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Higher-order aberrations and best-corrected visual acuity in Native American children with a high prevalence of astigmatism

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Abstract

Purpose—To determine whether higher-order aberrations (HOAs) in children from a highly astigmatic population differ from population norms and whether HOAs are associated with astigmatism and reduced best-corrected visual acuity.

Methods—Subjects were 218 Tohono O’odham Native American children 5–9 years of age. Noncycloplegic HOA measurements were obtained with a handheld Shack-Hartmann sensor (SHS). Signed (z06s to z14s) and unsigned (z06u to z14u) wavefront aberration Zernike coefficients Z(3,–3) to Z(4,4) were rescaled for a 4 mm diameter pupil and compared to adult population norms. Cycloplegic refraction and best-corrected logMAR letter visual acuity (BCVA) were also measured. Regression analyses assessed the contribution of astigmatism (J0) and HOAs to BCVA.

Results—The mean root-mean-square (RMS) HOA of $0.191 \pm 0.072 \mu\text{m}$ was significantly greater than population norms ($0.100 \pm 0.044 \mu\text{m}$). All unsigned HOA coefficients (z06u to z14u) and all signed coefficients except z09s, z10s, and z11s were significantly larger than population norms. Decreased BCVA was associated with astigmatism (J0) and spherical aberration (z12u) but not RMS coma, with the effect of J0 about 4 times as great as z12u.

Conclusions—Tohono O’odham children show elevated HOAs compared to population norms. Astigmatism and unsigned spherical aberration are associated with decreased acuity, but the effects of spherical aberration are minimal and not clinically significant.

Optical aberrations prohibit light from a single point on an object from coming into to focus as a single point on an image. The Shack-Hartmann sensor (SHS)—a marriage of the Hartmann lenticular array, a CCD camera, and the digital computer¹—provides objective

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measurements of optical aberrations. The short image acquisition time (<100 ms) and subsequent digital decomposition of the spot locations to the Zernike coefficients have allowed for characterization of the higher order aberrations (HOAs) of the eye.

The present study compared HOAs in children from a Native American population (the Tohono O’odham) with a high prevalence of astigmatism^{2–4} to population norms.⁵ Astigmatism in Tohono O’odham children is almost always with-the-rule and is primarily corneal in origin.² The Tohono O’odham tribe includes approximately 28,000 members. Their reservation is located in southern Arizona (www.tonation-nsn.gov). We hypothesize that, given the atypically high rate of lower order aberrations, children from this population may have atypically high levels of HOAs if astigmatic corneas are associated with other surface irregularities, as is seen in keratoconus.⁶ We were specifically interested in the relation between astigmatism and the two HOAs that typically contribute the most power in studies of populations: unsigned spherical aberration (z12u) and unsigned coma (root-mean-square z07u and z08u).

This study also examined the relation between HOAs, astigmatism, and best-corrected visual acuity (BCVA). Previous studies have documented reduced BCVA in astigmatic Tohono O’odham children, which has been attributed to astigmatism-related amblyopia (ie, a deficit that is neural and persists with spectacle correction).^{7–9} We hypothesize that some of these BCVA deficits may arise from uncorrected HOAs. If astigmatism is associated with higher rates of HOAs in this population, uncorrected HOAs may also limit the effectiveness of spectacle treatment. A previous study showed that reduced BCVA in astigmatic Tohono O’odham children persisted despite a full year of spectacle correction.¹⁰ A recent retrospective study found that hyperopic anisometropic amblyopia treatment failures (2 line interocular difference in BCVA after 12 months of treatment) had greater spherical aberration than treatment successes.¹¹

The present study aimed (1) to document the HOAs seen under conditions of minimal accommodation in a sample of Tohono O’odham children and to compare to existing population norms⁵; (2) to determine whether there is a relation between HOAs and J0 astigmatism (positive J0 values represent with-the-rule astigmatism) in this population.(we hypothesize that corneal astigmatism is associated with other surface irregularities that may lead to elevated HOAs); and (3) to determine whether HOAs are independently associated with reduced BCVA. We hypothesize that uncorrected HOAs may contribute to poor BCVA reported in astigmatic children from this population.^{7–9}

Methods

Subjects were children 5–9 years of age who participated in a longitudinal study of visual development. Most subjects were members of a Native American Tribe, the Tohono O’odham, who have a high prevalence of astigmatism that is present in infancy and on average remains clinically stable through the school years.^{2–4,12} Children were recruited from the Tohono O’odham Early Childhood Head Start program, the Tohono O’odham community, and from elementary schools on the Tohono O’odham reservation and were followed yearly. This study was approved by the Tohono O’odham Nation and the

Institutional Review Board of the University of Arizona and conformed to the requirements of the US Health Insurance Portability and Accountability Act of 1996. Parents provided written informed consent prior to testing.

Apparatus and Analysis of HOA Data

Measurements of HOAs were obtained with the Pediatric Wavefront Evaluator (PeWE), a handheld open-field SHS designed for measurement of infants and young children and permits binocular viewing of real targets at a variety of distances. A detailed description of the instrument has been previously published.^{13,14}

Zernike polynomials were computed and compared for a specified pupil diameter. The SHS in the PeWE aberrometer has spacing that requires a minimum pupil diameter of 4 mm for acceptable reconstruction of HOA wavefront error to the 4th order (see Appendix). The PeWE recorded multiple SHS images for each subject at a rate of 10 frames per second. Images containing SHS spots were extracted and inspected individually for focus, centration, and contrast. We excluded subjects with a pupil diameter of <4 mm. Each image was analyzed at the observed pupil size and pupil diameters >4 mm were rescaled to 4 mm for averaging within subjects.¹⁵ The Zernike coefficients were determined per OSA standards (ISO 24157:2008 Ophthalmic optics and instruments—reporting aberrations of the human eye). At least 7 images were required for averaging within each subject.¹⁴ The total root-mean-square (RMS) was calculated as the root of the sum of squared Zernike coefficients after scaling each observation to a 4 mm diameter pupil and averaging the coefficients within subjects. We also combined the individual Zernike coefficients related to coma (z07s and z08s) into a single unsigned RMS coma.

Because Zernike coefficients can be either positive or negative, it is possible for effects to be masked across subjects while averaging the values, that is, a positive wavefront error in one subject can mask or negate negative values of similar magnitude in another, resulting in an average value close to 0, but with both subjects experiencing image quality degradation. In estimating the effects of individual coefficients on image quality, unsigned magnitude reporting is useful. In other instances, the signed data is useful in interpreting the characteristics of the population with respect to eye structure. Both signed (z06s to z14s) and unsigned (z06u to z14u) coefficients were determined for our sample.

Procedures

We obtained right eye HOA observations on a cross section of 5- to 9-year-old Tohono O'odham children. Participants were imaged through their natural pupil with the PeWE while viewing an animated cartoon located at 2 m. Cycloplegic autorefraction measurements were obtained following measurement of HOAs. Cycloplegia was achieved with 1 drop of proparacaine 0.5% followed by 2 drops of cyclopentolate 1%. Autorefraction using the Retinomax K-plus 2 (Nikon Inc, Melville, NY) was conducted at least 30 minutes after instillation of eyedrops. The Retinomax provides a confidence number ranging from 1 (low) to 10 (high) with each measurement. The examiner attempted to obtain Retinomax measurements with a confidence of at least 8, per manufacturer recommendations. Spectacle correction was determined by subjectively refining the autorefraction result.

Letter visual acuity for the right eye wearing spectacle correction (full correction with the exception that sphere correction for hyperopic subjects was reduced by 1/3 or 1.00 D, whichever was greater) was conducted at a second test session using the ETDRS logMAR letter chart (Precision Vision, LaSalle, IL). Visual acuity was scored as the smallest logMAR stimulus size on which the subject was able to correctly identify at least 3 of 5 letters.

Subject Inclusion Criteria

Data were analyzed cross-sectionally. A single set of observations per subject (from one follow-up encounter) was selected from longitudinal measurements as follows: a preference was given for a data session in which the child provided the greatest amount of information (HOA measurement, cycloplegic refraction, best-corrected visual acuity) at the oldest age tested.

Results

The study included 218 children (105 girls) for whom measurements of HOAs at a pupil diameter of at least 4 mm, cycloplegic refraction, and BCVA were available. Average age was 6.6 years (range, 5.1–9.0 years).

The average pupil diameter with standard deviation was 4.53 ± 0.33 mm. The largest observed pupil diameter was 5.65 mm, and the 90th percentile of pupil diameter was 4.98 mm. On average, 29 ± 21.0 images were used to determine HOAs within subjects, with 75% of the subjects having 15 or more images and 90% having 10 or more images averaged.

A sample summary of right eye lower order aberrations M (spherical equivalent), J0 (astigmatism in the horizontal/vertical meridian) and J45 (astigmatism in the oblique meridian) derived from the cycloplegic autorefraction and the PeWE SHS are given in Table 1. Astigmatism is predominantly with-the-rule in Tohono O'odham children, and this is reflected in the positive mean values of J0 and lesser values of J45.

HOAs Compared to Population Norms

Several studies report HOA normative data. We chose to use the adult normative data provided by Salmon and Van de Pol⁵ because of the following advantages of this dataset: (1) the contribution of data across multiple laboratories and measurement systems, (2) the reporting of coefficients at 4 mm pupil size, and (3) the reporting of means and standard deviations of both signed and unsigned Zernike coefficients of HOA, which allowed for statistical comparison with our data using *t* tests.

Signed and unsigned Zernike coefficients for right eyes are summarized in Table 2 along with adult normative data.⁵ All unsigned aberrations from our sample significantly differed from adult population norms ($P < 0.001$), and z06s, z07s, z08s, z12s, Z13s, and z14s differed from population norms ($P < 0.001$).

The RMS HOA value for the Tohono O'odham subjects averaged 0.191 ± 0.072 μm for 3rd through 4th order and higher-order terms. This value was significantly greater than the adult

normative mean RMS value for a 4 mm pupil (mean, $0.100 \pm 0.044 \mu\text{m}$; $P < 0.0001$),⁵ despite the fact that the normative RMS value would be expected to be larger because of the inclusion of additional Zernike terms (3rd through 6th order). The 25th and 75th percentiles for RMS HOA for our sample were $0.138 \mu\text{m}$ and $0.273 \mu\text{m}$, respectively.

HOAs Compared to Data from Child and Young Adult Samples

Several studies report HOAs for child and young adult samples, although none of the available studies report data scaled to a pupil size of 4 mm. For studies of child and young adult samples that provided tables of mean HOAs, we scaled mean HOA data down to a 4 mm pupil.^{16–24} A summary is provided in Table 2 and Figure 1. Statistical analyses could not be used to compare our data to the published data, because measures of variability were not available for the 4 mm pupil size scaled means. Nevertheless, the data suggest that compared to child/young adult samples, the Tohono O’odham children have higher levels of most HOAs.

HOAs and J0 Astigmatism

Separate regression analyses for signed and unsigned HOAs were conducted including all HOAs (z06 to z14) as potential predictors of J0 astigmatism (from cycloplegic refraction), with age included in the model.

For unsigned coefficients, z9u (x trefoil, $P = 0.019$) and z10u (y-quadrafoil, $P = 0.003$) were positively correlated with J0 astigmatism. For signed coefficients, z09s (x trefoil, $P = 0.000$) was negatively correlated with J0 astigmatism and z10s (y-quadrafoil, $P = 0.018$) was positively correlated with J0 astigmatism.

Best-Corrected Visual Acuity, Cycloplegic Refraction, and HOAs

Regression analysis indicated that decreased BCVA was associated with elevated J0 ($P < 0.001$) and z12u ($P = 0.030$) but not RMS coma ($P = 0.392$). When age was added to the model ($P = 0.001$), the effect of J0 remained strong ($P < 0.001$), but the effect of z12u dropped in significance ($P = 0.092$) due to collinearity between age and z12u ($r^2 = 0.40$, $P = 0.026$).

We compared the relative effect of J0 astigmatism and z12u on BCVA based on regression coefficients (Table 3). BCVA is degraded 0.152 logMAR units per diopter of J0 astigmatism ($-1.00 + 2.00 \times 090$ in clinical refraction notation) and 0.583 logMAR units per μm of z12u. Thus, the degradation of visual acuity when comparing a child in the 25th to the 75th percentile of J0 (0.691 D) is 0.105 logMAR unit, or 1 line of visual acuity degradation attributable to the effects of J0 astigmatism. The deficit attributable to z12u is calculated to be 0.026 logMAR units. The effect of z12u is about 1/4 as strong as the effect of J0, or about one letter of acuity as opposed to 1 line of visual acuity.

Discussion

This study is the first to document the HOAs in a large number of children having a high prevalence of astigmatism. Our four main findings are as follows:

1. HOAs are elevated compared to population norms, suggesting that this population is atypical in terms of levels of HOAs as well as prevalence of astigmatism (Table 2).
2. Magnitude of J0 astigmatism is significantly related to magnitude of some HOAs: high J0 is associated with high levels of z09u, z10u, and z10s, and lower levels of z09s.
3. Decreased BCVA is associated with higher levels of J0 and z12u (RMS spherical aberration), but not with RMS coma.
4. The influence of z12u on BCVA in this population is statistically significant, but its clinical relevance is minimal compared to the influence of J0 astigmatism (Table 3).

Our first aim was to document the HOAs in this population with atypical lower order aberrations. The signed and unsigned HOAs in our population of Tohono O'odham children have larger mean values than the population norms reported by Salmon and Van de Pol (Table 2).⁵ The data indicate that our sample has elevated levels of unsigned Zernike polynomial coefficients through the 4th order. There is a negative mean spherical aberration z12s ($-0.034 \mu\text{m}$) in our sample and a positive mean spherical aberration ($+0.021 \mu\text{m}$) in the Salmon meta-analysis of multiple studies of adult subjects.⁵

The standard deviations of measurements of the Tohono O'odham children are greater than those reported by Salmon and Van de Pol (Table 2).⁵ This could indicate greater variability in HOAs in Tohono O'odham children. However, several factors may have resulted in higher variability in our sample, including instability created by using a handheld instrument to measure an unrestrained subject, younger subject age, smaller sample size, and fluctuations in accommodation due to absence of cycloplegia.

Comparison with other child/young adult samples should be made with due caution, because there are many methodological differences across studies (eg, different instruments, some measurements done with cycloplegia and others without) as well as differences in sample selection criteria. However, for the Tohono O'odham sample, coma term z07s is consistently more positive and coma term z08s is consistently more negative than data reported for other samples. Spherical aberration (z12s) means from other studies appears to be bimodal, with some reporting positive and some reporting negative mean spherical aberration as we did.

Our second aim was to determine whether with-the-rule astigmatism (J0) was associated with elevated HOAs. Several previous studies of children have examined the relation between spherical refractive errors and HOAs,^{16,18,19} but none have focused on the relation between astigmatism and HOAs. Hartwig and colleagues²⁵ reported the relation between higher-order RMS and limits of agreement in a large sample (24,604) of optometry patients. They observed significant associations between HOAs (higher-order RMS and some aberration coefficients) and limits of agreement (spherical equivalent, near addition, and astigmatism). However, spherical defocus rather than lower-order astigmatism was the greatest contributor to the relation, by a factor of over 10:1. We did not observe an association between elevated levels of J0 astigmatism and elevated z12u (spherical

aberration), but did observe associations between J0 astigmatism and z09u, z10u, z09s, and z10s.

Our final aim was to determine the effect of HOAs on BCVA. On average, a diopter of J0 astigmatism produced a 1 logMAR line reduction in BCVA. In contrast, for typical levels of spherical aberration seen in our population, a little more than a letter (of 5 letters on each line of a logMAR visual acuity chart) of BCVA reduction was observed. The effect is statistically significant but is not likely to be clinically significant or amblyogenic.

Traditional spectacle correction as the primary treatment for bilateral refractive amblyopia in this population should continue. This analysis assumes that the correction of lower-order aberrations is properly described and dispensed. However, it is possible to have the correct prescription but either with ocular roll in various positions of gaze or misplacement of the lenses in the frames a child can have a significant residual refractive error from spectacles being improperly aligned with the correct axis. For example, if a child has a prescription of $-1.00 +2.00 \times 090$ but the correcting lens is actually placed at axis 080, a residual refractive error of $-0.25 +0.75 \times 130$ is created.²⁶

The high prevalence of astigmatism allowed for assessment of the relation between HOAs, astigmatism, and BCVA in a large sample of children. However, because our study population is atypical in terms of levels of lower-order aberrations, the extent to which the results can be generalized to other populations is limited. The fact that our observations were made without cycloplegia can be seen as both a strength and a weakness. Measurements without cycloplegia made results of analyses of the relation between HOAs, astigmatism, and BCVA more generalizable to typical viewing conditions experienced by the children; however, absence of cycloplegia introduced an inconsistency in methodology used in our sample compared to methodology used to generate population norms. However, subjects were viewing a 2 m distant target through an open-field SHS, and previous analyses indicated that subjects were relaxing their accommodation when viewing the 2 m target (Miller JM et al. IOVS 2013;54:ARVO E-Abstract 2334).

In conclusion, this report makes three unique contributions to the literature. First, we document elevated levels of HOAs in Tohono O'odham children. Second, we note a significant relation between some HOAs and presence of astigmatism, although this finding should be further assessed to determine its generalizability. Finally, we report evidence that reduced BCVA observed in astigmatic Tohono O'odham children arises from amblyopia attributed to astigmatism, with only a small contribution from uncorrected HOAs.

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Appendix. Accuracy of the PeWE Aberrometer

Accuracy of the PeWE SHS was assessed through measurements of reference phase plates having known magnitudes of spherical aberration across a range of pupil diameters from 3 to 5 mm.

The SHS used in the PeWE has spot spacing selected to provide a large range of astigmatism measurement without aliasing. This measurement range comes at the expense of increased spot spacing and fewer spots for a given size of pupil. There are 27, 48, and 75 readily visible spots at 3, 4, and 5 mm diameter pupils, respectively. These spots are used to fit a set of Zernike polynomials; the more spots, the more data is available to fit the set of polynomials, and greater expected accuracy.

Six phase plates having positive and negative spherical aberration were constructed of water clear zinc sulfide (Cleartran; Rohm and Haas, Philadelphia, PA). Single-point diamond turning was used to create a rotationally symmetric surface with known Zernike wavefront error as a function of pupil diameter and wavelength of light. These six reference surfaces were then used in a model eye that was constructed to allow one-pass aberrometry to be performed with the PeWE. A plane wave was first used to align the PeWE SHS, and then the model eye used to verify the measurements obtained from the SHS of the PeWE. As the wavefront measurements obtained with the PeWE SHS are derived from the lenslet focal length, lenslet spacing, and CCD detector pixel spacing of the SHS, there is no calibration or adjustment per se, but rather verification of design.

The 6 phase plates with known quantities of spherical aberration were measured with the PeWE. We did not find acceptable agreement between observed and expected values of spherical aberration when a 3 mm pupil was used ($r^2 = 0.20$). For pupil sizes of 4 or 5 mm, the agreement between observed and expected values was very good ($r^2 = 0.87$). The associated regression equation ($p < 0.001$ for both slope and offset) relating observed and expected spherical aberration was:

$$\text{Observed } z_{12s} = 0.93 * \text{Expected } z_{12s} + 0.0001 \mu\text{m}.$$

Therefore, observations with a pupil size <4 mm were excluded from the dataset, and remaining observations were scaled to a 4 mm pupil.

FIG. 1.

Mean signed Zernike coefficient magnitudes (microns) for the Tohono O'odham sample (triangles), adult populations norms (squares),⁵ and studies of children and young adults (circles).¹⁶⁻²⁴ All means scaled to a 4 mm pupil. Bars represent ± 1 standard deviation.

Table 1

Mean value of the power vectors M, J0, and J45 for cycloplegic Retinomax autorefraction and for noncycloplegic PeWE with a distant (2 m) fixation target (n = 218).

Instrument/condition	Measurement	Mean	SD	Minimum	Maximum
Cycloplegic Retinomax	M	+0.75	1.08	-2.87	+5.25
	J0	+0.47	0.58	-0.62	+2.24
	J45	+0.01	0.21	-0.75	+0.81
Noncycloplegic PeWE with distant target	M	-0.01	0.86	-3.16	+2.31
	J0	+0.63	0.61	-0.35	+2.69
	J45	-0.18	0.28	-1.29	+0.76

SD, standard deviation.

Table 2

Summary of mean HOAs from the present study, adult population norms, and studies of children or young adults^a

Study	Refraction	Age, years	No. eyes	Zernike single index and Zernike double index, microns ($\pm$ SD)									
				$z06$ Z(3,-3)	$z07$ Z(3,-1)	$z08$ Z(3,1)	$z09$ Z(3,3)	$z10$ Z(4,-4)	$z11$ Z(4,-2)	$z12$ Z(4,0)	$z13$ Z(4,2)	$z14$ Z(4,4)	
Tohono O'odham	NC	5-9	218	0.059 $\pm$ 0.076	0.051 $\pm$ 0.090	-0.033 $\pm$ 0.080	0.004 $\pm$ 0.075	0.003 $\pm$ 0.027	-0.000 $\pm$ 0.018	-0.034 $\pm$ 0.045	0.034 $\pm$ 0.035	-0.009 $\pm$ 0.046	
Salmon & Van de Pol ⁵	C	Adults	2560	-0.015 $\pm$ 0.050	-0.006 $\pm$ 0.059	0.001 $\pm$ 0.042	0.000 $\pm$ 0.040	0.001 $\pm$ 0.016	-0.001 $\pm$ 0.012	0.021 $\pm$ 0.029	0.000 $\pm$ 0.018	0.002 $\pm$ 0.018	
Carkeet et al ¹⁶	C	7-12 ^b	273	-0.005	0.026	0.010	0.005	0.004	-0.004	0.020	0.004	0.004	
Hiraoka et al ¹⁷	NC	4-12 ^c	28	0.012	0.005	-0.004	-0.017	0.005	-0.003	0.007	0.003	-0.001	
Kirwan et al ¹⁸	C	4-14 ^d	162	0.017	-0.042	0.009	-0.008	0.003	-0.001	-0.032	0.004	-0.006	
Little et al ¹⁹	C	15-16 ^e	147	0.015	-0.010	0.031	0.000	0.008	-0.004	0.029	0.000	0.004	
		9-10 ^e	166	0.026	-0.031	0.031	0.010	0.004	0.004	0.029	-0.008	0.016	
Martinez et al 2009 ²⁰	C	6 & 12 ^{e,f}	771	0.010	-0.006	0.007	0.008	0.005	-0.003	0.016	0.005	0.005	
Papamastorakis et al ²¹	NC	10-11 ^b	152	-0.023	0.042	0.007	-0.006	0.003	-0.002	0.003	0.001	0.005	
		12-13 ^b	178	-0.029	0.051	0.004	0.002	0.005	-0.002	0.005	-0.002	0.007	
		14-15 ^b	227	-0.030	0.033	0.015	-0.002	0.005	-0.003	0.012	-0.006	0.007	
Prakash et al ²²	NC	9 $\pm$ 3 ^{d,g}	17	0.038	-0.065	0.019	-0.004	0.000	-0.008	-0.042	0.003	0.011	
		9 $\pm$ 3 ^{d,h}	17	0.019	-0.065	0.015	-0.023	0.003	-0.003	-0.039	0.017	-0.003	
Yazar et al ²³	NC	18-22 ^h	767	0.022	-0.018	-0.039	-0.024	-0.010	0.005	-0.046	0.002	-0.009	
		18-22 ⁱ	203	0.025	-0.013	-0.038	-0.025	-0.009	0.005	-0.037	-0.001	-0.007	
Zhang et al ²⁴	C	6-16 ^j	99	0.015	-0.047	-0.009	0.003	-0.002	0.000	-0.020	0.002	-0.006	
	C	6-16 ^k	49	0.009	-0.027	0.000	0.009	-0.002	-0.002	-0.018	0.002	-0.006	

C, cycloplegic; HOA, higher-order aberration; NC, noncycloplegic; SD, standard deviation.

^a All data have been scaled to a 4 mm pupil diameter.

^b School-based study population.

^c Patients with myopia.

^d Pediatric ophthalmology practice.

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- ^ePopulation-based (sub)sample.
- ^fPatients with emmetropia and hyperopia.
- ^gAmblyopic eyes.
- ^hEyes with normal vision.
- ⁱEyes with supernormal vision.
- ^jClinial cohort with quickly progressing myopia.
- ^kClinial cohort with slowly progressing myopia.

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Table 3

Relative raw effects of J0 astigmatism (from cycloplegic refraction) and unsigned spherical aberration (z12u) on best-corrected visual acuity

Parameters for determining logMAR effect	J0, D	z12u
25th Percentile	0.059 D	0.020 micron
75th Percentile	0.750 D	0.064 micron
75th–25th magnitude	0.691 D	0.044 micron
logMAR coefficient	0.152 logMAR/D	0.583 logMAR/ μ
logMAR effect ^a	0.105 logMAR	0.026 logMAR

D, diopters; *logMAR*, logarithm of the minimum angle of resolution.

^a Effect size calculated on difference between 25th and 75th percentiles of observations. The increase in logMAR score represents worsening, 0.1 logMAR units represents 1 line, 5 letters per line. Comparative effect: J0 astigmatism is 4.0 times as potent as z12u in the magnitude of its effect in decreasing best-corrected visual acuity in this population.