Monochromatic aberrations in hyperopic and emmetropic children

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We investigated differences in higher order monochromatic aberrations between hyperopic and emmetropic eyes from two large cohorts (mostly 6 and 12 year old) of Caucasian children. Additionally, we investigated the differences of higher order monochromatic aberrations between age groups. In both cohorts, hyperopic eyes had significantly higher levels of positive spherical aberration (SA) and higher orders (HO) RMS than emmetropic eyes. Higher levels of positive SA were also found in the older cohort (irrespectively of the refractive error) although this difference was statistically significant only for emmetropic, low hyperopic and moderate hyperopic eyes. The observed higher levels of positive SA found in hyperopic eyes could explain for the previously reported differences in accommodative responses between hyperopic and non-hyperopic eyes. Our results provide some evidence of a relationship between ocular changes that typically occur during eye growth and the observed levels of higher order aberrations in children eyes.

Keywords: hyperopia, monochromatic aberrations, human eye, spherical aberration, children, accommodation, Sydney Myopia Study, Sydney Childhood Eye Study


Introduction

Hyperopia is the resulting refractive error when pencils of light within an unaccommodated eye are intercepted by the retina before reaching their focus (Bennett & Rabbetts, 1998) (the circle of least confusion is formed behind the retina (Borish, 1970)). Hyperopia is a common refractive error in newborns and infants (Ehrlich et al., 1997; Gwiazda, Grice, Held, McLellan, & Thorn, 2000; Gwiazda, Thorn, Bauer, & Held, 1993; Ingram, 1979; Ingram & Barr, 1979; Saunders, Woodhouse, & Westall, 1995) and it has been estimated that approximately 88% of newborns have hyperopia of +1.00 D (Watanabe, Yamashita, & Ohba, 1999). However, a rapid decrease of hyperopia occurs thereafter until the eye reaches emmetropia usually by the age of 4 years (Mayer, Hansen, Moore, Kim, & Fulton, 2001) and this process occurs as a result of a series of physical changes (corneal flattening (Inagaki, 1986; York & Mandell, 1969), reduction of power of the crystalline lens (Garner, Yap, Kinnear, & Frith, 1995; Larsen, 1971b; Wood, Mutti, & Zadnik, 1996; Zadnik, 1997), and an increase of both the anterior (Larsen, 1971a) and posterior chamber (Garner et al., 1995; Larsen, 1971d) depths).

Hyperopia is a common refractive error in Australia in young children. The prevalence of low hyperopia (0.75 to 1.25 D) in children aged 4–12 has been reported to be 32.3% (Junghans & Crewther, 2005; Junghans, Kiely, Crewther, & Crewther, 2002). Recently, Ojaimi et al. (2005a) reported a prevalence of hyperopia (spherical equivalent [M] > 0.50 D) of 91% in children aged 6.7 years (range, 5.5–8.4 years). In addition, Ojaimi et al. (2005a)
found higher prevalence rates of hyperopia in children from a white European ethnic background (94.8%) in comparison to children from other ethnic backgrounds (84.1%). Higher prevalence rates of hyperopia in white children in comparison to other ethnic groups have been reported previously (Klein et al., 2003). Despite hyperopia being identified as a common refractive error in children, as well as being associated with different complications (amblyopia (Klimek, Cruz, Scott, & Davitt, 2004), strabismus (Tarczy-Hornoch, 2007), reduced reading efficiency and poor school performance (Grosvenor, 1970; Rosner & Rosner, 1997; Williams, Latif, Hannington, & Watkins, 2005; Young, 1963)), little attention has been given to the study of the ocular characteristics of the hyperopic eye in comparison to myopia research. A lower prevalence of hyperopia in young adult populations and in developed countries and its relative stability during life have been suggested as the causes for the decreased interest in the area (Strang, Schmid, & Carney, 1998). Another suggestion for a greater emphasis on myopia research in comparison to hyperopia is that myopia is commonly associated with poor vision and a range of associated pathological ocular changes which can contribute to permanent loss of vision (Grosvenor, 1971).

The ocular characteristics of hyperopic eyes may possibly explain the mechanisms involved in the development of the eye as it has been suggested that the final refractive state and axial length of the eye are not only predetermined by genetic factors, but, they are the result of an active vision-dependent mechanism (Goss & Criswell, 1981; Norton, 1999; Norton & Siegwart, 1995; Smith, Hung, & Harwerth, 1994; Wildsoet, 1997). Previous studies have suggested that defocus and higher order (HO) aberrations provide retinal image quality cues that drive the control of eye growth (Dieter & Schaeffel, 1997; Schaeffel & Howland, 1988; Wallman & Winawer, 2004; Wilson, Decker, & Roorda, 2002). It is therefore of interest to determine if hyperopic eyes have varying amounts of monochromatic ocular aberrations that could explain the condition.

The few studies that have looked at monochromatic aberrations of hyperopic eyes (Artal, Guirao, Berrio, & Williams, 2001; Carkeet, Luo, Tong, Saw, & Tan, 2002; Cheng, Bradley, Hong, & Thibos, 2003; Kirwan, O’Keefe, & Soeldner, 2006; Llorente, Barbero, Cano, Dorrorsoro, & Marcos, 2004) found mixed results. In a small group of adults (Llorente et al., 2004), hyperopic eyes were found to have higher values of total spherical aberration, third and higher order aberrations (PD = 6.5 mm) in comparison to myopes (although internal spherical aberration was not significantly different between hyperopic and myopic eyes). In addition, total spherical aberration was found to increase with age at a faster rate in hyperopic eyes. On the other hand, in a previous study with 19 hyperopic eyes (Cheng et al., 2003), there was no correlation between the variability of third, fourth and total higher aberrations RMS and the degree of ammetropia. Carkeet et al. (2002) reported data from 12 hyperopic (M > 1.00 D) children and found no differences between hyperopes and other refractive groups. In contrast, Kirwan et al. (2006) found children hyperopic eyes (n = 137) to have lower levels of higher-order aberrations (Total RMS, fourth order RMS, Z(3,—3), Z(3,—1), Z(3, 3), Z(4,—4), and Z(4, 2)) than children myopic eyes (n = 25).

The lack of agreement across these studies could be due to differences in age, ethnicity, and methodologies used for the measurement of aberrations. In order to obtain a better understanding of the optical changes associated during childhood, in this paper we report the characteristics of higher order monochromatic aberrations of hyperopic eyes and compare the data with those from emmetropic eyes in a large sample of Caucasian children. Data were collected from a sub-sample of Year 1 (mostly 6 year old) and Year 7 (mostly 12 year old) schoolchildren examined in the Sydney Myopia Study during the period 2003–2006. Data on myopic eyes from this sub-sample (4.1%) have been presented elsewhere (Martinez, Sankaridurg, Pandian, & Mitchell, 2006; Martinez, Sankaridurg, Rose, Mitchell, & John, 2006), thus they were not included in the current analysis.

Methods

Subjects

The Sydney Myopia Study was a population-based survey of refraction and other eye conditions in a large representative sample of Sydney school children. Methods of the Sydney Myopia Study have been described in detail elsewhere (Öjai et al., 2005b). Briefly, 34 primary schools and 21 high schools within the Sydney Metropolitan Area were randomly selected using a cluster-sampling design. Children in first and seventh grades of school were invited to participate. All examinations took place at the schools during school hours. Ethnicity information was collected from a 193-item questionnaire administered to the parents. Informed written consent from at least one parent and the verbal assent from each child were obtained. The study followed the tenets of the Declaration of Helsinki and received ethical approval from the University of Sydney Human Research Ethics Committee, and the New South Wales State Department of Education and Training, Australia.

Cycloplegia

Cycloplegia was induced using the same protocol in all children. Firstly, a single drop of 1% amethocaine hydrochloride (MINIMSTM, Chauvin Pharmaceuticals Ltd., England) was instilled in both eyes to improve comfort.
and to enhance the absorption of the subsequent drops (Mordi, Lyle, & Mousa, 1986). Cycloplegia/mydriasis of each eye was then attained with 2 cycles of cyclopentolate 1% (1 drop) and tropicamide 1% (1 drop) instilled 5 minutes apart. A small proportion of eyes that were slow to dilate received up to 2 drops of 2.5% phenylephrine. Refraction and aberrometry were obtained approximately 30 to 40 minutes after the last drop was instilled.

**Data collection**

Determination of refractive error and ocular aberrations was done using a commercial Shack-Hartmann aberrometer (Complete Ophthalmic Analysis System (COAS); Wavefront Sciences, Inc., Albuquerque, NM). One reading from each eye was obtained and recorded for analysis using a 5-mm pupil diameter. We have shown this approach to reliably measure refractive errors in young children (Martinez, Pandian et al., 2006). The calculation of refractive error included the “Seidel Sphere” option which incorporates the primary spherical aberration in the calculation of the spherical equivalent (Salmon, West, Gasser, & Kenmore, 2003). Refractive data were converted into power vectors (Thibos, Wheeler, & Horner, 1997) for analysis.

Zernike coefficients up to the 6\textsuperscript{th} order were fitted to the aberrometry data from each eye using the standards recommended by the VSIA of the Optical Society of America (OSA) (Thibos, Applegate, Schwiegerling, & Webb, 2000). The root-mean square (RMS) of defocus $Z(2,0)$, coma (combination of $Z(3,-1)$ and $Z(3,1)$), third orders (combination of $Z(3,-3)$, $Z(3,-1)$, $Z(3,1)$, and $Z(3,3)$), spherical aberration (SA) $Z(4,0)$, fourth orders (combination of $Z(4,-4)$, $Z(4,-2)$, $Z(4,2)$, and $Z(4,4)$), and higher order (HO) aberrations (third to sixth orders) (Atchison, 2004) was also calculated. To evaluate the association of refractive error and SA with physical ocular characteristics, axial length (AL) and central corneal radius of curvature (CR) were measured using an IOLMaster™ (Carl Zeiss, Meditec, Germany) (Vogel, Dick, & Krummenauer, 2001). The IOLMaster™ has been found to be a reliable and accurate instrument for measuring AL in adults (Lam, Chan, & Pang, 2001; Santodomingo-Rubido, Mallen, Gilmartin, & Wolffsohn, 2002; Sheng, Bottjer, & Bullimore, 2004; Vogel et al., 2001) and in children (Carkeet, Saw, Gazzard, Tang, & Tan, 2004; Hussin, Spry, Majid, & Gouws, 2005). Five valid readings of AL pre-cycloplegia were obtained from both eyes. Central corneal radius of curvature (CR) was defined as the mean radius taken along the two principal meridians (Grosvenor & Scott, 1994).

**Data analysis**

Definition of refractive error based on M was as follows: emmetropia ($M > -0.50$ and $<-0.50$ D), low hyperopia ($M > +0.50$ and $<+1.00$ D), moderate hyperopia ($M > +1.00$ D to $+3.00$ D) and high hyperopia ($M > +3.00$ D). Cases with cylinders $>-1.00$ D in one or both eyes were considered to be astigmatic and thus, excluded from this study. Data analysis was performed using SPSS (Version 15.0) statistical software. One-way Analysis of Variance (ANOVA) using Brown-Forsythe (B-F) statistic was used to test for differences in aberrometry data between refractive error groups. Multiple comparisons were performed using Games-Howell (G-H) test. Difference in the distribution of refractive errors between cohorts was tested using chi-squared ($\chi^2$) statistic. Independent samples $t$-test was used to test for differences in power vectors within RE groups between age groups. To analyze whether differences in HO aberrations within RE groups existed between age groups, multivariate-adjusted analyses of variance (MANOVA) were performed. Higher order Zernike coefficients and RMS were the dependent variables and significance levels were calculated using Pillai’s trace. Adjusted-multiple comparisons Bonferroni test was used to test for differences within RE groups between age groups. The level of significance was set at $p < 0.05$.

**Results**

**Biometric and refractive data**

Data from a total of 1414 Caucasian children (771 Year 1 [S1]; 643 Year 7 [S2]) were included in this analysis. Table 1 presents the biometric data for gender and age of the 1414 children. No differences in age existed between refractive error groups in both cohorts (B-F $0.49 \, df_f:3 \, df_r:111.51, \, p = 0.684$ [S1]; B-F $2.52 \, df_f:3 \, df_r:43.54, \, p = 0.071$ [S2]).

**Refractive and biometric data within cohorts**

The results of the refractive components and ocular physical characteristics for the different refractive error groups are as follows:

<table>
<thead>
<tr>
<th>Gender</th>
<th>n (%)</th>
<th>Mean ± SD (years)</th>
<th>Range</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Year 1 group (S1)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>403 (52%)</td>
<td>6.8 ± 0.4</td>
<td>5.8 to 7.8</td>
<td>0.684</td>
</tr>
<tr>
<td>Female</td>
<td>368 (48%)</td>
<td>6.7 ± 0.4</td>
<td>5.7 to 7.9</td>
<td></td>
</tr>
<tr>
<td>All subjects</td>
<td>771 (100%)</td>
<td>6.7 ± 0.4</td>
<td>5.7 to 7.9</td>
<td></td>
</tr>
<tr>
<td><strong>Year 7 group (S2)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>325 (51%)</td>
<td>12.6 ± 0.4</td>
<td>11.2 to 13.9</td>
<td>0.071</td>
</tr>
<tr>
<td>Female</td>
<td>318 (48%)</td>
<td>12.6 ± 0.4</td>
<td>11.5 to 13.6</td>
<td></td>
</tr>
<tr>
<td>All subjects</td>
<td>643 (100%)</td>
<td>12.6 ± 0.5</td>
<td>11.2 to 13.9</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Age distribution by gender among the 1414 children.
groups are presented in Tables 2 and 3 respectively. For both the cohorts, a high correlation was found for M between right and left eyes ($r = 0.872$, $p < 0.001$ [S1]; $r = 0.802$, $p < 0.001$ [S2]) and therefore, further analyses were performed using right eyes data only. Mean M was +1.27 ± 0.66 D (S1) and +0.92 ± 0.78 D (S2).

The distribution of refractive error groups across both cohorts was: emmetropes (6.9%, S1; 23.3%, S2), low hyperopes (27.9%, S1; 38.6%, S2), moderate hyperopes (63.7%, S1; 36.4%, S2), and high hyperopes (1.6%, S1; 1.7% S2). The difference in distribution of refractive error groups between cohorts was significant ($\chi^2 = 129.320$, $p < 0.001$).

As expected, differences existed between all refractive error groups for M (B-F 331.17 df1:3 df2:17.17, $p < 0.001$ [S1]; B-F 125.93 df1:3 df2:11.28, $p < 0.001$[S2], multiple comparisons $p < 0.001$). From the astigmatic components, a small difference was found for $J_{45}$ (B-F 3.30 df1:3 df2:40.71, $p = 0.03$) between S1 low hyperopes and moderate hyperopes only ($p = 0.011$). No differences were found in the mean values of central corneal radius of curvature between refractive error groups in both cohorts ($p < 0.05$). On the other hand, differences in axial length existed between refractive error groups (B-F 17.76 df1:3 df2:77.39, $p < 0.001$ [S1]; B-F 32.37 df1:3 df2:73.91, $p < 0.001$[S2]). High and moderate hyperopic eyes were significantly shorter than emmetropic and low hyperopic eyes in both cohorts (multiple comparisons $p < 0.01$). In addition, low hyperopic eyes were also significantly shorter than emmetropic eyes but only in S2 ($p = 0.012$).

### Table 2. Mean refractive components (D) from the right eyes of 1414 children.

<table>
<thead>
<tr>
<th></th>
<th>Year 1 group (S1)</th>
<th>Year 7 group (S2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$n$</td>
<td>Mean (D)</td>
</tr>
<tr>
<td>M (D) Emmetropes</td>
<td>53</td>
<td>0.20</td>
</tr>
<tr>
<td>Low hyperopes</td>
<td>215</td>
<td>0.78</td>
</tr>
<tr>
<td>Moderate hyperopes</td>
<td>491</td>
<td>1.53</td>
</tr>
<tr>
<td>High hyperopes</td>
<td>12</td>
<td>3.94</td>
</tr>
<tr>
<td>All subjects</td>
<td>771</td>
<td>1.27</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Year 1 group (S1)</th>
<th>Year 7 group (S2)</th>
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<tbody>
<tr>
<td></td>
<td>$n$</td>
<td>Mean (D)</td>
</tr>
<tr>
<td>$J_0$ (D) Emmetropes</td>
<td>53</td>
<td>0.04</td>
</tr>
<tr>
<td>Low hyperopes</td>
<td>215</td>
<td>0.04</td>
</tr>
<tr>
<td>Moderate hyperopes</td>
<td>491</td>
<td>0.04</td>
</tr>
<tr>
<td>High hyperopes</td>
<td>12</td>
<td>0.05</td>
</tr>
<tr>
<td>All subjects</td>
<td>771</td>
<td>0.04</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Year 1 group (S1)</th>
<th>Year 7 group (S2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$n$</td>
<td>Mean (D)</td>
</tr>
<tr>
<td>$J_{45}$ (D) Emmetropes</td>
<td>53</td>
<td>−0.01</td>
</tr>
<tr>
<td>Low hyperopes</td>
<td>215</td>
<td>0.00</td>
</tr>
<tr>
<td>Moderate hyperopes</td>
<td>491</td>
<td>0.02</td>
</tr>
<tr>
<td>High hyperopes</td>
<td>12</td>
<td>0.03</td>
</tr>
<tr>
<td>All subjects</td>
<td>771</td>
<td>0.01</td>
</tr>
</tbody>
</table>

### Table 3. Mean corneal radius of curvature ($n = 1398$) and axial length ($n = 1386$) values.

<table>
<thead>
<tr>
<th></th>
<th>Year 1 group (S1)</th>
<th>Year 7 group (S2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$n$</td>
<td>Mean (D)</td>
</tr>
<tr>
<td>Corneal radius of curvature (mm) Emmetropes</td>
<td>52</td>
<td>7.76</td>
</tr>
<tr>
<td>Low hyperopes</td>
<td>215</td>
<td>7.81</td>
</tr>
<tr>
<td>Moderate hyperopes</td>
<td>487</td>
<td>7.78</td>
</tr>
<tr>
<td>High hyperopes</td>
<td>11</td>
<td>7.76</td>
</tr>
<tr>
<td>All subjects</td>
<td>765</td>
<td>7.79</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Year 1 group (S1)</th>
<th>Year 7 group (S2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$n$</td>
<td>Mean (D)</td>
</tr>
<tr>
<td>Axial length (mm) Emmetropes</td>
<td>51</td>
<td>22.85</td>
</tr>
<tr>
<td>Low hyperopes</td>
<td>214</td>
<td>22.85</td>
</tr>
<tr>
<td>Moderate hyperopes</td>
<td>484</td>
<td>22.55</td>
</tr>
<tr>
<td>High hyperopes</td>
<td>10</td>
<td>21.80</td>
</tr>
<tr>
<td>All subjects</td>
<td>759</td>
<td>22.64</td>
</tr>
</tbody>
</table>
Refractive and biometric data between cohorts

When comparing the mean refractive components of the refractive groups between both cohorts, some differences were also observed. Eyes from S2 (all subjects) were on average 0.35 D less hyperopic ($p < 0.001$) than S1 eyes. Although the differences in both $J_0$ and $J_{45}$ between cohorts were small in magnitude (0.02 D), they were statistically significant ($p < 0.001$). Differences in M between refractive groups were found only for moderate hyperopic eyes. On average, moderate hyperopic eyes in S1 were 0.15 D more hyperopic (independent samples $t$-test, $p < 0.001$) than moderate hyperopic eyes in S2. In addition, small differences were also found in the astigmatic components between moderate hyperopic eyes: $J_0$ (independent samples $t$-test, $p = 0.002$) and $J_{45}$ (independent samples $t$-test, $p = 0.008$). Differences in J_{45} were also found between emmetropes (independent samples $t$-test, $p = 0.023$) and low hyperopes (independent samples $t$-test, $p < 0.001$). Comparison of mean values of corneal radius of curvature and axial length between cohorts did not show differences in corneal radius of curvature ($p > 0.05$). On the other hand, comparison of the mean axial length values between cohorts showed eyes from S2 (with the exception of high hyperopes) were significantly longer than eyes from S1 ($p < 0.001$).

### Higher order aberrations

The mean values of the HO Zernike coefficients and the RMS for the various refractive error groups are presented in Tables 4 and 5 respectively. In both the cohorts, third (Figure 1) and fourth (Figure 2) orders were found to be the largest in magnitude. Of the individual aberrations,
primary spherical aberration Z(4,0) was the largest in magnitude (0.04 ± 0.06μ [S1], 0.06 ± 0.05μ [S2]) followed by coma-like aberrations Z(3,−1) (−0.01 ± 0.1μ [S1], 0.003 ± 0.1μ [S2]) and Z(3,1) (0.01 ± 0.07μ [S1], −0.003 ± 0.07μ [S2]) which also presented the largest variability. Mean values of fifth and sixth order aberrations were almost negligible.

### Aberrations data within cohorts

From the individual coefficients, differences were found for Z(4,0) (B-F 20.524 df1:3 df2:31.70, p < 0.001 [S1]; B-F 23.64 df1:3 df2:37.23, p < 0.001 [S2]). In both the cohorts, emmetropic eyes had less positive SA than moderate hyperopic (p < 0.001 [S1 and S2]) and high hyperopic eyes (p = 0.038 [S1]; p = 0.009 [S2]), low hyperopic eyes had also less positive SA than moderate hyperopic eyes (p < 0.001 [S1 and S2]). Additionally, S2 emmetropic eyes had less positive SA than low hyperopic eyes (p < 0.001), and S2 low hyperopic eyes had less positive SA than high hyperopic eyes (p = 0.043). Differences between refractive groups for other HO modes were found only in S1 for Z(4,−2) (B-F 2.73 df1:3 df2:75.04, p = 0.050) between low hyperopic and moderate hyperopic eyes (p < 0.001), for Z(5,−1) (B-F 3.316 df1:3 df2:229.932, p = 0.021) between emmetropic and high hyperopic eyes (p = 0.02) and for Z(6,4) (B-F 5.674 df1:3 df2:62.71, p = 0.002) between low hyperopic and emmetropic eyes (p = 0.001).

As expected, differences were found between all refractive groups in both cohorts for second orders RMS (BF 236.70 df1:3 df2:20.45, p < 0.001 [S1]; BF 83.038 df1:3 df2:11.13, p < 0.001 [S2]), and total aberrations RMS (BF 234.20 df1:3 df2:19.07, p < 0.001 [S1]; BF 81.214 df1:3 df2:11.02, p < 0.001 [S2]), multiple comparisons...
Figure 1. Mean values for third order Zernike coefficients in microns for a 5 mm pupil diameter across refractive groups. Data are shown for the right eyes of 771 children in Year 1 (A) and 643 children in Year 7 (B). Error bars are 1 SD.

Figure 2. Mean values for fourth order Zernike coefficients in microns for a 5 mm pupil diameter across refractive groups. Data are shown for the right eyes of 771 children in Year 1 (A) and 643 children in Year 7 (B). Error bars are 1 SD.

$p < 0.001$, all groups). Figure 1, top (A) and bottom (B) show the distribution of coma, third orders, SA, fourth orders and HO aberrations RMS across the different refractive groups. Differences in fourth orders RMS (BF 7.98 $df_1$:3 $df_2$:32.65, $p < 0.001$) existed between low hyperopic and moderate hyperopic eyes ($p < 0.001$) in S1 group only; while in S2 group, differences were found between all groups (BF 42.53 $df_1$:3 $df_2$:69.89, $p < 0.001$; multiple comparisons $p < 0.01$). Differences in spherical aberration RMS were found in both cohorts (BF 10.55 $df_1$:3 $df_2$:21.62, $p < 0.001$ [S1]; BF 19.50 $df_1$:3 $df_2$:28.03, $p < 0.001$ [S2]). In the S1 group, moderate hyperopic eyes had higher levels of SA RMS than emmetropic ($p < 0.001$) and low hyperopic eyes ($p < 0.001$). In the S2 group, emmetropic eyes had lower levels of SA RMS than all other refractive groups ($p < 0.05$), whereas low hyperopic eyes also had lower SA RMS than moderate hyperopic eyes only ($p < 0.001$). Differences in HO RMS were
found in S2 group only (B–F 14.90 df:3 df:289.35, \( p < 0.001 \)). High hyperopic eyes had higher levels of HO RMS than all refractive groups (\( p < 0.001 \)), while moderate hyperopic eyes also had higher levels of HO RMS than low hyperopic (\( p = 0.005 \)) and emmetropic eyes (\( p < 0.001 \)) (Figure 3).

### Aberration data between cohorts

Despite there being statistical differences in the refractive components (M, \( J_0 \), and \( J_{45} \)) within emmetropic, low hyperopic, and moderate hyperopic eyes between S1 and S2 (Table 2), only the magnitude of the difference in M between high hyperopes (1.02 D) was of clinical significance in comparison to the magnitude of the differences for the astigmatic components (\(<0.25\) D). After adjusting for the combined contribution of the refractive components (defined as the P vector (Thibos et al., 1997)), multivariate analysis of coma, third order, spherical aberration, fourth order and HO aberrations RMS, showed an association with age for low hyperopic (Pillai’s Trace 0.103; F 6.509 df:1 df:8, \( p < 0.001 \)) and moderate hyperopic eyes (Pillai’s Trace 0.087; F 8.49 df:1 df:72, \( p < 0.001 \)) only. Adjusted-multiple comparisons Bonferroni test showed 12 year old low hyperopic eyes had higher levels of SA RMS (\( p < 0.001 \)) and fourth orders RMS (\( p < 0.001 \)) than 6 year old low hyperopic eyes. In comparison to 6 year old moderate hyperopic eyes, 12 year old moderate hyperopic eyes also had higher levels of SA RMS (\( p < 0.001 \)) and fourth orders RMS (\( p < 0.001 \)) than 6 year old low hyperopic eyes. In comparison to 6 year old moderate hyperopic eyes, 12 year old moderate hyperopic eyes also had higher levels of SA RMS (\( p < 0.001 \)) and fourth orders RMS (\( p < 0.001 \)) than 6 year old low hyperopic eyes. In comparison to 6 year old moderate hyperopic eyes, 12 year old moderate hyperopic eyes also had higher levels of SA RMS (\( p < 0.001 \)) and fourth orders RMS (\( p < 0.001 \)) than 6 year old low hyperopic eyes. In comparison to 6 year old moderate hyperopic eyes, 12 year old moderate hyperopic eyes also had higher levels of SA RMS (\( p < 0.001 \)) and fourth orders RMS (\( p < 0.001 \)) than 6 year old low hyperopic eyes. In comparison to 6 year old moderate hyperopic eyes, 12 year old moderate hyperopic eyes also had higher levels of SA RMS (\( p < 0.001 \)) and fourth orders RMS (\( p < 0.001 \)) than 6 year old low hyperopic eyes.

Figure 3. Mean values in microns of the RMS of coma, third orders, spherical aberration, fourth orders, and higher order aberrations in microns for a 5 mm pupil diameter across refractive groups. Data are shown for the right eyes of 771 children in Year 1 (A) and 643 children in Year 7 (B). Error bars are 1 SD.
Discussion

Aberrations

As previously reported (Carkeet et al., 2002; He et al., 2002; Martinez, Sankaridurg, Sweeney, Rose, & Mitchell, 2006), for both the cohorts, the dominant aberrations in hyperopic and emmetropic eyes were second order aberrations: Z(2,−2), Z(2,0), Z(2,2). The largest differences between refractive error groups were found for Defocus Z(2,0), second orders RMS and these differences were also reflected in the Total RMS. Mean levels of higher order aberrations were small in magnitude. Of the HO aberrations, the dominant aberrations in both the hyperopic and emmetropic eyes were third (Z(3,−3), Z(3,−1), Z(3,1), Z(3,3)) and fourth order aberrations (Z(4,−4), Z(4,−2), Z(4,0), Z(4,2), Z(4,4)). When only hyperopic eyes were considered, for both the cohorts, they were seen to have higher levels of positive spherical aberration Z(4,0) (two to four-fold) than emmetropic eyes in both age groups. In contrast to the study by Kirwan et al. (2006), who found hyperopes having lower levels of higher order aberrations than myopes (Total RMS, 4th orders RMS, Z(3,−3), Z(3,−1), Z(3,3), Z(4,−4), and Z(4,2)); we found that hyperopes had higher levels of Z(4,0), HO RMS, Total RMS, SA RMS than emmetropes. In the older children (S2), higher levels of HO RMS were also seen in the hyperopic groups in comparison to the emmetropic group.

Spherical aberration

An interesting finding was the increase in the mean levels of Z(4,0) (and SA RMS) in all refractive groups with age (although this was only statistically significant for emmetropic, low hyperopic and moderate hyperopic eyes). This increment could be indicative of or associated to the typical changes of eye growth in the young eye such as corneal curvature flattening (Friedman, Mutti, & Zadnik, 1996), crystalline lens thinning (Zadnik, Mutti, Fusaro, & Adams, 1995) or increase in axial length (Mutti et al., 1998). From the differences observed in refractive error and ocular biometry, it seems that the increment in positive SA with age could be closely related to the changes in the crystalline lens. Thinning and flattening of the crystalline lens could reduce the amount of negative spherical aberration of the lens (Smith, 2003; Smith, Cox, Calver, & Garner, 2001) and as a result, the total positive spherical aberration of the eye. Previous studies in adults (Amano et al., 2004; Fujikado et al., 2004; McLellan, Marcos, & Burns, 2001), found positive correlations between age with ocular Z(4,0) and SA RMS but not with corneal Z(4,0). Guirao, Redondo, and Artal (2000) measuring corneal aberrations obtained from videokeratography, found a significant correlation of SA, third order terms with age in adults and the SA becoming more negative in older subjects. Furthermore, Amano et al. (2004) reported a positive correlation of corneal and ocular coma RMS with age. These findings suggest that in adults, the main contribution to an increment of the ocular spherical aberration comes from the internal optics of the eye with a limited or null contribution of the cornea. Moreover, Wang and Candy (2005) measuring monochromatic aberrations in infant eyes, found that the mean Z(4,0) coefficient was less positive than in adults. They suggested that the positive increase in mean Z(4,0) with age is consistent with the same trend across the adult range (McLellan et al., 2001). This is in agreement with our results of an increment of positive Z(4,0) in the older refractive groups. While moderate changes in the central corneal curvatures between ages 2 and 14 (Friedman et al., 1996) and a decrease in the asphericity of the corneal anterior surface from childhood to adulthood (Brunette, Bueno, Parent, Hamam, & Simonet, 2003) are expected, we ruled out a relation between CR and an increment of Z(4,0) because the mean values of CR from both age groups did not differ between refractive groups (see Table 5). Similarly, the likelihood of an association between the differences in SA and differences in AL was small (Figure 4): correlation (2-tailed) between Z(4,0) and AL (r = −0.28, p < 0.001 [S1]; r = −0.33, p < 0.001 [S2]).

Spherical aberration in hyperopic eyes

As mentioned above and in line with previous studies (Carkeet et al., 2004; Collins, Wildsoet, & Atchison, 1995; Llorente et al., 2004), hyperopic eyes had higher levels of positive SA and SA RMS than emmetropic eyes. The results could possibly be explained on the basis of the anatomical characteristics of the eyes such as corneal asphericity and crystalline lens features. Corneas that
flatter less rapidly in the periphery (more spherical) have higher levels of positive SA than prolate corneas. Although a tendency for a less prolate shape with increasing amounts of myopic error has been reported (Carney, Mainstone, & Henderson, 1997; Davis, Raasch, Mitchell, Mutti, & Zadnik, 2005; Horner, Soni, Vyas, & Himebaugh, 2000), Mainstone et al. (1998) did not find any association of corneal asphericity with hyperopic refractive error. Additionally, Llorente et al. (2004) found hyperopes (23 to 40 years) had less prolate corneas than myopes but the differences were not significant ($p > 0.05$). It is possible that there was no difference in corneal asphericity and corneal SA in the different refractive error groups, and it is possible that the differences in SA were due to differences in internal aberrations, with hyperopes presenting lower levels of compensatory negative SA than emmetropic eyes.

There is great interest in the field of refractive error development research to identify if higher order aberrations contribute to the onset or progression of refractive error. Animal studies have provided evidence that support the concept of an active emmetropization mechanism and development of refractive error (Wallman & Winawer, 2004; Wildsoet, 1997). Of all the higher order aberrations, SA has been more widely studied because of the role it plays in accommodative function and potentially in the development of myopia. Ocular SA shifts from positive levels (unaccommodated state) toward negative values (accommodated state) (Buehren & Collins, 2006; Hazel, Cox, & Strang, 2003; Plainis, Ginis, & Pallikaris, 2005). Positive SA produces an apparent lead of accommodation for far targets (Plainis et al., 2005), whereas negative SA produces an apparent lag of accommodation for near targets (Buehren & Collins, 2006; Hazel et al., 2003; Plainis et al., 2005). Several studies have reported different characteristics in the accommodative function in hyperopic eyes in comparison to emmetropic and myopic eyes (see Chen, Schmid, & Brown, 2003 for a review). Specifically, hyperopic eyes have been found to present lead of accommodation in comparison to emmetropic or myopic eyes (which usually present lag of accommodation) (McBrien & Millodot, 1986a). Furthermore, hyperopic children were found to have greater shifts of tonic accommodation (resting state of accommodation) after near work (Gwiazda, Bauer, Thorn, & Held, 1995) and the lowest AC/A ratio in comparison to emmetropic and myopic children (Mutti, Jones, Moeschberger, & Zadnik, 2000). Explanations for such differences in accommodative responses between refractive errors have been proposed on the basis of a) the sympathetic and parasympathetic innervations in the control and regulation of accommodation (hyperopic eyes having a strong sympathetic or weak parasympathetic innervation) (McBrien & Millodot, 1986a, 1986b); b) differences on the zonular tension of the crystalline lens (Mutti et al., 2000).

Interestingly, the above mentioned studies measured accommodative responses using mostly a Canon R-1 autorefractor which was widely used for research purposes in the past 3 decades. Until recently (Collins, 2001), the effect of SA on the validity of Canon R-1 measurements was unknown. Collins (2001) found that if an eye had positive SA (in an unaccommodated state), the Canon R-1 rendered a myopic reading (lead of accommodation); whereas if the eye had negative SA, the Canon R-1 rendered a hyperopic reading (lag of accommodation). Collins (2001) added that while the errors generated by the Canon R-1 were relatively constant within refractive error groups, in studies comparing accommodation between refractive error groups, differences in monochromatic aberrations between refractive error groups could be important. Thus, it could be argued that the greater shifts in tonic accommodation in hyperopic eyes observed by (Gwiazda et al., 1995) could have been the result of hyperopic eyes having higher levels of positive SA in comparison to emmetropic eyes (as seen in our study). If hyperopic eyes had small amounts (say 0.1 µm) of positive SA during accommodation this could have induced a lead of accommodation of approximately 0.50 D (Plainis et al., 2005). Due to the limitations of the current study, we can not be sure of the levels of spherical aberration that hyperopic eyes would have during accommodation. It is thus advisable for future studies to compare the accommodative responses between refractive error groups by using wavefront sensors using natural pupil sizes.

Refractive and biometric data

The aim of the Sydney Myopia Study was to document the prevalence of refractive error (especially myopia) and other eye conditions in a large representative sample of Sydney school children (Ojaimi et al., 2005b). Children in Year 1 (age 6 years) and Year 7 (age 12 years) were chosen to participate in the study as this covers a key period in ocular development. In the current study, it was evident from the observed mean refractive error distribution values in both age groups (mean M 0.35 D less hyperopic in S2) and axial length (mean AL 0.57 mm longer in S2) that a difference in the ocular development stages existed between both cohorts. One of the most important changes that occur during ocular development is the increase of AL (mainly associated with an increase in the vitreous chamber depth (Garner et al.,1995)). On average there is increase in vitreous chamber depth of 1.1 mm from the age of 7 until the age of 13 reaching the mean values of young emmetropic adults (Larsen, 1971c). An interesting finding from our results is that the difference in axial length alone between both the cohorts could not explain alone for the observed difference in mean refractive error. If we assume that a difference of 1 mm in axial length (while keeping a constant central corneal radius of curvature) would be equivalent to a difference of 3.00 D, then the difference observed in axial length of 0.57 mm would have resulted in eyes from S2 being 1.71 D
less hyperopic than eyes from S1. If we considered the difference in mean M and the difference in central radius of curvature between age groups (0.01 mm or 0.06 D steeper in S1 eyes), eyes from S2 should have been approximately 1.30 D less hyperopic (or more myopic) than the observed 0.35 D difference.

It seems possible that the difference between the expected, minus the observed power could be a result of the structural changes of the crystalline lens and to a lesser extent of the cornea. Several studies have reported that the main change that the crystalline lens experiences during infancy and childhood is a reduction of power of approximately 20 D (Garner et al., 1995; Larsen, 1971b; Wood et al., 1996; Zadnik, 1997). Two main mechanisms have been attributed to this reduction of power: (a) a decrease in the equivalent refractive index of the crystalline lens (Wood et al., 1996); and (b) lens thinning (as the result of a flattening of the crystalline surface (Larsen, 1971b; Zadnik, 1997)). The major contribution to this decrease is the equivalent refractive index (approximately 75%) with the remaining 25% due to changes in the radius of curvature (Wood et al., 1996). Furthermore, using mathematical models, it has been shown that in order to obtain emmetropia and to match the increase of AL observed during childhood, most of the compensation required is attributable to the lens (57%) followed by the cornea (36%) (Dunne, 1993).

Because we did not evaluate the lenticular optical characteristics or corneal topography in the protocol of the Sydney Myopia Study we can not be completely certain about the magnitude that each ocular structure contributed to this difference in power. It is apparent that in children aged 6 to 15 years, corneal flattening of approximately 0.30 D over 3 years normally occurs (irrespective of the refractive state) (Friedman et al., 1996). However, the difference in corneal radius of curvature (0.01) between cohorts observed in the current study does not offer support to a significant corneal contribution.

In summary, we found higher levels of positive Spherical Aberration Z(4,0) and higher levels of Coma RMS and HO RMS in hyperopic eyes (12-years old children only) in comparison to emmetropic eyes. Differences in the levels of positive SA found in hyperopic eyes could explain for previously reported differences in accommodative responses between refractive errors. An increment of positive Z(4,0) was also found in the low hyperopic groups with age, showing a small correlation with axial length and which might support the findings of lens physical changes with growth during childhood.

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