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Wavefront aberrations in eyes of emmetropic and moderately myopic school children and young adults

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Abstract

Wavefront aberrations were measured using a psychophysical ray-tracing technique in both eyes of 316 emmetropic and moderately myopic school children and young adults. Myopic subjects were found to have greater mean root mean square (RMS) value of wavefront aberrations than emmetropic subjects. Emmetropic adults had the smallest mean RMS, which remained smaller than the values for myopic adults and children and for emmetropic children both when second order Zernike aberrations (astigmatism) and third order Zernike aberrations were removed. Twenty percent of myopic adults had RMS values greater than values for all of the emmetropic adults, with significantly greater values for Zernike aberrations from second to seventh orders. High amounts of wavefront aberrations, which degrade the retinal image, may play a role in the development of myopia.

Keywords: Wavefront aberrations; Zernike aberrations; Myopia; Emmetropia; Emmetropization

1. Introduction

The human eye is an imperfect optical imaging system. It may suffer deficiencies in the regularity of local surface curvature of the cornea and the lens, in the alignment between the optical axes of its refracting surfaces, and in the spatial distribution profile of the refractive indices. Optical defects in the eye have been precisely described as wavefront aberrations at the pupil plane and have been measured using a variety of ray-tracing techniques (He, Marcos, Webb, & Burns, 1998; Howland & Howland, 1976; Liang, Grimm, Goetz, & Bille, 1994; Liang & Williams, 1997; Smirnov, 1961; Walsh, Charman, & Howland, 1984; Webb, Penney, & Thompson, 1992). When a two dimensional (2D) surface is used to represent the distribution of the wavefront aberrations at the pupil plane, it almost always shows an irregular shape which can vary substantially between the two eyes of a single individual and between the eyes of different individuals (He et al., 1998; He, Gwiazda, et al., 2000; Liang & Williams, 1997; Marcos & Burns, 2000). Wavefront aberrations blur the retinal image, thus reducing contrast sensitivity and visual acuity as a function of the severity of the individual's aberrations.

The myopic eye is axially elongated so that the image of a distant object is focused in front of the retina instead of on the retina as would occur in a perfect refractive state (emmetropia). The excess optical power in myopia is traditionally treated with either spectacles or contact lenses with negative power or, more recently, by flattening the cornea with laser surgery in order to bring the focused image onto the retina. Since wavefront aberrations vary from eye to eye, it is of interest to learn if a myopic eye has wavefront aberrations different from an emmetropic eye.

Studies of the relationship between wavefront aberrations and refraction are also of interest for research on the development of myopia. Most children's eyes approach emmetropia at about five years of age from hyperopia or myopia in infancy (Gwiazda, Thorn, Bauer, & Held, 1993). While many children maintain their emmetropia into adulthood, others become myopic because the eye grows too long for the eye's optics. Animal studies for various species ranging from chicken to monkey indicate that degrading image quality by either

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lid fusion or other means of depriving the eye of spatial information causes axial myopia, although the underlying mechanisms are not fully understood (for a review see Norton (1999)). Wavefront aberrations in the human eye degrade the retinal image in a similar manner, and therefore it is important to know if aberrations are risk factors for myopia development.

Larger root mean square (RMS) magnitudes of wavefront aberrations recently have been reported in the eyes of myopic compared with emmetropic adults in several studies (Bueno, Priest, & Campbell, 2000; Cheng et al., 2000; He, Gwiazda, et al., 2000; Marcos, Moreno-Barriuso, Llorente, Navarro, & Barbero, 2000; Simonet, Hamam, Brunette, & Campbell, 1999). Some studies have shown that RMS magnitudes are correlated with refractive errors when there is a broad range of myopic refractive errors. Neither wavefront aberrations nor their relation to refractive error have yet been studied in children, although they are at an age when the most prevalent form of myopia develops. The purpose of the present report is study of wavefront aberrations in children of school age and their relationship to the development of myopia.

2. Methods

2.1. Subjects

Wavefront aberrations of both eyes were measured in 83 emmetropic and 87 myopic children, and 54 emmetropic and 92 myopic young adults, for a total of 316 subjects and 632 eyes. The ages of the children ranged from 10 to 17, with the means equal to 14.9 and 14.6 years, for the emmetropes and the myopes, respectively. The ages of the adults ranged from 18 to 29 years, with the means equal to 21.1 and 21.5 years, for the emmetropes and myopes, respectively. These measurements were taken in both Beijing ($n = 229$ subjects) and Boston ($n = 87$ subjects), using identical instruments for measurement of wavefront aberration and refractive procedures providing comparable measures of spherical equivalent. All eyes were refracted before testing for aberrations.

Refraction was measured by noncycloplegic distance retinoscopy in Boston, and assessed in Beijing by a subjective refraction using spherical trial lenses to optimize the visual acuity for a Chinese standard visual acuity test chart positioned 5 m from the subject. Eyes with spherical equivalent refractive errors within ± 0.5 D were categorized as emmetropic (mean $= +0.22$ D). Those with refractive errors less than -0.5 D were classified as myopic. The mean spherical equivalent refractive error for myopes was -2.8 D (range from -0.75 to -9.00 D). All but 16 eyes of the myopes had mild to moderate refractive errors (between -0.75 and -6.0 D). There were no hyperopes in this group. No eye disease was reported for any of the subjects.

The research followed the tenets of the Declaration of Helsinki. Informed consent was obtained after verbal and written explanation of the nature and possible consequences of the study. The New England College of Optometry institutional review board approved the research in Boston and the research committee at the Institute of Psychology at the Chinese Academy of Science approved the research in Beijing.

2.2. Apparatus

The apparatus used in this study was a three channel optical system that included a testing, a recording, and a pupil-monitoring channel. In principle it shares the design of the psychophysical ray-tracing wavefront sensor described in previous studies (He, Burns, & Marcos, 2000; He et al., 1998; Smirnov, 1961; Webb et al., 1992), but was changed to a computer-monitor version. The testing channel provides a green cross target on the retina via a movable aperture with a 1 mm diameter. As the image of the aperture is moved from trial to trial among 37 locations within the subject's natural pupil, the cross shifts its retinal location as a function of the aberrations of the eye. The cross shifts were tracked by the subject with a cursor on a computer monitor in the recording channel. During the experiment the position of the subject's pupil was monitored by a CCD camera with a video monitor. Any eye displacement relative to the optical axis of the system was compensated for by the experimenter who moved a 3D translator on which the subject's head rested. Within the system a movable stage with two mirrors on the common path of a Badal system compensated for the subject's defocus.

2.3. Procedure

The subject's right eye was first aligned in the optical system. Looking at the monitor screen through a 1 mm aperture, the subject adjusted the Badal system to clear the screen, which positioned the eye at its accommodative resting state. The measurements consisted of a few practice trials and three tests. Each test consisted of 39 trials with the first and the last trials for the center of the pupil. The other 37 trials randomly sampled the entire pupil within a 7×7 matrix in 1 mm steps except for the 12 points in the four corners. The subject's task on each trial was to align the cursor with the center of the cross and click the mouse to record the position. Each test lasted about 3 min. After finishing with the right eye, the procedure was repeated on the left eye. The entire session lasted approximately a half hour.

Wavefront aberrations were measured with natural pupils. The pupil diameter was almost always greater than 6 mm because the screen was very dim (retinal illumination was less than $2\log td$) and the room light was off during the experiment. Data from the few subjects whose pupil size remained less than 6 mm in diameter were excluded.

2.4. Data analysis

The shifts in the cross target recorded by the computer were translated into the slope of the wavefront at each of the 37 pupil locations. A least squares procedure was used to fit the slope measurements to the derivatives of the first 35 terms of the Zernike polynomial functions (Z_1–Z_{35}) (He et al., 1998). The derived coefficients (C_i) provide estimates of the weight of individual Zernike aberrations (Z_i), and the wavefront aberration $W(x,y)$ is expressed as

$$W(x,y) = \sum_{i=1}^{35} C_i Z_i(x,y), \quad (1)$$

where the x and y represent the coordinates at the pupil plane. The Zernike polynomials (Z_i) are defined by

$$Z_i(x,y) = \begin{cases} \sqrt{2(n+1)}R_n^m(\rho(x,y))\cos m\theta(x,y) \\ \quad \text{for } m > 0 \\ \sqrt{2(n+1)}R_n^m(\rho(x,y))\sin m\theta(x,y) \\ \quad \text{for } m < 0 \\ \sqrt{n+1}R_n^m(\rho(x,y)) \\ \quad \text{for } m = 0 \end{cases}, \quad (2)$$

where $\rho(x,y) = \sqrt{x^2+y^2}$, $\theta(x,y) = \arctan(x/y)$ and

$$R_n^m(\rho) = \sum_{s=0}^{(n-m)/2} \frac{(-1)^s(n-s)!}{s!((n+m)/2-s)!((n-m)/2-s)!}\rho^{n-2s}. \quad (3)$$

The coefficients C_i are numbered according to the indices of the Zernike polynomials Z_i as shown in Table 1, and correspond to the order recommended by the OSA Standardization Committee (Thibos, Applegate, Schwiegerling, Webb, & VSIA Standards Taskforce Members, 2000). The integers n and m in Eq. (2) represent the order of the polynomial in the radial direction and the frequency in the azimuthal direction, respectively.

Table 2
The correspondence of some Zernike aberrations to classical aberrations

Z_1^{-1}	y-axis tilt
Z_1^1	x-axis tilt
Z_2^{-2}	Astigmatism in 45°
Z_2^0	Defocus
Z_2^2	Astigmatism in 0° or 90°
Z_3^{-1}	y-axis coma
Z_3^1	x-axis coma
Z_4^0	Sherical aberration

The correspondence between the Zernike aberrations used in this study and classical Seidel aberrations is illustrated in Table 2. In the data analysis, the effect of the tilts (C_1 and C_2) and defocus (C_4) on the wavefront aberration $W(x,y)$ were excluded.

We have derived an estimate of the overall wavefront aberration for each eye by taking the mean of the 32 Zernike coefficients of the three measurements and then calculating the RMS of the averaged wavefront aberrations.

3. Results

Measurement of wavefront aberration in the human eye with a psychophysical ray-tracing system has been reported to be highly repeatable for adults (He et al., 1998). Repeatability in children, however, has not been tested. Since we have three measurements for each eye in our experiments, we can test the repeatability of the measurements for children by comparing the standard deviations within the three measurements for children with those for adults. We used the RMS of the wavefront error as the estimate of the wavefront aberration for each measurement, and the three RMSs were then used to derive the standard deviation of the measurements for each eye. The 170 children were found to have a mean SD of 0.229 μm, which is almost equal to the mean SD of 0.212 μm found for the 146 adults. The difference, however, is not significant ($t = 1.043$, n.s.), indicating that the repeatability of measures is essentially the same for children and adults.

Table 1
Numbering of the Zernike polynomial functions used in this study

Order	Frequency														
	−7	−6	−5	−4	−3	−2	−1	0	1	2	3	4	5	6	7
First							Z_1		Z_2						
Second						Z_3		Z_4		Z_5					
Third					Z_6		Z_7		Z_8		Z_9				
Fourth				Z_{10}		Z_{11}		Z_{12}		Z_{13}		Z_{14}			
Fifth			Z_{15}		Z_{16}		Z_{17}		Z_{18}		Z_{19}		Z_{20}		
Sixth		Z_{21}		Z_{22}		Z_{23}		Z_{24}		Z_{25}		Z_{26}		Z_{27}	
Seventh	Z_{28}		Z_{29}		Z_{30}		Z_{31}		Z_{32}		Z_{33}		Z_{34}		Z_{35}

3.1. Root mean square of wavefront aberrations for emmetropic and myopic adults and children

A four-way analysis of variance (refractive group, age group, ethnicity, and eye) shows that the mean RMS of wavefront aberrations is significantly different between emmetropes and myopes ($F = 12.46$, $p < 0.001$). There is no significant difference between eyes or between populations from Beijing and Boston or between adults and children, nor do the single interactions between pairs of these terms differ significantly. Thus we combined data for the two eyes and for Boston and Beijing, but did not combine age groups since the single interaction between age group and refractive group approached significance ($p = 0.07$).

Frequency histograms of the RMS of all wavefront aberrations in each eye for each subject are shown in Fig. 1 for four groups: emmetropic adults, emmetropic children, myopic adults, and myopic children. Every eye has an RMS of all wavefront aberrations greater than 0.35, thereby confirming that every human eye suffers image degradation from deficiencies in its optics.

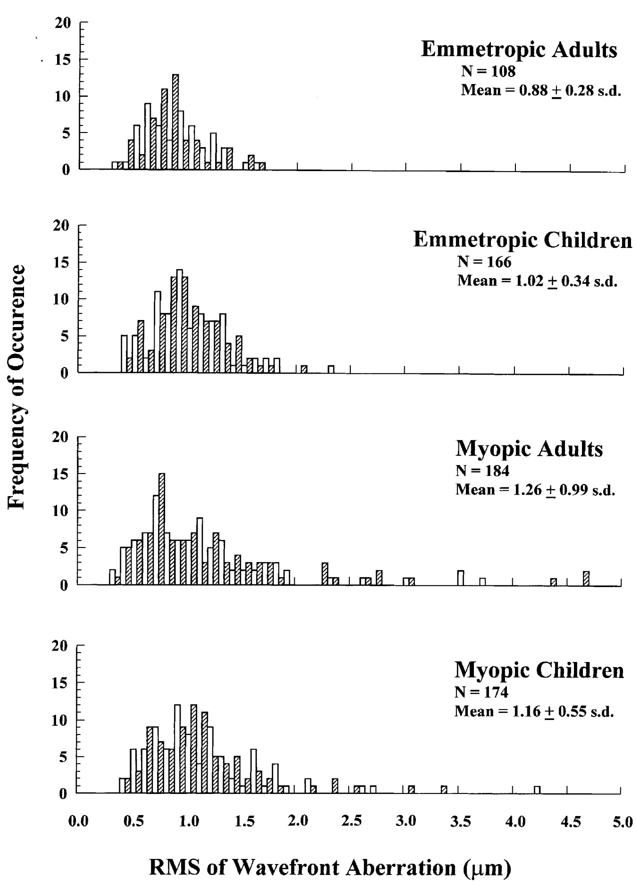

Fig. 1. Frequency histograms of the RMS of wavefront aberration from right eye (empty bar) and left eye (slashed bar) in the human eye for emmetropic adults (a), emmetropic children (b), myopic adults (c), and myopic children (d). The number of eyes (N) and the mean RMS with standard deviation are indicated for each group.

Each emmetropic group has a lower mean RMS of wavefront aberrations than each myopic group, and three of the four comparisons were significant (emmetropic adults vs myopic adults, $F = 15.91$, $p < 0.001$; emmetropic adults vs myopic children, $F = 27.38$, $p < 0.001$; and emmetropic children vs myopic children, $F = 6.30$, $p < 0.02$). The difference between emmetropic children and myopic adults was not significant but approached significance ($F = 3.58$, $p = 0.07$). In addition, emmetropic adults have lower mean aberrations than emmetropic children ($F = 11.67$, $p < 0.001$). All statistical analyses were performed for the data in Fig. 1 after a log transformation along the x-axis since the distributions are skewed, particularly for the myopic groups.

The range of RMS values varies across refractive groups. At the lower end of the range, the lowest RMS values for the four groups are almost the same. At the high end, the myopic adults have the highest RMS values (4.7 μm), while the emmetropic adults have no RMS value higher than 1.65 μm. In our sample this value is exceeded by 20% of myopic adult eyes, 13% of myopic children's eyes, and 4% of emmetropic children's eyes. Some subjects have high RMS values in only one eye. Twenty-six percent of myopic adults, 22% of myopic children and 7% of emmetropic children have values that exceed the maximum value of emmetropic adults (1.65 μm) in at least one eye.

The differences between mean RMS values of the left and right eyes for all four groups are not significant, and the wavefront aberration in one eye is correlated with that in the other eye. The correlation coefficients (pearson r) between the left eye and right eye for the four groups (emmetropic adults, emmetropic children, myopic adults, and myopic children) are 0.38, 0.34, 0.82, and 0.48, respectively. The myopic adults have a higher correlation in wavefront aberrations between the two eyes, most likely because of the wider range of values. Correlations between spherical equivalent refractive error and aberrations for myopic children and myopic adults are low: $R = 0.04$ ($t = 0.37$, $p = 0.72$) and $R = 0.15$ ($t = 1.44$, $p = 0.15$), respectively.

3.2. Mean root mean square of wavefront aberrations with second and third order Zernike aberrations removed

In order to examine the contribution of high order Zernike aberrations to the RMS of the overall wavefront aberrations shown in Fig. 1, second order Zernike aberrations were removed from the overall wavefront aberrations, as shown in Fig. 2a. The second order Zernike aberrations only include astigmatism, since the defocus term (coefficient of Zernike function Z_2^0) has been removed from all calculations. As shown in Fig. 2a, emmetropic adult eyes continue to have the lowest mean RMS with second order aberrations removed among the four groups (vs emmetropic children, $F = 7.76$, $p < 0.01$;

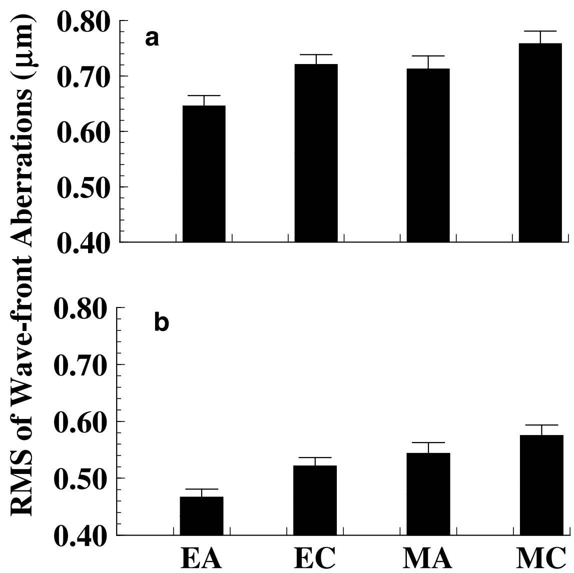

Fig. 2. Mean RMS of wavefront aberrations for emmetropic adults (EA), emmetropic children (EC), myopic adults (MA) and myopic children (MC) with second order Zernike aberrations (astigmatism) removed (a) and with the second and third orders of Zernike aberrations removed. Error bars represent the standard error of the mean.

vs myopic adults, $F = 3.78$, approaches significance with $p = 0.06$; and vs myopic children, $F = 11.85$, $p < 0.001$). Although myopic children have the highest RMS value, it is not significantly different from either emmetropic children or myopic adults.

Fig. 2b shows the RMS of wavefront aberrations with the second and third Zernike aberrations (including both astigmatism and coma) removed for the four groups of subjects. The emmetropic adults still have the lowest mean RMS values of the four groups (vs emmetropic children, $F = 6.34$, $p < 0.02$; vs myopic adults, $F = 7.88$, $p < 0.01$; and vs myopic children, $F = 17.30$, $p < 0.001$). The only significant pair-wise comparison among the other three groups was between the mean RMS value of the myopic children and that of the emmetropic children ($F = 4.99$, $p < 0.05$), with myopic children having a higher mean RMS.

3.3. Distribution of RMS of Zernike aberrations in each order for both myopic adults with large wavefront errors and emmetropic adults

As can be seen in Fig. 1, 20% of myopic adult eyes in our sample have an RMS of overall wavefront aberrations greater than those of all emmetropic adult eyes. This comparison does not reveal how these larger RMS values are distributed among their Zernike components. In order to reveal those variations and compare them with those of the emmetropic eye, Zernike aberrations from second to seventh orders for the highly aberrated myopic adult eyes are plotted in Fig. 3 together with

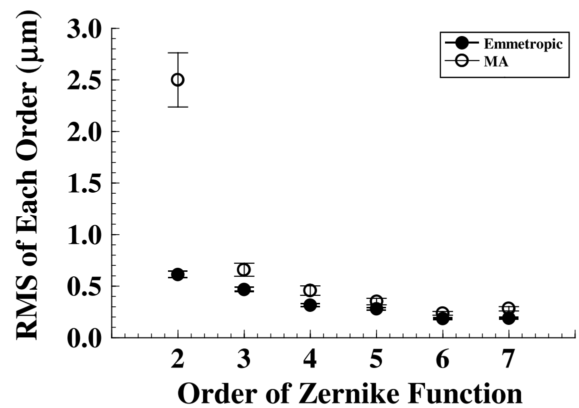

Fig. 3. Comparison of Zernike aberrations in the second to seventh orders between myopic adults with high wavefront aberrations (empty circles) and emmetropic adults (solid circles). Error bars indicate the standard error of the mean.

those of the emmetropic adults. The x-axis in Fig. 3 shows the order of Zernike functions and the y-axis indicates the RMS of the aberrations within each order. As illustrated in Fig. 3, the eyes of the high RMS myopic adults (empty circles) always have a higher mean RMS value than that in the emmetropic adults (solid circles) for all six orders of Zernike aberrations. The differences between emmetropic adults and these myopic adults are significant for all six orders (for second order, $F = 145.6$, $p < 0.0001$; for third order, $F = 14.5$, $p < 0.001$; for fourth order, $F = 16.2$, $p < 0.005$; for fifth order, $F = 6.9$, $p < 0.01$; for sixth order, $F = 10.1$, $p < 0.01$; and for seventh order, $F = 28.3$, $p < 0.001$).

Statistical comparison of the mean RMS values for emmetropic adults and myopic children with high wavefront aberrations also shows significant differences for all six orders (for second order, $F = 126.7$, $p < 0.0001$; for third order, $F = 12.2$, $p < 0.001$; for fourth order, $F = 6.4$, $p < 0.025$; for fifth order, $F = 38.4$, $p < 0.0001$; for sixth order, $F = 46.9$, $p < 0.0001$; and for seventh order, $F = 64.5$, $p < 0.0001$). While the increase in second order Zernike aberrations in these myopic eyes compared to emmetropic eyes is much larger than that of the higher orders, all orders are significantly greater in the eyes of myopic adults and children with high wavefront aberrations.

4. Discussion

4.1. Differences in wavefront aberrations

Our study is the first to measure wavefront aberrations in the eyes of children. Both myopic children and adults were found to have larger wavefront aberrations than emmetropic adults as indicated in Fig. 1. This result is in agreement with several recent reports on measurements of wavefront aberrations in myopic and emmetropic adult eyes (Bueno et al., 2000; Cheng et al., 2000; Marcos et al., 2000; Simonet et al., 1999). The RMS of wavefront aberrations in myopia has been reported to increase significantly with refractive error, but only when high myopes (> 6.0 D) were included (Marcos et al., 2000). In our study the RMS was found to have little correlation with the amount of refractive error for either myopic children or myopic adults, which is not surprising considering that there were only a few high myopes in our sample.

Astigmatism (second order Zernike) is often included in wavefront aberration, although some have suggested that it should not be included in wavefront aberration because it, like defocus, is readily corrected by eyeglasses. We have treated it as an aberration because we are testing the hypothesis that image degradation in childhood can induce myopia. Young nonmyopic children do not wear spectacle corrections unless they have high hyperopia or high amounts of astigmatism ($\geqslant$2 D). Thus, during a child's premyopic stage, astigmatism would not be corrected and could act to degrade the retinal image.

The differences between emmetropic adults and myopic children and between emmetropic and myopic adults found in this study are due in part to differences in astigmatism, a type of aberration that has been found to be a risk factor in developing myopia (Gwiazda, Grice, Held, McLellan, & Thorn, 2000). However, even when the second order Zernike aberrations are removed, the differences between groups remain, as shown in Fig. 2a. This may explain why it is often difficult in clinical practice to clear the vision of a myopic patient using available techniques, since they are used to correct only defocus and/or astigmatism, but not the higher order aberrations. Given the high amount of wavefront aberrations in some of these myopic eyes, it is necessary to develop new techniques to correct these aberrations.

Emmetropic children have significantly higher wavefront aberrations than emmetropic adults. The mean RMS of the two groups remains significantly different even with the second and third orders of Zernike aberrations removed. Assuming that the two groups have representative values, the more highly aberrated eyes found among emmetropic children are either corrected naturally with age or shift into the myopic category so as to be absent among emmetropic adults. The latter explanation seems more plausible and, if valid, would argue that for the human eye to maintain emmetropia the wavefront aberrations that cause retinal image degradation must remain small. Children with strongly aberrated eyes suffer severe image degradation and may fail to maintain the match between the focal and retinal planes, thereby developing myopia. This finding suggests that the causal link between aberrations and myopia is in the direction of aberrations producing myopia. This is consistent with the hypothesis developed in animal models that degrading the retinal image plays a role in causing myopia. However, the fact that the majority of myopes have levels of aberration similar to emmetropes necessarily indicates contributions from other factors in myopia development (Gwiazda & Marran, 2000).

To better understand the hypothesis that wavefront aberrations induce myopia we must look more closely at the retinal image quality of the myopes and at the other factors that promote myopia.

4.2. Retinal image quality

In this study we have used the RMS of the wavefront aberrations at the plane of the pupil as an indication of optical degradation in the eye. This is the index for optical degradation used in most recent studies (Liang et al., 1994; Liang & Williams, 1997; He et al., 1998; He, Burns, et al., 2000). However, wavefront RMS is an indirect indicator of image blur on the retina. We have simulated the retinal image quality of text and natural scenes from subjects with different RMS amplitudes (Thorn, He, & Thorn, 2000; Thorn, He, Thorn, Held, & Gwiazda, 2000). Retinal image degradation increases with increasing RMS values although this relationship is not simple. Using natural scenes and text typical of school books in grades 3 through 10, an RMS value of less than 1.0 has virtually no noticeable effect on the clarity of retinal images even when a large pupil (6.0 mm) is assumed. Blur can be seen in simulated images with 1.0–1.5 μ of wavefront aberrations. For RMS values greater than this, the measured aberrations interfere with legibility and qualitatively alter the appearance of text, creating a combination of ghost images and distortions.

We have assumed a 6 mm pupil diameter which is not unusual in grade school children. With 4 or 5 mm pupils, which are also common in children, the effects of defocus and the aberrations within the eye (including astigmatism) are reduced, but large aberrations (i.e., greater than 2.5 μ) continue to induce visible image degradation.

One might ask how significant is the image degradation that is induced by higher order aberrations compared to that induced by defocus and astigmatism. A 2.5 μ RMS aberration appears to induce image degradation as severe as that induced by 0.75 D of defocus in an eye with an aberration pattern typical of that of adult emmetropes (Thorn, He, & Thorn, 2000; Thorn, He, Thorn, et al., 2000). Even more interesting is the fact that wavefront aberrations in excess of 1.5 μ RMS combine with a small amount of defocus ($\leqslant$ 0.75 D) so as to obscure the defocus signal. In some cases, the retinal image for text is clearest when the eye is out of focus by 0.5 D or more (Bour & Apkarian, 1996; Guirao

& Williams, 2000; Thorn, He, & Thorn, 2000; Thorn, He, Thorn, et al., 2000).

4.3. Myopia development

Wavefront aberration as an underlying optical mechanism in myopia development most likely has both genetic and environmental aspects. Genetic contributions to myopia have long been recognized (Curtin, 1985; Pacella et al., 1999; Zadnik, Satariano, Mutti, Sholtz, & Adams, 1994), but the underlying mechanisms are unclear. Aberrations of the eye caused by defects in the cornea and lens may be inherited. Thus aberrations causing image degradation may be one of the genetic mechanisms leading to myopia. Meanwhile, environmental factors, such as near work, cannot be excluded. Stronger aberrations have been reported for an accommodated eye (He, Burns, et al., 2000). Accommodation induced by near work would expose the eye to stronger image degradation and thus impose a higher risk of developing myopia.

Previous investigations have entertained the possibility that wavefront aberration is caused by myopia (Collins, Wildsoet, & Atchison, 1995; Simonet et al., 1999), but if the elongation of the eye in myopia caused optical deficiencies in the cornea and lens, we would expect all or most myopes to have more aberrations than emmetropes. This is not the case, since the majority of myopes have the same magnitude of aberrations as emmetropes. In addition, the fact that emmetropic children have more aberrations than emmetropic adults argues against this direction of causality, as discussed above. Although it is conceivable that myopia has optical consequences that increase aberrations, we favor the direction of aberrations producing myopia because it is in accord with the known process of myopization produced by blur. Longitudinal studies, presently underway in our laboratory, will help elucidate the role of wavefront aberrations in myopigenesis.

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