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Peripheral astigmatism in emmetropic eyes

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Summary

The long-term aim of the work introduced here is to investigate the influence of off-axis aberrations on human vision, especially for subjects with a large central scotoma. The latter use their peripheral vision in spite of its poor off-axis optical quality, and a correction of the off-axis aberrations might be of great assistance. The eccentric fixation angles used by these subjects can be up to 20–30°. In this initial study we have measured oblique astigmatism, the major off-axis aberration, in 20 emmetropic eyes in 10° steps out to 60° nasally and temporally using a 'double pass' setup. The results show very large individual differences and the oblique astigmatism also varies from nasal to temporal side. In an off-axis measurement angle of 30° the astigmatism varied between subjects from 1 to 7-D, with a mean astigmatism of about 4-D on the nasal side and about 1.5-D lower on the temporal side. At 60° temporally, the mean astigmatism was 7-D. At 60° nasally, all subjects had astigmatism larger than 8-D and the mean astigmatism was 11-D. The results indicate that any attempt to correct the off axis astigmatism in an eye with central scotoma cannot be based on central refraction; instead, individual measurements are necessary. © 2001 Published by Elsevier Science Ltd on behalf of The College of Optometrists.

Introduction

The quality of the optical image in the human eye outside the area of central vision has, so far, been less studied than the central visual quality. The reason for the relatively low interest in the peripheral optics of the eye is that for healthy eyes peripheral vision is considered to be of less importance. The eye is by nature optimised for central vision. Most people use peripheral vision mainly for orientation and motion detection with fewer demands on image quality. However, if central vision is lost, i.e. there is a central scotoma, any improvement of the peripheral visual function is most valuable. The eccentric fixation angles used in these cases can be up to 20–30°. Age-related macular degeneration (ARMD) is the most common cause of central scotoma, and with the ageing population there is an increasing number of people with visual handicaps related to ARMD. In the age group of 70 and older, about 30% have some type of agerelated defect in central vision, which for some of them, results in a total central scotoma. About half of them are sufficiently visually impaired that they can be regarded as low vision patients (The Lighthouse, 1994). There are also a group of younger subjects with retinal problems, like Stargart's disease or opticusatrophy, that lead to central scotomas. The long-term goal of this project is to help patients with central scotoma to use their remaining vision in the best possible way. We want to investigate if it is possible to improve their visual function by correcting the off-axis aberrations.

Background

Many authors have investigated the optical limitations and aberrations of the human eye. Already in 1801, Thomas Young (Young, 1801) discovered that there is astigmatism in oblique angles in all-human eyes. It is now well known that the aberrations greatly increase for objects located off-axis, and that astigmatism and defocus are the most important aberrations. In the present work we have measured the off-axis refraction by using double-pass measurements in an optical laboratory on a group of emmetropic subjects. The future purpose for this study is to test if any improvement of

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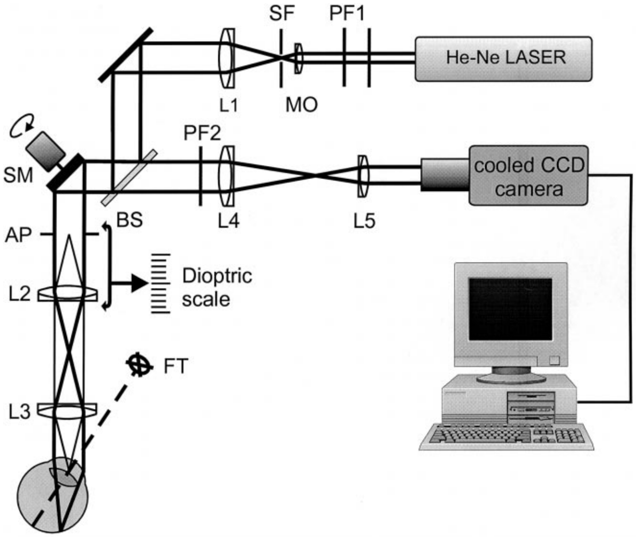

Figure 1. The experimental set-up for double-pass measurements of the off-axis astigmatism.

visual functions can be measured in subjects with central scotomas by correcting these aberrations.

Ferree and colleagues (Ferree *et al*., 1931, 1932, 1933) studied oblique astigmatism using a Zeiss parallax optometer and Millodot (1981) used a Hartinger optometer. We have tried to use a Hartinger optometer to measure oblique astigmatism and found this to be most difficult because the results are not reproducible. Retinoscopy was used (Rempt *et al*., 1971) to assess the off-axis astigmatism. They used a method called 'double sliding-door effect' to interpret the reflex. Technically, peripheral retinoscopy is complicated and we found it impossible to get reliable results with this method. A quite common situation is when the retinoscope reflex in the peripheral parts of the pupil moves 'against' while the central part of the reflex has a 'with' motion. In central retinoscopy this corresponds to spherical aberration but in the periphery it can be caused by a variety of aberrations. Because of this we have found this method to be unreliable and we question that the 'double sliding-door effect' can be used in clinical practice.

There are also many previous works that have used mathematical models of the eye for theoretical predictions (Lotmar and Lotamar, 1974; Pomerantzeff *et al*., 1984; Dunne *et al*., 1987a; Smith and Lu, 1991). We have also tried this by using commercial ray-tracing software, but there is a lack off sufficient information on the off-axis structure of the eye to create a good mathematical model for the peripheral vision. Many eye models have been developed for a restricted set of conditions (Wang *et al*., 1983; Liou and Brennan, 1997; Wang and Thibos, 1997; Escudero-Sanz and Navarro, 1999). Work done in modelling by Dunne and colleagues show that the off-axis astigmatism is virtually unchanged in Gullstrand's model eye, when the lens is removed (Dunne *et al*., 1987b). This is in conflict with experimental reports stating that aphakic eyes have less off-axis astigmatism than phakic eyes (Millodot, 1984), showing that the lens contributes to the oblique astigmatism. Models inevitably only reflect the behaviour of the 'average' eye, whereas individual differences and their influence on the visual ability in the peripheral visual field are of great interest.

More recently some researchers have measured refraction and optical performance in the peripheral field with modern techniques. The double-pass-method has been used for off-axis measurement in several works (Jennings and Charman, 1978, 1981, 1997; Navarro *et al*., 1993; Guirao and Artal, 1999). However, in these references only 3–4 eyes have been measured with a variety of refractive (on-axis) errors. In some studies MTF measurements have been performed together with corrections of peripheral defocus and astigmatism (Artafl *et al*., 1995a).

Methods

The major off-axis aberration in the eye for large field angles is astigmatism. Since macula degeneration is a disease in the retina, it is not obvious that it is connected to optical anomalities of the eye. As a background material for future studies on low vision patients we chose emmetropic, healthy eyes because they are easy to measure. We have measured astigmatism and curvature of field in 20 eyes with a double-pass method. The inclusion criterion for the selection of subjects was that the eye should not have a refractive error of more than ±0.5 dioptres in either sphere or cylinder. This is within the range of the normal classification of emmetropia. We screened all the subjects to include only those with normal visual function and a visual acuity of at least 1.0 (20/20 or 6/6). The subjects ages range from 20 to 45 years and the mean age was 28 years.

Apparatus

We used a double-pass apparatus (Santamaría *et al*., 1987) much similar to those used by others in peripheral measurements (Artal *et al*., 1995a; Guirao and Artal, 1999). *Figure 1* shows a schematic layout of the experimental setup. The light from a 10 mW He–Ne laser is focused to a point source by a spatial filter, SF, and collimated by lens L1. The collimated light is reflected by beam splitter BS ($R = 10\%$) and the diameter is controlled by the artificial pupil AP (3 mm in diameter), conjugate to the entrance pupil of the eye. Lenses L2 and L3 image the point source to the far point of the examined eye. By moving lens L2 together with AP, the image of the point source can be adjusted within the range of -10 to D refractive errors. The optics of the eye then focuses the light to an aberrated image on the retina. The diffusely reflected light from the retina is imaged via a 4× telescope (L4 and L5) onto a

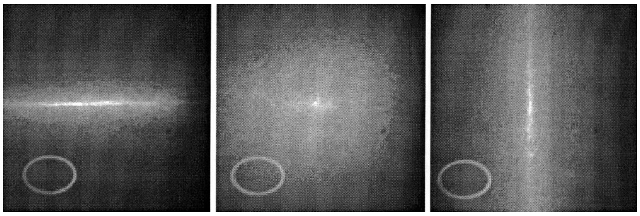

Figure 2. The two line foci and the circle of least confusion as recorded by the CCD-camera. The small elliptic shape is caused by a reflection from one of the lenses.

cooled scientific-grade CCD camera. *Figure 2* shows typical CCD-images of the two line-foci and the circle of least confusion. To minimise the problem of speckles, a spinning mirror SM (3000 rpm) is used to move the spot in a circle (0.2 arc–min in diameter) on the retina during the exposure (about 250 ms) of the CCD. PF2 and PF3 are crossed polarisation filters to remove specularly reflected light from, e.g., the cornea. Polarisation filter PF1 was rotated to adjust the power of the laser so that 3 μw entered the eye during the measurements. The subject was exposed to laser light for a maximum of 5 min for every measurement angle. This gives an exposure of about 1 mJ at each location of the retina, which is almost two orders of magnitude below safety standards.

No cycloplegic drugs were used. The subject's head was fixed by use of a well fitting bite bar permitting rotation of the head around a vertical axis through the centre of the pupil. This allowed a rapid change of measurement angle while maintaining the centration of the artificial pupil. The centration of the pupil was monitored by an external CCD-camera. During the measurements the subject looked straightforward at a diffusely illuminated fixation target that moved along with the rotation of the bite bar. The fixation target was imaged to infinity by a lens system to relax the accommodation. The position of the two line foci were subjectively defined by the operator as the two most narrow light distributions in the CCD image while manually moving lens L2. The actual measurement of the position of the two line foci and the circle of least confusion took about 1 min for every angle.

Spherical and plano-cylindrical lenses of known powers were used to test the system for systematic errors. The test lenses where placed at the pupil plane and the movable block (L2 and AP in *Figure 1*) was adjusted so that the laser beam was focused 2 m after the test lenses. This procedure was then repeated several times for spherical test lenses with focal powers up to ±10-D and plano-cylindrical test lenses with focal powers up to ±3-D. The repeatability and linearity was found to be within ±0.2-D over the full range. The position of the block and the distance that the block needed to be displaced in order to achieve a certain focal power at the corneal plane corresponded to theoretically calculated values.

It should be noticed that the refraction is measured at the pupil plane and not at the spectacle plane.

Measurements

We measured each patient at angles from 60° nasally to 60° temporally in steps of 10°. For each measurement angle we measured five different parameters. We measured the refraction for the circle of least confusion and for each one of the two line-foci we measured the refraction and the orientation of the line. Of these five measurements, three were used for further calculation; the refraction of the two line-foci and the angle of the most hyperopic line. The position of the circle of least confusion and the angle of the most myopic line were only used for comparison. In some subjects the angle between the two line foci was different from 90°. In other subjects, the circle of least confusion was significantly different from the midpoint of the two line foci. At large measurement angles, the circle of least confusion actually showed a systematic drift from the midpoint towards the most hyperopic line focus. These anomalies probably arise from significant contributions from other aberrations.

One particular subject was measured on eight different occasions and the standard deviation was calculated for each angle separately. We found the mean value, over all angles, of the standard deviation of the measured astigmatism to be 0.60-D. The difficulty in taking precise readings varied between test subjects; this subject was considered representative, being somewhere in the middle on the difficulty scale.

Results

The refraction of the focal lines as a function of the measurement angle varies greatly between different test subjects. For example, at a measurement angle of 60°, the standard deviation of the refraction of the more myopic line is close to 4 dioptres. For each individual eye, however, the measured refraction, as a function of measurement angle, normally shows a smooth curve with only small deviations from the general shape of the curve.

In *Figure 3* the refraction for the two line foci and the circle of least confusion is plotted as a function of the measurement angle for three different subjects. For the subject in *Figure 3a* the curve is growing astigmatism in higher eccentricities, almost symmetrical on nasal and temporal sides. The subject in *Figure 3b*, on the other hand, has a much lower peripheral astigmatism, but with a marked hyperopic shift in larger angles. *Figure 3c* shows an example of a subject with a large nasal-temporal asymmetry.

In order to analyse the results statistically we used astigmatic decomposition, mapping the refraction of the two line foci and the angle at the most hyperopic line to M, X and Y co-ordinates. M is the spherical equivalent,

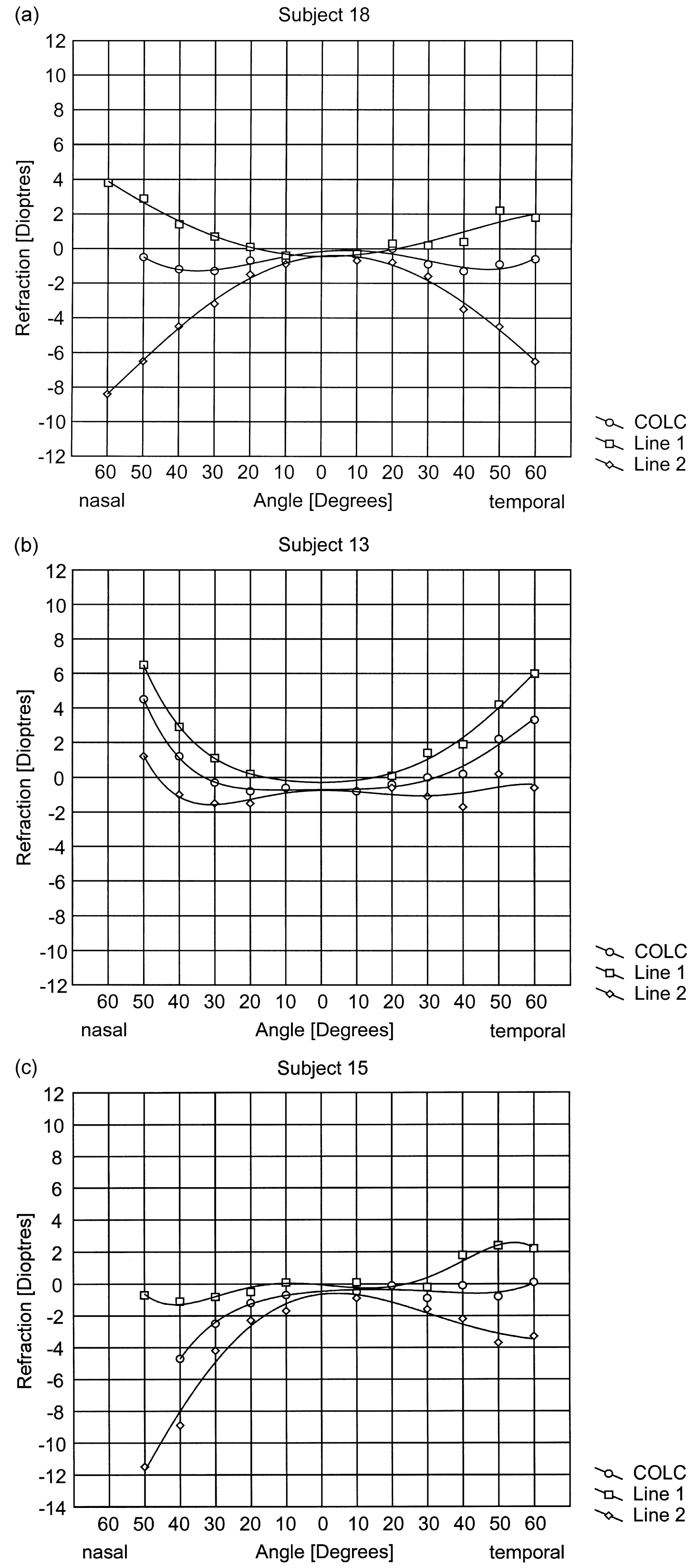

Figure 3. The refraction for the two line foci (line 1, line 2) and the circle of least confusion (COLC) plotted as a function of the measurement angle for three different subjects. The lines connecting the data points are only to guide the reader's eye.

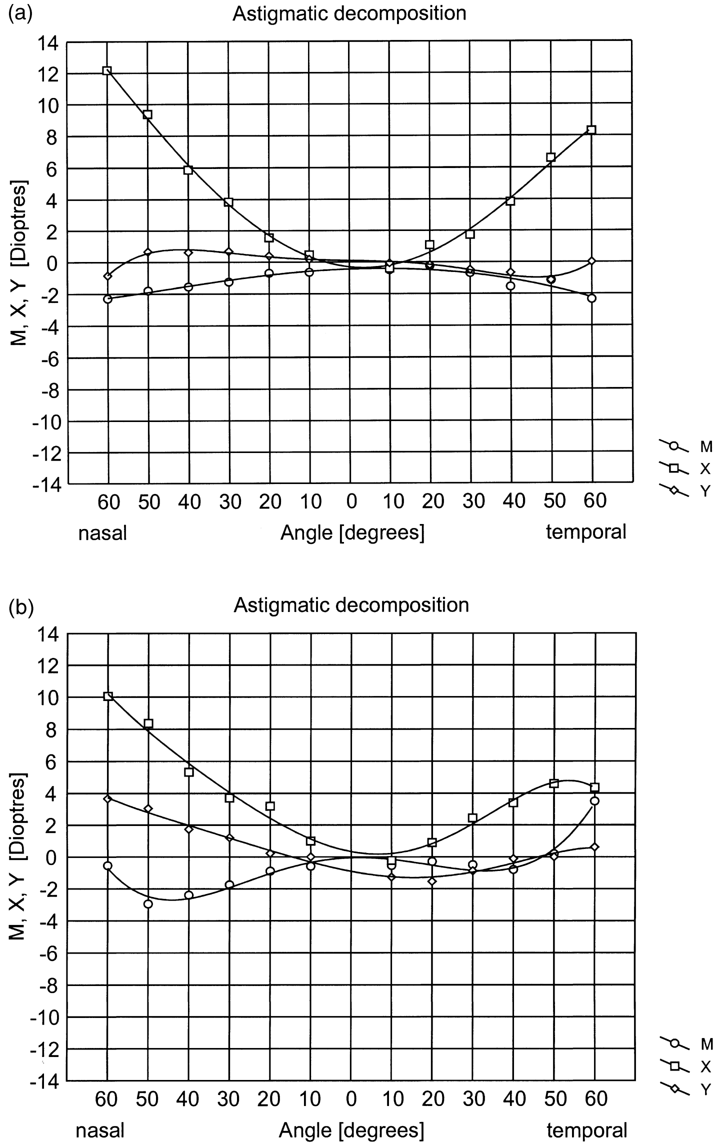

Figure 4. Astigmatic decomposition of the measured data for two subjects. (a) shows a normal situation with an induced astigmatism mainly in the vertical and horizontal direction ($X - D$). In (b) the astigmatism in 45° and 135° ($Y - D$) is as large as 4-D at 60° nasally. This corresponds to a rotation of the cylinder axis of about 10°.

which is the mean refraction of the two line foci. X is the with/against the rule component of the astigmatism (often written as $C00$) which is calculated from $C * \cos(2v)$, where C is the magnitude of the cylinder and v is the angle of the cylinder axis. Similarly, Y is the oblique component of the astigmatism (often written as $C45$), calculated from $C * \sin(2v)$. The new set of co-ordinates (M, X, Y) creates an additive vector space that is well suited for statistical purposes. More information on astigmatic decomposition can be found in textbooks on visual optics (Rabbetts, 1998).

Contrary to the case of a rotationally symmetric lens system, the astigmatism caused by off-axis fixation within the horizontal plane is not always aligned 'against the rule'. For some subjects, the astigmatism induced along the 45 or 135-° meridians (the Y co-ordinate) was as large as four dioptres. *Figure 4b* shows such an example.

Mean astigmatism and spherical error for all test subjects

Figure 5a shows the mean and the spread of the 'against the rule astigmatism' (X-value) for all test-subjects. At a measurement angle of 30° nasally the mean astigmatism is about 4-D and about 1.5-D lower on the temporal side. At larger angles the astigmatism increases dramatically and significantly more so for measurements made on the nasal side of the fixation point. For example, at 60° temporally,

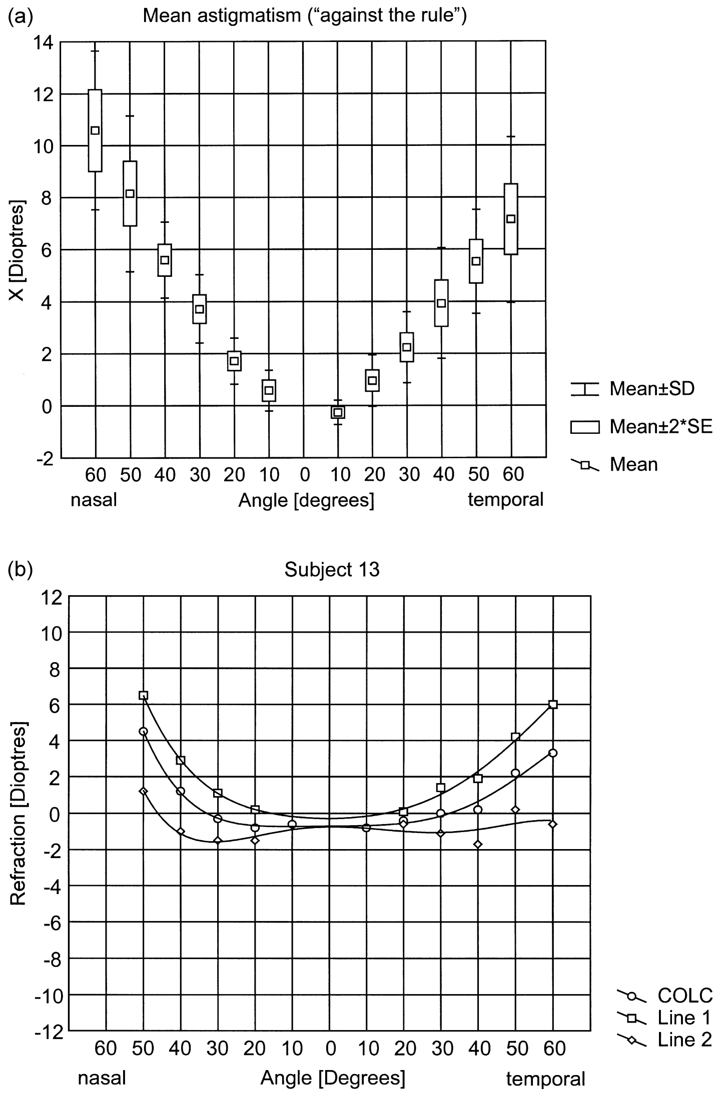

Figure 5. (a) the mean 'against the rule' astigmatism (*X*) for all test-subjects. (b) the mean value of the spherical equivalent (*M*) for all test-subjects. The small squares show the measured mean value as a function of the measurement angle. The larger rectangles show the confidence interval of the mean value at a 95% confidence level. The bars show the standard deviation (SD) of the individual data.

the mean astigmatism was 8-D. At 60° nasally, all subjects had astigmatism larger than 8-D and the mean astigmatism was 11-D. The angle for minimum astigmatism is shifted towards the temporal side due to the angle between the eye's optical axis and the visual axis (angle 'alpha'). Near the minimum we measure a slight 'with the rule' astigmatism.

The mean spherical refractive error of all subjects is shown in *Figure 5b.* For measurement angles up to about 40° there is a clear myopic shift towards the periphery. At larger angles there is an opposite effect leading to lower myopia or even hypermetropia in the far periphery. *Table 1* shows all the mean values of the measured peripheral refraction (*M*, *X* and *Y*) in a table format.

Discussion

As expected, the results show an increased astigmatism with increased fixation angle for most eyes. This is in agreement with other studies. From the present study it is not possible to distinguish groups of subjects with typical behaviour of astigmatism and defocus in the way described in the early papers about off-axis astigmatism (Ferree et al., 1933; Millodot, 1981; Rempt *et al.*, 1971; Lotmar and Lotmar 1974). We found large individual differences between all subjects and in some cases the differences were dramatic (*Figure 3*). This shows that there are the same or even larger individual differences in the 'off-axis' aberrations of the human eye as for

Table 1. Mean values of the astigmatic decomposition of the peripheral refraction. *M* is the spherical equivalent, which is the mean refraction in the two principal meridians. *X* and *Y* are the with/against the rule component and oblique component of the astigmatism, respectively

	Nasal					Angle				Temporal		
	60°	50°	40°	30°	20°	10°	10°	20°	30°	40°	50°	60°
X	10.6	8.2	5.6	3.7	1.7	0.6	− 0.3	1.0	2.2	3.9	5.5	7.1
Y	1.2	0.5	0.7	0.3	0.3	− 0.3	− 0.1	− 0.5	− 0.3	− 0.3	− 0.3	− 0.6
M	− 0.9	− 2.2	− 2.2	− 2.0	− 1.2	− 0.9	− 0.4	− 0.4	− 0.6	− 1.1	− 0.8	− 0.1

normal, on-axis, and refractive errors like myopia, hypermetropia and astigmatism.

In some cases, especially the older subjects (45 years) we have seen a marked influence of other aberrations like coma. The line-foci then looked more like a cross (Guirao and Artal, 1999; Williams *et al*., 1997; Artal *et al*., 1995b). The number of these cases is too small to say if this phenomenon is a function of age or if is just another individual difference.

It would seem reasonable to believe that the peripheral refraction of two, otherwise normal, emmetropic eyes would be similar. From the present study, however, we now know that the individual differences in the peripheral refraction are so large that we have to measure and correct each subject with central scotoma individually. The measured amount of astigmatism in the mid-range eccentricity is so large for several subjects that it can have an impact on the peripheral visual performance.

In mean values, the results we found in this study generally show a larger value for the peripheral astigmatism compared to a recent compilation of earlier measurements (Atchison and Smith, 2000). This difference is probably a result of the different measurement techniques used. Furthermore, our measurements show a significant nasal-temporal asymmetry in the oblique astigmatism with the point of minimum astigmatism shifted towards the temporal side. This is in good agreement with previous work and the shift in the minimum has been shown before (Dunne et al., 1993). We also see a relevant myopic shift of the spherical refractive error, especially in the mid-periphery, which has not been pointed out before.

Contrary to other published papers that have used the double-pass method to measure peripheral astigmatism we have included only emmetropic eyes. This makes our data useful also for wide-angle eye modelling with a correct description of the oblique astigmatism in the average emmetropic human eye.

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