Astigmatism and Its Components in 6-Year-Old Children

Son C. Huynh,[1] *Annette Kifley*,[1] *Kathryn A. Rose*,[2] *Ian Morgan*,[3] *Gillian Z. Heller*,[4] *and Paul Mitchell*[1]

Purpose. The purpose of the present study was to report the prevalence of refractive (RA), corneal (CA), and internal astigmatism (IA) in a population of 6-year-old children; examine their variation with gender, ethnicity, and refraction; and examine the effects of gender, ethnicity, and spherical equivalent refraction on the relationship between CA and RA in this population.

Methods. The Sydney Myopia Study is a population-based survey of refraction and eye health in 6-year-old children. A random cluster design was used to recruit children from schools across Sydney, Australia, during 2003 to 2004. Data collection used a detailed questionnaire and comprehensive eye examination. Keratometric and cycloplegic autorefraction data from right eyes were analyzed.

Results. Of 2238 eligible children, 1765 (78.9%; 50.7% boys) had parental consent to participate. Overall prevalence of RA (≥1.0 diopter [D]) was 4.8% (95% confidence interval [CI] 3.8%–6.1%), CA (≥1.0 D) 27.7% (CI 23.8%–32.3%), and IA (≥1.0 D) 21.1% (CI 19.0%–23.5%). The RA axis was fairly evenly distributed, with predominance of oblique axis (39.1%; CI 35.9%–42.6%). CA axis was mainly with the rule (75.1%; CI 72.6%–77.8%), while IA axis was mainly against the rule (76.7%; CI 74.2%–79.3%). After adjustment for multiple variables, girls had significant, marginally greater mean CA and IA than boys. East Asian and South Asian children had significantly greater prevalence and mean RA and CA than European Caucasian children. There were no significant ethnic differences of mean IA. Compared to reference (spherical equivalent [SEq] 1.01–1.50 D), mean RA and CA increased significantly with more hyperopic and more myopic refractions. Mean IA was significantly greater only for hyperopic refractions (SEq > 2.00 D).

Conclusions. The prevalence of astigmatism found in this population of 6-year-old children was relatively low, and showed significant variation with ethnicity. The data suggest that emmetropization for RA occurs by a compensatory process between CA and IA. (*Invest Ophthalmol Vis Sci.* 2006;47:55–64) DOI:10.1167/iovs.05-0182

Astigmatism is a common refractive anomaly. Two components of astigmatism can be independently measured—refractive (total) astigmatism (RA) and corneal astigmatism (CA). The difference between the two, internal astigmatism (IA), is thought to arise from the internal optics of the eye, including asymmetries related to the crystalline lens. Knowledge of the distribution and relationship between the components of astigmatism is important for understanding the development and progression of RA.[1–5] It is also relevant to corneal, refractive and cataract surgery.

Past studies have documented the prevalence of astigmatism in a range of samples, including urban and rural populations,[6,7] special groups,[8,9] and clinic patients.[10] Marked differences in RA and CA have been reported in different ethnic groups.[11–15] Typically, these studies have reported high prevalence rates of RA among children in Singapore[16] (19.2%) and Taiwan[17] (14.6%) and in children of some Native American tribes[10] (44.2%), and low prevalence rates in urban southern India[18] (3.8%), rural India[6] (5.9%), and Finland[2] (3.8%). A number of studies also reported on the association of RA with myopia.[3–5] Gender variations have received less attention. There are also few population-based studies of astigmatism in young children,[6,7,17,19,20] and these have not reported on the components of astigmatism. The associations of these variables with IA and their effect on the relationship between CA and RA has also been less well studied. Most of the studies on young children have been limited by relatively small sample size; have not considered the influences of gender, ethnicity and spherical error; have not performed their analyses using the exact cylinder axis, and have mostly excluded oblique axes.[8,21–25]

In the present study, our aims were to describe the prevalence of RA, CA, and IA; examine the effect of gender, ethnicity, and spherical equivalent refraction on the distribution of the components of astigmatism; and examine the effects of gender, ethnicity, and spherical equivalent refraction on the relationship between CA and RA.

Methods

Subjects

The Sydney Myopia Study is a large population-based study of refractive errors and eye health in schoolchildren living within the Sydney Metropolitan Area, Australia. This article presents cross-sectional data for 6- to 7-year-old children examined during 2003 to 2004.

Study methods have been described in detail elsewhere.[26–28] In brief, the city of Sydney was stratified by socioeconomic status, using data from the 2001 Australian Bureau of Statistics National Census. Thirty-four primary schools were identified through a random-cluster sampling method, with a proportionate mix of private- and government-funded schools. Parents of all Year 1 children in each school were invited to have their children participate in the study.

From the [1]Centre for Vision Research, Department of Ophthalmology, and the Westmead Millennium Institute, University of Sydney, and the Vision Cooperative Research Centre, Sydney, Australia; the [2]School of Applied Vision Sciences, Faculty of Health Sciences, University of Sydney, Sydney, Australia; the [3]Research School of Biological Sciences and Centre for Visual Science, Australian National University, Canberra, Australia; and the [4]Department of Statistics, Macquarie University, Sydney, Australia.

Supported by the Australian National Health and Medical Research Council, Canberra, Australia (Grant 253732) and the Vision Cooperative Research Centre, Sydney, Australia.

Submitted for publication February 11, 2005; revised April 6, May 30, July 5, and September 16, 2005; accepted November 16, 2005.

Disclosure: **S.C. Huynh**, None; **A. Kifley**, None; **K.A. Rose**, None; **I. Morgan**, None; **G.Z. Heller**, None; **P. Mitchell**, None

The publication costs of this article were defrayed in part by page charge payment. This article must therefore be marked "*advertisement*" in accordance with 18 U.S.C. §1734 solely to indicate this fact.

Corresponding author: Paul Mitchell, FRANZCO Centre for Vision Research, Department of Ophthalmology, University of Sydney, Hawkesbury Road, Westmead, NSW 2145, Australia; paul_mitchell@wmi.usyd.edu.au.

The study was approved by the University of Sydney Human Research Ethics Committee and the Department of Education and Training, both in Sydney, Australia, and conducted in accordance with the principles of the Declaration of Helsinki. Informed written consent was obtained from at least one parent of all participating children. Verbal consent was also obtained from these children before examinations.

Keratometry and Cycloplegic Autorefraction

Precycloplegic keratometry was performed using a commercial instrument (IOLMaster; Carl Zeiss Meditec AG, Jena, Germany). Corneal refractive power was calculated using an equivalent refractive index of 1.3375. This refractive index value takes into account the negative refractive power of the posterior corneal surface. Each keratometry reading was the average of five internal measurements made by the instrument. Three consistent readings were obtained in which corneal astigmatism did not vary >0.10 diopter (D) between readings, and the astigmatic axis varied ≤5° for astigmatism ≥ 0.50 D and ≤10° for astigmatism < 0.50D. The last of these readings was used in analyses. Borderline readings in which one or more of the six points of light on the measurement mire were not in focus were removed during the examination. After instilling one drop of 1% amethocaine, cycloplegia was induced by instilling two drops, separated by 5 minutes, of 1% cyclopentolate and 1% tropicamide. Autorefraction was performed using an autoref-keratometer (RK-F1; Canon Inc., Tokyo, Japan), 25 to 30 minutes after the last drop. In fully automated mode, the autoref-keratometer performed at least five autorefractions in each eye, and gave a standardized value as its output. Keratometry data from this instrument, however, were not used in the analysis, as the 0.12-D increments were considered too coarse. Analysis of the comparability of keratometry between the two instruments found that the autoref-keratometer gave significantly ($P < 0.0001$) greater estimates of corneal astigmatism (0.12 D, 95% confidence interval [CI] 0.10–0.13 D).

Questionnaire Data

Data on ethnicity, socioeconomic status, and parental education were obtained using a questionnaire sent to each child's parents. Parents were asked to indicate their ethnic origin and that of their own parents, as well as their country of birth. The major ethnic groups represented included European Caucasian, East Asian, South Asian (Indian/Pakistani/Sri Lankan), African, Melanesian/Polynesian, Middle Eastern, Indigenous Australian, and South American. "Other" was also included as a group.

Socioeconomic status was determined from the employment status of either parent and from home ownership. Both parents were also asked to indicate the highest education level they had achieved.

Definitions

RA, CA, and IA were expressed in negative correcting cylinder form. RA was given in the autorefractor output. CA was calculated as $K_{min} - K_{max}$, where K_{min} represents the meridian with the least refractive power and K_{max} the meridian with the greatest refractive power. Corneal cylinder axis was set along the K_{min} meridian. We used the vector method modified by Thibos[29] to convert refractive and corneal cylinders into Cartesian (J_0) and oblique (J_{45}) vectors as follows:

$$J_0 = -\frac{C}{2}\cos 2\theta$$

$$J_{45} = -\frac{C}{2}\sin 2\theta$$

where C is the cylinder power and θ is the cylinder axis. The J_0 vector describes a Jackson cross-cylinder (JCC) with its axes at 180° and 90°, while the J_{45} vector describes a JCC with its axes at 45° and 135°. A positive J_0 corresponds to with-the-rule (WTR) astigmatism, while a negative J_0 corresponds to against-the-rule (ATR) astigmatism. A positive J_{45} indicates that power is greatest at 135°, while a negative J_{45} indicates that power is greatest at 45°. For descriptions of the distribution of astigmatic axes, WTR astigmatism was defined as cylinder axes from 1° to 15° or 165 ° to 180°, and ATR astigmatism as cylinder axes from 75 ° to 105°. Oblique astigmatism was defined as cylinder axes from 16 ° to 74° or 106 ° to 164°.

Internal astigmatism was calculated as the vector difference between the refractive and corneal astigmatic components.

The prevalence of astigmatism was determined for cylinder powers ≥0.50, ≥0.75, and ≥1.00 D to facilitate comparison with other studies. Spherical equivalent (SEq) refractive error was calculated as sphere + ½ cylinder.

Statistical Analysis

Statistical analyses were performed on right eyes using a software package (SAS v.8.2; SAS Institute, Cary, NC). Means with 95% CI were estimated using mixed models, and prevalence rates with 95% CI were estimated using generalized estimating equations. These methods adjust for clustering within schools by taking into account the potential correlation between children attending the same school.

Associations between astigmatism and gender, ethnicity, and SEq refraction were assessed in unadjusted and multivariable-adjusted analyses. Mixed-models linear regression was used to examine the relationship between CA and RA. Correlations between right and left eyes were assessed using Pearson correlation coefficients. For comparisons of gender, ethnic, or refraction subgroups, the most common category was used as the reference group.

Results

Characteristics of the Study Population

Of 2238 eligible children, 1765 (78.9%) had parental consent to participate in the study. Twenty-four children were absent from school at the time of examination, one 9-year-old child was excluded from all analyses because she was outside the age range examined in this study, and one child did not have keratometry or autorefraction data, leaving 1739 children who were included in this report. Of these, 15 did not have autorefraction data, and 12 did not have keratometry data, because they did not sit still for measurement or refused eye drops. The 1712 children with both autorefraction and keratometry data in right eyes did not differ significantly from children with missing data in regard to age ($P = 0.8$), gender ($P = 0.2$), ethnicity ($P = 0.3$), and uncorrected visual acuity ($P = 0.5$).

Among the children included in this study, 50.7% were boys, the mean age was 6.7 years (range, 5.5–8.4 years, with 70.2% aged 6 years), and mean right-eye SEq refraction was 1.26 D (CI 1.19–1.33 D). The cluster-adjusted prevalence of myopia (SEq ≤ −0.50 D) was 1.4% (CI 0.9%–2.2%), and of hyperopia (SEq > 2.00 D) was 10.4% (CI 9.2%–11.9%). Most children (88.8%) were of European Caucasian ($n = 1120$, 64.4%), East Asian ($n = 299$, 17.2%), Middle Eastern ($n = 86$, 4.9%), or South Asian origin ($n = 40$, 2.3%). The ethnic origins of the remaining children included Polynesian/Melanesian ($n = 25$, 1.4%), South American ($n = 16$, 0.9%), Indigenous Australian ($n = 10$, 0.6%), and African ($n = 6$, 0.4%). However, their individual numbers were too small for meaningful analysis. The ethnicity of 137 children (7.9%) was mixed or unknown. Gender distribution did not differ significantly across ethnic groups (all $P > 0.05$).

Pearson correlations between right- and left-eye refractive and corneal astigmatic error were 0.67 ($P < 0.0001$) and 0.78 ($P < 0.0001$), respectively. The difference between eyes for RA was 0.01 ± 0.32 D (mean ± SD; left eye more positive), and for CA was 0.01± 0.32 D (left eye more positive). The between-

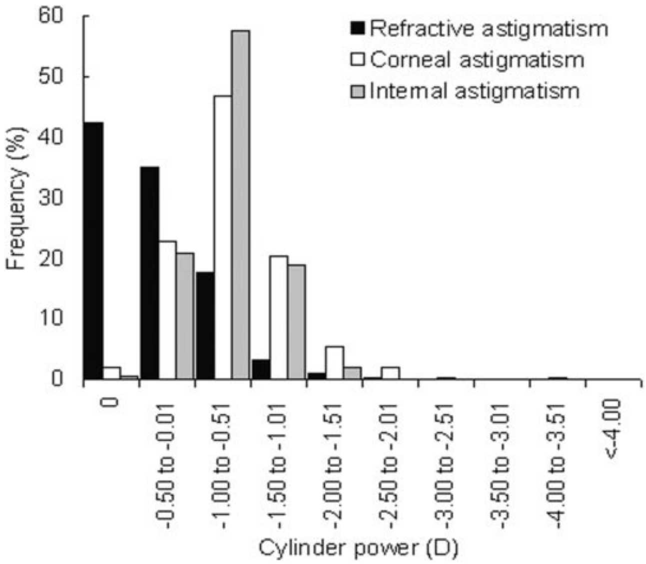

FIGURE 1. Whole sample distribution of RA, CA, and IA.

eye correlation of SEq refraction was 0.87 ($P < 0.0001$), with a difference of 0.04 ± 0.46 D (left eye more positive).

Distribution of the Magnitude of Astigmatism

Distributions of the magnitude of RA, CA, and IA are shown in Figure 1. RA showed an almost exponential distribution, with most children having little or no astigmatism. The distributions of CA and IA were right skewed. Most children had some degree of CA and IA, while only a small proportion had no astigmatism. The prevalence of RA ≥ 0.50 D (22.6%) was considerably lower than the prevalence of CA (74.9%) or IA (78.5%).

Variations in Prevalence of Astigmatism. Gender differences in the prevalence of RA (all $P > 0.2$) and CA (all $P > 0.2$) were not significant, but the prevalence of IA was higher in girls than boys (all $P < 0.02$). For IA ≥ 0.50 D, the prevalence in girls was 80.9% (CI 78.3%–83.6%), and in boys was 76.2% (CI 73.3%–79.2%). For IA ≥ 0.75 D, the prevalence in girls was 52.4% (CI 48.8%–56.3%), and in boys was 44.7% (CI 41.0%–48.7%). For internal astigmatism ≥ 1.00 D, the prevalence in girls was 24.8% (CI 21.9%–28.2%), and in boys was 17.6% (CI 15.2%–20.3%).

The prevalence of RA, CA, and IA among different ethnic groups is presented in Table 1. European Caucasian children tended to have lower prevalences of RA and CA than East Asian and South Asian children. Apart from a marginally significant higher prevalence of IA (≥1.00 D) in East Asian children compared to European Caucasian children, there were no other ethnic differences in the prevalence of IA.

Ethnic variations in rates of RA and CA ≥ 1.00 D remained unchanged after adjusting for the effects of gender, employment status of either parent, home ownership, and SEq refraction. All ethnic variations in IA became nonsignificant (all $P > 0.2$). For children of South Asian origin, the difference in rates of RA (≥0.75 D) and CA (≥0.50 D) became nonsignificant ($P > 0.06$). Finally, the difference in rates of CA (≥0.75) for children of Middle Eastern origin became significant ($P = 0.004$).

The prevalence of RA (≥1.00 D) was 28.0% in children with myopia (SEq ≤ −0.50 D, $n = 25$), and 11.2% in children with emmetropia (SEq −0.49 to 0.50 D, $n = 134$). In children with hyperopia, the prevalences were 2.8% (SEq 0.51–2.00 D, $n = 1386$) and 12.9% (SEq > 2.00 D, $n = 179$).

Variations in Mean Astigmatism. Means of RA, CA, and IA stratified by gender, ethnicity, and SEq refraction are pre-

TABLE 1. Prevalence of Right-Eye RA, CA, and IA by Different Definitions and Adjusted for Cluster Sampling

		Prevalence					
		≥0.50 D		≥0.75 D		≥1.00 D	
Astigmatism Type	***n* (%)**	**% (95% CI)**	***P*-Value**	**% (95% CI)**	***P*-Value**	**% (95% CI)**	***P*-Value**
RA							
Whole group	1724	22.6 (20.0–25.4)		10.3 (8.5–12.4)		4.8 (3.8–6.1)	
European Caucasian	1109 (64.3)	19.4 (17.0–22.1)	Referent	7.5 (6.2–9.0)	Referent	3.6 (2.8–4.7)	Referent
East Asian	295 (17.1)	33.5 (29.0–38.7)	<0.0001	20.7 (16.7–25.6)	<0.0001	11.2 (9.0–14.0)	<0.0001
Middle Eastern	86 (5.0)	25.0 (16.4–38.1)	0.3	12.8 (7.3–22.6)	0.09	4.9 (1.8–13.5)	0.6
South Asian*	40 (2.3)	32.7 (22.9–46.5)	0.004	15.0 (8.7–25.9)	0.02†	7.6 (2.8–21.1)	–‡
Other§	194 (11.3)	25.5 (21.1–30.8)	0.02	10.9 (6.7–17.7)	0.2	2.1 (0.9–5.3)	0.3
CA							
Whole group	1727	74.9 (71.8–78.0)		49.5 (45.6–53.7)		27.7 (23.8–32.3)	
European Caucasian	1112 (64.4)	71.6 (68.5–74.9)	Referent	44.3 (40.8–48.0)	Referent	22.2 (18.8–26.1)	Referent
East Asian	296 (17.1)	85.3 (81.9–88.9)	<0.0001	67.2 (62.3–72.5)	<0.0001	43.4 (39.0–48.2)	<0.0001
Middle Eastern	85 (4.9)	74.6 (66.6–83.5)	0.5	52.0 (43.8–61.7)	0.07‖	29.7 (21.6–40.7)	0.1
South Asian*	40 (2.3)	84.9 (73.7–97.8)	0.03†	67.5 (53.1–85.7)	0.002	48.1 (34.9–66.4)	<0.0001
Other§	194 (11.2)	77.7 (70.8–85.3)	0.1	51.4 (44.1–59.7)	0.04	31.6 (25.0–40.0)	0.005
IA							
Whole group	1712	78.5 (76.4–80.8)		48.4 (45.6–51.5)		21.1 (19.0–23.5)	
European Caucasian	1101 (64.3)	78.6 (76.2–81.0)	Referent	48.3 (45.5–51.3)	Referent	20.5 (18.3–22.9)	Referent
East Asian	292 (17.1)	79.1 (74.3–84.3)	0.8	52.8 (48.0–58.0)	0.1	25.8 (20.8–32.1)	0.04†
Middle Eastern	85 (5.0)	75.1 (66.7–84.6)	0.4	46.8 (38.3–57.1)	0.7	18.4 (13.6–24.8)	0.5
South Asian*	40 (2.3)	70.2 (57.6–85.7)	0.3	39.8 (29.3–54.1)	0.2	12.3 (6.1–24.8)	0.2
Other§	194 (11.3)	80.9 (75.2–87.1)	0.5	45.7 (38.0–55.1)	0.6	21.2 (17.2–26.0)	0.8

* Indian/Pakistani/Sri Lankan.
† Nonsignificant after adjusting for gender, employment status of either parent, home ownership, and SEq refraction.
‡ Numbers were too small for meaningful analysis.
§ Ethnic groups include Polynesian/Melanesian, South American, Indigenous Australian, African, and mixed.
‖ Significant after adjusting for gender, employment status of either parent, home ownership, and SEq refraction.

sented in Table 2. Girls had significantly greater mean RA, CA, and IA than boys. However, these differences were small. Gender differences remained significant for RA (−0.04; CI −0.01 to −0.06), CA (−0.06; CI −0.02 to −0.09), and IA (−0.08; CI −0.05 to −0.10) after adjusting for ethnicity and parental education level. Differences for CA and IA, but not RA, remained significant after further adjusting for SEq refraction. Mean RA was significantly greater in East Asian and South Asian children than in European Caucasian children. Mean CA was greater in East Asian and South Asian children, as well as in children from the other non-European Caucasian ethnic groups, than in European Caucasian children. There were no significant ethnic differences in mean IA.

Compared to children in the reference group (SEq 1.01–1.50 D), mean RA and CA were significantly greater in children who had myopia (SEq < -0.50 D), emmetropia (SEq −0.49 to 0.50 D), or hyperopia (SEq $>$ 2.00 D). Mean RA was also significantly greater in the less hyperopic groups (SEq 0.51–1.00 and 1.51–2.00 D). Mean IA was significantly greater only in children with SEq $>$ 2.00 D. The findings for RA and IA remained significant after adjusting for gender, ethnicity, and parental education. Findings for CA remained significant after adjusting for gender and ethnicity. Parental education was not a significant confounder for the effect of SEq refraction on CA.

Distribution of the Axis of Astigmatism

The distribution of axes of RA, CA, and IA is presented in Table 3. The axis of RA was most commonly oblique, followed by WTR and ATR axes. In comparison, the axis of CA was predominantly WTR, followed by oblique and a small proportion of ATR axes. The axis of IA was predominantly ATR, with a smaller proportion of oblique and an extremely small proportion of WTR axes.

Variations in the Axis of Astigmatism

Girls had a significantly lower prevalence of WTR and a marginally significant higher prevalence of ATR RA. However, after adjusting for ethnicity, the difference for ATR astigmatism became nonsignificant. There were no significant gender differences in the prevalence of oblique RA. The prevalence of WTR RA was significantly higher in East Asian, Middle Eastern, and South Asian children compared to European Caucasian children. East Asian children had a remarkably low prevalence of ATR RA compared to European Caucasian children. Children from the ethnic groups in the "Other" category had a significantly higher prevalence of WTR and a significantly lower prevalence of ATR astigmatism compared to European Caucasian children. There were no ethnic differences in the prevalence of oblique RA, and no significant variations in axis distribution with SEq refraction were present.

We found a marginally significant higher prevalence of WTR axis of CA in girls, while the gender difference in oblique CA was borderline nonsignificant. The prevalence of ATR astigmatic axes did not differ by gender. Apart from a significantly higher prevalence of WTR and a significantly lower prevalence of ATR axis in East Asian children compared to European Caucasian children, there were no ethnic differences in the axis of CA. There was also no significant variation in axis distribution with SEq refraction.

There was a higher prevalence of ATR axis and a lower prevalence of oblique axis of IA in girls than in boys. However, the gender difference in the prevalence of WTR axis was not significant. South Asian children had a significantly higher prevalence of oblique axis of IA compared to European Caucasian children. However, the CI was quite wide. East Asian children had a marginally nonsignificant greater prevalence of oblique IA, which became significant after adjusting for gender. Apart from this, there were no ethnic differences in distribution of the axis of IA, and there were no significant variations with spherical equivalent refraction.

Relationship between CA and RA

The correlation between corneal and refractive J_0 was 0.76 ($P < 0.0001$), and for J_{45} was 0.45 ($P < 0.0001$). There was no RA in 732 children, whose corresponding mean level of CA was −0.7 D (range 0 to −1.95 D). Further linear regression analyses were performed with and without these 732 children, adjusting for gender, ethnicity, and SEq refraction.

Relationship between Corneal and Refractive J_0. A plot of the relationship between corneal and refractive J_0 is shown in Figure 2A. The plot shows that almost all values were below the line of unit slope. Thus, most children had more CA than RA along the Cartesian axes.

When the analysis was performed using data from all children, the slope of the relationship between corneal and refractive J_0 differed significantly among children with different refractions (all $P < 0.02$), being lowest in the reference group (0.41; SEq 1.01–1.50 D). The slope for both children with myopia (SEq ≤ -0.50 D) and children with emmetropia (SEq −0.49 to 0.50 D) was 0.80. Among the three hyperopic groups (SEq 0.51–1.00, 1.51–2.00, and >2.00 D), the slope was 0.54, 0.55, and 0.80, respectively. The slope did not appear to depend on gender (P = 0.8) but was steeper in East Asian children compared to European Caucasian children (P = 0.02). This could be due to a higher proportion of East Asian children (3%) than European Caucasian children (0.2%) with a relatively high level of corneal J_0 (>1.3). In nonlinear analyses, the slope of the relationship between corneal and refractive J_0 was steeper at high positive (WTR) values of corneal J_0 than at low positive (WTR) or low negative (ATR) values.

At mean levels of corneal J_0, the adjusted mean refractive J_0 was significantly higher in boys than in girls (0.07 vs. 0.03; $P < 0.0001$) and in East Asian (0.07; $P < 0.0001$), Middle Eastern (0.05; P = 0.004), and South Asian children (0.11; $P < 0.0001$) than in European Caucasian children (0.0006). There were also no significant differences in mean refractive J_0 for the various refraction categories ($P > 0.2$). Since the relationship between corneal and refractive J_0 varies with SEq refraction, mean refractive J_0 at other values of corneal J_0 may differ significantly between the refraction categories.

When children with no RA were excluded from the analyses, the slopes were generally steeper and the means were generally higher. Ethnicity had no significant effect. Differences between gender and refraction categories were unchanged except that the greater slope for two hyperopic groups (SEq 0.51–1.00 and 1.51–2.00 D) became nonsignificant.

Relationship between Corneal and Refractive J_{45}. A plot of the relationship between corneal and refractive J_{45} is shown in Figure 2B. The plot shows values for corneal and refractive J_{45} distributed fairly evenly on either side of a line of unit slope.

When the analysis was performed using data from all children, the slope of the relationship between corneal and refractive J_{45} differed significantly among children with different refractions, but did not appear to depend on gender (P = 0.3) or ethnicity (P = 0.7). The slope was higher ($P < 0.01$) in children with myopia (0.65, SEq ≤ -0.50 D), emmetropia (0.48, SEq −0.49 to 0.50 D), or hyperopia (0.57, SEq $>$ 2.00 D) than in children in the reference group (0.16, SEq 1.01–1.50 D). It was not significantly higher in two hyperopic groups (0.24, SEq 0.51–1.00 D; 0.20, SEq 1.51–2.00 D).

At mean levels of corneal J_{45}, adjusted mean refractive J_{45} did not differ significantly between boys and girls (P = 0.1),

Table 2. Mean Right-Eye RA, CA, and IA of Children with Both Keratometry and Autorefraction Data, Adjusted for Cluster Sampling

		RA (D)		CA (D)		IA (D)	
Characteristic	***n* (%)**	**Mean (95% CI)**	***P*-Value**	**Mean (95% CI)**	***P*-Value**	**Mean (95% CI)**	***P*-Value**
Whole group	1712	−0.29 (−0.32 to −0.26)		−0.82 (−0.87 to −0.77)		−0.76 (−0.78 to −0.74)	
Gender							
Boys	868 (50.7)	−0.28 (−0.31 to −0.25)	Referent	−0.80 (−0.84 to −0.76)	Referent	−0.72 (−0.74 to −0.70)	Referent
Girls	844 (49.3)	−0.31 (−0.35 to −0.27)	0.01*	−0.84 (−0.90 to −0.78)	0.01	−0.79 (−0.82 to −0.77)	<0.0001
Ethnicity							
European Caucasian	1101 (64.3)	−0.26 (−0.28 to −0.23)	Referent	−0.75 (−0.79 to −0.72)	Referent	−0.75 (−0.77 to −0.73)	Referent
East Asian	292 (17.1)	−0.44 (−0.53 to −0.36)	<0.0001	−1.05 (−1.13 to −0.97)	<0.0001	−0.79 (−0.83 to −0.74)	0.1
Middle Eastern	85 (5.0)	−0.29 (−0.37 to −0.20)	0.5	−0.82 (−0.93 to −0.72)	0.2	−0.73 (−0.79 to −0.66)	0.4
South Asian†	40 (2.3)	−0.41 (−0.53 to −0.29)	0.02	−0.99 (−1.13 to −0.85)	0.002	−0.68 (−0.76 to −0.60)	0.08
Other‡	194 (11.3)	−0.28 (−0.32 to −0.24)	0.3	−0.85 (−0.93 to −0.77)	0.02	−0.77 (−0.82 to −0.73)	0.4
SEq refraction (D)							
≤−0.50	25 (1.5)	−0.65 (−0.84 to −0.46)	<0.0001	−1.10 (−1.36 to −0.84)	0.01	−0.81 (−0.91 to −0.71)	0.1
−0.49 to 0.50	134 (7.8)	−0.42 (−0.54 to −0.29)	0.002	−0.86 (−0.95 to −0.77)	0.048	−0.76 (−0.82 to −0.71)	0.4
0.51 to 1.00	386 (22.4)	−0.29 (−0.32 to −0.27)	<0.0001	−0.79 (−0.84 to −0.74)	0.3	−0.76 (−0.79 to −0.73)	0.3
1.01 to 1.50	699 (40.6)	−0.22 (−0.24 to −0.20)	Referent	−0.77 (−0.81 to −0.73)	Referent	−0.74 (−0.76 to −0.72)	Referent
1.51 to 2.00	301 (17.5)	−0.27 (−0.31 to −0.23)	0.01	−0.80 (−0.88 to −0.72)	0.4	−0.74 (−0.78 to −0.70)	0.9
>2.00	179 (10.4)	−0.49 (−0.61 to −0.38)	<0.0001	−1.04 (−1.17 to −0.90)	<0.0001	−0.83 (−0.89 to −0.78)	0.0003

* Not significant after adjusting for ethnicity, parental education, and SEq refraction.
† Indian/Pakistani/Sri Lankan.
‡ Ethnic groups include Polynesian/Melanesian, South American, Indigenous Australian, African, and mixed.

TABLE 3. Prevalence of Different Types of Axis of Right-Eye RA, CA, and IA by Gender and Ethnicity

Astigmatism Type	WTR		ATR		Oblique	
	% (95% CI)	*P*-Value	% (95% CI)	*P*-Value	% (95% CI)	*P*-Value
RA (n = 992)						
Whole group	31.6 (26.5–37.7)		28.7 (23.8–34.5)		39.1 (35.9–42.6)	
Gender						
Boys	34.3 (28.7–41.1)	Referent	26.4 (21.7–32.2)	Referent	38.1 (34.7–41.9)	Referent
Girls	28.9 (23.6–35.4)	0.02	30.9 (25.3–37.9)	<0.05*	40.1 (35.7–44.9)	0.4
Ethnicity						
European Caucasian	23.3 (19.3–28.1)	Referent	38.4 (33.6–43.9)	Referent	38.5 (34.3–43.2)	Referent
East Asian	49.6 (43.0–57.2)	<0.0001	5.8 (4.0–8.5)	<0.0001	38.9 (33.9–44.6)	0.9
Middle Eastern	41.0 (27.8–60.6)	0.006	–†	–†	41.2 (27.2–62.6)	0.8
South Asian‡	63.8 (47.0–86.6)	<0.0001	–†	–†	33.6 (19.1–59.1)	0.6
Other§	34.5 (26.1–45.5)	0.01	22.1 (14.2–34.5)	0.007	42.9 (33.5–54.9)	0.4
CA (n = 1693)						
Whole group	75.1 (72.6–77.8)		2.1 (1.5–3.1)		22.7 (20.4–25.3)	
Gender						
Boys	73.2 (70.1–76.4)	Referent	2.1 (1.4–3.1)	Referent	24.7 (21.9–27.9)	Referent
Girls	77.2 (73.9–80.6)	<0.05	2.2 (1.4–3.4)	0.9	20.6 (17.5–24.3)	0.051
Ethnicity						
European Caucasian	73.0 (70.1–75.8)	Referent	2.8 (1.9–4.0)	Referent	24.2 (21.6–27.2)	Referent
East Asian	81.9 (76.3–88.0)	0.004	0.4 (0.06–2.1)	0.03	17.7 (12.6–25.0)	0.09
Middle Eastern	76.2 (67.7–85.7)	0.5	–†	–†	21.6 (14.6–32.0)	0.6
South Asian‡	77.4 (64.2–93.6)	0.6	–†	–†	22.6 (11.8–43.3)	0.8
Other§	77.2 (71.1–83.8)	0.2	1.6 (0.6–4.5)	0.3	21.2 (16.3–28.0)	0.4
IA (n = 1702)						
Whole group	0.6 (0.3–1.0)		76.7 (74.2–79.3)		22.6 (20.1–25.4)	
Gender						
Boys	0.6 (0.2–1.3)	Referent	73.2 (70.0–76.8)	Referent	26.1 (22.7–30.0)	Referent
Girls	0.6 (0.2–1.3)	0.9	80.4 (77.0–83.9)	0.003	19.0 (15.8–22.8)	0.005
Ethnicity						
European Caucasian	0.5 (0.2–1.1)	Referent	78.5 (75.4–81.7)	Referent	20.8 (17.9–24.2)	Referent
East Asian	0.4 (0.1–1.7)	0.7	73.6 (68.4–79.3)	0.1	26.0 (21.0–32.3)	0.06‖
Middle Eastern	–†	–†	72.1 (63.6–81.7)	0.2	25.5 (18.5–35.0)	0.2
South Asian‡	–†	–†	62.1 (47.8–80.7)	0.08	38.3 (25.0–58.6)	0.008
Other§	0.5 (0.1–3.8)	0.9	76.4 (71.9–81.3)	0.5	22.9 (18.9–27.7)	0.4

* Nonsignificant after adjusting for ethnicity (P = 0.2).
† Numbers were too small for meaningful analysis.
‡ Indian/Pakistani/Sri Lankan.
§ Ethnic groups include Polynesian/Melanesian, South American, Indigenous Australian, African, and mixed.
‖ Significant after adjusting for gender (P = 0.04).

but was significantly higher in South Asian than European Caucasian children (0.002 vs. −0.031, P = 0.008), and significantly lower in children with emmetropia (−0.06, P = 0.005), very mild hyperopia (−0.023; P = 0.007), or moderate hyperopia (−0.035; P = 0.04) compared to children in the reference group (−0.01). Since the relationship between corneal and refractive J_{45} varies with SEq refraction, these differences in mean refractive J_{45} may change for other values of corneal J_{45}.

When children with no RA were excluded from the analyses, slopes were generally steeper and means generally higher. Differences between gender, ethnic, and refraction categories were unchanged, except that the difference in mean refractive J_{45} between children with hyperopia (SEq > 2.00 D) and children in the reference group (SEq 1.01–1.50 D) became nonsignificant (P = 0.1). In nonlinear analyses, the slope of the relationship between corneal and refractive J_{45} was flatter for corneal J_{45} values close to zero.

DISCUSSION

Prevalence of Astigmatism

In this population of predominantly 6-year-old children with a mildly hyperopic mean SEq refraction (1.26 D) and a mix of ethnicities, we found a relatively low prevalence of RA, even when using different definitions, in comparison to the prevalence findings from many other populations (Table 4). Comparison of prevalence rates of astigmatism between studies is difficult because different definitions have been used. Most previous studies used 1.0 D as a cutoff. This is usually considered to be a clinically significant level of astigmatic error. In determining the most appropriate definition, however, other potentially important factors include age-related changes in the level of astigmatism, because the incidence and degree of astigmatism appear to be highest in the first two years of life,[31,32] and the possible effect of different magnitudes of astigmatism on the development of spherical refractive errors.[1,2]

The prevalence of astigmatism in this population is similar to that found for similarly aged children in urban India,[18,20] urban Xiamen in China,[33] and Caucasian children in England.[15] However, the studies conducted by Fuller et al.[15] and Zhang et al.[33] may not be representative of the general population due to relatively small sample sizes and a subsequent greater likelihood of selection bias. The low prevalence rates found in these studies could also have resulted, at least in part, from the use of retinoscopy rather than auto-refraction, as was reported in studies by Dandona et al.[6] and Murthy et al.[20] The prevalence of astigmatism found in the present study was slightly higher compared to children in rural India[6] and Vanuatu.[34]

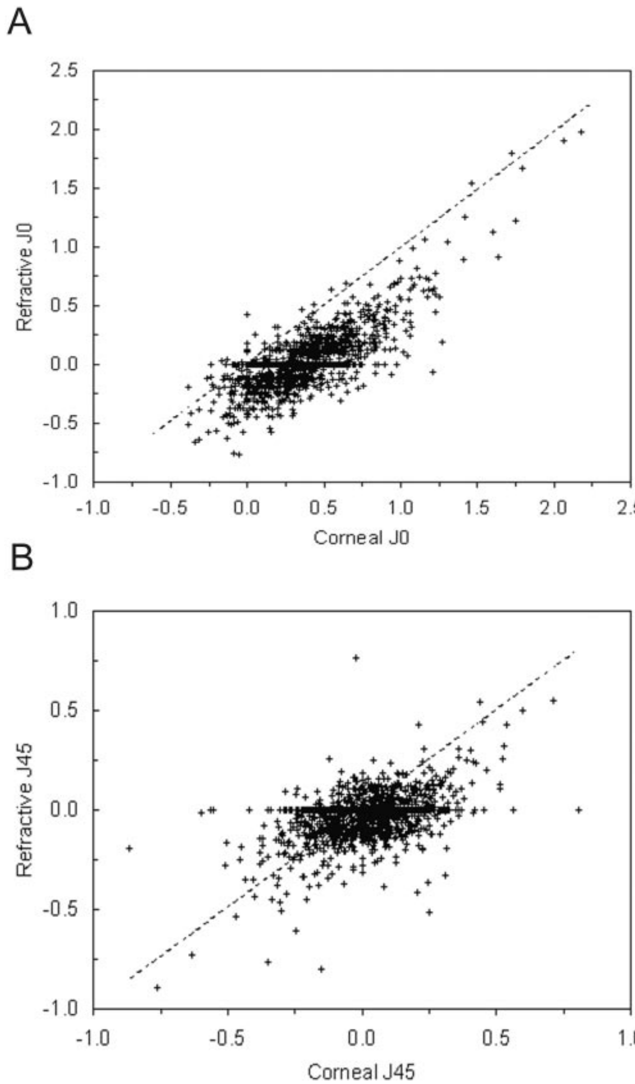

FIGURE 2. Scatter plots of corneal versus refractive Cartesian astigmatism (J_0 vector) (**A**), and corneal versus refractive oblique astigmatism (J_{45} vector) (**B**). The *dashed line* in each plot has a slope of 1.

Past studies have also documented the marked ethnic variability of RA. In general, these studies report a higher prevalence of astigmatism in East Asian[1,7,16,17,19,33] and Native American children[8–10] than in Caucasian children[7,15,35] of similar age. When the data were stratified, we also found that the prevalence and mean of RA were lowest in European Caucasian children compared to East Asian and South Asian children. The low overall prevalence of astigmatism (≥1.00 D) in the present study thus reflects the predominance of European Caucasian children.

Ethnic variability of RA may also be confounded by the effect of spherical refractive error and CA. A number of studies have shown an association between RA and myopia,[2–5] while fewer have shown an association with hyperopia.[36,37] In the present study, rates of RA (≥1.00 D) varied between ethnic groups even when adjusted for the effects of gender, SEq refraction, and socioeconomic factors. The greater rates of CA in East Asian and South Asian children compared to European Caucasian children may also contribute to the higher rates of RA in these children.

Many previous studies have reported finding no gender differences in RA.[1,10,16,18,38] However, the findings from a number of larger, population-based studies have been inconclusive.[6,19,20] Dandona et al.[6] and Murthy et al.[20] both reported gender differences in refractive astigmatism in right eyes, but not in left eyes. He et al.[19] reported significant gender differences with retinoscopy but not with auto-refraction or for astigmatism > 2.0 D. Even in studies conducted in Native American children, who have relatively high degrees of CA, the association of gender with RA was not clear.[10,39] We found that girls had greater mean RA than boys, which is consistent with findings by Maples et al.[39] However, this gender difference in mean RA was very small and should be interpreted with caution, because the distribution was extremely skewed and the difference was not significant after adjusting for ethnicity, parental education, and SEq refraction. The differences between our findings and those of previous reports may be due to differences in instrumentation, examination technique, or differences in the use of cycloplegic agents. In addition, a number of previous studies appeared to have presented only univariate findings on gender.[1,10,38]

Marked ethnic variability of CA has been reported in a number of studies conducted in both children and adults.[12,14,39–42] In Navajo Indian preschool children, Garber[13] reported a relatively high prevalence (68.5%) of CA ≥ 1.0 D, while 31% of the children had CA ≥ 2.0 D. The range of CA reported by Maples et al.[39] in Navajo children aged 6 years was 1.9 to 2.2 D. Children examined in the present study had a comparatively low prevalence of CA, but ethnic differences were apparent by all definitions. Adult levels of CA tend to be lower than in children, but similar ethnic differences have been reported, such as between Nigerian adults[40] (mean 0.61 D) and a sample of adults attending an optometry clinic in the United States[42] (mean 0.38 D). Ethnic differences in CA could be related to possible differences in genetic background,[43,44] eyelid tension,[45] or intraocular pressure,[46] but these associations need to be confirmed in future research.

To our knowledge, there have been no large population-based reports of the distribution of IA in children. Previous reports were drawn from studies of clinic records,[39] university students,[47] or selected groups.[8] In the present study, we found that mean IA was slighter greater in girls and in children with more hyperopic refractions, but did not vary significantly with ethnic background. The mean IA found in our study was similar to that reported by Anstice[41] in children of similar age, but was higher than that reported by Dunne et al.[47] (mean 0.50 D). Participants in the study by Dunne et al.[47] were university students, suggesting that there may be an age-related difference in IA. The difference could also be partly explained by the use of cycloplegia in our study. The lack of variation of IA with ethnicity is consistent with the study by Dobson et al.[8] of 250 Tohono O'Odham Indian children aged 3 to 5 years, in whom the reported mean IA measured using two different keratometers was 0.75 to 0.86 D. We found that the effect of SEq refraction on IA was independent of any effects of gender and ethnicity.

Distribution of Components of Astigmatism and Emmetropization

We found a near-exponential distribution of RA in which there was a high prevalence of low astigmatic errors. This is similar to findings in adults[13,48] and in children[1,9,10,16] with a higher prevalence of myopia. Previous studies have also reported on the less leptokurtic distribution of CA[8–10,34,49] and IA,[8,47] the predominantly WTR orientation of CA[14,39] and RA,[15–17,32,35,50] and the predominantly ATR orientation of IA.[41,47,51] However, this may be the first report on the distribution of CA and IA in a large, population-based sample of young children with a mix of ethnic backgrounds. Our finding of a fairly even distribution

Table 4. Prevalence of Astigmatism in Other Countries

Study	Country	Study Population	Age (y)	*n*	Refraction Method	Myopia* Prevalence (%)	Astigmatism Definition (D)	Astigmatism Prevalence (%)
Current study	Australia	Urban, population-based	6–7	1765	C, A	1.4	≥0.75	10.3
							≥1.0	4.8
Dandona et al.[6]	India	Rural, population-based	7–15	4074	C, A	4.1	≥0.75	5.9
Murthy et al.[20]	India	Urban, population-based	5–15	6447	C, A	7.4	≥0.75	9.8
Dandona et al.[18]	Southern India	Urban, population-based	≤15	663	C, R	4.4†	≥1.0	3.8‡
Kalikivayi et al.[38]	Southern India	Urban, population-based	3–18	4029	C,§ SR	8.6	≥0.5	8.7‖
Garner et al.[34]	Vanuatu	Melanesian children from 4 schools	6–19	788	NC, R	2.8	≥1.0	0.3
Fuller et al.[15]	United Kingdom	Bangladeshi children from 1 urban school	5.7¶	31	NC, R	NR	>1.0	22.6
	United Kingdom	Caucasian children from 1 urban school	6¶	31	NC, R	NR		3.2
Gwiazda et al.[32]	United States	Children from day care, nursery schools, camps, and birth registry	0–6	1000	NC, R	NR	≥1.0	39.0
Parssinen[2]	Finland	Schoolchildren with myopia and ≤2 D astigmatism	10.9¶	238	C, SR	−0.25 to −3#	≥1.0	3.8
Dobson et al.[8]	United States	Tohono O'Odham Indian (Head Start program)	3–5	250	C, R	NR	≥1.0	44.0
Pensyl et al.[10]	United States	Sioux Indian clinic subjects	0–19	174	C, A	18.8	≥1.0	44.2
Heard et al.[9]	United States	Zuni Indian schoolchildren	K–6**	420	R	NR	≥1.0	50
Fan et al.[1]	Hong Kong	Children from 2 kindergartens	2–6.4	522	C, A	NR	≥1.0	21.1
He et al.[19]	China	Urban, population-based (Guangzhou)	5–15	4364	C, A	5.7	≥0.75	42.7
Shih et al.[17]	Taiwan	Urban, population-based	7–18	11175	C, A	20	≥1.0	18.4
Zhang et al.[33]	China	Children from 1 urban school (Xiamen)	6–7	132	C, A	9.1†	>1.0	6.8
	China	Children from 1 rural school (Xiamen)	6–7	104	C, A	3.9†		8.7
	Singapore	Children from 1 urban school	6–7	146	C, A	12.3†		17.1
Tong et al.[16]	Singapore	Children from 2 schools	7–9	1028	C, A	32	≥1.0	19.2
Kleinstein et al.[7]	United States	Population-based—Overall	5–17	2523	C, A	10.5	≥1.0	28.4
	United States	African American		534		8.6		20.0
	United States	Asian		491		19.8		33.6
	United States	Hispanic		463		14.5		36.9
	United States	White		1034		5.2		26.4
Kawuma and Mayeku[30]	Uganda	Population-based	6–9	623	C, R		NR	52

C, cycloplegic; A, autorefraction; R = retinoscopy; SR, subjective refraction; NC, noncycloplegic; NR, not reported.
* Defined as SEq ≤ −0.5 D unless indicated.
† Prevalence defined for SEq < −0.5 D.
‡ Astigmatism in the worse eye.
§ Performed only for children with hyperopia.
‖ Prevalence for children <10 y old.
¶ Mean age.
\# Range of SEq refraction.
** Schoolchildren from kindergarten to grade 6.

of the axis of RA, with a slight predominance of oblique axis, contrasts with previous reports.[15–17,32,35,50] The prevalence of oblique axis in the present study is higher than that found in studies that used the same definitions[32,50] or different definitions for axes.[15–17,35] This could be due to the relatively high prevalence of oblique axis for both CA and IA, the mirror-image distribution of the axes of CA and IA, or the wide category used for oblique astigmatism when compared to studies that used narrower definitions.[15,17]

Considering the distribution data in Figure 1, it is apparent that compensation occurs between CA and IA to minimize the magnitude of RA. However, it is not possible to determine the nature of the compensatory process from these cross-sectional data. We found slight but significant increases in the magnitude of both CA and IA with more hyperopic refractions. These processes occurred in the absence of significant changes in the axis of both components of astigmatism with greater hyperopia.

The existence of this compensatory process was also evident from the relationship between corneal and refractive J_0 and J_{45}, since without compensation, the slope of this relationship should be 1. We found the slope to be <1 for both vectors. Of the three possibly influential variables examined in the present study, only SEq refraction had a substantial effect on the strength of these relationships in multivariable-adjusted analyses. The slope of the relationship increased in children who had myopia (SEq < −0.50 D), emmetropia (SEq −0.49–0.50 D), or moderate hyperopia (SEq > 2.00 D) compared to those with refractions near the population mean (SEq 1.01–1.50 D). This suggests that compensation becomes less complete when refraction of the eye becomes more myopic or more hyperopic. The lower adjusted mean refractive J_0 found in European Caucasian children compared to East Asian, Middle Eastern, and South Asian children also suggests that compensation of Cartesian astigmatism may be more complete in European Caucasian children than in children of other ethnic groups.

These results contrast with those reported by Shankar et al.,[52] who did not find evidence of compensation when 3- to 5-year-old children with higher and lower degrees of RA (≥1.00 and (≤0.75 D, respectively) were compared. However, the authors noted that their study was limited by the small sample size. Whether the compensatory mechanism found in the present study represents an active emmetropization or a passive process needs to be confirmed. In a recent study of 30 adult subjects using a Hartmann-Shack aberrometer, Kelly et al.[53] found a significant negative correlation ($r = -0.524$, $P = 0.0025$) between corneal and internal horizontal/vertical astigmatism and concluded that there was active compensation between these two components. Since this compensation process was found to be individual-specific, they also proposed that it involved a feedback-driven fine-tuning process.

Strengths of the present study include its large, population-based sample, the detailed structured examination, the use of cycloplegic refraction, and the use of a vector method of analysis that takes into account the exact astigmatic axis. A possible weakness of the study is that CA was calculated using an assumed refractive index, and no account was taken of any possible variations of astigmatism of the posterior surface of the cornea.

In summary, in this Australian population of young children, we found relatively low overall prevalence of RA and CA that did not vary significantly with gender. Children of East Asian and South Asian origin had significantly greater RA and CA than European Caucasian children. However, there were no ethnic differences in IA. The magnitude of all components of astigmatism varied significantly with refraction. We found a fairly uniform distribution of the axis of RA, with oblique astigmatism being slightly predominant. In contrast, the axis of CA was largely WTR, and the axis of IA was largely ATR. The distribution of axes of all components of astigmatism generally varied with gender and ethnicity, but not with refraction. Findings on the relationship between CA and RA suggest that a compensatory process exists between CA and IA to minimize RA, but this compensation appears to be less complete with more myopic and more hyperopic refractions, and in non–European Caucasian ethnic groups.

References

1. Fan DS, Rao SK, Cheung EY, et al. Astigmatism in Chinese preschool children: prevalence, change, and effect on refractive development. *Br J Ophthalmol*. 2004;88:938–941.
2. Parssinen O. Astigmatism and school myopia. *Acta Ophthalmol (Copenh)*. 1991;69:786–790.
3. Gwiazda J, Grice K, Held R, et al. Astigmatism and the development of myopia in children. *Vision Res*. 2000;40:1019–1026.
4. Fulton AB, Hansen RM, Petersen RA. The relation of myopia and astigmatism in developing eyes. *Ophthalmology*. 1982;89:298–302.
5. Kaye SB, Patterson A. Association between total astigmatism and myopia. *J Cataract Refract Surg*. 1997;23:1496–1502.
6. Dandona R, Dandona L, Srinivas M, et al. Refractive error in children in a rural population in India. *Invest Ophthalmol Vis Sci*. 2002;43:615–622.
7. Kleinstein RN, Jones LA, Hullett S, et al. Refractive error and ethnicity in children. *Arch Ophthalmol*. 2003;121:1141–1147.
8. Dobson V, Miller JM, Harvey EM. Corneal and refractive astigmatism in a sample of 3- to 5-year-old children with a high prevalence of astigmatism. *Optom Vis Sci*. 1999;76:855–860.
9. Heard T, Reber N, Levi D, Allen D. The refractive status of Zuni Indian children. *Am J Optom Physiol Opt*. 1976;53:120–123.
10. Pensyl CD, Harrison RA, Simpson P, Waterbor JW. Distribution of astigmatism among Sioux Indians in South Dakota. *J Am Optom Assoc*. 1997;68:425–431.
11. Kame RT, Jue TS, Shigekuni DM. A longitudinal study of corneal astigmatism changes in Asian eyes. *J Am Optom Assoc*. 1993;64:215–219.
12. Garber JM. High corneal astigmatism in Navajo school children and its effect on classroom performance. *J Am Optom Assoc*. 1981;52:583–586.
13. McKendrick AM, Brennan NA. Distribution of astigmatism in the adult population. *J Opt Soc Am A*. 1996;13:206–214.
14. Garber JM, Hughes J. High corneal astigmatism in the adult Navajo population. *J Am Optom Assoc*. 1983;54:815–818.
15. Fuller JR, Baxter LA, Harun S, Levy IS. Astigmatism in Bangladeshi and white school entrants in East London: a prospective comparative study. *Eye*. 1995;9:794–796.
16. Tong L, Saw SM, Carkeet A, et al. Prevalence rates and epidemiological risk factors for astigmatism in Singapore school children. *Optom Vis Sci*. 2002;79:606–613.
17. Shih YF, Hsiao CK, Tung YL, et al. The prevalence of astigmatism in Taiwan schoolchildren. *Optom Vis Sci*. 2004;81:94–98.
18. Dandona R, Dandona L, Naduvilath TJ, et al. Refractive errors in an urban population in Southern India: the Andhra Pradesh Eye Disease Study. *Invest Ophthalmol Vis Sci*. 1999;40:2810–2818.
19. He M, Zeng J, Liu Y, et al. Refractive error and visual impairment in urban children in southern china. *Invest Ophthalmol Vis Sci*. 2004;45:793–799.
20. Murthy GV, Gupta SK, Ellwein LB, et al. Refractive error in children in an urban population in New Delhi. *Invest Ophthalmol Vis Sci*. 2002;43:623–631.
21. Grosvenor T, Quintero S, Perrigin DM. Predicting refractive astigmatism: a suggested simplification of Javal's rule. *Am J Optom Physiol Opt*. 1988;65:292–297.
22. Auger P. Confirmation of the simplified Javal's rule (Letter). *Am J Optom Physiol Opt*. 1988;65:915.
23. Grosvenor T, Ratnakaram R. Is the relation between keratometric astigmatism and refractive astigmatism linear? *Optom Vis Sci*. 1990;67:606–609.

24. Keller PR, Collins MJ, Carney LG, et al. The relation between corneal and total astigmatism. *Optom Vis Sci*. 1996;73:86–91.
25. Lam AK, Chan CC, Lee MH, Wong KM. The aging effect on corneal curvature and the validity of Javal's rule in Hong Kong Chinese. *Curr Eye Res*. 1999;18:83–90.
26. Ojaimi E, Rose KA, Smith W, et al. Methods for a population-based study of myopia and other eye conditions in school-children: the Sydney Myopia Study. *Ophthalmic Epidemiol*. 2005;12:59–69.
27. Ojaimi E, Rose KA, Morgan IG, et al. Distribution of ocular biometric parameters in a population-based study of Australian children. *Invest Ophthalmol Vis Sci*. 2005;46:2748–2754.
28. Robaei D, Rose K, Ojaimi E, et al. Visual acuity and the causes of visual loss in a population-based sample of 6-year old Australian children. *Ophthalmology*. 2005;112:1275–1282.
29. Thibos LN, Wheeler W, Horner D. Power vectors: an application of Fourier analysis to the description and statistical analysis of refractive error. *Optom Vis Sci*. 1997;74:367–375.
30. Kawuma M, Mayeku R. A survey of the prevalence of refractive errors among children in lower primary schools in Kampala district. *Afr Health Sci*. 2002;2:69–72.
31. Abrahamsson M, Fabian G, Sjostrand J. Changes in astigmatism between the ages of 1 and 4 years: a longitudinal study. *Br J Ophthalmol*. 1988;72:145–149.
32. Gwiazda J, Scheiman M, Mohindra I, Held R. Astigmatism in children: changes in axis and amount from birth to six years. *Invest Ophthalmol Vis Sci*. 1984;25:88–92.
33. Zhan MZ, Saw SM, Hong RZ, et al. Refractive errors in Singapore and Xiamen, China—a comparative study in school children aged 6 to 7 years. *Optom Vis Sci*. 2000;77:302–308.
34. Garner LF, Kinnear RF, McKellar M, et al. Refraction and its components in Melanesian schoolchildren in Vanuatu. *Am J Optom Physiol Opt*. 1988;65:182–189.
35. Cowen L, Bobier WR. The pattern of astigmatism in a Canadian preschool population. *Invest Ophthalmol Vis Sci*. 2003;44:4593–4600.
36. Garber JM. The relation of astigmatism and hyperopia (more effective plus). *J Am Optom Assoc*. 1985;56:491–493.
37. Garber JM. Relation of astigmatism and hyperopia (Letter). *J Am Optom Assoc*. 1986;57:9.
38. Kalikivayi V, Naduvilath TJ, Bansal AK, Dandona L. Visual impairment in school children in southern India [published erratum appears in *Indian J Ophthalmol.* 1997;45:168]. *Indian J Ophthalmol*. 1997;45:129–134.
39. Maples WC, Herrmann M, Hughes J. Corneal astigmatism in preschool Native Americans. *J Am Optom Assoc*. 1997;68:87–94.
40. Kragha IK. Corneal power and astigmatism. *Ann Ophthalmol*. 1986;18:35–37.
41. Anstice J. Astigmatism—its components and their changes with age. *Am J Optom Arch Am Acad Optom*. 1971;48:1001–1006.
42. Baldwin WR, Mills D. A longitudinal study of corneal astigmatism and total astigmatism. *Am J Optom Physiol Opt*. 1981;58:206–211.
43. Clementi M, Angi M, Forabosco P, Di Gianantonio E, Enconi R. Inheritance of astigmatism: evidence for a major autosomal dominant locus. *Am J Hum Genet*. 1998;63:825–830.
44. Teikari JM, O'Donnell JJ. Astigmatism in 72 twin pairs. *Cornea*. 1989;8:263–266.
45. Wilson G, Bell C, Chotai S. The effect of lifting the lids on corneal astigmatism. *Am J Optom Physiol Opt*. 1982;59:670–674.
46. Ninn-Pedersen K. Relationships between preoperative astigmatism and corneal optical power, axial length, intraocular pressure, gender, and patient age. *J Refract Surg*. 1996;12:472–482.
47. Dunne MC, Elawad ME, Barnes DA. A study of the axis of orientation of residual astigmatism. *Acta Ophthalmol (Copenh)*. 1994;72:483–489.
48. Attebo K, Ivers RQ, Mitchell P. Refractive errors in an older population: the Blue Mountains Eye Study. *Ophthalmology*. 1999;106:1066–1072.
49. Friedman NE, Mutti DO, Zadnik K. Corneal changes in schoolchildren. *Optom Vis Sci*. 1996;73:552–557.
50. Dobson V, Fulton AB, Sebris SL. Cycloplegic refractions of infants and young children: the axis of astigmatism. *Invest Ophthalmol Vis Sci*. 1984;25:83–87.
51. Sarver MD. A study of residual astigmatism. *Am J Optom Arch Am Acad Optom*. 1969;46:578–582.
52. Shankar S, Bobier WR. Corneal and lenticular components of total astigmatism in a preschool sample. *Optom Vis Sci*. 2004;81:536–542.
53. Kelly JE, Mihashi T, Howland HC. Compensation of corneal horizontal/vertical astigmatism, lateral coma, and spherical aberration by internal optics of the eye. *J Vis*. 2004;4:262–271.