Effect of accommodation on peripheral ocular aberrations

Ankit Mathur  
School of Optometry and Institute of Health and Biomedical Innovation, Queensland University of Technology, Brisbane, Australia

David A. Atchison  
School of Optometry and Institute of Health and Biomedical Innovation, Queensland University of Technology, Brisbane, Australia

W. Neil Charman  
Faculty of Life Sciences, Moffat Building, University of Manchester, Manchester, UK

Changes in peripheral aberrations, particularly higher order aberrations, as a function of accommodation have received little attention. Wavefront aberrations were measured for the right eyes of 9 young adult emmetropes at 38 field positions in the central 42° × 32° of the visual field. Subjects accommodated monocularly to targets at vergences of either 0.3 or 4.0 D. Wavefront data for a 5-mm diameter pupil were analyzed either in terms of the vector components of refraction or Zernike coefficients and total RMS wavefront aberrations. Relative peripheral refractive error (RPRE) was myopic at both accommodation demands and showed only a slight, not statistically significant, hypermetropic shift in the vertical meridian with the higher accommodation demand. There was little change in the astigmatic components of refraction or the higher order Zernike coefficients, apart from fourth-order spherical aberration, which became more negative (by 0.10 μm) at all field locations. Although it has been suggested that nearwork and the state of peripheral refraction may play some role in myopia development, for most of our adult emmetropes any changes with accommodation in RPRE and aberration were small. Hence it seems unlikely that such changes can be of importance to late-onset myopization.

Keywords: emmetropia, peripheral aberrations, peripheral refraction, accommodation


Introduction

Accommodation induces dramatic changes in the optics of the eye, especially in the shape and refractive index distribution of the crystalline lens (e.g., Jones, Atchison, & Pope, 2007; Kasthurirangan, Markwell, Atchison, & Pope, 2008). It has long been known that these changes result in a negative shift in axial (foveal) spherical aberration (Atchison, Collins, Wildsoet, Christensen, & Waterworth, 1995; Cheng et al., 2004; Hazel, Cox, & Strang, 2003; He, Burns, & Marcos, 2000; He, Marcos, Webb, & Burns, 1998; Howland & Buettner, 1989; Koomen, Tousey, & Scolnik, 1949; Ninomiya et al., 2002; Radhakrishnan & Charman, 2007a; Smirnov, 1961). Changes in other aberrations such as coma and astigmatism are not as systematic (Cheng et al., 2004; He et al., 2000; Howland & Buettner, 1989; Lu, Campbell, & Munger, 1994; Plainis, Ginis, & Pallikaris, 2005; Radhakrishnan & Charman, 2007a, 2007b).

In the peripheral visual field, most studies have reported Zernike aberrations for relaxed accommodation and have been largely limited to the horizontal visual field (Atchison, 2006; Atchison & Scott, 2002; Lundström, Gustafsson, & Unsbo, 2009; Navarro, Moreno, & Dorronsoro, 1998) or to a few locations in the visual field (Lundström, Unsbo, & Gustafsson, 2005; Sheehan, Goncharov, O’Dwyer, Toal, & Dainty, 2007). Aberrations with relaxed accommodation increase away from the center of the visual field and are dominated by defocus and astigmatism (Atchison, 2006; Atchison & Scott, 2002; Guirao & Artal, 1999; Lundström, Gustafsson et al., 2009; Navarro et al., 1998). Mathur et al. (Mathur, Atchison, & Charman, 2009; Mathur, Atchison, & Scott, 2008) have recently extended these distance measurements to cover 42° × 32° of the central visual field.

There have also been numerous studies of the variation in refractive error across the visual field when accommodation is relaxed (see Atchison & Smith, 2000 for review of earlier work). For the present purposes, the most interesting is the longitudinal study by Hoogerheide, Rempt, and Hoogenboom (1971) who found that the pattern of peripheral refraction differed between different adult refractive groups and that relative peripheral hyperopia (i.e., a positive rather than a negative relative peripheral refractive error, RPRE) tended to favor the...
development of myopia in originally hyperopic or emmetropic young adults. In a study of groups of existing adult ametropes, Millodot (1981) showed that, at least for field angles up to about 30°, both astigmatic image surfaces in hyperopic eyes along the horizontal meridian usually showed relative peripheral myopia with respect to the axial refraction, whereas in myopic eyes there was relative hyperopia; in emmetropes the two astigmatic image surfaces tended to lie on opposite sides of the retina. Somewhat similar results have since been obtained by several other authors (Atchison, Pritchard, & Schmid, 2006; Love, Gilmartin, & Dunne, 2000; Lundström, Gustafsson et al., 2009; Mutti, Sholtz, Friedman, & Zadnik, 2000; Seidemann, Schaeffel, Guirao, López-Gil, & Artal, 2002), some of whose work also shows differences between the patterns of refraction in different meridians.

The few studies of the changes in peripheral refraction with accommodation, mainly along the horizontal meridian, gave different results. Smith, Millodot, and McBrien (1988) found that astigmatism at large field angles (>40°) tended to increase with accommodation, almost entirely as a result of the tangential power error becoming increasingly negative, so that the focus in the periphery became relatively more myopic with respect to the axial focus as the accommodation demand increased (i.e., the RPRE became more negative, or myopic). In contrast, Walker and Mutti (2002) found that accommodation to a 3 D stimulus initially caused the peripheral refraction (spherical equivalent) at 30° nasal visual field to become relatively more hyperopic with respect to the axial refraction but that this shift decreased if near accommodation was maintained over a period of 2 h. They suggested that this was associated with longer term changes in the shape of the retina rather than with the optical components of the eye. In a more comprehensive study, confined to myopes in the range 0.5 to −4.5 D, Whatham et al. (2009) determined that the positive RPRE found at distance tended to decrease with accommodation (i.e., the peripheral refraction became relatively more myopic), although effects differed in the nasal and temporal semi-meridians. The regular astigmatism vector J_{180} tended to become more negative particularly at larger field angles (40°), while oblique astigmatic vector J_{45} underwent little change. Although Calver, Radhakrishnan, Osuobeni, and O’Leary (2007) found that J_{180} and overall cylindrical power over the central ±30° tended to decrease with a 2.5-D accommodation stimulus, particularly in the nasal field, their overall conclusion was that “viewing distance has little general effect on peripheral refraction”. Lundström, Mira-Agudelo, and Artal (2009) measured aberrations out to ±40° horizontally and ±20° vertically for 6 emmetropes and 6 myopes and two different states of accommodation (targets at 0.5 D and 4.0 D). The emmetropic group had the expected positive C_{20}^{0} (defocus) coefficient (corresponding to negative RPRE) for the lower accommodation stimulus and this became slightly more positive for the higher stimulus. The low negative C_{20}^{0} (corresponding to positive RPRE) of the myopic group was little affected by accommodation. It may be that the differences between these various studies can be explained partly by the different ranges of accommodation stimulus and field positions employed.

There is only one previous study on changes in the higher order aberrations with accommodation in the peripheral visual field. While their emphasis was on the second-order coefficients, Lundström, Mira-Agudelo et al. (2009) noted statistically significant effects of accommodation on some higher order aberration coefficients.

In this paper, we extend previous investigations of the influence of accommodation on central aberrations to the measurement of aberrations across the central visual field. The study was restricted to young adult emmetropes, in an attempt to ensure homogeneous results, and the vergence of the near accommodative stimulus approximated to that of typical real-life near tasks.

**Methods**

We recruited 9 young (mean age: 25 years, age range: 21–30 years) emmetropic volunteers (mean and standard deviation of spherical equivalent refraction: 0.2 D ± 0.3 D). Right eyes were assessed, while left eyes were occluded during measurements. Subjects were screened for ocular pathology. All subjects had visual acuities ≥6/6 or better and <0.75 D of central astigmatism.

Peripheral aberrations were measured using a COAS-HD Hartmann-Shack aberrometer (Wavefront Sciences, Albuquerque, USA) across 38 targets arranged in a 6 row × 7 column matrix, covering 42° × 32° of the central visual field. For each measurement, subjects placed their heads on the instrument’s chin rest and sequentially fixated the targets. Two measurements were taken at each field point and their aberration coefficients were averaged. The center of the target matrix was aligned with the instrument’s internal fixation target. The pupil center was aligned with the instrument’s measurement axis and the cornea was made conjugate to the lenslet array prior to each measurement, using the instrument’s alignment camera. A detailed description of the methods has been given previously (Mathur et al., 2008). For 0.3-D accommodative demand, 0.3° black crosses were placed on a white wall 3.0 m from the eye; the luminance of the wall as viewed through the beam splitter was 10 cd/m². For 4.0-D accommodative demand, 0.5° red spots were projected on a back-projection screen 0.25 m from the eye; the luminances of the red lights as viewed through the beam splitter were 12 cd/m². Since the screen was flat, the accommodation demand varied slightly across its area, from a maximum of 4.0 D on axis to a minimum of 3.71 D at the largest field angle used (22°). Compensation was made for this by altering the spherical equivalent refraction, in diopters, for the 4.0-D
demand by \(3.6(\cos(\phi) - 1)\), where \(\phi\) is the field angle and 3.6 D is the mean accommodation response of the subjects (see below). Prior to presenting targets for the two accommodative demands, the internal target of the COAS-HD was fogged by 1.5 D for axial measurements at 0-D accommodative demand. The difference between the axial spherical equivalent refraction for a given accommodative demand and for 0-D accommodative demand, with sign reversed, was taken as the accommodative response.

When measuring peripheral aberrations of the eye, the elliptical shape of the pupil must be taken into account. Zernike coefficients for the elliptical pupils were estimated using a Matlab-based algorithm, which assumes that the minor axis of the pupil shortens by the cosine of the off-axis angle along a given meridian. The algorithm expands the pupil along its minor axis to form a circular pupil and estimates Zernike coefficients for the resultant circular pupil (Atchison, Scott, & Charman, 2007). Zernike coefficients up to 6th order for 555-nm wavelength as per the ANSI and ISO standards were estimated for 5.0-mm pupils (ANSI, 2004; ISO, 2008). The room illumination was reduced to ensure that the pupil diameter was at least 5.0 mm with 4.0-D accommodative demand, when any accommodative miosis was maximal. Spherical equivalent refraction \(M\), with/against-the-rule astigmatism \(J_{180}\) and oblique astigmatism \(J_{45}\) were calculated from second, fourth, and sixth Zernike-order coefficients, as described by Atchison, Scott, and Charman (2007, 2008).

The contour plots representing the magnitude of aberrations at each visual field location were generated using triangle-based interpolation.

### Results

The mean accommodative responses for 0.3-D and 4.0-D accommodative demands were 0.0 D ± 0.3 D and 3.6 D ± 0.6 D, respectively.

The refraction components and 3rd- to 4th-order Zernike aberration coefficients were analyzed by repeated measures analyses of variance for the variables of accommodation demand (2 states) and field position (38 positions). Table 1 shows the results. The refraction components are oblique astigmatism \(J_{45}\), relative peripheral refractive error (RPRE), which is the change in \(M\) relative to axial \(M\), and with/against-the-rule astigmatism \(J_{180}\). Results for the higher order root-mean-squared aberrations (HORMS) and the total root-mean-squared aberrations except for defocus (Total RMS) are also shown. Coefficients \(C^1_3\) and \(C^2_4\) and Total RMS were affected significantly by accommodation demand. The refraction components and nearly all the coefficients were affected significantly by field position, and most of them had significant accommodation-field position interactions.

Figure 1 shows the means of the 9 emmetropes’ refractive components: (a) \(J_{45}\), (b) RPRE, and (c) \(J_{180}\) at (A) 0.3 D and (B) 4.0 D accommodative demands across the visual field. Figure 1C shows the differences between mean results at the two accommodative demands (B − A).

The RPRE became significantly more negative \((p < 0.001)\), or myopic, as the peripheral field angle increased for both accommodative demands (Figures 1Ab, 1Bb, and 2). This shift appeared less marked for the 4.0-D demand than for the 0.3-D demand (Figures 1Cb and 2), but this difference was not significant when analyzed across the field or along the vertical and horizontal meridians (Table 1, Figure 2). \(J_{45}\) (Figures 1Aa and 1Ba) and \(J_{180}\) (Figures 1Ac and 1Bc) did not demonstrate any obvious changes in pattern or magnitude with changes in accommodation (Table 1). The pattern of variation of \(J_{45}\) and \(J_{180}\), primarily along the 45/135 oblique and 90/180 meridians, respectively, is that expected for astigmatism with local axes oriented symmetrically toward a point slightly temporally displaced from the center of the field.

The overall patterns of change between the 2 stimulus demands can be more readily appreciated in Figure 1C.

<table>
<thead>
<tr>
<th>Aberration coefficient</th>
<th>Accommodation demand</th>
<th>Field position</th>
<th>Field position interaction</th>
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<tr>
<td>(J_{45})</td>
<td>0.58</td>
<td>0.00*</td>
<td>0.10</td>
</tr>
<tr>
<td>RPRE</td>
<td>0.33</td>
<td>0.00*</td>
<td>0.17</td>
</tr>
<tr>
<td>(J_{180})</td>
<td>0.22</td>
<td>0.00*</td>
<td>0.00*</td>
</tr>
<tr>
<td>(C^2_{3})</td>
<td>0.98</td>
<td>0.00*</td>
<td>0.00*</td>
</tr>
<tr>
<td>(C^2_{1})</td>
<td>0.13</td>
<td>0.00*</td>
<td>0.00*</td>
</tr>
<tr>
<td>(C^2_{2})</td>
<td>0.28</td>
<td>0.00*</td>
<td>0.00*</td>
</tr>
<tr>
<td>(C^3_{3})</td>
<td>0.63</td>
<td>0.00*</td>
<td>0.46</td>
</tr>
<tr>
<td>(C^4_{3})</td>
<td>0.65</td>
<td>0.00*</td>
<td>0.00*</td>
</tr>
<tr>
<td>(C^4_{1})</td>
<td>0.04*</td>
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<td>(C^4_{2})</td>
<td>0.38</td>
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<td>(C^5_{4})</td>
<td>0.15</td>
<td>0.00*</td>
<td>0.00*</td>
</tr>
<tr>
<td>(C^5_{2})</td>
<td>0.67</td>
<td>0.84</td>
<td>0.64</td>
</tr>
<tr>
<td>(C^5_{4})</td>
<td>0.00*</td>
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<td>0.99</td>
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<tr>
<td>(C^6_{2})</td>
<td>0.35</td>
<td>0.00*</td>
<td>0.00*</td>
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<tr>
<td>(C^6_{4})</td>
<td>0.92</td>
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<td>0.00*</td>
</tr>
<tr>
<td>HORMS</td>
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<td>0.02*</td>
<td>0.99</td>
</tr>
<tr>
<td>Total RMS</td>
<td>0.02*</td>
<td>0.00*</td>
<td>0.00*</td>
</tr>
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</table>

Table 1. The p-values of repeated measures analyses of variance for refraction components, Zernike aberration coefficients and root-mean-squared aberrations for the variables of accommodation demand and field position. The defocus coefficient \(C^0_0\) is relative to its central field for each accommodation demand but has a correction for the slightly changing accommodation demand with field position as described in the Methods section for RPRE. Asterisks indicate effects which are significant at the 5% level.
which shows the differences between the values of the astigmatic power components and the RPRE at the two accommodation demands (B − A). There was a hyperopic (positive) change in the RPRE with accommodation in the inferior field of up to 0.3 D, but as mentioned above, this shift was not significant. Changes in the two astigmatic components were small.

Figures 3A and 3B show mean higher order elliptical wavefront maps across the pupil for each visual field location for 0.3-D and 4.0-D accommodative demands, respectively. With second-order aberrations excluded, the main peripheral aberrations appear to be 3rd-order coma and 4th-order spherical aberration. The combination of vertical and horizontal coma dominated the visual field at 0.3-D accommodative demand, with an orientation that was approximately radial with respect to the field center, but negative spherical aberration became relatively more important at 4-D demand.

Figures 4A and 4B show some mean higher order aberration coefficients, HORMS and Total RMS across the visual field for 0.3-D and 4.0-D accommodative demands, respectively. Figure 4C shows the differences between mean results at the two accommodative demands (B − A). Third-order aberrations showed little change between the two accommodation demands, although horizontal coma coefficient $C_{31}^3$ was affected significantly by accommodation demand (Table 1). Oblique trefoil coefficient $C_{3j}^3$ increased linearly from the inferior to the superior visual field (Figures 4Aa and 4Ba), vertical coma coefficient $C_{31}^3$ increased linearly from the superior to the inferior visual field (Figures 4Ab and 4Bb), and horizontal coma coefficient $C_{3j}^1$ increased linearly from the nasal to the temporal visual field (Figures 4Ac and 4Bc). The spherical aberration coefficient $C_{40}^4$ had a significant shift of $-0.10 \pm 0.04 \mu m (p < 0.001)$ across the field with increase in accommodative demand, from a mean value of about $+0.03 \mu m$ to $-0.06 \mu m$ (compare Figure 4Ad with Figure 4Bd), but it did not show any pattern across the visual field for either accommodation demand (Table 1). HORMS increased slightly with field angle (Figures 4Ae and 4Be). Total RMS also increased from the center of the visual field; the increase with field angle was slightly larger for the 0.3-D demand (Figure 4Af) than for 4-D demand (Figure 4Bf; Table 1).

It is again helpful to study the changes by subtracting the two sets of aberration maps from one another (i.e., wavefront aberration for 4.0-D stimulus − wavefront aberration for 0.3-D stimulus). The results confirm that most of the aberration terms showed only small changes (Figure 4C). The exception was $C_{40}^0$, for there was an almost uniform change of $-0.10 \mu m$ across the field (Figure 4Cd).

Figure 1. Mean refractive components, (a) oblique astigmatism $J_{45}$, (b) spherical equivalent $M$, expressed as relative peripheral refractive error (RPRE), and (c) with/against-the-rule astigmatism $J_{180}$ at (A) 0.3-D and (B) 4.0-D accommodative demands across the visual field. (C) The color scales represent the magnitudes in diopters and are the same for all refractive components at both accommodative demands. Differences in $J_{45}$, RPRE and $J_{180}$ between the two accommodative demands (B − A); the color scales are the same for all refractive components. S, I, N and T represent superior, inferior, nasal and temporal visual fields. Pupil size is 5 mm.
The use of mean data in preceding figures may conceal marked inter-subject variations. However, examination of plots for individual subjects indicated that most followed the same broad pattern as the mean data. The changes in coma coefficients across the visual field with change in accommodation were further analyzed. The slopes of coma coefficients, along vertical and horizontal visual field meridians, for the two accommodative demands were compared using paired *t*-tests. Figures 5a and 5b show mean vertical coma coefficient $C_3$ and mean horizontal coma coefficient $C_1$ across vertical and horizontal visual field meridians, respectively, for 0.3-D and 4.0-D accommodative demands. Although the coma slopes were slightly greater at the lower than at the higher accommodative demand, the differences were not significant. Note that the plots in Figure 5 pass close to the origin and are very similar in the two meridians, implying that total coma tends to increase with field angle and that its orientation is essentially radial.

**Discussion**

In this study, peripheral aberrations were determined across the central $42^\circ \times 32^\circ$ of the visual field for 0.3-D and 4.0-D accommodation stimuli. At both accommodation

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**Figure 2.** RPRE along (a) the vertical visual field meridian and (b) the horizontal visual field, for 0.3-D and 4.0-D accommodative demands. Error bars are standard deviations and lines are quadratic fits. Plots are staggered horizontally to make them more legible. As there were no measurements along the horizontal visual field, results were obtained by averaging results at vertical field angles of ±3.3°. A second-order fit was made to each subject's results along each meridian for each of the two accommodation demands. Paired *t*-tests using the second-order coefficients of the fits did not show significant effect of accommodation on RPRE along either the vertical ($p = 0.41$) or horizontal meridians ($p = 0.14$).

**Figure 3.** Mean higher order elliptical wavefront maps at each visual field location for (A) 0.3-D and (B) 4.0-D accommodative demands. Aberrations in the third to sixth Zernike orders are included. The minor axis of the elliptical wavefront maps is cosine of visual field angle times the major axis. I, N, S and T represent inferior, nasal, superior and temporal visual fields. Pupil size is 5 mm.
demands RPRE was mostly myopic. RPRE showed a slight positive (hypermetropic) shift at the higher accommodation demand in the inferior and superior field, but this shape change was not significant (Figure 2). The astigmatic components of refraction and most higher order Zernike coefficients, except 4th-order spherical aberration, changed little across the field with accommodation (Figures 1 and 4, Table 1). The increase in accommodation caused a significant negative shift (by 0.10 μm) at all field locations in 4th-order spherical aberration.

The aberrational data have some limitations. First, they cover only a field of radius of approximately 20°.
measurements of peripheral astigmatism suggest that the largest changes with accommodation occur at field angles of 30° and more (Smith et al., 1988; Whatham et al., 2009). On the other hand, sensitivity to defocus as evidenced by depth-of-focus (Wang & Ciuffreda, 2004; Wang, Ciuffreda, & Irish, 2006) or accommodation response (Bullimore & Gilmartin, 1987; Gu & Legge, 1987) declines quite rapidly with field angle over the central 10° radius of visual field, due largely to the fall-off in cone and ganglion cell density (Jonas, Schneider, & Naumann, 1992), so that, if retinal control of eye growth as a result of local defocus were to follow a similar pattern, this constraint may not be serious. Second, our measurements rely on subjects maintaining the same level of accommodation during the lengthy series of measurements at the different field angles: this would be expected to have greatest effect on the stability of the values of the spherical equivalent $M$. We attempted to minimize this problem by allowing subjects to have breaks on request and at least once during each measurement series. Third, our analysis is in terms of the values of the accommodation stimulus demands, rather than response levels. The actual values of response differed somewhat between subjects. However, examination of the individual data suggested that all the response changes between the 2 stimulus demands were broadly similar (mean and SD 3.6 ± 0.5 D). Fourth, our subjects were emmetropes, all of whom had essentially myopic $RPRE$ for the 0.3-D accommodation stimulus. It remains possible that, for example, subjects with hyperopic $RPRE$ might have displayed more striking changes in aberration. Fifth (as in most earlier studies), subjects maintained accommodation for only relatively short periods of time. It may be that during long periods of nearwork larger aberrational changes might occur, either as a result of corneal change (Buehren, Collins, & Carney, 2003, 2005) or change in the shape of the globe (Mutti et al., 2007). Lastly, we compared the two accommodation demands at a common pupil size, whereas pupil size decreases linearly with increase in accommodation demand at constant illumination (e.g., Kasthurirangan & Glasser, 2005). Thus it must be appreciated that if the unaccommodated pupil size was actually 5 mm, the aberrations in the accommodated case would be smaller than shown here and have different effects on retinal imagery. The rate of change of coma would reduce across the field and the negative spherical aberration would be smaller. As our actual pupil sizes all exceeded 5 mm, the pupil centers were likely to be slightly inaccurate for a 5-mm pupil (Walsh, 1988; Wilson, Campbell, & Simonet, 1992) and this would affect aberrations. However, shifts in pupil center, because of the differences in pupil size with accommodation, are allowed for in the analysis of the Shack–Hartmann patterns and are hence taken account of in the results.

Within these constraints, the data suggest that, across the measured field, $RPRE$ for emmetropes changes little with accommodation (see Figures 1Cb and 2). This accords with the findings of earlier authors (Calver et al., 2007; Lundström, Mira-Agudelo et al., 2009; Smith et al., 1988), who found only small changes for field angles of 20° or less. Among the higher order Zernike coefficients, spherical aberration was the only coefficient that changed.
both significantly and markedly with accommodation. For this coefficient the average off-axis changes were similar to those occurring on axis. Total higher order RMS aberrations were slightly lower with accommodation than at distance.

In this study, the off-axis Zernike coefficients were calculated over an elliptical pupil by expanding it along its minor axis to form a circle. An alternate approach would be to use a circular pupil with the same diameter as the major axis of the elliptical pupil (e.g., Lundström, Gustafsson et al., 2009; Lundström, Mira-Agudelo et al., 2009). We verified that this gave slightly larger absolute coefficients than those reported here but did not affect the conclusions.

Are these results of relevance to our understanding of myopia development? Myopia is an increasing problem in many parts of the world (Zadnik & Mutti, 1998) and it has long been hypothesized that prolonged periods of nearwork encourage its development (Cohn, 1886). The axial growth and myopia produced in chicks and other animals fitted with negative lenses to place the image behind the retina (see, e.g., Norton, 1999; Smith, 1998; Wildsoet, 1997 for reviews) led to the suggestion that a similar role could be played by accommodative lag, or under-accommodation, during nearwork (Abbott, Schmid, & Strang, 1998; Allen & O’Leary, 2006; Gwiazda, Thorn, Bauer, & Held, 1993). However it now appears that larger lags in accommodation accompany the development of myopia in children, rather than preceding it (Mutti et al., 2007). Although in its simple form this mechanism does not necessarily involve nearwork and accommodation, it would follow that if accommodation increased relative peripheral hyperopia, or perhaps image blur as a result of increased aberration, myopia development would become more likely.

Overall, the present results over the central field of a relatively small group (N = 9) of young adult emmetropes do not support the concept that accommodation increases hyperopic RPRE or higher order aberrational blur. They thus make it unlikely that late-onset myopia in adult emmetropes is triggered by nearwork-induced changes in RPRE or aberration. However, they do not exclude the potential importance of accommodative lags or the possibility that other specific at-risk individuals or refractive groups (Lundström, Mira-Agudelo et al., 2009) might show different patterns of change in RPRE and aberration. Hoogerheide et al. (1971) found in their longitudinal study that only about 10% of their initially emmetropic adult subjects had a hyperopic RPRE in one or both horizontal semi-meridians and that, of these, only about half developed myopia, so that studies on larger subject groups than that used in the present study may be required to ensure that such possibly at-risk individuals are included.

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Corresponding author: Ankit Mathur.
Email: a.mathur@qut.edu.au.
Address: School of Optometry and Institute of Health and Biomedical Innovation, Queensland University of Technology, Brisbane, Australia.

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