Clinical and Epidemiologic Research

Higher Order Ocular Aberrations and Their Relation to Refractive Error and Ocular Biometry in Children

Julie-Anne Little, Sara J. McCullough, Karen M. M. Breslin, and Kathryn J. Saunders

Vision Science Research Group, Biomedical Sciences Research Institute, University of Ulster, Northern Ireland, United Kingdom

Correspondence: Julie-Anne Little, School of Biomedical Sciences, University of Ulster, Coleraine, NI, United Kingdom, BT52 1SA; ja.little@ulster.ac.uk.

Submitted: October 30, 2013
Accepted: June 24, 2014

Citation: Little J-A, McCullough SJ, Breslin KMM, Saunders KJ. Higher order ocular aberrations and their relation to refractive error and ocular biometry in children. *Invest Ophthalmol Vis Sci*. 2014;55:4791–4800. DOI:10.1167/iovs.13-13533

Purpose. The interaction between higher order ocular aberrations (HOA) and refractive error is not yet fully understood. This study investigated HOA in relation to refractive error and ocular biometric parameters in a population with a high prevalence of ametropia.

Methods. The HOA were investigated in two cohorts of Caucasian children aged 9 to 10 and 15 to 16 years ($n = 313$). These aberrations were measured for a 5-mm pupil with the IRX3 aberrometer. Cycloplegic refractive error and ocular biometry measures, including axial length and corneal curvature, also were assessed with the Shin-Nippon SRW-5000 autorefractor and Zeiss IOLMaster, respectively. Participants were divided into refractive groups for analysis of HOA.

Results. The magnitude of total HOA was higher in this population at 0.27 μm (interquartile range [IQR], 0.22–0.32 μm) than other HOA reported in the literature. The profile of HOA was not significantly different across the two age cohorts or across refractive groups, nor did spherical aberration differ significantly with age ($Z_4^0 = 0.07$ μm for both cohorts). Multivariate linear regression analysis demonstrated spherical aberration was significantly related to axial length (but not refractive grouping), with longer eyes having less positive values of fourth order and root mean square (RMS) spherical aberration.

Conclusions. This study found no significant difference in HOA across refractive groups. The current study also highlights the importance of knowledge of axial length when analyzing HOA.

Keywords: monochromatic aberrations, higher order ocular aberrations, children, spherical aberration, axial length, myopia, hyperopia, NICER study

A growing body of research has been published concerning higher order ocular aberrations (HOA), some of which have explored changes in HOA with age,[1–4] and potential maturation of HOA throughout infancy and childhood into adulthood.[5–9] Some studies have investigated HOA and their relationship to refractive error,[7–11] other ocular parameters,[8,12,13] and ethnicity[14,15] in adult and younger populations.

The relationship between HOA and refractive error is of particular interest as it has been suggested that retinal defocus and cues from HOA contribute to the growth of the eye.[16–18] However, studies investigating this theory report conflicting results. Figure 1 summarizes the differences between studies with regard to the relation between refractive error and HOA over a broad age range. In brief, Thapa et al.[19] analyzed HOA for children three to six years of age and reported slightly but significantly increased levels of HOA as hyperopia increased ($n = 423$). In contrast, Carkeet et al.[20] reported no difference in HOA ($n = 273$) between hyperopes and myopes or emmetropes, and Kirwan et al.[7] found that their hyperopes ($n = 137$ eyes) had lower amounts of HOA compared to myopes ($n = 25$ eyes). He et al.[10] also reported higher levels of HOA in their myopic group of children and young adults compared to their emmetropic age-matched group ($n = 316$). As part of the Sydney Myopia study, Martinez et al.[8] investigated HOA in a large group of hyperopic and emmetropic children aged 6 to 7 and 12 to 13 years. They found that for both age groups, hyperopic eyes had higher amounts of HOA than emmetropic eyes. In addition, Martinez et al.[8] and a number of these studies report a positive correlation with refractive error and magnitude of spherical aberration, indicating that spherical aberration decreases, or becomes more negative, with myopia (studies indicated in blue shading in Fig. 1).

Despite these potential differences in HOA with refractive error, animal studies report a significant role for peripheral defocus in eye growth[31,32] and peripheral HOA, peripheral refractive errors, and eye shape have been examined in many studies (e.g., the studies of Seidemann et al.,[33] Atchison,[34] and Rosén et al.,[35] and see the report of Charman[36] for review) indicating peripheral defocus has a stronger role in influencing eye growth. In support of this, Hartwig et al.[13] investigated HOA in anisometropia, and reported no significant increase in magnitude of HOA in the more ametropic eye. However, large pupil sizes for young children may mean that on-axis and peripheral HOA may have a role in eye growth and refractive error development, and a recent study investigating HOA in progressing myopic schoolchildren in China reported that participants whose myopia was progressing faster had significantly higher levels of HOA after progression than those whose myopia was progressing more slowly.[37]

These conflicts in the literature comparing HOA and refractive error may exist due to sample size, differing classifications of refractive error, differences in subject age, ethnicity, and methodological differences. The current study sought to investigate HOA in relation to refractive error and

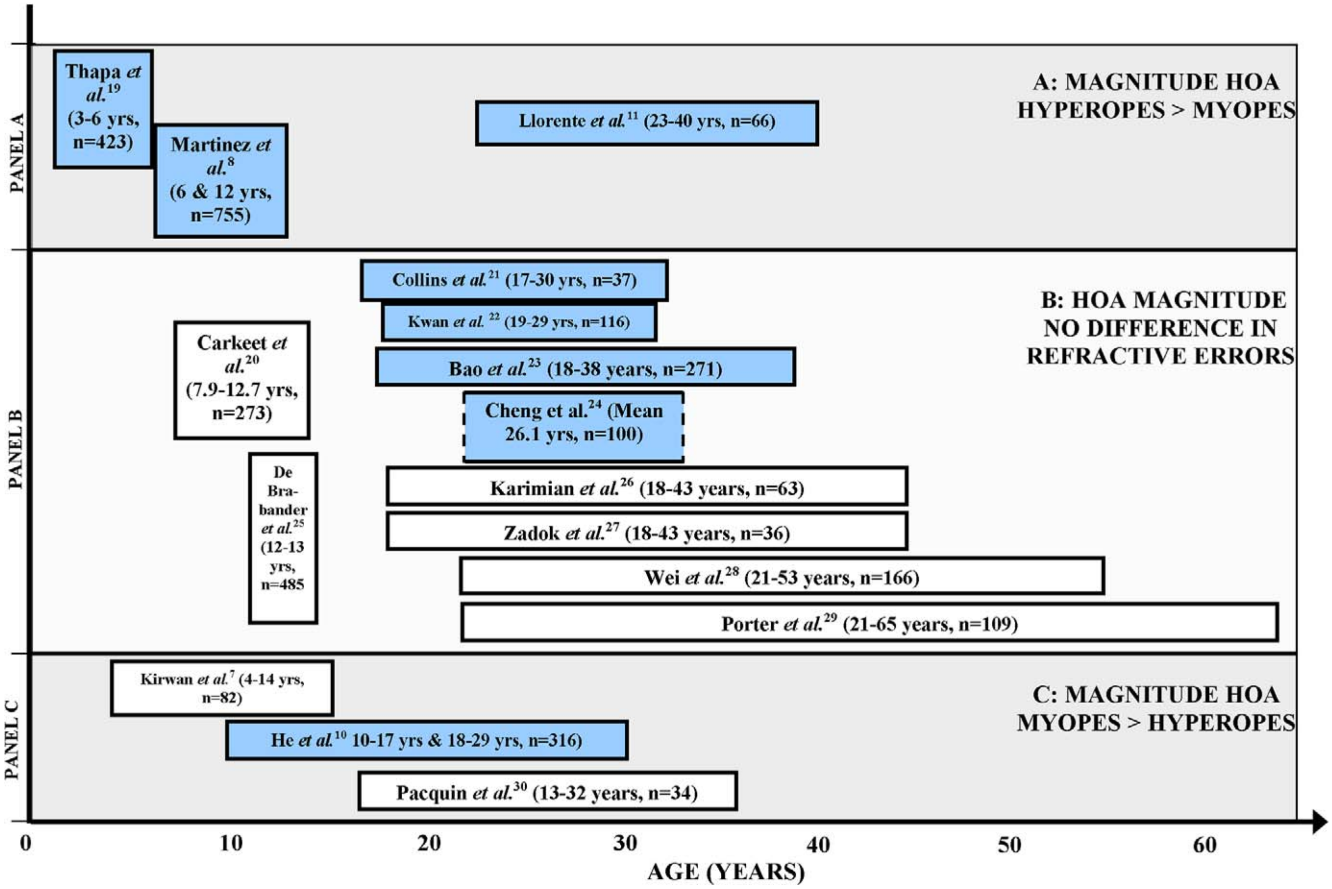

FIGURE 1. Schematic diagram summarizing the differing findings[7,8,10,11,19–30] regarding the relation between HOA and refractive error from several studies across a broad age range. The *x* axis indicates increasing age in years, and the *three horizontal panels* group studies according to whether they found (**A**) a greater magnitude of HOA in hyperopes compared to myopes, (**B**) no difference in HOA across refractive groups, or (**C**) a greater magnitude of HOA in myopes compared to hyperopes. The studies shaded in *blue* described a positive correlation with spherical equivalent refractive error and spherical aberration/total fourth order HOA.

ocular biometric parameters in a population with a high prevalence of ametropia[38–40] to aid further understanding of the profile of HOAs, and particularly spherical aberration and their association with refractive error.

METHODS

Study Population

The Northern Ireland Childhood Errors of Refraction (NICER) study is a population-based study of refractive error in Northern Ireland.[41] The second phase of the NICER study involved the longitudinal assessment of participants after a period of three years from the initial investigation, with children aged 9 to 10 years (primary year six, grade 4) and 15 to 16 years (postprimary year 12, grade 10).[42] Information packs containing a letter of invitation outlining the study, a description of the test procedures, and a consent form were distributed to parents/guardians of these children. Seven primary and six postprimary schools were used for data collection in the present study. The children came from a wide range of socioeconomic backgrounds and participants attending academically selective and nonselective schools were equally represented in the sample. Ethical approval for the study was obtained from the University of Ulster Research Ethics Committee and the research followed the tenets of the Declaration of Helsinki.

A subgroup of participants from Phase 2 of the NICER study were invited to participate in the present study and 173 children aged 9 to 10 years (consent rate 82.4%) and 150 children aged 15 to 16 years (consent rate 62.5%) were recruited. On initial assessment, information regarding ocular history was obtained and participants with significant systemic and/or ocular conditions, such as significant amblyopia, keratoconus, and Down syndrome, were excluded (three participants were excluded from the younger age cohort and two from the older age cohort). Of the 170 remaining participants in the younger age cohort (mean age, 10.09 ± 0.39 years; 79 females, 91 males), refractive error and axial length (AL) data were obtained for all children, and HOA and corneal curvature (CR) data were obtained successfully from 166 children. Of the 148 participants in the older age cohort (year 12; mean age, 16.06 ± 0.31 years; 83 females, 65 males), refractive error, AL, and HOA data were obtained successfully from 147 children, and corneal CR data were obtained successfully from 143 children.

Protocol

One drop of proxymetacaine hydrochloride 0.5% (MINIMS; Chauvin Pharmaceuticals Ltd.) was instilled into both eyes to mitigate discomfort from subsequent instillation of one drop of cyclopentolate hydrochloride 1.0% (MINIMS; Chauvin Pharmaceuticals Ltd.). A period of 30 minutes elapsed for the cycloplegic drops to take effect. Participants had one extra

Table 1. Median and IQR for M, J_0 and J_{45} Power Vectors, AL and CR Across Refractive Groups

	Age 9–10 y			Age 15–16 y		
	n	**Median**	**IQR**	***n***	**Median**	**IQR**
M						
All participants	170	+0.63 D	+0.13 to +1.13	147	+0.50 D	+0.13 to +1.13
High hyperopes	11	+4.50 D	+4.13 to +7.50	7	+3.38	+3.25 to +4.13
Moderate hyperopes	37	+1.50 D	+1.25 to +1.88	29	+1.63 D	+1.38 to +2.00
Low hyperopes	60	+0.75 D	+0.63 to +0.88	55	+0.63 D	+0.50 to +0.88
Emmetropes	46	+0.06 D	−0.13 to +0.25	39	+0.13 D	−0.13 to +0.38
Myopes	16	−0.75 D	−1.44 to −0.50	17	−1.13 D	−1.63 to −0.63
J_0						
All participants	170	0.00 D	−0.19 to +0.13	147	+0.02 D	−0.08 to +0.18
High hyperopes	11	−0.13 D	−0.36 to +0.39	7	+0.27 D	−0.09 to 0.36
Moderate hyperopes	37	−0.04 D	−0.25 to +0.08	29	+0.08 D	−0.05 to +0.23
Low hyperopes	60	0.00 D	−0.12 to +0.12	55	0.00 D	−0.08 to +0.11
Emmetropes	46	+0.10 D	−0.06 to +0.23	39	+0.05 D	−0.10 to +0.19
Myopes	16	−0.12 D	−0.21 to +0.07	17	+0.03 D	−0.12 to +0.18
J_{45}						
All participants	170	+0.01 D	−0.17 to +0.19	147	−0.03 D	−0.18 to +0.11
High hyperopes	11	0.00 D	−0.31 to 0.18	7	0.00 D	−0.26 to 0.13
Moderate hyperopes	37	−0.02 D	−0.17 to +0.12	29	−0.09 D	−0.24 to +0.07
Low hyperopes	60	+0.02 D	−0.10 to +0.19	55	0.00 D	−0.13 to +0.14
Emmetropes	46	+0.02 D	−0.20 to +0.21	39	0.00 D	−0.18 to +0.13
Myopes	16	+0.09 D	−0.06 to +0.22	17	−0.07 D	−0.17 to +0.03
AL						
All participants	170	23.04 mm*	22.55 to 23.58*	147	23.44 mm*	22.88 to 23.88*
High hyperopes	11	21.64 mm*	21.22 to 22.44	7	22.26 cm*	21.61 to 22.77
Moderate hyperopes	37	22.80 mm*	22.62 to 23.23	29	22.81 mm*	22.55 to 23.44
Low hyperopes	60	23.02 mm*	22.57 to 23.60	55	23.48 mm*	23.09 to 23.81
Emmetropes	46	23.15 mm*	22.80 to 23.53	39	23.49 mm*	23.00 to 23.97
Myopes	16	23.73 mm*	23.26 to 24.36	17	23.97 mm*	23.37 to 24.78
CR						
All participants	166	7.81 mm	7.65 to 8.02	143	7.86	7.66 to 8.04
High hyperopes	11	7.93 mm	7.78 to 8.10	6	7.90 mm	7.56 to 7.97
Moderate hyperopes	37	7.83 mm	7.72 to 8.08	29	7.81 mm	7.67 to 7.98
Low hyperopes	57	7.77 mm	7.56 to 8.05	54	7.91 mm	7.74 to 8.06
Emmetropes	46	7.75 mm	7.48 to 7.89	37	7.93 mm	7.64 to 8.08
Myopes	15	7.79 mm	7.65 to 7.95	17	7.66 mm	7.59 to 7.90

Mann-Whitney and Kruskal-Wallis tests were used to determine significant differences between refractive error categories across and within age cohorts.

* Repeated measures Bonferroni corrected statistically significant differences.

drop of cyclopentolate HCl 1.0% instilled 15 minutes after instillation of the first drop if loss of accommodation was not evident at this time.

Once cycloplegia was attained, the following measures were recorded:

1. Refractive error: Refractive errors were measured using the open field infrared Shin-Nippon SRW-5000 autorefractor (also branded as Grand Seiko WV-500; Shin-Nippon, Tokyo, Japan). The Shin-Nippon SRW-5000 is a highly repeatable instrument used extensively in epidemiological studies of refractive error and has been reported in the literature to be comparable with cycloplegic and noncycloplegic refraction in children[43] and adults.[44] The representative value[45] of five measures were used to describe the refractive error for the right and left eyes of each participant individually.
2. Axial length and corneal CR: These measurements were made using the IOLMaster (Carl Zeiss Meditec, Jena, Germany). At least five reliable AL measurements and three corneal radius of CR measurements were obtained from each eye, and the average used for analysis.
3. HOAs: Measurements of HOA were obtained with a commercially available Shack-Hartmann aberrometer (IRX3; Imagine Eyes, Orsay, France). The IRX3 aberrometer has a 32 × 32 lenslet sampling array at 780 nm wavelength and has been shown to provide repeatable measures of HOA.[46] A minimum of three repeatable measurements were taken from both eyes of each participant.

Zernike polynomials were calculated over a fixed 5 mm pupil diameter centered on the participant's dilated pupil (similar to the study of Carkeet et al.[20]). Zernike coefficients from the third up to the sixth order were fitted to the aberration data using the standards recommended by the Optical Society of America.[47] The root mean square (RMS) of total coma (incorporating Z_3^{-1}, Z_3^1, Z_5^{-1}, Z_5^1), trefoil (incorporating Z_3^{-3}, Z_3^3, Z_5^{-3}, Z_5^3), spherical aberration (incorporating Z_4^0 and Z_6^0), third, fourth, fifth, and sixth orders, and combined higher order aberrations (third to sixth orders) also were

Table 2. Median and IQR for the Zernike Coefficients for Third and Fourth Order, and the RMS of Total Trefoil, Coma, and Spherical Aberration, Total Third, Fourth, Fifth, and Sixth Orders, and Combined HOA and VSX Ratios From 166 Children in 9- to 10-Year-Old and 147 in 15- to 16-Year-Old Groups

	Age 9–10 y		Age 15–16 y	
	Median, μm	**IQR, μm**	**Median, μm**	**IQR, μm**
Zernike coefficient				
Z_3^{-3}	0.05	−0.03–0.11	0.03	−0.04–0.10
Z_3^{-1}	−0.06	−0.16–0.02	−0.02	−0.12–0.05
Z_3^{1}	0.06	0.00–0.12	0.06	0.00–0.14
Z_3^{3}	0.02	−0.03–0.07	0.00	−0.05–0.06
Z_4^{-4}	0.01	−0.01–0.03	0.02	0.00–0.04
Z_4^{-2}	0.01*	−0.01–0.02*	−0.01*	−0.02–0.01*
Z_4^{0}	0.07	0.04–0.12	0.07	0.02–0.11
Z_4^{2}	−0.02*	−0.05–0.01*	0.00*	−0.03–0.03*
Z_4^{4}	0.04*	0.02–0.07*	0.01*	−0.01–0.04*
RMS				
Trefoil	0.12	0.08–0.17	0.11	0.07–0.17
Coma	0.15	0.10–0.21	0.15	0.10–0.23
Spherical	0.08	0.05–0.12	0.07	0.04–0.11
Third order	0.21	0.16–0.28	0.21	0.15–0.28
Fourth order	0.13	0.11–0.16	0.11	0.09–0.15
Fifth order	0.06	0.05–0.07	0.06	0.04–0.07
Sixth order	0.04	0.03–0.05	0.04	0.03–0.04
Combined total HOA	0.27	0.23–0.33	0.27	0.21–0.31
Visual Strehl ratio (VSX)	0.23	0.16–0.31	0.26	0.17–0.37

Mann-Whitney U tests used to determine significant differences in HOAs between age cohorts.

* Repeated measures Bonferroni corrected statistically significant differences.

evaluated. Individual Zernike coefficients were analyzed for third and fourth order. Visual Strehl ratios computed in the spatial domain were used as an indicator of overall image quality derived from the wavefront profiles, described by Thibos et al.[48] and endorsed by Marsack et al.[49] as the most useful image quality metric, and denoted with the abbreviation "VSX."[48] These were calculated using analytical software (Get Metrics 2.5; Visual Optics Institute, University of Houston, Houston, TX, USA). The VSX ratios incorporate a standardized neural weighting to the Strehl ratio, and range from 0 to 1, with a value of 1 indicating a perfect optical system.

Right eye data were used for analysis. Significant astigmatism was defined as $\geq$ 0.75 diopter cylinder (DC). Refractive errors were described as power vectors.[50] Spherical equivalent refractive error (M) was used to classify participants into refractive error groups, in accordance with the study of Martinez et al.[8]: (1) myopia $M \leq -0.50$ diopters (D), (2) emmetropia -0.50 D $< M \leq +0.50$ D, (3) low hyperopia $+0.50$ D $< M \leq +1.00$ D, (4) moderate hyperopia $+1.00$ D $< M \leq +3.00$ D, and (5) high hyperopia $M > 3.00$ D.

RESULTS

Neither HOA nor refractive error data demonstrated a normal distribution; therefore, data are described as medians with interquartile range (IQR) and nonparametric statistics were used for analyses, including Kruskal-Wallis H and Mann-Whitney U tests. For repeated measures statistical analysis of HOA, Bonferroni corrections were applied. Multivariate linear regression analyses also were used once data were transformed to meet normality assumptions to explore the relationship between HOA, refractive groups and ocular biometry.

The majority of participants in both cohorts were hyperopic (9–10 years old 63.5%, $n = 108$; 15–16 years old 61.2%, $n = 90$). For the younger and older cohorts respectively, 28% and 24% of participants had hyperopia of +1.00 D or more, and 6.5% of the younger cohort and 4.8% of the 15 to 16 years older cohort demonstrated hyperopia of at least +3.00 D. Approximately 9.4% ($n = 16$) of the younger cohort and 12% ($n = 18$) of the older cohort were classified as myopic.

Cylindrical errors ranged from 0 to 3.75 DC in the younger cohort, with 66 participants (38.8%) having a cylindrical error of greater than or equal to 0.75 DC, and from 0 to 3.25 DC in the older cohort, with 52 participants (35.3%) having a cylindrical error of $\geq$ 0.75 DC.

Table 1 summarizes the median and IQR of M, J_0, and J_{45} power vectors, AL and CR for the two cohorts.

Overall, the refractive profiles of the two cohorts were similar. The median M vector for the younger cohort was +0.63 D, (range, −3.00 to +9.38 D) and the M vector for the older cohort was +0.50 D (range, −6.00 to +6.38D). However, these differences were not statistically significant (Mann-Whitney U tests, with Bonferroni correction for multiple comparisons applied $P < 0.05/38$). For the ocular biometric data, there was no difference in CR between the two cohorts, but AL was significantly greater for the older cohort ($z = 14.48$, $P = 0.0001$) and was significantly different across refractive groups in both cohorts (9–10 years old, $H = 38.29$, $P = 0.0001$; 15–16 years old, $H = 32.15$, $P = 0.0001$).

Table 2 shows the median and the IQRs for the Zernike coefficients from third and fourth order, the RMS of combined HOAs; total third, fourth, fifth, and sixth orders, and total trefoil, coma, and spherical aberration, and VSX for the two cohorts.

The distribution of Zernike coefficients between the two cohorts was similar. The median spherical aberration term (Z_4^0), was the predominant aberration of equal, positive value 0.07 μm (9–10 years old, IQR = 0.04–0.12 μm; 15–16 years old, IQR = 0.02–0.11 μm) followed in magnitude by horizontal coma (Z_3^1) with median magnitude of 0.06 μm in both cohorts, (IQR, 9–10 years old 0.00–0.12 μm; 15–16 years old, 0.00–0.14 μm).

Table 3. Nine- to 10-Year-Old Cohort: Median and IQRs for the Zernike Coefficients for Third and Fourth Order and the RMS of Total Trefoil, Coma and Spherical Aberration, Total Third, Fourth, Fifth, and Sixth Orders, Combined HOA and VSX Ratios (for Each Refractive Error Grouping From 166 Year 6 Children

	High Hyperopes, $n = 10$	**Moderate Hyperopes, $n = 35$**	**Low Hyperopes, $n = 59$**	**Emmetropes, $n = 46$**	**Myopes, $n = 16$**
	Median (IQR, µm)	**Median (IQR, µm)**	**Median (IQR, µm)**	**Median (IQR, µm)**	**Median (IQR, µm)**
Zernike coefficient					
Z_3^{-3}	−0.01 (−0.05 to 0.08)	0.02 (−0.05 to 0.11)	0.06 (−0.02 to 0.14)	0.04 (−0.03 to 0.11)	0.06 (0.01 to 0.13)
Z_3^{-1}	−0.05 (−0.08 to 0.00)	0.01 (−0.12 to 0.07)	−0.06 (−0.14 to 0.00)	−0.08 (−0.17 to 0.01)	−0.12 (−0.22 to −0.04)
Z_3^{1}	0.11 (0.06 to 0.12)	0.01 (−0.02 to 0.12)	0.05 (−0.01 to 0.11)	0.08 (0.00 to 0.12)	0.06 (−0.04 to 0.13)
Z_3^{3}	0.05 (0.02 to 0.12)	0.02 (−0.04 to 0.07)	0.03 (−0.03 to 0.08)	0.03 (−0.03 to 0.07)	−0.01 (−0.05 to 0.05)
Z_4^{-4}	0.01 (−0.02 to 0.04)	0.01 (−0.02 to 0.02)	0.02 (−0.01 to 0.04)	0.00 (−0.01 to 0.02)	0.02 (−0.02 to 0.03)
Z_4^{-2}	0.02 (0.00 to 0.03)	0.01 (−0.01 to 0.03)	0.01 (−0.01 to 0.02)	0.01 (0.00 to 0.02)	0.01 (−0.01 to 0.02)
Z_4^{0}	0.07 (0.05 to 0.10)	0.09 (0.04 to 0.13)	0.06 (0.03 to 0.11)	0.09 (0.06 to 0.12)	0.07 (0.04 to 0.09)
Z_4^{2}	−0.01 (−0.02 to 0.01)	−0.02 (−0.06 to 0.02)	−0.03 (−0.06 to 0.00)	−0.02 (−0.05 to 0.02)	−0.03 (−0.05 to −0.01)
Z_4^{4}	0.05 (0.04 to 0.05)	0.04 (0.00 to 0.07)	0.05 (0.02 to 0.07)	0.04 (0.00 to 0.08)	0.05 (−0.01 to 0.08)
RMS					
Trefoil	0.11 (0.07 to 0.14)	0.12 (0.09 to 0.16)	0.13 (0.09 to 0.20)	0.11 (0.07 to 0.18)	0.10 (0.06 to 0.15)
Coma	0.13 (0.12 to 0.16)	0.14 (0.08 to 0.21)	0.16 (0.09 to 0.20)	0.18 (0.12 to 0.22)	0.15 (0.09 to 0.30)
Spherical	0.06 (0.05 to 0.10)	0.09 (0.05 to 0.13)	0.06 (0.05 to 0.11)	0.09 (0.06 to 0.12)	0.08 (0.04 to 0.10)
Third order	0.18 (0.14 to 0.23)	0.21 (0.13 to 0.27)	0.22 (0.18 to 0.28)	0.22 (0.18 to 0.28)	0.19 (0.15 to 0.33)
Fourth order	0.12 (0.11 to 0.12)	0.14 (0.11 to 0.17)	0.14 (0.11 to 0.16)	0.13 (0.10 to 0.15)	0.12 (0.10 to 0.15)
Fifth order	0.05 (0.04 to 0.06)	0.06 (0.05 to 0.08)	0.06 (0.05 to 0.08)	0.06 (0.05 to 0.07)	0.06 (0.05 to 0.07)
Sixth order	0.03 (0.03 to 0.04)	0.04 (0.03 to 0.06)	0.03 (0.03 to 0.05)	0.04 (0.03 to 0.04)	0.04 (0.04 to 0.05)
Combined total HOA	0.23 (0.19 to 0.25)	0.28 (0.23 to 0.32)	0.28 (0.24 to 0.33)	0.27 (0.23 to 0.35)	0.27 (0.20 to 0.38)
Visual Strehl (VSX) ratio	0.25 (0.24 to 0.34)	0.22 (0.16 to 0.30)	0.23 (0.14 to 0.35)	0.23 (0.15 to 0.29)	0.23 (0.15 to 0.34)

Table 4. Fifteen- to 16-Year-Old Cohort: Median and IQRs for the Zernike Coefficients for Third and Fourth Orders and the RMS of Total Trefoil, Coma and Spherical Aberration, Total Third, Fourth, Fifth, and Sixth Orders, Combined HOA and Visual Strehl Ratios (VSX) for Each Refractive Error Grouping From 147 Year 12 Children

	High Hyperopes, $n = 7$	**Moderate Hyperopes, $n = 29$**	**Low Hyperopes, $n = 55$**	**Emmetropes, $n = 39$**	**Myopes, $n = 17$**
	Median (IQR, µm)	**Median (IQR, µm)**	**Median (IQR, µm)**	**Median (IQR, µm)**	**Median (IQR, µm)**
Zernike coefficient					
Z_3^{-3}	−0.07 (−0.11 to 0.00)	0.03 (−0.04 to 0.10)	0.03 (−0.04 to 0.07)	0.00 (−0.04 to 0.08)	0.08 (−0.02 to 0.15)
Z_3^{-1}	−0.01 (−0.03 to 0.13)	−0.01 (−0.08 to 0.04)	−0.03 (−0.14 to 0.04)	0.01 (−0.07 to 0.13)	−0.09 (−0.14 to 0.01)
Z_3^{1}	0.12 (0.03 to 0.16)	0.04 (0.00 to 0.12)	0.08 (0.01 to 0.15)	0.06 (0.03 to 0.13)	−0.01 (−0.03 to 0.11)
Z_3^{3}	−0.01 (−0.05 to 0.01)	−0.02 (−0.03 to 0.02)	0.02 (−0.05 to 0.07)	0.00 (−0.07 to 0.08)	0.00 (−0.02 to 0.08)
Z_4^{-4}	−0.01 (−0.01 to 0.03)	0.02 (0.00 to 0.04)	0.02 (0.00 to 0.04)	0.02 (0.00 to 0.05)	0.03 (0.00 to 0.04)
Z_4^{-2}	−0.01 (−0.03 to 0.01)	0.00 (−0.03 to 0.01)	−0.01 (−0.02 to 0.01)	0.00 (−0.02 to 0.02)	0.00 (−0.02 to 0.01)
Z_4^{0}	0.13 (0.09 to 0.15)	0.07 (0.04 to 0.10)	0.05 (0.01 to 0.11)	0.07 (0.04 to 0.10)	0.07 (0.00 to 0.11)
Z_4^{2}	−0.04 (−0.12 to 0.01)	0.00 (−0.02 to 0.02)	0.005 (−0.03 to 0.04)	0.01 (−0.02 to 0.04)	−0.005 (−0.05 to 0.03)
Z_4^{4}	0.03 (0.02 to 0.06)	0.02 (−0.01 to 0.05)	0.02 (−0.01 to 0.04)	0.00 (−0.02 to 0.03)	0.03 (−0.01 to 0.06)
RMS					
Trefoil	0.10 (0.08 to 0.15)	0.11 (0.06 to 0.15)	0.10 (0.08 to 0.17)	0.13 (0.09 to 0.17)	0.14 (0.10 to 0.21)
Coma	0.14 (0.12 to 0.18)	0.15 (0.06 to 0.21)	0.15 (0.10 to 0.23)	0.14 (0.08 to 0.25)	0.15 (0.13 to 0.24)
Spherical	0.13 (0.09 to 0.15)	0.07 (0.04 to 0.10)	0.07 (0.03 to 0.11)	0.08 (0.05 to 0.10)	0.07 (0.02 to 0.11)
Third order	0.20 (0.17 to 0.24)	0.20 (0.15 to 0.26)	0.21 (0.14 to 0.27)	0.21 (0.15 to 0.30)	0.24 (0.17 to 0.34)
Fourth order	0.15 (0.11 to 0.20)	0.12 (0.09 to 0.14)	0.11 (0.08 to 0.15)	0.11 (0.09 to 0.14)	0.10 (0.08 to 0.15)
Fifth order	0.08 (0.06 to 0.08)	0.05 (0.04 to 0.07)	0.05 (0.04 to 0.07)	0.06 (0.05 to 0.07)	0.06 (0.05 to 0.08)
Sixth order	0.03 (0.02 to 0.06)	0.04 (0.03 to 0.04)	0.04 (0.03 to 0.04)	0.03 (0.03 to 0.04)	0.04 (0.03 to 0.04)
Combined total HOA	0.29 (0.23 to 0.31)	0.26 (0.20 to 0.31)	0.26 (0.22 to 0.31)	0.25 (0.21 to 0.32)	0.30 (0.22 to 0.36)
Visual Strehl (VSX) ratio	0.18 (0.14 to 0.32)	0.27 (0.20 to 0.45)	0.24 (0.17 to 0.33)	0.28 (0.14 to 0.37)	0.25 (0.15 to 0.36)

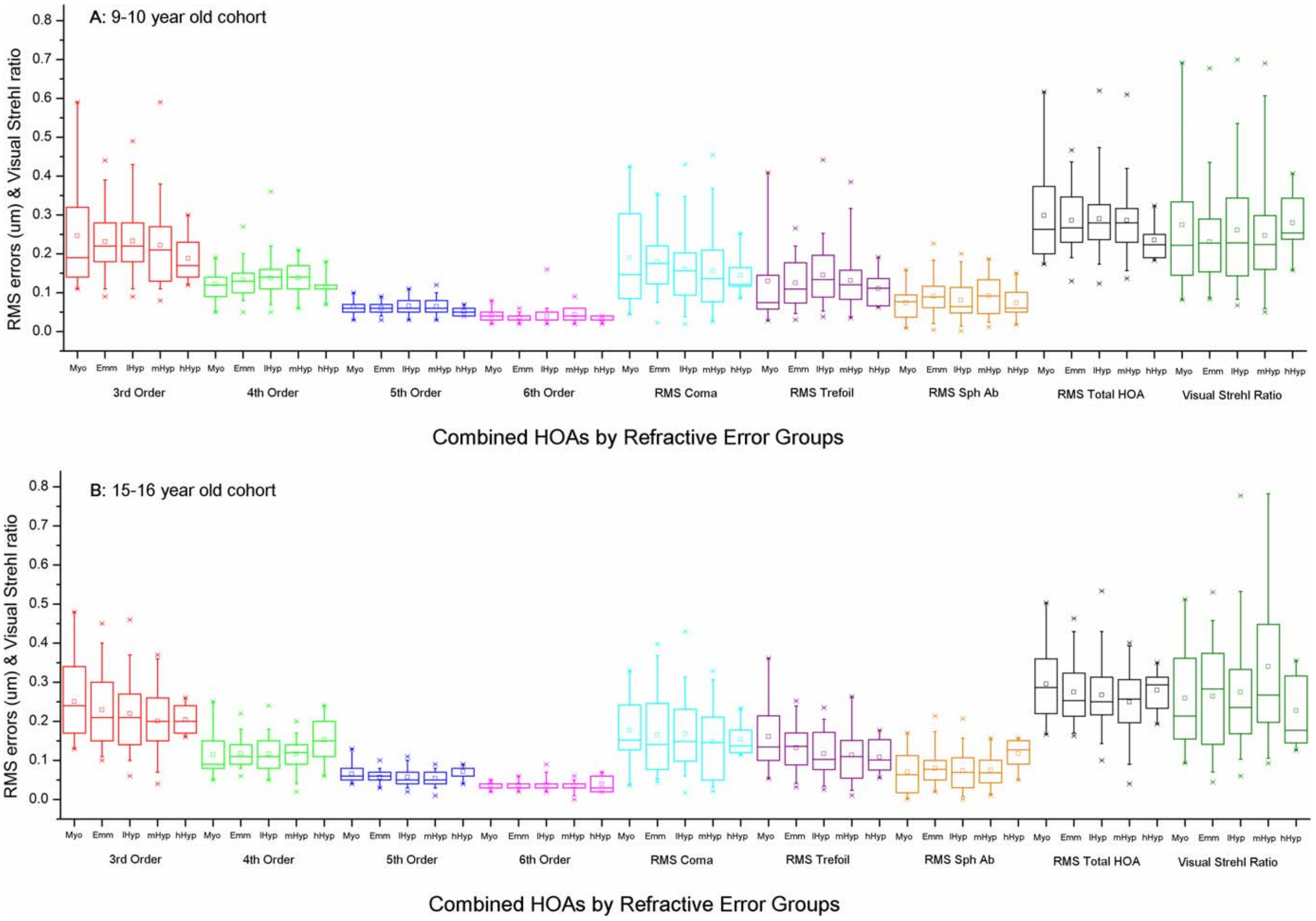

FIGURE 2. Box plots depicting the median (*line*), mean (*square*), IQR (*box*), fifth and 95th centiles (*whiskers*), and first and 99th centiles (*crosses*) of the RMS of total third, fourth, fifth, sixth, trefoil, coma, spherical aberration, and combined HOAs across refractive error groups. The VSX distributions also are shown on the *far right*. Data are shown for (**A**) 166 children in 9- to 10-year-old and (**B**) 147 in 15- to 16-year-old groups. *Refractive error groups*: Myo, myopic group; Emm, emmetropic group; lHyp, low hyperopic group, mHyp, moderately hyperopic group, and hHyp, high hyperopic group.

Although the overall trends were similar, Bonferroni-corrected ($P < 0.05/18$) statistically significant differences were found between the two cohorts for the individual aberration terms for quadrafoil of the cosine phase (Z_4^4, $z = 5.62$, $P < 0.0001$), secondary oblique (Z_4^{-2}, $z = 4.23$, $P < 0.0001$), and cartesian astigmatism (Z_4^2, $z = -4.01$, $P < 0.001$). However, these differences would not be deemed clinically significant.

To examine the relation between astigmatism and HOA, participants were divided into astigmats ($\geq$0.75 DC) and nonastigmats ($<$0.75 DC). No statistically significant differences were found between astigmats and nonastigmats for any of the HOA Zernike coefficients or for any of the RMS of aberration terms or Visual Strehl (Mann-Whitney U tests, $P > 0.05$).

Tables 3 and 4 show the median and IQRs of JOAs and Visual Strehl across refractive error groupings in each cohort.

For both cohorts, there were no statistically significant differences in Zernike coefficients or for the RMS of combined HOA (all tests $P > 0.05$). Figure 2 illustrates the distribution of the RMS aberrations and Visual Strehl between the refractive error groups for (Fig. 2A) 9- to 10- and (Fig. 2B) 15- to 16-year-old cohorts. Overall, third order and coma-like aberrations had the greatest magnitude across both cohorts. While no significant differences were found between refractive groups, inspection of Figure 2 illustrates that despite the greater range of refractive errors in the highly hyperopic group compared to the myopic group, aberrations in the myopic group including the RMS of combined HOA showed the greatest variation.

While several biometric measurements and Zernike terms were not normally distributed, fourth order spherical aberration and CR both had normal distributions and the transformation of other data enabled multivariate linear regression models for fourth order spherical aberration (Z_4^0), RMS total spherical aberration, RMS total HOA, and Visual Strehl to be conducted with AL, CR, and refractive group as explanatory variables. Bonferroni correction ($P < 0.05/4$) was applied to determine significance of regression models.

For the younger age cohort there were significant relations with RMS total spherical aberration ($F_{(3,159)} = 8.02$, $P = 0.0001$ $R^2 = 0.13$) and fourth order spherical aberration (Z_4^0) ($F_{(3,159)} = 4.72$, $P = 0.004$, $R^2 = 0.08$) with AL, CR, and refractive group, but not for RMS total HOA and Visual Strehl. For the older cohort, similar relations were found for fourth order spherical aberration (Z_4^0) and total RMS spherical aberration. Table 5 summarizes the coefficients of these models, demonstrating that AL had a significant relation with fourth order spherical aberration and total RMS spherical aberration (for the 15–16-year cohort) controlling for refractive group and CR. To visualize this, Figure 3 illustrates the relation between AL, and fourth order (Z_4^0) and total RMS spherical aberration for the (Fig. 3A) 9- to 10-year-old cohort and (Fig. 3B) 15- to 16-year-old

Table 5. Details of Significant Multivariate Regression Models for Both Age Cohorts

	Multivariate Regression	Variable	Coefficient	*t*-Test and *P* Value	95% Confidence Interval
Age 9–10 y cohort					
Fourth order spherical aberration	$F_{(3,159)} = 4.72$, $P = 0.0035$, $R^2 = 0.082$, adjusted $R^2 = 0.065$	Axial length	−0.023	$t = -2.37$, $P = 0.019$	−0.04 to −0.004
		Corneal curvature	−0.003	$t = -0.12$, $P = 0.90$	−0.06 to 0.05
		Refractive group	−0.009	$t = -1.31$, $P = 0.19$	−0.02 to 0.004
		Constant	0.65	$t = 4.17$, $P = 0.00$	0.34 to 0.96
RMS total spherical aberration	$F_{(3,159)} = 8.02$, $P = 0.0001$, $R^2 = 0.13$, adjusted $R^2 = 0.12$	Axial length	−0.013	$t = -1.85$, $P = 0.06$	−0.026 to 0.0008
		Corneal curvature	−0.027	$t = -1.57$, $P = 0.12$	−0.062 to 0.008
		Refractive group	−0.003	$t = -0.36$, $P = 0.72$	−0.01 to 0.008
		Constant	0.63	$t = 5.57$, $P = 0.00$	0.40 to 0.84
Age 15–16 y cohort					
Fourth order spherical aberration	$F_{(3,159)} = 6.07$, $P = 0.0007$, $R^2 = 0.12$, adjusted $R^2 = 0.10$	Reciprocal of axial length	15.59	$t = 2.78$, $P = 0.006$	4.51 to 26.67
		Corneal curvature	0.013	$t = 0.46$, $P = 0.65$	−0.04 to 0.07
		Refractive group	−0.005	$t = -0.74$, $P = 0.46$	−0.018 to 0.008
		Constant	−0.69	$t = -1.60$, $P = 0.11$	−1.54 to 0.16
RMS total spherical aberration	$F_{(3,159)} = 4.14$, $P = 0.008$, $R^2 = 0.08$, adjusted $R^2 = 0.06$	Reciprocal of axial length	10.32	$t = 2.36$, $P = 0.02$	1.68 to 18.94
		Corneal curvature	0.012	$t = 0.53$, $P = 0.60$	−0.03 to 0.06
		Refractive group	−0.003	$t = -0.54$, $P = 0.59$	−0.01 to 0.008
		Constant	−0.45	$t = -1.34$, $P = 0.18$	−1.11 to 0.21

cohort. As AL increased, spherical aberration tended to become more negative.

DISCUSSION

This study explored changes in HOA with age in a population-based cohort with a high prevalence of ametropia. Analysis of refractive error data demonstrated that the profile of ametropia was similar between the two age cohorts.

Furthermore, the distribution of HOA also was similar across both age cohorts. The current study calculated HOA for a fixed 5-mm pupil, in line with what one would expect natural pupil size to be for a childhood population. The VSX ratios were similar for both cohorts, at 0.23 and 0.26 units for the younger and older cohorts, respectively. This is in line with other studies reporting Strehl ratios for a moderately large pupil diameter.[51,52] For both cohorts, the RMS of total HOA had a combined median of 0.27 μm (combined IQR, 0.22–0.32, and combined mean value ± SD of 0.28 ± 0.09 μm to facilitate comparison with other studies). The RMS of total combined HOA is higher than in the study of Martinez et al.,[8] who reported a mean total RMS HOA of 0.18 ± 0.06 μm for their 6-year-old and 12-year-old Caucasian participants analyzed across a 5-mm pupil. It also is higher than published data on adult populations, such as the study of Salmon and Van de Pol,[53] who reported a mean total RMS HOA of 0.19 ± 0.08 μm, and Kwan et al.,[22] with an average total RMS HOA of 0.16 ± 0.06 μm, both analyzing at 5-mm pupil diameters. This is unlikely to be due to an instrument artefact as data from Salmon and Van de Pol[53] were obtained from combining a large amount of HOA data from several studies using a range of aberrometers. Furthermore, as Martinez et al.[8] report HOA data for Caucasian participants only, it is difficult to regard ethnicity as an explanation for the higher magnitude of HOA reported in the present study.

Some previous studies have reported higher amounts of HOA in hyperopes compared to myopes,[8,11] while others have found no difference in HOA between refractive groups,[20] or lower amounts of HOA for hyperopes compared to myopes[7] or emmetropes.[10] It is important to note that the classification of refractive error differed between these studies. For the present study, refractive error classification aligned with that of Martinez et al.,[8] yet we found very few significant differences in HOA between refractive groups. However, Figure 2 shows that the myopic group demonstrated the greatest variability in HOA, especially in the younger age cohort. This is despite the fact that the range in myopic errors was considerably less than those exhibited by the high hyperopes. The variability in individual HOA profiles within the myopic group perhaps reflects the variable rate at which growth occurs in myopic eyes. Consistent with other studies examining HOA, third and fourth order aberrations were higher in magnitude than fifth and sixth order aberrations. There were a few differences in HOA between the cohorts, and the 9- to 10-year-old cohort had more "nonzero" terms than the older cohort. Perhaps surprisingly, there were no significant differences across age cohorts for the spherical aberration term (Z_4^0) or for the RMS of total spherical aberration in the present study. The median spherical aberration (Z_4^0) was 0.07 μm for both age cohorts. Previous studies have reported a positive shift in the Zernike term spherical aberration (Z_4^0) from infancy (when it typically is negative) through to early childhood (when values typically are positive).[6,9] Others investigating HOA in childhood and throughout life report a positive increase in spherical aberration.[1,3] The nature of HOA as a whole is influenced by the balance between the internal and corneal optics. The cornea is relatively consistent in shape through later childhood and adulthood, and the positive shift in spherical aberration is attributed to crystalline lens change (see the report of Glasser et al.[54] for review). However, the present study examined children with only a 6-year age difference between cohorts, and no significant difference in M vector was found between the two cohorts. These factors may account for the consistency in spherical aberration values. Martinez et al.[8] did report a significant increase in positive spherical aberration between two groups of children with a 6-year age difference, but they found a greater difference in M vector between their two groups (0.35 D less positive for the older age group), and both age groups were younger than the participants in the present study.

While the current data do not show a significant difference in spherical aberration between the two cohorts, multivariate regression demonstrated significant relations between RMS total spherical aberration and fourth order spherical aberrations (Z_4^0), and AL for both cohorts. This is consistent with other studies reporting more positive spherical aberration in

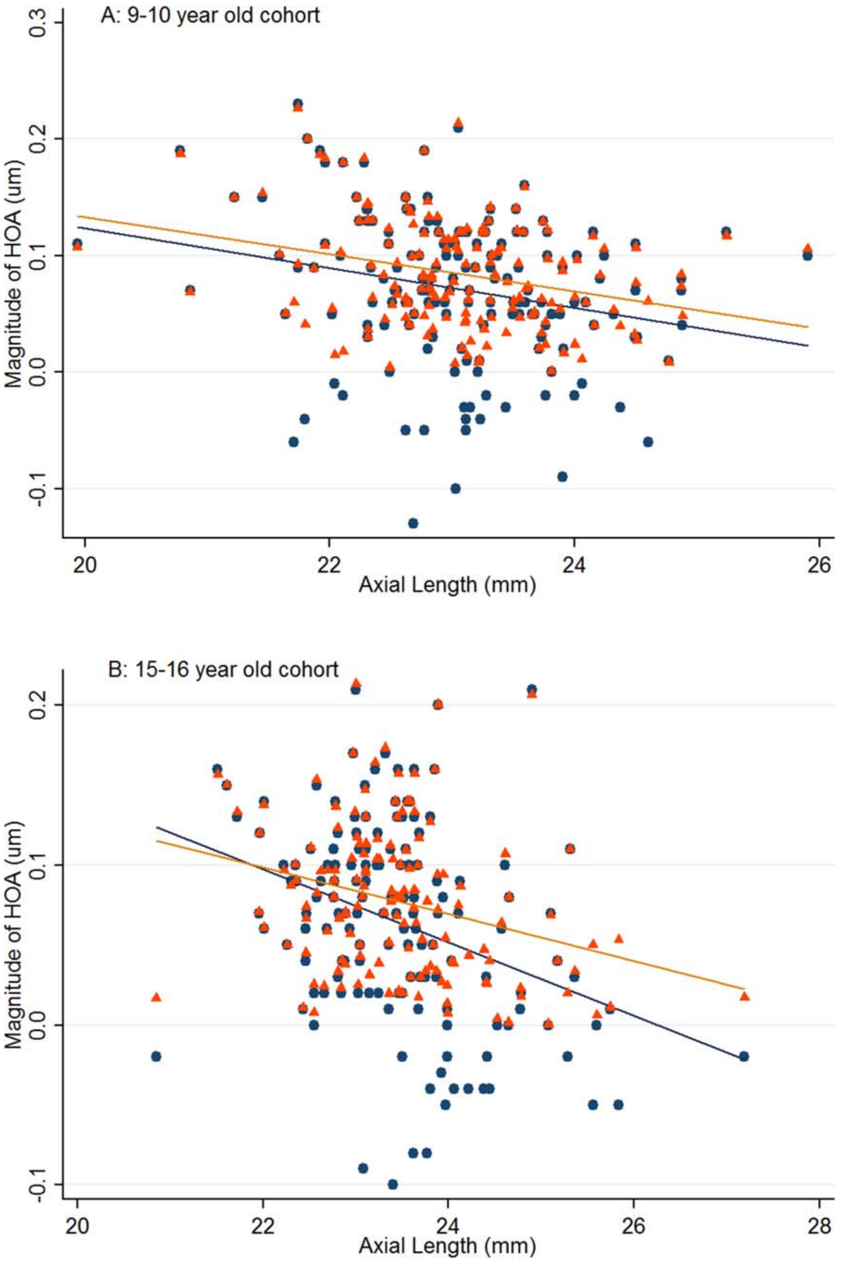

Figure 3. Scatterplots depicting AL against fourth order spherical aberration (*navy circles*) and total RMS spherical aberration (*red triangles*). *Lines* indicate linear regressions of the data. Data are shown for (**A**) 9- to 10-year-old cohort and (**B**) 15- to 16-year-old cohort.

hyperopes[8] or less positive spherical aberration in myopes.[11] Figure 3 illustrates the relation between fourth order (Z_4^0) and RMS total spherical aberration and AL, demonstrating that as AL increased, spherical aberration tended to become less positive/more negative. This indicated that knowledge of AL in addition to refractive error is an important consideration in analysis of HOA. This finding may signify that differences in spherical aberration between refractive groups could be merely the consequence of the differing geometrical properties of the ocular components of the ametropic eye, and not attributable as a cause of ametropia. However, spherical aberration remains particularly interesting to study as it has a role in accommodative function,[55,56] which, in turn, may impact eye growth. The current study measured HOA under conditions of cycloplegia, and it would be interesting to examine spherical aberration under natural conditions across refractive groups.

Corneal asphericity measurements were not captured during data collection for the present study. It is known that a more spherical cornea would result in higher levels of positive spherical aberration, so it is possible this could have had an impact across refractive groups. However, Llorente et al.[11] reported only a marginally significant difference in corneal asphericity between their hyperopic and myopic group, and neither Mainstone et al.[57] nor Budak et al.[58] found any differences across groups or correlation between asphericity and refractive error.

There is relatively little in the literature describing the HOA of astigmatic eyes, rather concentrating on the irregular astigmatism created by ocular pathology, such as keratoconus. One may expect slightly higher coma-like aberrations in an astigmatic eye, or alternatively that astigmatism is a second order aberration that does not impact on HOA. Overall, there were no systematic differences in HOA in those participants with greater amounts of astigmatism for either age cohort in the current study.

CONCLUSIONS

For school-aged children in Northern Ireland, HOA are higher than reported elsewhere for ethnically similar groups. There is a higher prevalence of ametropia in this population, but ametropia did not demonstrate a systematic relationship with HOA. The distribution of HOA was similar across both age cohorts and no significant difference in HOA was found across refractive error groups. The VSX ratios also are reported for both age cohorts and refractive groups, and again no significant difference in this metric of optical quality was found across age or refractive groups. This study provided further evidence that there are no differences in the magnitude of HOA with different refractive errors for school-aged children. However, the myopic group for both age cohorts demonstrated the greatest variability in HOA. Similar to other studies, there was a correlation between increasing AL and more negative values of spherical aberration. The current study revealed that AL rather than refractive grouping was the significant contributor for this relationship, suggesting that the different geometrical properties of the longer and shorter eye give rise to differences in spherical aberration terms, and this also highlights the importance of knowledge of AL when analyzing HOA.

Acknowledgments

The authors thank the children and schools for their participation in the study.

Supported by a PhD studentship by the Department of Education and Learning in Northern Ireland (SJM), and the NICER study is generously supported by the College of Optometrists, United Kingdom.

Disclosure: **J.-A. Little**, None; **S.J. McCullough**, None; **K.M.M. Breslin**, None; **K.J. Saunders**, None

References

1. McLellan JS, Marcos S, Burns SA. Age-related changes in monochromatic wave aberrations of the human eye. *Invest Ophthalmol Vis Sci*. 2001;42:1390–1395.
2. Kuroda T, Fujikado T, Ninomiya S, Maeda N, Hirohara Y, Mihashi T. Effect of aging on ocular light scatter and higher order aberrations. *J Refract Surg*. 2002;18:S598–S602.
3. Fujikado T, Kuroda T, Ninomiya S, et al. Age-related changes in ocular and corneal aberrations. *Am J Ophthalmol*. 2004;138:143–146.
4. Applegate RA, Donnelly WJ III, Marsack JD, Koenig DE, Pesudovs K. Three-dimensional relationship between high-order root-mean-square wavefront error, pupil diameter, and aging. *J Opt Soc Am A Opt Image Sci Vis*. 2007;24:578–587.
5. Brunette I, Bueno JM, Parent M, Hamam H, Simonet P. Monochromatic aberrations as a function of age, from childhood to advanced age. *Invest Ophthalmol Vis Sci*. 2003;44:5438–5446.
6. Wang J, Candy TR. Higher order monochromatic aberrations of the human infant eye. *J Vis*. 2005;23:543–555.
7. Kirwan C, O'Keefe M, Soeldner H. Higher-order aberrations in children. *Am J Ophthalmol*. 2006;141:67–70.
8. Martinez AA, Sankaridurg PR, Naduvilath TJ, Mitchell P. Monochromatic aberrations in hyperopic and emmetropic children. *J Vis*. 2009;9:23.1–14.
9. Athaide HV, Campos M, Costa C. Study of ocular aberrations with age. *Arq Bras Oftalmol*. 2009;72:617–621.
10. He JC, Sun P, Held R, Thorn F, Sun X, Gwiazda JE. Wavefront aberrations in eyes of emmetropic and moderately myopic school children and young adults. *Vision Res*. 2002;42:1063–1070.
11. Llorente L, Barbero S, Cano D, Dorronsoro C, Marcos S. Myopic versus hyperopic eyes: axial length, corneal shape and optical aberrations. *J Vis*. 2004;22;4:288–298.
12. Vincent SJ, Collins MJ, Read SA, Carney LG. Monocular amblyopia and higher order aberrations. *Vision Res*. 2012;166;39–48.
13. Hartwig A, Atchison DA, Radhakrishnan H. Higher-order aberrations and anisometropia. *Curr Eye Res*. 2013;38:215–219.
14. Prakash G, Sharma N, Choudhary V, Titiyal JS. Higher-order aberrations in young refractive surgery candidates in India: establishment of normal values and comparison with white and Chinese Asian populations. *J Cataract Refract Surg*. 2008;34:1306–1311.
15. Cervino A, Hosking SL, Ferrer-Blasco T, Montes-Mico R, Gonzalez-Meijome JM. A pilot study on the differences in wavefront aberrations between two ethnic groups of young generally myopic subjects. *Ophthalmic Physiol Opt*. 2008;28:532–537.
16. Schaeffel F, Howland HC. Mathematical model of emmetropization in the chicken. *J Opt Soc Am*. 1988;5:2080–2086.
17. Wilson BJ, Decker KE, Roorda A. Monochromatic aberrations provide an odd-error cue to focus direction. *J Opt Soc Am A Opt Image Sci Vis*. 2002;19:833–839.
18. Wallman J, Winawer J. Homeostasis of eye growth and the question of myopia. *Neuron*. 2004;43:447–468.
19. Thapa D, Fleck A, Lakshminarayanan V, Bobier WR. Ocular wavefront aberration and refractive error in pre-school children. *J Modern Optics*. 2011;58:19–20.
20. Carkeet A, Luo HD, Tong L, Saw SM, Tan DT. Refractive error and monochromatic aberrations in Singaporean children. *Vision Res*. 2002;42:1809–1824.
21. Collins MJ, Wildsoet CF, Atchison DA. Monochromatic aberrations and myopia. *Vision Res*. 1995;35:1157–1163.
22. Kwan WC, Yip SP, Yap MK. Monochromatic aberrations of the human eye and myopia. *Clin Exp Optom*. 2009;92:304–312.
23. Bao J, Le R, Wu J, Shen Y, Lu F, He JC. Higher-order wavefront aberrations for populations of young emmetropes and myopes. *J Optom*. 2009;2:51–58.
24. Cheng X, Bradley A, Hong X, Thibos LN. Relationship between refractive error and monochromatic aberrations of the eye. *Optom Vis Sci*. 2003;80:43–49.
25. De Brabander J, Hendricks T, Chateau N, et al. Ametropia and higher order Aberrations in Children 12–13 years of age. *Invest Ophthalmol Vis Sci*. 2004;ARVO; 45: E-Abstract 2761.
26. Karimian F, Feizi S, Doozande A. Higher-order aberrations in myopic eyes. *J Ophthalmic Vision Res*. 2010;5:3–9.
27. Zadok D, Levy Y, Segal O, Barkana Y, Morad Y, Avni I. Ocular higher-order aberrations in myopia and skiascopic wavefront repeatability. *J Cataract Refract Surg*. 2005;31:1128–1132.
28. Wei RH, Lim L, Chan WK, Tan DT. Higher order ocular aberrations in eyes with myopia in a Chinese population. *J Refract Surg*. 2006;22:695–702.
29. Porter J, Guirao A, Cox IG, Williams DR. Monochromatic aberrations of the human eye in a large population. *J Opt Soc Am Opt Image Sci Vis*. 2001;18:1793–1803.
30. Paquin MP, Hamam H, Simonet P. Objective measurement of optical aberrations in myopic eyes. *Optom Vis Sci*. 2002;79:285–291.
31. Smith EL III, Kee CS, Ramamirtham R, Qiao-Grider Y, Hung LF. Peripheral vision can influence eye growth and refractive

development in infant monkeys. *Invest Ophthalmol Vis Sci*. 2005;46:3965–3972.

32. Smith EL III, Hung LF, Huang J. Relative peripheral hyperopic defocus alters central refractive development in infant monkeys. *Vision Res*. 2009;49:2386–2392.
33. Seidemann A1, Schaeffel F, Guirao A, Lopez-Gil N, Artal P. Peripheral refractive errors in myopic, emmetropic, and hyperopic young subjects. *J Opt Soc Am A Opt Image Sci Vis*. 2002;19:2363–2373.
34. Atchison DA. Anterior corneal and internal contributions to peripheral aberrations of human eyes. *J Opt Soc Am A Opt Image Sci Vis*. 2004;21:355–359.
35. Rosén R, Lundström L, Unsbo P. Sign-dependent sensitivity to peripheral defocus for myopes due to aberrations. *Invest Ophthalmol Vis Sci*. 2012;17:53:7176–7182.
36. Charman WN. Aberrations and myopia. *Ophthalmic Physiol Opt*. 2005;25:285–301.
37. Zhang N, Yang XB, Zhang WQ, et al. Relationship between higher-order aberrations and myopia progression in schoolchildren: a retrospective study. *Int J Ophthalmol*. 2013;6:295–299.
38. O'Donoghue L, McClelland JF, Logan NS, Rudnicka AR, Owen CG, Saunders KJ. Refractive error and visual impairment in school children in Northern Ireland. *Br J Ophthalmol*. 2010; 94:1155–1159.
39. O'Donoghue L, Rudnicka AR, McClelland JF, Logan NS, Owen CG, Saunders KJ. Refractive and corneal astigmatism in white school children in Northern Ireland. *Invest Ophthalmol Vis Sci*. 2011;52:4048–4053.
40. French AN, O'Donoghue L, Morgan IG, Saunders KJ, Mitchell P, Rose KA. Comparison of refraction and ocular biometry in European Caucasian children living in Northern Ireland and Sydney, Australia. *Invest Ophthalmol Vis Sci*. 2012;53:4021–4031.
41. O'Donoghue L, Saunders KJ, McClelland JF, et al. Sampling and measurement methods for a study of childhood refractive error in a UK population. *Br J Ophthalmol*. 2010;94:1150–1154.
42. Breslin KM, O'Donoghue L, Saunders KJ. A prospective study of spherical refractive error and ocular components among Northern Irish schoolchildren (the NICER study). *Invest Ophthalmol Vis Sci*. 2013;54:4843–4850.
43. Chat SW, Edwards MH. Clinical evaluation of the Shin-Nippon SRW-5000 autorefractor in children. *Ophthalmic Physiol Opt*. 2001;21:87–100.
44. Mallen EA, Wolffsohn JS, Gilmartin B, Tsujimura S. Clinical evaluation of the Shin-Nippon SRW-5000 autorefractor in adults. *Ophthalmic Physiol Opt*. 2001;21:101–107.
45. Tang WC, Tang YY, Lam CS. How representative is the 'representative value' of refraction provided by the Shin-Nippon NVision-K 5001 autorefractor? *Ophthalmic Physiol Opt*. 2014;34:89–93.
46. Miranda MA, O'Donnell C, Radhakrishnan H. Repeatability of corneal and ocular aberration measurements and changes in aberrations over one week. *Clin Exp Optom*. 2009;92:253–266.
47. Thibos LN, Applegate RA, Schwiegerling JT, Webb R, VSIA Standards Taskforce Members. Vision science and its applications. Standards for reporting the optical aberrations of eyes. *J Refract Surg*. 2002;18:S652–S660.
48. Thibos LN, Hong X, Bradley A, Applegate RA. Accuracy and precision of objective refraction from wavefront aberrations. *J Vis*. 2004;4:329–351.
49. Marsack JD, Thibos LN, Applegate RA. Metrics of optical quality derived from wave aberrations predict visual performance. *J Vis*. 2004;4:322–328.
50. 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.
51. Guirao A, González C, Redondo M, Geraghty E, Norrby S, Artal P. Average optical performance of the human eye as a function of age in a normal population. *Invest Ophthalmol Vis Sci*. 1999;40:203–213.
52. Villegas EA, Alcón E, Artal P. Optical quality of the eye in subjects with normal and excellent visual acuity. *Invest Ophthalmol Vis Sci*. 2008;49:4688–4696.
53. Salmon TO, van de Pol C. Normal-eye Zernike coefficients and root-mean-square wavefront errors. *J Cataract Refract Surg*. 2006;32:2064–2074.
54. Glasser A, Croft MA, Kaufman PL. Aging of the human crystalline lens and presbyopia. *Int Ophthalmol Clin*. 2001; 41:1–15.
55. Hazel CA, Cox MJ, Strang NC. Wavefront aberration and its relationship to the accommodative stimulus-response function in myopic subjects. *Optom Vis Sci*. 2003;80:151–158.
56. Plainis S, Ginis HS, Pallikaris A. The effect of ocular aberrations on steady-state errors of accommodative response. *J Vis*. 2005; 5:466–477.
57. Mainstone JC, Carney LG, Anderson CR, Clem PM, Stephensen, AL, Wilson MD. Corneal shape in hyperopia. *Clin Exp Optom*. 1998;81:131–137.
58. Budak K, Khater TT, Friedman NJ, Holladay JT, Koch DD. Evaluation of relationships among refractive and topographic parameters. *J Cataract Refract Surg*. 1999;25:814–820.