# Peripheral optical errors and their change with accommodation differ between emmetropic and myopic eyes

**Linda Lundström**

Laboratorio de Optica, Departamento de Física, Universidad de Murcia, Campus de Espinardo, Murcia, Spain

**Alejandro Mira-Agudelo**

Laboratorio de Optica, Departamento de Física, Universidad de Murcia, Campus de Espinardo, Murcia, Spain, & Grupo de Óptica y Fotónica, Instituto de Física, Universidad de Antioquia, Medellín, Colombia

**Pablo Artal**

Laboratorio de Optica, Departamento de Física, Universidad de Murcia, Campus de Espinardo, Murcia, Spain

The progression of myopia is thought to be controlled by the retinal image quality, but its triggering factors are not yet well known. The differences between the peripheral optics in emmetropic and myopic eyes might explain why some eyes become myopic. The present study further investigates peripheral optical quality and how it is affected by accommodation. The refraction and aberrations of the right eyes of five emmetropes and five myopes were measured using a laboratory Hartmann–Shack wave front sensor, specially designed for peripheral measurements with an open field of view. The off-axis optical quality was assessed in steps of 10° out to ±40° horizontally and ±20° vertically for two different states of accommodation (targets at 0.5 D and 4.0 D). As expected, the emmetropes had a higher relative peripheral myopia, that is, more positive $c_2^0$ coefficient, than the myopes. The new results of this study are that this well-known difference was found to be asymmetric over the visual field and that it increased with accommodation. This increase was because the relative peripheral defocus profile of the myopes did not show a consistent change between far and near vision, whereas the emmetropes became relatively more myopic in the periphery with accommodation. These findings may indicate a difference between emmetropic and myopic eyes that could be an important clue to understand myopia progression.

Keywords: visual optics, myopia progression, development of myopia, peripheral refractive errors, off-axis wave front aberrations, field curvature in the human eye, relative peripheral defocus

## Introduction

Peripheral spatial vision is degraded by large optical errors and coarse retinal sampling density. The largest off-axis optical aberrations are oblique astigmatism, coma, and field curvature induced by the oblique viewing angle (Atchison, 2006; Guirao & Artal, 1999; Jennings & Charman, 1978, 1981; Mathur, Atchison, & Scott, 2008; Navarro, Artal, & Williams, 1993; Navarro, Moreno, & Dorronsoro, 1998). The low density of visual neurons in the periphery means that the resolution acuity here is much lower than in the fovea and, normally, peripheral high-contrast resolution is unaffected by improved image quality (Lundström et al., 2007). Nevertheless, the main tasks for the peripheral eye, that is, detection and orientation discrimination, depend on the retinal image quality and therefore vary with optical correction (Artal,

Derrington, & Colombo, 1995; Thibos, Still, & Bradley, 1996; Wang, Thibos, & Bradley, 1997). The peripheral image quality has also been suggested to influence ocular growth, which is especially interesting in the study of myopia development.

Myopia most commonly occurs because the eye has grown too long in relation to its focal length and myopic eyes are in general larger and longer than normal emmetropic eyes (Atchison et al., 2004; Logan, Gilmartin, Wildsoet, & Dunne, 2004; Wallman & Winawer, 2004). To date, most cases of myopia are known to be triggered by environmental factors (Morgan & Rose, 2005), and animal studies have confirmed that retinal image quality regulates the ocular growth and thereby the progression of myopia (e.g., Hung, Crawford, & Smith, 1995; Irving, Sivak, & Callender, 1992; Kee, Hung, Qiao-Grider, Roorda, & Smith, 2004; McFadden, Howlett, & Mertz, 2004; Schaeffel, Glasser, & Howland, 1988; Whatham & Judge,

2001). Not all eyes develop myopia although they experience similar visual environments. This suggests that there might be a difference in how the optical system forms the image on the retina for eyes, which are about to become myopic, compared with eyes that remain emmetropic. In particular, two mechanisms have been suggested as potential factors that seem to differ between emmetropic and myopic eyes: the accommodation to near targets and the relative peripheral defocus (RPD, i.e., the mean spherical equivalent error in off-axis angles given in relation to the foveal on-axis value). For myopic eyes, the lag of accommodation during near work seems to be larger than normal (Abbott, Schmid, & Strang, 1998; Allen & O'Leary, 2006; Gwiazda, Thorn, Bauer, & Held, 1993). Therefore, some studies have fitted schoolchildren with reading spectacles to ensure that the sharpest image was placed on the retina during near tasks, unfortunately with limited success in preventing myopia progression (Fulk, Cyert, & Parker, 2000; Gwiazda et al., 2003; Leung & Brown, 1999; Shih et al., 2001). One possible explanation to why reading glasses did not work as intended could be that no attention was given to the image quality outside the fovea. The optical errors in the peripheral field of view are thought to affect the growth of the eye and the course of myopia development (Diether & Schaeffel, 1997; Mutti et al., 2007; Smith, Kee, Ramamirtham, Qiao-Grider, & Hung, 2005; Smith et al., 2007; Wallman & Winawer, 2004). One hypothesis is that the eye has an increased risk of becoming myopic if the RPD is hyperopic, that is, the focal plane is placed behind the peripheral retina (Hoogerheide, Rempt, & Hoogenboom, 1971). Myopic subjects have indeed been found to have a less myopic RPD compared with emmetropic and hyperopic eyes, but that difference can be explained by the more elongated shape of the myopic eye and might therefore merely be an effect of the myopic growth instead of a triggering factor (Atchison, Pritchard, & Schmid, 2006; Mutti, Sholtz, Friedman, & Zadnik, 2000; Mutti et al., 2007; Schmid, 2003; Seidemann, Schaeffel, Guirao, Lopez-Gil, & Artal, 2002).

The knowledge of the peripheral optical errors in emmetropic and myopic eyes is still too limited to explain their potential relation to the progression of myopia, especially during near work. Earlier studies on accommodative changes in peripheral refraction show varying results (Calver, Radhakrishnan, Osuobeni, & O'Leary, 2007; Smith, Millodot, & McBrien, 1988; Walker & Mutti, 2002; Whatham et al., 2009). Calver et al. (2007) performed a study on emmetropic and myopic eyes out to 30° and found no change in RPD between the accommodative states of 0.2 D to 1.7 D (the fixation targets were placed at 0.4 D and 2.5 D but the accommodative lag was large). On the other hand, in a recent study out to 40° by Whatham et al. (2009), low myopes (average mean sphere of −2.17 D) had a more myopic RPD when they accommodated 2.4 D (fixation target at 3.3 D). This disagreement between the two studies might be explained by the study of Smith et al. (1988), which found that a myopic shift in RPD can only be detected for field angles smaller than 30° if the emmetropic eye is accommodating more than 3 D. However, the results of Smith et al. cannot explain why Walker and Mutti (2002) found a hyperopic shift in RPD with 3 D of accommodation in a mixture of low and high myopes (mean sphere ranged from −0.41 to −6.31 D). The combined result of these four studies suggests that there could be a difference in how RPD changes with accommodation for emmetropes and moderate-to-high myopes. In this study, we therefore measure the peripheral optical quality over the horizontal and vertical meridians of emmetropic and myopic (average mean sphere of −5 D) eyes separately for the accommodative states of 0.5 D and 4.0 D. The differences found between the two types of eyes are compared with an eye model and the relevance for the development of myopia is discussed.

## Methods

The peripheral optical quality was assessed with a laboratory Hartmann–Shack wave front sensor (for the principle, see e.g., Prieto, Vargas-Martín, Goelz, & Artal, 2000), which is presented with details in Figure 1. The sensor was constructed with an open field of view to allow binocular fixation to off-axis targets at different distances and in any meridian (same as in Mira-Agudelo, Lundström, & Artal, 2009). A bitebar was used to stabilize the head of the subject while he or she was viewing the target through a hot mirror, which reflected the infrared light into the eye and the emerging wave front back to the sensor. The measurements were performed at the fovea (0°) and out to ±40° in the horizontal meridian and ±20° in the vertical meridian, in steps of 10° (angles measured from the visual axis in the entrance pupil of the eye). During the off-axis measurements, the subject kept the head in a straight forward position and only turned the eyes to view the off-axis fixation targets. In each angle, three or more Hartmann–Shack images were recorded with an exposure time of 1 second. The procedure was repeated for two different states of accommodation: fixation target at 2 m distance (0.5 D) and fixation target at 25 cm distance (4.0 D). The fixation targets were star-shaped figures (*) of 1 cm for far and of 0.6 cm for near. For far vision, the fixation targets were placed in one plane, but for near vision the targets were mounted on a spherically curved surface to maintain the same accommodation for all off-axis angles.

The right eyes of 10 young (age range from 25 to 36 years) healthy subjects were measured; five emmetropes (spherical refractive error between ±0.5 D and maximum astigmatism of 0.5 D) and five myopes (spherical refractive errors of −2.75, −3 D, −3.5 D, −7.25 D, and −8.5 D

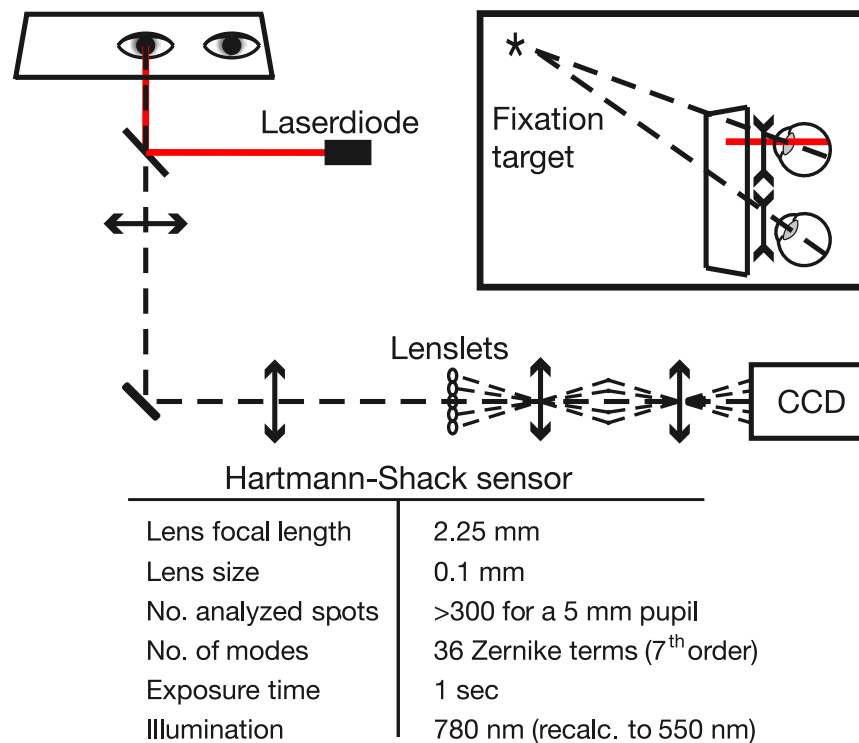| Hartmann-Shack sensor | |
| --- | --- |
| Lens focal length | 2.25 mm |
| Lens size | 0.1 mm |
| No. analyzed spots | >300 for a 5 mm pupil |
| No. of modes | 36 Zernike terms (7th order) |
| Exposure time | 1 sec |
| Illumination | 780 nm (recalc. to 550 nm) |

Figure 1. Schematic drawing, data, and photo of the open field wave front sensor. The subject views the fixation targets through a large hot mirror and the rest of the sensor is located below and to the side of the subject to avoid obstructing the field of view. The inset shows the setup from above during an off-axis measurement with spectacles.

and maximum astigmatism of 0.75 D). No cycloplegia was used and the background illumination in the room was low to have naturally large pupils. The study followed the ethical principles of the declaration of Helsinki. To be able to use the same fixation targets for all subjects, the myopic subjects were measured with their spectacle correction.

The three resulting Hartmann–Shack images for every subject, angle, and fixation distance were fitted with Zernike polynomials (American National Standards Institute, 2004) over a circular aperture that encircled the true pupil, which was elliptic in off-axis viewing angles. The coefficients were recalculated from the measurement wavelength of 780 to 550 nm to facilitate comparisons with other studies. In addition, the coefficients were also recalculated to only describe the 4-mm central part of the

wave front (i.e., a circle of 4 mm in diameter was cut out in the center of the wave front); this is to facilitate the comparison between the different off-axis angles (for more details on the data analysis, see Lundström, 2007).

## Results

The peripheral aberrations were successfully measured in all 10 subjects. The average accommodation to the far target was 0.39 D and to the near target 3.55 D, that is, there was a small lag of accommodation for near vision. Separately, the accommodation changed from 0.29 D to 3.37 D for the emmetropes and from 0.49 D to 3.74 D for the myopes. As an example, the wave fronts measured
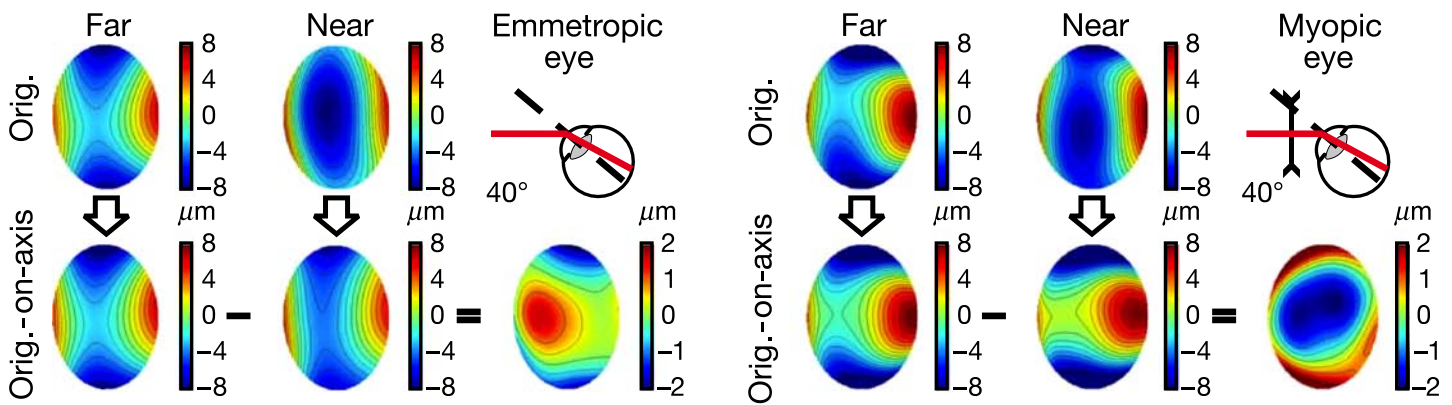
Figure 2. Video showing the wave front error (average of three measurements) for one emmetropic and one myopic subject over the temporal retina in 0°, 10°, 20°, 30°, and 40° off-axis. Five wave front maps are plotted for each subject and angle: the original wave front measured for the fixation target at 0.5 D and at 4.0 D (upper row), the same two wave fronts subtracted with the on-axis data to give the relative change with angle (the lower row), and how this change differs between the relaxed and the accommodative state (the map furthest to the right). The wave fronts are exiting the right eye and are plotted as coming out from the paper.

over the whole pupil for an emmetrope and a myope are shown in the video of Figure 2. The results for all subjects are presented in the form of Zernike coefficients over the central 4-mm zone of the pupil in Figures 3 and 4. Here, the on-axis value has been subtracted to more clearly illustrate the changes with off-axis angle. The on-axis values are given in the figure captions. Each graph contains four curves with average values for the emmetropes and the myopes, separately, with and without accommodation. The error bars indicate the standard deviation of the distribution of the measured values. Figure 5 gives an overview of the variation in optical quality by plotting the root mean square (RMS) error of different orders over the horizontal field of view. It shows that the image quality is worse on the temporal side of the retina.

## Statistical analysis

The variance of the measured Zernike coefficients of the 2nd, 3rd, and 4th radial order was analyzed with three variables (ANOVA, $p < 0.01$): off-axis measurement angle with 13 levels (angle: on-axis, 4 temporal angles, 4 nasal, 2 superior, and 2 inferior); state of accommodation with two levels (Acc. state: far and near); and refractive error group with two levels (Refr. state: on-axis emmetropia and on-axis myopia). Apart from these three main effects, the two-factor interactions were also computed. A summary of the ANOVA tests is given in Table 1. The results of these tests are discussed in detail in the two following paragraphs, but in short the differences found between myopes and emmetropes were as follows (all three differences are visible in Figure 3):

1. The already known difference in RPD, with the myopes having a less myopic RPD.

2. A difference in the symmetry of RPD over the visual field, with the myopes becoming relatively hyperopic on the temporal retina.
3. A difference in how the RPD changes with accommodation, with the emmetropes showing a myopic shift that was not present in the myopes.

The first three columns of Table 1 contain the main effects. The first column, variation with off-axis angle, shows that all aberrations vary significantly with angle. This increase of optical errors in the peripheral field of view is well known and it can for example be seen in the video in Figure 2, in the RMS error of Figure 5, and in Figure 4 with a quadratic variation with angle for astigmatism, a linear variation for coma, and a trend towards negative values for spherical aberration. In the second column of Table 1, variation with state of accommodation, it was found that, among others, defocus and spherical aberration changed with accommodation. The third column in Table 1, variation with refractive error group, shows that some aberrations differ between emmetropes and myopes, e.g., defocus in Figure 3, with the myopes having a less myopic RPD.

The last three columns of Table 1 show whether there was a significant interaction or not between the main effects. The fourth column shows that almost no significant interaction was found between the state of accommodation and the off-axis angle, that is, accommodation generally affects the whole aberration profile in a similar manner independent of angle. The fifth column of Table 1 presents significant interactions between refraction and off-axis angle for some coefficients, which means that these aberrations vary differently with the angle depending on whether the eye is emmetropic or myopic. This is evident for defocus in Figure 3, which is more asymmetric for the myopes. The last column in Table 1 is especially interesting because it shows that the interaction between
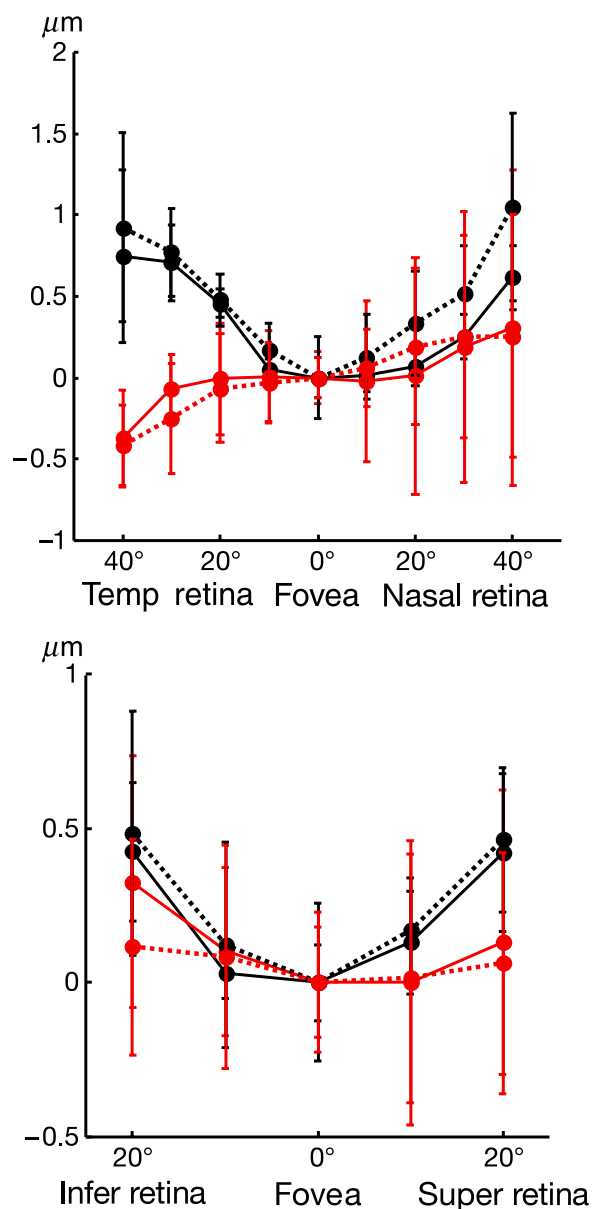
Figure 3. Variation of the defocus-coefficient $c_2^0$ with the off-axis angle averaged for emmetropes (black) and myopes (red) in the relaxed (solid lines) and the accommodated (dotted lines) state. The values are in $\mu$m over a 4-mm pupil, given relative to the foveal values, which are (mean value ± standard deviation): $0.27 \pm 0.13$ and $1.95 \pm 0.25$ $\mu$m for emmetropes relaxed and accommodating and for the myopes $0.40 \pm 0.16$ and $2.13 \pm 0.12$ $\mu$m. Upper graph is over the horizontal meridian and lower graph is over the vertical meridian. Note that a more positive value means relatively more myopia.

accommodative state and refractive error group is significant for defocus, coma, and spherical aberration, that is, the effect of accommodation differs depending on whether the eye is emmetropic or myopic on-axis. This difference in defocus-coefficient $c_2^0$ can be seen in Figure 3 both over the horizontal and the vertical meridian; the emmetropic eyes had a myopic shift (i.e., more positive $c_2^0$) in the

periphery with accommodation, whereas the myopic eyes have smaller or opposite shifts, e.g., at 40° on the nasal retina the defocus relative to on-axis increased by 0.44 $\mu$m (0.76 D more myopia) for the emmetropes, but decreased slightly (less than 0.1 D) with accommodation for the myopes. This can also be seen in the 40°-frame of the video in Figure 2 (compare the wave front maps furthest to the right); the emmetropic eye becomes more myopic with accommodation whereas the myopic eye goes in the opposite direction.

## Field curvature in an accommodating eye model

Emmetropic and myopic eyes are different, with the myopic eye often being longer and more stretched in the axial direction (Atchison et al., 2004; Logan et al., 2004). Naturally, this difference in shape influences how defocus varies over the visual field and is manifested in a less myopic RPD for myopes (see Figure 3 and Atchison et al., 2006; Mutti et al., 2000, 2007; Schmid, 2003; Seidemann et al., 2002). Similarly, if the elongation of the myopic eye is not symmetric around the fovea, this will lead to an asymmetric profile, e.g., for defocus in Figure 3. But can the ocular shape also explain the difference in how the peripheral defocus changes with accommodation for myopes and emmetropes?

To examine this, a simulation using a ray-tracing software (ZEMAX, Bellvue, USA) with a schematic eye (Navarro, Santamaria, & Bescos, 1985) was performed for far (accommodation 0.4 D) and near (accommodation 3.5 D) vision for an emmetropic and a −4.5 D myopic eye model. In this simulation, it was assumed that the optics of myopic and emmetropic eyes was the same and that the eyes only differed in axial length and shape of the retina. The curvatures of the image planes with the line foci (i.e., the extremes of the Sturm interval) were assessed and compared with the retinal shape. For the emmetropic model, a spherical retina was used with a radius of curvature of 12 mm and for the myopic model the retina was ellipsoidal (prolate) with a radius of 14 mm along the visual axis and 12 mm in the other directions.

In the left graph of Figure 6, the distances from the retina to the extremes of the Sturm interval for the two eye models are given in diopters (if the optical image was located on the retina in all off-axis angles this would correspond to a horizontal line at 0 D). The right graph of Figure 6 shows the corresponding average data for the subjects participating in this study. The model predicts both types of eyes to become relatively more myopic in the periphery with accommodation (i.e., the dotted lines are shifted downwards); 40° in the periphery, accommodation made both models approximately 1.4 D more myopic. The trend remained the same also when other retinal geometries were tested, as well as when the model was made myopic by reducing the radius of curvature of
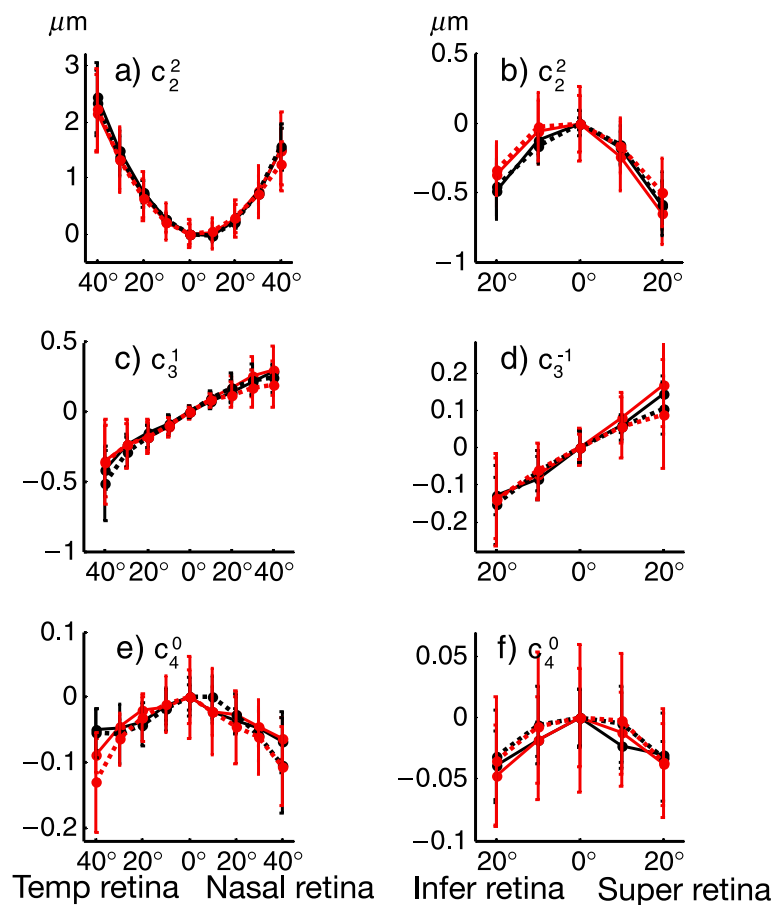
Figure 4. Variation of aberrations ($\mu$m relative to the foveal value for a 4-mm pupil) with off-axis angle averaged for emmetropes (black) and myopes (red), in the relaxed (solid) and the accommodated (dotted) state. Left column shows the horizontal and right column the vertical meridian. First row shows astigmatism $c_2^2$ (a–b) (foveal mean value ± standard deviation relaxed and accommodated: $-0.05 \pm 0.05$ and $0.01 \pm 0.06$ $\mu$m for emmetropes, $-0.14 \pm 0.26$ and $-0.14 \pm 0.18$ $\mu$m for myopes). Second row shows coma: $c_3^1$ over the horizontal meridian (c) (foveal values $-0.04 \pm 0.04$ and $-0.05 \pm 0.05$ $\mu$m for emmetropes, $-0.01 \pm 0.05$ and $0.00 \pm 0.03$ $\mu$m for myopes) and $c_3^{-1}$ over the vertical (d) (foveal values $0.00 \pm 0.05$ and $0.02 \pm 0.04$ $\mu$m for emmetropes, $-0.05 \pm 0.05$ and $-0.01 \pm 0.03$ $\mu$m for myopes). Last row shows spherical aberration $c_4^0$ (e–f) (foveal values $0.03 \pm 0.02$ and $0.00 \pm 0.03$ $\mu$m for emmetropes, $0.03 \pm 0.04$ and $-0.01 \pm 0.06$ $\mu$m for myopes).

the first corneal surface instead of changing the axial length. Although the eye model is simple, it clearly shows that a difference between myopes and emmetropes in how the RPD changes with accommodation cannot be explained by the difference in ocular shape.

# Discussion

## Validation of procedure

The procedure with the subjects turning their eyes for the off-axis measurements and with myopic subjects wearing their spectacles is not ideal. This section will list the disadvantages and evaluate how they might influence the results compared with an ideal situation without spectacles and rotating the whole head.

Turning the eye in large angles implies extra muscular stress on the eyeball that might affect the ocular aberrations slightly (Prado et al., 2009). The effect of rotating the eye instead of the head was therefore investigated for one emmetrope and the $-3.5$ D myope over the horizontal meridian (left graph of Figure 7). No significant differences were found in the measured peripheral refractive errors in agreement with earlier studies (Mathur et al., 2009; Radhakrishnan & Charman, 2008). Still, some 3rd- and 4th-order aberrations showed significant changes ($p < 0.01$), among them spherical aberration that became more negative when the eye was turned. However, since all subjects were measured with the same procedure, we do not believe that the eye-turn influences the comparisons in this study.

Spectacle corrections will of course change the measured wave front. First of all, the optical power of a spectacle lens will depend on the position and angle in
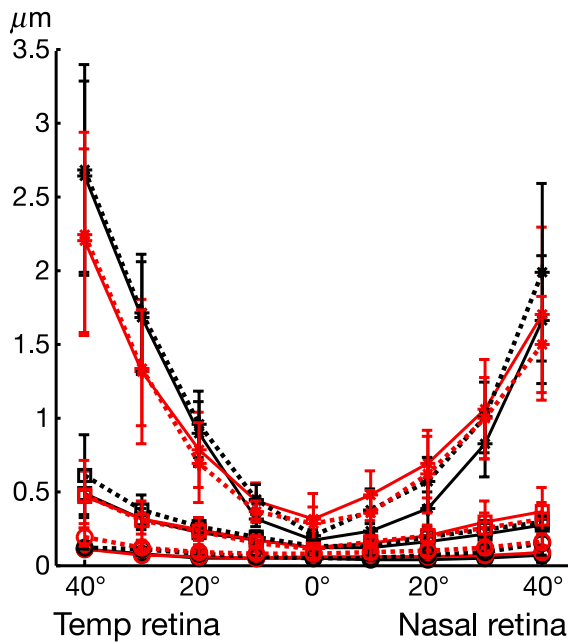
Figure 5. Variation of the root mean square error (RMS, standard deviation of the wave front error in $\mu$m over a 4-mm pupil) with off-axis angle, averaged for emmetropes (black) and myopes (red), in the relaxed (solid) and the accommodated (dotted) state over the horizontal meridian. Different orders of RMS are shown; stars (*) denote the RMS of 2nd–7th order Zernike coefficients, squares (□) denote 3rd–7th order RMS, and circles (○) 4th–7th order RMS. For the 2nd–7th order RMS, the on-axis $c_2^0$ (foveal defocus) was subtracted from all off-axis $c_2^0$ to enable the comparison between the accommodative states. The rest of the plotted values are given as they were measured.

which the measurement is performed. Because the subjects only turned the eye, the spectacles were kept perpendicular to the measurement axis for all angles. Thereby off-axis effects of the spectacles were minimized and only a small parallel displacement of the measure-

ment axis relative to the lens axes occurred because of the rotation of the eye. A second effect of negative lenses is that they will diminish the image of the pupil seen by the sensor, which means that the high-order aberrations will be slightly overestimated. Thirdly, the prismatic effect of the spectacle lenses means that the off-axis angle will be reduced; however, this shift is typically smaller than 5° even for a −8.5 D myope in 40° off-axis.

To evaluate the effect of using spectacles on the measured peripheral defocus, additional measurements were performed on three of the myopes (spherical refractive errors of −3 D, −3.5 D, and −7.25 D) without spectacles in the unaccommodated state over the horizontal meridian (in ±20° and ±40°). The Zernike coefficient for defocus, $c_2^0$, was normalized to the foveal value and then compared with the same data measured with spectacles (solid red line in Figure 3). As can be seen in the right graph of Figure 7, there was no general shift in RPD with spectacles. However, there is a fourth disadvantage with using negative spectacles; the eye will accommodate slightly less with the spectacles in place. This means that whereas the emmetropic subjects experience a 4.0-D accommodation stimulus, the myopic subjects with spectacles experience approximately 3.0–3.5 D. According to the study by Smith et al. (1988), this should still be enough to see a difference in field curvature with accommodation.

## Discussion of the results

Many of the characteristics noted in this article have also been found in earlier studies. It is, e.g., well known that astigmatism and high-order aberrations increase with the off-axis angle, that on-axis spherical aberration decreases towards negative values with accommodation, and that the RPD is more myopic in emmetropic eyes than in myopic eyes (see e.g., the review by Charman, 2005).

| | Angle | Acc. state | Refr. state | Acc. with angle | Refr. with angle | Acc. with Refr. |
|---|---|---|---|---|---|---|
| $c_2^{-2}$ | 0.00* | 0.10 | 0.00* | 0.23 | 0.81 | 0.29 |
| $c_2^{0}$ | 0.00* | 0.00* | 0.00* | 0.38 | 0.00* | 0.01* |
| $c_2^{2}$ | 0.00* | 0.38 | 0.00* | 1.00 | 0.00* | 0.45 |
| $c_3^{-3}$ | 0.00* | 0.03 | 0.00* | 0.40 | 0.04 | 0.25 |
| $c_3^{-1}$ | 0.00* | 0.00* | 0.00* | 0.13 | 0.78 | 0.01* |
| $c_3^{1}$ | 0.00* | 0.02 | 0.00* | 0.71 | 0.09 | 0.52 |
| $c_3^{3}$ | 0.00* | 0.00* | 0.25 | 0.00* | 0.00* | 0.11 |
| $c_4^{-4}$ | 0.00* | 0.61 | 0.00* | 0.46 | 0.00* | 0.14 |
| $c_4^{-2}$ | 0.00* | 0.12 | 0.43 | 0.00* | 0.00* | 0.07 |
| $c_4^{0}$ | 0.00* | 0.00* | 0.00* | 0.10 | 0.00* | 0.00* |
| $c_4^{2}$ | 0.00* | 0.00* | 0.00* | 0.00* | 0.00* | 0.35 |
| $c_4^{4}$ | 0.00* | 0.74 | 0.47 | 0.80 | 0.00* | 0.31 |

Table 1. The $p$ values of ANOVA tests on each Zernike coefficient separately (notation in consensus with American National Standards Institute, 2004) with the variables off-axis angle (Angle), accommodative state (Acc. state), and refractive state (Refr. state). The last three columns show the interaction between the variables. Stars (*) denote significant ($p < 0.01$) differences and interactions.
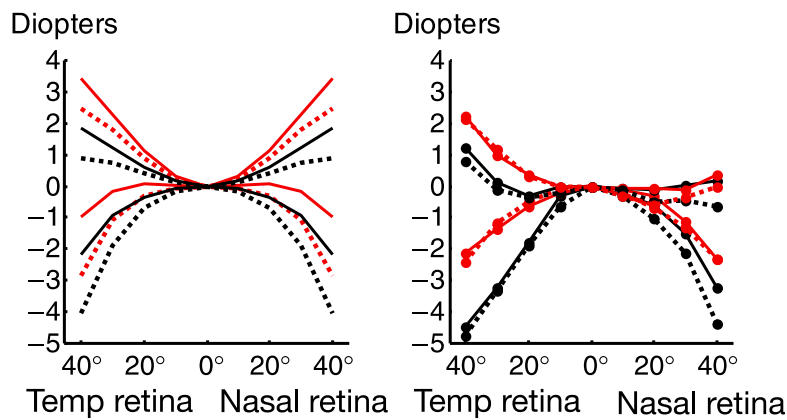
Figure 6. Variation of line-foci in diopters with off-axis angle over the horizontal meridian for the Navarro eye model (left graph) and for the subjects of this study (right graph). Emmetropic eyes are shown in black and myopic eyes in red. Solid lines represent the relaxed and dotted lines the accommodated state.

Regarding the change of RPD along the different meridians, the results of this study show a temporal–nasal and a smaller inferior–superior asymmetry between emmetropes and myopes (Figure 3). That the emmetropes are more myopic in the temporal retina can also be seen in the graphs of two studies using the Shin–Nippon autorefractor (Atchison et al., 2006; Calver et al., 2007) but was not noted by Seidemann et al. (2002) using a Power-Refractor and a double-pass instrument, probably because they only measured the temporal retina for angles over 25°. The asymmetry between emmetropes and myopes in the vertical meridian has not been found in earlier studies.

Regarding the changes induced by accommodation, our data confirm the findings of Smith et al. (1988) that emmetropic eyes had a more myopic RPD with accommodation. However, most interestingly, accommodation seems to have a different effect on myopes; the RPD of the myopic eyes in this study showed no or a small hyperopic change in RPD with accommodation. This finding is in agreement with the study by Walker and Mutti (2002), but opposite to the study by Whatham et al.

(2009), which found myopic shifts in RPD with accommodation for low myopes similar to that of the emmetropes in our study. The reason to the different results might be due to subject selection, especially if changes with accommodation are correlated with the degree of myopia. Furthermore, when comparing peripheral defocus measurements from different studies, it should be kept in mind that the large off-axis aberrations and the elliptic shape of the pupil can influence the outcome differently for different techniques. Note especially that the defocus results of this study were simply calculated directly from the Zernike coefficient $c_2^0$ over a 4-mm circular subaperture of the elliptic pupil.

A lack of or less myopic accommodative change of RPD for myopes can have consequences for the present understanding of myopia development. It means that the difference in RPD between emmetropes and myopes, which have already attracted interest within the research of myopia progression, is likely to be even larger during near work. For the 10 subjects in this study, 40° off-axis on the nasal retina, the difference between emmetropes
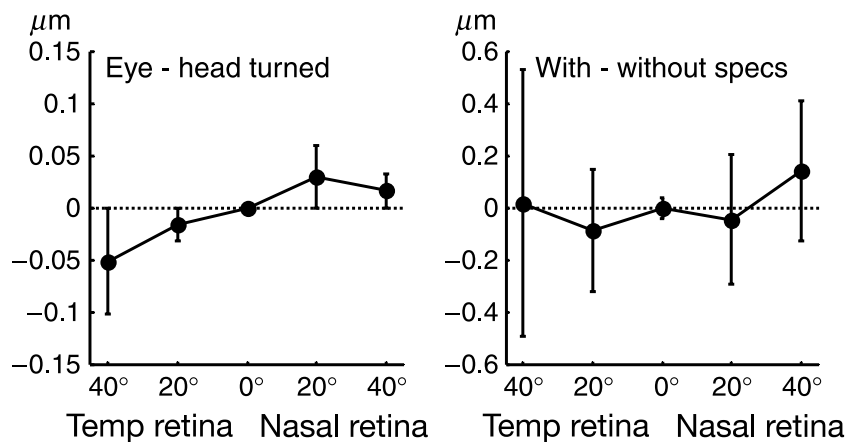


Figure 7. Changes in the Zernike coefficient for defocus ($c_2^0$ given in $\mu$m for a 4-mm pupil) over the horizontal meridian when the subjects (left graph) turn the eye instead of the whole head and (right graph) wear spectacles compared with naked eye.

and myopes in RPD was 0.2 $\mu$m (0.3 D) in the relaxed state and increased to 0.6 $\mu$m (1.1 D) with the fixation target at 25 cm. On the temporal retina 40° off-axis, the increase was from 1.7 D to 2.0 D. In addition, the fact that this effect cannot be reproduced from a difference in retinal shape in eye models implies that some other differences may exist between myopic and emmetropic eyes. The more exact nature of this difference is beyond the scope of this article, but since it does not depend on the retinal shape there is a possibility that it can be present in the eye before myopia develops. One hypothesis is that the risk of developing myopia is greater if the eye does not experience an increased curvature of field during near work. If this indeed is the case, it might be possible to detect the to-become-myopic eyes through RPD measurements. It would thereby be possible to start early with a treatment to reduce or completely avoid myopia, maybe by introducing peripheral myopia. However, this report only includes 10 subjects and more studies are needed on changes in RPD with accommodation comparing eyes with different refractive errors. Because the current measurement procedure is time consuming (approximately 1.5–2 hours per subject), a more efficient methodology needs to be developed to enable large population studies.

## Conclusions

In this study, the peripheral optical quality was measured for two accommodative states in emmetropic and myopic eyes. The results of the two groups were found to differ on three points: the myopes had a smaller relative peripheral myopia, they showed a larger asymmetry in defocus over the visual field, and their relative peripheral myopia, which increased with accommodation for emmetropes, did not change or decreased with accommodation. The difference in relative peripheral defocus between emmetropes and myopes therefore seems to be even larger during near work. This cannot be explained by simple modeling of different retinal shapes for the two types of eyes. Further research is needed to determine the extent of this phenomena and how it correlates with myopia development.

## Acknowledgments

## References

Abbott, M. L., Schmid, K. L., & Strang, N. C. (1998). Differences in the accommodation stimulus response curves of adult myopes and emmetropes. *Ophthalmic & Physiological Optics, 18,* 13–20. [PubMed]

Allen, P. M., & O'Leary, D. J. (2006). Accommodation functions: Co-dependency and relationship to refractive error. *Vision Research, 46,* 491–505. [PubMed]

American National Standards Institute (2004). *Methods for reporting optical aberrations of eyes* (ANSI Z80.28-2004). Washington, DC: Author.

Artal, P., Derrington, A. M., & Colombo, E. (1995). Refraction, aliasing, and the absence of motion reversals in peripheral vision. *Vision Research, 35,* 939–947. [PubMed]

Atchison, D. A. (2006). Higher order aberrations across the horizontal visual field. *Journal of Biomedical Optics, 11,* 34026. [PubMed]

Atchison, D. A., Jones, C. E., Schmid, K. L., Pritchard, N., Pope, J. M., Strugnell, W. E., et al. (2004). Eye shape in emmetropia and myopia. *Investigative Ophthalmology & Visual Science, 45,* 3380–3386. [PubMed] [Article]

Atchison, D. A., Pritchard, N., & Schmid, K. L. (2006). Peripheral refraction along the horizontal and vertical visual fields in myopia. *Vision Research, 46,* 1450–1458. [PubMed]

Calver, R., Radhakrishnan, H., Osuobeni, E., & O'Leary, D. (2007). Peripheral refraction for distance and near vision in emmetropes and myopes. *Ophthalmic & Physiological Optics, 27,* 584–593. [PubMed]

Charman, W. N. (2005). Aberrations and myopia. *Ophthalmic & Physiological Optics, 25,* 285–301. [PubMed]

Diether, S., & Schaeffel, F. (1997). Local changes in eye growth induced by imposed local refractive error despite active accommodation. *Vision Research, 37,* 659–668. [PubMed]

Fulk, G. W., Cyert, L. A., & Parker, D. E. (2000). A randomized trial of the effect of single-vision vs. bifocal lenses on myopia progression in children with esophoria. *Ophthalmology & Vision Science, 77,* 395–401. [PubMed]

Guirao, A., & Artal, P. (1999). Off-axis monochromatic aberrations estimated from double pass measurements

in the human eye. *Vision Research, 39,* 207–217. [PubMed]

Gwiazda, J., Hyman, L., Hussein, M., Everett, D., Norton, T. T., Kurtz, D., et al. (2003). A randomized clinical trial of progressive addition lenses versus single vision lenses on the progression of myopia in children. *Investigative Ophthalmology & Visual Science, 44,* 1492–1500. [PubMed] [Article]

Gwiazda, J., Thorn, F., Bauer, J., & Held, R. (1993). Myopic children show insufficient accommodative response to blur. *Investigative Ophthalmology & Visual Science, 34,* 690–694. [PubMed] [Article]

Hoogerheide, J., Rempt, F., & Hoogenboom, W. P. (1971). Acquired myopia in young pilots. *Ophthalmologica, 163,* 209–215. [PubMed]

Hung, L. F., Crawford, M. L., & Smith, E. L. (1995). Spectacle lenses alter eye growth and the refractive status of young monkeys. *Nature Medicine, 1,* 761–765. [PubMed]

Irving, E. L., Sivak, J. G., & Callender, M. G. (1992). Refractive plasticity of the developing chick eye. *Ophthalmic & Physiological Optics, 12,* 448–456. [PubMed]

Jennings, J. A. M., & Charman, W. N. (1978). Optical image quality in the peripheral retina. *American Journal of Optometry and Physiological Optics, 55,* 582–590. [PubMed]

Jennings, J. A. M., & Charman, W. N. (1981). Off-axis image quality in the human eye. *Vision Research, 21,* 445–455. [PubMed]

Kee, C.-S., Hung, L.-F., Qiao-Grider, Y., Roorda, A., & Smith, E. L., III. (2004). Effects of optically imposed astigmatism on emmetropization in infant monkeys. *Investigative Ophthalmology & Visual Science, 45,* 1647–1659. [PubMed] [Article]

Leung, J., & Brown, B. (1999). Progression of myopia in Hong Kong Chinese schoolchildren is slowed by wearing progressive lenses. *Optometry and Vision Science, 76,* 346–354. [PubMed]

Logan, N. S., Gilmartin, B., Wildsoet, C. F., & Dunne, M. C. (2004). Posterior retinal contour in adult human anisomyopia. *Investigative Ophthalmology & Visual Science, 45,* 2152–2162. [PubMed] [Article]

Lundström, L. (2007). *Wavefront aberrations and peripheral vision.* PhD thesis, Royal Institute of Technology, Stockholm, Sweden. Retrieved from www.biox.kth.se/research/visualoptics/publications/PhD_thesis_linda_lundstrom.pdf.

Lundström, L., Manzanera, S., Prieto, P. M., Ayala, D. B., Gorceix, N., Gustafsson, J., et al. (2007). Effect of optical correction and remaining aberrations on peripheral resolution acuity in the human eye. *Optics Express, 15,* 12654–12661.

Mathur, A., Atchison, D. A., & Scott, D. H. (2008). Ocular aberrations in the peripheral visual field. *Optics Letters, 33,* 863–865. [PubMed]

Mathur, A., Atchison, D. A., Kasthurirangan, S., Dietz, N. A., Luong, S., Chin, S. P., et al. (2009). The influence of oblique viewing on axial and peripheral refraction for emmetropes and myopes. *Ophthalmic & Physiological Optics, 29,* 155–161. [PubMed]

McFadden, S. A., Howlett, M. H., & Mertz, J. R. (2004). Retinoic acid signals the direction of ocular elongation in the guinea pig eye. *Vision Research, 44,* 643–653. [PubMed]

Mira-Agudelo, A., Lundström, L., & Artal, P. (2009). Temporal dynamics of ocular aberrations: Monocular vs binocular vision. *Ophthalmic & Physiological Optics, 29,* 256–263. [PubMed]

Morgan, I., & Rose, K. (2005). How genetic is school myopia? *Progress in Retinal and Eye Research, 24,* 1–38.

Mutti, D. O., Sholtz, R. I., Friedman, N. E., & Zadnik, K. (2000). Peripheral refraction and ocular shape in children. *Investigative Ophthalmology & Visual Science, 41,* 1022–1030. [PubMed] [Article]

Mutti, D. O., Hayes, J. R., Mitchell, G. L., Jones, L. A., Moeschberger, M. L., Cotter, S. A., et al. (2007). Refractive error, axial length, and relative peripheral refractive error before and after the onset of myopia. *Investigative Ophthalmology & Visual Science, 48,* 2510–2519. [PubMed] [Article]

Navarro, R., Artal, P., & Williams, D. R. (1993). Modulation transfer of the human eye as a function of retinal eccentricity. *Journal of the Optical Society of America A, Optics and Image Science, 10,* 201–212. [PubMed]

Navarro, R., Moreno, E., & Dorronsoro, C. (1998). Monochromatic aberrations and point-spread functions of the human eye across the visual field. *Journal of the Optical Society of America A, Optics, Image Science, and Vision, 15,* 2522–2529. [PubMed]

Navarro, R., Santamaria, J., & Bescos, J. (1985). Accommodation-dependent model of the human eye with aspherics. *Journal of the Optical Society of America A, Optics and Image Science, 2,* 1273–1281. [PubMed]

Prado, P., Arines, J., Bará, S., Manzanera, S., Mira-Agudelo, A., & Artal, P. (2009). Changes of ocular aberrations with gaze. *Ophthalmic & Physiological Optics, 29,* 264–271. [PubMed]

Prieto, P. M., Vargas-Martín, F., Goelz, S., & Artal, P. (2000). Analysis of the performance of the Hartmann–Shack sensor in the human eye. *Journal of the Optical Society of America A, Optics, Image Science, and Vision, 17,* 1388–1398. [PubMed]

Radhakrishnan, H., & Charman, W. N. (2008). Peripheral refraction measurement: Does it matter if one turns the eye or the head? *Ophthalmic & Physiological Optics, 28,* 73–82. [PubMed]

Schaeffel, F., Glasser, A., & Howland, H. C. (1988). Accommodation, refractive error and eye growth in chickens. *Vision Research, 28,* 639–657. [PubMed]

Schmid, G. F. (2003). Variability of retinal steepness at the posterior pole in children 7–15 years of age. *Current Eye Research, 27,* 61–68. [PubMed]

Seidemann, A., Schaeffel, F., Guirao, A., Lopez-Gil, N., & Artal, P. (2002). Peripheral refractive errors in myopic, emmetropic, and hyperopic young subjects. *Journal of the Optical Society of America A, Optics, Image Science, and Vision, 19,* 2363–2373. [PubMed]

Shih, Y.-F., Hsiao, C. K., Chen, C.-J., Chang, C.-W., Hung, P. T., & Lin, L. L.-K. (2001). An intervention trial on efficacy of atropine and multi-focal glasses in controlling myopic progression. *Acta Ophthalmologica Scandinavica, 79,* 233–236. [PubMed]

Smith, E. L., III., Kee, C.-S., Ramamirtham, R., Qiao-Grider, Y., & Hung, L.-F. (2005). Peripheral vision can influence eye growth and refractive development in infant monkeys. *Investigative Ophthalmology & Visual Science, 46,* 3965–3972. [PubMed] [Article]

Smith, E. L., III., Ramamirtham, R., Qiao-Grider, Y., Hung, L.-F., Huang, J., Kee, C.-S., et al. (2007). Effects of foveal ablation on emmetropization and form-deprivation myopia. *Investigative Ophthalmology & Visual Science, 48,* 3914–3922. [PubMed] [Article]

Smith, G., Millodot, M., & McBrien, N. (1988). The effect of accommodation on oblique astigmatism and field curvature of the human eye. *Clinical and Experimental Optometry, 71,* 119–125.

Thibos, L. N., Still, D. L., & Bradley, A. (1996). Characterization of spatial aliasing and contrast sensitivity in peripheral vision. *Vision Research, 36,* 249–258. [PubMed]

Walker, T. W., & Mutti, D. O. (2002). The effect of accommodation on ocular shape. *Optometry and Vision Science, 79,* 424–430 [PubMed]

Wallman, J., & Winawer, J. (2004). Homeostasis of eye growth and the question of myopia. *Neuron, 43,* 447–468. [PubMed] [Article]

Wang, Y. Z., Thibos, L. N., & Bradley, A. (1997). Effects of refractive error on detection acuity and resolution acuity in peripheral vision. *Investigative Ophthalmology & Visual Science, 38,* 2134–2143. [PubMed] [Article]

Whatham, A. R., & Judge, S. J. (2001). Compensatory changes in eye growth and refraction induced by daily wear of soft contact lenses in young marmosets. *Vision Research, 41,* 267–273. [PubMed]

Whatham, A., Zimmermann, F., Martinez, A., Delgado, S., de la Jara, P. L., Sankaridurg, P., et al. (2009). Influence of accommodation on off-axis refractive errors in myopic eyes [Abstract]. *Journal of Vision, 9*(3):14, 1–13, http://journalofvision.org/9/3/14/, doi:10.1167/9.3.14.