The Glenn A. Fry Award Lecture 2011 – Peripheral Optics of the Human Eye

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ABSTRACT

There has been a low level of interest in peripheral aberrations and corresponding image quality over 200 hundred years. Most work has been concerned with the second-order aberrations of defocus and astigmatism that can be corrected with conventional lenses. Studies have found high levels of aberration, often amounting to several dioptres, even in eyes with only small central defocus and astigmatism. My investigations have contributed to understanding shape changes in the eye with increase in myopia, changes in eye optics with ageing, and how surgical interventions intended to correct central refractive errors have unintended effects on peripheral optics.

My research group has measured peripheral second and higher-order aberrations over a 42° horizontal x 32° vertical diameter visual field. There is substantial variation in individual aberrations with age and pathology. While the higher-order aberrations in the periphery are usually small compared with second-order aberrations, they can be substantial and change considerably following refractive surgery.

The thrust of my research in the next few years is to understand more about the peripheral aberrations of the human eye, to measure visual performance in the periphery and determine whether this can be improved by adaptive optics correction, to use measurements of peripheral aberrations to learn more about the optics of the eye and in particular the gradient index structure of the lens, and to investigate ways of increasing the size of the field of good retinal image quality.

Key Words: higher-order aberrations; magnetic resonance imaging; myopia; peripheral refraction

Introduction

I would like to thank the American Optometric Foundation for the honour of receiving the Glenn A. Fry Lecture Award.

I think that nearly all people who met Professor Glenn Fry would have interesting memories of this great man. One of my memories concerned an American Academy of Optometry meeting in the late 1980s, where a young colleague was espousing the benefits of signal detection theory and was saying that you should not rely on subjects' opinions in visual experimentation. Glenn replied that he would believe a subject who told him that a particular event had occurred. I jumped to the conclusion that Glenn did not understand the signal detection approach, but realised later that he was just trying to find more about our colleague's understanding of this field. A second memory was of Glenn Fry's external examiner report of my PhD thesis; half the report was an irrelevant but highly interesting discourse on various optical instruments that he had designed and built.

The award has been presented only four times to someone outside Northern America, although I note proudly that it has been given to Australian expatriates Tony Adams, Ian Bailey, Suzi Fleiszig and Christine Wildsoet. It was given to Nathan Efron from my University last year for his work on ophthalmic markers of diabetic retinopathy. At one time as graduate students Nathan and I sat in adjacent cubicles. Nathan and I have advanced from those days and we now have rooms rather than cubicles. However, these rooms are still next to each other.

My main interests in vision science have been the optics of the eye, the optics of its correcting devices and how these combine to affect visual performance. Optics was not that interesting to Optometrists and Vision Scientists when I became a graduate student at the Department of Optometry at the University of Melbourne in 1976. Things have changed a lot

since then, particularly with the realisation that we can manipulate corneal refractive surgery and designs of spectacle, contact and intraocular lenses to optimize outcomes for patients.

Fortunately for me, a Physicist named George Smith had recently taken a lecturing position in the Department of Optometry and was trying to learn about vision at the same time that I was trying to learn about optics. This started a collaboration that was to last for thirty years. I have paid tribute to George elsewhere[1].

One aspect of visual optics that has been of particular interest to me is the optics corresponding to the periphery of the visual field. While there has been considerable interest in the eye's higher-order aberrations and retinal image quality in the last decade, spurred by advances in technology and refractive surgery, most interest has been associated with foveal vision corresponding to the central 5° diameter of the visual field. While central vision is important for resolving fine detail under daylight conditions, peripheral vision is important for detecting stationary and moving objects and becomes increasingly important for navigation when luminance drops as night-time approaches. Recently it has been implicated as a driver in the development of refractive errors. Little is known about how the peripheral optics, and in particular the peripheral higher-order aberrations, affect visual performance.

This paper covers the development of our understanding of the peripheral optics of the human eye.

PERIPHERAL REFRACTION

Many people in visual optics do not realise that consideration of peripheral refraction of the human eyes goes back beyond the study of Ferree, Rand and Hardy, in the early 1930s[2-4], to Thomas Young's famous paper "On the mechanism of the eye" in 1801[5]. It the midst of fascinating material including refraction, accommodation, aberrations, and gradient index,

Young produced a diagram of the formation of image shells based on biometric measurements of his left eye, an annotated version of which appears as Figure 1. The figure shows image shells for refraction at the cornea (1-3), refraction at the cornea and anterior lens (4-6), and refraction at the cornea and the whole lens (7-9). Young had 4 D of myopia in the vertical meridian of his left eye and set the object surface as a circular arc of 25 cm radius in front of the eye. The shells show where light refracted in the principal meridians and passing through the pupil is focused. For the vertical visual field, the tangential shell corresponds to refraction of a fan of rays in the vertical section and the sagittal shell corresponds to refraction of a fan of rays orientated perpendicularly to the vertical fan. The average of these shells for refraction of all the components, containing the circles of least confusion (9, 10), is slightly in front of the retina (11), which is actually the case in most emmetropic eyes. Curve 12 is the supposed locus of the circles of least confusion if an accurate variation of the lens could be incorporated into the model. Further information about peripheral refraction of Young's eye model appears elsewhere.[6]

Following Thomas Young, there were a few studies of peripheral refraction near the start of the 20th century using a variety of techniques.[7,8]

The aforementioned study by Ferree, Rand and Hardy in the 1930s used a commercial coincidence optometer.[2-4] They recognized different patterns of peripheral refraction in the horizontal visual field. The Type A pattern was the typical pattern in emmetropes and hypermetropes, with light refracted along the vertical meridian showing a hypermetropic shift into the periphery and light refracted along the horizontal meridian showing a myopic shift into the periphery (Figure 2a). The type B pattern was typically found in myopes, with light refracted in both meridians showing hypermetropic shifts into the periphery (Figure 2b). A further Type C pattern showed asymmetry between the nasal and temporal sides of the visual field (Figure 2c). One important feature is astigmatism in the periphery, which when given as

the difference between vertical and horizontal refractions is as high as 16 D as shown in Figure 2a at 60° eccentricity in the nasal visual field.

The next interesting study of peripheral refraction was by Rempt, Hoogenboom and Hoogerheide in the 1970s[9-11]. They renumbered the type A, B and C patterns as types IV, I and III, respectively (Figure 2a-c). They identified a pattern II intermediate in type between that of Ferree et al's types A and B (Figure 2d), and a type V pattern in which refraction changed little along the vertical meridian and show a considerable shift in the myopic direction along the horizontal meridian (Figure 2e)[9]. This study was done in candidate pilots. They found that those hypermetropic and emmetropic people who went on to develop myopia "during the following years" had different patterns from those who did not, with the former usually showing the type I (type B) pattern (65% of cases) and the latter usually showing the type IV (type A) pattern (58% of cases).[10]

While Ferree et al. and Rempt et al. were restricted to describing refraction components in terms of horizontal and vertical meridians because of limitations with their equipment, with the automation available now in the form of autorefractors and wavefront sensors and with the use of vector terminology, we are able to have a more complete description of peripheral refraction. Peripheral refraction is considered in terms of three components: mean refraction and crossed-cylinder components horizontal/vertical astigmatism and oblique astigmatism (Figure 3). Often, we refer to the change in peripheral mean refraction from the central mean refraction as *relative peripheral refraction*, and specifically as relative peripheral hypermetropia or relative peripheral myopia. For the horizontal and vertical meridians of the visual fields, the horizontal/vertical astigmatism can become large and oblique astigmatism tends to change little. [To forestall some confusion, oblique astigmatism is sometimes used to refer to astigmatism induced by oblique incidence of light at surfaces and could refer to either of the aforementioned astigmatisms]. In the vector terminology, the Type V pattern shows

relative peripheral myopia, Type IV can show either relative peripheral myopia or hypermetropia, and Types I and II show relative peripheral hypermetropia.

Translating the findings of Rempt et al. and Ferree et al. into vector terminology indicates that, along the horizontal visual field, most adult hypermetropes show relative peripheral myopia, most emmetropes show relative peripheral myopia or minimal relative peripheral refraction, and most myopes show relative peripheral hypermetropia. The shifts of relative peripheral refraction in the hypermetropic (positive) and myopic (negative) directions with increases in central myopia and central hypermetropia, respectively, have been confirmed in many subsequent studies eg[12-15].

The findings of Rempt et al. regarding the relationship between peripheral refraction patterns and the development of myopia were largely forgotten for 30 years, when the possibility of peripheral refraction driving myopia regained interest[15-17] . One schema by which this might occur is as follows. Considering a young emmetropic eye (Figure 4, top), if the retina is flat there will be peripheral myopia and no stimulus to growth. However, if the retina is steep, there will be peripheral hypermetropia which might drive growth of the eye. This might give peripheral myopia again (Figure 4, middle), but if a myopia correction is applied in the form of a contact lens or a spectacle lens (Figure 4, bottom), the eye has relative peripheral hypermetropia and growth continues. [Note here that the correction would have some influence on the new peripheral refraction pattern.] Howard Howland suggested that growth might occur by comparisons of outputs of neurons tuned to detail orientated parallel and perpendicular to a particular field meridian[18,19]: in the case of the emmetropic eye with the steeper retina and with peripheral hypermetropia (Figure 4, top), the detail orientated perpendicular to the field meridian would be in better focus than detail oriented parallel to the field meridian. The flaw with this schema is that it suggests that, if left uncorrected, myopia would develop only to a certain, relatively small level.

Researchers at the Queensland University of Technology made some contributions to the area of peripheral refraction. In 2002 – 2005 Katrina Schmid, Nicola Pritchard and Jim Pope and I conducted a cross-sectional study into the optics and visual performance in myopia. Like most studies of peripheral refraction before us, we took measurements along the horizontal meridian of the visual field and found patterns that were similar to what had been reported previously. At the same time, we were measuring eye shape in our subjects with magnetic resonance imaging. We found considerable variation in shapes of eyes, but we noticed that the overall rate at which eye increased in size, as myopic refraction increased, differed between length, height and width (Figure 5).[20,21] For each 3 mm increase in length, the height increased by approximately 2 mm and the width increased by approximately 1 mm.

Because of the differences between the vertical and horizontal dimensions of myopic eyes, we took further peripheral refraction measurements in a third of our subjects along the vertical visual field[22]. This revealed different patterns in the mean spherical refraction in the horizontal and vertical visual fields. The horizontal visual field showed a pattern in which relative peripheral myopia for emmetropes became relative peripheral hypermetropia refraction at about 1-2 D myopia, and thereafter progressed only slowly. However, in the vertical meridian the majority of myopes showed similar patterns as for the emmetropes, that is, relative peripheral relative myopia (Figure 6). As our participants were young adult emmetropes and stable myopes, our study did not indicate what happens to eye shape or peripheral refraction during the development of myopia. Our findings have been confirmed in both adults and children.[23,24] Unfortunately, these results of the vertical field refraction have been ignored often in subsequent studies of peripheral refraction and how it relates to eye shape. My attempts at developing schematic eyes for myopia were only partially successful at

modelling the changes in peripheral refraction patterns[25] between the two meridians; this is an area that needs improving.

Corneal refraction surgery for myopia was becoming very popular by the start of the 21st century. However, it was not working as well as it should because of the increased higher-order aberrations, particularly spherical aberration, produced by flattening the central but not the peripheral part of the cornea. Effectively, the cornea steepens from the centre to the periphery rather than the usual flattening. I was interested in finding out whether these disturbances extended into the peripheral field. Together with a visiting Chinese ophthalmologist Lucy Ma, I determined peripheral refraction along the horizontal visual field in people who had laser assisted in situ keratomileusis (LASIK) surgery.[14] Not surprising, accompanying the changes in anterior corneal shape were dramatic changes in patterns of peripheral refraction. Figure 7 shows peripheral refraction for an uncorrected myope, with relative peripheral hypermetropia, and that of a 5 D myope corrected by surgery who developed considerable relative peripheral myopia. He had increased peripheral astigmatism also, as shown by the J_{180} values. The opposite situation occurred in hypermetropic LASIK, with relative peripheral myopia changing to relative peripheral hypermetropia and with peripheral astigmatism decreasing. The findings regarding myopic LASIK were confirmed in a recent comprehensive study[26].

I realised that what happens in LASIK will probably happen in orthokeratology, which is the process of flattening the cornea by overnight wear of special contact lenses. I was joined by Neil Charman, a Prentice Awardee of the American Academy of Optometry[27], in work that showed change in refraction pattern similar to that found in the LASIK study (Figure 8). At the time we noted "… this method of correction creates an overall pattern of peripheral refraction which Hoogenheide et al. and Wallman and Winawar suggested would minimize the chances of myopia progression. It appears, then, that it may be possible to explain the

reduced myopia progression rates in young ortho-K patients in these terms."[28] The relationships between orthokeratology, peripheral refraction and rates of myopia progression are being pursued by others eg[29-32].

Other interesting developments have occurred in the last decade. Zadnik and Mutti's group began to measure and follow biometry in children, including the determination of peripheral refraction at a single location in 30° in the nasal visual field[33-35]. Earl Smith's group's work with young monkeys showed that the peripheral retina is important to emmetropization and the development of myopia. If you ablate the central retina or block it, the monkeys can still emmetropize but if you interfere with the peripheral retina, myopic errors can result[36,37]. The shape of the retina can be changed locally by lenses that alter the peripheral refraction in part of the visual field[38]. For a fuller coverage of this work, see Smith's recently published Charles Prentice Award lecture[39]. His group's work provided the basis for Brien Holden's research group to go ahead with clinical trials with spectacle lens and contact lenses with additional positive/less negative power in the periphery to treat relative peripheral hypemetropia. This work is showing promising reductions in rates of myopia progression in children[40,41].

Despite the compelling findings of Earl Smith's group with monkeys, I wonder whether the enthusiasm for treating myopia by correcting relative peripheral hypemetropia will continue. In 2007 Mutti et al.[33] reported that children who became myopic had more relative peripheral hypermetropia than did emmetropes from two years before myopia onset. However earlier this year they concluded "relative peripheral hyperopia appears to exert little consistent influence on the risk of the onset of myopic refractive error, on the rate of myopia progression"[35]. A recently longitudinal Singaporean study found that relative peripheral hypermetropia was not associated with a greater possibility of becoming myopic, nor the rate

at which this occurred.[42] Indeed relative peripheral refraction seems to be mainly a function

of central refraction, with little influence of age[13,23,43,44]

I will finish this section with some further thoughts on how relative peripheral refraction

might drive eye growth and development of myopia:

1. Given that myopes seem to have peripheral relative myopia in the vertical visual field,
    which would contribute a "stop" signal to eye growth, possibly the eye/brain pays
    attention mainly to the horizontal visual field and nearby meridians. How does the
    eye/brain take into account in the (variable) blurred imagery produced by longitudinal
    and transverse chromatic aberration?

2. Relative peripheral refraction may explain the (limited) success of spectacle lens
    bifocals and progressive lenses in slowing myopia progression (see Cheng et al[45] for a
    review of bifocal lens control of myopia progression).

3. Neil Charman[19] has suggested that near work provides a variable distance
    environment in which it might be hard to sustain a peripherally driven refractive
    status, and thus a condition for any emmetropization mechanism based on peripheral
    imagery would require a reasonable period of outdoor activity; this links theories of
    the roles of peripheral refraction and indoors/outdoors activities in myopia
    development.[46-48]

PERIPHERAL HIGHER-ORDER ABERRATIONS

In vision science, we now think of aberrations of the eye in terms of Zernike

polynomials[49-53]. The second-order aberrations of defocus, astigmatism and oblique

astigmatism dominate the determination of refraction. The higher-order aberrations, which

were investigated more than two hundred years ago by Thomas Young[5], have reached the consciousness of the ophthalmic professions in the last decade because of the important effects that they have on vision when combined with refractive modalities such as corneal refractive surgery, intraocular lenses, and some contact lenses. There have been many studies of aberrations associated with central (fovea) vision[54].

In 1998 Rafael Navarro used the laser raytracing technique to determine the peripheral aberrations, including third- and fourth-order terms, in the nasal visual fields of eyes of 4 subjects[55]. Dion Scott, Ankit Mathur, Neil Charman and I extended Navarro's work using the Hartmann-Shack sensor approach. In recent years, we have been using a commercial instrument in which we place a beam splitter in front of the eye and provide a system of fixation points covering 42° horizontally x 32° vertically of the visual field[56]. We have used our approach to investigate higher-order aberrations in different refractive error types[57], with accommodation[58] and ageing[59], with refractive interventions such as LASIK[60], IOLs[60] and orthokeratology[61], and in keratoconus[62]. In recent years, others have made considerable advances in automating the process[63-66] Instruments may be used for determining just refractions or determining both refraction and aberrations coefficients.

One way of showing the aberrations is to investigate what happens to the individual aberration coefficients across the field. The subject in Figure 9 shows the typical patterns of the astigmatisms increasing quadratically with angle away from fixation, coma varying linearly and spherical aberration changing little[56]. Another approach is to show pupil aberration maps corresponding to each tested location in the visual field (Figure 10).

The most interesting of the higher-order aberrations are the comas and spherical aberration, as these change most quickly across the field in the higher-order aberrations (coma) or are most susceptible to treatments (comas and SA) As an example in the higher-order wave aberration maps of a group of myopic subjects and a group of LASIK patients,

the spherical aberration is much greater for across the visual field for the latter group and the rate at which coma changes across the visual field is reversed (Figure 10).

Usually the changes that we noticed in the aberrations could be explained by the accompanying changes in the biometrics eg anterior corneal asphericity in the case of corneal refractive surgery[60] and orthokeratology[61] and the lens in case of ageing[67].

While the higher-order aberrations in peripheral vision are relatively small compared to the second-order aberrations, they may play a role in image quality and are of interest when trying to correct the periphery imagery such as with adaptive optics.

SPECIFYING ABERRATIONS IN PERIPHERAL VISION

As mentioned before, in visual optics we use the system of Zernike polynomials to describe aberrations. These are actually circular polynomials. For the vast majority of eyes, the assumption of a circular pupil is reasonable in foveal vision, but the pupil becomes increasing elliptical off-axis and this cannot be ignored. We have taken this into account by stretching the pupil along the minor axis[68-71]. While this gives a complete description of wave aberrations, this has some anomalies such as a spherical wavefront (corrected by a spherical lens) having both defocus and astigmatism wave aberrations terms, and the approach breaks down if the pupil is not elliptical. The other common approach has been to use a circular pupil, either smaller[72-74] than or larger[75] than the "true" elliptical pupil; this approach which is of course not physiological, but analysis is simpler. Aberration coefficients determined for an elliptical pupil of a fixed semi-major diameter, a "larger circle" of this diameter, and a "smaller circle" of diameter corresponding to the semi-minor axis will give similar results within 20° of fixation, but will be very different at larger angles.[76] The advantages and disadvantages of circular and elliptical pupils for peripheral wave aberrations have been

considered in greater detail.[76] [A method for converting between circular and elliptical pupils is available[77]].

They are other issues to be considered with peripheral aberrations: adopting a visual field or a retina based direction system eg temporal/nasal visual field or nasal/temporal retina; a sign convention to go with the directions; the form in which data can be presented; comparisons involving right and left eyes. Most commercial instruments measure aberrations in the near infrared and make corrections for defocus (mean sphere), but minimal if any allowance for other aberrations. Two investigations indicated that the negative correction applying on-axis is insufficient for the periphery[73,78], which means that relative peripheral myopia/hypermetropia is underestimated/overestimated, but the available data are not complete enough to make systematic corrections. Infrared peripheral astigmatism is probably smaller than the astigmatism for visible wavelengths[73], but errors associated with measuring higher-order aberrations in the infrared are negligible. I hope that these issues will be considered for revisions of national and international standards of wavefront aberrations in visual optics.[50,52]

CURRENT AND PLANNED WORK

The thrust of my research in the next few years will be to understand more about the peripheral aberrations of the human eye, investigate whether visual performance in the periphery can be improved by adaptive optics correction, to use measurements of peripheral aberrations to learn more about the optics of the eye and in particular the gradient index structure of the lens, and to investigate ways of increasing the size of the field of good image quality of the retina.

One current project is designing and manufacturing lenses to correct peripheral refraction in the horizontal visual field meridian (Figure 11). This has been done for several subjects, and, continuing the work of others[11,79-81], Ankit Mathur and I will investigate how corrections in the periphery can improve visual performance.

CONCLUDING REMARKS

I have covered advances in knowledge about the peripheral optics of the human eye over the last 200 years, including refraction and higher-order aberrations, with some consideration of the role that peripheral refraction might play in the development of myopia. I have briefly mentioned current and future work. Much remains to be done!

You may have noticed that I have referred to a few of the great people with whom I have worked over the last 30 years. Interacting with such people is the most rewarding part of a research or professional career, and it is a pleasure to give a fuller list of their names below.

Lucy Ma, Jim Pope, Nicola Pritchard, Dion Scott, Katrina Schmid, Neil Strang, Lawrence Stark, Larry Thibos, Joanne Wood and Russell Woods. I thank my wife Janette for her wonderful support over 34 years.

Figure captions

Figure 1. The image surfaces of the human eye according to Thomas Young, with annotation to make the numbers and letters clearer. See text for explanation of the numbers. [similar to JV paper, mark retina]

Figure 2. Examples showing the classification of refraction patterns of Ferree et al. (Types A-C) and Rempt et al. (Types I-V) along the horizontal visual field. H and V indicate refraction in horizontal and vertical directions. Error bars indicate standard deviations of three measurements with a Hartmann-Shack sensor instrument. The symbols indicate the representation of the patterns in Figure 4 of the Rempt et al. paper. T and N indicate temporal and nasal sides, respectively, of the visual field. Note that not all refraction patterns fit neatly into these categories and are sometimes a mixture of the different types.

Figure 3. Examples of peripheral refraction from Figure 2 according to the M, J_{180}, J_{45} format, in which the mean sphere M, horizontal/vertical astigmatism J_{180} and oblique astigmatism J_{45} are related to conventional sphere S, cylinder C and axis θ by $M = S + C/2$, $J_{180} = -C/2\cos(2\theta)$ and $J_{45} = -C/2\cos(2\theta)$. Refractions along the horizontal and vertical visual fields are given by $H = S + C\sin^2\theta$ and $V = S + C\cos^2\theta$ or by $H = M + J_{180}$ and $V = M - J_{180}$.

Figure 4. Possible scenario for the development of myopia: a) peripheral focus in front of a flat retina and behind steep retina in an emmetropic eye, b) growth of the eye, with a steep retina, to become myopic, and c) spectacle or contact correction causes the peripheral focus to again be behind the retina and continue growth of the eye. Based on Figure 1 of Atchison et al.[21]).

Figure 5. Dimensions of eyes as a function of refractive error in young adult eyes for a) length, b) height, and c) width. Based on Figure 3 of Atchison et al.[20]

Figure 6. Mean refraction for different refraction groups as a function of visual field position for a) horizontal, and b) vertical visual fields. Errors bars are standard errors of means. Legends give central refraction range and number of people in each group. Based on Figure 1 of Atchison et al.[22]

Figure 7. Peripheral refraction in a) an uncorrected 5.5 D myope, and b) a LASIK patient who was 6 D myopic before surgery. Error bars are standard deviations. Based on Figures 2 and 3 of Ma et al.[14]

Figure 8. Peripheral refraction a) before, and b) after 2 weeks overnight wear of an orthokeratology lens. Errors bars are standard deviations. Based on Figure 3 of Mathur & Atchison[61].

Figure 9. Selected aberration coefficients across the visual field for one subject (5 mm pupil). Superior, inferior etc are referenced to the visual field. Scale is in micrometers. Note that the aberration coefficient scales vary between coefficients. Based on Figure 2 of Mathur et al.[56]

Figure 10. Higher order wave aberration maps at different positions in the visual field for groups of a) myopes, and b) myopic LASIK patients (5 mm pupil). Many of the maps for the LASIK group are reversed in appearance compared with their corresponding maps for the myopic group. This is due to the corneas in the myopes having prolate corneas (flattening

away from the centre), whereas the LASIK patients have oblate (steepening) corneas. Based on Figure 2 of Mathur et al.[60])

Figure 11. Design of a lens to correct peripheral refraction for one subject(with kind permission from Carl Zeiss Vision).
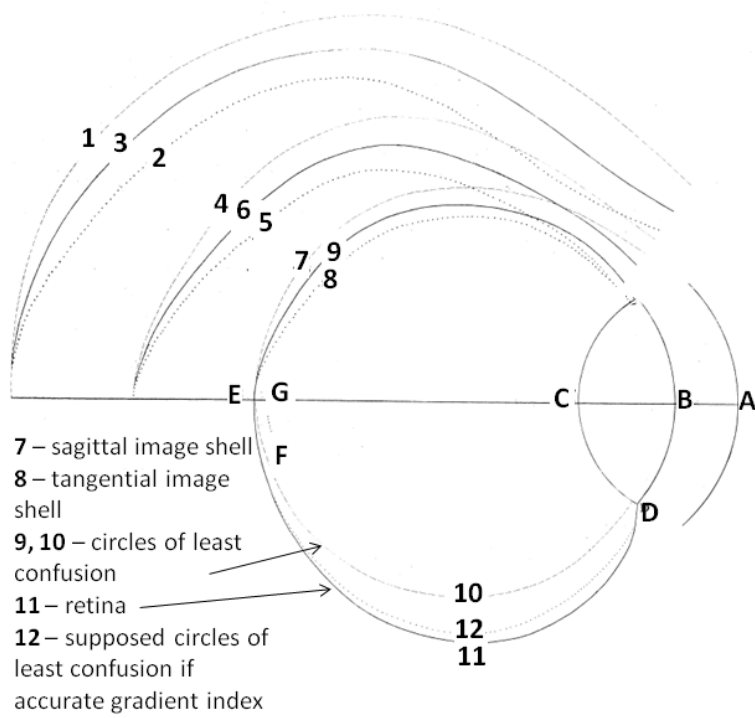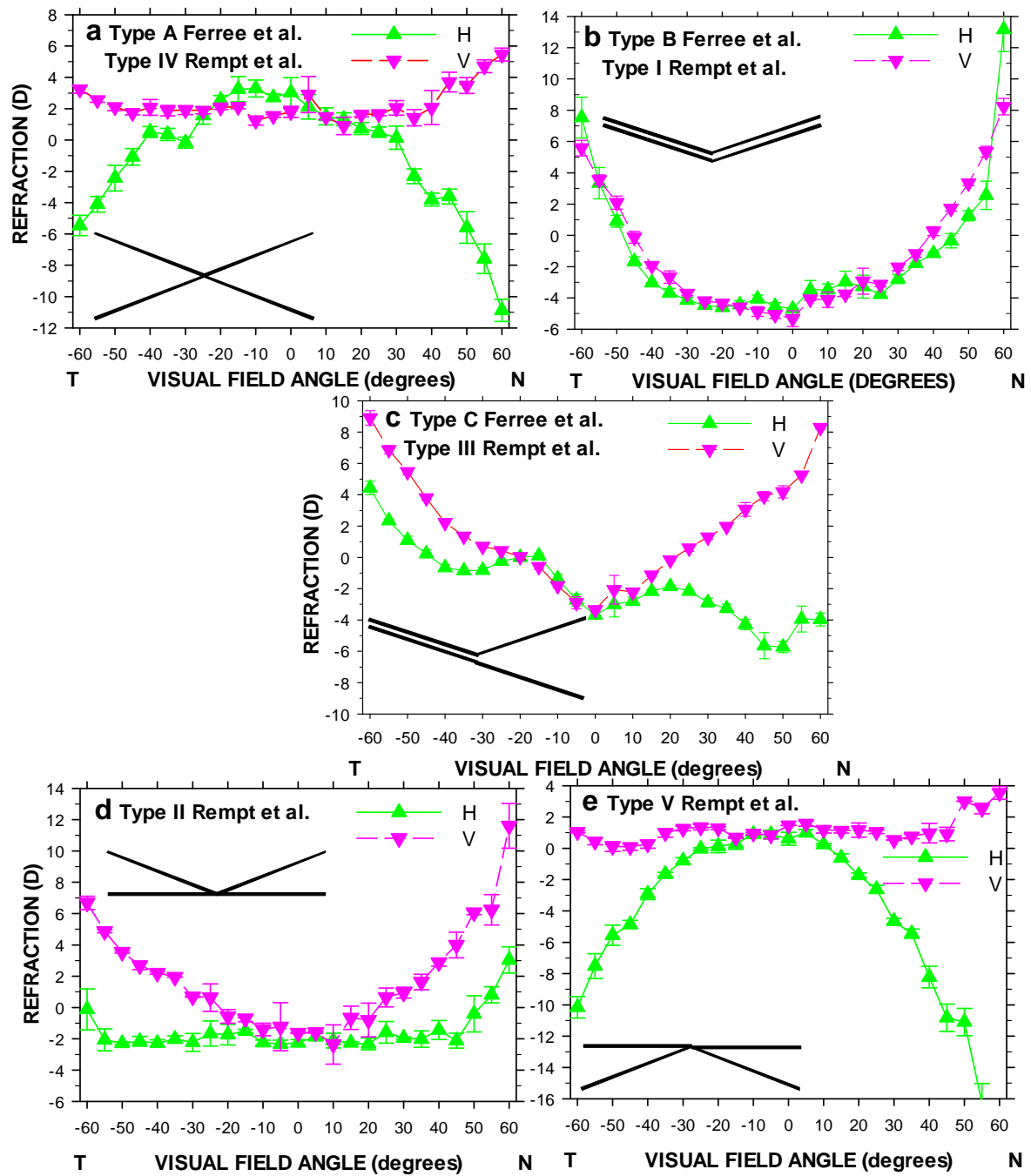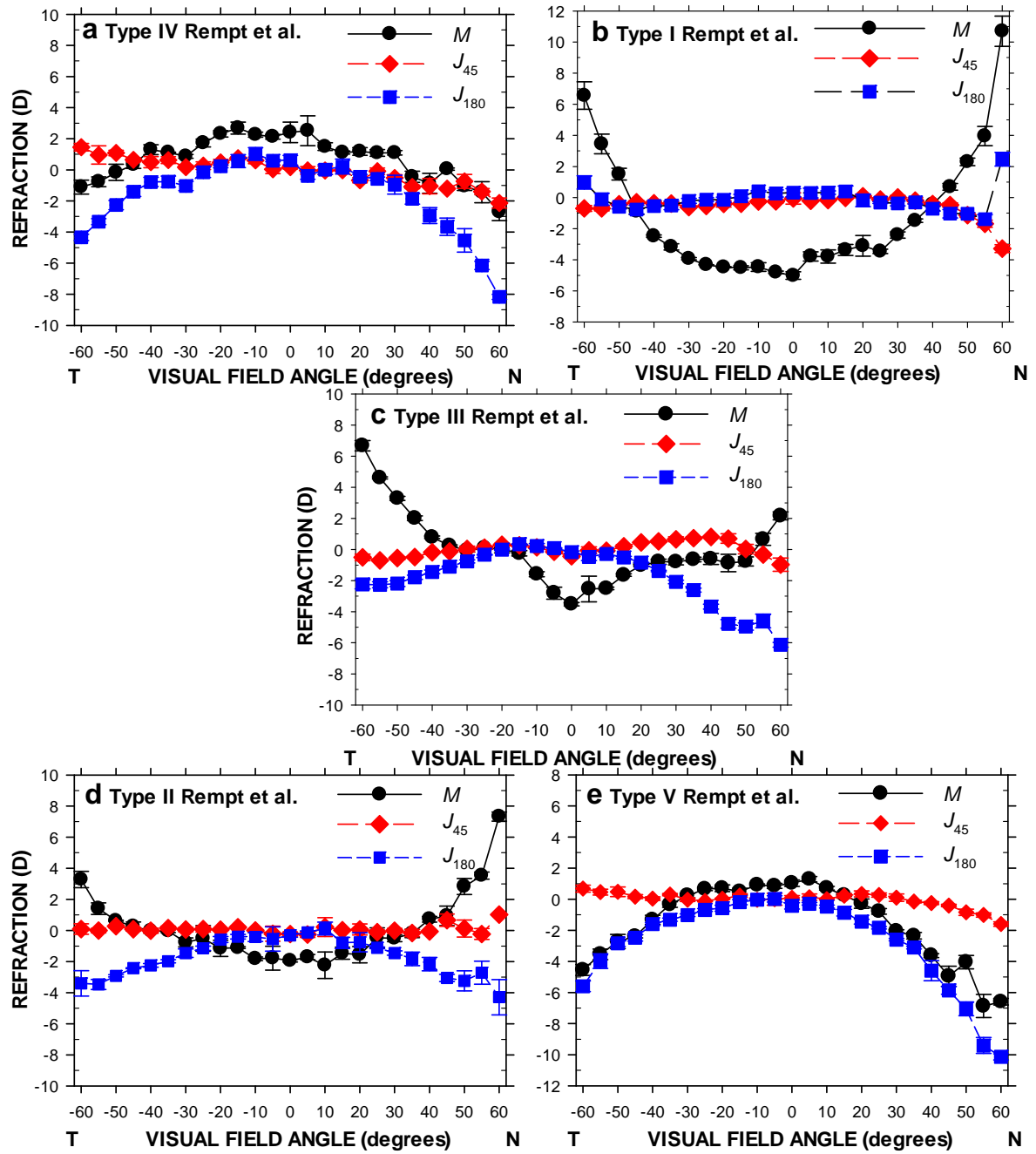
Figures

7 – sagittal image shell
8 – tangential image shell
9, 10 – circles of least confusion
11 – retina
12 – supposed circles of least confusion if accurate gradient index

Figure 1

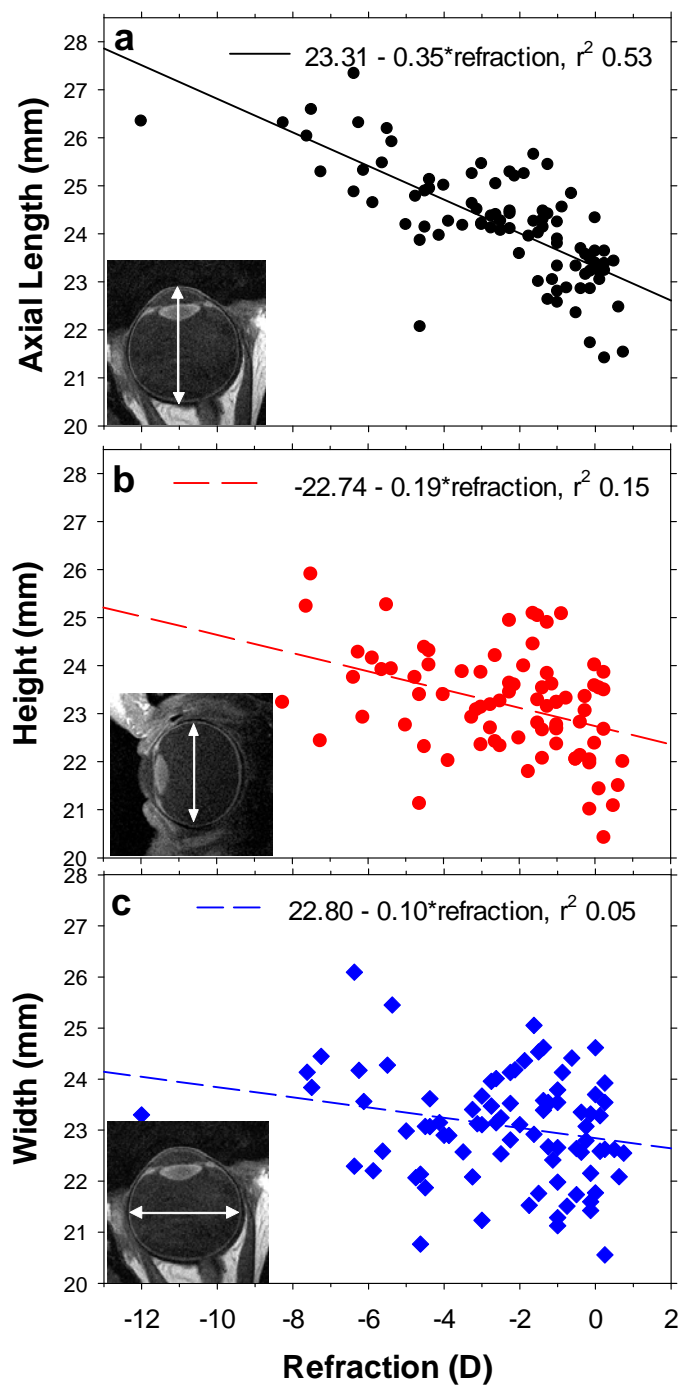**Figure 2**

Figure 3

a

steep retina

flat retina

b

c
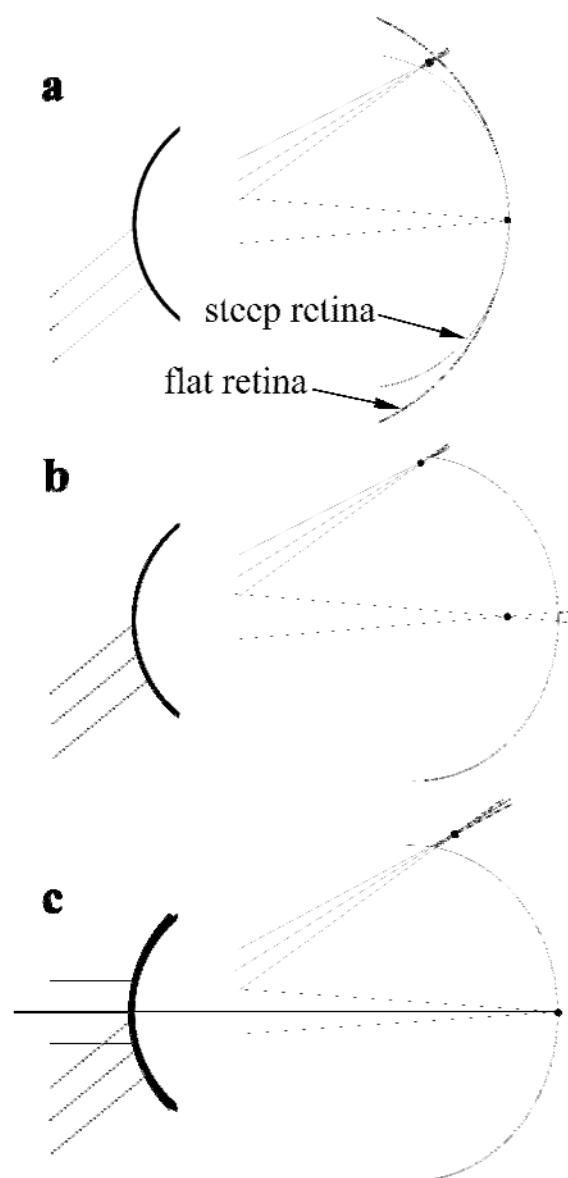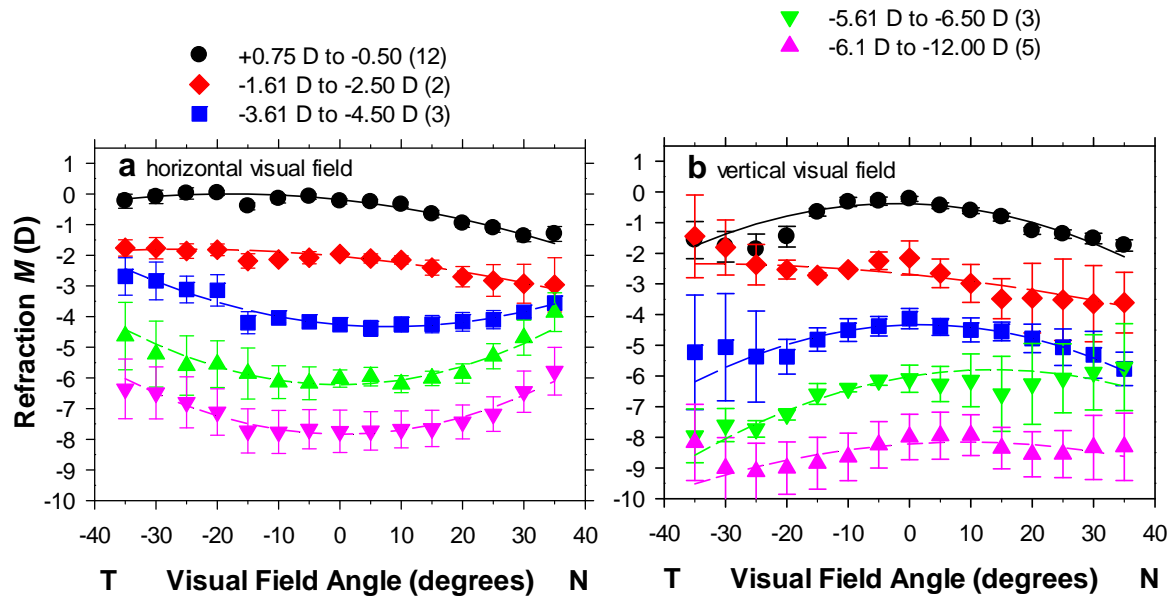
Figure 4

Figure 5

Figure 6
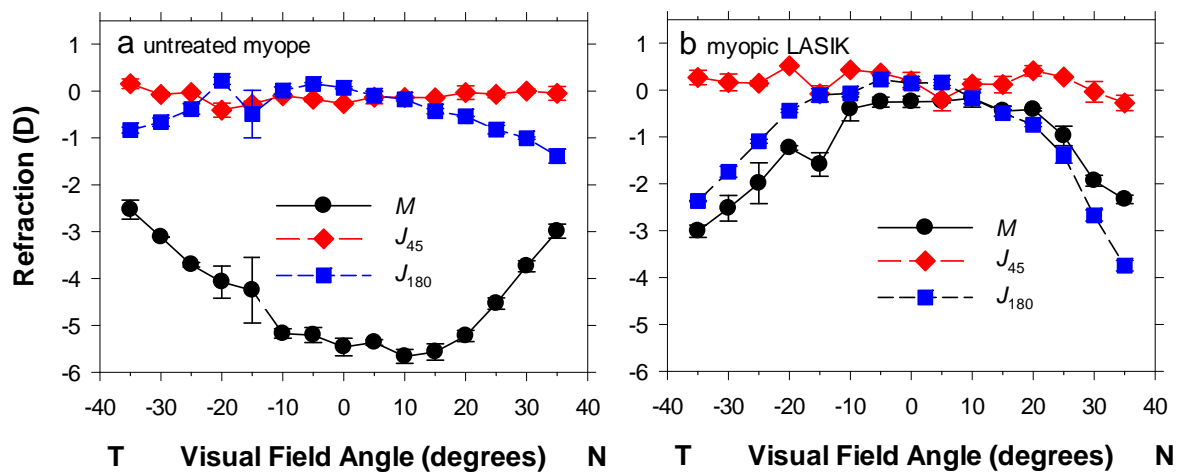
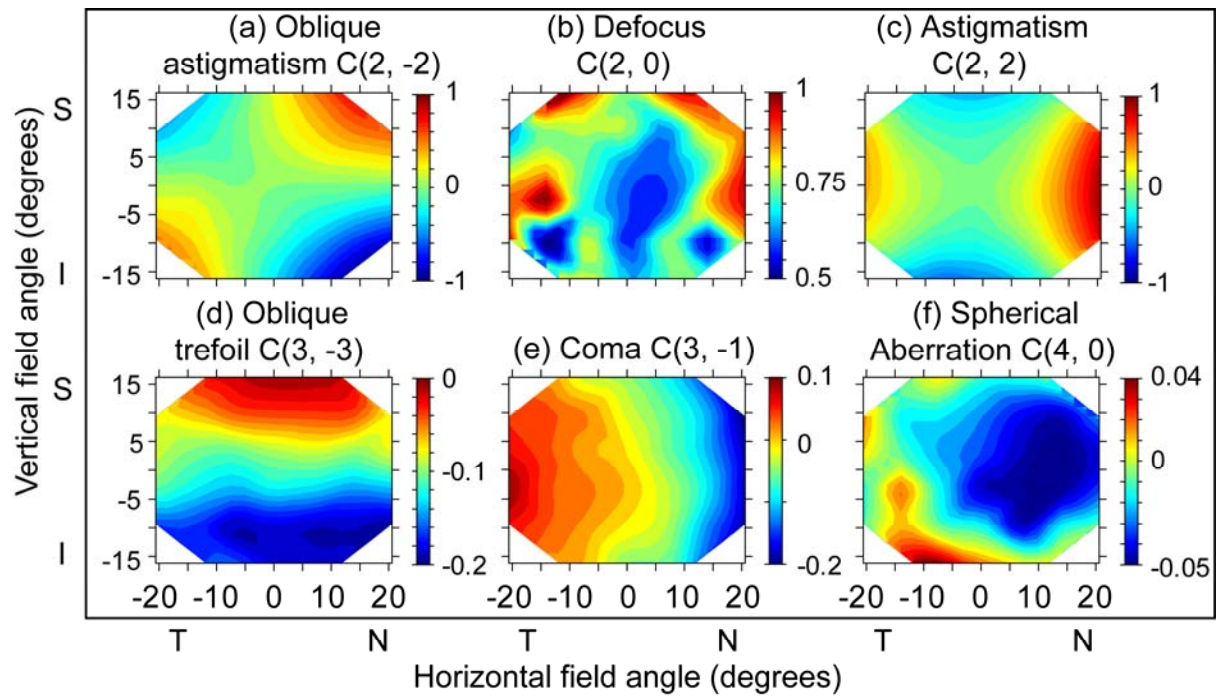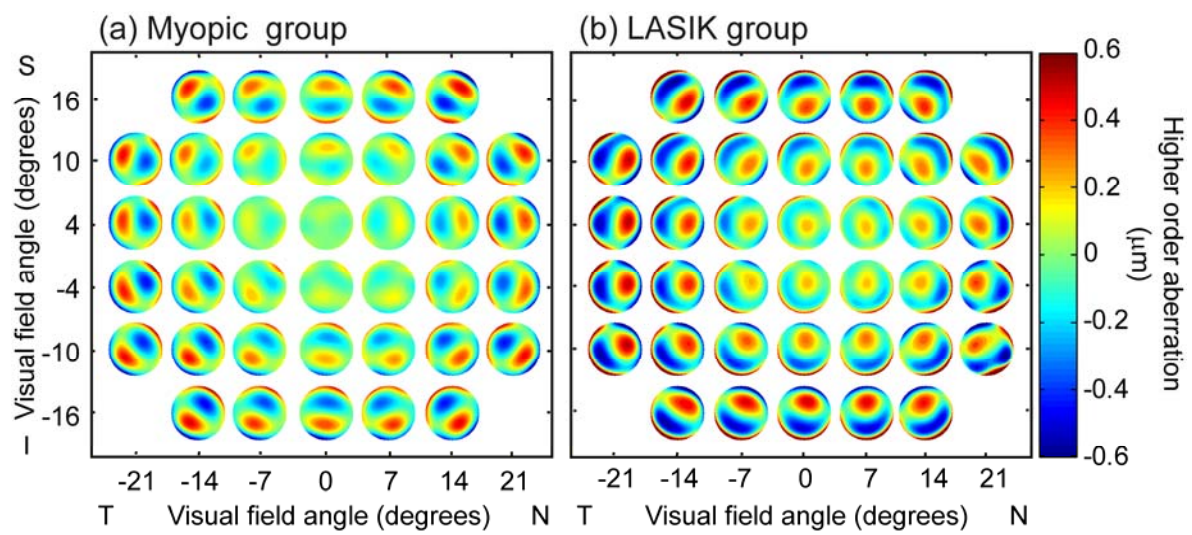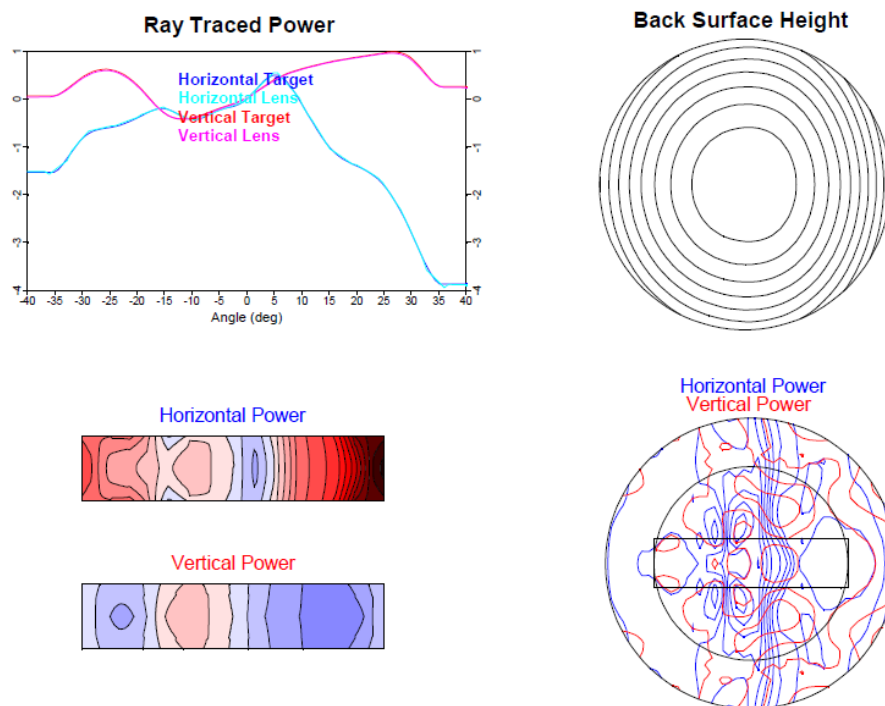Figure 7
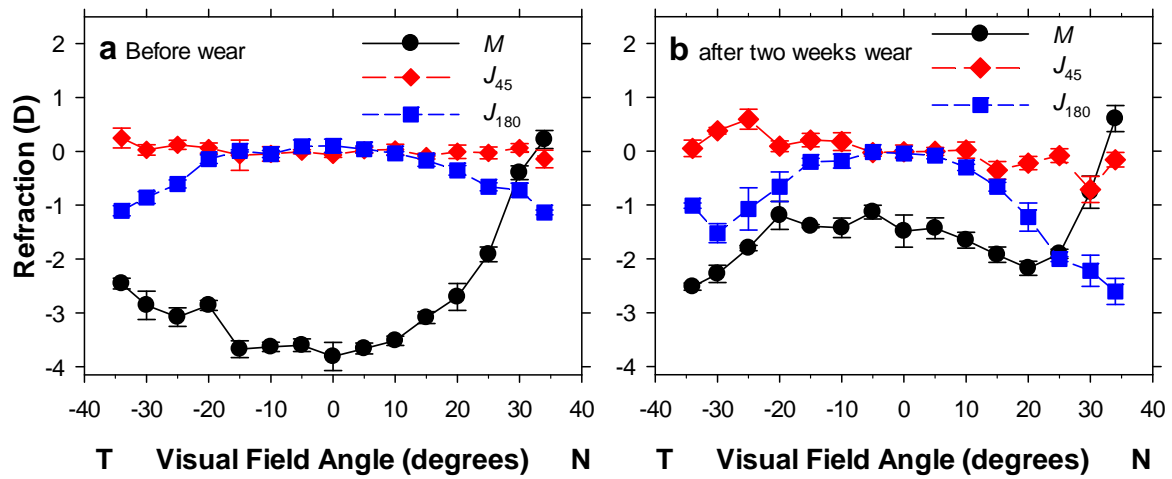
Figure 8

Figure 9

Figure 10

Figure 11

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