Mirror Symmetry of Peripheral Monochromatic Aberrations in Fellow Eyes of Isomyopes and Anisomyopes

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PURPOSE. To investigate mirror symmetry of peripheral ocular aberrations in fellow eyes of isomyopes and anisomyopes.

METHODS. Peripheral aberration was measured over the central 42° × 32° visual field for a 5-mm pupil in both eyes of 19 isomyopic (spherical equivalent refraction M [right/left]: −2.5 ± 2.1 diopters [D]/−2.7 ± 2.3 D) and 10 anisomyopic (M: −4.0 ± 1.8 D/−4.3 ± 2.8 D) young adults. Isomyopes had less than 1.0 D fellow eye refraction difference and anisomyopes had between 1.0 D and 2.6 D fellow eye differences (mean difference: 1.3 ± 0.6 D). Orthogonal regression of Zernike coefficients determined right-left eye correlations in isomyopes. For anisomyopes, higher and lower myopic eye coefficients were compared.

RESULTS. For isomyopes, the percentages of visual field locations with significant coefficient correlations between fellow eyes varied from 100% for astigmatism (C_2^4) to 18% for tetrafoil (C_4^4). Positive correlations were found for C_2^2, C_3^-1, C_3^-3, C_4^0, C_4^1, and C_4^4, and negative correlations were found for C_2^-2, C_4^1, C_4^3, and C_4^-4 coefficients, indicating that the signs are different for corresponding locations of fellow eyes for the last five of these coefficients. Slopes of correlations were not different from ± 1, except for C_2^-2, C_4^1, and C_4^-4 (+0.95, −0.97, and +0.52, respectively). In anisomyopes, significant but small fellow eye differences were found for only C_2^-2 and C_4^-2 coefficients, with significant interactions between anisometropia and field position for only two coefficients.

CONCLUSIONS. Peripheral aberration coefficients across the visual field show mirror symmetry in isomyopes, and in a pooled data set the coefficients with negative correlations require sign changes for left eye data. Anisometropia contributes no more to peripheral aberration differences between fellow eyes than could be expected on the basis of refraction differences between people.

Keywords: anisometropia, COAS-HD aberrometer, higher-order aberrations, mirror symmetry, myopia, peripheral aberrations

Foveal (on-axis) vision has been the main concern of vision performance research, but during the past decade and spurred by advances in technology, interest has grown in the optics and image quality of the peripheral (off-axis) retina. Despite poorer acuity in the periphery than the center, peripheral vision is important for detection and motion and has been associated with myopia development. Information gained from peripheral vision research has been used to improve vision of people living with central visual field loss.

Peripheral aberration coefficients have been measured in only one eye of participants in most studies for reasons of time efficiency, with the assumption that they change similarly across the visual fields of fellow eyes. Comparisons of ocular aberration coefficients have been made for central vision, in both isometropes (similar refraction in fellow eyes) and anisometropes (dissimilar refraction in fellow eyes). The coefficients of fellow eyes are significantly correlated. To account for mirror symmetry when comparing or combining data of right and left eyes, it is recommended that the signs of left eye Zernike polynomial coefficients are altered if they have either negative, even m indices or positive, odd m indices. Normal eyes tend to have mirror symmetry because the anatomies of right and left eyes are similar, but they are on opposite sides of the body. As the shape of one side of the body is similar to the other, although with small variations, the abberations in fellow eyes of an individual are generally mirror symmetric.

Biologic vision performance is better than monocular visual performance, but this advantage tends to become lost if the higher-order aberrations of the two eyes are different. Two studies failed to find significant differences of higher-order aberration coefficients between fellow eyes of anisometropes, but another two studies found significantly more positive spherical aberration coefficient (C_2^4) in the less myopic eyes than in the more myopic eyes of anisomyopes. In a study of more than 20,000 patients, Hartwig and Atchinson attempted to separate the effects of anisometropia from those of refraction, and were able to identify significant, but minor,
effects of anisometropia for vertical coma ($C_{1j}^{-1}$), secondary astigmatism ($C_{2j}^1$), and tetrafoil ($C_{3j}^2$).

One study compared peripheral ocular aberrations of fellow eyes at a few angles along the horizontal meridian out to $\pm 40\degree$ and another considered many angles along the horizontal meridian out to $\pm 35\degree$. From linear regression analysis at corresponding temporal or nasal visual field locations, 10 of 12 second- to fourth-order aberration coefficients$^{16}$ and all 12 aberration coefficients$^{32}$ had significant correlations between fellow eyes and showed a degree of mirror symmetry because the correlations between the corresponding locations were negative only for “odd over the horizontal meridian” coefficients having either negative, even $m$ indices or positive, odd $m$ indices. A requirement for mirror symmetry between eyes is an absolute slope of 1.0. Across all visual field angles and participants, absolute slopes of 0.90 to 1.10 occurred in regressions for all second-order terms ($C_{2j}^1$, $C_{1j}^2$, and $C_{1j}^{-1}$) and horizontal coma ($C_{1j}^3$),$^{16}$ and for $C_{1j}^{-1}$, $C_{1j}^2$, and $C_{1j}^3$,$^{32}$ indicating mirror symmetry for these coefficients, although the significances were not tested. The studies did not mention whether any of the participants had anisometropia.

Anisometropia can be considered as a spherical equivalent refraction difference between fellow eyes of 1.00 diopter (D) and more. It is usually due to a difference in axial length$^{33}$ and is often associated with strabismus.$^{34}$ Understanding the relationship between anisometropia and peripheral aberration may contribute toward understanding why fellow eyes with similar accommodation, receiving the same hormonal influences, performing the same tasks and having many other similarities may attain different refractions.

This study investigates the mirror symmetry of peripheral ocular aberrations by measuring the peripheral aberrations across the visual fields in fellow eyes of isomyopes and anisomyopes. We considered whether the peripheral monochromatic aberrations are different between the higher myopic and lower myopic eyes of anisomyopes.

**METHODS**

**Participants**

The study was approved by the Queensland University of Technology Human Research Ethics committee and adhered to the tenets of the Declaration of Helsinki. All participants gave written consent after explanation of the nature and possible consequences of the study. There were 29 participants (15 males, 14 females) aged between 19 and 38 years (mean $\pm$ SD, 28 $\pm$ 5 years). All participants had $\leq 0.50$ D spherical equivalent refraction in both eyes. The 19 isomyopes (28 $\pm$ 6 years) and 10 anisomyopes (27 $\pm$ 5 years) had $<1.0$ D and $>1.00$ D differences, respectively, in spherical equivalent refraction between fellow eyes. All participants had normal visual acuities, were free of ocular disease, did not have amblyopia or strabismus, had no lens changes or opacities, and had no previous ocular surgery. Soft contact lens wearers did not wear their lenses for at least 24 hours before testing and rigid contact lens wearers were not used.

**Instrumentation and Aberration Determination**

A COAS-HD aberrometer (Wavefront Sciences, Albuquerque, NM, USA) was used for peripheral aberration measurements. This has been described in detail elsewhere, including the adaptations to ensure that it can measure high levels of aberrations.$^{8,35}$

The participants looked at 38 fixation targets covering $42\degree \times 32\degree$ of the central visual field on a 310-cm distant wall. These were viewed through a $45\degree$ angled glass slide beam-splitter placed close to the eye. Head position was stabilized by a chin and head rest. Before obtaining on-axis measurements, the center fixation target was aligned with the center of the instrument’s internal fixation target, which was then turned off. Participants fixated the targets sequentially. XYZ alignment was achieved with the instrument’s alignment camera, so that the pupil of the tested eye was centered with respect to the measuring axis and the cornea was conjugate with the sensor lenslet array. Right eye measurements were obtained on the first visit and left eye measurements were taken on the second visit, with at least 24 hours between visits. For left eye measurements, the instrument, Table, and beam-splitter were rotated away from those of the right eye to reestablish alignment with the screen.

Two drops of tropicamide hydrochloride 1% (Minims; Chauvin Pharmaceuticals Ltd, Surrey, UK) were instilled 5 minutes apart into the tested eye, and measurements were taken 10 minutes after the second drop. Two aberration images were taken for each fixation target with the COAS-HD aberrometer under low background lighting conditions. Approximately 40 minutes were required to measure each eye.

Data and images were exported for analysis in MATLAB R2013a (Math Works Inc., Chatsworth, NSW, Australia) using custom software. Zernike aberration coefficients according to the ophthalmic aberration standard$^{36}$ were estimated up to the sixth radial order for an elliptical pupil with 5.0-mm major axis along the visual field meridian and a minor axis varying in diameter according to the cosine of the visual field eccentricity. Spherical equivalent $M$, with/against-the-rule astigmatism $J_{180}$, and oblique astigmatism $J_{45}$ were calculated from second- to sixth-order Zernike coefficients.$^{37}$ Contour plots representing the mean magnitudes of aberrations at each visual field location were generated using triangle-based interpolation.$^{35}$ For one isomyope, there were several missing spots in the Hartmann-Shack image at one field position of one eye, making wavefront reconstruction for that position unfeasible. For this participant, data for this position and for the corresponding field position in the fellow eye were not used in the analysis.

**Statistical Analysis**

Statistical analysis was done using SPSS Statistics for Windows version 21.0 (IBM Corp., Armonk, NY, USA). $P$ values less than 0.05 were considered statistically significant. The Shapiro-Wilk test of normality showed that all aberration coefficients across the visual fields of iso- and anisomyopic subjects were normally distributed; thus, data analysis was performed using parametric tests. Data were expressed as mean $\pm$ SD.

Orthogonal linear regression, rather than conventional linear regression, was used, as it overcomes the multicollinearity problem associated with analyzing a large data set of interrelated variables,$^{38}$ such as data from fellow eyes, for which it is not valid to consider that one variable is dependent on another. Rather than minimizing the vertical or horizontal distance as in ordinary linear regression, orthogonal regression minimizes the perpendicular distances from the data points to the fitted line.$^{38}$ For isomyopes, orthogonal linear regression was conducted for the means of each combination of Zernike aberration coefficient and visual field location, the latter meaning that the temporal/nasal positions of right eyes were matched with the same temporal/nasal positions for left eyes.

Coefficients of fellow eyes were compared using repeated measures analysis of variance with two within-subject factors of eye (right and left eyes for isomyopes, and higher and lower myopic eyes for anisomyopes) and visual field position. For Zernike aberration coefficients that showed negative fellow eye correlations in the orthogonal linear regressions, left eye coefficient signs were changed for isomyopes and anisomyopes.
**FIGURE 1.** Mean aberration coefficients for a 5-mm pupil across the visual fields of (i) right eyes and (ii) left eyes of isomyopes: (a) oblique astigmatism $C_2^2$, (b) with/against-the-rule astigmatism $C_2^2$, (c) defocus $C_2^1$, (d) oblique trefoil $C_3^2$, (e) oblique astigmatism $C_2^4$, (f) oblique trefoil $C_3^2$, and (b) spherical aberration $C_4^0$. Color scales represent the magnitude of each coefficient in micrometers and differ according to the aberration coefficient. S, I, N, and T indicate superior, inferior, nasal, and temporal visual fields.

**TABLE.** Slopes and Intercepts of Orthogonal Regressions Between the Fellow Eyes for Zernike Aberration Coefficients Across the Visual Field of Isomyopes

<table>
<thead>
<tr>
<th>Zernike Coefficient</th>
<th>Slope</th>
<th>Intercept</th>
<th>95% CI</th>
<th>Limits of Slope</th>
<th>$r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_2^2$</td>
<td>-0.95</td>
<td>-0.00</td>
<td>-0.98 to -0.92</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>$C_2^1$</td>
<td>+0.96</td>
<td>+0.08</td>
<td>+0.85 to +1.08</td>
<td>+0.94</td>
<td></td>
</tr>
<tr>
<td>$C_2^3$</td>
<td>+0.96</td>
<td>-0.05</td>
<td>+0.92 to +1.01</td>
<td>+0.99</td>
<td></td>
</tr>
<tr>
<td>$C_4^2$</td>
<td>+0.89</td>
<td>+0.03</td>
<td>+0.72 to +1.09</td>
<td>+0.85</td>
<td></td>
</tr>
<tr>
<td>$C_4^1$</td>
<td>+0.89</td>
<td>+0.01</td>
<td>+0.78 to +1.01</td>
<td>+0.94</td>
<td></td>
</tr>
<tr>
<td>$C_4^3$</td>
<td>-0.88</td>
<td>-0.03</td>
<td>-0.96 to -0.82</td>
<td>-0.97</td>
<td></td>
</tr>
<tr>
<td>$C_4^4$</td>
<td>-0.69</td>
<td>-0.00</td>
<td>-1.00 to -0.45</td>
<td>-0.66</td>
<td></td>
</tr>
<tr>
<td>$C_6^2$</td>
<td>-0.97</td>
<td>+0.00</td>
<td>-1.50 to -0.62</td>
<td>-0.62</td>
<td></td>
</tr>
<tr>
<td>$C_6^1$</td>
<td>-0.41</td>
<td>-0.00</td>
<td>-3.24 to -0.74</td>
<td>-0.46</td>
<td></td>
</tr>
<tr>
<td>$C_6^3$</td>
<td>+1.23</td>
<td>+0.00</td>
<td>+0.81 to +1.95</td>
<td>+0.62</td>
<td></td>
</tr>
<tr>
<td>$C_6^4$</td>
<td>+1.52</td>
<td>+0.01</td>
<td>+1.00 to +2.46</td>
<td>+0.62</td>
<td></td>
</tr>
<tr>
<td>$C_8^2$</td>
<td>+0.38</td>
<td>+0.00</td>
<td>+0.18 to +0.61</td>
<td>+0.52</td>
<td></td>
</tr>
</tbody>
</table>

Correlation coefficients $r$ and 95% confidence interval (CI) limits of the slopes are included. Where absolute values of slopes are greater than 1, left eye coefficients change more quickly than right eye coefficients.

**RESULTS**

For isomyopes, on-axis $M_{180}$, and $J_{15}$ refraction components were $-2.5 \pm 2.1$ D, $+0.2 \pm 0.3$ D, and $+0.1 \pm 0.3$ D, respectively, for right eyes and $-2.7 \pm 2.3$ D, $+0.1 \pm 0.5$ D, and $-0.03 \pm 0.3$ D, respectively, for left eyes. For anisomyopes, on-axis $M_{180}$ and $J_{15}$ refraction components were $-4.0 \pm 1.8$ D, $+0.1 \pm 0.6$ D, and $+0.1 \pm 0.2$ D, respectively, for right eyes and $-4.3 \pm 2.8$ D, $+0.2 \pm 0.5$ D, and $-0.1 \pm 0.2$ D, respectively, for left eyes. On-axis $M$ refraction components for higher and lower myopic eyes of anisomyopes were $-4.9 \pm 2.6$ D (range, $-8.9$ D to $-1.4$ D) and $-3.6 \pm 2.1$ D (range, $-6.3$ D to $-0.5$ D), respectively, with a mean difference of $1.3 \pm 0.6$ D.

Figure 1 shows coefficient contour maps of isomyopes for right and left eyes, and a range of coefficients. Other coefficients are not shown because of their small magnitudes. Patterns across the visual field include quadratic rates of change for astigmatism coefficients (a and b), linear rates for coma coefficients (c and f), and little change for the spherical aberration coefficient (h). Ignoring $C_2^2$, the aberration coefficients and the percentages of locations with significant correlations from orthogonal linear regression between fellow eyes of isometropes at each visual field location were as follows: $C_2^2$ 100%, $C_2^1$ 95%, $C_4^0$ 90%, $C_4^1$ 79%, $C_4^2$ 76%, $C_4^3$ 47%, $C_4^4$ 47%, $C_6^2$ 34%, $C_6^3$ 21%, and $C_6^4$ 18%. Six coefficients, $C_2^2$, $C_2^3$, $C_3^1$, $C_4^0$, $C_4^2$, and $C_4^4$ had predominantly
positive correlations. Five coefficients, $C_{22}^2$, $C_{13}^1$, $C_{33}$, $C_{44}^2$, and $C_{02}^4$ had predominantly negative correlations, which indicates that they had differences in sign for corresponding temporal or nasal visual field locations of fellow eyes. These trends match those expected from the ISO standard. The Table shows orthogonal regressions of aberration coefficients between fellow eyes of isomyopes across the field, and Figure 2 shows orthogonal regression plots between fellow eyes for some aberration coefficients. All coefficients had correlations and slopes that were significantly different from zero. Disregarding $C_{33}$, correlations ranged from low at $(\langle C_{22}^2 \rangle)^{0.46}$ for $C_{22}^4$ to high at $(\langle C_{13}^1 \rangle)^{1.00}$ for $C_{33}$. The only slopes significantly different from either $+1$ or $-1$ were those for $C_{22}^2$, $C_{13}^1$, and $C_{33}$ at $-0.95$, $-0.97$, and $+0.52$, respectively.

Figure 3 shows contour maps of aberration coefficient differences across the visual field of isomyopes. The repeated measures ANOVA did not show significant fellow eye aberration differences for any coefficients, nor any significant interaction between eye and visual field position.

Figure 4 shows contour maps of aberration coefficient differences of anisomyopes across the visual field. Disregarding $C_{02}^4$, which from the selection of eyes was expected to show significance, repeated measures ANOVAs for anisometropes found significant fellow eye aberration differences for only $C_{04}$ and $C_{22}^4$ coefficients, which were more positive for the lower myopic eyes than for the higher myopic eyes (mean difference $0.009 \pm 0.014 \mu m$ and $0.008 \pm 0.011 \mu m$, respectively). The interaction between anisometropia and visual field position was close to being significant for $C_{22}^2$ and $C_{33}^2$ ($P = 0.06$ and $0.08$, respectively). The former coefficient changed less quickly for the higher myopes than for the lower myopes into the horizontal and vertical peripheries, whereas the latter coefficient changed less quickly for the higher myopes than for the low myopes along the horizontal meridian.

Further comparison between the eyes of anisometropes was made for the important higher-order aberration of coma. The rates of change of vertical coma coefficient $C_{13}^1$ along the vertical meridian and of horizontal coma coefficient $C_{33}$ along the horizontal meridian were determined for each person. Figure 5 shows the results. The rates for vertical coma between lower and higher myopic eyes were significantly different, with respective values of $-0.004 \pm 0.007 \mu m/deg$ and $-0.006 \pm 0.007 \mu m/deg$.
**FIGURE 4.** Mean fellow eye aberration differences (higher myopic eye minus lower myopic eyes) of anisomyopes for various aberration coefficients. Other details are as for Figure 3.

**FIGURE 5.** Vertical coma coefficient $C^{-1}_3$ and horizontal coma coefficient $C^1_3$ along the vertical field meridian for (a) lower myopic eyes, and (b) higher myopic eyes, and horizontal coma coefficient $C^1_3$ along the vertical field meridian for (c) lower myopic eyes, and (d) higher myopic eyes. Different symbols represent different subjects. As there were no measurements along the horizontal visual field, horizontal coma was obtained by averaging results at vertical field angles of $\pm 3.3^\circ$. Different symbols represent different subjects.
0.005 μm/deg (paired t-test, t = 3.8, 80, P = 0.004). The rates for horizontal coma between lower and higher myopic eyes were not significantly different, with respective values of −0.006 ± 0.008 μm/deg and −0.005 ± 0.009 μm/deg (t = 0.28, P = 0.78).

**Discussion**

Peripheral aberrations measured across the two-dimensional field at a pupil diameter of 5 mm were similar in pattern and magnitude between fellow eyes of isomypic subjects: a quadratic change in astigmatism coefficients $C_{2}^{2}$ and $C_{2}^{2}$, linear change in coma coefficients $C_{3}^{1}$ and $C_{3}^{3}$, little change in spherical aberration $C_{4}^{0}$, and almost no change in other fourth-order aberrations, across the field (Fig. 1). These patterns are consistent with our previous reports measuring single eyes.8,11,15,35

The aberration coefficients with negative, even $m$ indices or positive, odd $m$ indices had negative fellow eye correlations across the visual field because the coefficients had opposite signs at corresponding temporal or nasal visual field locations of fellow eyes. Supporting previous studies for aberrations at fixation or along the horizontal meridian of the visual field,14,16–28 in a pooled data set the sign of these coefficients should be altered for left eye data.36 Mirror symmetry was found between fellow eyes across the visual field for most peripheral aberration coefficients. This justifies the prevalent modus operandi of measuring only one eye of a person in peripheral aberration studies. Of the three coefficients that were significantly different from ±1, the important coefficients, $C_{2}^{2}$ and $C_{2}^{2}$, were close to unity at −0.95 and −0.88, respectively, which means that the coefficients changed at slightly slower rates across the field for left eyes than for right eyes; we do not know why this occurred.

Hartwig et al.28 suggested that ocular aberrations may play a role in anisomyopia, such that elevated higher-order aberrations in the higher myopic eye indicates the involvement of higher-order aberrations in refractive error development. The mean aberration differences across the field between more myopic and less myopic eyes of anisomyopes were not significantly different except for spherical aberration ($C_{4}^{0}$) and secondary oblique astigmatism ($C_{3}^{4}$) coefficients, which showed small effects. The value of the differences increase as myopia increases. Using the same instrumentation and pupil sizes as in this study, Mathur et al.19 found less positive $C_{4}^{4}$ in eyes of young adult myopes than of young adult emmetropes, with little variation across the field. The mean difference in their study was 0.020 μm as compared with 0.009 μm in this study, and the two times ratio is close enough to the ratio of refractions of the groups in the two studies (3.8 D/1.3 D = 3) to indicate that anisometropia contributes no more to peripheral aberration differences between fellow eyes than could be expected on the basis of refraction differences between people.

The interaction between anisometropia and visual field angle approached significance only for $C_{2}^{2}$ and $C_{2}^{2}$. The lower myopic eyes were slightly more positive than the higher myopic eyes across the field. The rates of coma change were significantly different between higher and lower myopic eyes along the vertical field meridian for $C_{3}^{1}$ (ratio 1.5), but not along the horizontal meridian for $C_{4}^{1}$ (ratio 0.8) (see Fig. 5). The corresponding results of Mathur et al.19 were 2.8 times higher for $C_{3}^{1}$ in myopes than in emmetropes (myopes −0.013 μm/deg, emmetropes −0.005 μm/deg) and 2.2 times higher for $C_{3}^{4}$ in myopes than emmetropes (myopes −0.015 μm/deg, emmetropes −0.007 μm/deg). As for the mean spherical aberration across the field, the difference in rate of change of coma across the field of fellow eyes of anisometropes provides no evidence that anisometropia contributes more to peripheral aberration differences between fellow eyes than can be expected on the basis of refraction differences.

The study is limited by the small number of participants. As some aberration coefficients changed quickly away from the center of the field, it was expected that differences between groups or eyes might be magnified into the periphery, and that any real differences would become obvious in these participants.

In summary, across the visual field, peripheral aberrations were mirror symmetric, or close to mirror symmetric, between fellow eyes of isomypes. Significant right-left correlations occurred for all 12 coefficients with negative correlations for coefficients with negative, even $m$ indices or positive, odd $m$ indices: $C_{2}^{2}$, $C_{4}^{1}$, $C_{4}^{3}$, and $C_{4}^{4}$. In a pooled data set (i.e., combining data of right and left eyes of individuals, or combining data of different people each contributing only one eye to the analysis), the coefficients with negative correlations require sign changes for left eye data. This shows that peripheral aberration measurements obtained in one eye of isomypes can be used to predict the aberration pattern in the fellow eye. For anisomyopes, peripheral aberrations of fellow eyes were similar in pattern and magnitude except for spherical aberration and secondary astigmatism, which were marginally more positive for the less myopic eye. These findings do not support a role for peripheral aberrations in anisomyopia.

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