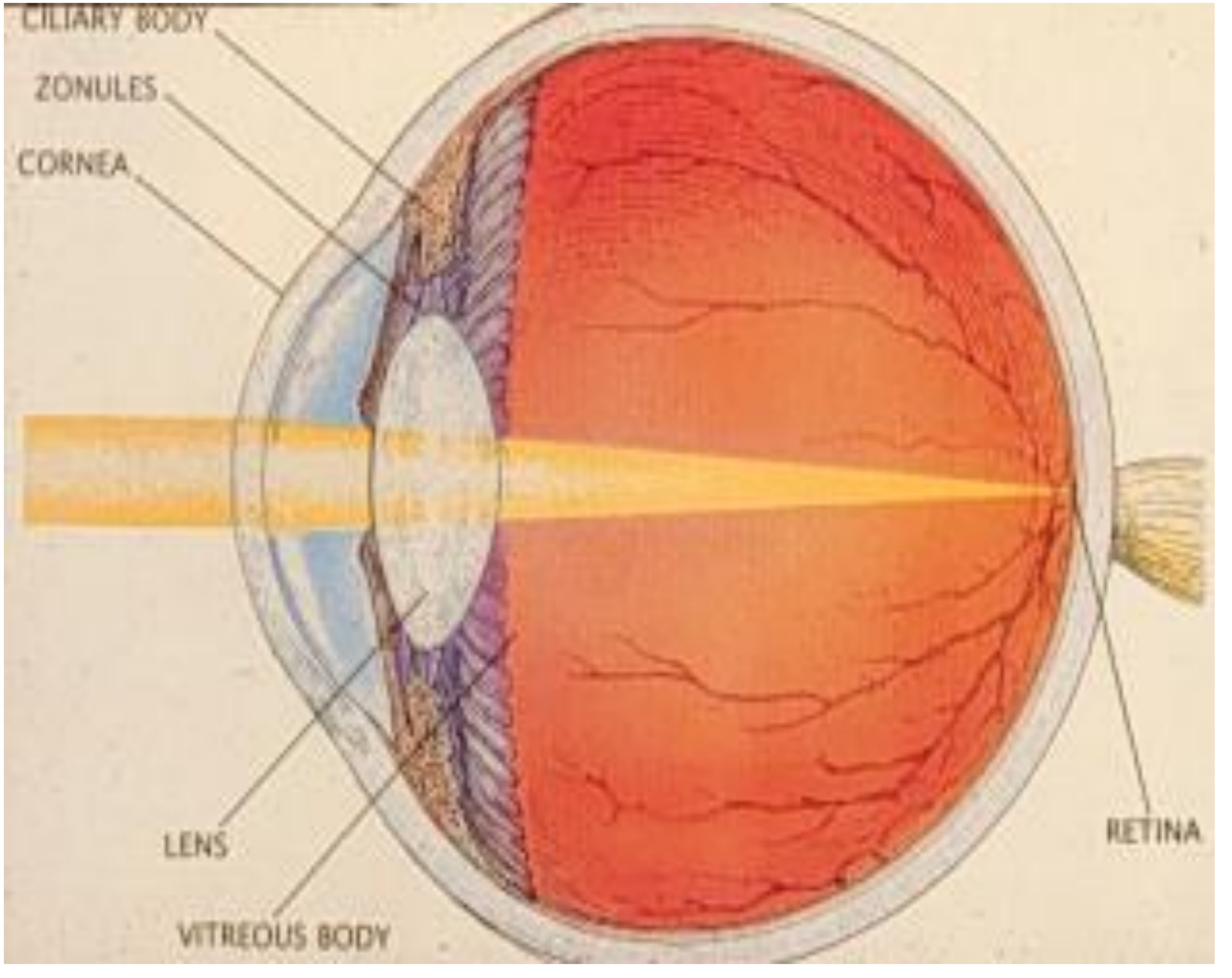
Accommodation in a Young Lens



Reproduced from Koretz, J.F., and Handelman, G.H., (1988), Scientific American

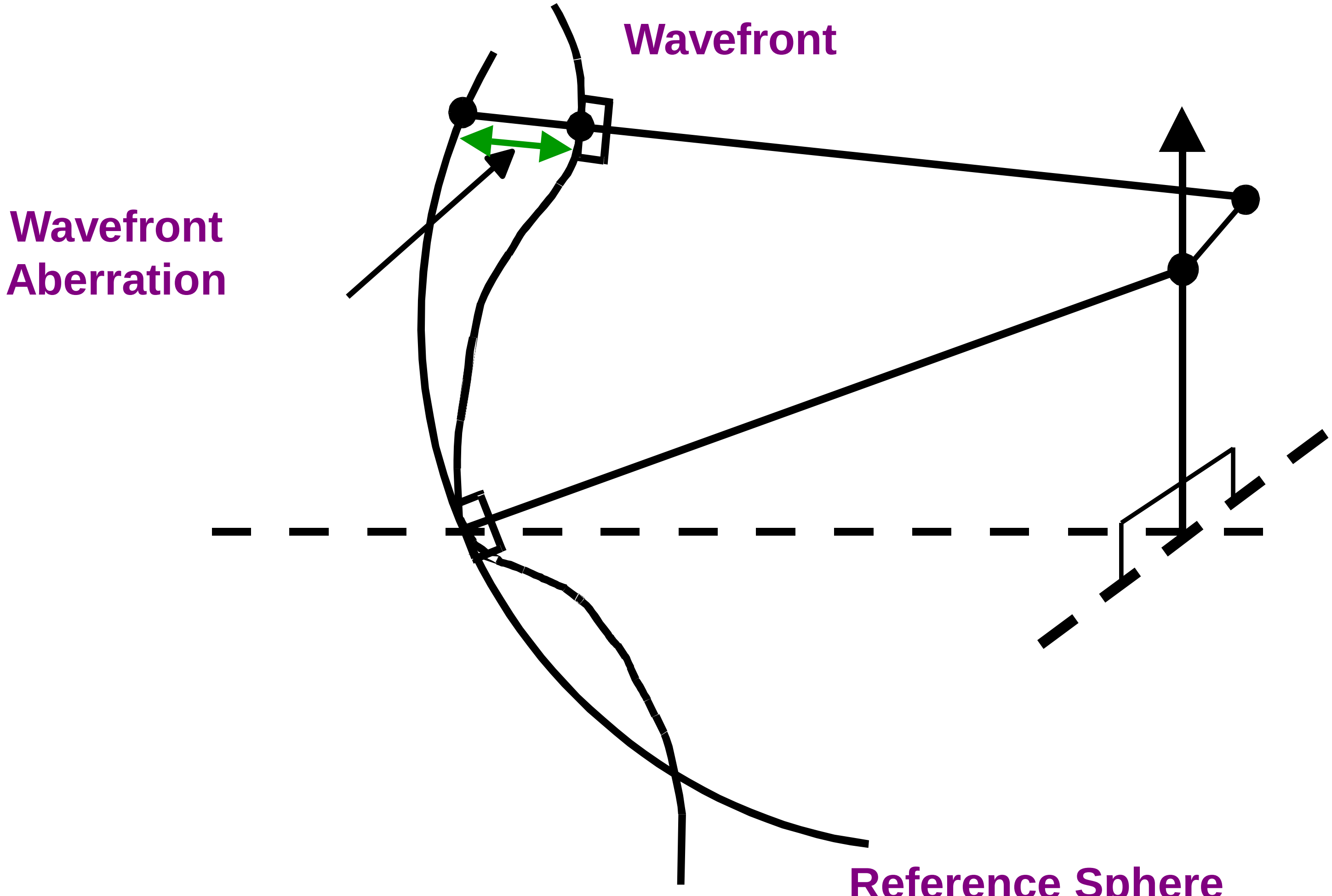
Monochromatic Aberrations and Image Quality

Optics of the Eye



Note components are normally misaligned

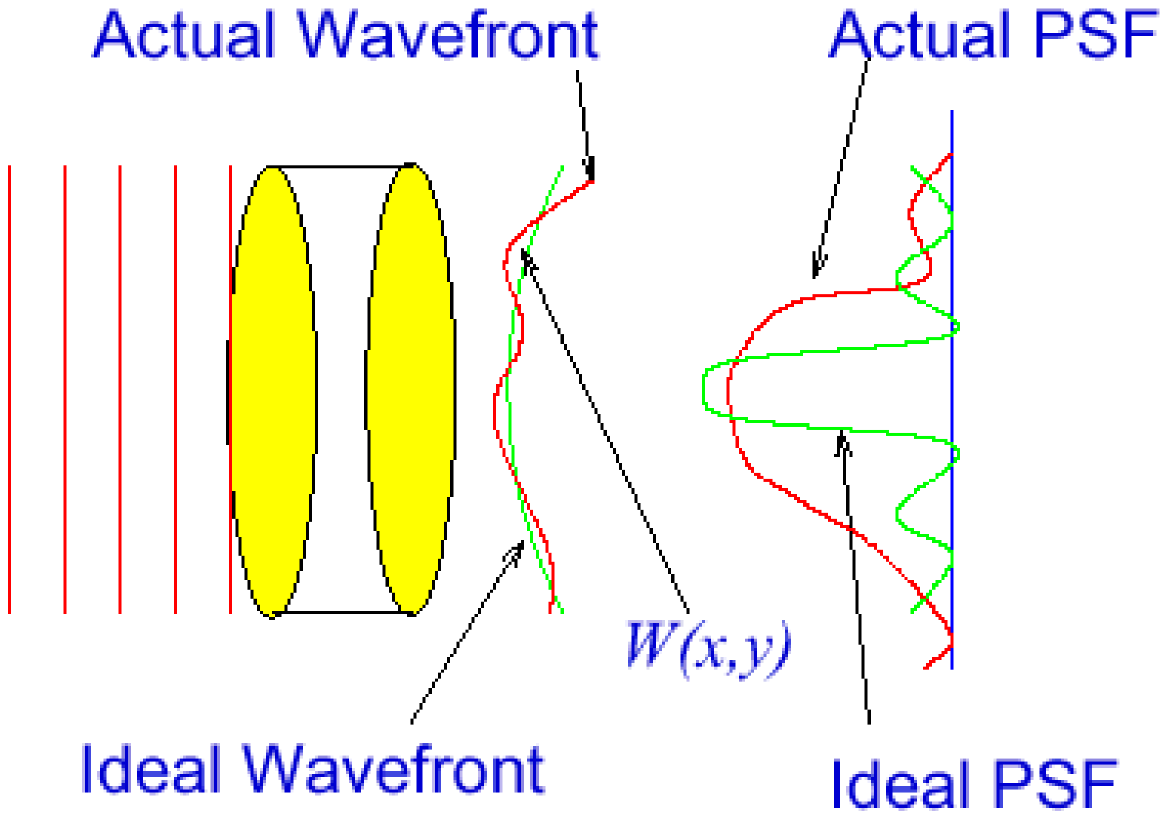
Monochromatic Wavefront Error



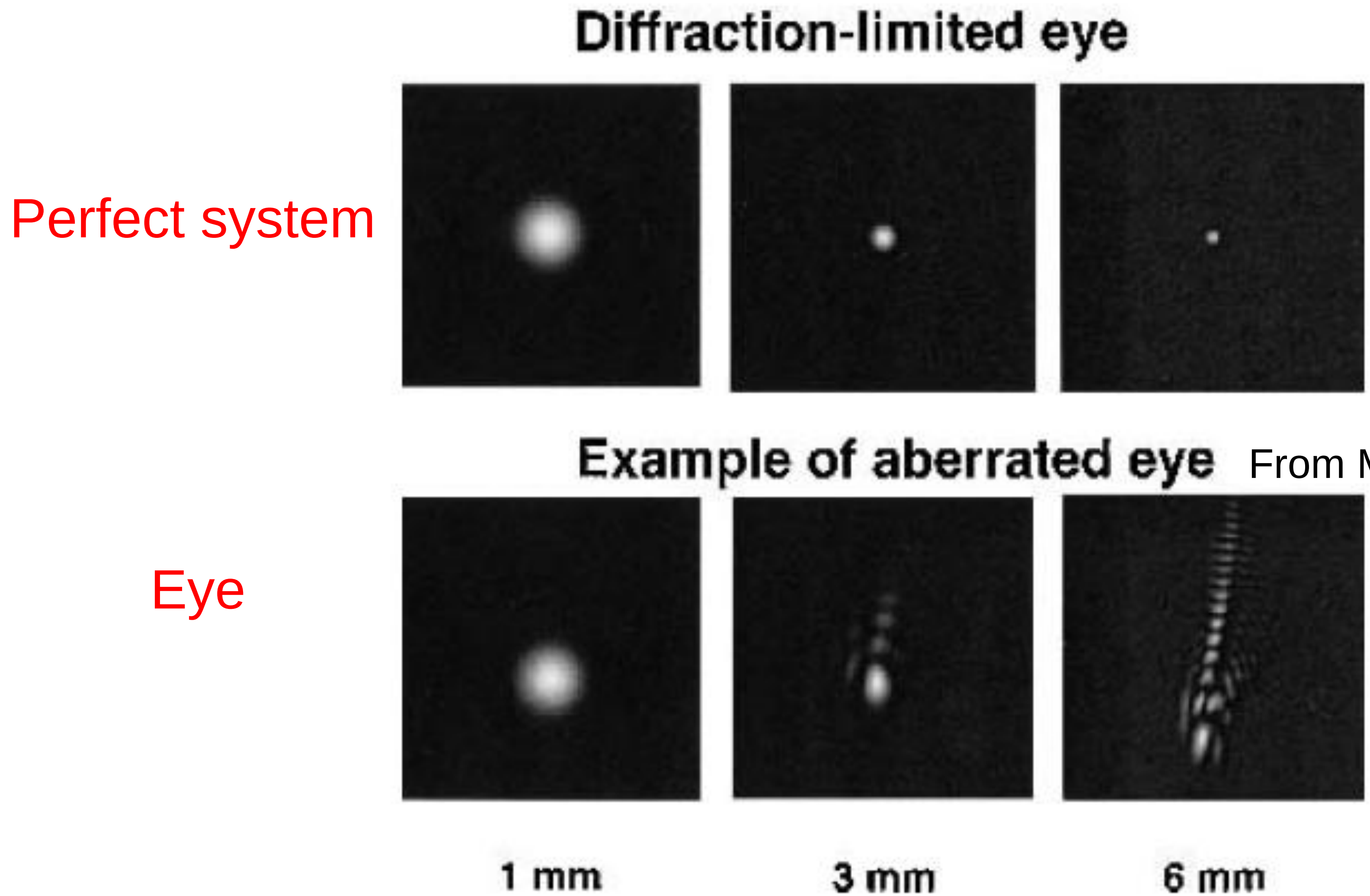
Note dependence on pupil size

Wavefront Aberration and Point Spread Function (PSF)

Actual wavefront may vary from this ideal.



PSF's as a Function of Pupil Size



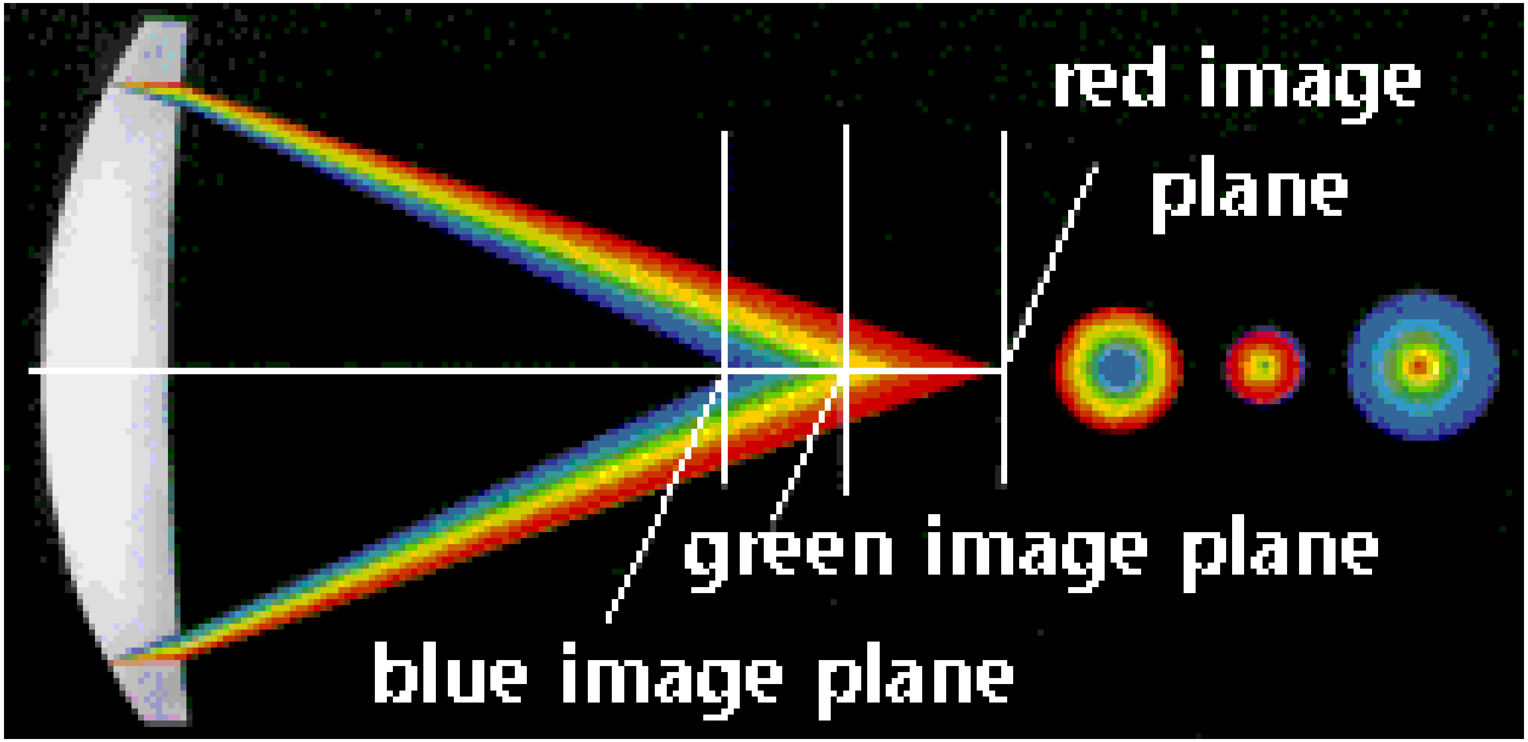
From Marcos

Monochromatic Aberrations and Vision

- Monochromatic aberrations reduce effects of chromatic aberrations
- Determines contrast sensitivity at intermediate spatial frequencies
- Reduces resolution at lower light levels with larger pupils

Chromatic Aberration of the Eye

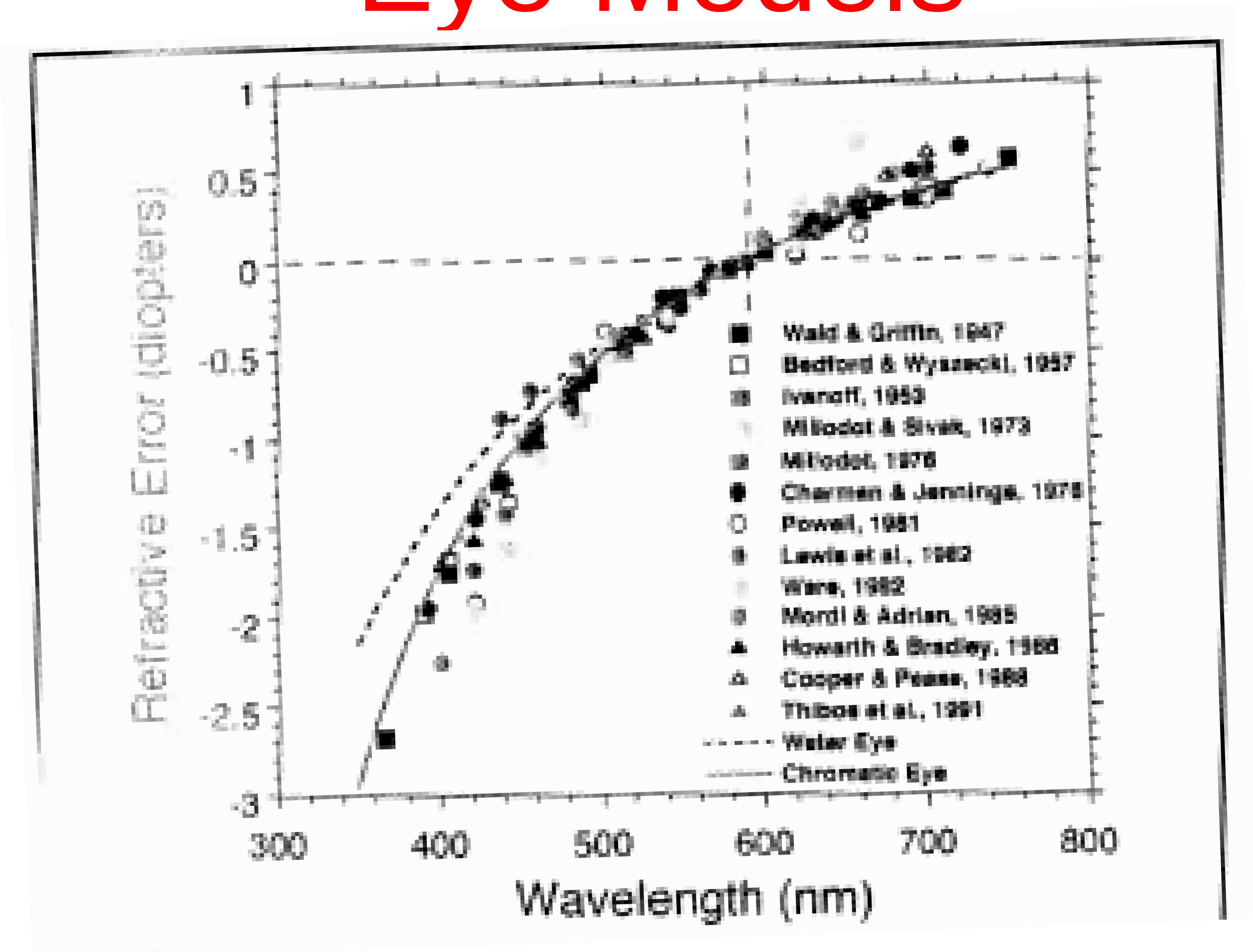
Longitudinal Chromatic Aberration



Chromatic fringing: Eye has lower sensitivity to red and blue fringes

Usually corrected in commercial lenses with achromatic doublets of two different refractive indices

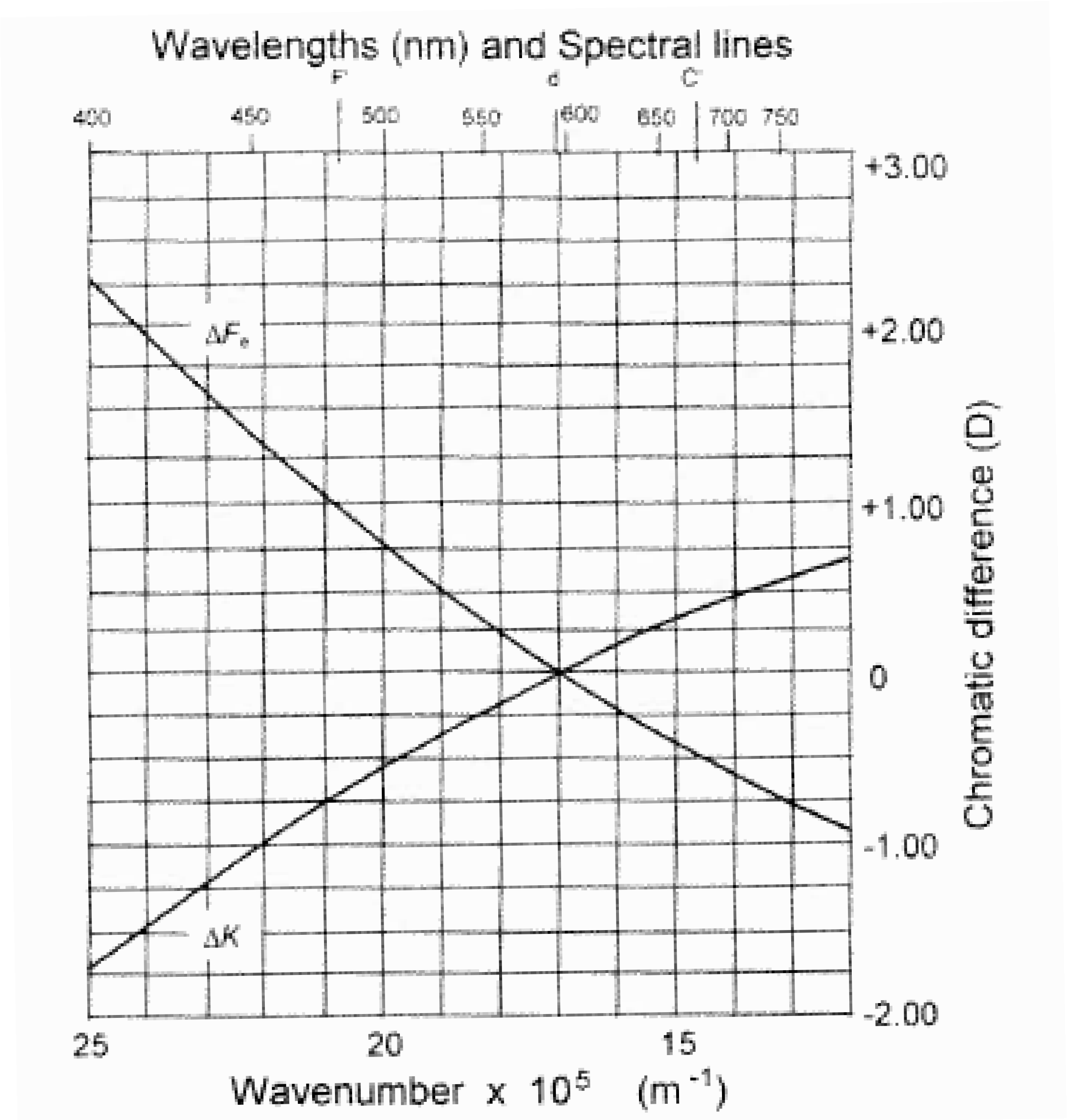
Longitudinal Chromatic Aberration: Eye Models



Bradley, 1992

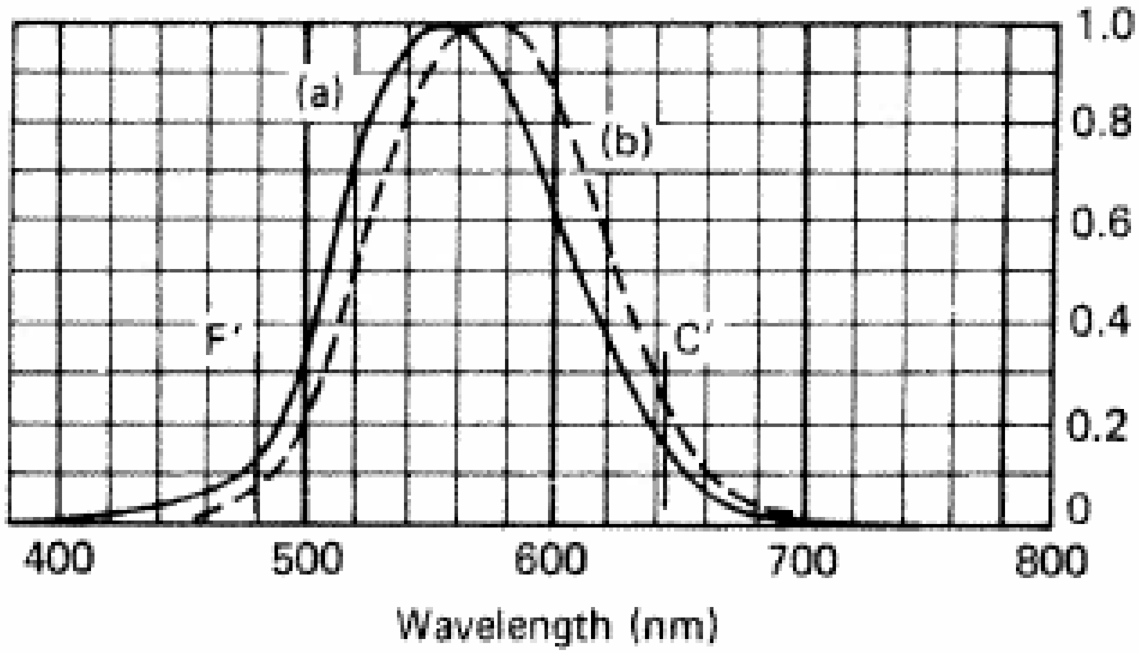
- Water eye model gives a similar curve
- Crystalline lens dispersion responsible for deviation

Longitudinal Chromatic Aberration



Bennett and Rabbetts

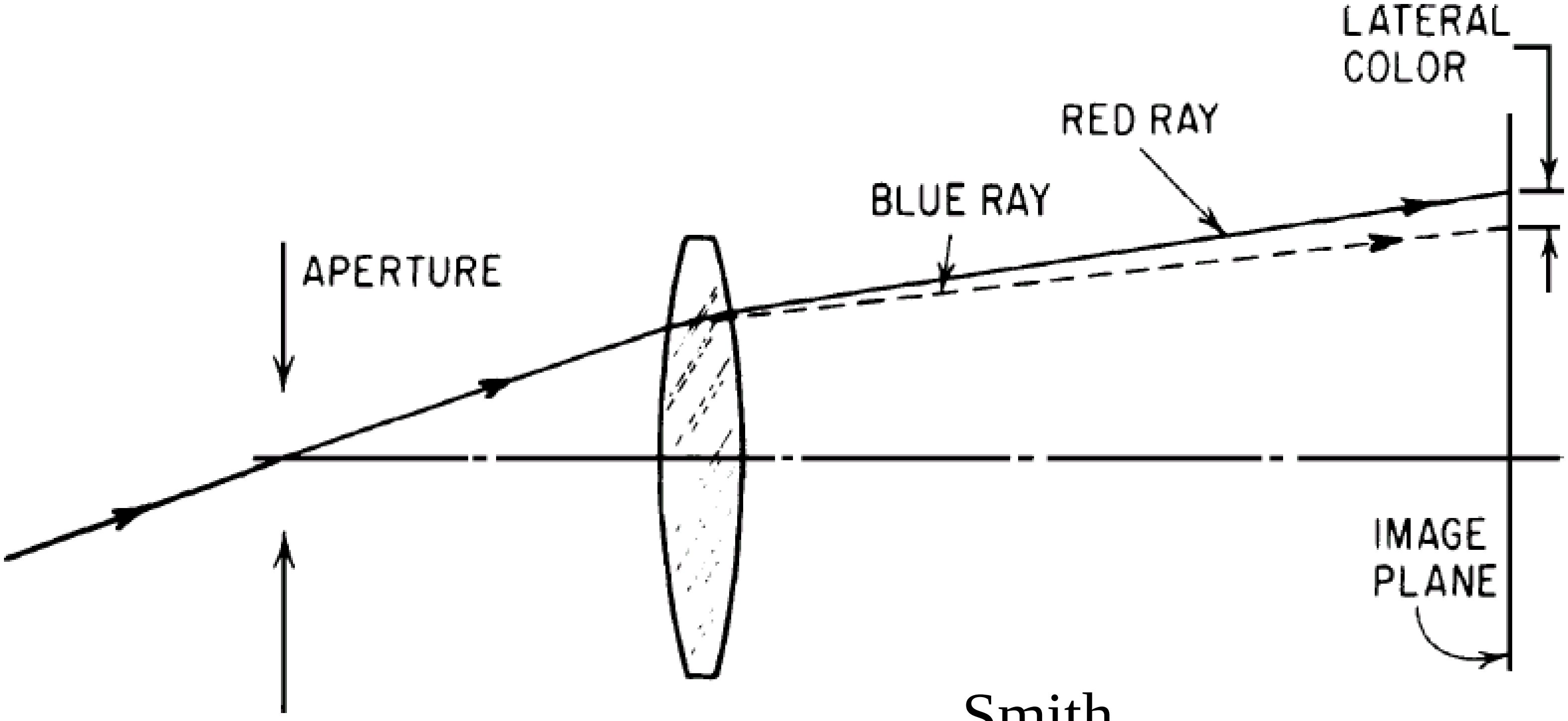
Longitudinal Chromatic Aberration Visual Effects



Bennett and Rabbetts

Because of V(λ) curve, effect of LCA (Longitudinal) on image contrast is equivalent to ~0.2 D of defocus (Thibos, 1991)

Chromatic Difference of Magnification (CDM)



Smith

• Use the principal ray to define the image size, depends on stop position, dispersion

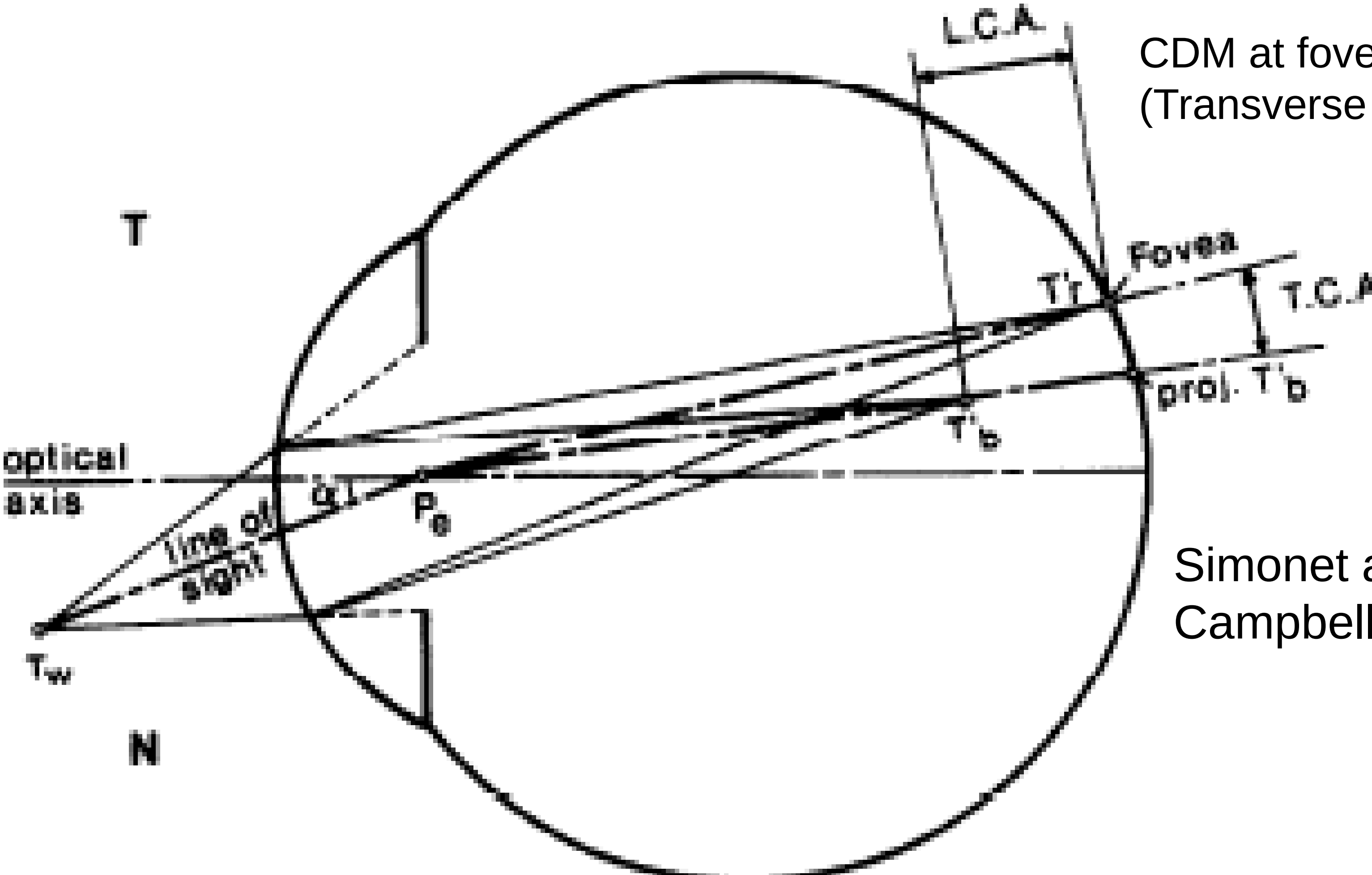
• Eye's pupil decentered

• CDM will increase linearly with field angle

•Also called Lateral CA, Transverse CA

CDM Increases in Periphery

Centered Eye: LCA and CDM



CDM at fovea = TCA
(Transverse CA)

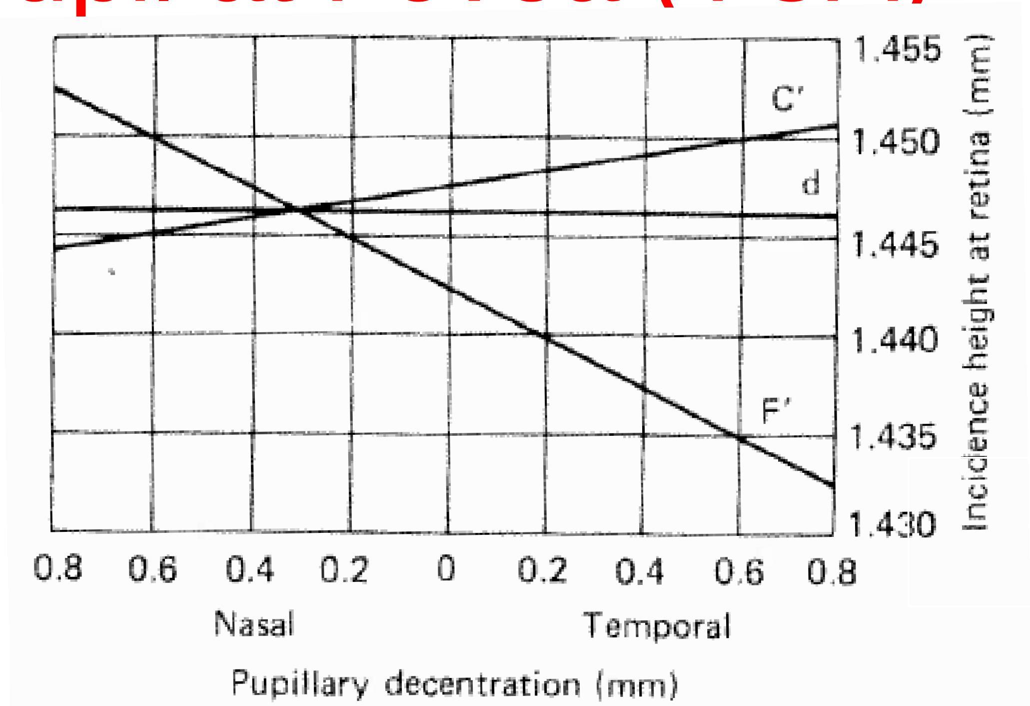
Simonet and
Campbell, 1990

CDM is a function of stop position and decentration because

- it is defined wrt to the **principle ray** and
- increases linearly with field angle

Chromatic Aberration and Vision

Predicted Ocular CDM Centered Pupil at Fovea (TCA)



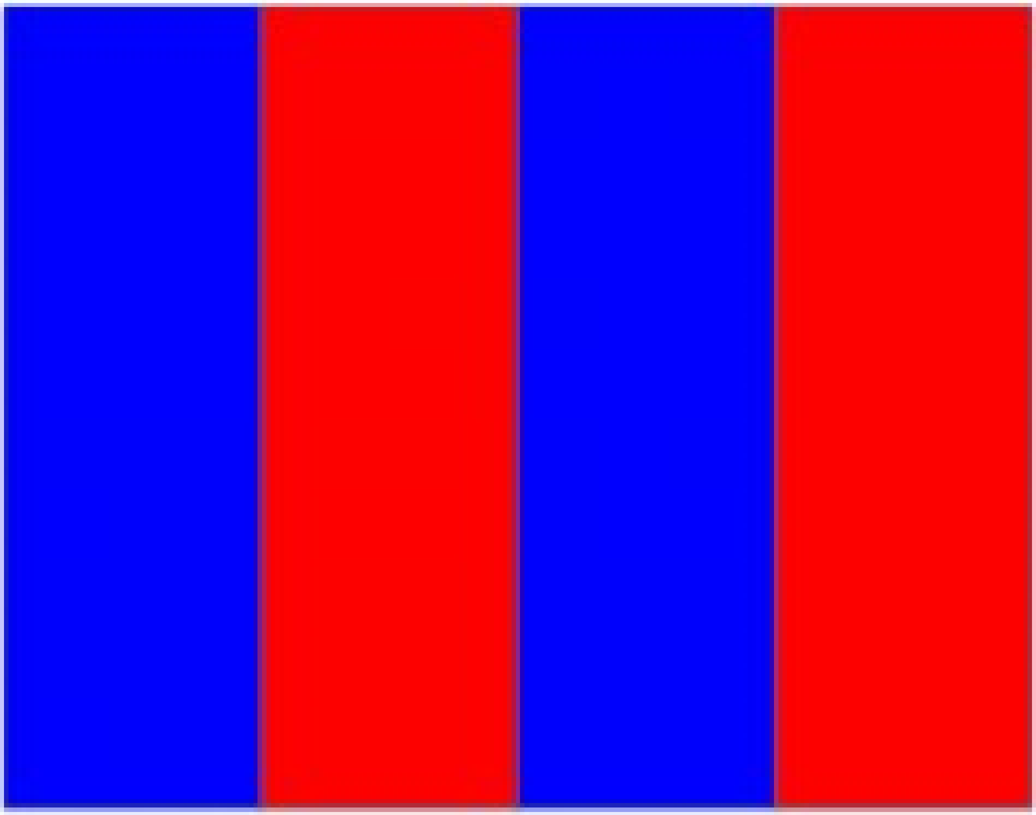
Bennett and Rabbetts

- For a centered pupil, CDM is predicted as 67 sec of arc, < 1% but within acuity limit
- Nasal pupil decentration neutralises CDM, averages 30 sec but variable
- CDM very sensitive to pupil decentration, sign flips
- Increases if pupil in front of the eye

Attempts to Correct CDM

- CDM variable with pupil size, pupil centre shifts up to 0.6 mm with pupil size; CDM sign changes at larger pupils
- Without precise centration, induced CDM cancels advantage of LCA correction (Carmen design)
- Powell lens has relatively low CDM when decentered
- Diffractive corrections of positive power partially compensate chromatic aberration
- Contact lens or IOL- effects of decentration lower, lens CDM important
- LCA is constant across individuals, CDM is variable

CDM and Chromostereopsis



Perception of a difference in depth arises from CDM (TCA)
See Simonet and Campbell

Imperfect Optics Protect against Chromatic Blur

- McLellan, 2002
- When monochromatic aberrations are corrected, chromatic degradation more visible
- Chromatic correction could provide a larger benefit than monochromatic correction alone (Yoon, 2002)
- In presence of monochromatic aberrations, MTF less sensitive to wavelength

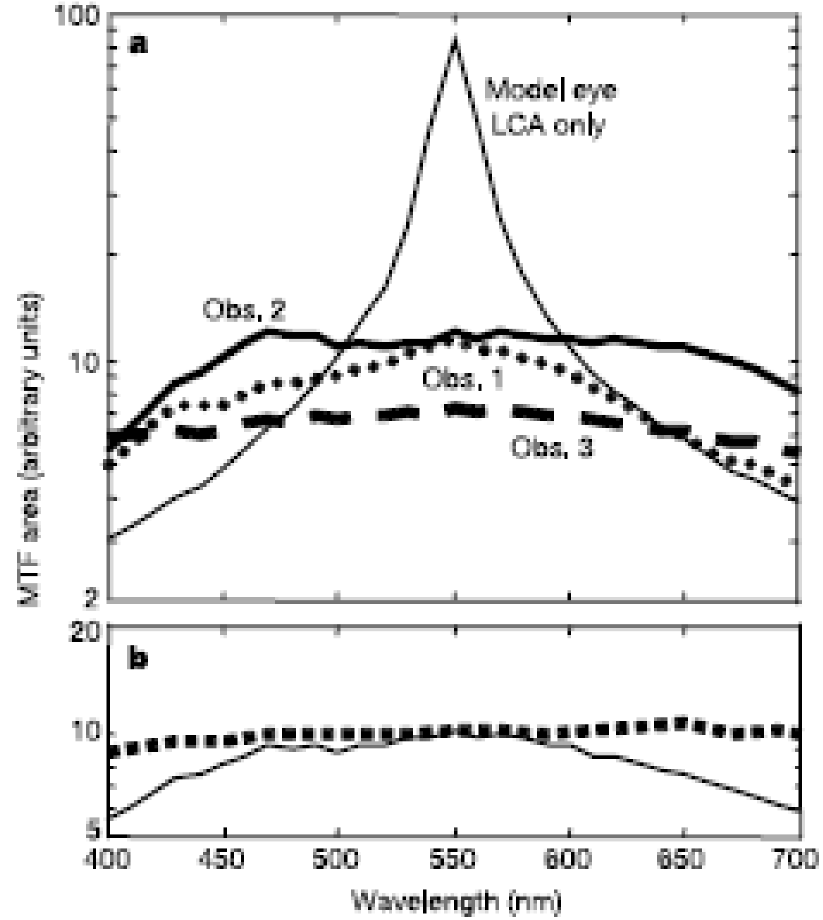
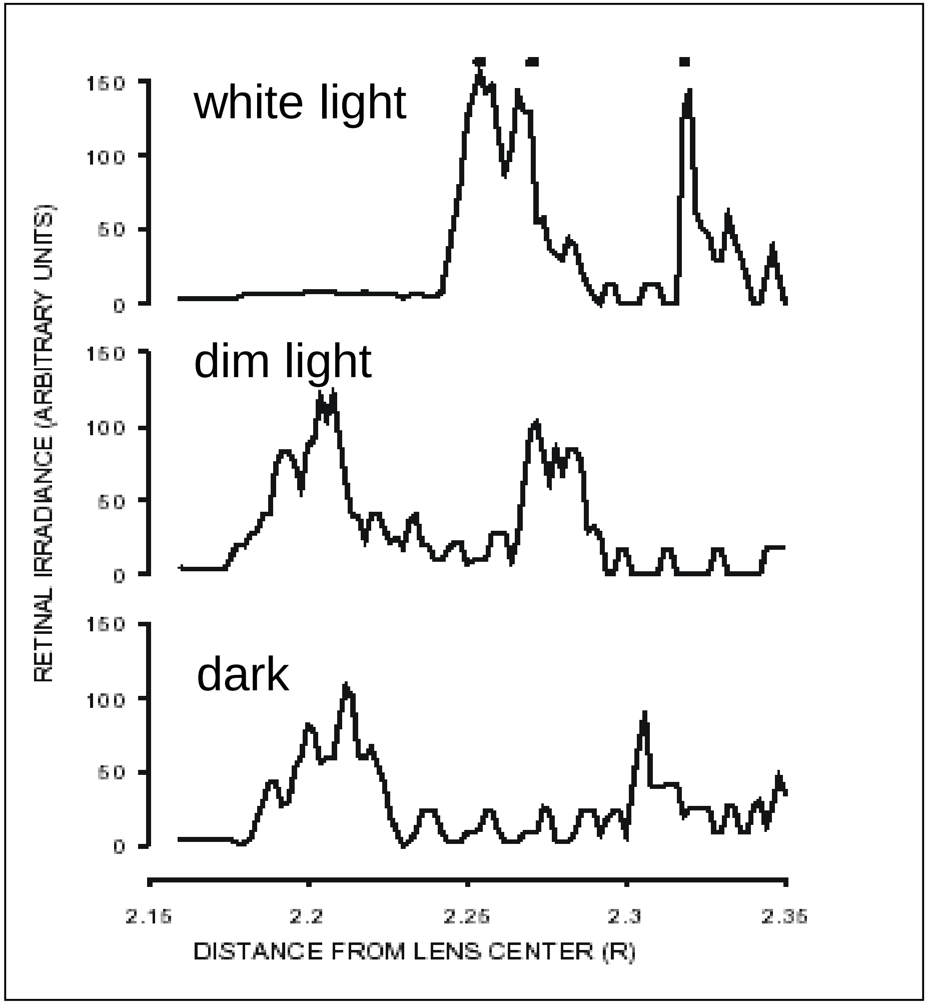


Figure 2 MTF area. **a**, Area under the MTF (arbitrary units) as a function of wavelength for a theoretical model eye with LCA only and for three subjects with measured wave aberrations. **b**, Mean MTF area for all three subjects when defocus is set to optimize area at 550 nm (solid line) and when each wavelength is individually optimized (dashed line). The dashed line shows that MTF area at any single wavelength can be improved further by correcting focus at that wavelength.

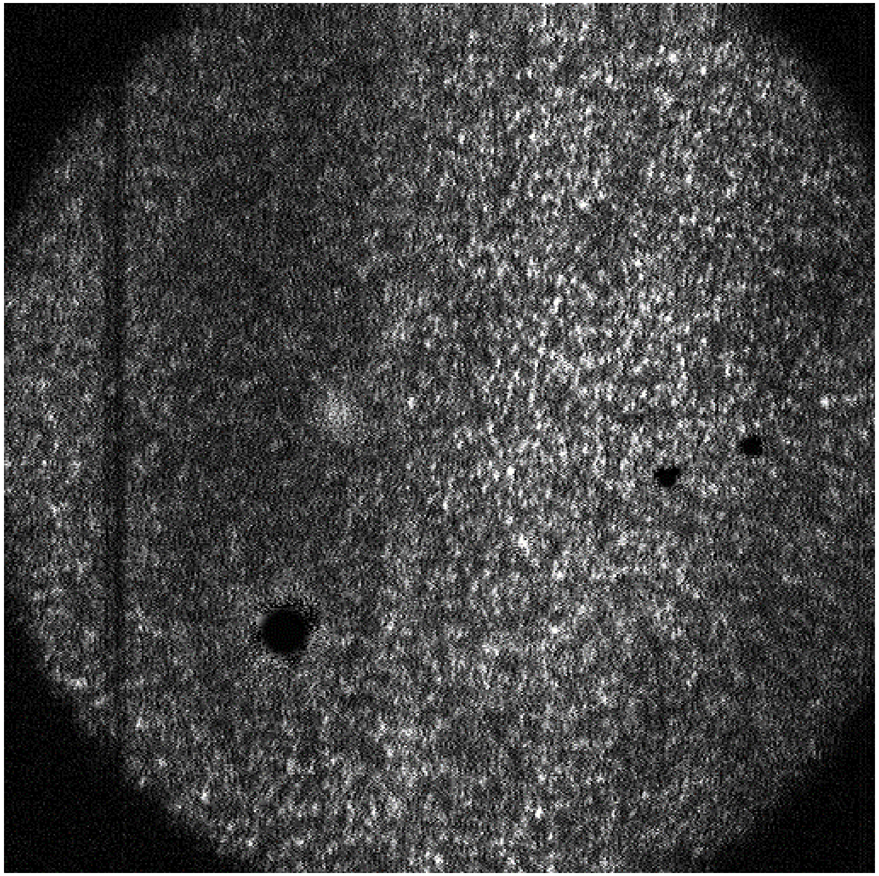
Aberrations and Eye Growth

- Net aberrations change with rearing conditions
- Monochromatic and chromatic aberrations could provide signals to eye growth
- A match of image blur to cone sampling provides a stop signal to growth in the chick eye

Irradiance on the Cichlid Retina in Differing Rearing Conditions

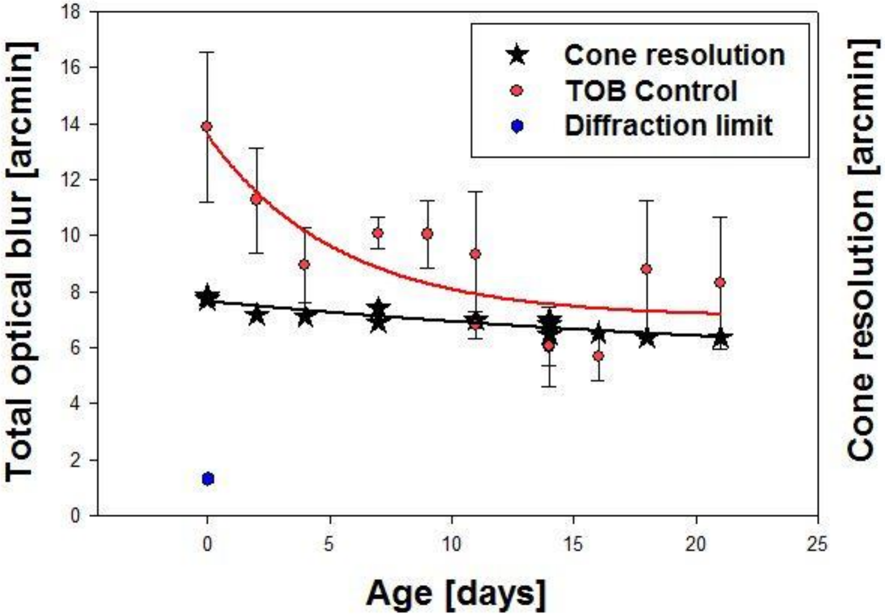


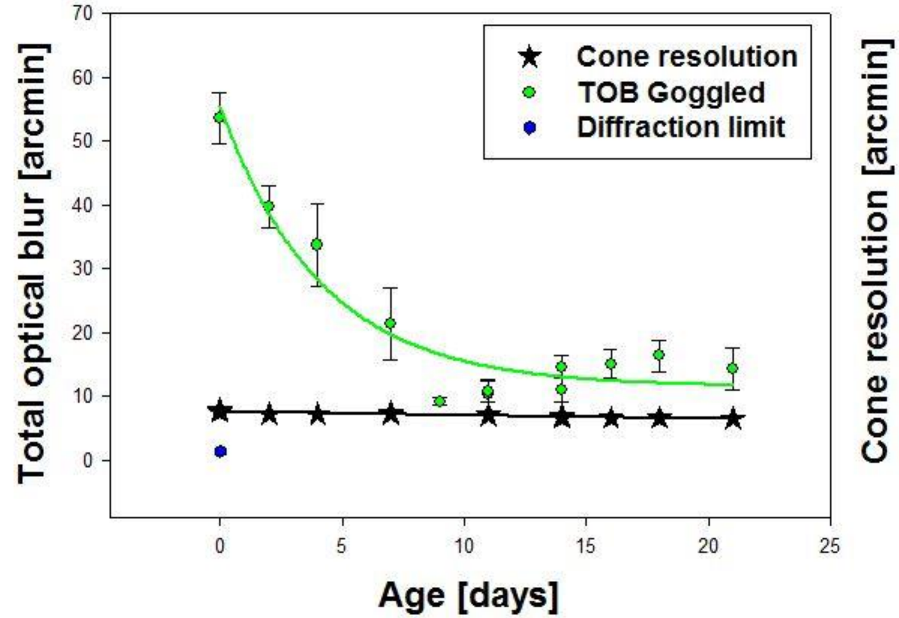
Chick Model of Normal Development and Myopia



Optical Blur and Cone Resolution

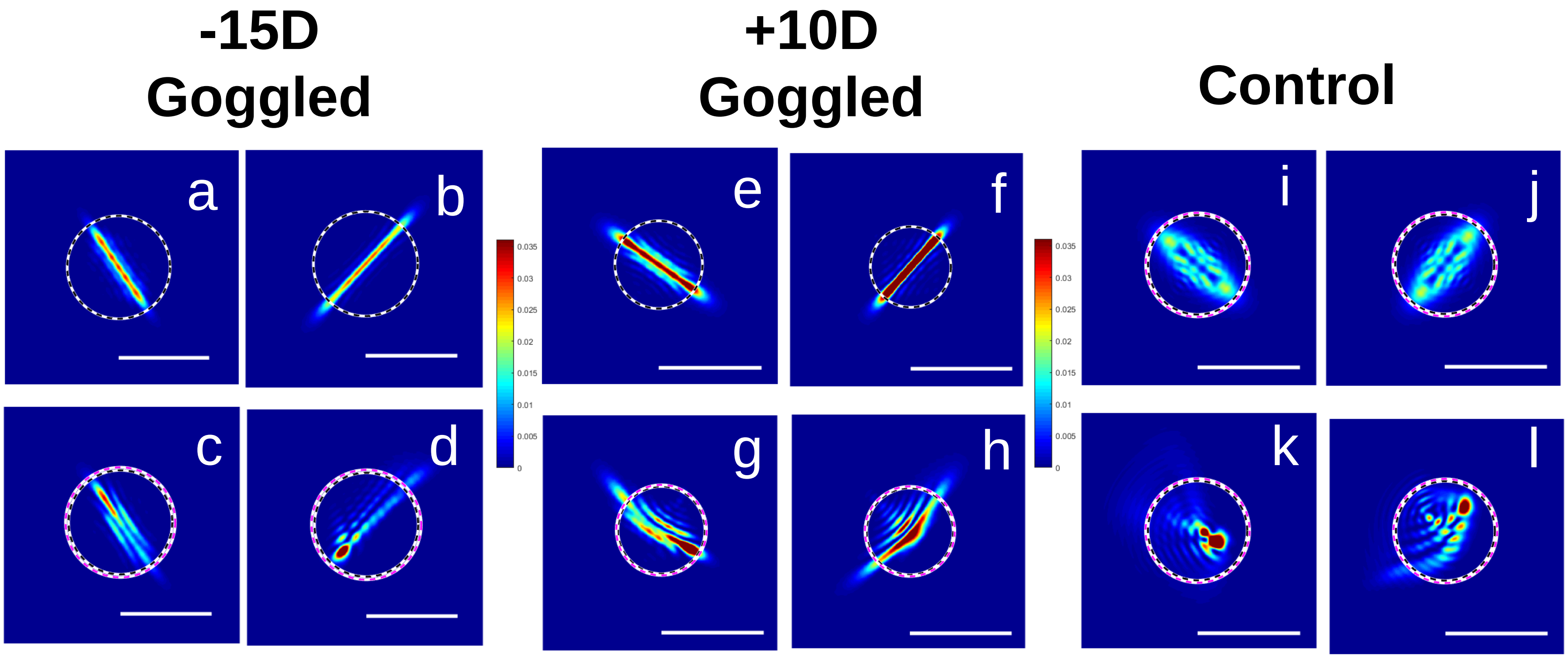
As optical blur reduces
to match cone resolution,
axial elongation stops





Does sensitivity to blur determine who will become myopic?

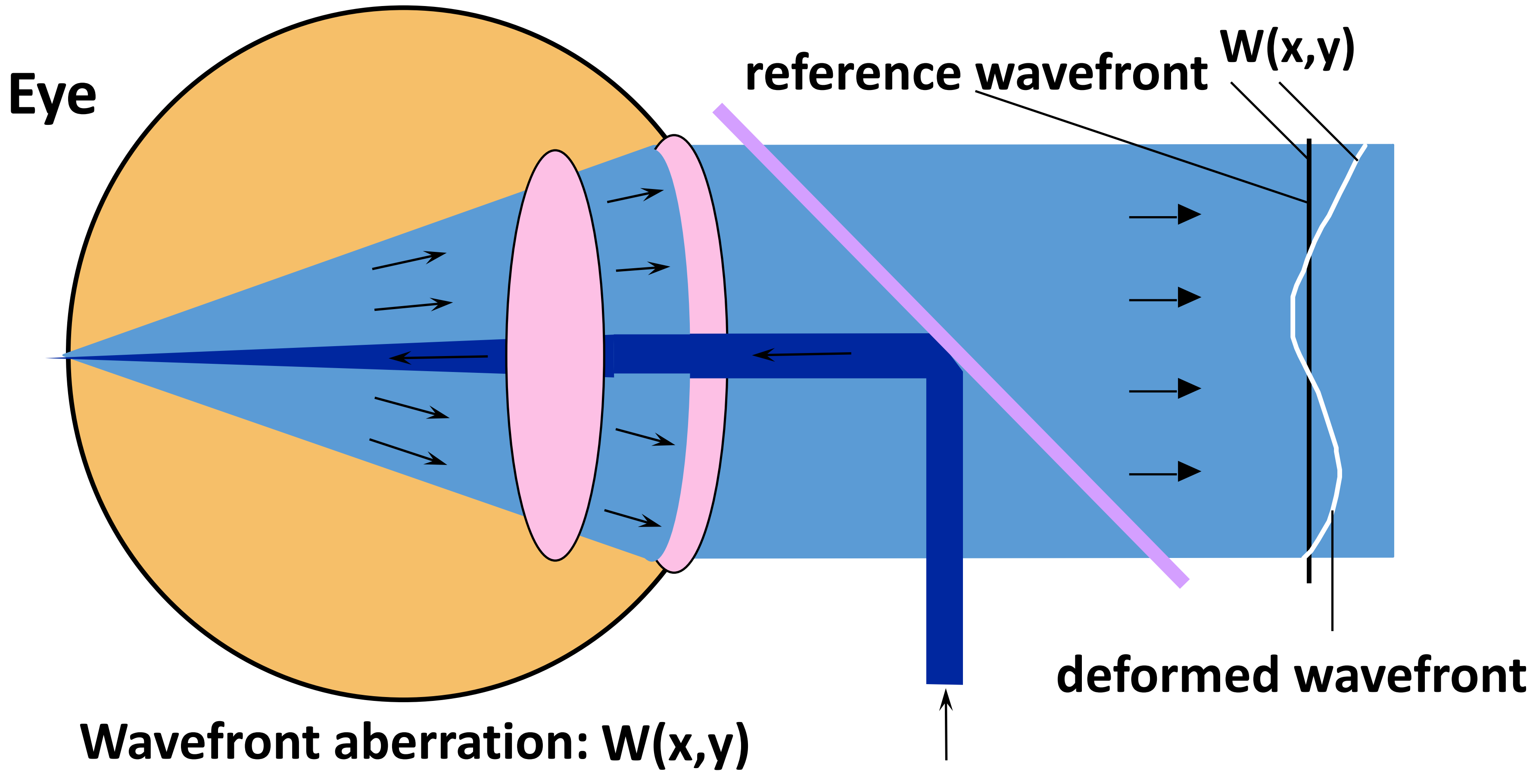
Optical Signals for Sensing Defocus



Retinal blur after response to the goggle for eyes with and without goggles calculated from measured aberrations and defocus. During accommodative fluctuations, there is a clear, visible signal to the direction of defocus, primarily from astigmatism.
Scale bars are 15arcmin.

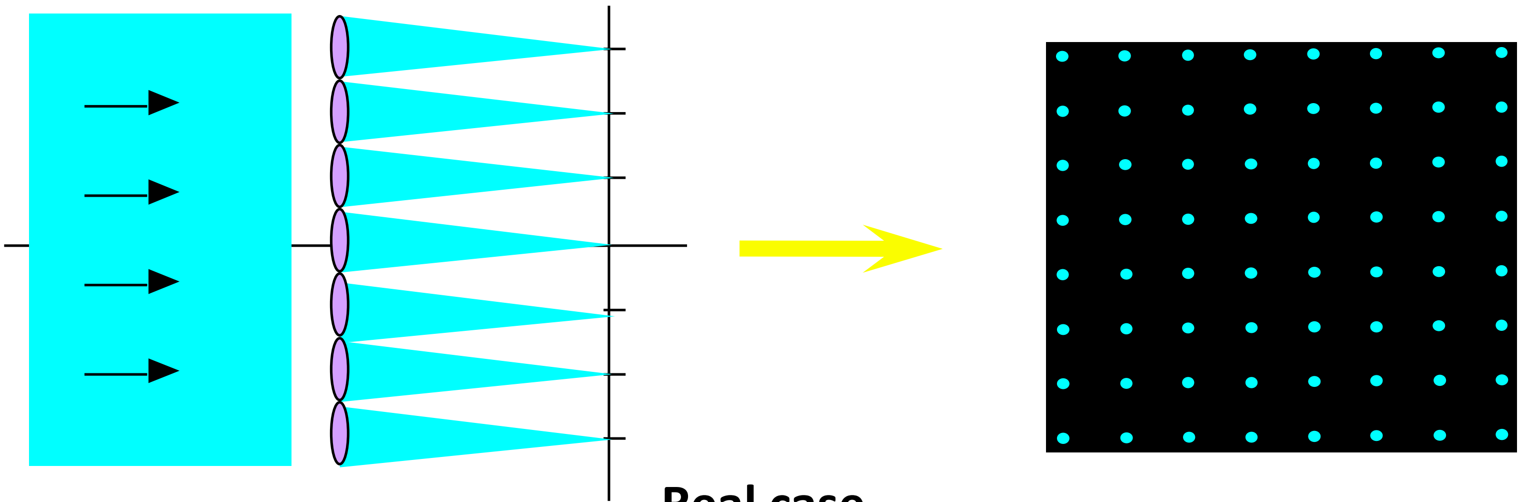
Correction of Monochromatic Aberrations for High Resolution Imaging

Measurement of Wavefront Error

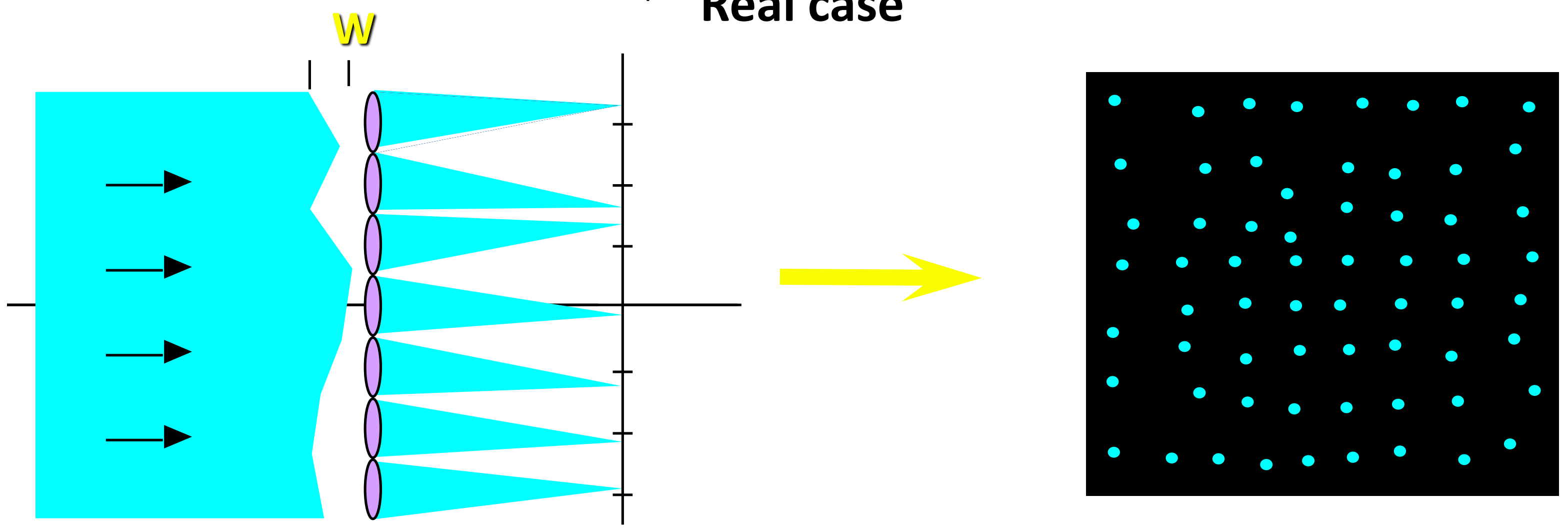


Hartmann-Shack Images

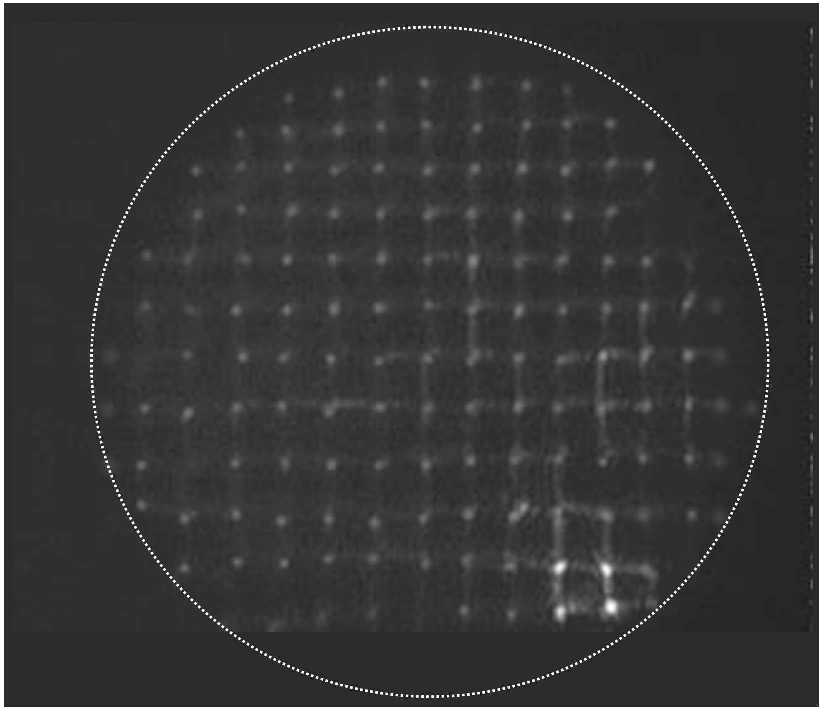
Ideal case



Real case

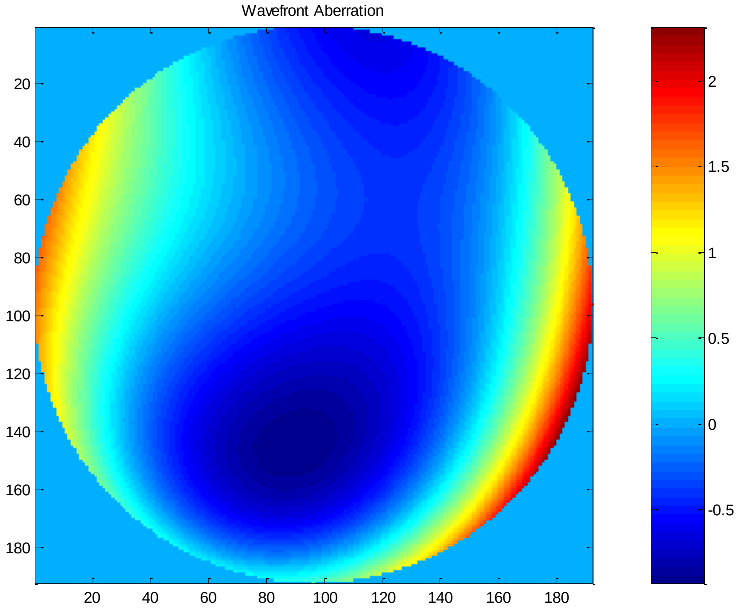


Typical Wavefront Error

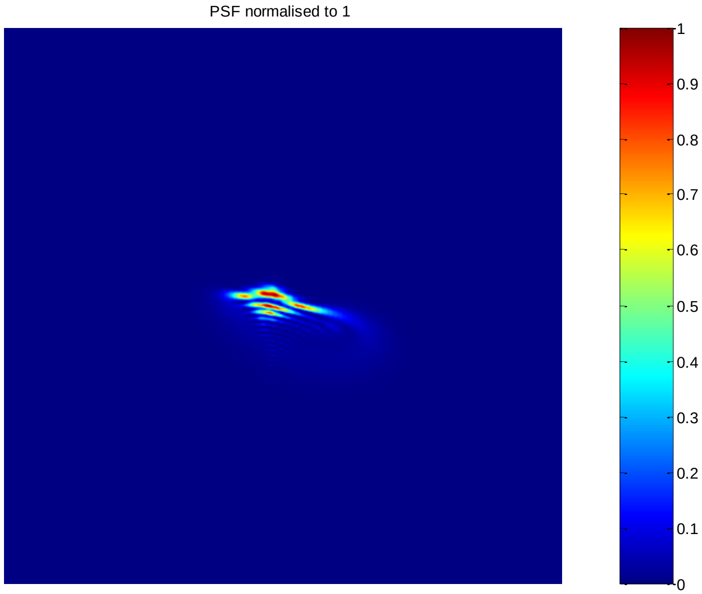


Sample Human Wavefront & PSF

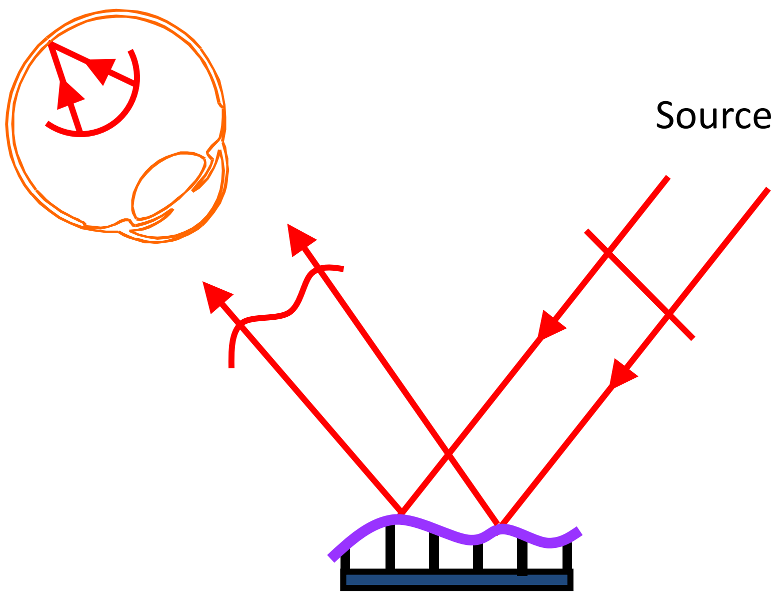
Wavefront

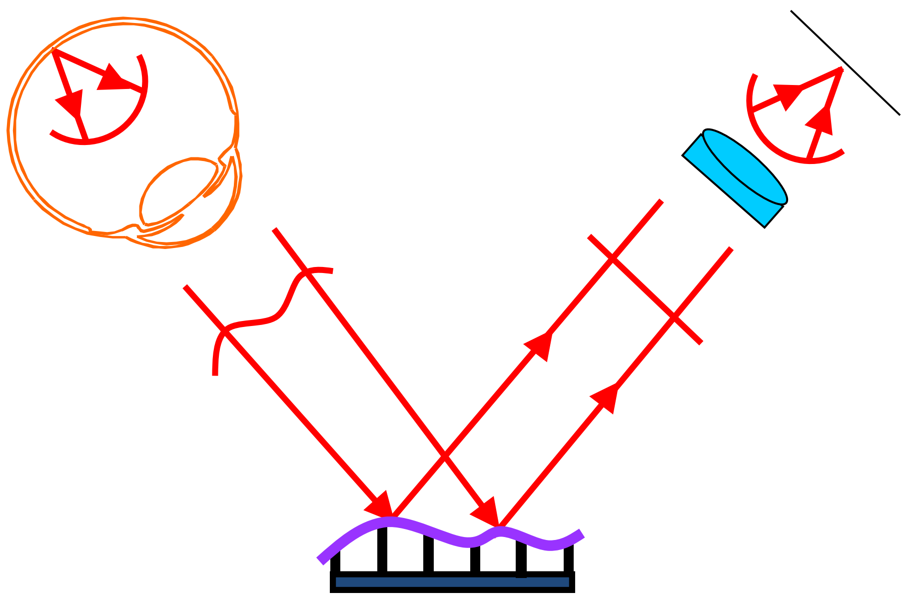


Point Spread Function (PSF)



Correction of Blur of the Eye's Optics

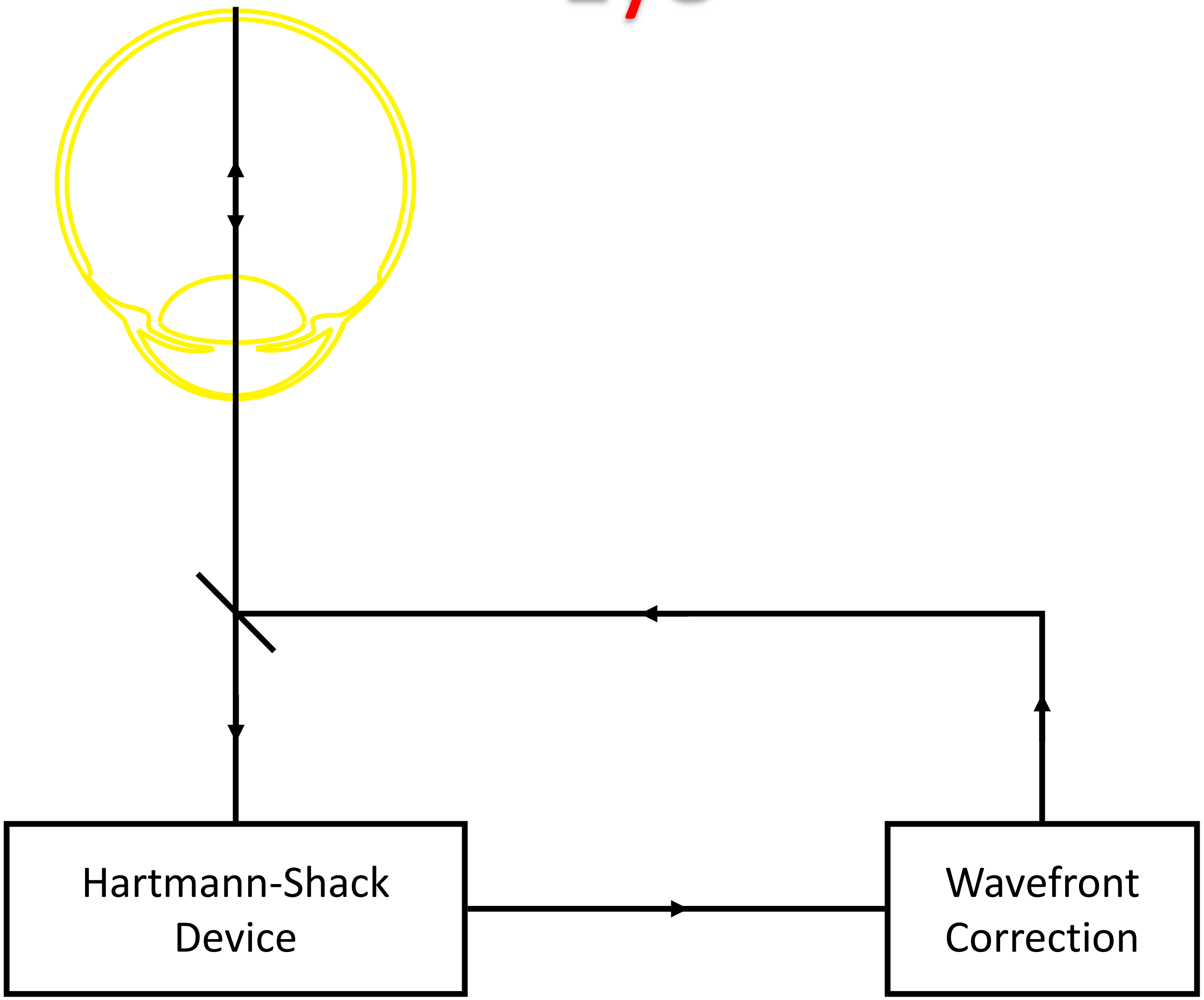




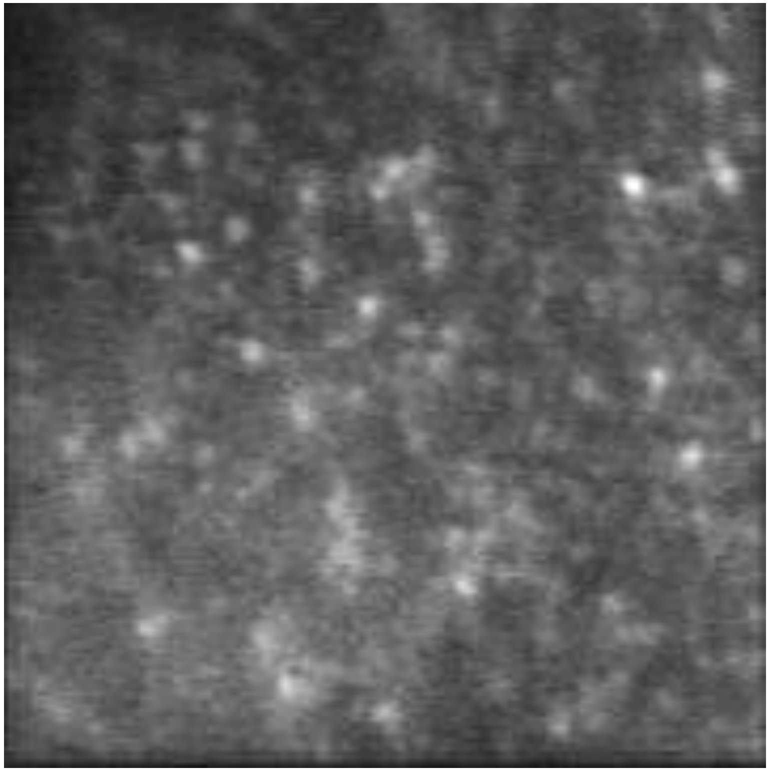
Important to light activated therapies

Imaging - correction in both directions

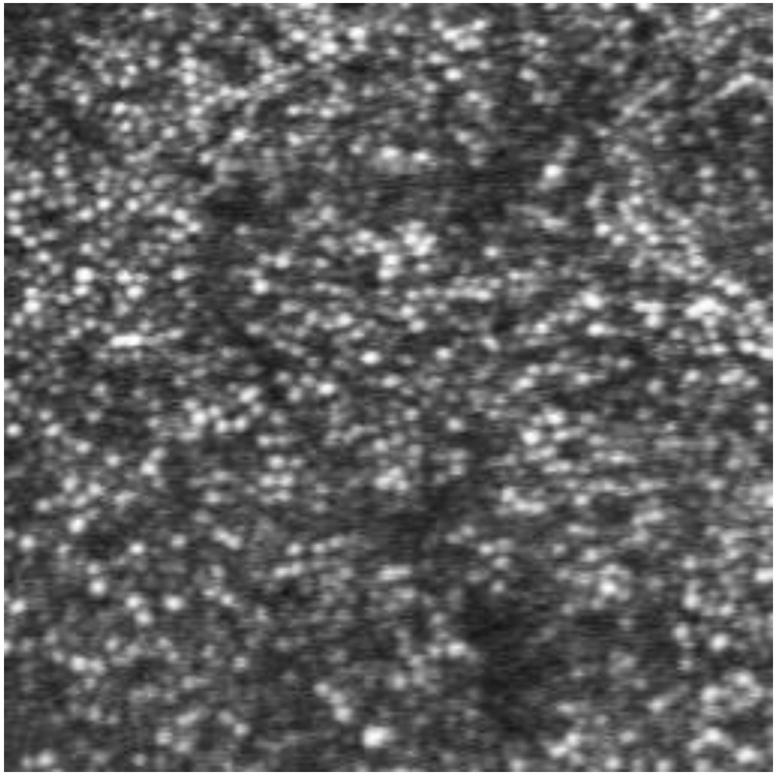
Adaptive Optics Correction of the Eye



Imaging Cones with Adaptive Optics

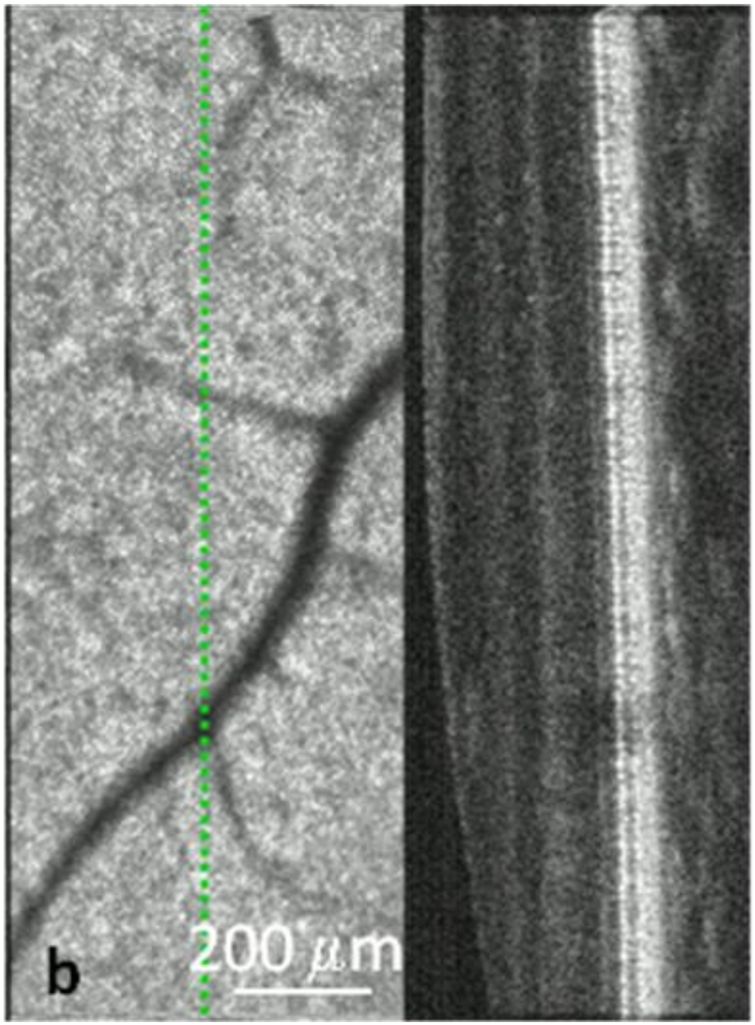


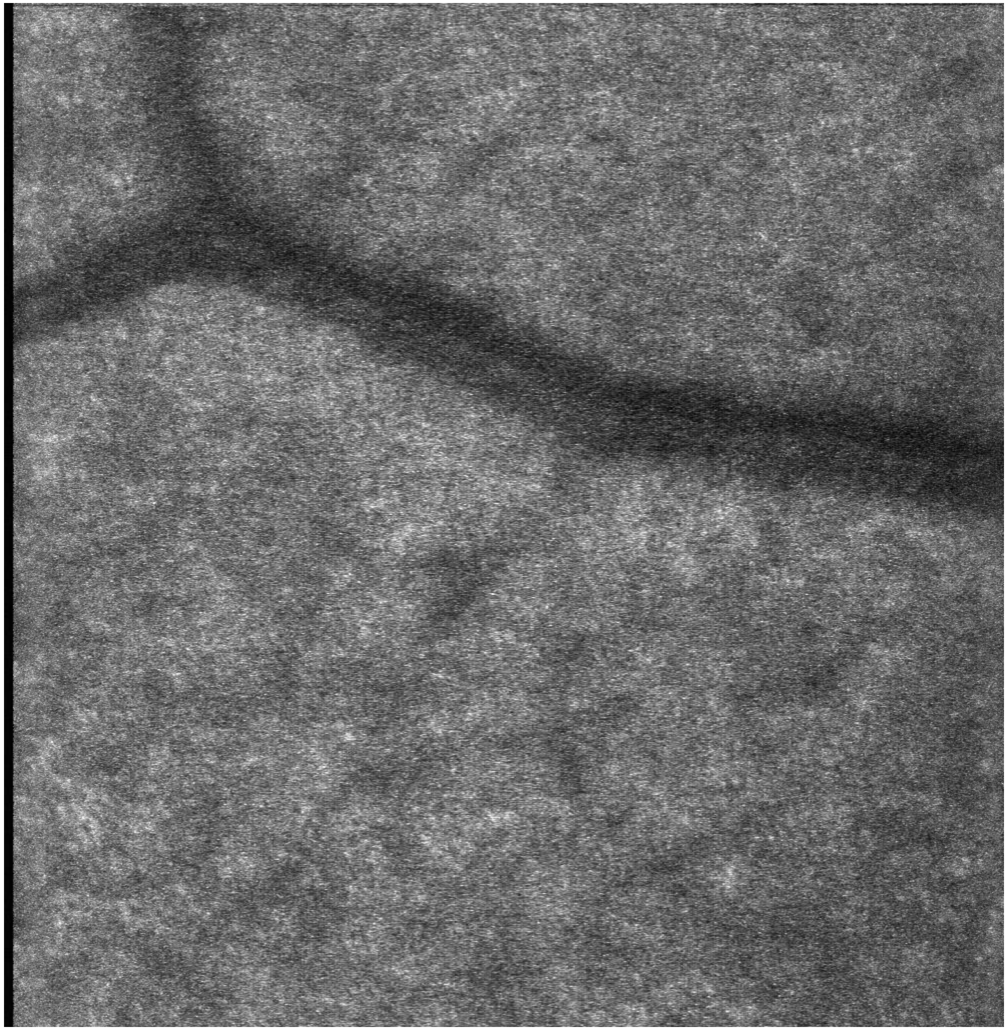
Uncorrected



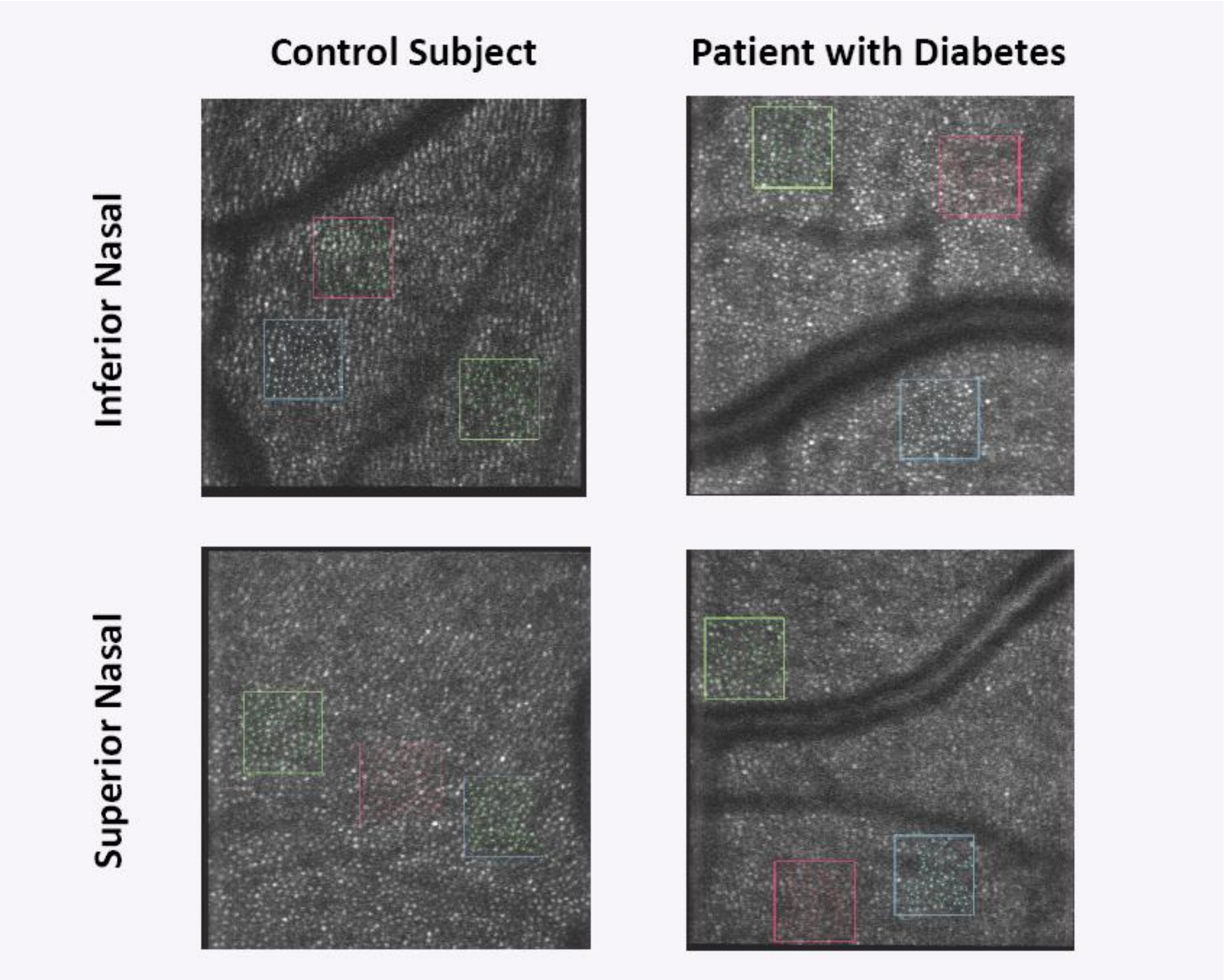
Corrected

AO Corrected Imaging for Monitoring Diabetic Retinopathy





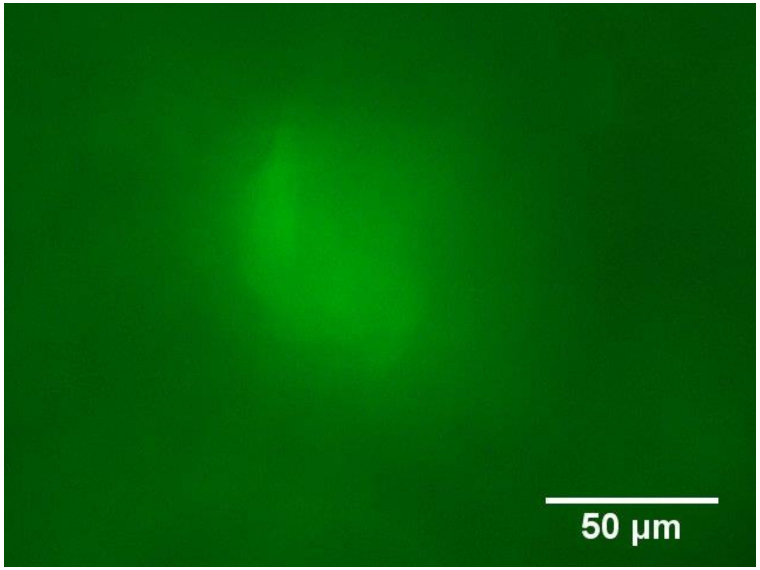
AO-Corrected Images for Monitoring Diabetic Retinopathy



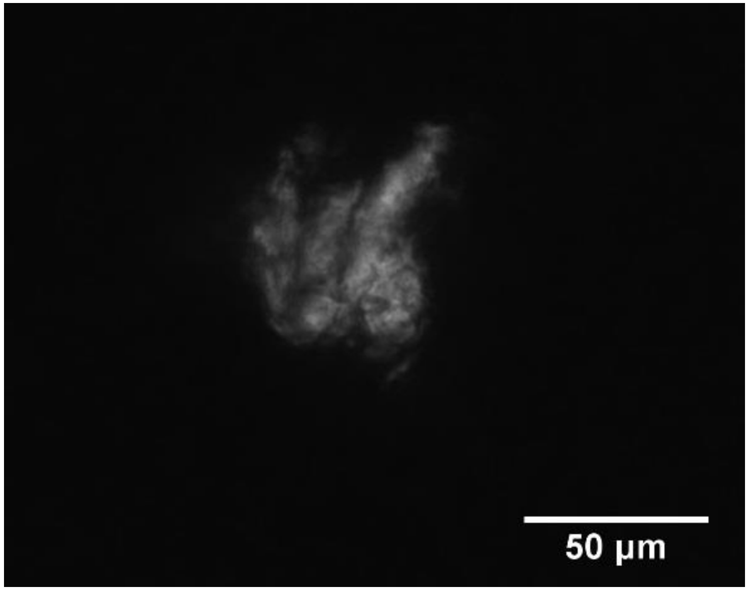
Cone densities of controls (left) differed from patients (right)

Amyloid Deposits as a Biomarker of Alzheimer's disease

Colour (FITC)



Crossed Polarisation



Primary Pathology AD

Acknowledgements

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THE EYEBANK OF CANADA
Ontario Division
Helping save sight for over 40 years

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Canadian Institutes of Health Research
Instituts de recherche en santé du Canada

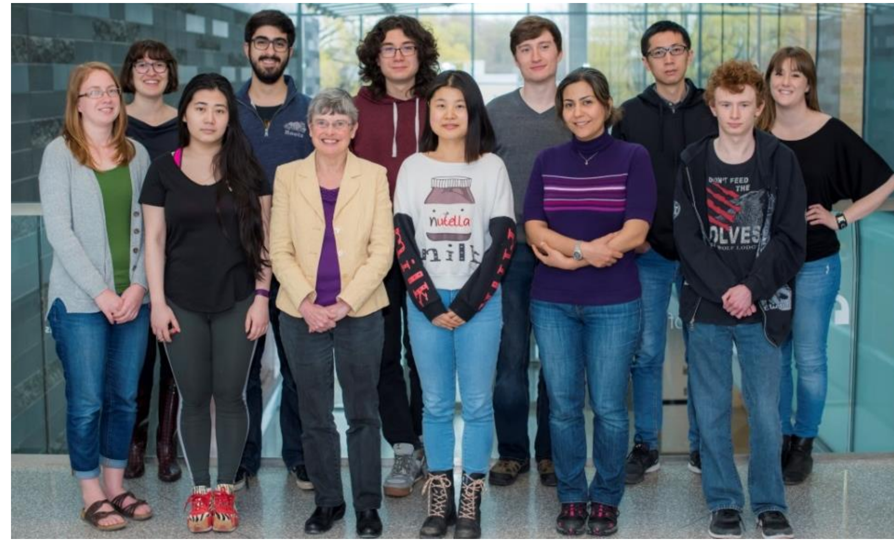
CCNA
Canadian Consortium on Neurodegeneration in Aging
CCNV
Consortium canadien en neurodégénérescence associée au vieillissement

Clinic for Alzheimer Disease and Related Disorders
UBC Hospital

PATHOLOGY
laboratory medicine
UNIVERSITY OF BRITISH COLUMBIA

ELCAN
Optical Technologies
A Raytheon Company

UNIVERSITY of ROCHESTER



Students and Postdoc Openings

- Graduate student and Postdoctoral positions for Physics, Biophysics and Vision Science students

Chromatic Aberration Correction

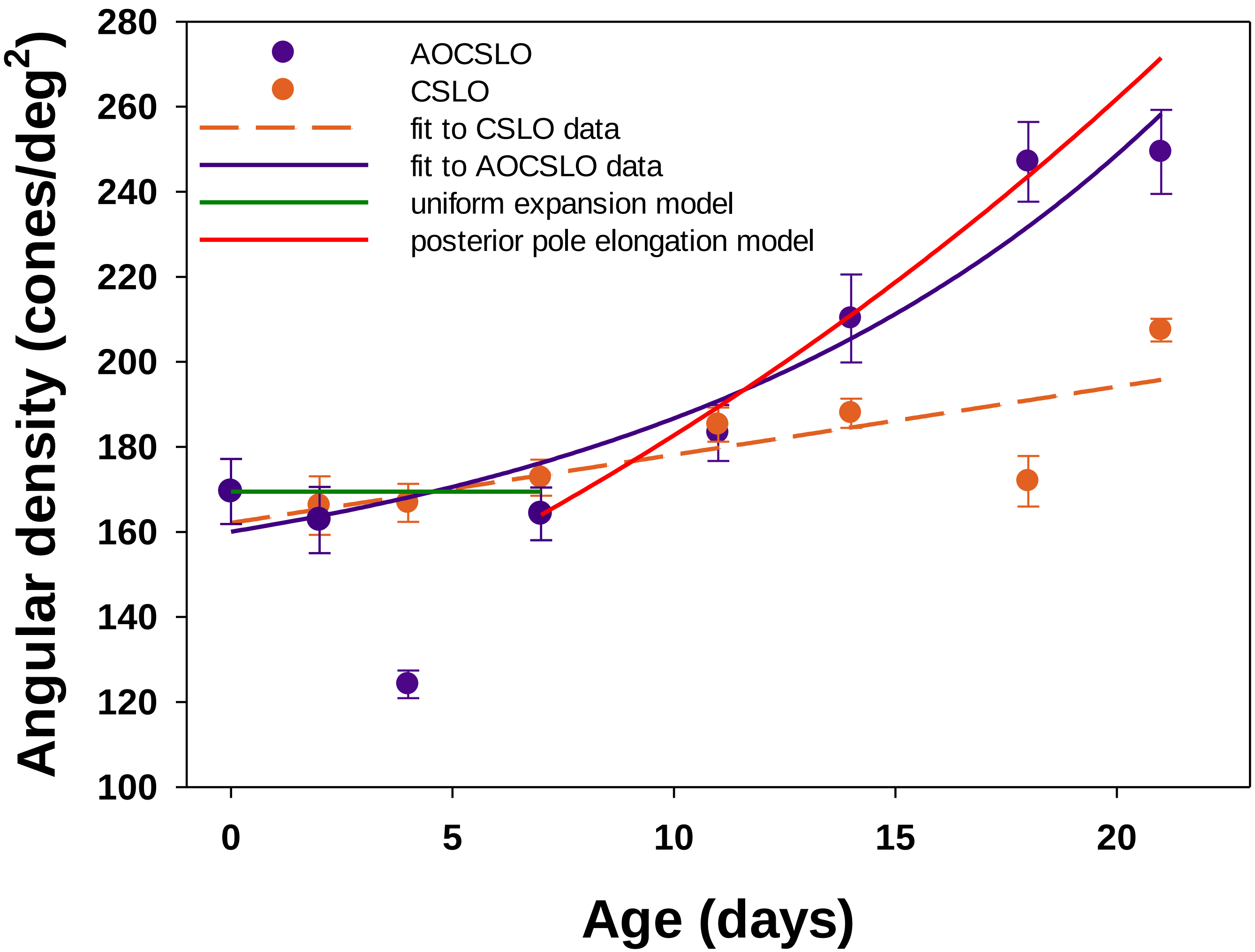
Table 15.3 Details of an achromatizing lens of the Carman design

Spectral line	h	d	
Wavelength (nm)	404.7	587.6	750
Refractive indices			
Positive component	1.63776	1.62041	1.61417
Negative components	1.65120	1.62049	1.61076
Back vertex power	−1.86 D	−0.01 D	+0.47 D
Effective power at cornea (d = 12 mm)	−1.82 D	−0.01 D	+0.48 D
Eye's ΔK (experimental)	−1.70 D	0	+0.58 D
Residual ΔK	−0.12 D	+0.01 D	+0.10 D
Chromatic difference of magnification	0.963 (−3.7%)	1	1.011 (+1.1%)

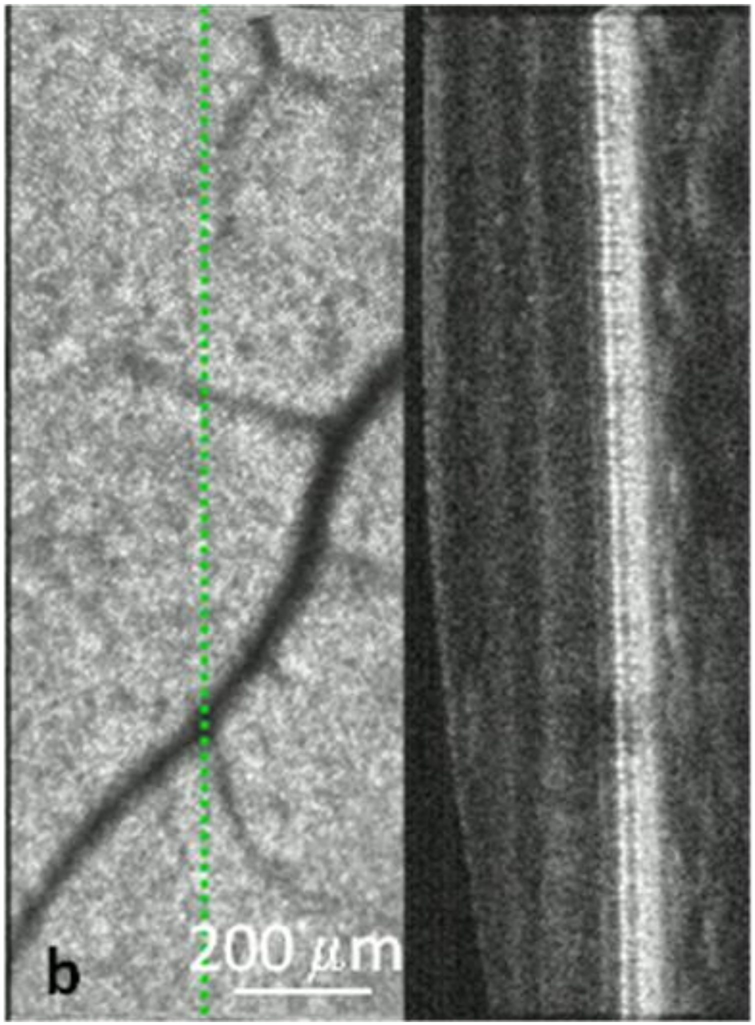
Powell lens is better

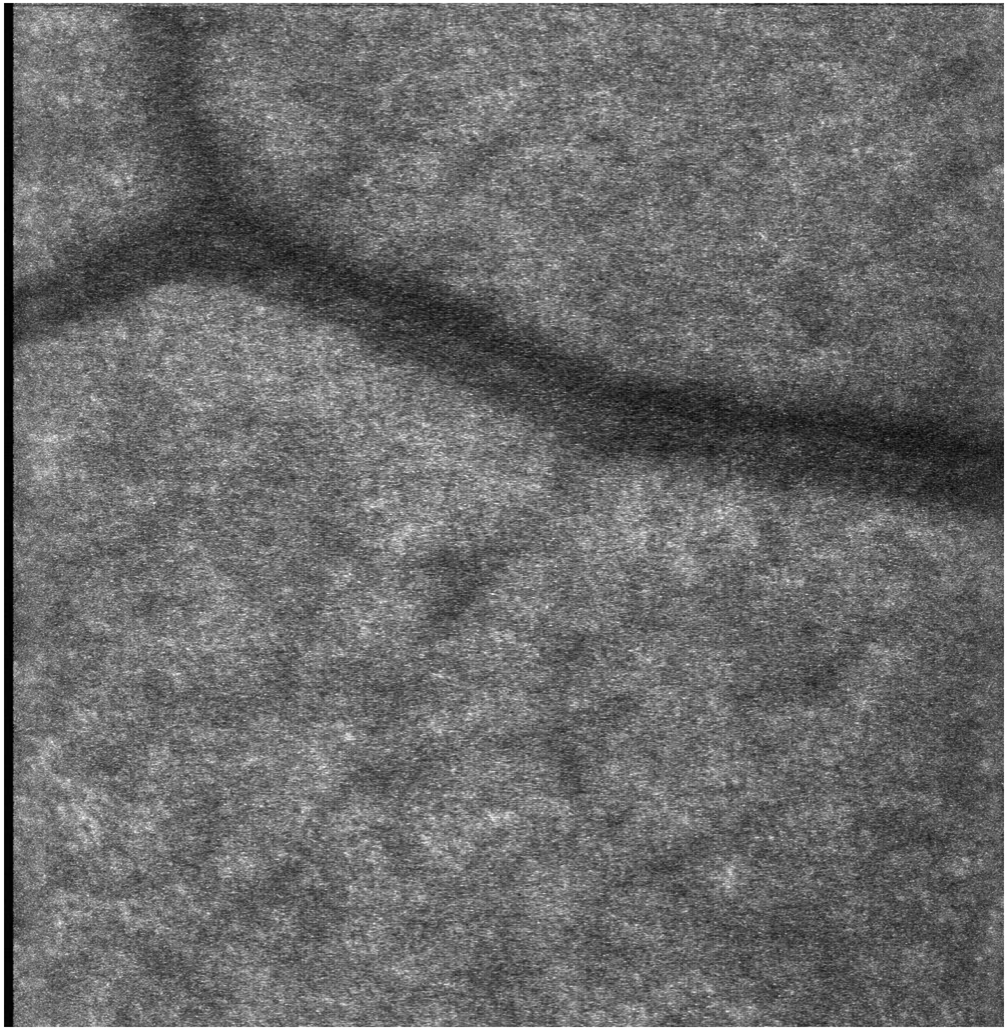
0.4 mm misalignment of achromatising lens cancels the effect of LCA correction (Zhang)

AO and Increased Pupil Allows Resolution of more Cones in Chick with Age

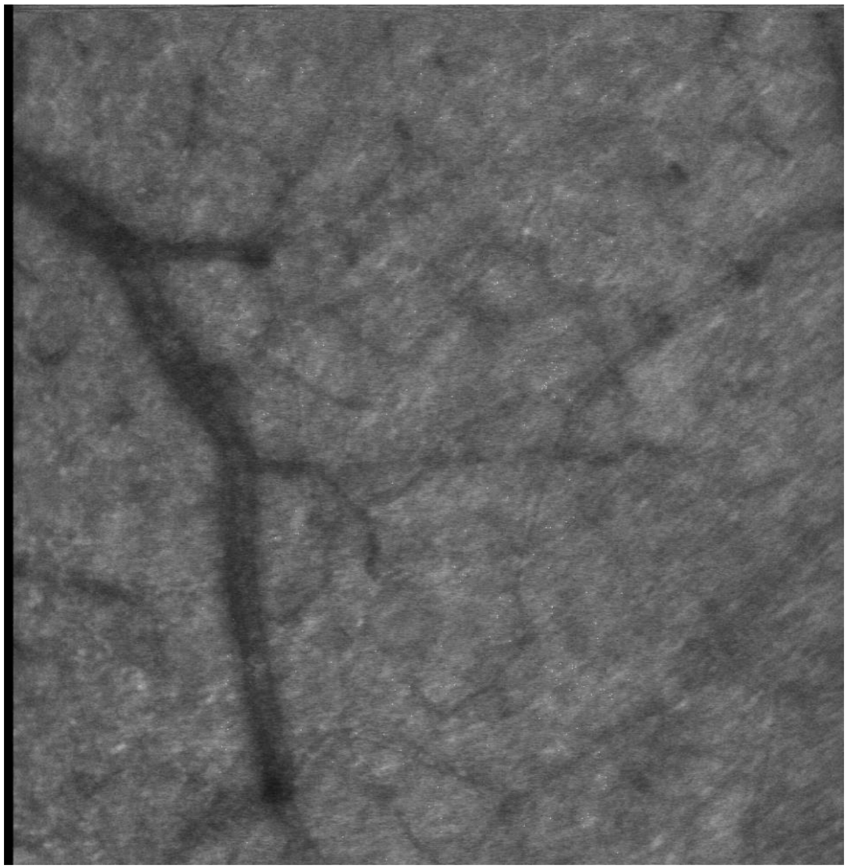


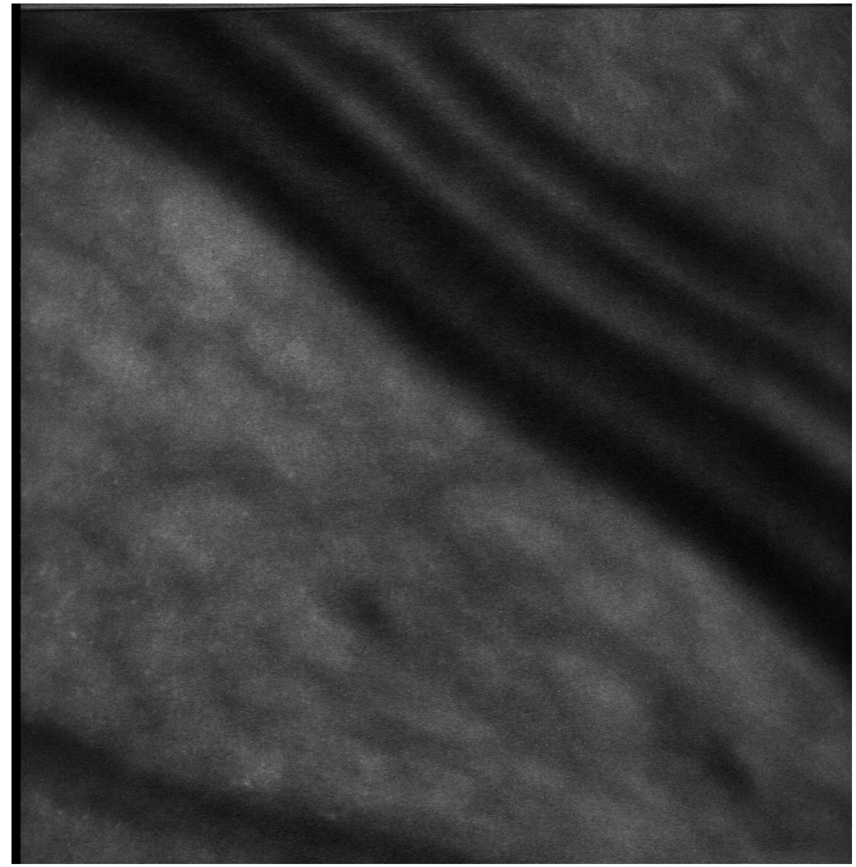
AO Corrected Imaging for Monitoring Diabetic Retinopathy





AO Corrected Images for Monitoring Blood Flow in a Human Eye





Optical Blur and Cone Resolution

As optical blur reduces
to match cone resolution,
axial elongation stops