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Peripheral refraction along the horizontal and vertical visual fields in myopia

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Abstract

Peripheral refractions were measured to 35° eccentricity using a free-space autorefractor in young adult emmetropic and myopic subjects. Refractions were measured along horizontal and vertical visual fields for 116 subjects and a 43 subject subset, respectively. Along the horizontal visual field, peripheral myopic shifts in spherical equivalent M of emmetropes changed to relative hypermetropic shifts in the myopes, there were temporal-nasal asymmetries of 90° to 180° astigmatism J_{180} which decreased as myopia increased, and 45° to 135° astigmatism J_{45} was linearly related to field angle. Along the vertical visual field, both peripheral myopic shifts in peripheral M and J_{180} asymmetry were unaffected by magnitude of myopia, and J_{45} changed at three times the rate as for the horizontal visual field. Myopia has more effect on peripheral refraction of adult eyes along the horizontal than along the vertical visual field. The peripheral variations in refraction match well what is known about the shapes of emmetropic and myopic eyes.

Keywords: Astigmatism; Myopia; Optics of the human eye; Peripheral refraction; Refractive error

1. Introduction

Interest in peripheral refraction has increased recently because of the idea that defocus in the retinal periphery might influence the development of myopia. Hoogerheide, Rempt, and Hoogenboom (1971) noted that some emmetropic and hypermetropic trainee pilots developed myopia while others did not. The pilots who went on to develop myopia, in general, had peripheral refractive errors that were more characteristic of those observed in already myopic individuals than those who were emmetropic (and stayed emmetropic) or hypermetropic. The pilots who developed myopia had relative hypermetropia rather than relative myopia in the periphery. It has been hypothesized that, if an emmetropic eye has a relatively hypermetropic periphery, this could stimulate compensating eye growth and that this signal would persist even if the central visual field becomes myopic (Wallman & Winawer, 2004).

Several studies have reported differences in the peripheral refraction patterns of emmetropes, hypermetropes and myopes (Atchison, Pritchard, White, & Griffiths, 2005; Logan, Gilmartin, Wildsoet, & Dunne, 2004; Love, Gilmartin, & Dunne, 2000; Millodot, 1981; Mutti, Sholtz, Friedman, & Zadnik, 2000; Rempt, Hoogerheide, & Hoogenboom, 1971; Schmid, 2003; Seidemann, Schaeffel, Guirao, Lopez-Gil, & Artal, 2002). Collectively these published data suggest that emmetropes and hypermetropes usually have relative myopic shifts into the periphery, which are greater for the latter, while myopes usually have relative hypermetropic shifts. All but two of these studies (Schmid, 2003; Seidemann et al., 2002) investigated refraction changes only along the horizontal visual field.

Information on refractive changes in both the horizontal and vertical visual fields is of particular interest because of the more complete regional refractive picture it provides. Seidemann et al. (2002) measured refraction, for 31 adults, out to 22° along several meridians and Schmid (2003) measured refraction, for 63 children (7–15 years), along the vertical visual field as well as along the horizontal visual field.

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Seidemann et al.'s (2002) results with the PowerRefractor (a pupillometry based instrument) are different from those of other studies (Love et al., 2000; Millodot, 1981; Mutti et al., 2000) in that they found peripheral myopic shifts in all refractive groups, although consistent with other studies these shifts were less for the myopic group than for the emmetropic and hypermetropic groups. Along the vertical visual field, they found more myopia in the inferior visual field (superior retina) than along the superior visual field (inferior retina). Schmid (2003) measured refractions at fixation and at 15° nasally, superiorly, inferiorly and temporally, but the last position was not analysed because of large variability in the data associated with the optic disc. The author used an autorefracting instrument—a Shin Nippon NVision K5001 (Davies, Mallen, Wolffsohn, & Gilmartin, 2003) which is the "successor" to the Shin-Nippon SRW-5000 used in this study (Mallen, Wolffsohn, Gilmartin, & Tsujimura, 2001). A group of 10 children with low myopia had a small myopic refractive shift nasally, but showed relative hypermetropic shifts inferiorly and superiorly, In contrast the emmetropic ($n = 21$) and hypermetropic ($n = 18$) children had relative myopic shifts along all three meridians.

In light of recent findings on the sizes and shapes of adult emmetropic and myopic eyes, reports of differences in peripheral refractions along the horizontal and vertical visual fields are not surprising. Amidst considerable inter-individual variation, Atchison et al. (2004) found that length, height and width of eyes increase as myopia increases in the approximate ratio 3:2:1, such that the increases in length corresponded approximately to that required for the development of myopia. The shape of the posterior retina surface can be well modelled by asymmetrical ellipsoids for which the width semi-diameter changes only slightly in comparison to increases in vertical semi-diameter as myopia increases (Atchison, Pritchard, Schmid et al., 2005).

There has been no comprehensive investigation of the relationship of peripheral refractive errors in both horizontal and vertical visual fields to the on-axis refraction and what effect the degree of myopia has on this relationship. We report here a study in which peripheral refractions were determined along both horizontal and vertical visual field in emmetropes and in myopes (up to 12 D). Using vector analysis, we sought to determine whether the relative hypermetropic peripheral shift in myopic eyes that has been reported in the literature continues to increase as myopia increases, and how peripheral refraction profiles differ in horizontal and vertical visual fields.

2. Methods

This study followed the tenets of the Declaration of Helsinki and received ethical clearance from the Queensland University of Technology's Human Research Ethics Committee. Informed consent was obtained from each subject after explanation of the nature of the study.

The study cohort comprised 116 subjects within the age range 18–35 years of which 74 (64%) were female. Ninety-nine (85%) and 17 (15%) subjects were of Causasian and Asian backgrounds, respectively. Subjects with >0.50 D of astigmatism, as measured by subjective refraction, or with a corrected visual acuity poorer than 6/6 in the test eye were excluded. Subjects were also excluded if they had any ocular disease, previous ocular surgery, or had intraocular pressures greater than 21 mm Hg in either eye. Right eyes were measured in 94% of cases. The left eye was used where it met the inclusion criteria and the refraction of the right eye was outside spherical or astigmatic limits (9 cases). A subset of 52 of these participants with emmetropia and myopia (up to 2.58 D) was used in a study on age and peripheral refraction along the horizontal visual field reported previously (Atchison, Pritchard, White et al., 2005). Refraction details of subjects are given in Table 1.

Non-cycloplegic refractions were measured along the horizontal and vertical visual fields in 5° steps out to 35°. Originally we intended to measure along the horizontal visual field only, but added the vertical visual field measurements after finding differences in horizontal and vertical dimensions of myopic eyes (Atchison et al., 2004). Consequently the horizontal visual field was assessed for all 116 subjects and the vertical visual field was assessed for 43 subjects. The Shin-Nippon SRW5000 autorefractor was used for measurements. Its use for horizontal measurements has been described previously (Atchison, Pritchard, White et al., 2005). It gives results in good agreement with those for a Canon R-1 autorefractor and those obtained using a Hartmann-Shack instrument (Atchison, 2003). Room illumination was adjusted as necessary to ensure that pupil sizes were at least 4 mm diameter.

For measurements along the horizontal visual field, five measurements of refraction were taken at each position, with subjects rotating their eyes to look at targets along a flat wall 3.3 m away. These targets were usually black crosses, with the subjects' task being to fixate at the centre of each cross. For most subjects the arms of the crosses provided adequate fixation cues, but bright LEDs were used for the higher myopes. For right eyes, fixation to a subject's right side corresponded to the nasal visual field (or temporal retina). Translation of the eye upon rotation required realignment of the pupil along the instrument axis. Averages of two complete data sets were taken. The instrument was aligned such that the alignment mire was maintained in clear focus over the centre of the pupil.

A similar procedure was used for the vertical visual field, but modifications were required because the vertical range of viewing angles through the instrument is restricted. We placed a light emitting diode 2.0 m above and slightly forward of the subject's head. An apparatus was designed to mount and rotate a microscope slide, in front of the eye, so that subjects could view the diode target by reflection. Alignment was carefully checked by ensuring that the diode was initially seen as superimposed upon a target viewed straight ahead through the beamsplitter. Comparisons we made showed that the presence of the beamsplitter did not affect refractions made when viewing this second target. The beamsplitter was then rotated about a horizontal axis in 2.5° steps to force eye rotations of 5° steps upwards or downwards to maintain fixation on the diode target. At some of the downwards

Table 1
Subject numbers and M (spherical equivalent) for the refractive correction groups

Refractive correction group	n	Total group ($n = 116$) M (D)	n	Subset ($n = 43$) M (D)
Emm. (+0.75 to −0.50)	32	0.02 ± 0.31	12	+0.06 ± 0.35
−1 D (−0.51 to −1.50)	24	−1.17 ± 0.24	8	−1.14 ± 0.33
−2 D (−1.51 to −2.50)	16	−2.12 ± 0.29	2	−1.94 ± 0.44
−3 D (−2.51 to −3.50)	12	−3.03 ± 0.28	7	−3.00 ± 0.19
−4 D (−3.51 to −4.50)	7	−4.25 ± 0.25	3	−4.08 ± 0.26
−5 D (−4.51 to −5.50)	7	−4.98 ± 0.35	2	−5.19 ± 0.27
−6 D (−5.51 to −6.50)	7	−6.09 ± 0.30	3	−6.08 ± 0.40
−8 D (−6.51 to −12.00)	11	−8.33 ± 1.53	6	−9.02 ± 1.77

Data are means ± SD, range in parentheses. Note that the total group took part in the horizontal visual field measures and the subset took part in the vertical measures.

gaze positions, gentle upwards pressure was applied to the upper eyelid to ensure that it did not obstruct the instrument's view of the eye. The beamsplitter attachment to the instrument allowed only right eyes to be measured along the vertical visual field.

The equipment configuration meant that the target was closer than optical infinity and thus emmetropic subjects had a low level accommodation stimulus, which may have altered the spherical equivalent refraction slightly. The accommodation stimuli changed less than 0.25 D across the horizontal visual field and not at all along the vertical visual field. Peripheral refraction profiles are not affected by accommodation stimuli less than 1 D (Smith, Millodot, & McBrien, 1988).

The instrument's sphere/cylinder/axis refractions $S/C \times \theta$ were converted to vector components of spherical equivalent M, 90° to 180° astigmatism J_{180}, and 45° to 135° astigmatism J_{45} by Thibos, Wheeler, and Horner (1997).

$$M = S + C/2, \tag{1a}$$

$$J_{180} = -C\cos(2\theta)/2, \tag{1b}$$

$$J_{45} = -C\sin(2\theta)/2. \tag{1c}$$

Subjects were subdivided on the basis of central (on-axis) spherical equivalent (determined from subjective refraction) in 1 D steps (Table 1). For statistical analyses, data corresponding to the optic disc location (15° temporal) were disregarded. Statistical significances were determined for a criterion of $p < 0.05$.

Data on the components of refraction versus visual field eccentricity were fit with polynomial functions that included those orders found to contribute significantly ($p < 0.05$) to explaining the variation in the data. This significance was determined by orthogonal polynomial regression (Edwards, 1979; Wilkinson, Mullins, Bjerknes, & McHale, 1991) of the refractive group mean data. Second-order (quadratic) fits were appropriate for all refractive groups for J_{180} and nearly all refractive groups for M, and first-order (linear) fits were appropriate for nearly all refractive groups for J_{45}. Accordingly, quadratic fits were used for M and J_{180}, and linear fits were used for J_{45}. When determining function fits, nasal and superior visual field angles were assigned as positive, and temporal and inferior visual field angles were assigned as negative.

The fits used a weighted least squares procedure where the weightings were provided by the inverse of the variances at each field angle. First-order fits were given by

$$y = bx + c \tag{2a}$$

and second-order fits were given by

$$y = a(x + b)^2 + c, \tag{2b}$$

where x is visual field angle, y is refraction component and a, b and c are coefficients. Equation fits are given in Table 2. The significance of these coefficients relative to zero were determined using t tests.

In addition to this analysis of shape of refractive components within refractive groups, two additional analyses were done using data from all subjects. To investigate whether peripheral M, J_{180} and J_{45} at each visual field angle changed as a function of myopia, the difference between the refractive component at that angle and at the centre of the visual field was linearly correlated with the central spherical equivalent. To determine whether the shape across the visual field of each refraction component was affected by the degree of myopia, the highest order fitted coefficient in Eq. (2), this being the second-order coefficient a for both M and J_{180} and being the linear coefficient b for J_{45}, was linearly correlated with the central spherical equivalent.

To further investigate asymmetries of peripheral astigmatism, we determined the turning points of the second-order functions fitted to subjects' J_{180} data for both horizontal and vertical visual fields ($-b$ in Eq. (2b)). The turning points give the visual field angles about which the functions are symmetric, e.g., if $b = +5°$, a function is symmetrical about $-5°$ (temporal or inferior depending upon whether the horizontal or vertical visual field is being investigated). These were compared, as appropriate

Table 2
Polynomial fit coefficients for M (spherical equivalent), J_{180} (90° to 180° astigmatism) and J_{45} (45° to 135° astigmatism) for each refractive correction group shown in Figs. 1–3, respectively

		Horizontal ($n = 115$)				Horizontal ($n = 42$)				Vertical ($n = 42$)			
		a	b	c	R^2	a	b	c	R^2	a	b	c	R^2
M	Emmetrope	−0.0006	+12.757	−0.133	0.95	−0.0006	+18.030	+0.003	0.96	−0.0013*	+2.005	−0.373	0.87
	−1 D	+0.0001	−28.630	−1.280*	0.51	+0.0000	+58.098	−1.168*	0.18	−0.0015	+1.774	−1.482*	0.96
	−2 D	+0.0003	−13.258	−2.237*	0.86	−0.0004	+25.711	−1.802*	0.91	−0.0003	+35.233	−2.342*	0.53
	−3 D	+0.0005	−11.389	−3.051*	0.88	+0.0005	−6.767	−3.143*	0.78	−0.0017	−2.353	−3.324*	0.80
	−4 D	+0.0011	−1.181	−4.352*	0.96	+0.0010*	−8.027	−4.334*	0.96	−0.0014	−1.833	−4.323*	0.88
	−5 D	+0.0007	+2.792	−4.783*	0.89	−0.0002	−6.247	−4.481*	0.27	−0.0005*	+13.738	−4.560*	0.95
	−6 D	+0.0010	−0.734	−6.197*	0.83	+0.0015*	+0.124	−6.225*	0.85	−0.0012	−13.652	−5.795*	0.93
	−8 D	+0.0011	+0.855	−7.352*	0.96	+0.0014	−0.383	−7.838*	0.93	−0.0007	−9.084	−8.158*	0.67
J_{180}	Emmetrope	−0.0010*	+6.394*	+0.084	0.99	−0.0009*	+7.726	+0.033	0.99	+0.0011*	+1.029	+0.133	0.99
	−1 D	−0.0009*	+5.451	+0.018	0.99	−0.0009*	+4.996	+0.011	0.96	+0.0010*	+2.262	+0.168	0.98
	−2 D	−0.0009*	+5.592	+0.056	0.99	−0.0008*	+8.924*	+0.204*	1.00	+0.0010*	+6.021*	+0.313*	0.93
	−3 D	−0.0010*	+5.933*	+0.108	0.98	−0.0009*	+6.043*	+0.079	0.96	+0.0011*	+4.461	+0.165	0.96
	−4 D	−0.0008*	+4.812*	−0.062	0.98	−0.0008*	+8.981*	−0.185*	0.96	+0.0013*	+5.255*	−0.093*	0.97
	−5 D	−0.0008*	+2.971	+0.156	0.98	−0.0004*	−5.629	0.200	0.95	+0.0008*	+10.097	+0.406*	0.96
	−6 D	−0.0010*	+2.499	+0.246	0.99	−0.0012*	+4.417*	0.464*	0.85	+0.0014*	−1.878	+0.265*	0.98
	−8 D	−0.0008*	+3.920	+0.105	0.99	−0.0009*	+3.299	0.033	0.99	+0.0013*	+2.173	+0.174	0.99
J_{45}	Emmetrope	—	+0.0019	−0.057	0.46	—	+0.0031	−0.058	0.77	—	+0.0114*	−0.037	0.87
	−1 D	—	+0.0070	−0.070	0.94	—	+0.0061	−0.175	0.60	—	+0.0098	−0.211	0.65
	−2 D	—	+0.0054	−0.042	0.86	—	+0.0094*	−0.041	0.89	—	+0.0153*	−0.029	0.88
	−3 D	—	+0.0018	−0.063	0.47	—	+0.0026	−0.056	0.85	—	+0.0127*	+0.041	0.88
	−4 D	—	+0.0045	−0.032	0.58	—	+0.0192*	−0.170*	0.32	—	+0.0175*	−0.155*	0.89
	−5 D	—	+0.0013	−0.060	0.10	—	+0.0069*	+0.007	0.88	—	+0.0075*	+0.178*	0.87
	−6 D	—	+0.0034	+0.027	0.79	—	+0.0044*	−0.113*	0.65	—	+0.0024	−0.045*	0.82
	−8 D	—	+0.005	+0.036	0.72	—	+0.0017	+0.029	0.13	—	+0.0140*	−0.017	0.95

* $P < 0.05$.

and where there were data available, with refraction, horizontal lens tilt, and horizontal angle α. The second of these measurements were obtained from magnetic resonance imaging measurements (Atchison, Pritchard, Schmid et al., 2005). Angle α was measured in the uncorrected state with a Tscherning ophthalmophakometer (Atchison & Smith, 2000) to a precision of 0.5°. This involves finding the best alignment of the first, third and fourth Purkinje images and comparing this "optical" axis with the visual axis passing between the object of interest and the nodal points (in practice actually finding the angle between the optical axis and the line of sight).

3. Results

Peripheral refractions determined along both horizontal and vertical visual fields in emmetropes and myopes up to −12 D refraction are shown in Figs. 1–3. These figures show the spherical equivalent M, 90° to 180° astigmatism J_{180} and 45° to 135° astigmatism J_{45} as a function of visual field angle for the different refractive correction groups. The horizontal visual field results were similar for the total group (Figs. 1A, 2A and 3A) and for the subset that also had vertical visual field measurements (Figs. 1B, 2B and 3B, respectively), so in the presentation of horizontal visual field results, the total group data are considered in detail. Figs. 1C, 2C and 3C show the vertical visual field results.

The emmetropic group had a small myopic shift for M into the horizontal visual field, but this changed to become a relative hypermetropic shift for the −2 D group (Fig. 1A). The steepness of this myopic shift increased for the −3 D and −4 D groups, but there was little further change for the higher myopic groups. For the whole group of subjects, the differences between peripheral and central refraction were significantly affected by central M for temporal visual angles beyond 20° to 25° and for nasal field visual angles beyond 5° (asterisks in figure). Because of the considerable inter-subject variation within the groups, none of the second-order coefficients a for the groups in Eq. (2b) were significant (Table 2), but further statistical support for the refraction profile being affected by level of myopia was given by the second-order fitting coefficient a for the whole group of subjects changing significantly as a function of myopia (Fig. 4A).

Peripheral refraction profiles for M were different for the vertical visual field than for the horizontal visual field (compare Figs. 1A and C). The emmetropes had steeper changes along the vertical visual field than along the horizontal visual field. Unlike the situation for the horizontal visual field, for the vertical visual field myopic shifts occurred into the periphery for all refractive groups with changes in peripheral refraction relative to the central refraction being significantly affected by central M for a few positions only. This is supported by the second-order fitting coefficient a for all subjects not changing significantly as a function of myopia (Fig. 4A).

Fig. 2 shows J_{180} as a function of visual field angle. For clarity, the plots have been staggered along the vertical axis. There was temporal-nasal asymmetry in which the turning points of the functions were in the temporal visual field (Fig. 2A) but regression showed that this asymmetry decreased with increases in myopia at a rate of 0.39 degrees/D (adjusted $R^2 = 0.035$, $t = -2.26$, $p < 0.05$) as shown in Fig. 5. The second-order coefficients a in

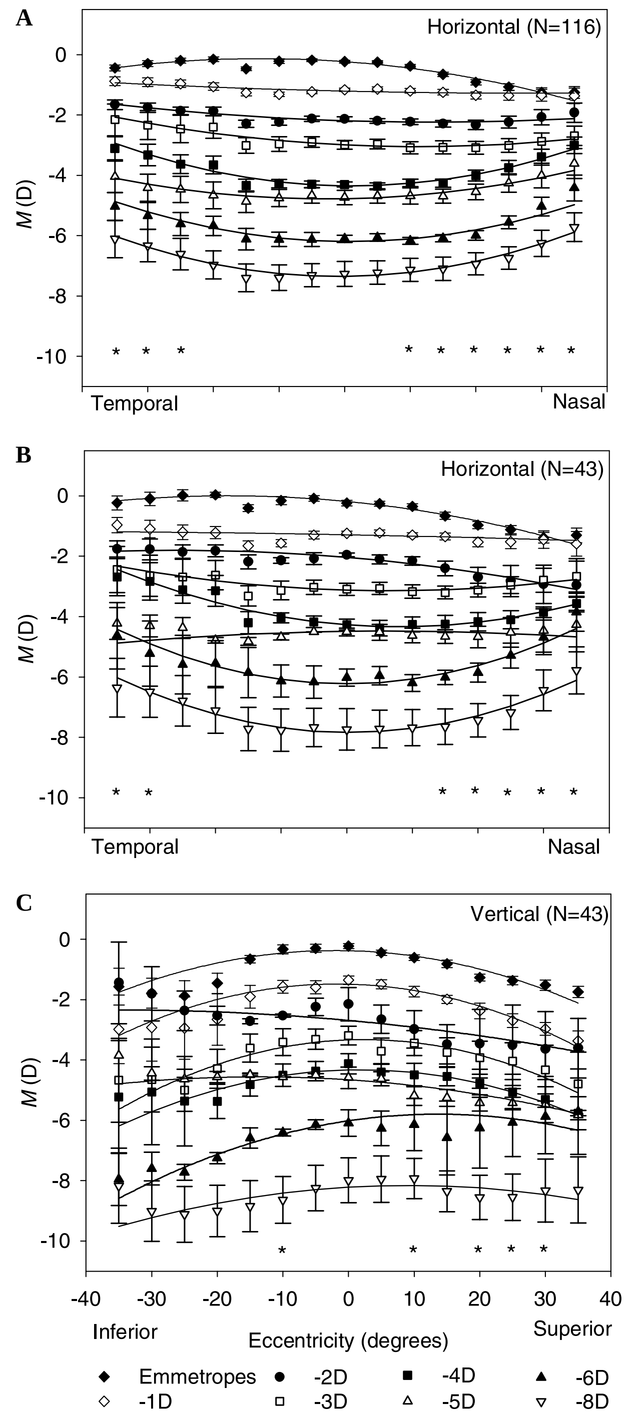

Fig. 1. Spherical equivalent M as a function of visual field angle for (A) the horizontal visual field of all subjects ($n = 116$), (B) the horizontal visual field of the subset of subjects who also did vertical visual field measurements ($n = 43$), and (C) the vertical visual field ($n = 43$). Errors bars indicate ± SE (some error bars are smaller than the plot symbols). Visual field points marked with an asterisk are those for which the differences between peripheral and central M are significantly correlated with central M ($p < 0.05$).

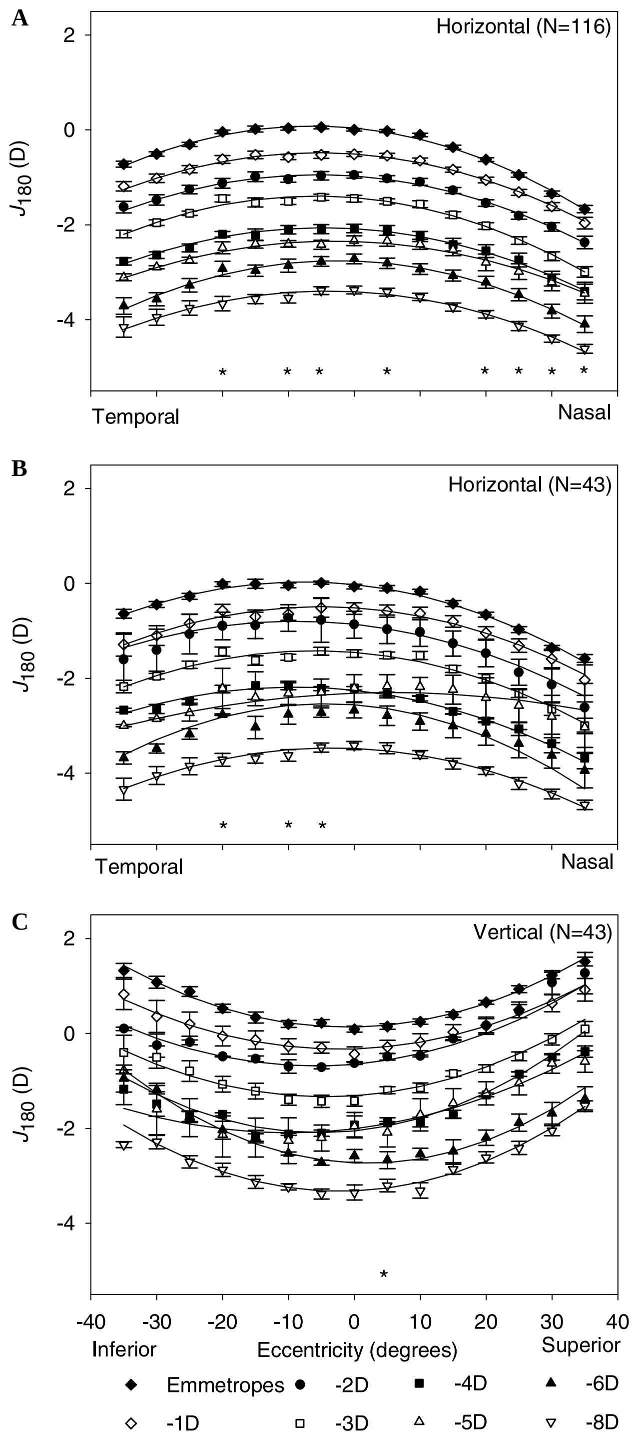

Fig. 2. Mean J_{180} astigmatism as a function of visual field angle for (A) the horizontal visual field of all subjects ($n = 116$), (B) the horizontal visual field of the subset of subjects who also did vertical visual field measurements ($n = 43$), and (C) the vertical visual field ($n = 43$). Errors bars indicate ± SE (some error bars are smaller than the plot symbols). Visual field points marked with an asterisk are those for which the differences between peripheral and central J_{180} are significantly correlated with central M ($p < 0.05$). Results for each myopic group (and the corresponding fitted curves) have been offset vertically for clarity by increments of 0.5 D such that the −8 D group is offset by 3.5 D. Curve fit coefficients before the offsets are shown in Table 2.

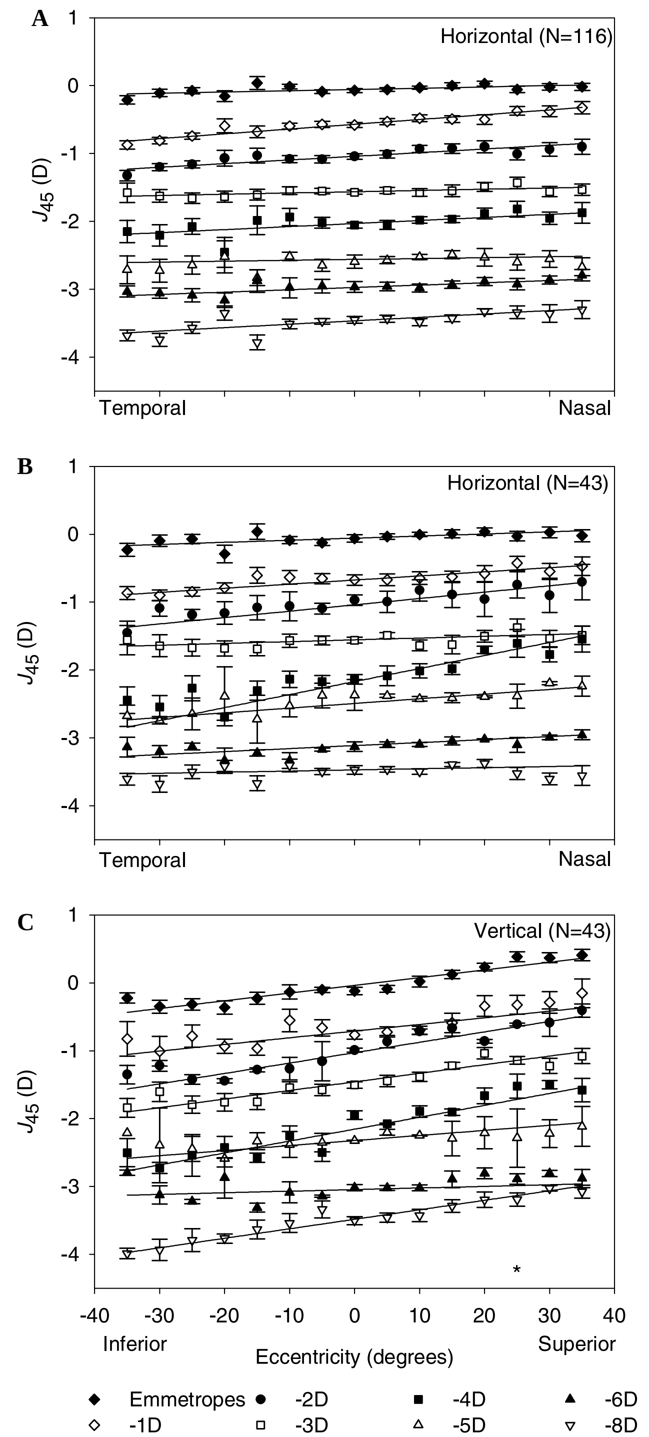

Fig. 3. Mean J_{45} astigmatism as a function of visual field angle for (A) the horizontal visual field of all subjects ($n = 116$), (B) the horizontal visual field of the subset of subjects who also did vertical visual field measurements ($n = 43$), and (C) the vertical visual field ($n = 43$). Errors bars indicate ± SE (some error bars are smaller than the plot symbols). Visual field points marked with an asterisk are those for which the differences between peripheral and central J_{45} are significantly correlated with central M ($p < 0.05$). Results for each myopic group (and the corresponding fitted curves) have been offset vertically for clarity by increments of 0.5 D such that the −8 D group is offset by 3.5 D. Curve fit coefficients before the offsets are shown in Table 2.

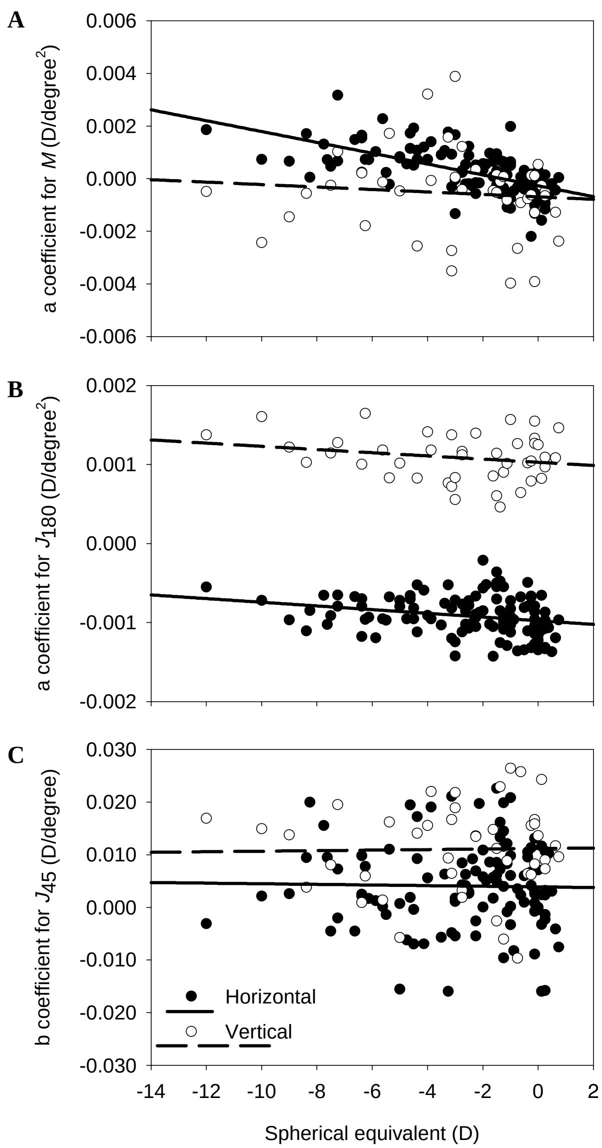

Fig. 4. Highest order coefficient in Eq. (2) for all subjects along both horizontal and vertical visual fields as a function of central spherical equivalent. (A) Coefficient "a" for mean spherical equivalent M, with $y = -0.000206x - 0.000270$, adjusted $R^2 = 0.42$, $t = -8.43$, $p < 0.0001$, ($n = 116$) horizontally, and $y = -0.000047x - 0.000694$, adjusted $R^2 = -0.016$, $t = -0.59$, $p = 0.56$ ($n = 43$) vertically; (B) coefficient "a" for J_{180} astigmatism with $y = -0.000023x - 0.000977$, adjusted $R^2 = 0.056$, $t = -2.79$, $p = 0.006$, ($n = 116$) horizontally, and $y = -0.000020x + 0.001027$, adjusted $R^2 = 0.056$, $t = 1.44$, $p = 0.16$ ($n = 43$) vertically; (C) coefficient "b" for J_{45} astigmatism, with $y = -0.000060x + 0.003897$, adjusted $R^2 = -0.008$, $t = -0.21$, $p = 0.83$ ($n = 116$) horizontally, and $y = +0.000051x + 0.011187$, adjusted $R^2 = 0.121$, $t = 0.12$, $p = 0.90$ ($n = 43$) vertically [note that the constants in both equations are significant at $t = 3.72$, $p = 0.0003$ horizontally and $t = 6.12$, $p < 0.0001$ vertically].

Eq. (2b) were highly significant. Although these appear similar for all groups, there was a significant change in the second-order fitting coefficient a as a function of myopia (Fig. 4B) indicating a slow flattening of the astigmatism profile with increase in myopia (approximately 25% reduction in a for a 10 D myope as compared with an emmetrope).

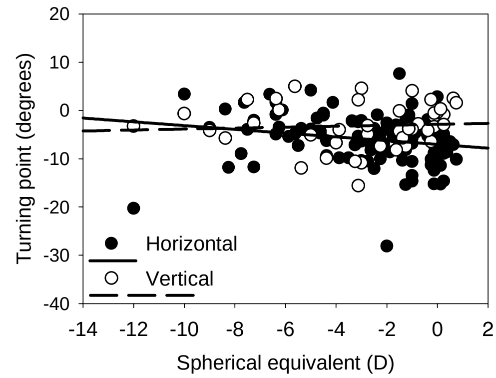

Fig. 5. The turning points of subjects' J_{180} astigmatism plots along the horizontal and vertical visual field as a function of central spherical equivalent. Correlation coefficient and p value of linear regression are adjusted $R^2 = 0.035$, $t = -2.26$, $p = 0.03$ ($n = 116$) horizontally, and adjusted $R^2 = -0.020$, $t = 0.43$, $p = 0.67$ ($n = 43$) vertically.

For J_{180} along the vertical visual field, the periphery showed positive refraction shifts rather than the negative shifts occurring for the horizontal visual field (Fig. 2C), but the magnitudes of the shifts were similar. There was slight inferior–superior asymmetry in which the turning points of the functions were in the inferior visual field (mean −3.29°, 95% CI = −4.6 to −1.7°), but unlike the horizontal field these did not change with the amount of myopia (adjusted $R^2 = -0.02$, $t = 0.43$, $p = 0.67$) as shown in Fig. 5. The second-order coefficients a in Eq. (2b) were highly significant and similar for all refractive groups. This is supported by the second-order fitting coefficient a for all subjects not changing significantly as a function of myopia (Fig. 4B).

Fig. 3 shows J_{45} as a function of visual field angle. As in the case of Fig. 2, for clarity the plots have been staggered along the vertical axis. Along both the horizontal and vertical visual fields, there were linear relationships between J_{45} and visual field angle that were unaffected by the amount of myopia [e.g., the first-order fitting coefficient b for all subjects did not change significantly with myopia (Fig. 4C)]. Along the horizontal visual field, the slopes for the groups were shallow and the first-order coefficients b in Eq. (2a) were not significantly different from zero. Most of the slopes for the vertical visual field were significantly different from zero, and were about three times greater than along the horizontal field.

Fig. 6 shows the turning points of subjects' J_{180} fits along the horizontal visual field as a function of angle α and horizontal lens tilt. The turning points were significantly correlated with angle α (adjusted $R^2 = 0.27$, $p < 0.0001$), but not with lens tilt ($p = 0.89$).

4. Discussion

The important finding of this investigation is that there were differences in the effect of central (on-axis) myopia on peripheral refraction along the horizontal and vertical visual fields of adult eyes. Consistent with most previous

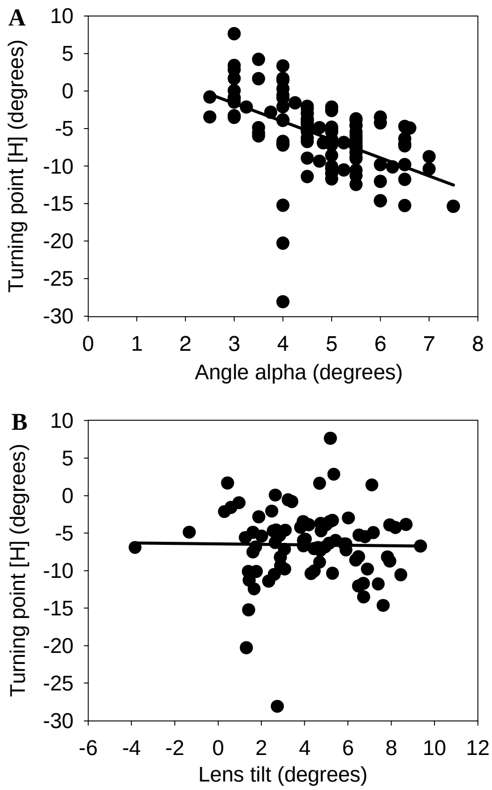

Fig. 6. The turning points of individuals' J_{180} astigmatism plots along the horizontal visual field as a function of (A) angle α and (B) horizontal lens tilt. Correlation coefficients and p values of linear regression are (A) adjusted $R^2 = 0.27$, $t = -6.25$, $p < 0.0001$ ($n = 108$); (B) adjusted $R^2 = -0.001$, $t = -0.14$, $p = 0.89$ ($n = 84$).

studies for the horizontal visual field (Atchison, Pritchard, White et al., 2005; Logan et al., 2004; Love et al., 2000; Millodot, 1981; Mutti et al., 2000; Rempt et al., 1971) most emmetropic eyes showed myopic shifts into the periphery whereas most myopes greater than about 2 D showed relative hypermetropic shifts (Figs. 1A and B), although the degree of the hypermetropic shift did not appear to be influenced by the amount of myopia beyond about 4 D. In contrast to the horizontal visual field, we present the new finding that the myopic shifts of the vertical visual field were not dependent upon the degree of central myopia (Fig. 1C). It must be noted that some of the myopic groups had small numbers, and two of the plots appearing to be out of synchrony with others are ones with small numbers (−2 D and −5 D groups). Despite the small numbers in a few groups, the lack of change in shape of M along the vertical meridian with increase in myopia is compelling (see Fig. 4A).

Astigmatism J_{180} had greater asymmetry about fixation along the horizontal visual field than along the vertical visual field, and this asymmetry decreased slightly with increase in myopia for the horizontal meridian (Figs. 2A–C). Similar to previous studies (Atchison, Pritchard, White et al., 2005; Millodot, 1981; Seidemann et al., 2002), we noted a small flattening of the J_{180} astigmatism profile along the horizontal meridian with increase in myopia (Fig. 4B). There was a tendency for steepening of the J_{180} astigmatism profile along the vertical meridian with increase in myopia, but this was not significant (Fig. 4B).

A difference between the horizontal and vertical visual fields, not related to myopia, was that the rates of change of J_{45} with change in visual angle were about three times greater along the vertical visual field than along the horizontal visual field (compare Figs. 3A and B with Fig. 3C and see Fig. 4C).

The main differences between peripheral refractive shifts along the horizontal and vertical visual fields are consistent with what has been learned recently about the shape of the eye (Atchison et al., 2004; Atchison, Pritchard, Schmid et al., 2005). In general, the changes in M along the horizontal visual field (myopic peripheral shifts in emmetropes turning to relative hypermetropic peripheral shifts in refraction in myopic subjects) can be explained by the simple models of Charman and Jennings (1982) and Dunne et al. (1987) that assume that the retinal equator stays the same distance from the visual axis as myopia increases. However, the eye increases in size both horizontally and vertically as well as axially with increase in myopia (Atchison et al., 2004; Atchison, Pritchard, Schmid et al., 2005). This increase is asymmetrical, being much greater vertically than horizontally. The retina will be flatter along the vertical than along the horizontal meridian, thus reducing the tendency for relative hypermetropia as myopia increases. On average, from our results the vertical expansion would appear to eliminate the relative hypermetropic shift altogether.

The asymmetries in J_{180} along the horizontal visual field can be attributed to asymmetries in the anterior optics about the vertical axis, and in particular the cornea as no correlation was found between the lens tilt and the turning point of the J_{180} plots. Our mean turning point for J_{180} along the horizontal visual field was $-6.0 \pm 5.0°$. Other estimates of this are $\sim -4°$ by Lotmar and Lotmar (1974) using Rempt et al.'s (1971) data, and $-8.8 \pm 7.0°$ and $-9.4 \pm 9.8°$ by Dunne, Misson, White, and Barnes (1993) using two instruments. Unlike the present study, Dunne et al. failed to find a significant correlation between turning points and angle α ($R^2 = 0.04$, $p = 0.23$ and $R^2 = 0.08$, $p = 0.09$ for 34 subjects). The vertical visual field is more inclined to the "optical" axis than is the horizontal visual field, and this obliquity is manifest in the greater rate of change of J_{45} we found along the vertical than along the horizontal visual field.

Our results for the vertical visual field are different in some respects from those of Seidemann et al. (2002) and Schmid (2003). Seidemann and co-workers found a greater myopia inferiorly than superiorly, but this is not evident in our results (Fig. 1C). Schmid found a small hypermetropic relative shift in his group of low myopic children at 15° superior and inferior positions, compared with the myopic shift we found into the periphery of the vertical visual field. A reason for the discrepancy is not obvious, but Schmid's group was small (10 subjects) and he measured at only two positions in this meridian. There may be an age effect as many of the 7- to 15-year old eyes would have been still growing, whereas the majority of our group's eyes had probably stopped growing as refraction was stable in most cases. However, there is no evidence of an age effect in the horizontal meridian, where Schmid's myopic group showed a slight myopic shift of −0.2 D at 15° nasal visual field which is not inconsistent with our finding of flat profiles for mean sphere M of our two lowest myopic groups (Fig. 1A and Table 2). Our results are also reasonably consistent with Mutti et al.'s (2000) results in 5- to 14-year old children at 30° nasal visual field; although the hypermetropic shift for their -2.8 ± 2.1 D myopic group is 0.5 D more than the hypermetropic shift of our -3.5 ± 2.5 D myopic subjects, the shift relative to those of the emmetropic groups is similar (+1.2 and +1.4 D, respectively).

Our findings have implications for the potential role of peripheral refraction in the development of myopia, such as the theory outlined by Wallman and Winawer (2004) in which a relatively hypermetropic periphery can stimulate compensating eye growth. Although we do not know what the peripheral refractions and eye shapes were in our subjects before they developed myopia, the finding that most emmetropic and myopic subjects have relative myopic shifts along the vertical visual field makes it unlikely that the majority of retinas provide a hypermetropic defocus eye growth stimulus, at least in the uncorrected state. Also, regardless of the spherical equivalent, most eyes have considerable astigmatism in the periphery (the J_{180}'s shown in Fig. 2 are approximately half that of the conventional cylinders). While the astigmatism may result in reduced image quality that could theoretically promote myopia, the fact that the level is similar in adult emmetropes makes this unlikely.

Wallman and Winawer (2004) suggested that hypermetropic periphery growth cues might be treatable with ophthalmic corrections similar to progressive additional lenses. By manipulating the curvatures and asphericities of conventional spectacle lens surfaces, or the asphericities of contact lens surfaces, it should be possible to do this, although the correction of peripheral astigmatism will not be possible by such a means. It is possible to design spectacle lenses to completely correct peripheral refraction along at least one visual field meridian (Smith, Atchison, Avudainayagam, & Avudainayagam, 2002) and we have designed and had manufactured such lenses for two subjects. The problem with spectacle lenses of either level of sophistication is that the eye would have to maintain fixation through the lens centres; the usual eye movements scanning across the lenses would provide disruptive variable foveal vision. Contact lens correction to eliminate peripheral hypermetropia may be feasible, but may produce unacceptable aberrations for foveal vision. Mutti et al. (2000) related the peripheral refraction of eyes to the shape of eyes, describing myopic eyes as prolate (elongated) in shape relative to emmetropic and hypermetropic eyes, although Stone and Flitcroft (2004) emphasised that the large range of peripheral refractions within each of Mutti et al.'s refractive groups indicates a wide range of shapes within each group. The concept of prolate shapes for myopic eye does not hold at the level of posterior retinal shape as most retinas are oblate (steepening towards periphery), although this reduces with increase in myopia (Atchison, Pritchard, Schmid et al., 2005). Instead of optical cues predisposing towards myopia development, biomechanical factors in emmetropic ''prolate'' eyes might be responsible (Mutti et al., 2000).

Despite our findings and consequent argument against peripheral refraction playing a role in myopia development, a recent animal study provides some evidence to the contrary. Smith, Kee, Ramamirtham, Qiao-Grider, and Hung (2005) found that infant rhesus monkeys were able to emmetropize after ablation of the central 4° to 6° of retina, but ablating the ''mid- to far-periphery'' led to the majority of eyes having low levels of hypermetropia 5 months after surgery (Hung et al., 2005). It is possible that ablation of large areas of the retinal periphery induced ocular inflammation that resulted in the hyperopic shift observed. In addition, while our data suggest that peripheral refractive errors do not appear to be involved in the common form of myopia development in individuals with normal retinal function, the outcomes of this study do not indicate what might occur if the central retina was non-functional (perhaps in that circumstance a parafoveal area could take over the role of controlling the eye's growth) or the role of peripheral refractive errors in the pathological form of myopia.

5. Conclusion

Myopia has more effect on peripheral refraction in adult eyes along the horizontal than along the vertical visual field. In particular, a peripheral myopic shift in M for emmetropes changes to relative hypermetropic shift in myopes for the horizontal visual field, but this change is not found for the vertical visual field. The differences in peripheral refraction between the two visual fields are consistent with what is known about the shapes of emmetropic and myopic eyes.

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