Title
The Optical Image on the Retina

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The Optical Image on the Retina

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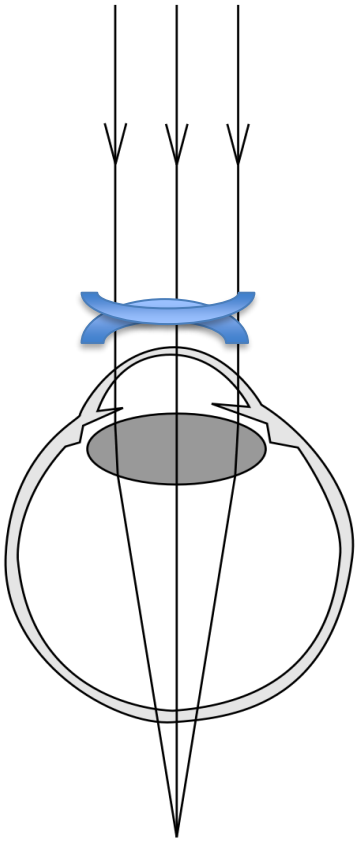
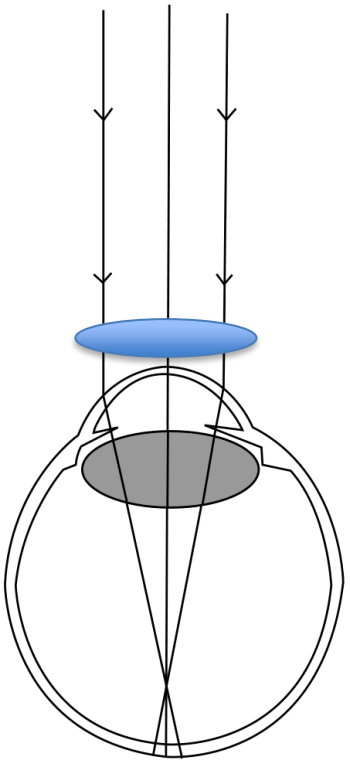
Defocus

Hyperopic



Myopic



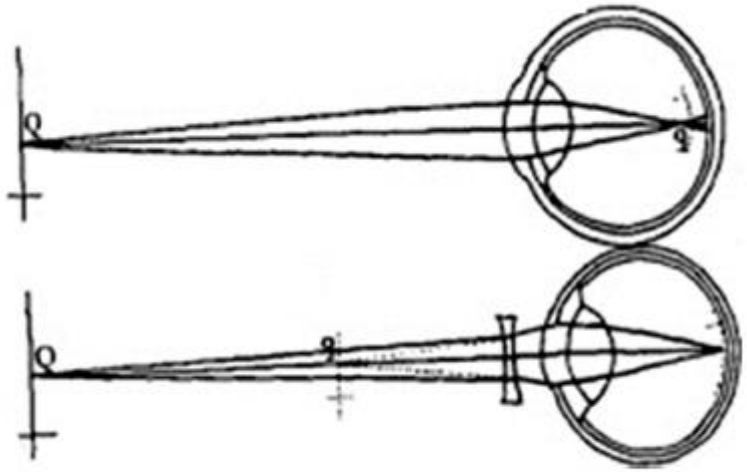
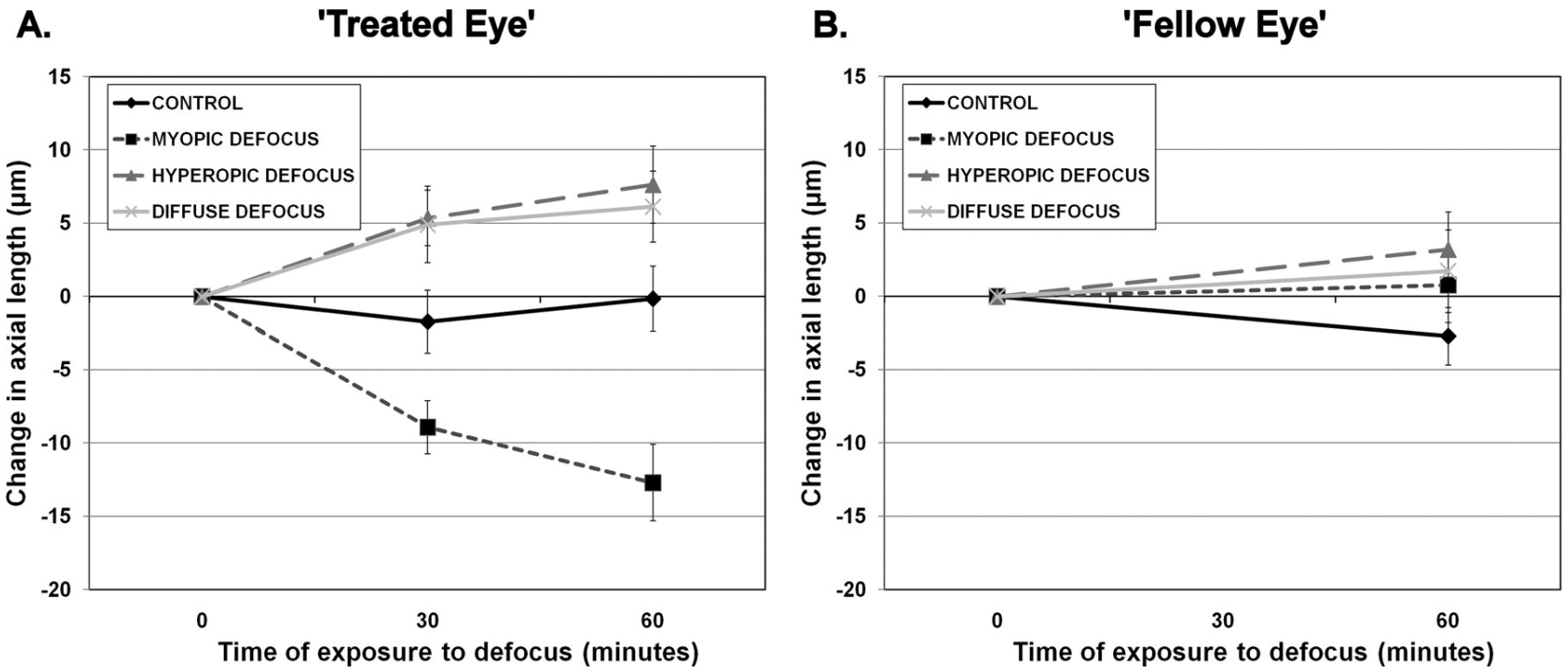
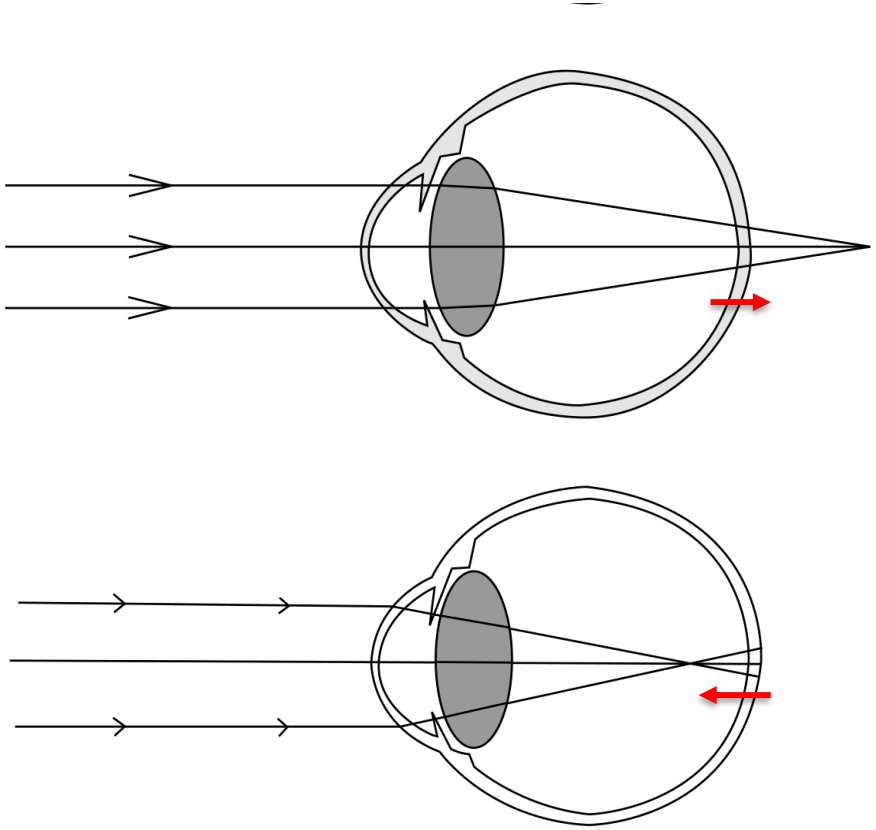


Fig. 2 A pair of diagrams from Smith's *Compleat System of Opticks* , ***1738***

Scott A. Read; Michael J. Collins; Beata P. Sander

Investigative Ophthalmology & Visual Science December 2010, Vol.51, 6262-6269





Defocus

Hyperopic

Myopic

What are the properties of the defocused optical image that drive axial length changes?

I. Characterizing the degradation of retinal images that are defocused

II. Distinguishing between myopic and hyperopic defocus

Defining degraded images

Full and complete descriptor is the

POINT-SPREAD FUNCTION

the image of a point object, because the image of all other targets is the superposition of that of the points constituting them.

Point-spread function in Geometrical Optics

Geometrical Optics

Blur circles proportional to defocus and pupil diameter

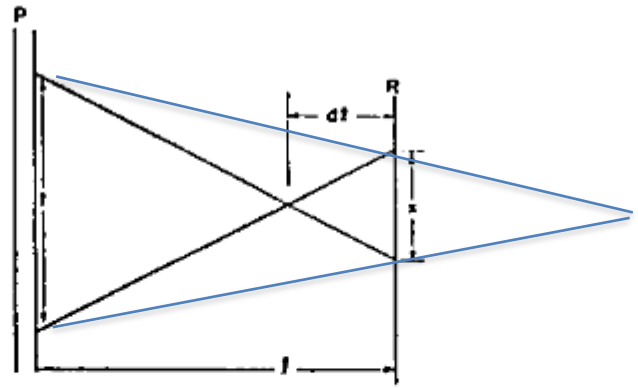


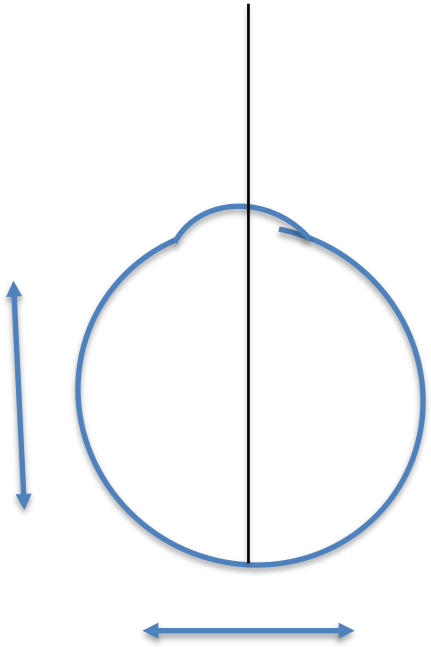
Fig. 2. Formation of a blur circle of diameter x on the retina R when the pupil diameter is t.

$$\frac{x}{t} = \frac{dl'}{l' - dl'} = \frac{dl'}{l'} \text{ appr.}$$

Westheimer, G. The effect of spectacle lenses on the depth of focus of the eye. *Am J Optom Arch Am Acad Optom.* 1953;30(10):513-519.

Units and dimensions

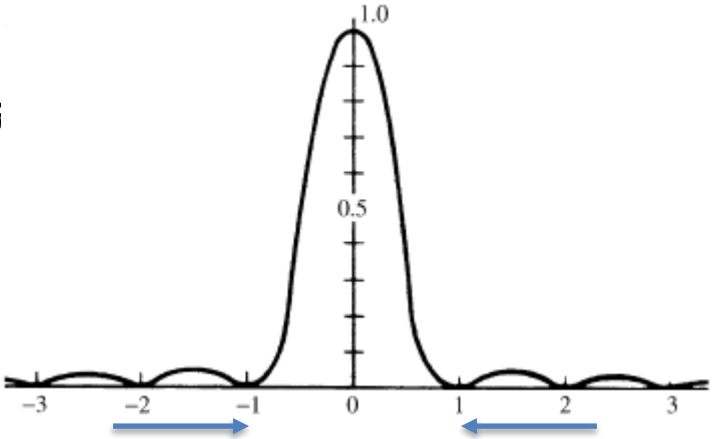
Axial dimensions	μ
1 Diopters Defocus	330
Length of cone outer segment	~50
Defocus receptor length change	~20
Light-induced receptor length change	0.1 – 0.5
Wavelength of light	0.550



Retinal distance	*arcmins*
Cone diameter	< 1 in fovea
Aberration-free point-spread function	1-2
Geometrical blur patch	
5mm pupil dimeter, 3D defocus	~12

Point-spread functions in diffraction theory

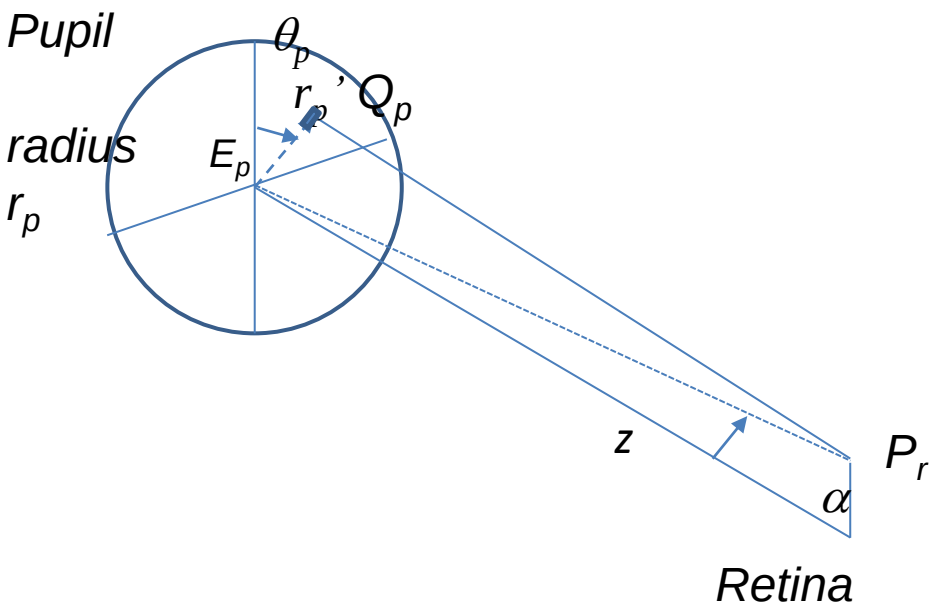
monochromatic light λ
round pupil, diameter ***a***
in focus
aberration free



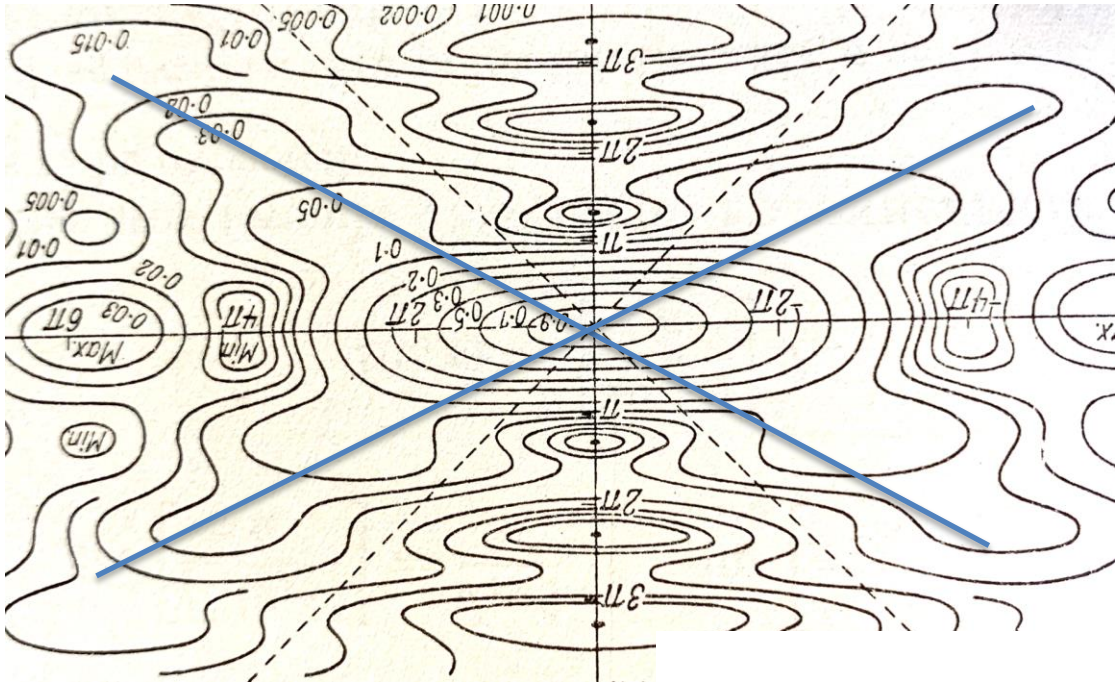
Airy disk
1.22 λ /a

Circularly symmetric Pupil Aperture Function $A(r_p')$

Element $r_p'.d\theta_p.dr_p'$ at Q_p on wavefront

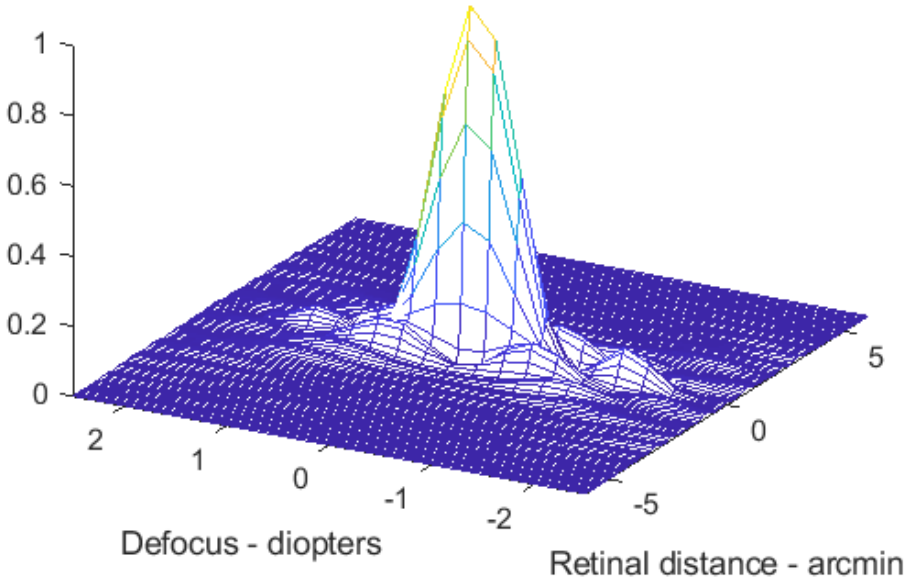


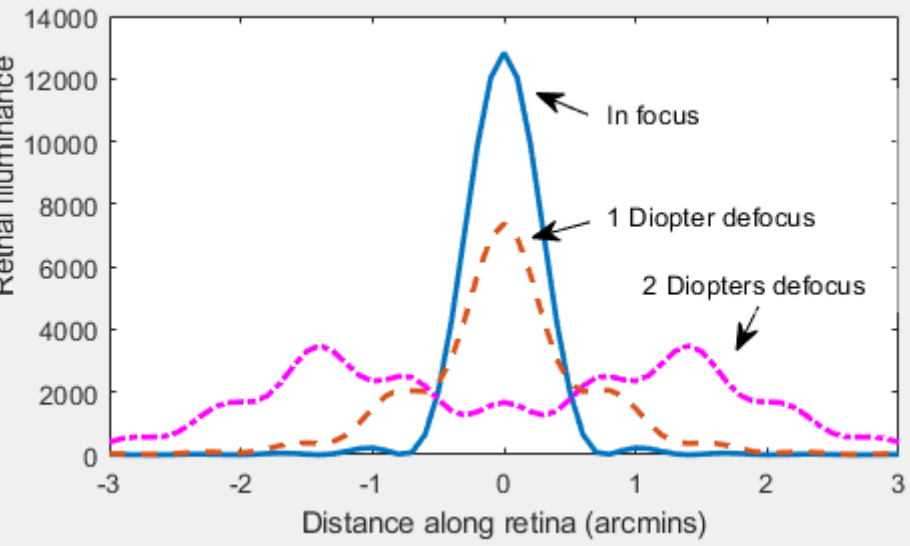
$$U_{Pr} = \int_o^{r_p} \int_o^{2\pi} A(r_p') \, .e^{-i.k.\,\alpha.\,r_p'.\cos(\theta p)} . r_p' . d\theta_p . dr_p'$$

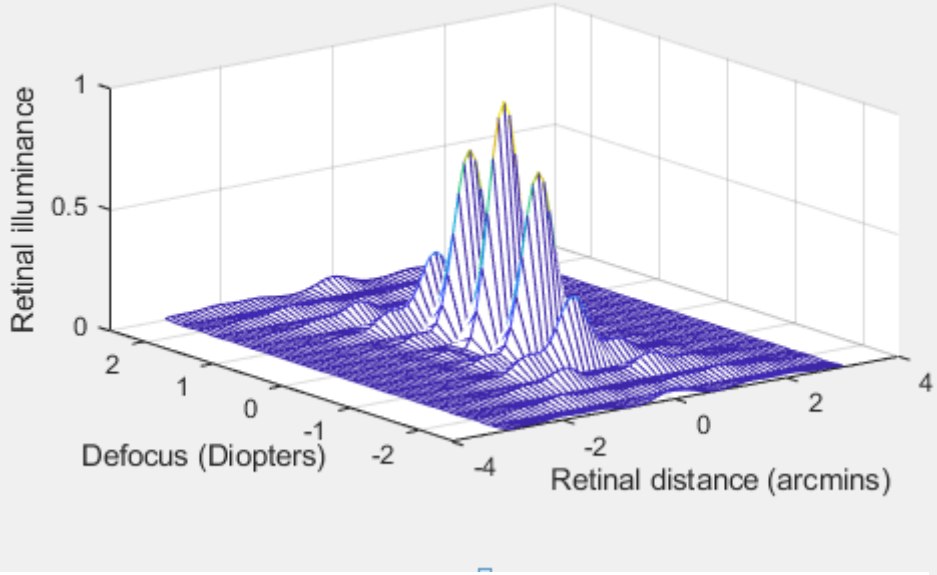


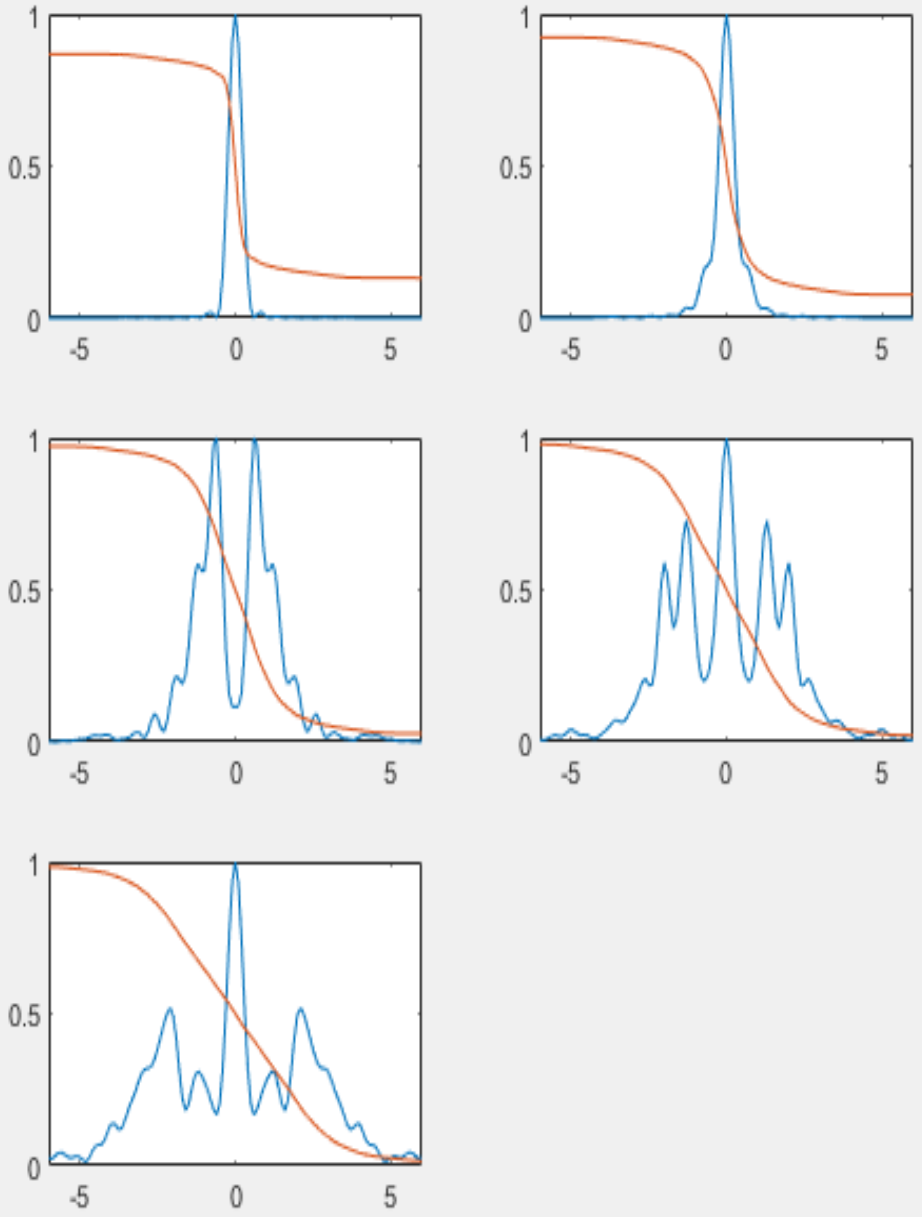
Linfoot, E.H., Wolf, E.
Proc.Phys.Soc. 1957

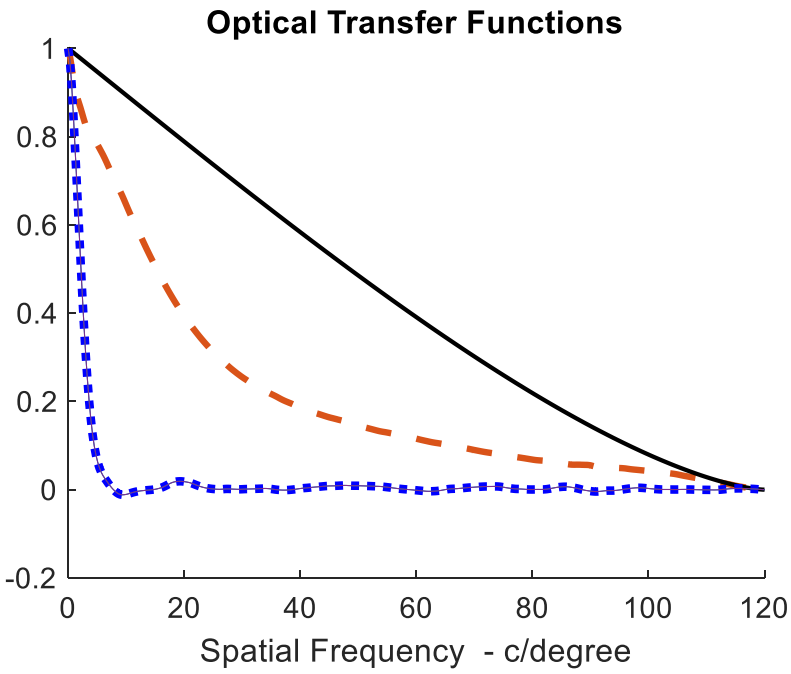
Westheimer, G. MATLAB 2020

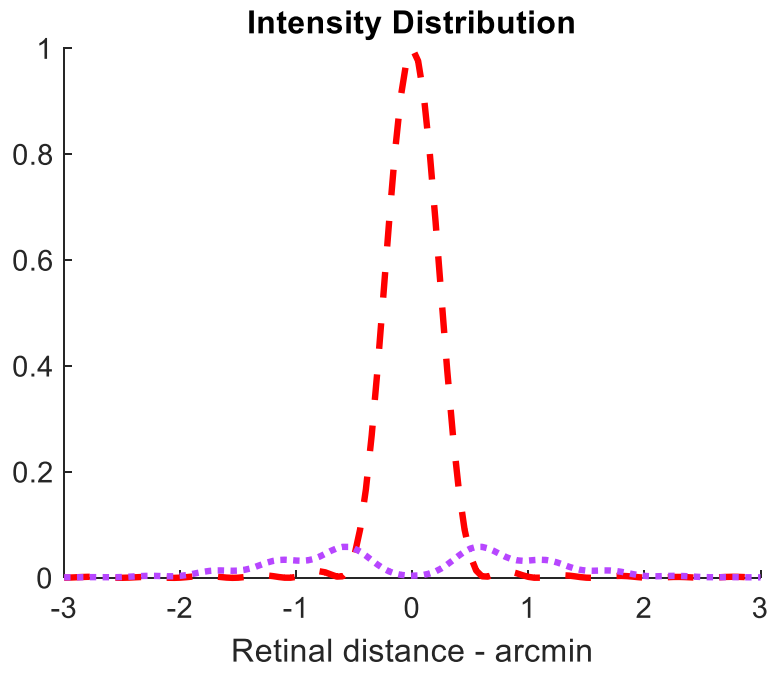


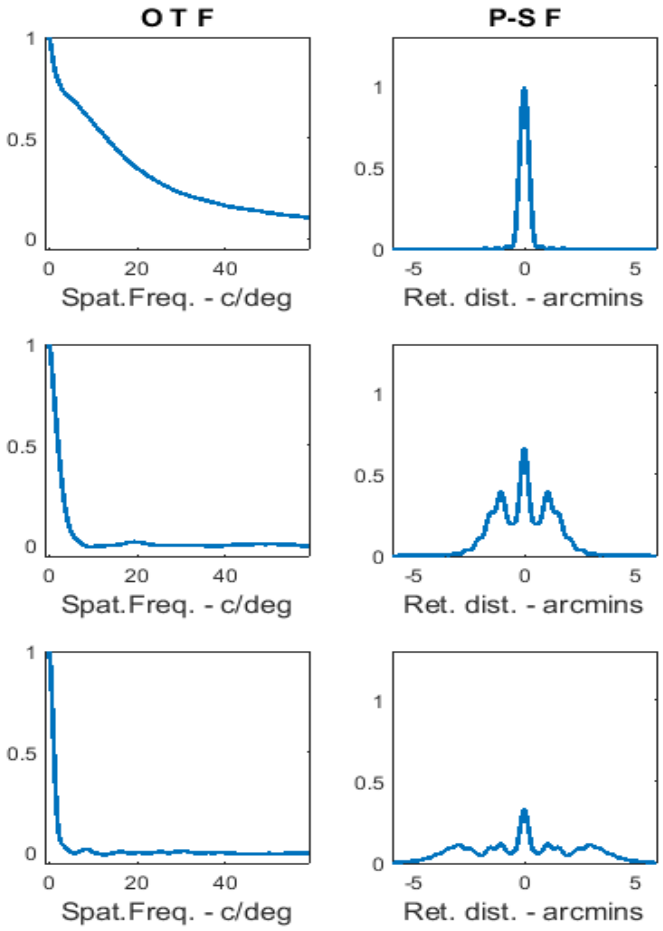

Retinal illuminance
14000
12000
10000
8000
6000
4000
2000
0
-3
-2
-1
0
1
2
3
In focus
1 Diopter defocus
2 Diopters defocus
Distance along retina (arcmins)

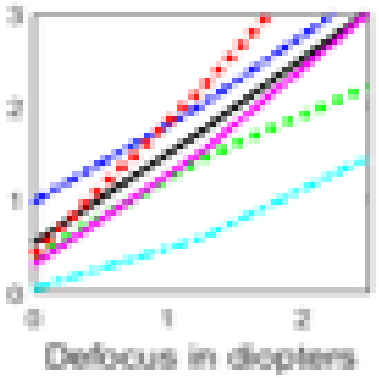

Retinal illuminance
1
0.5
0
2
1
0
-1
-2
Defocus (Diopters)
-4
-2
0
2
4
Retinal distance (arcmins)

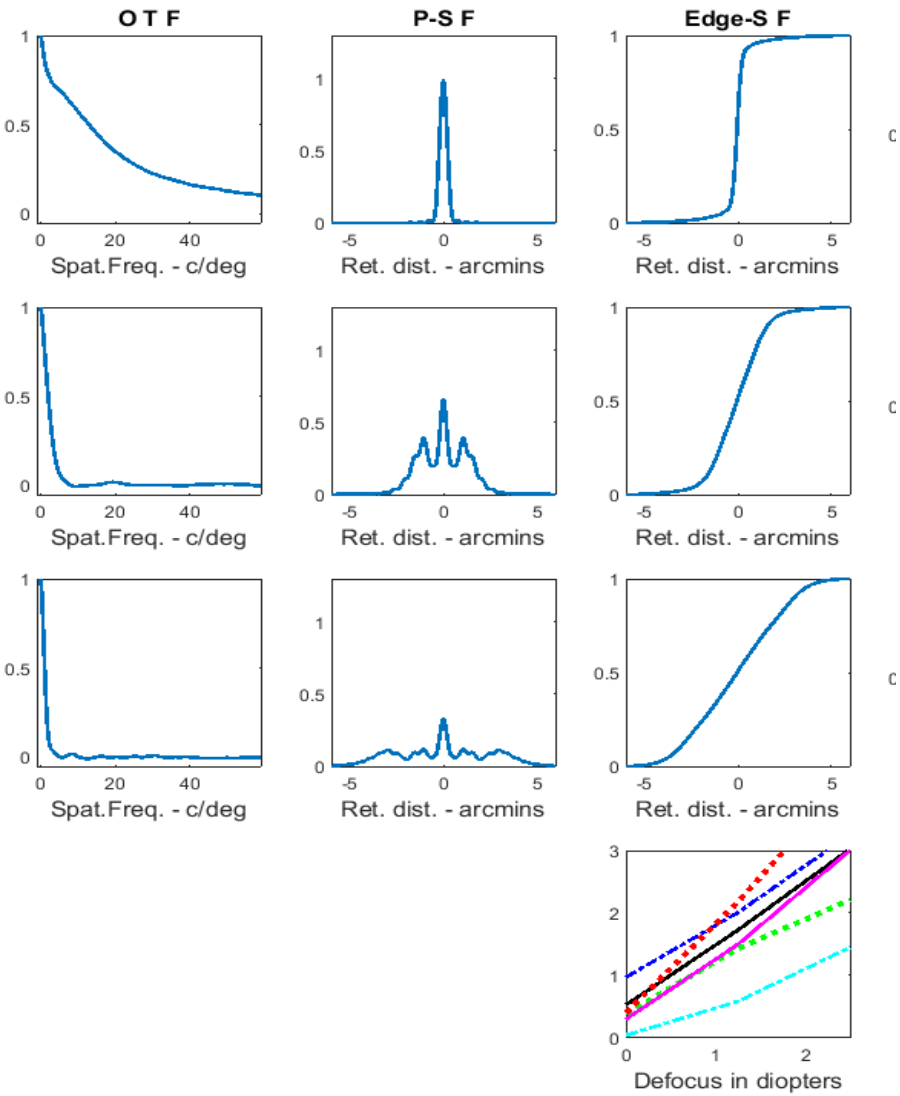

1
0.5
0
-5
0
5


Optical Transfer Functions
1
0.8
0.6
0.4
0.2
0
-0.2
0
20
40
60
80
100
120
Spatial Frequency - c/degree

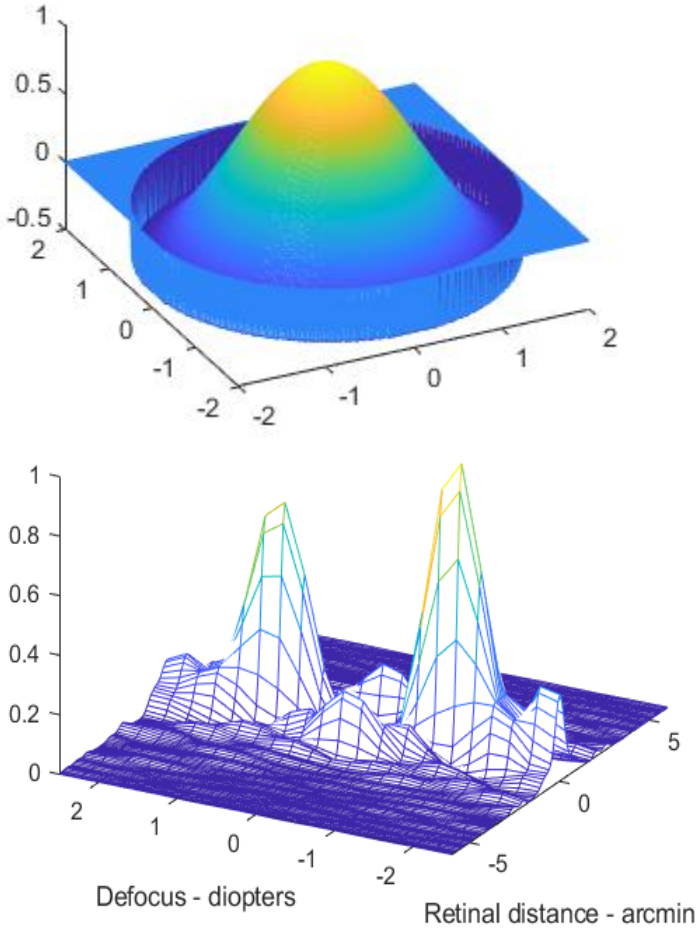

Intensity Distribution
1
0.8
0.6
0.4
0.2
0
-3
-2
-1
0
1
2
3
Retinal distance - arcmin

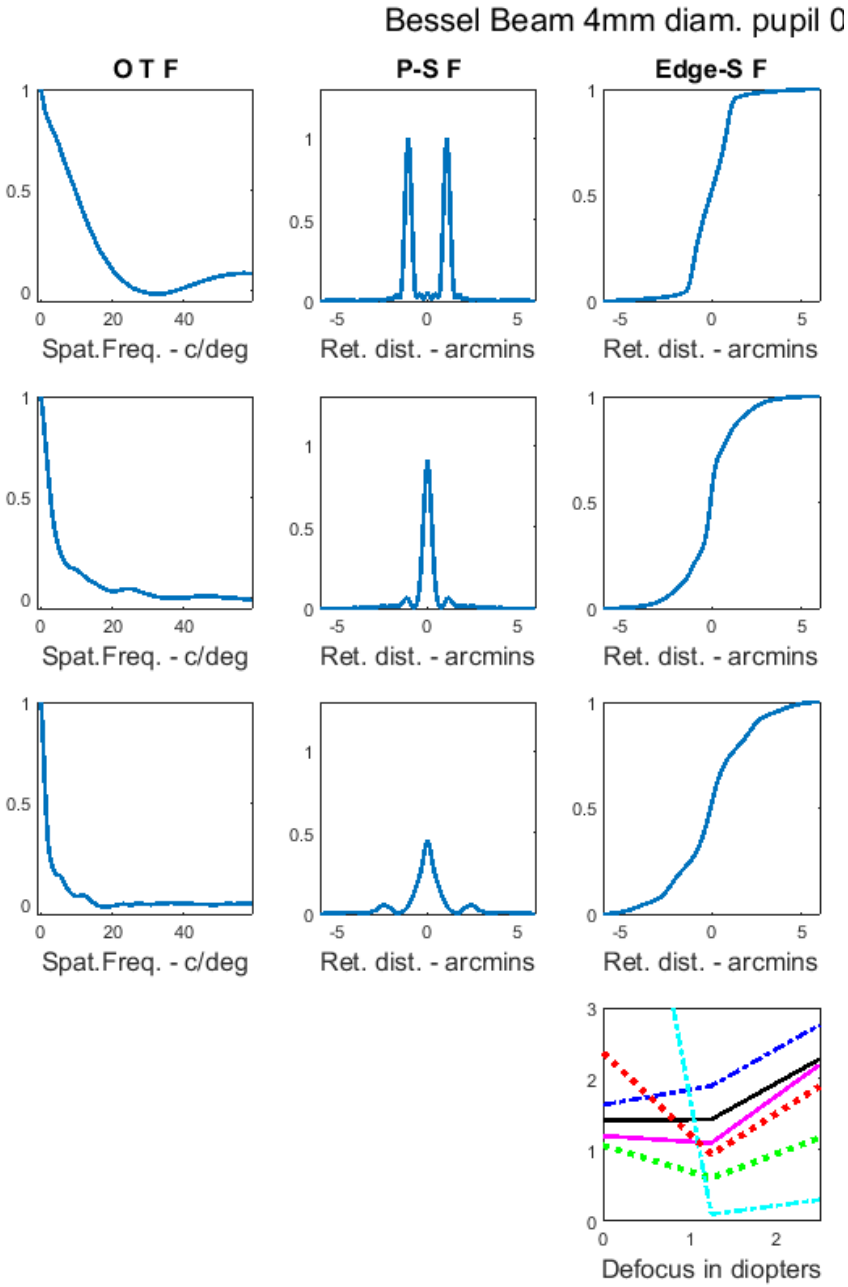

O T F
P-S F
1
0.5
0
0
20
40
Spat.Freq. - c/deg
1
0.5
0
-5
0
5
Ret. dist. - arcmins


Defocus in diopters

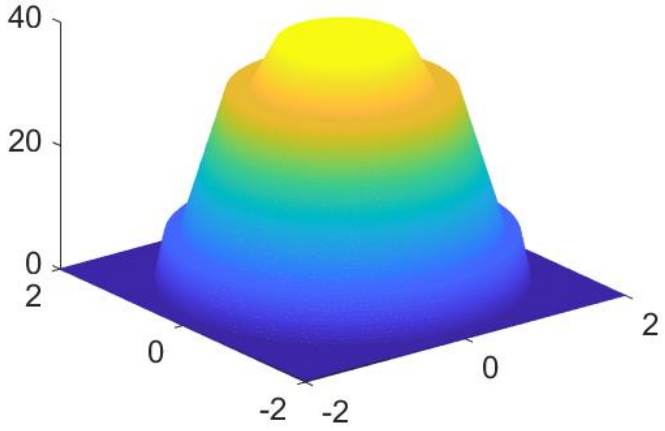

O T F
P-S F
Edge-S F
Spat.Freq. - c/deg
Ret. dist. - arcmins
Ret. dist. - arcmins
Spat.Freq. - c/deg
Ret. dist. - arcmins
Ret. dist. - arcmins
Spat.Freq. - c/deg
Ret. dist. - arcmins
Ret. dist. - arcmins
Defocus in diopters

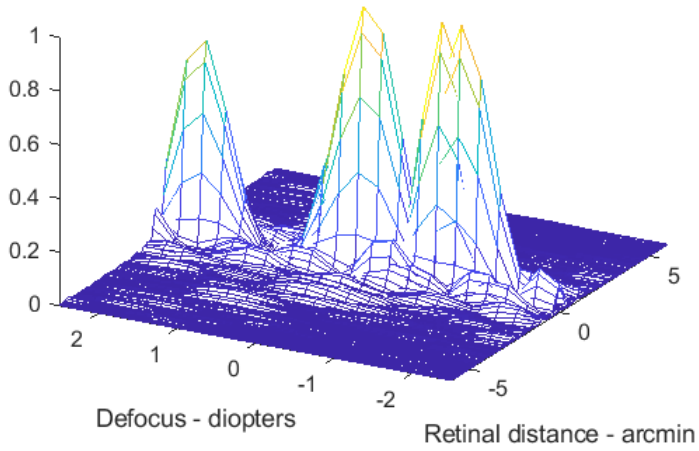
Bessel function, truncated, pupil amplitude transmission

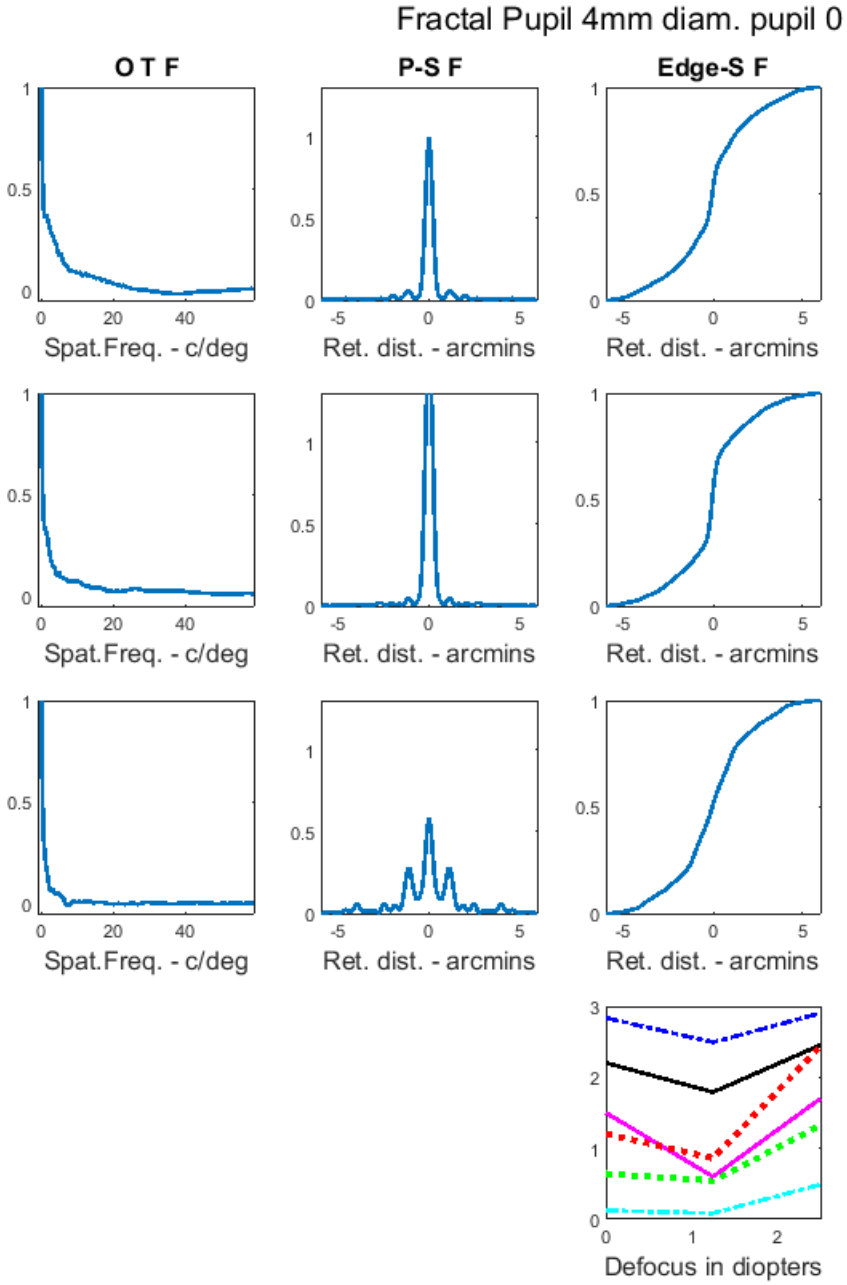



Bessel Beam 4mm diam. pupil 0
O T F
P-S F
Edge-S F
Spat.Freq. - c/deg
Ret. dist. - arcmins
Ret. dist. - arcmins
Spat.Freq. - c/deg
Ret. dist. - arcmins
Ret. dist. - arcmins
Spat.Freq. - c/deg
Ret. dist. - arcmins
Ret. dist. - arcmins
Defocus in diopters

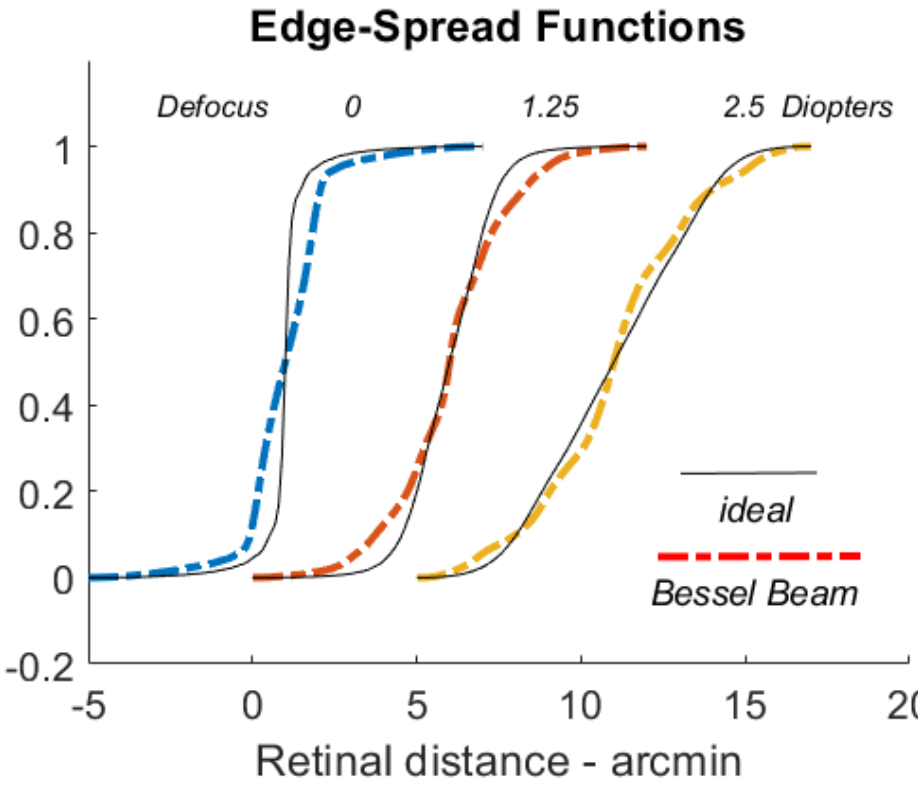
"Fractal" phase zones in pupil

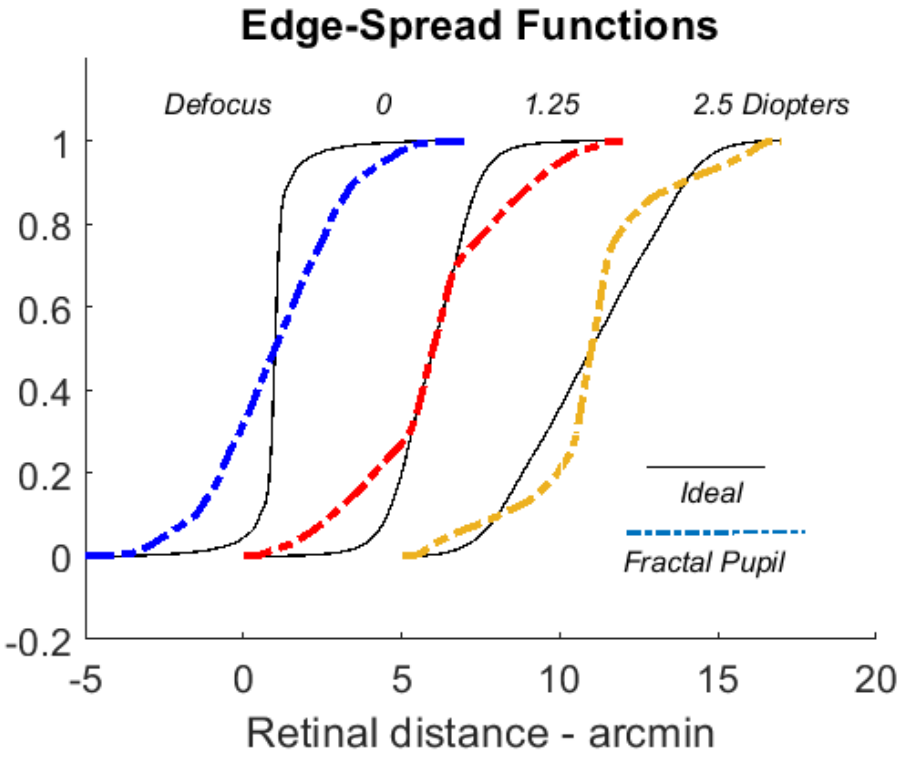





Fractal Pupil 4mm diam. pupil 0
O T F
P-S F
Edge-S F
Spat.Freq. - c/deg
Ret. dist. - arcmins
Ret. dist. - arcmins
Spat.Freq. - c/deg
Ret. dist. - arcmins
Ret. dist. - arcmins
Spat.Freq. - c/deg
Ret. dist. - arcmins
Ret. dist. - arcmins
Defocus in diopters

Edge-spread functions: characterize degradation of retinal image
are informative yet optimally compact
smooth meaningless peaks in p.s.f.
are representative of natural stimuli





Part II

How can Myopic and Hyperopic Defocus

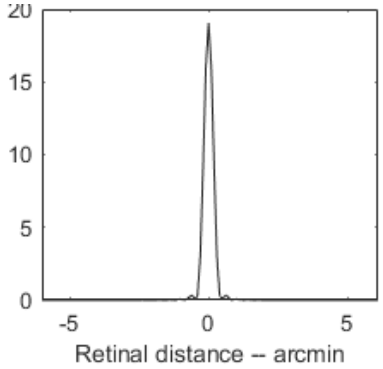
be distinguished

A.

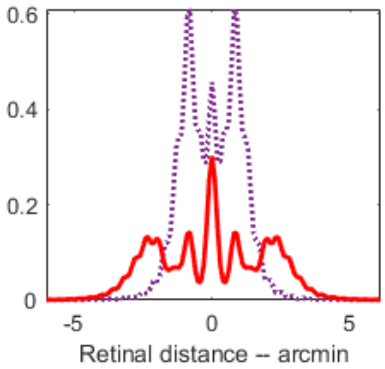
Point spread

Edge

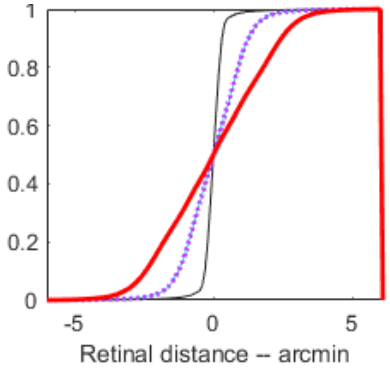
In Focus



1.5 and 3 Diopters defocus

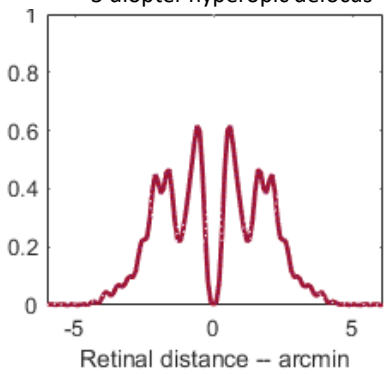


0, 1.5 and 3 Diopters defocus

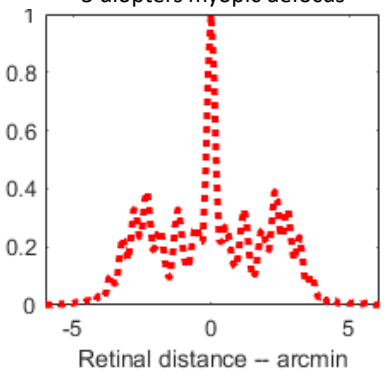


B.

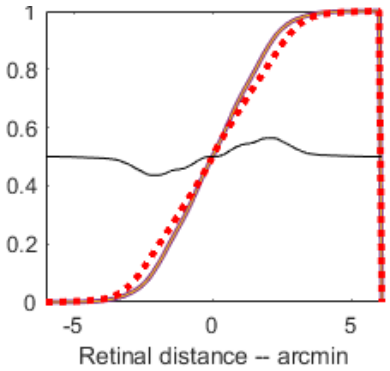
3 diopter hyperopic defocus

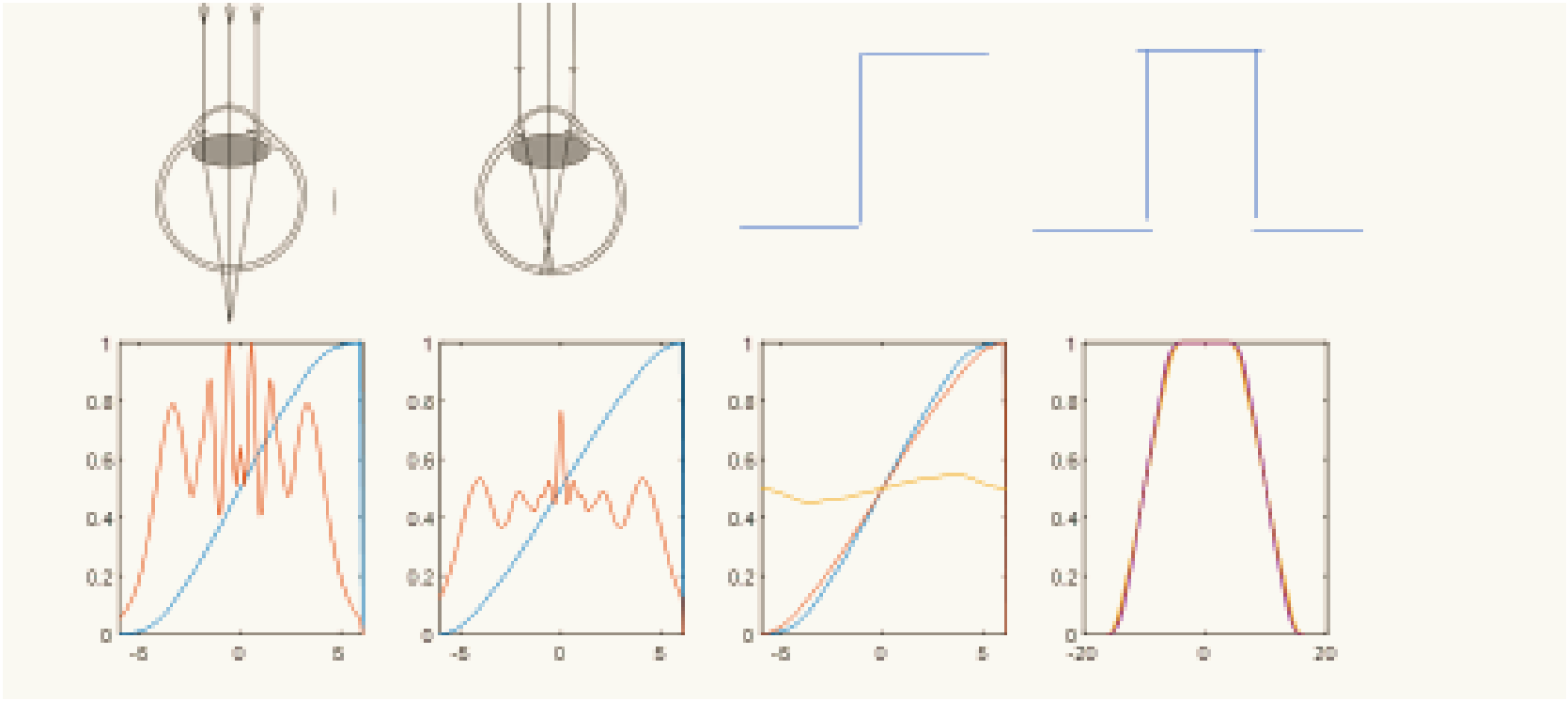


3 diopters myopic defocus



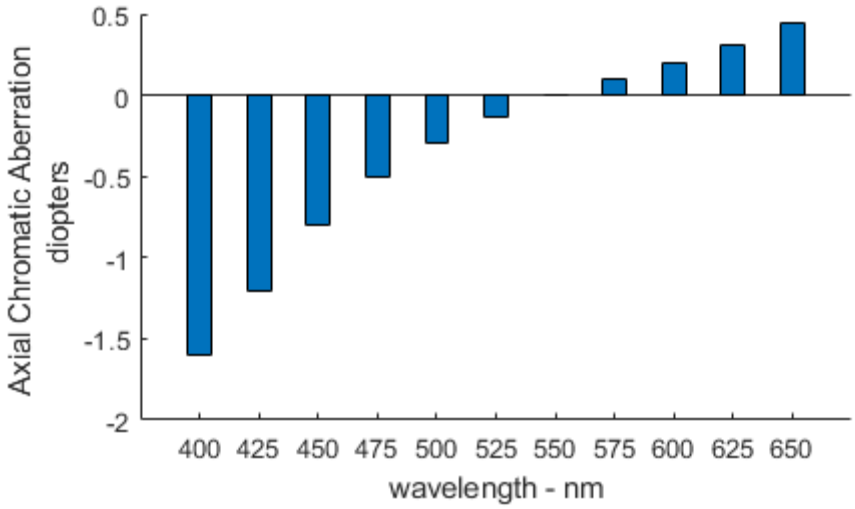
+ and – defocus and difference

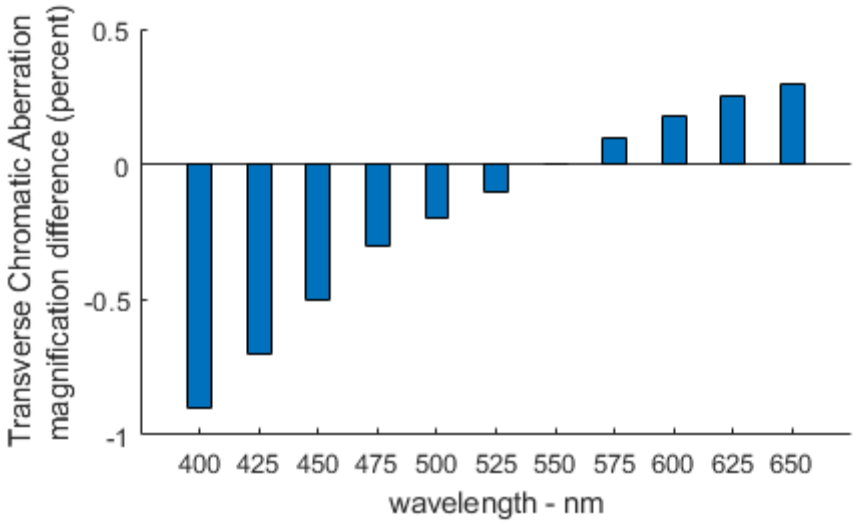



1
0.8
0.6
0.4
0.2
0
-5
0
5
-20
20

Polychromatic

changes with wavelength -- refractive index
refractive state

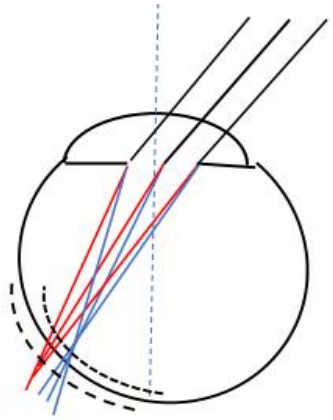

Axial Chromatic Aberration
diopters
0.5
0
-0.5
-1
-1.5
-2
400 425 450 475 500 525 550 575 600 625 650
wavelength - nm


Transverse Chromatic Aberration
magnification difference (percent)
0.5
0
-0.5
-1
400 425 450 475 500 525 550 575 600 625 650
wavelength - nm

Polychromatic

changes with wavelength -- refractive index
refractive state

Duochrome two wavelengths

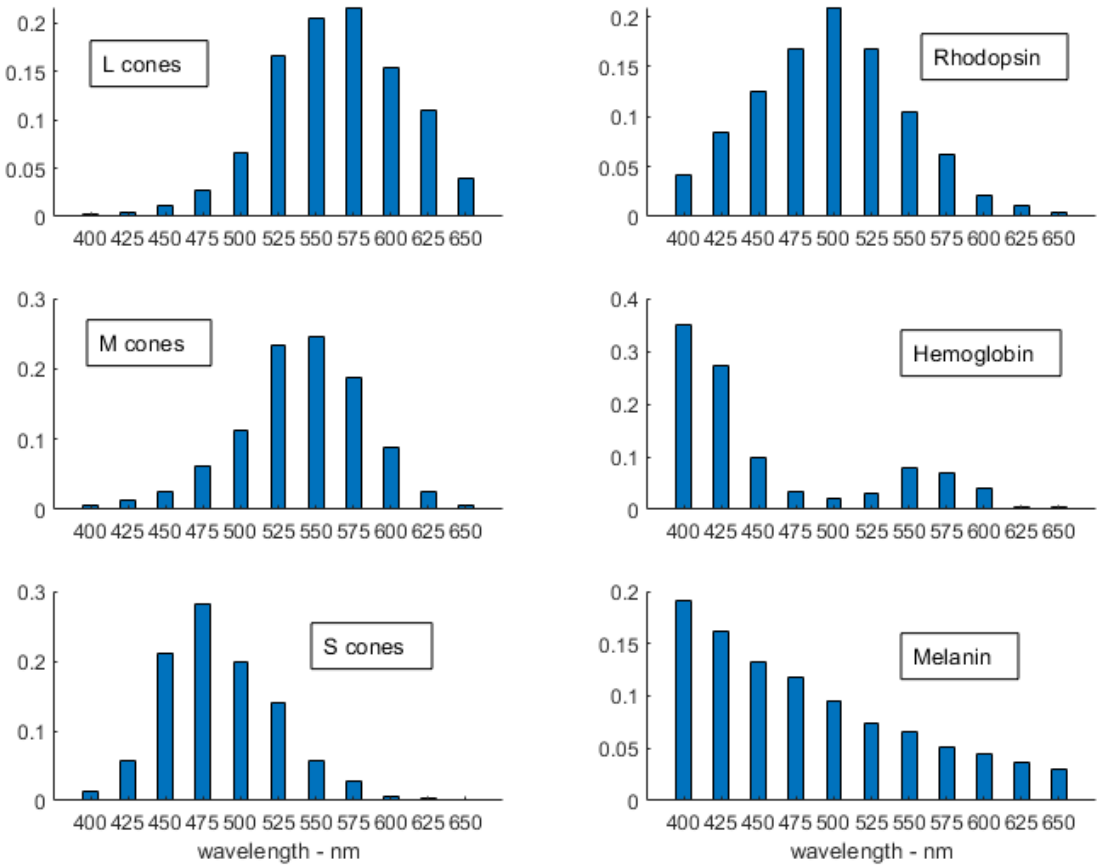


Polychromatic

changes with wavelength -- refractive index
refractive state

Duochrome — two wavelengths superimposed

White Light — (equi) energy across spectrum
11 bands 400- 650 nm
sensitivity of detecting substances


L cones
Rhodopsin
M cones
Hemoglobin
S cones
Melanin
400 425 450 475 500 525 550 575 600 625 650
wavelength - nm

Spatial Pattern of Excitation in a Detecting Mechanism

Given a polychromatic point object,

for each wavelength λ

at each retinal point *x.y*

determine

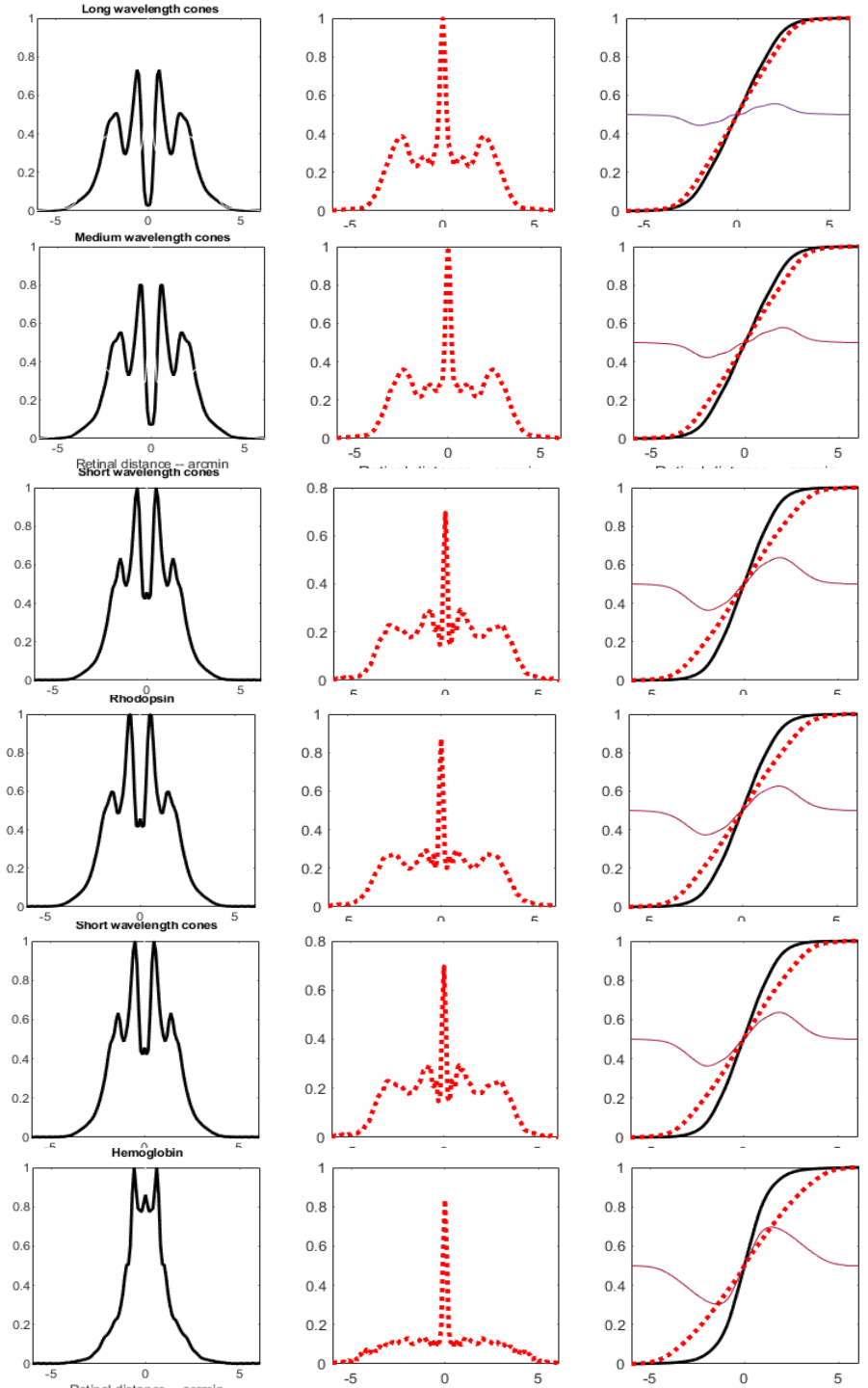
the height of the point-spread function $I_{x,y}(\lambda)$

multiply by

spectral sensitivity of the detecting substance $a(\lambda)$,

and sum

$$A_{x,y} = \sum_{\lambda=1}^{\lambda=11} (I_{x,y}(\lambda) \quad a(\lambda))$$



L cones

M cones

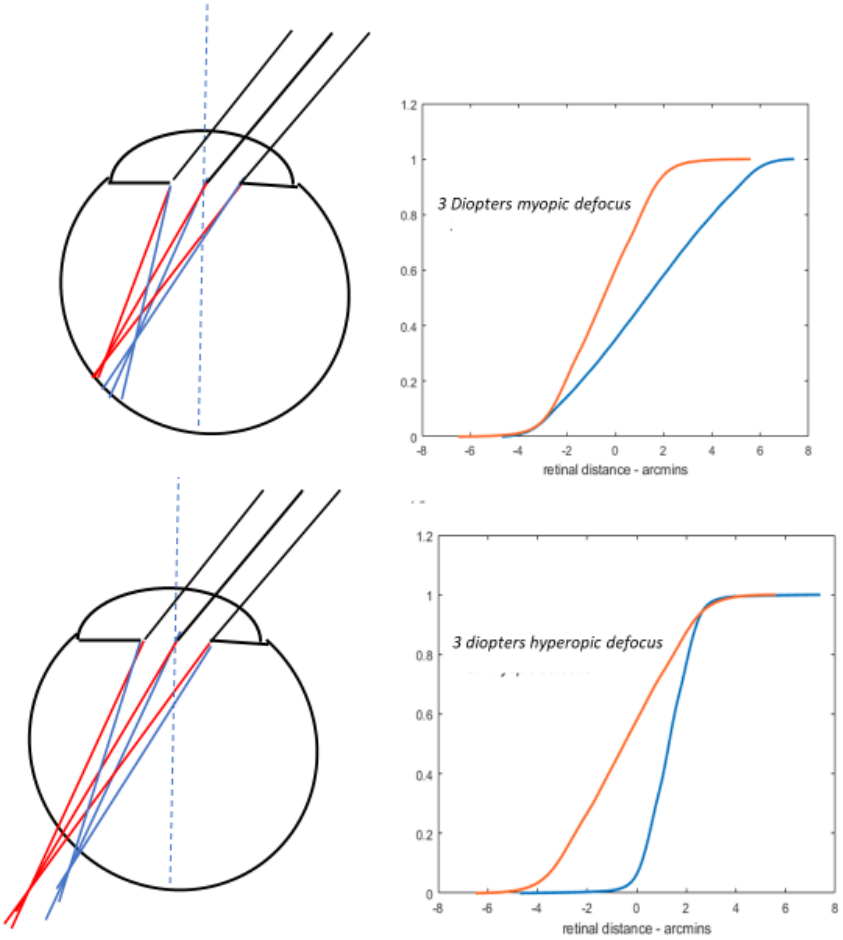
S cones

Rhodopsin

Melanin

Hemoglobin

Eccentric targets and lateral chromatic aberration



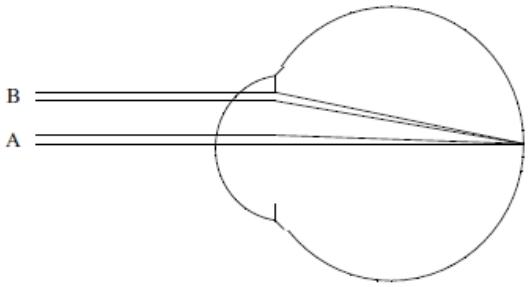
To differentiate hyperopic from myopic defocus using Stiles-Crawford Effect

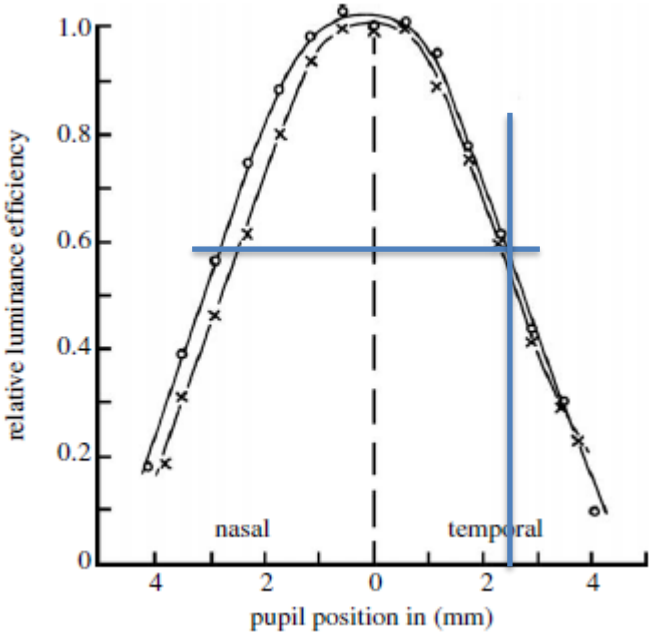
Available only in cone vision
Distinguish small intensity differences in
narrow fringes 1-3 arcmins
Differentiate direction (right/left, up/down)
of obliquity

Stiles-Crawford Effect

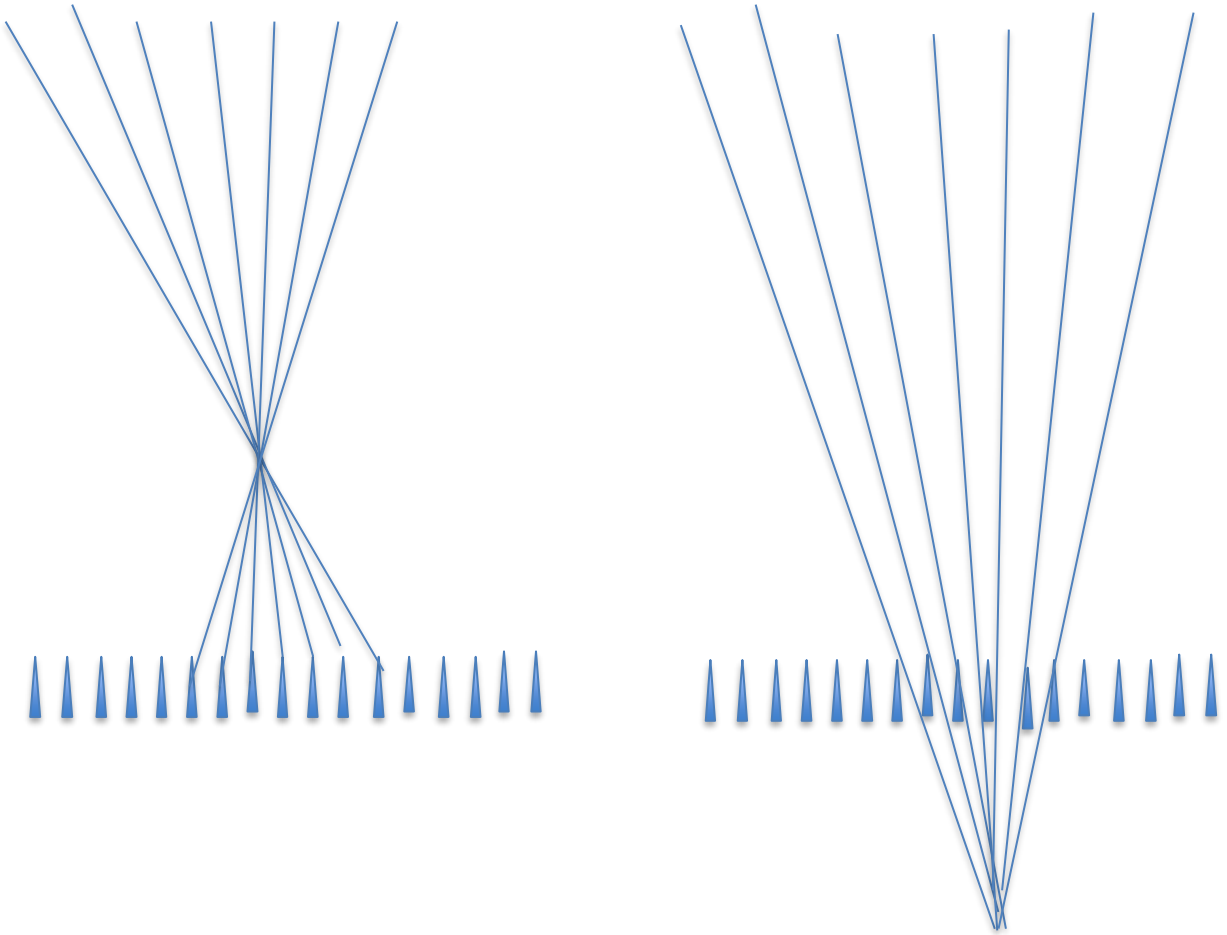
Reduced light efficiency with obliquity

60% at edge of 5mm diameter pupil

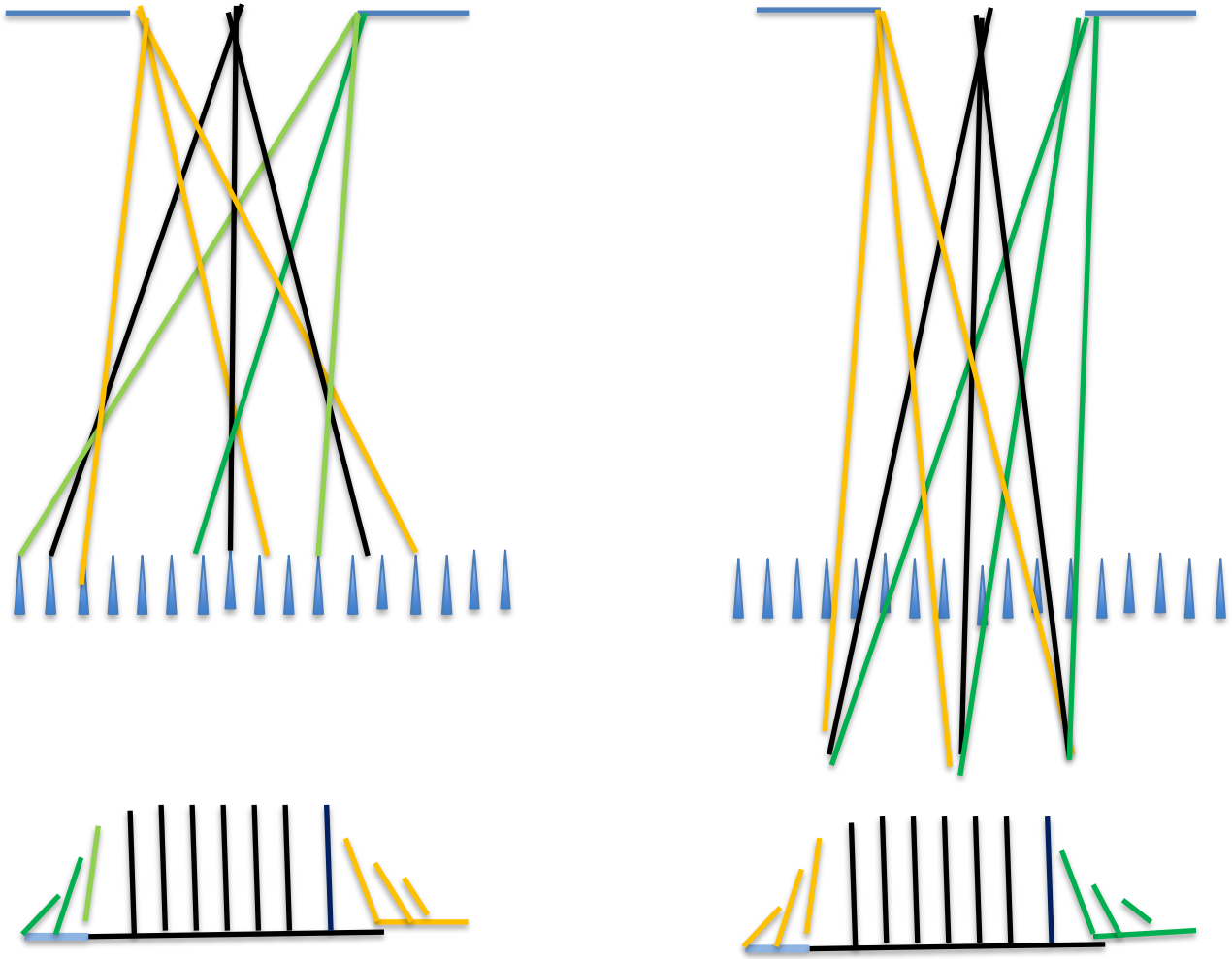




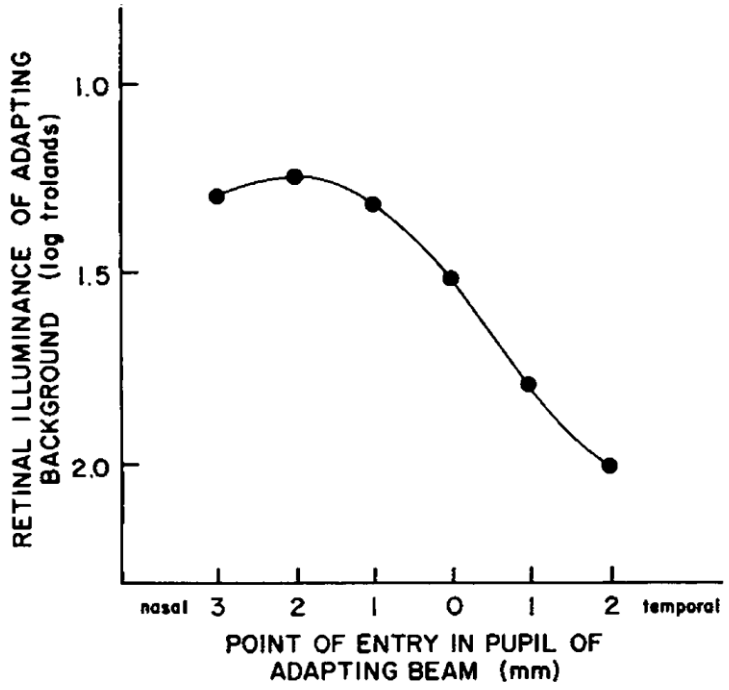
Oblique Incidence

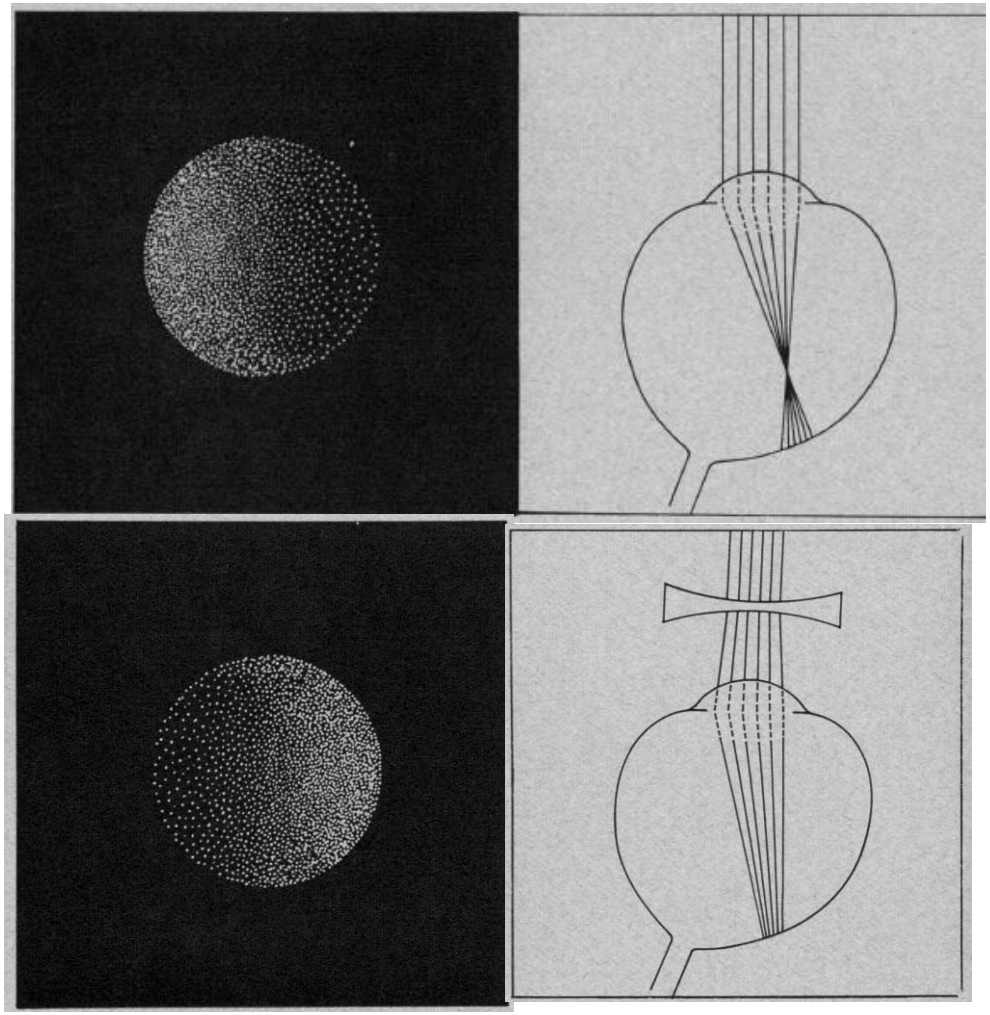


Oblique Incidence



Entoptic Visualization of Stiles-Crawford Effect





CONCLUSIONS

1. Polarity differences are in hyperacuity range and require high resolution and attention (retina vs brain)
2. For edges, polarity differences are quantitative not qualitative, except for Stiles-Crawford obliquity detection
3. For edges, polarity differences can be nulled out by defocus differences
4. Increase with eccentricity, but so does spatial grain

CAVEATS

1. Round pupil and circular symmetry
2. Depend on Spectral Emission of Source
3. Transmission of Ocular Media not included
4. Every Eye has its own Aberrations

What is the status?

Since axial length changes are induced differentially by light stimuli, polarity differences must reside in the optical image, where their detection triggers pathways to effect length changes.

Individual eyes idiosyncratic optics allow differentiation by entoptic inspection

Optical image polarity differences are minute and detectable only in cones and retino-cortical pathways, and hence unlikely to activate direct local path to axial length changes.

They are largest for melanin, but only quantitatively, not qualitatively.

An as yet unknown mechanism? Ophthalmic dark matter?

Stay tuned ……

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