What is Quality of Vision?

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Financial Disclosure

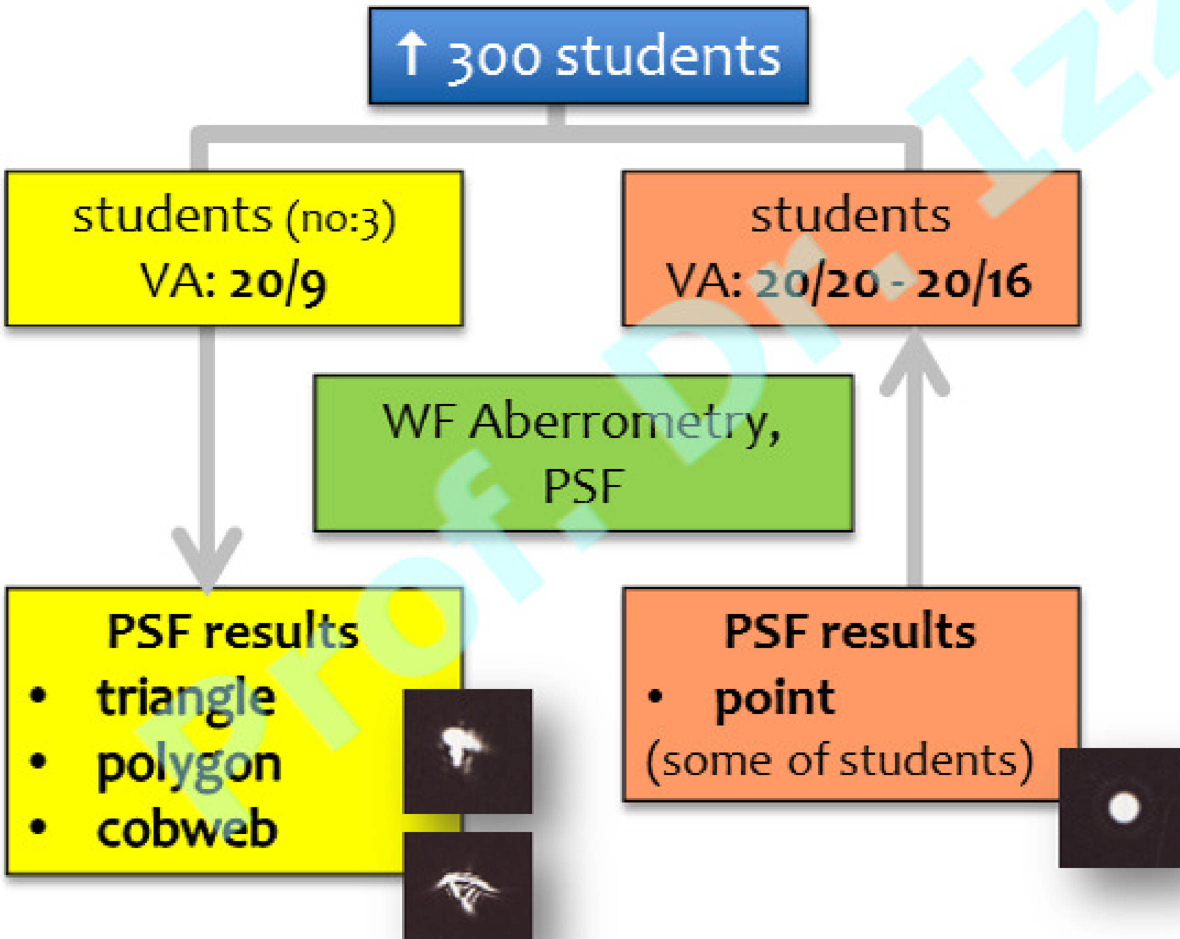
* I have no financial and proprietary interest in any material or method mentioned in this presentations.

What is High Quality Vision?

- The vision that was purified from all its optical aberrations and obtained from the image with highest contrast on the retina...
- ?????

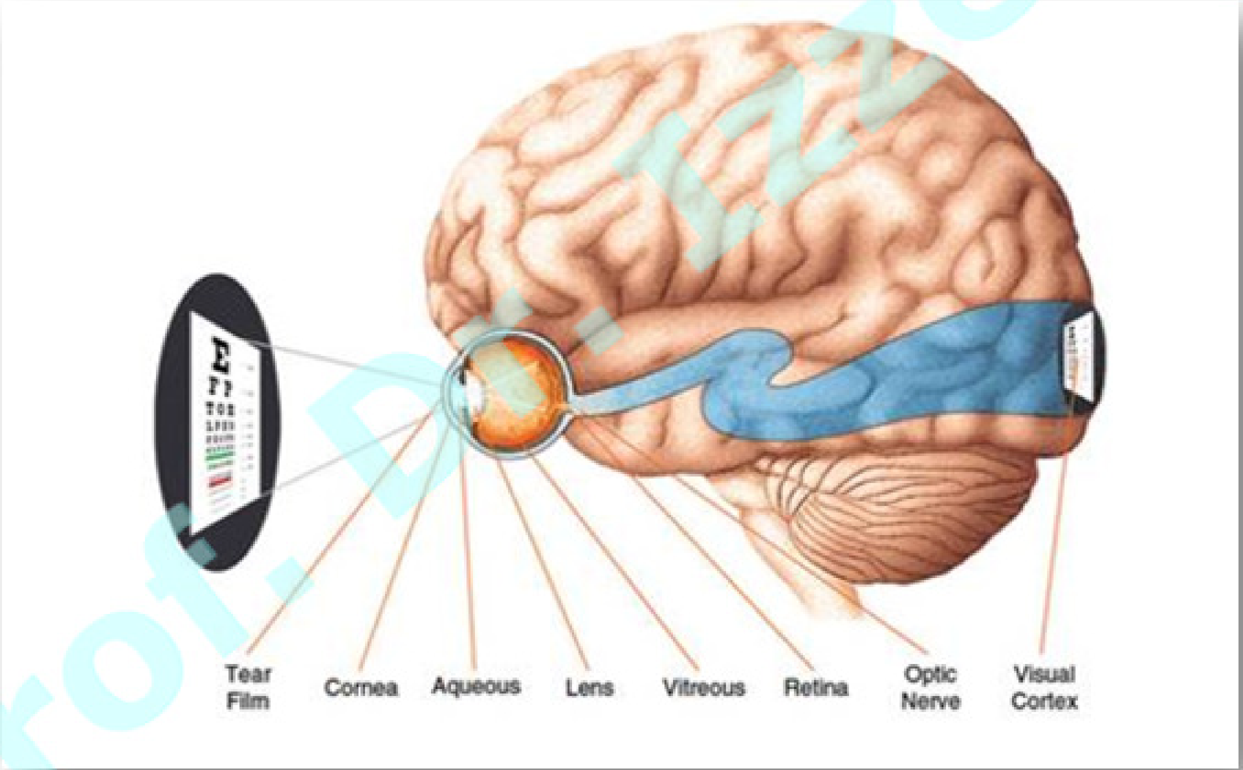
Vision Contest of Pablo Artal

2004; Universidad de Murcia, Spain



* **Lesson:** It is not the the subjects with best optical components in their visual systems who had the 20/9 vision, it was the people with best computer enhancement software in their sensory components filtering and enhancing the optical aberrations.

Components of Visual System



1.Optical system 2.Photoreceptors 3.Neural effects

Optical System and It’s Imperfections

<u>Helmholtz’s Comment on Eye</u>

* Now, it is not too much to say that if an optician wanted to sell me an instrument (the eye) which had all these defects, I should think myself quite justified in blaming his carelessness in the strongest terms and giving him back his instrument.

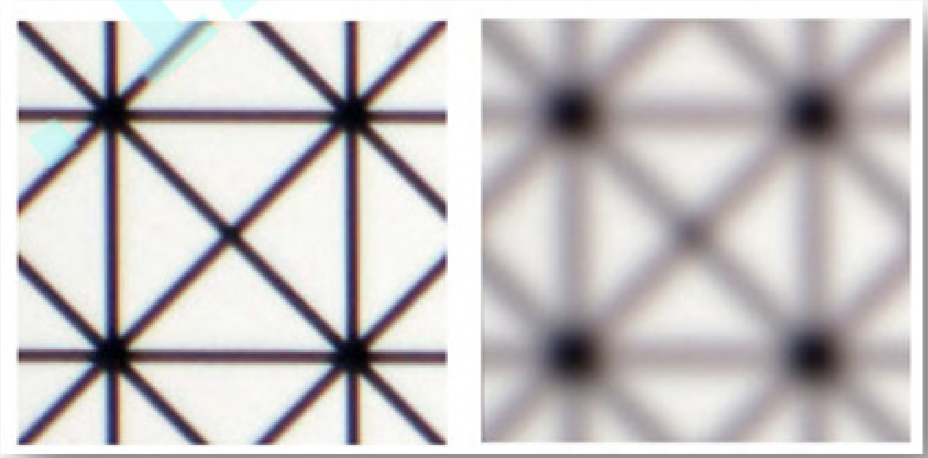
Hermann Ludwig Ferdinand von Helmholtz
(1821-1894)

Helmholtz,
Berlin, Humboldt University

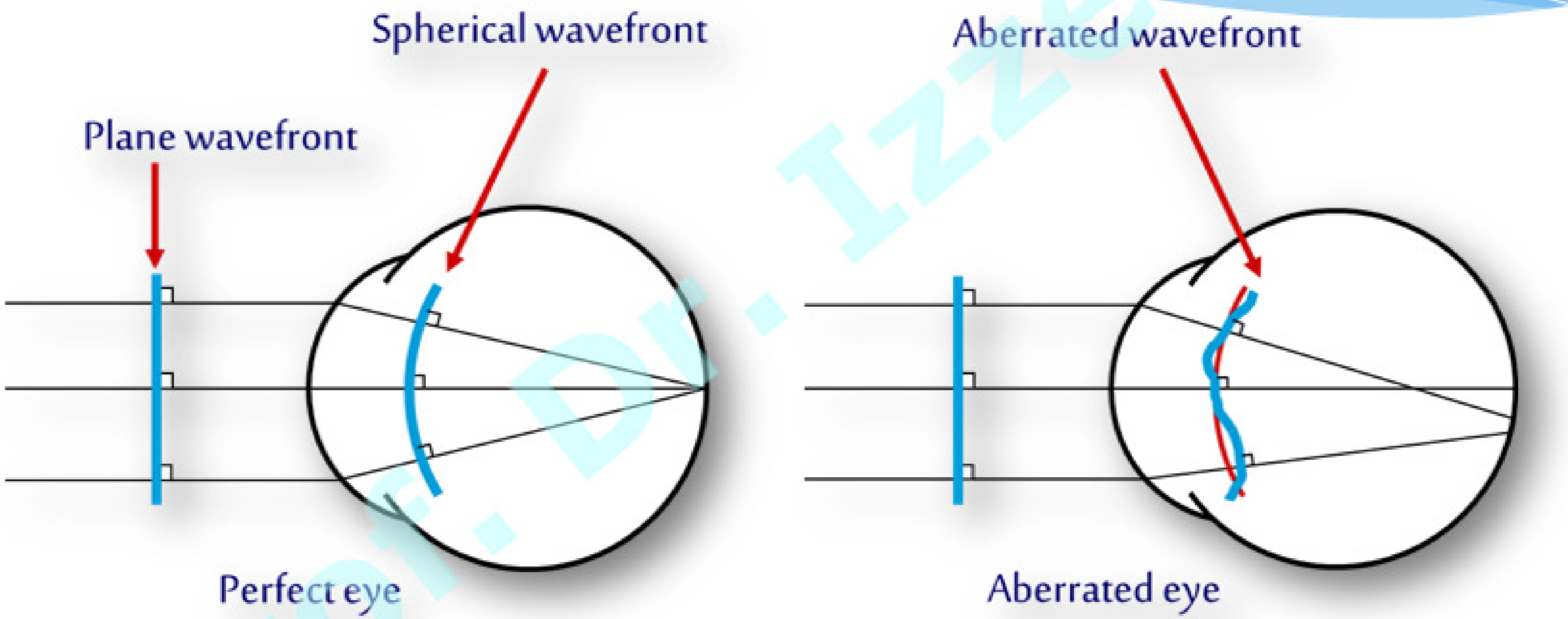
Optical System and It’s Imperfections

* Optical sources of image blur

1. Scatter
2. Diffraction
3. Aberrations



What is Wavefront and Wave Aberration?



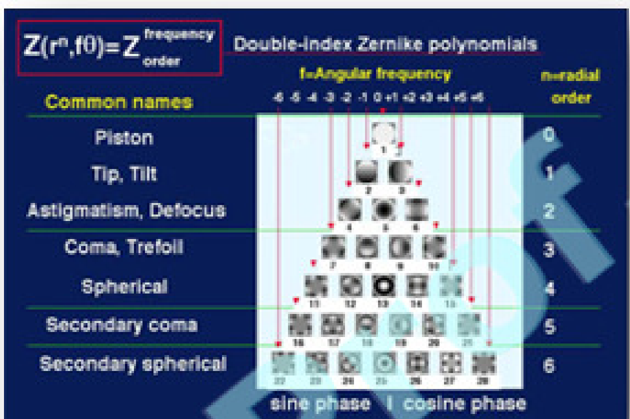
Wave aberration is defined as the difference between the actual aberrated wave front and the ideal or intended wave front. That is a function that characterize the image forming properties of the any optical system.

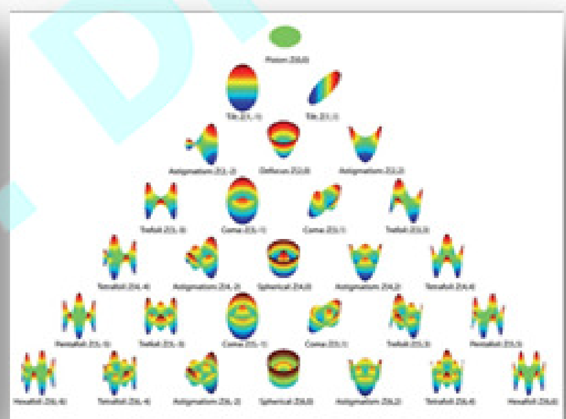
Born M, Wolf E. Principles of Optics 1985

What is Wavefront and Wave Aberration? / Describing Irregular or Complex Surfaces

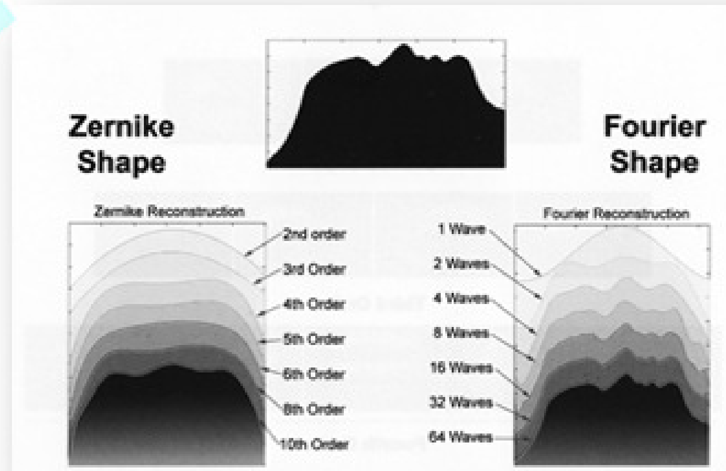
Expansion series:

* Jean Bapiste Joseph **Fourier** → 1800
* Fritz **Zernike** → 1934



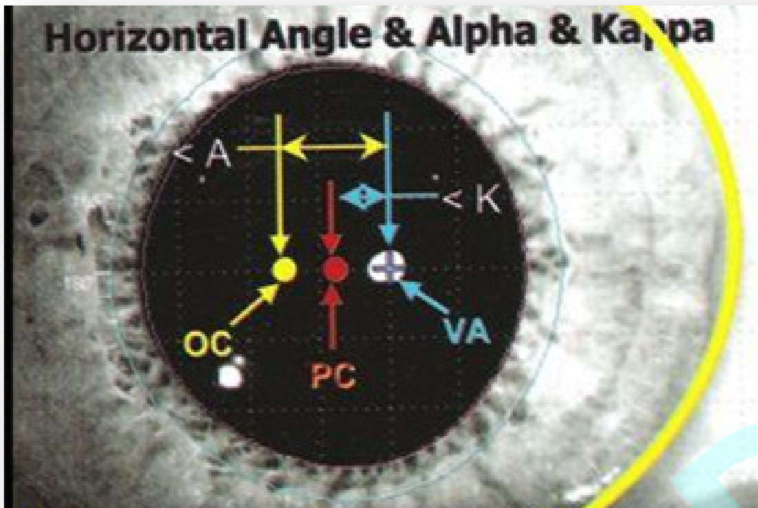


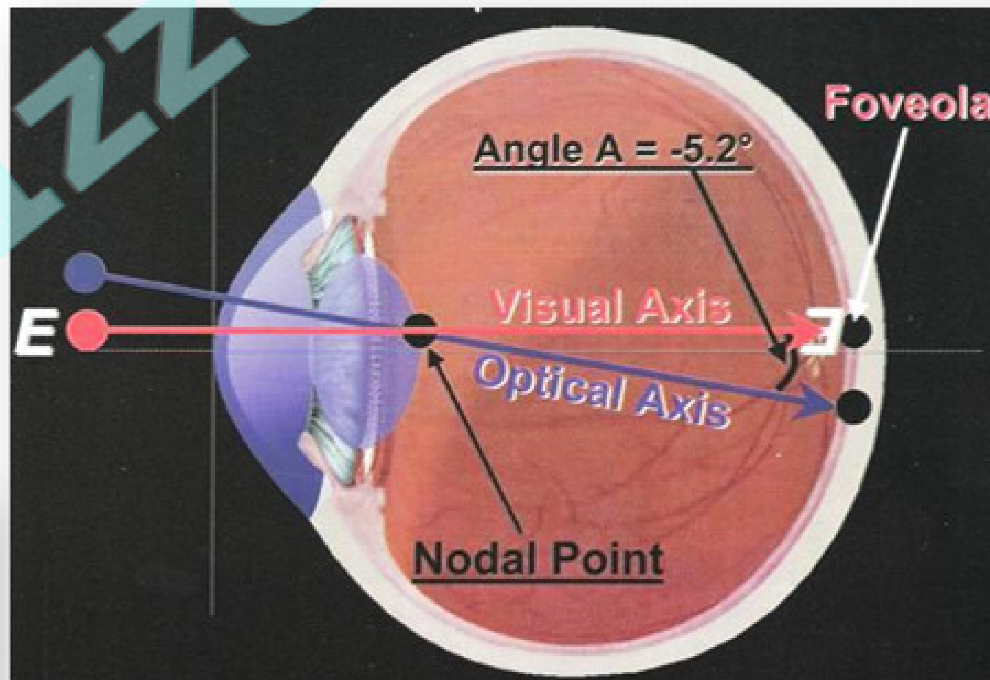
Zernike polinomials 2-D and 3-D

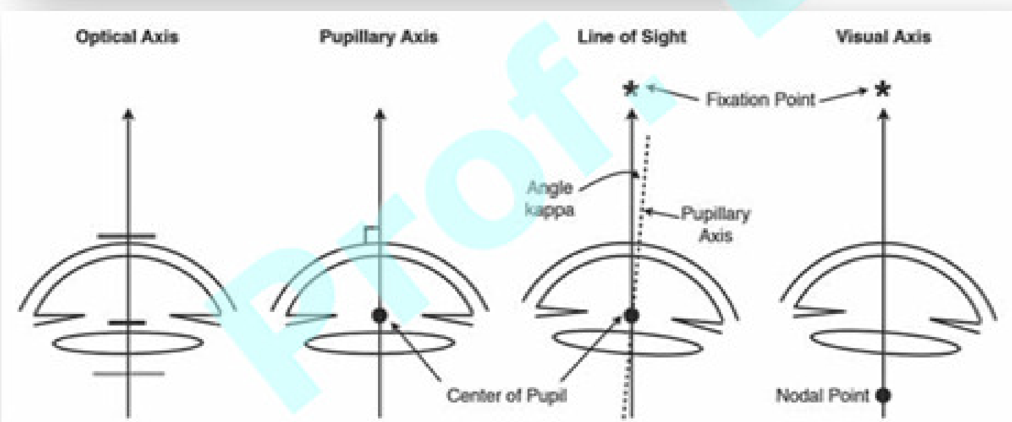


Zernike 10th order (mode) and Fourier with 64 terms of facial profile.
The higher the degree of irregularity, the closer the approximation of the Fourier series.

Optical System and It's Imperfections / Anatomical Limitations



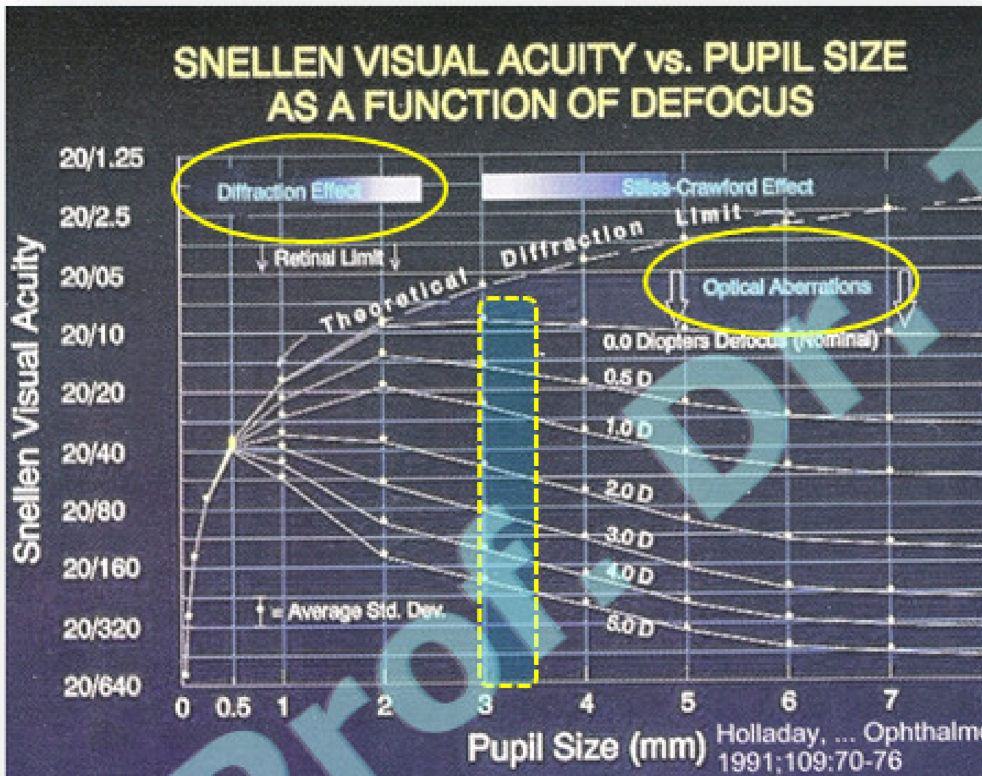




α ve λ angles

- α angle: 5.2° horizontally and 1.4° vertically
- λ angle: 2.6° horizontally and 0.6° vertically

Optical System and It's Imperfections / Limitations of Pupil Size

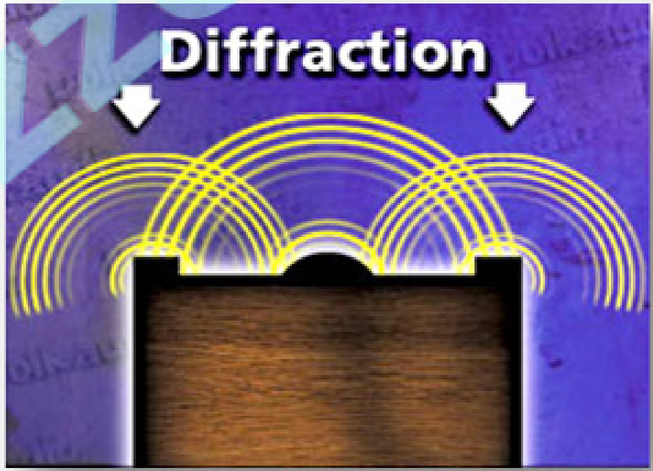


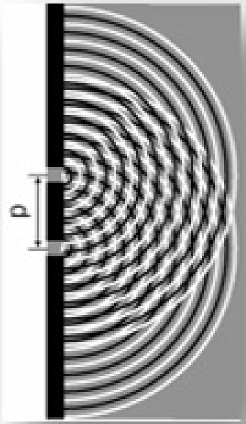
Holladay JT, et al. The relationship of visual acuity, refractive error, and pupil size after radial keratotomy. *Arch Ophthalmol*. 1991; 109: 70-6.

* The larger the pupillary diamater, **aberrations** increase, the smaller the pupillary diamater decrease but if it gets smaller, then **diffraction** becomes effective.
* In normal emmetropic human eye, 3,0 – 3,2 mm. is the optimal pupil size for achieving best uncorrected visual acuity.

What is Diffraction?

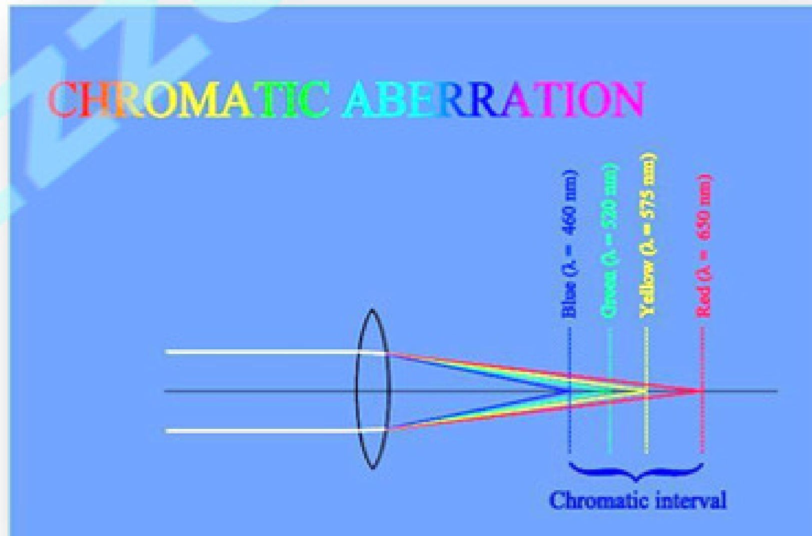
* Diffraction is defined as any deviation of light rays from a rectilinear path which cannot be interpreted as reflection and refraction. It is a tendency for light to bend around edges.
* When the wavefront is interrupted by an aperture, new wavefronts form and new wavefronts interacts with each other causing positive and negative effects (such as phase variations) called interference.





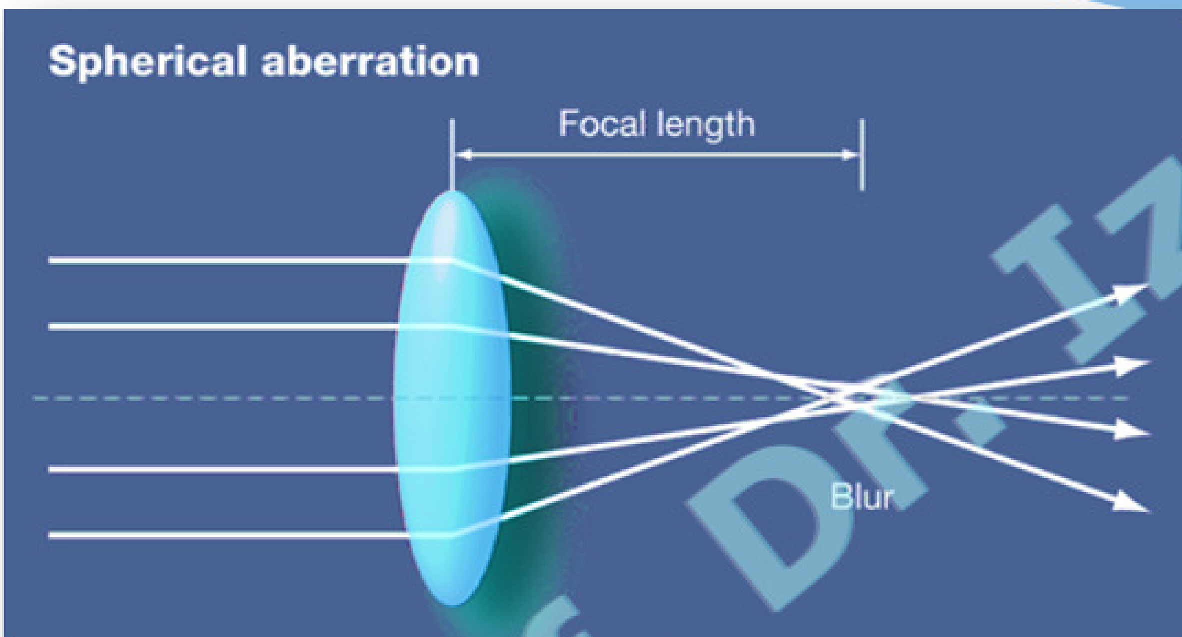
Optical System and It's Imperfections / Chromatic Aberration

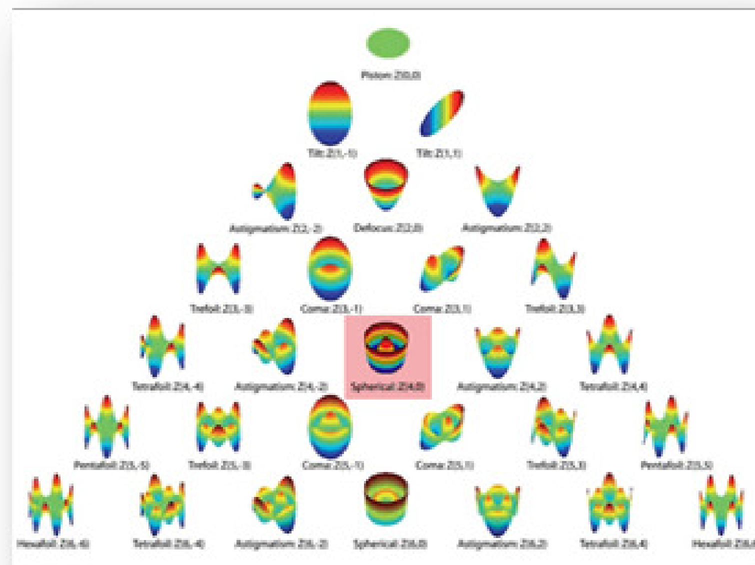
* Chromatic aberration arises entirely because the index of refraction of media is not the same for all wavelenghts.
* Typically, the index of refraction is higher as the wavelenght decreases.



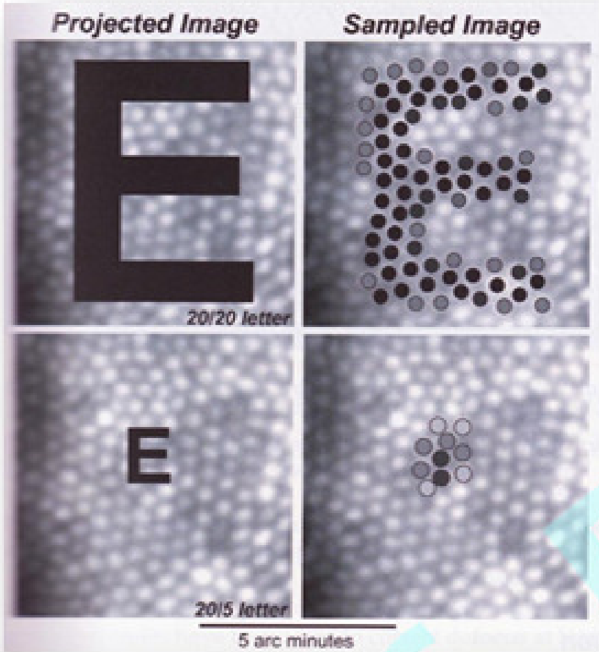
* Normal human eye has ~ 1.25 D. of axial chromatic aberration [between red (+0.37) and blue (-0,87)]. That may span 2.0 D.

Optical System and It's Imperfections / Spherical Aberration





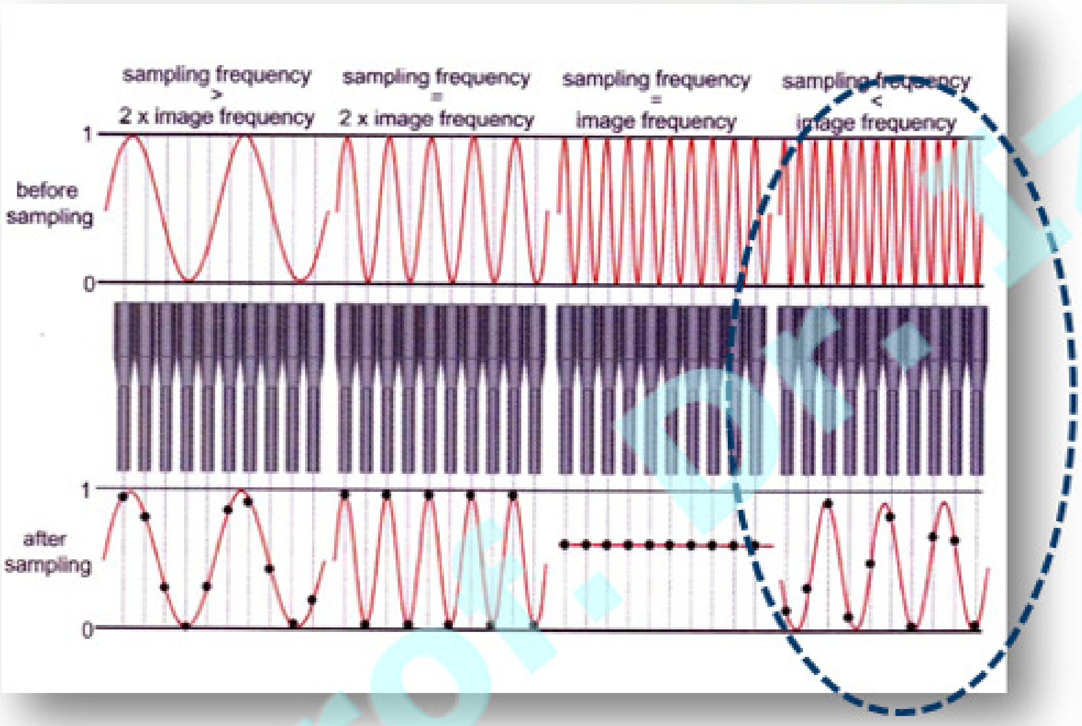
Optical System and It's Imperfections / Nyquist Sampling Limit

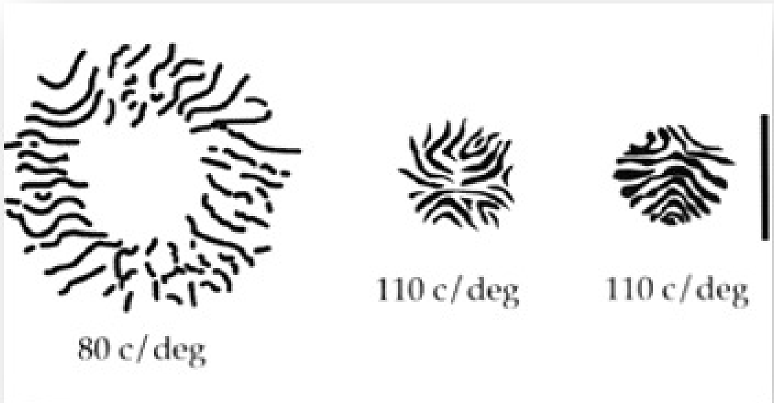


Source	Density (Cones /mm²)	Spacing (microns)	Spacing (Min of Arc)	Nyquist (c/deg)	Acuity (Min)
Osterberg (1935)	147 x 10³	2.43	0.50	60	1
Miller (1979)	128 x 10³	2.6	0.54	55.9	1.07
Yuodelis and Hendrikson (1986)	208 x 10³	2.04	0.42	71.4	0.84
Curcio et al (1987)	162 x 10³	2.57	0.53	56.6	1.06
Curcio et al (1990)	197 x 10³	2.55	0.53	56.6	1.06
Williams (1985)	126 x 10³	2.62	0.54	55.6	1.08
Williams (1988)	129 x 10³	2.59	0.54	55.6	1.08
Avarage	**157 x 10³**	**2.49**	**0.51**	**58.8**	**1.03**

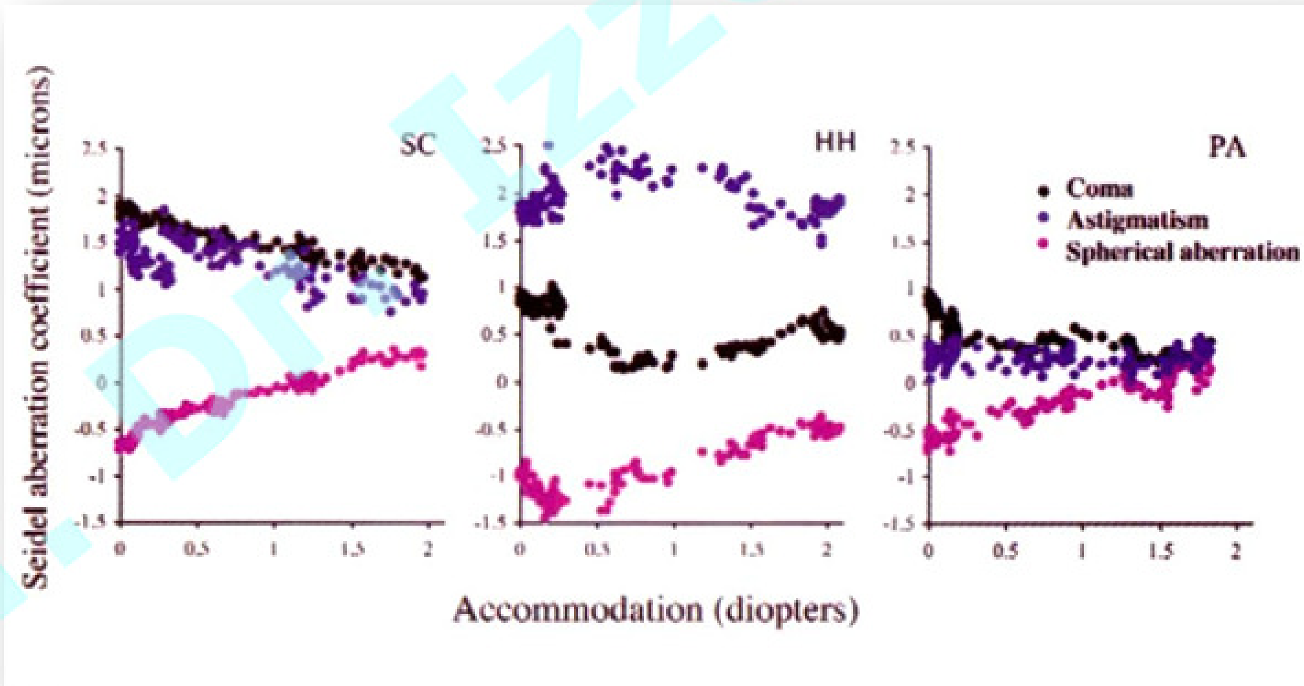
Nyquist rule: Spatial frequencies are only properly detected by foveal photoreceptors when they are less than one half of the sampling frequency.
Foveal photoreceptor density → 120 c/deg.
Highest frequency can be sampled→ 60 c/deg.

Optical System and It's Imperfections / Nyquist Sampling Limit





Optical System and It's Imperfections / Effect of Accommodation



Artal P, et al. Dynamics of ocular aberrations during accomodation. Optical Society of America Annual Meeting, 1999.

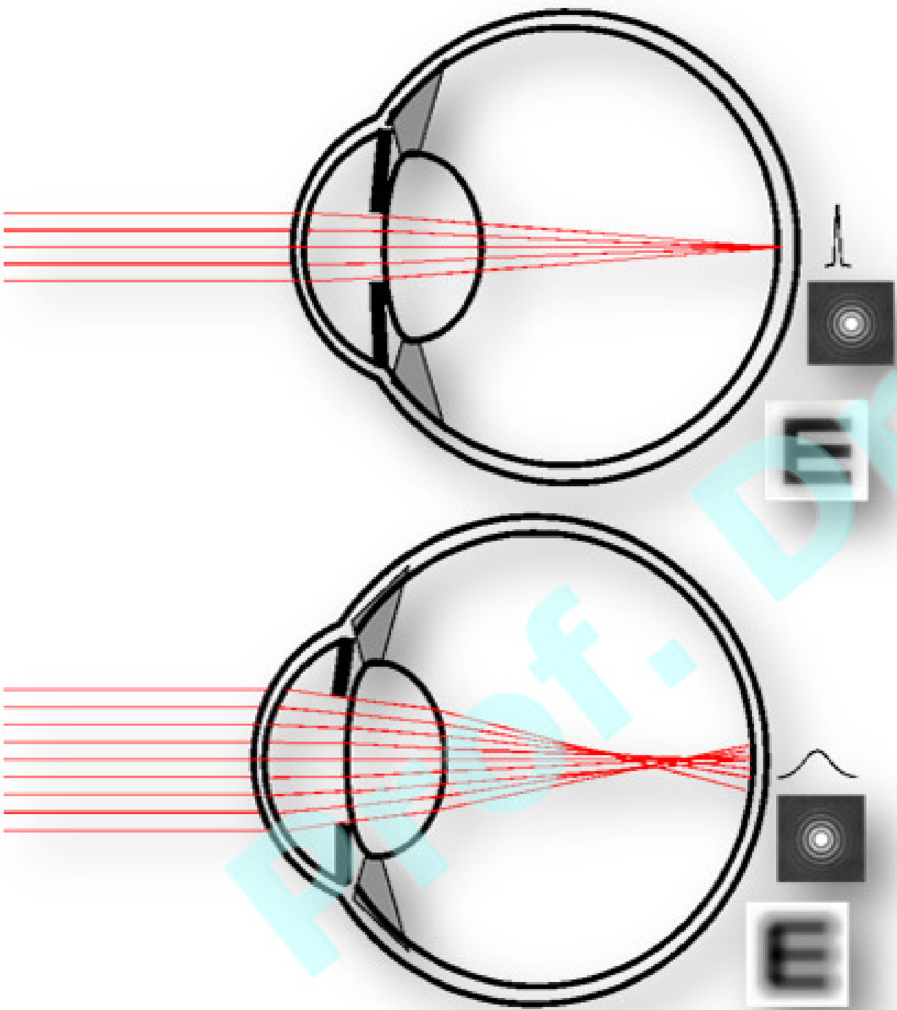
Optical System / Compensation Mechanisms

Charles Darwin
(1809 -1882)

To suppose that the eye with all its inimitable contrivances for adjusting the focus to different distances, for admitting different amounts of light, and for the correction of spherical and chromatic aberration, could have been formed by natural selection, seems, I freely confess, absurd in the highest degree.

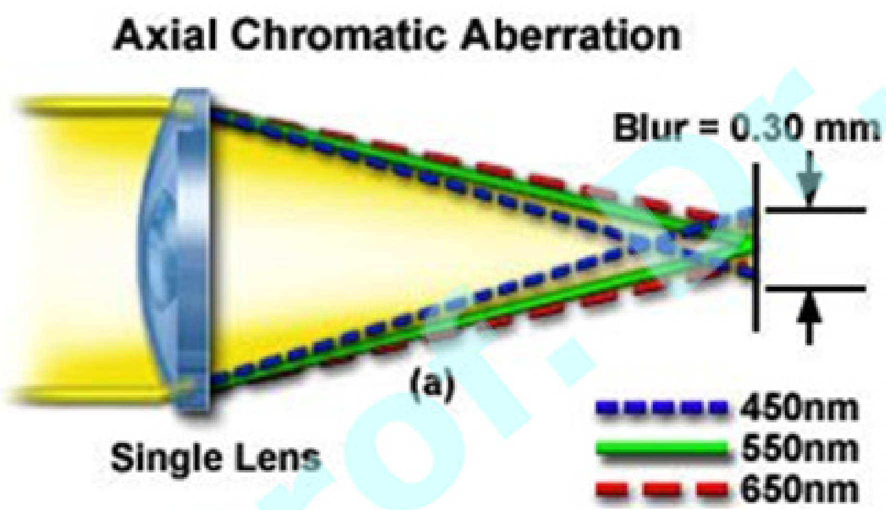
Charles Darwin, The Origin of Species, Chapter 6 "Organs of Extreme Perfection and Complication" 1859.

Optical System / Compensation Mechanisms / Large Pupil and Stiles-Crawford Effect



- The Stiles-Crawford effect, described in 1933, is caused by directional sensitivity in retinal photoreceptor cells.
- The rays of light that strike the retina obliquely have a reduced effect on vision compared to those that strike the retina more perpendicularly.
- Consequently, the quality of an image in human eye is far better than could be achieved with large pupil if the Stiles-Crawford effect did not exist.
- *In this way, the eye is superior to a camera.*

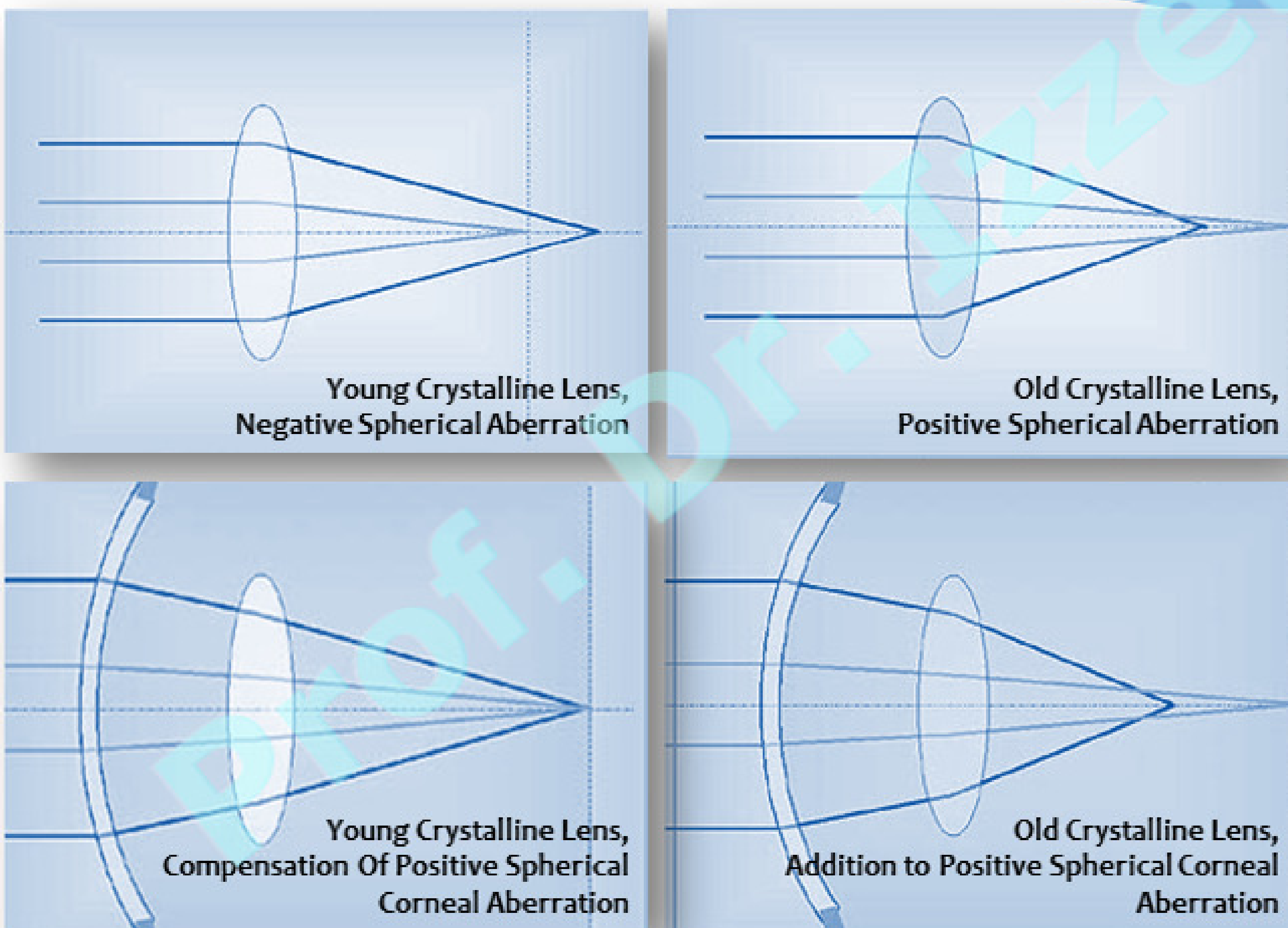
Optical System
/ Compensation Mechanisms
/ Chromatic Aberrations and Balancing HOAs



* Chroma, or rainbows around lights, appear around objects when white light is prismatically dispersed which may cause the visual blur.
* We do not see chromatic rainbows because it is shown that achromatic higher order aberrations balance out the chromatic aberrations.

McLellan PS, et al. Imperfect optics may be the eye's defence against chromatic blurs. *Nature* 2002; 417: 174-6.

Optical System
/ Compensation Mechanisms
/ Balancing Corneal Positive Spherical Aberration by Crystalline Lens



Optical System
/ Compensation Mechanisms
/ Compensation by the Internal Optics

Journal of Vision (2001) 1, 1-8

Compensation of corneal aberrations by the internal optics in the human eye

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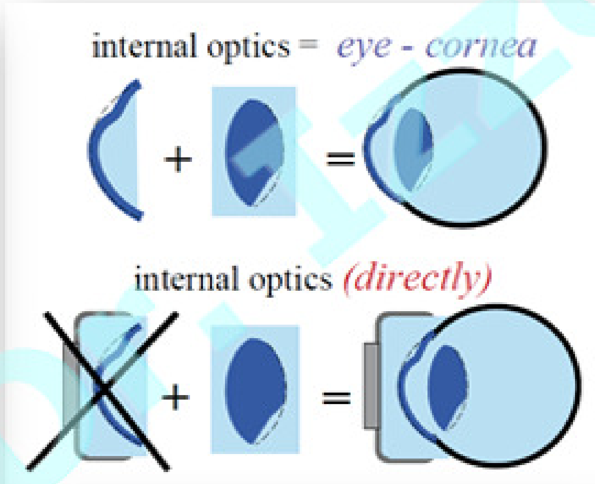
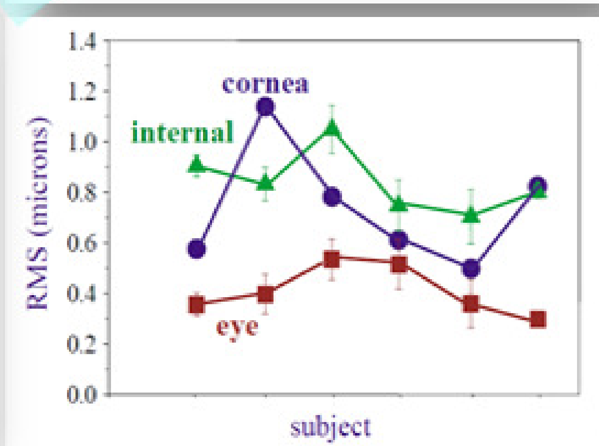
The objective was to study the relative contribution of the optical aberrations of the cornea and the internal ocular optics (with the crystalline lens as the main component) to overall aberrations in the human eye. Three sets of wave-front aberration data were independently measured in the eyes of young subjects: for the anterior surface of the cornea, the complete eye, and internal ocular optics. The amount of aberration of both the cornea and internal optics was found to be larger than for the complete eye, indicating that the first surface of the cornea and internal optics partially compensate for each other's aberrations and produce an improved retinal image. This result has a number of practical implications. For example, it shows the limitation of corneal topography as a guide for new refractive procedures and provides a strong endorsement of the value of ocular wave-front sensing for those applications.

Key Words: optical aberrations, eye, cornea, lens, retinal image quality

Introduction





* Corneal, internal and total aberrations were measured one by one.
* Corneal + Internal optics aberrations > Total Eye aberrations
* Conclusion: Cornea and internal optics neutralizes each other's aberrations.

Artal P, et al. *J Vis* 2001; 1: 1-8.

Optical System / Compensation Mechanisms / Compensation with Binocularity and Stereoacuity

* Angle alpha, the 5.2° horizontal tilt of the eye, induces coma, a distortion that causes a point of light to appear as a comet shaped image.
* Because coma exists in both eyes, brain have learned over time that a coma image with its tail in opposite directions in the two eyes should be a point.
* The brain can eliminate the tail and still achieve depth perception using binocular fusion.
* It is possible that reducing or eliminating coma may actually decrease stereoacuity at night, rather than improve it.

Compensation Mechanisms / Neural Adaptation

- Optical component
  - Cornea
  - Crystalline lens or IOL
  - Optic media
- Sensory Component
  - Photoreceptors
  - Occipital cortex
    - Broadman 17, 18 and 19. areas

Compensation Mechanisms / Neural Adaptation

* Neural adaptation is the process that takes place as the brain adapts over time (temporal) to changes in the visual information being supplied by the eye's optical component.
* Quick phase: Few seconds or minutes
* Longer phase: Several months to a year.
  * Schallhorn SC et al. *Ophthalmology* 2003; 110: 1606-14.
  * Mester U et al. *J Cataract Refract Surg* 2003; 29: 652-60.

Compensation Mechanisms / Neural Adaptation

Neural compensation for the eye's optical aberrations

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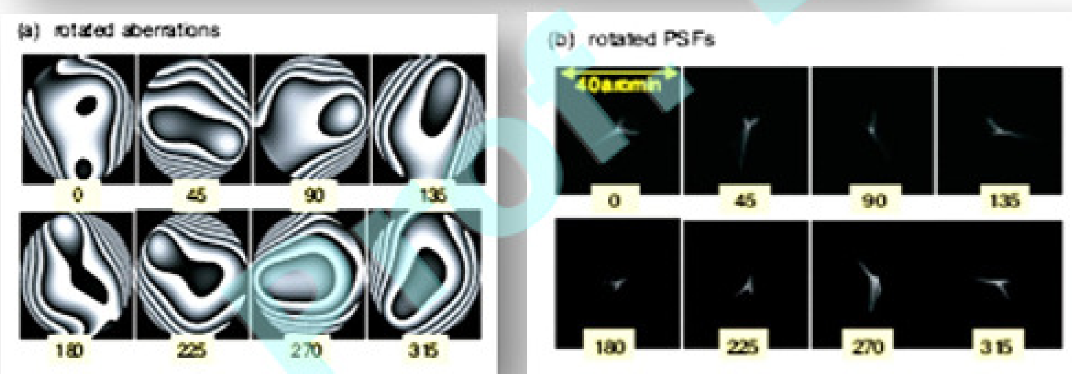
A fundamental problem facing sensory systems is to recover useful information about the external world from signals that are corrupted by the sensory process itself. Retinal images in the human eye are affected by optical aberrations that cannot be corrected with ordinary spectacles or contact lenses, and the specific pattern of these aberrations is different in



- **2nd Study→** 20/9 VA subjects
- Using adaptive optics, he rotated their aberrations optically in 30° increments from their original orientations.
- After just 30° rotation, patient's visual acuity and contrast sensitivity values were 60-80% dropped.
- Lesson 1: Neural computer is always adapted to the patients own particular optical system. If you change this optical system, neural software will be shut down until it will be readapted.
- Lesson 2: When you change these aberrations by using surgical or non surgical methods you may face with patients who have lost their neural adaptation , and dropped visual acuity and quality.

Artal P, et al. Neural compensation for the eye's optical aberrations. *J Vis* 2004; 4: 281-7.

Compensation Mechanisms / Neural Adaptation

Neural compensation for the best aberration correction

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We use adaptive optics (AO) to study whether neural adaptation influences the amount of higher order aberration correction that produces the best subjective image quality. Three subjects performed two tasks, method of adjustment and matching, while viewing a monochromatic stimulus through the Rochester AO system. In both tasks, after correcting the subject's lower order aberrations with trial lenses, AO was used to modify the subject's higher order aberrations, multiplying it by a scaling factor between 1 and −1. In the adjustment task, subjects adjusted the scaling factor to find the best subjective image quality. In the matching task, subjects viewed the same stimulus sequentially blurred either by defocus or a scaled version of their own wave aberration, adjusting the defocus to match the blur corresponding to different scaled versions of their aberrations. Results from both tasks are consistent with a small amount of neural adaptation because the best subjective image quality occurred when some higher order aberrations were left uncorrected for all three subjects. Neural adaptation slightly modifies the best aberration correction, although this effect averaged only ~12% of complete adaptation. These results may have practical consequences for customized vision correction.

Keywords: neural adaptation, physiological optics, optical aberrations, adaptive optics

Citation: Chen, L., Artal, P., Gutierrez, D., & Williams, D. R. (2007). Neural compensation for the best aberration correction. *Journal of Vision*, 7(10):9, 1–9, http://journalofvision.org/7/10/9/, doi:10.1167/7.10.9.

Introduction

The human eye suffers from wave aberrations that degrade vision. The lower order aberrations, defocus and astigmatism, have been measured at least 200 years ago (Young, 1801). These lower order aberrations are corrected with spectacles, contact lenses, intraocular lenses, and refractive surgery. Higher order wave aberrations, beyond defocus and astigmatism, have been known to exist in the eye for more than 150 years (Helmholtz, 1881). Since Smirnov (1961) used a psychophysical method to provide a description of the third and forth order aberrations, investigators have demonstrated a variety of different methods for estimating the wave aberrations of the human eye (Artal, Guirao, Berrio, & Williams, 2001; Campbell, Harrison, & Simonet, 1990; He, Marcos, Webb, & Burns, 1998; Hofer, Artal, Singer, Aragón, & Williams, 2001; Howland & Buettner, 1989; Howland & Howland, 1977; Iglesias, Berrio, & Artal, 1998; Liang, Grimm, Goelz, & Bille, 1994; Navarro & Losada, 1997; Mierdel, Krinke, Wiegand, Kaemmerer, & Seiler, 1997; Rosenblum & Christensen, 1976; Van den Brink, 1962; Walsh, Charman, & Howland, 1984). These pioneering studies greatly increased our understanding of the eye's higher order wave aberration. In recent years, the Shack–Hartmann wavefront sensor has become a popular method for wave aberration measurement with the goal of compensating these higher order aberrations to achieve diffraction-limited optics in the living eye (Fernández, Iglesias, & Artal, 2001; Hofer, Chen, Yoon, Yamauchi, & Williams, 2001; Liang & Williams, 1997) and customized vision correction with contact lens, intraocular lenses, and refractive surgery. However, the subjective image quality of the human eye depends not only on the optical blur caused by the wave aberrations but also on neural factors and the experience of the observer (George & Rosenfield, 2004; Mon-Williams, Tresilian, Strang, Kochhar, & Wann, 1998; Pesudovs & Brennan, 1993; Rosenfield & Hong, 2001; Rosenfield, Hong, & George, 2004; Watt, 1987; Webster, 2005; Webster, Georgeson, & Webster, 2002). This fact is well known among clinicians who often use a two step procedure to achieve a full correction of astigmatism, allowing time between the two steps for the patient's nervous system to adjust to a partial correction. There is adaptation not only to defocus and astigmatism, but also to the particular pattern of higher order aberrations (Artal et al., 2004). The subjective blur produced when viewing a scene through one's own wave aberration was less than that when the wave aberration was rotated. In the present paper, we investigate whether this neural compensation

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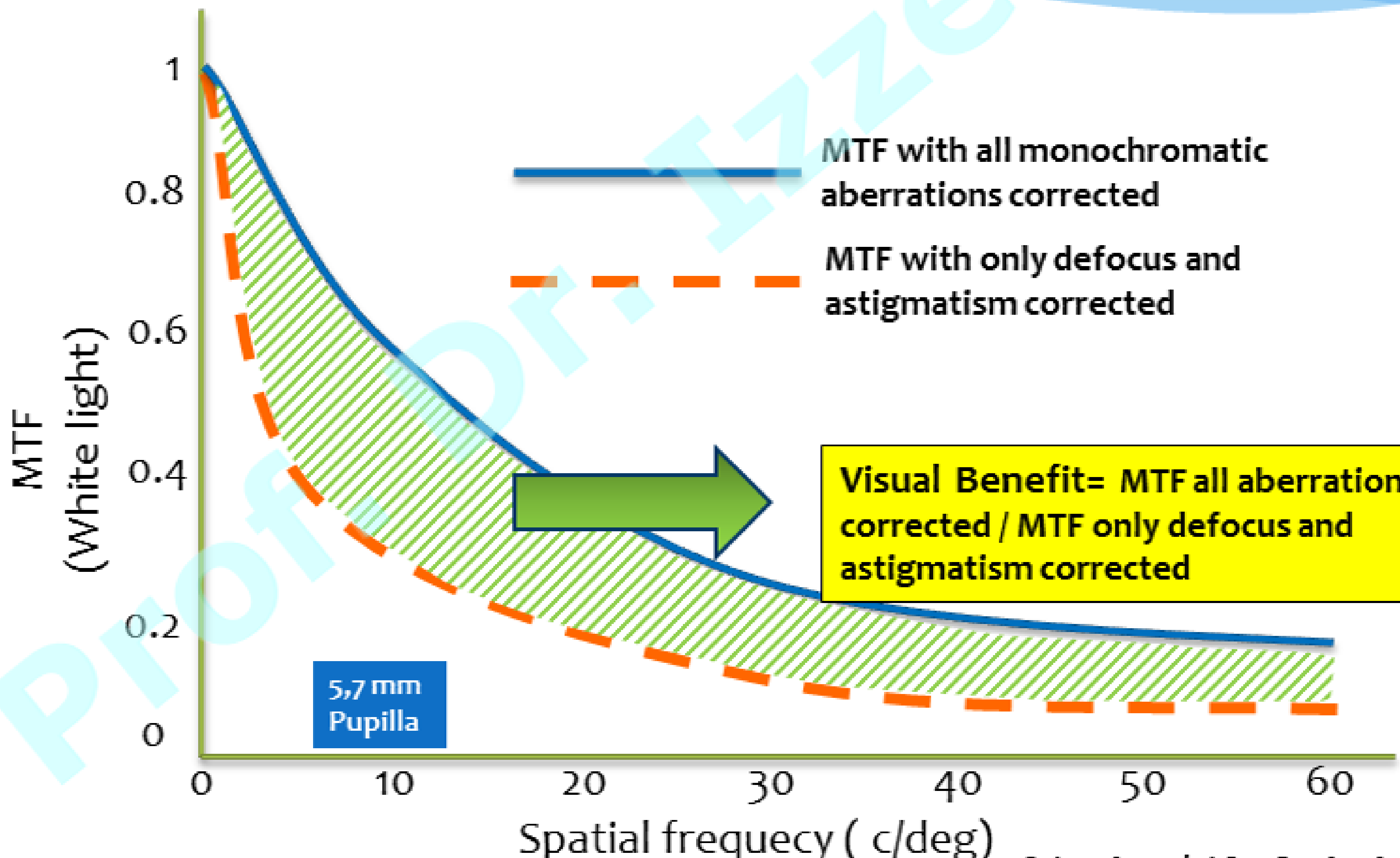
- Patient's aberrations were corrected by using Rochester adaptive optics system (deformable mirror) step by step.
- Visual acuity and quality measurements were performed for each step.
- It was seen that best subjective image quality occurred when some higher order aberrations were left uncorrected. (Best result was obtained after 88% correction)
- Lesson 1: It has shown that the best subjective image quality does not necessarily occur when the quality of the retinal image is highest.
- Lesson 2: Neural adaptation slightly modified the best aberration correction, although this effect averaged only about 12% of complete adaptation.

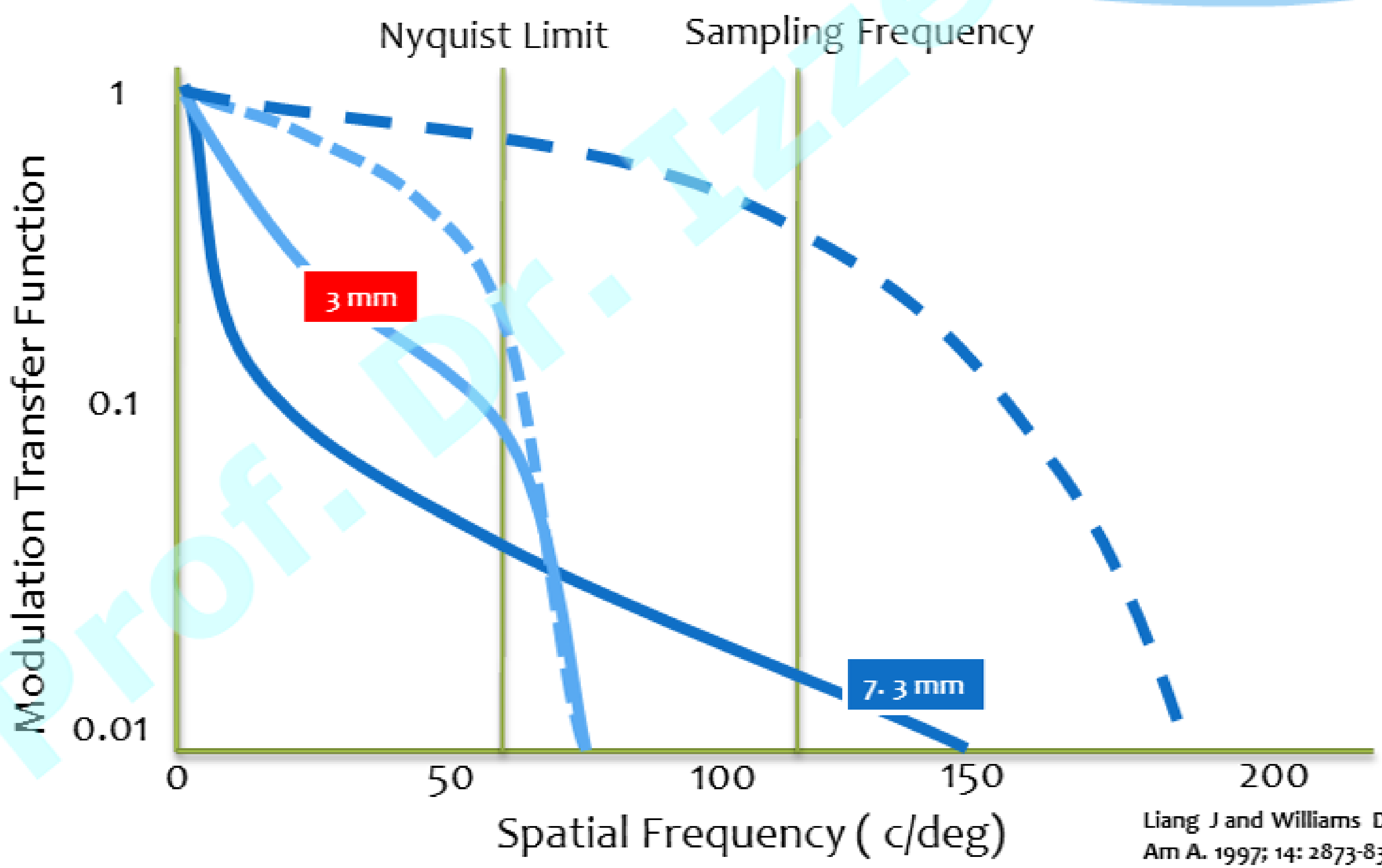
Chen L, et al. Neural compensation for the best aberrtion correction. *J Vis* 2007; 7: 1-9.

Visual Benefit of Higher Order Aberration Correction



Guirao A, et al. J Opt Soc Am A. 2002; 19: 620-8.

Visual Benefit of Higher Order Aberration Correction



Liang J and Williams DR. J Opt Soc Am A. 1997; 14: 2873-83)

What is High Quality Vision?

* The vision, provided by normal optical but perfect *neural* systems, ended up with highest contrast sensitivity perception.

Thank you very much for your attention.