Refractive changes associated with oblique viewing and reading in myopes and emmetropes

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The effect of brief periods of monocular oblique viewing on axial refractive error in myopes and emmetropes was studied in 20 normal subjects. Refractive error and higher order aberrations were measured either with the subject's head positioned such that the subject looked straight into an aberrometer with the right eye or the subject's head rotated to the right or left by approximately 30° so that the subject had to make an eye rotation of the same angle to see the aberrometer's fixation target. In the first experiment, 10 measurements of wavefront aberration were taken over a period of 3 min at each head position. The refractive changes with oblique viewing showed high levels of intersubject variability. Some subjects showed evidence of systematic change in refraction with oblique viewing. All subjects showed pupil constriction. In the second experiment, after the initial measurement of central and oblique refraction, subjects were made to binocularly read a text placed at 25 cm for 20 min, and the refraction measurements were repeated. No systematic changes in refraction were noted during oblique viewing after 20 min of reading. The data from Experiment 1 give some support for the view that short-term pressures from structures external to the eye may affect its axial refraction. However, the results from Experiment 2 suggest that any such pressures during short-term reading tasks have no significant impact on the axial refraction.

Keywords: oblique viewing, refractive error, monochromatic aberrations, reading, myopia

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Introduction

There is considerable concern about the rising incidence of myopia in many parts of the world, particularly in the Far East (Logan, Davies, Mallen, & Gilmartin, 2005; Saw, 2003). If the causes of this refractive shift could be better understood, it might be possible to forestall it by taking suitable precautionary measures.

Most workers generally agree that both genetic and environmental factors play a role in the development of myopia. Considerable attention has been focused on the possibility that increased amounts of closework associated with tasks such as reading may precipitate myopia in genetically susceptible individuals (Rosenfield & Gilmartin, 1998). In particular, the need to exercise considerable accommodation to perform close tasks has been suggested as a significant factor, it often being hypothesized that lag of accommodation leads to a blurred retinal image, which acts as a precursor to myopia (Gwiazda, Bauer, Thorn, & Held, 1995; Gwiazda, Thorn, Bauer, & Held, 1993). Others have suggested that accommodation itself may affect both corneal curvature (Yasuda, Yamaguchi, & Ohkoshi, 2003) and ocular shape (Walker & Mutti, 2002). This has led to many trials of the utility of bifocals or varifocals in slowing possible myopia progression, with somewhat ambiguous results (Gwiazda et al., 2004).

Peripheral refractive errors may be yet another factor in the development of myopia. Myopes have been found to have a relatively hyperopic peripheral refraction, and hyperopes have relatively myopic peripheral refractive errors (Millodot, 1981; Mutti, Mitchell, Moeschberger, Jones, & Zadnik, 2002; Seidemann, Schaeffel, Guirao, Lopez-Gil, & Artal, 2002). Hoogerheide, Rempt, and Hoogenboom (1971) have found evidence to suggest that relative hyperopia in the periphery may be a precursor to late-onset myopia in humans, whereas Smith, Kee, Ramamirtham, Qiao-Grider, and Hung (2005) show that form deprivation in peripheral retina can influence the development of foveal refractive error in primates. However, there is no evidence that the peripheral image quality influences axial refraction in chicks (Schippert & Schaeffel, 2006).

One factor that has received rather less attention is the possible impact of structures external to the eyeball on myopia development, although the basic concept goes back at least as far as Donders (1864) and Landolt (1886). Reading differs from many near tasks in that the eyes not only must converge and accommodate but also normally scan from the side under the influence of the extraocular muscles. Following earlier work by Bowman, Smith, and Carney (1978), Buehren, Collins, and Carney (2003, 2005) have recently shown that lid pressure allied to lateral scanning during relatively short periods of reading

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can have a significant impact on corneal shape; they suggested that the additional aberrations generated may have a role in myopia development. It is plausible that the pressure of the extraocular muscles and lid forces in some directions of gaze may also affect the shape of the globe and, if repeated often enough in susceptible individuals, might lead to the permanent globe lengthening seen in myopia. Such lengthening might result not only directly from the action of the muscles on the globe but also indirectly through the intermediary of raised intraocular pressure (see Duke-Elder & Abrams, 1970; Goss & Rosenfield, 1998, for general reviews of the area and of the possible role of vergence in relation to myopia).

There is at least some evidence to support the hypothesis of a role for the extraocular muscles. Ferree and Rand (1932) observed differences in the pattern of peripheral refraction that depended on whether the latter was rotated with respect to the fixed refraction equipment or was rotated about a fixed eye. When the instrument remained stationary and the eye was rotated to view the sequence of the fixation targets, they found that if oblique fixation was held for any appreciable length of time, the refraction shifted in the myopic direction. They state on page 259 that "with prolonged fixation this change amounted to as much as 2.5 D". The phenomenon persisted even with eyes under cycloplegia, and they suggest the possibility "that as the fixation is prolonged the muscles of the eye gradually produce an elongation of the eyeball". More recently, Seidemann et al. (2002) found in three subjects a mean difference of about 0.70 D in spherical refraction when the eye was rotated through 40°, the shift again being in the myopic direction.

A second strand of evidence comes from the work of Simensen and Thorud (1994) on textile workers whose task was to inspect and repair weaving errors in a slowly moving textile, with the area viewed being about 1 m^2. Although the accommodation demands were modest (less than 2 D), over a period of years, nearly all of these adult workers experienced myopic shifts (of about 3 D) associated with increases in axial length, with these changes possibly being associated with the eye movements required to scan the area of moving fabric (see also Goldschmidt, 2003).

Lastly McCollim (2004) records a single case where vigorous exercise of the superior obliques led to a marked increase in existing myopia and an apparent long-standing change in ocular aberrations.

There are a number of studies on the incidence of myopia in situations where both vigorous accommodation and convergence are required. For example, Zylbermann, Landau, and Berson (1993) found that male teenagers in Jewish orthodox schools who studied religious texts having type sizes as small as 1 mm for up to 16 hours a day and swayed back and forth during study so that the working distances changed regularly showed a much higher prevalence of myopia than did female students in religious schools or students of either gender in general schools from a similar racial and family background, none of whom engaged in such strenuous study. The students in general schools were taught with similar methods as those used in Western schools, and girls in orthodox schools learnt adapted texts and general subjects taught in Western schools, with both groups being involved in near tasks for up to 9 hr at the maximum.

Clearly, there are many different possibilities that might link the action of the extraocular muscles with changes in refraction. The aim of this study was to determine whether any refractive change could be detected as a result of relatively brief periods of monocular, oblique viewing.

Experiment 1

Methods

The study was conducted on 20 normal young-adult subjects composed of 10 myopes and 10 nonmyopes. The mean ± *SD* age of the emmetropic group was 23.9 ± 5.2 years, and that of the myopic group was 23.5 ± 6.0 years. The myopic subjects had a subjectively determined spherical equivalent refractive error ranging between −1.25 and −7.75 D (mean = −3.44 ± 2.27 D), and the refractive error in the emmetropic subjects ranged between plano and +0.67 D (mean = +0.10 ± 0.22 D); no subject had astigmatism greater than 1.25 D. All subjects included in the study had a best-corrected visual acuity of 6/5 or better in both eyes and normal subjective amplitudes of accommodation for their age. Subjects were screened to exclude those with binocular vision anomalies, myopic retinal degeneration, or any other ocular disease. The Tenets of the Declaration of Helsinki were followed. Informed consent was obtained from every subject after verbal and written explanation of the nature and possible consequences of the study.

A Hartmann-Shack aberrometer (IRX3, Imagine Eyes, Paris) was used to measure axial refraction and higher order aberrations. Measurements were obtained from the right eye of each subject while the left eye was occluded. Either the subject's head position was arranged so that the subject looked straight in to the aberrometer with the right eye to observe the internal fixation target (a high-contrast 6/12 Snellen "E" with a background luminance of 85 cd/m^2) or the subject's head was rotated to the right or the left by approximately 30° so that the eye had to either adduct or abduct by approximately 30° to see the fixation target. This is a larger angle of eye turn than would normally be maintained during typical visual tasks, but it was chosen to maximize the chance of changes in refraction being detected. All measurements were taken in the automatic refraction mode, where the instrument moved the target to the far point of the eye during the measurement process. No cycloplegic or mydriatic was used, and no correction was worn.

The observing sequence was initiated with 3 min of recording with the eye straight ahead; a Hartmann-Shack image was recorded every 20 s. One minute was then allowed for readjusting the head position with a right head turn and realigning the eye for leftward (nasalward) gaze, and a further 3 min of observations were made. A further minute was allowed for the resumption of straight-ahead viewing, and then recordings were made for a further 3 min. Measurements were then made for 3 min with the head turned approximately 30° to the left and the eye in rightward (temporalward) gaze to see the fixation target, with 1 min being allowed for realignment. Finally, after the rightward gaze measurements, 1 min was allowed for the resumption of straight-ahead viewing, and recordings were

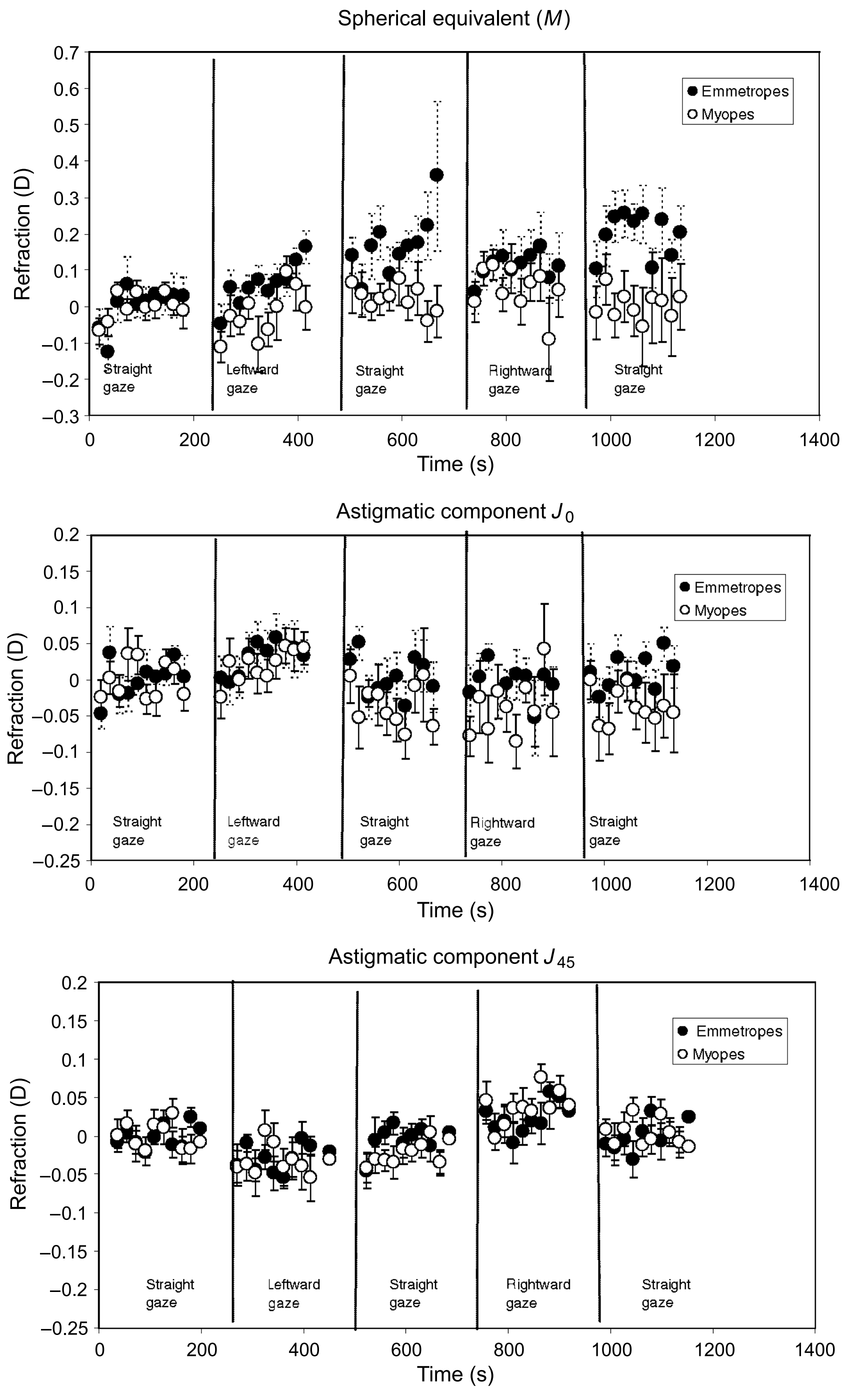

Figure 1. Changes in the mean values across subjects of the refractive components *M*, J_0, and J_{45} for the two refractive groups in comparison with the corresponding baseline values (i.e., the corresponding overall mean values found in the initial 3-min straight-ahead session) as a function of time in the experimental session. The error bars represent ±1 *SEM*.

made for another 3 min with the eye fixating the internal target in the straight-ahead position.

Refractions derived with the manufacturer's software from the wavefront aberration were expressed in terms of their M, J_0, and J_{45} vector components (Atchison, 2004; Thibos, Wheeler, & Horner, 1997). Analyses of refractive error and all ocular aberrations were performed for a constant pupil diameter (3.5 mm) corresponding to the smallest pupil diameter of any subject.

Results

Figure 1 and Table 1 show the mean changes in the refractive power vectors with time from their baseline values during the various periods of straight and oblique viewing in myopes and emmetropes. For each subject, the mean value of the recordings made during the initial 3-min period of straight-ahead viewing was considered as the baseline value for each refractive component.

Figure 1 and Table 1 suggest the possibility of continuing small changes in mean refraction over each 3-min period of different gaze directions. The mean sphere in the emmetropic group appears to change during the straight-ahead gaze after each monocular viewing condition. In both the refractive groups, the variability in the data increased toward the end of the measurement period. This was perhaps due to fatigue effects resulting from maintaining fixation for a prolonged amount of time. It is evident from Figure 1 and Table 1 that the overall mean changes in axial refraction with short durations of oblique viewing in both the myopic and emmetropic groups are only of the order of 0.10 D and that, hence, individually, they would appear to be of little clinical significance.

As illustrations of the behavior of individual myopes, Figure 2 shows the refractive shifts over time with oblique viewing in two subjects with initial spherical errors of approximately −2.00 D (Subject A) and −4.00 D (Subject B). Subject A showed no marked change in mean spherical refraction, M, and astigmatic components over time and observing condition. Subject B, on the other hand, showed a myopic shift in M during rightward gaze and in straight-ahead gaze after the rightward gaze. The astigmatic components do not show any marked changes during the viewing sequence.

Repeated measures analysis of variance (ANOVA) was carried out to compare the change in each refractive component with oblique viewing. A significant difference was found between the spherical equivalent (M) of axial refractive error measured in central gaze (an average of the 10 readings obtained in the initial 3 min) and oblique gazes of 30°, $F(4, 19) = 3.15$, $p = .019$. Post hoc tests showed a significant difference in spherical equivalent refractive error between the initial straight-ahead gaze and the rightward (temporalward) gaze of 30° (Bonferroni comparison: $p = .02$). No significant difference was found between the spherical equivalent refractive error in the leftward (nasalward) gaze and the central gaze. The refractive group of the subject obviously had a significant effect on refractive error measurements in the central and oblique gazes, $F(4, 19) = 18.38$, $p = .0005$, but there was no significant interaction between the refractive group and the changes in refraction in oblique gazes, $F(4, 19) = 1.91$, $p = .118$. The axial astigmatic component, J_0, $F(4, 19) = 2.0$, $p = .103$, showed no significant change on oblique viewing, but the J_{45} component changed significantly, $F(4, 19) = 7.68$, $p = .005$ (repeated measures ANOVA). Post hoc analysis (Bonferroni comparison) showed that the J_{45} component was significantly different from the straight-ahead gaze only during the rightward gaze ($p = .001$).

The changes with respect to baseline in the mean spherical error, M, over each 3-min session for all individual subjects are illustrated in Figure 3. Figure 3a shows the spherical equivalent refractive error in the rightward and leftward gazes for each subject plotted as a function of the corresponding baseline refractive error in the initial session of straight-ahead gaze (Session 1). Most subjects showed a gradual drift in the hyperopic direction during the 3 min of oblique viewing. One myopic subject

	Straight-ahead gaze		Leftward gaze		Straight-ahead gaze		Rightward gaze		Straight-ahead gaze	
	M	*SEM*	*M*	*SEM*	*M*	*SEM*	*M*	*SEM*	*M*	*SEM*
Emmetropes										
Spherical equivalent, M_0	0	0.017	0.061	0.019	0.171	0.026	0.111	0.011	0.198	0.019
Astigmatic component, J_0	0	0.008	0.031	0.007	0.004	0.009	−0.005	0.007	0.009	0.007
Astigmatic component, J_{45}	0	0.005	−0.029	0.006	−0.007	0.006	0.023	0.006	−0.001	0.006
Myopes										
Spherical equivalent, M_0	0	0.011	−0.019	0.021	0.023	0.011	0.049	0.019	0.003	0.012
Astigmatic component, J_0	0	0.008	0.020	0.007	−0.033	0.009	−0.037	0.012	−0.037	0.008
Astigmatic component, J_{45}	0	0.005	−0.032	0.006	−0.022	0.005	0.037	0.007	0.003	0.005

Table 1. Mean change in refractive error components in the two refractive groups.

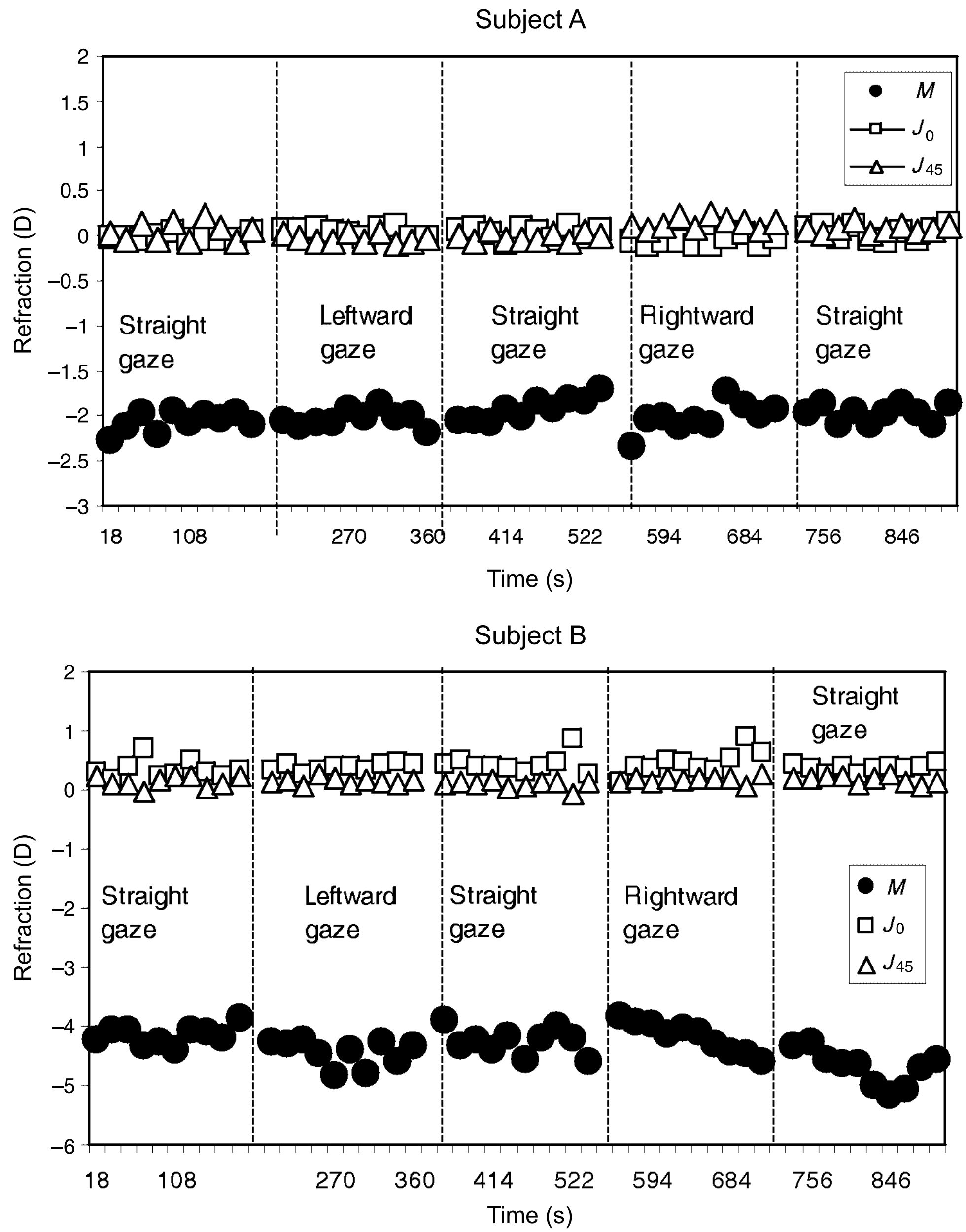

Figure 2. Changes in the refractive components *M*, J_0, and J_{45} with time for two myopic subjects during straight-ahead and oblique gazes.

showed a myopic shift of approximately 1.0 D during rightward gaze.

The mean value of the spherical equivalent refractive error on resumption of straight-ahead gaze after the oblique gazes is shown in Figure 3b as a function of the initial spherical equivalent refractive error in straight-ahead gaze. After both rightward and leftward gazes, the spherical equivalent refractive error with straight-ahead gaze shifted considerably in the myopic direction in one subject. Most of the other subjects showed only moderate shifts in refractive error.

The changes in root-mean-square (RMS) error of total (third to seventh) higher order monochromatic aberrations, third-order vertical and horizontal coma, and fourth-order spherical aberration for a 3.5-mm pupil over the observing sequence in myopes and emmetropes are shown in Figure 4, with change being determined in comparison with the mean baseline value over the initial 3-min straight-ahead recording period. The means over each 3-min observing session of the total RMS monochromatic aberrations (third to seventh order), third-order vertical coma, and fourth-order spherical aberration showed no significant differences between the central and oblique viewing conditions ($p > .05$). No significant interaction was found between refractive group and RMS error of mean monochromatic aberrations in the central and oblique gazes with repeated measures ANOVA, $F(1, 199) = 1.0$, $p = .387$.

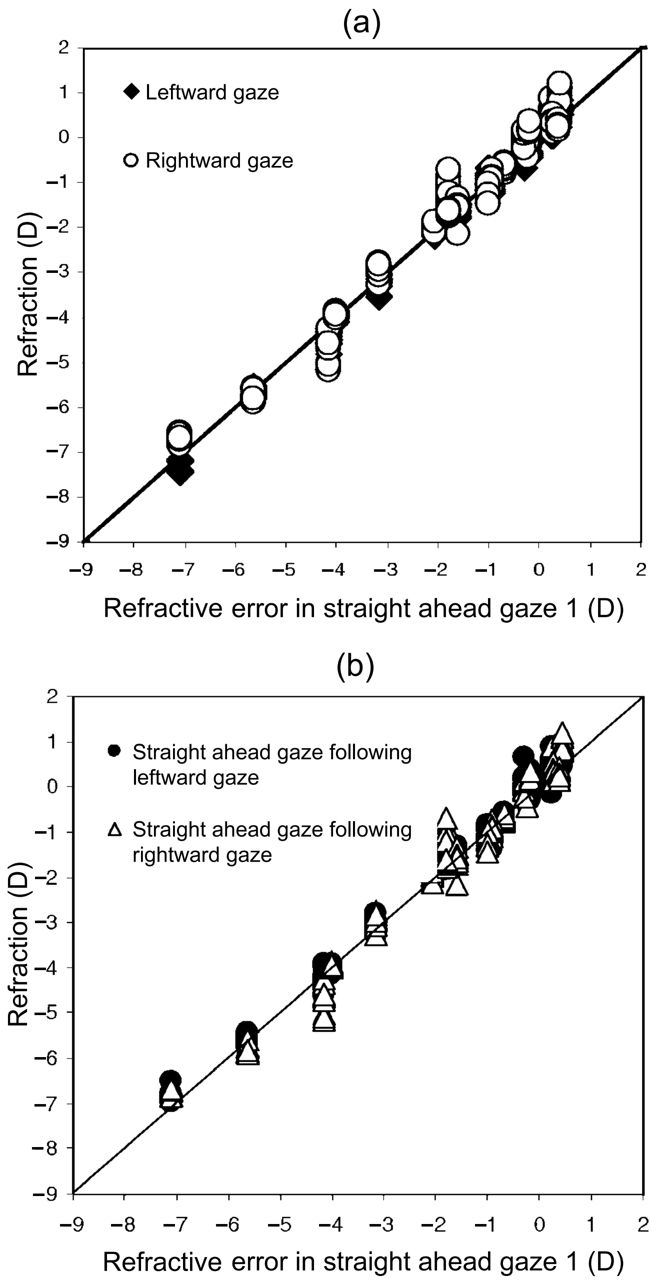

Figure 3. Spherical equivalent refractive error for each subject in (a) rightward and leftward gazes and (b) on resumption of straight-ahead gaze immediately after the oblique gaze as a function of the refractive error in the initial straight-ahead gaze.

The pupil size of the subjects was found to change systematically with oblique viewing. Figure 5 shows the pupil size measurements in myopes and emmetropes with oblique viewing. The pupil was found to constrict considerably during oblique viewing, and the constriction was found to be higher in the leftward gaze compared with the rightward gaze. Repeated measures ANOVA showed that pupil size changed significantly with oblique gazes, $F(4, 19) = 4.098$, $p = .005$. Post hoc test (Bonferroni comparison) showed that pupil size in the rightward and leftward gazes was significantly different from that in the straight-ahead gazes ($p < .05$). No significant difference was found in pupil size measurements between the three straight-ahead gazes ($p > .05$). No significant interaction was found between refractive group and pupil size changes with oblique viewing, $F(4, 19) = 1.23$, $p = .305$.

Because in some subjects, systematic changes in axial refractive error were found over periods of only a few minutes of relatively extreme oblique viewing, and some oblique viewing must occur as the eyes scan a page during reading, a further experiment was conducted to study the effect of somewhat longer periods of reading on axial refraction measured during direct and oblique gazes.

Experiment 2

Methods

Ten normal subjects (4 emmetropes and 6 myopes) took part in the study. The mean ± *SD* age of the subjects was 22.3 ± 3.6 years. The myopic subjects had a spherical equivalent refractive error ranging between −1.25 and −7.75 D (mean = −3.25 ± 2.33 D), and the refractive error of the emmetropic subjects ranged between plano and +0.67 D (mean = +0.14 ± 0.35 D). All subjects had a best-corrected visual acuity of 6/5 or better. Subjects were screened to exclude those with astigmatism greater than 1.25 D, myopic retinal degeneration, or any other ocular disease. The Tenets of the Declaration of Helsinki were followed. Informed consent was obtained from every subject after verbal and written explanation of the nature and possible consequences of the study.

A Hartmann-Shack aberrometer (IRX3, Imagine Eyes, Paris) was again used to measure axial refraction and higher order aberrations. The technique used for measuring axial refraction during oblique viewing conditions was similar to that used in Experiment 1, except that less readings were taken to minimize subject fatigue. All measurements were obtained from the subject's right eye while the left eye was occluded. The initial observing sequence was three recordings of refraction at 20-s intervals with the eye straight ahead, following which the head position was readjusted and the eye realigned to make an approximately 30° leftward turn to fixate at the target in the Hartmann-Shack; three readings were taken in this gaze position. The head was then turned toward the left by approximately 30°, and subjects made a rightward gaze to fixate at the test target; three measurements were then made in this rightward gaze. Refractions were again calculated for a fixed pupil size of 3.5 mm and expressed in terms of their M, J_0, and J_{45} vector components (Atchison, 2004; Thibos et al., 1997).

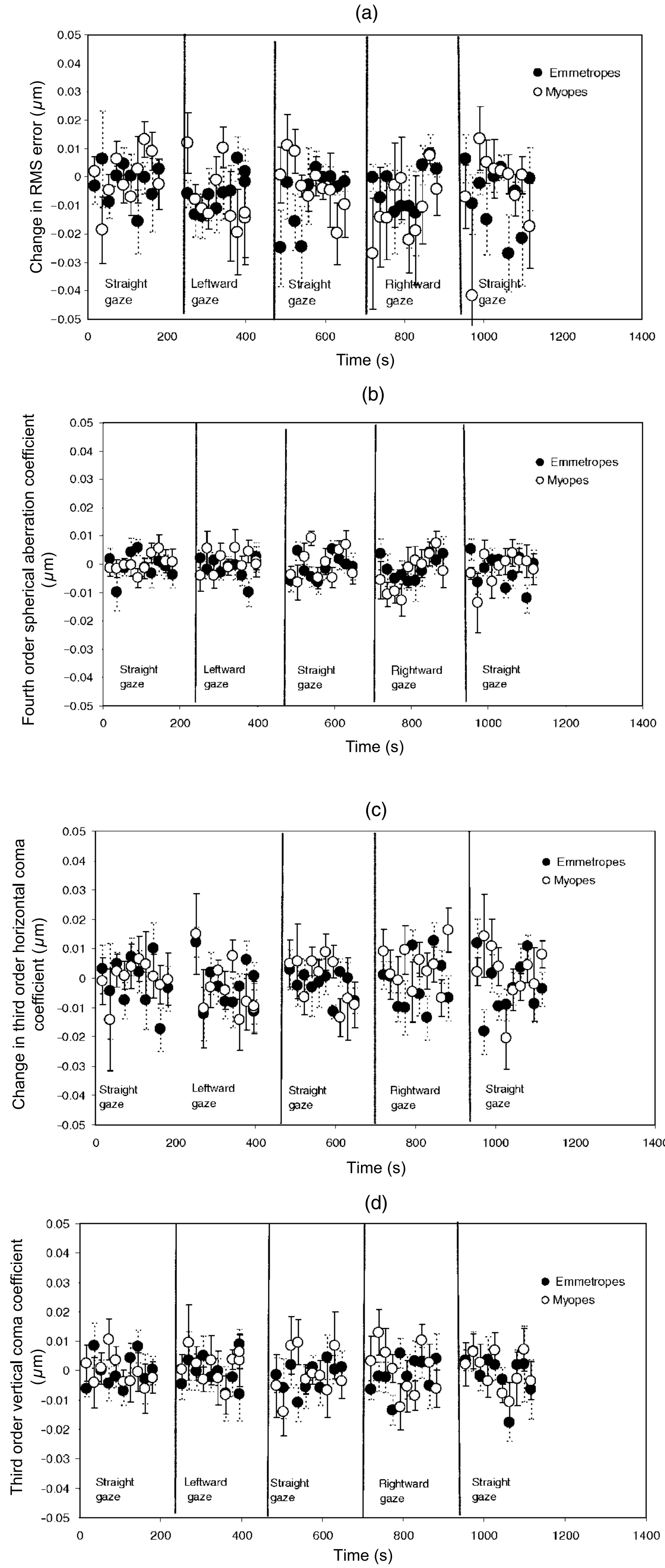

Figure 4. Changes with time in the differences between the mean values of (a) the total RMS wavefront error, (b) fourth-order spherical aberration, (c) horizontal coma, and (d) vertical coma for the two refractive groups and the baseline values (i.e., the corresponding overall mean values found in the initial 3-min straight-ahead session). The error bars represent ±1 *SEM,* and the pupil diameter is 3.5 mm.

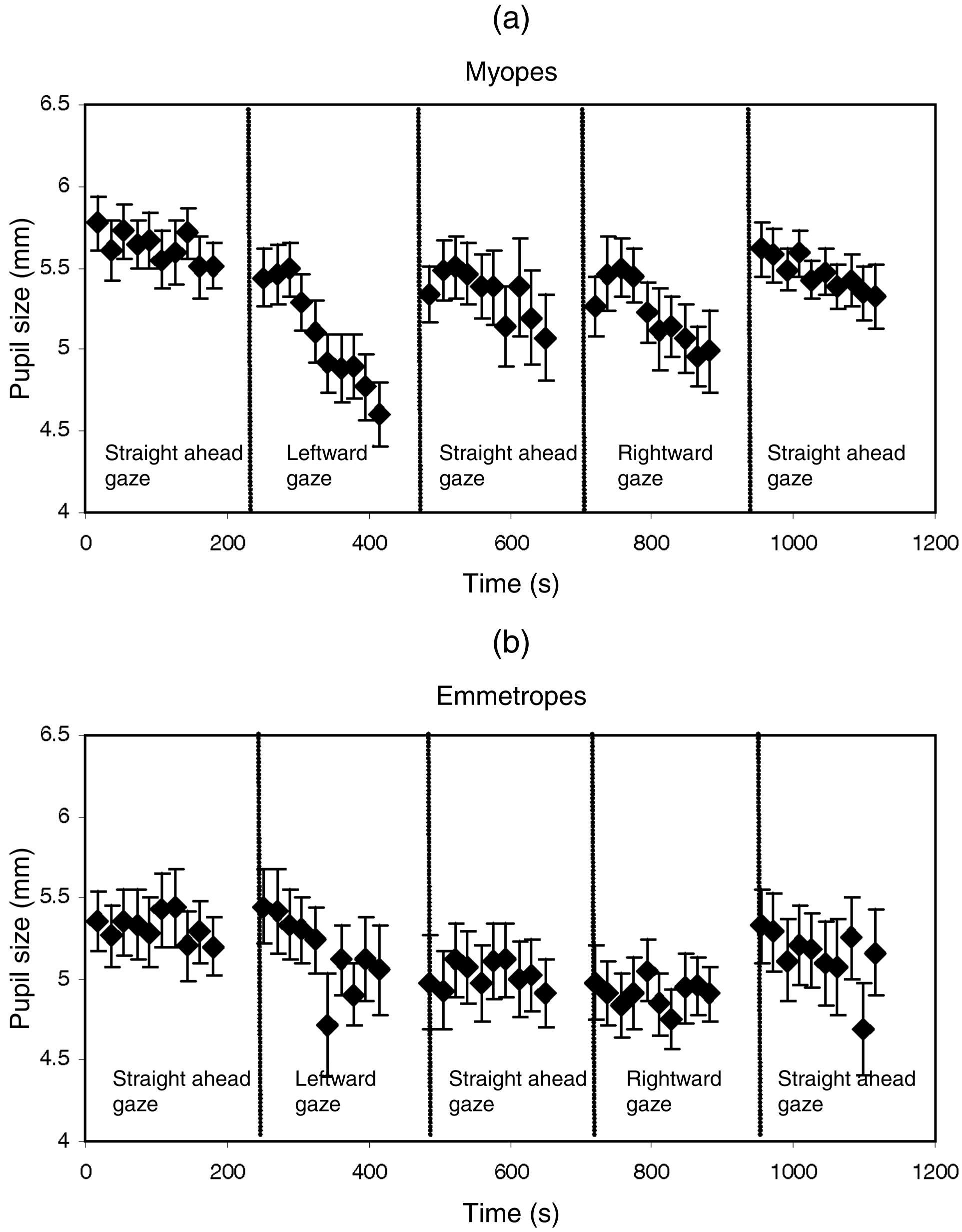

Figure 5. Changes in the mean values of pupil diameter across subjects for the two refractive groups as a function of time in the experimental session. The error bars represent ±1 *SEM*.

The occluder over the left eye was then removed, and subjects were given their normal binocular distance corrections to wear. They were asked to read binocularly a text printed in 10-point size and placed at a distance of 25 cm (vergence = −4.0 D) from the eye. The 10-point letters then subtended 0.45° (27 min) at the eye. The text on the page subtended an angle of 27.8° on either side of the visual axis. The head position was fixed with respect to the page with the help of a chin rest in a modified Sheedy-Disparometer-type setup. The subjects were given a small choice of texts from which they selected one to read. The text consisted of a note on the procedure for performing the cover test, an essay on the art of writing by Robert Louis Stevenson, or an extract from *Adventures of Sherlock Holmes*. After 20 min of uninterrupted reading, refractive error measurements were repeated in the same sequence as described above, with the aim of determining whether the convergence, accommodation, and eye movements associated with reading had any impact on axial refraction.

Results

The mean spherical equivalent axial refractions in the rightward and leftward gazes before and after 20 min

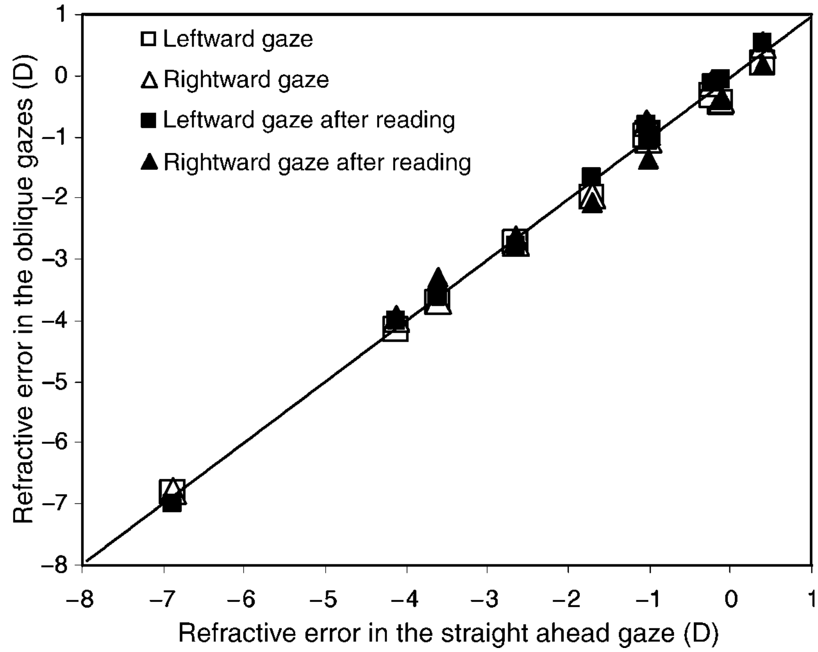

Figure 6. Spherical equivalent refractive error in the rightward and leftward gazes before and after 20 min of reading as a function of initial refractive error in the straight-ahead gaze.

of reading as a function of the refractive error in the initial straight-ahead gaze measurements are shown in Figure 6. The axial refraction measured in the leftward and rightward gazes appears to be similar to that measured in the straight-ahead gaze when only three measurements are taken with the measurement process lasting approximately 60 s. Repeated measures ANOVA showed no significant difference between the straight-ahead and oblique gazes when comparing the spherical equivalent refractive error, $F(4, 29) = 0.54$, $p = .71$, J_0 astigmatic component, $F(4, 29) = 0.84$, $p = .506$, and the J_{45} component, $F(4, 29) = 1.52$, $p = .208$. No significant interaction was found between refractive group and the difference in refractive error between straight-ahead and oblique gazes for all three components of refraction ($p > .05$).

Table 2 shows the mean change in spherical equivalent and astigmatic components of refractive error in the straight-ahead and oblique gazes obtained by subtracting refractive error measured at baseline from that measured after 20 min of reading. The baseline values of the power vectors correspond to those found in the initial prereading measurements in that direction of gaze. The 95% limits of agreement of the measurements obtained before and after the reading task in the straight-ahead gaze were the following: spherical equivalent (M) = +0.21 to −0.32 D; J_0 astigmatic component = +0.14 to −0.12 D; and J_{45} astigmatic component = +0.12 to −0.12 D. It can be noted that the mean difference for all the refractive components is found to be very close to 0, indicating the lack of any significant refractive shift after the reading task.

Repeated measures ANOVA showed no significant change in spherical equivalent refractive error measured before and after 20 min of reading, $F(1, 29) = 2.989$, $p = .094$. The astigmatic components J_0, $F(1, 29) = 0.004$, $p = .984$, and J_{45}, $F(1, 29) = 0.09$, $p = .76$, also showed no significant change (repeated measures ANOVA). The refractive group of the subject and gaze direction showed no significant interaction with the change in refractive error after reading ($p > .05$).

The higher order aberrations for a 3.5-mm pupil were found to be similar before and after 20 min of reading in

	Straight-ahead gaze		Leftward gaze		Rightward gaze	
	M	*SEM*	*M*	*SEM*	*M*	*SEM*
Spherical equivalent, M_0	−0.057	0.042	−0.129	0.062	0.010	0.068
Astigmatic component, J_0	0.007	0.021	0.027	0.020	−0.037	0.040
Astigmatic component, J_{45}	0.004	0.019	0.011	0.013	−0.024	0.017

Table 2. Mean change in refractive error components after 20 min of reading.

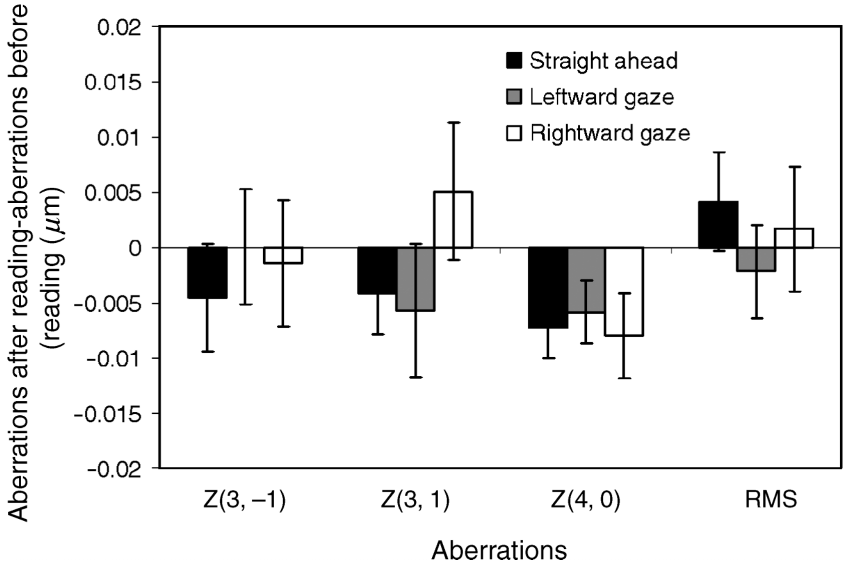

Figure 7. Mean change in the ocular aberration components for a 3.5-mm pupil in each gaze position after 20 min of reading. The error bars represent ±1 *SEM*.

all three positions of gaze. Figure 7 shows the change in third-order vertical and horizontal coma, fourth-order spherical aberration, and higher order RMS error (third to seventh order) after 20 min of reading. Repeated measures ANOVA showed no significant change in any of the higher order aberrations or the RMS error after 20 min of reading ($p > .05$). No significant interaction was found between gaze direction and change in aberrations after a short period of reading.

Discussion

This study evaluates the effects of brief periods of oblique viewing on axial refractive error. In interpreting the data, it must be remembered that, for the range of refractive errors of the subjects included in the study, repeated measurements of the axial values of M, J_0, and J_{45} with Hartmann-Shack aberrometers under constant observing conditions typically exhibit a reliability of about 0.12, 0.10, and 0.10 D, respectively (Cheng, Himebaugh, Kollbaum, Thibos, & Bradley, 2003). This sets a limit to the changes that can be detected as observing conditions are altered. Although the fogging technique used in the aberrometer is supposed to relax the accommodation of the eye, the possibility that accommodation changes might occur with the young noncyclopleged subjects who participated in the study must also be borne in mind.

The results of Experiment 1 support the view that, on average, shifts in axial refraction with short-term changes in gaze direction are small (around 0.1 D; see Figure 1 and Table 1). Most of the individual emmetropic subjects showed no clinically significant change in axial refractive error during oblique viewing. However, half of the myopic subjects showed larger shifts, ranging up to 1 D in the hyperopic direction during the oblique gaze (Figures 2 and 3). This is similar in magnitude, but opposite in direction, to that found by earlier studies (Ferree & Rand, 1932; Seidemann et al., 2002). However, it is important to note that the previous studies showed a myopic shift when peripheral refraction was measured after short periods of oblique viewing, and this study investigated the effect of oblique viewing on axial refractive error. Only 2 of the 20 subjects included in this study showed a myopic shift (of more than 0.50 D) in refractive error during oblique viewing. Interestingly, all the subjects who exhibited a gradual shift in refraction to the hyperopic direction during oblique gaze also had a history of myopia progression by 0.50 D or more in the last 2 years. All other myopic subjects were found to have stable myopia. Further experiments on a larger subject group are required to determine the relationship between myopia progression and systematic shifts in refraction during oblique viewing.

The overall differences found in this experiment, although statistically significant, were only of the magnitude of 0.12 D or less, and these changes are unlikely to be of any clinical significance. However, the appearance of these changes over a relatively short period of oblique viewing does suggest that, if the subjects were to perform oblique viewing tasks for a prolonged amount of time, the cumulative hyperopic or, indeed, myopic shifts occurring with oblique viewing might reach clinical significance and lead to growth signals being generated that could promote axial refractive development. These refractive shifts may be able to explain the process of myopia development noted in textile workers in some previous studies (Simensen & Thorud, 1994). Under most practical situations, it is unlikely that people will maintain peripheral fixation for prolonged periods. Because in Experiment 1, any axial refractive shifts were evident only after 1.5–2 min of continuous oblique viewing, most individuals undertaking near tasks such as reading, which do not require prolonged, extreme, oblique fixation, are unlikely to experience refractive shifts.

The pupil size of the subjects constricted considerably during oblique viewing (Figure 5). Because most subjects have positive spherical aberration, constriction in the pupil would further increase the hyperopic change in refractive error. The data analysis in this study was performed for a fixed pupil size of 3.5 mm and hence does not include the additional changes in refraction that the change in pupil size is likely to introduce. The analysis of refractive error over a smaller pupil diameter than the physiological pupil size is likely to have underestimated the changes in image quality that an individual might experience during oblique viewing. Restricting the pupil diameter to 3.5 mm during data analysis (the minimum diameter for any subject) inevitably reduced the aberration coefficients to low magnitudes because the eye is then approaching diffraction-limited performance. This made it less likely that changes in aberrations with gaze direction would be detected.

The systematic contraction of the pupil on oblique viewing indicates the stress experienced by the subjects in maintaining oblique gaze for a considerable amount of time. Gianelli (1907) suggested that the mechanical pressures exerted by the eye during lateral movement lead to pulling of the ciliary nerves. This in turn leads to a change in pupil size during oblique viewing. However, Loewenfeld (1993) found that 10 s of oblique viewing had no significant effect on pupil-size measurements. The measurements in this study were conducted at intervals of 18 s, and Figure 5 shows a systematic increase in pupil contraction with time during the oblique gazes. Loewenfeld did not specify the angle of oblique gaze employed in her study; hence, it is difficult to compare her results with those of this study, where the angle of oblique gaze was kept constant at 30°.

To investigate the effect of slightly longer periods of oblique viewing (10 min) on axial refractive error, Experiment 1 was repeated on two subjects (one showed a significant change in refraction with oblique viewing in Experiment 1 and one did not). Measurements were obtained with 10 min of viewing straight ahead, followed by 10 min of leftward gaze, 10 min of straight-ahead gaze, and 10 min of rightward gaze. The results are shown in Figure 8. Subject C (Figure 8a) showed significant changes in spherical equivalent axial refractive error on oblique viewing and minimal changes in astigmatic components, whereas Subject D (Figure 8b) showed minimal changes in M but some small changes in the astigmatic components during leftward gaze.

To investigate whether the refractive changes observed during oblique gazes originated from changes in accommodation, Experiment 1 was repeated on two subjects (the same as those included in the above control experiment) under cycloplegia. Tropicamide 1% was instilled in the right eye of the subjects, and measurements were obtained 30 min after the instillation of the drug. The refractive error measurements under the effect of cycloplegia are shown in Figure 9. Subject C (Figure 9a) still showed systematic changes in axial refractive error during oblique viewing even under cycloplegia, which indicates that the refractive changes observed in Experiment 1 are unlikely to be solely due to accommodative changes.

In Experiment 1 (Figure 3), the changes in spherical equivalent refractive error were statistically significant in the rightward (temporalward) gaze, and the changes in refractive error in the leftward gaze were not significant. This is perhaps due to the action of the lateral rectus muscle on the globe, as it has the maximum/primary action in abducting the eye. The presence of these changes in myopes is in line with the theory that suggests that as the myopic eyes elongate axially, in some individuals, the extraocular muscles might be exerting an increasing pulling effect during oblique viewing. The increased pulling effect is likely to be produced by the longer course that the muscles are stretched to take around the globe between their insertion and the annulus of Zinn (Fuchs, 1884). When the muscles contract during oblique gaze, hyperopic refractive shifts might be induced in susceptible individuals whose sclera is perhaps not as rigid as in other individuals. On the other hand, the refractive error does not appear to change significantly in the leftward (nasalward) gaze. This suggests that the action of the medial rectus has less effect on the refractive error. The reason for this difference in the refractive changes caused during the action of the lateral rectus and medial rectus remains unclear. Also, the level of extraocular muscle exertion might be different in the monocular viewing condition compared with the binocular viewing condition.

In Experiment 2, 20 min of reading at a distance of 25 cm appeared to have little effect on axial refraction. This is, perhaps, not surprising because, using a much more stressful near task lasting 2 hr at a distance of 20 cm, Ehrlich (1987) found a transient myopic shift of only about 0.3 D. Although the reading task involved accommodation and eye turn, and even if it is assumed that fixations were made right to the edge of the text at 28° eye turn, a value comparable with that used in Experiment 1, these gaze angles were not sustained. Horizontal scanning is likely to impose less consistent stress on the eyeball than prolonged eye turn in a fixed direction (Experiment 1). Experiment 2 therefore reflects a more realistic situation as seen during everyday life, where near tasks such as reading involve

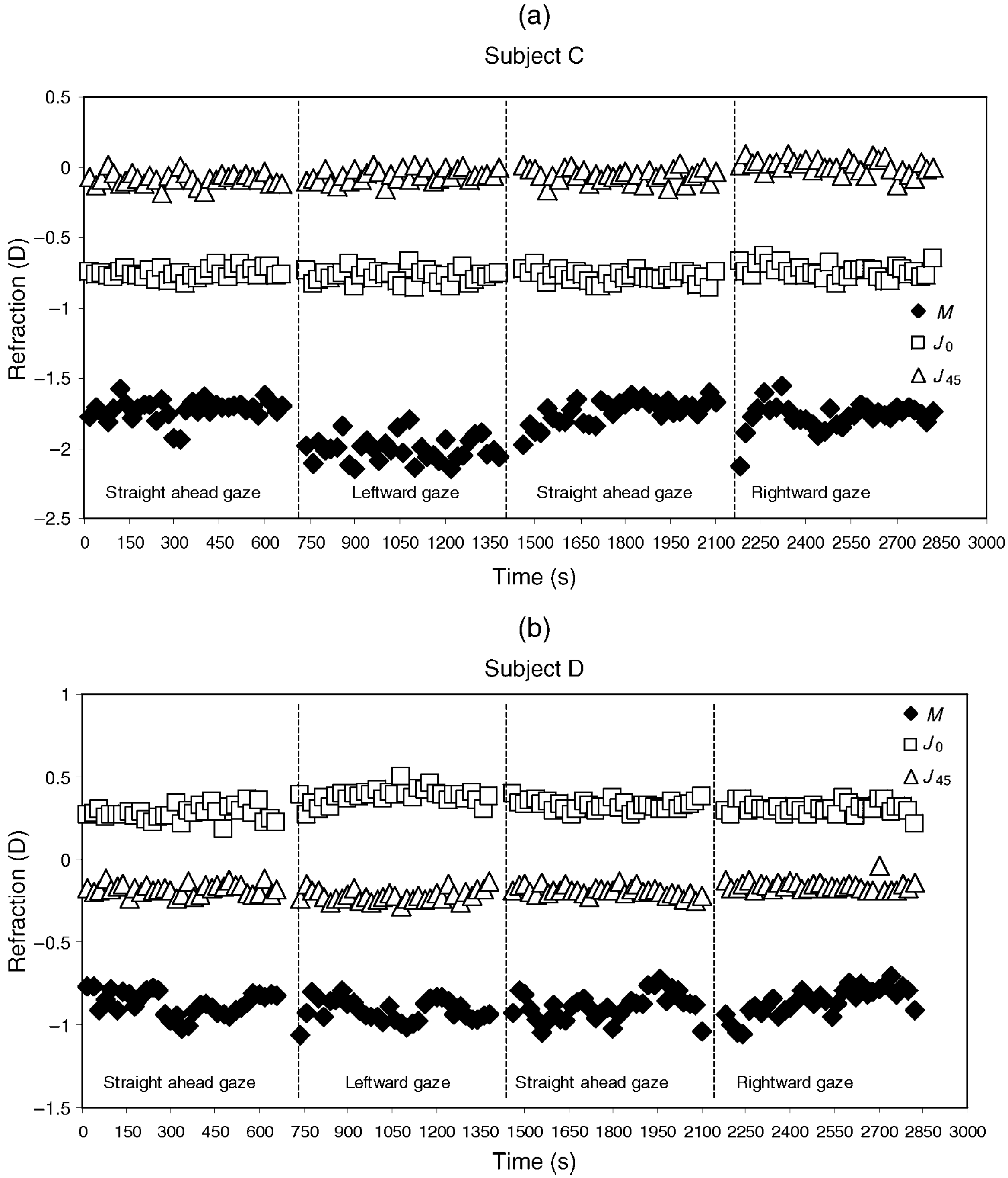

Figure 8. Changes in the refractive components *M*, J_0, and J_{45} with time for two subjects during straight-ahead and oblique gazes.

some oblique fixation, but not for sustained periods. The cumulative stress imposed by the extraocular structures during such tasks (lasting 20 min) does not seem to alter axial refraction.

We were unable to confirm the effect of reading on corneal aberration as found by Buehren et al. (2003) probably because any changes lay outside the boundaries of the 3.5-mm pupil used in our analysis of total ocular aberration. Buehren et al. also used a longer period of reading (1 hr).

The lack of changes in refractive error after 20 min of reading could also indicate that relatively short periods of reading are unlikely to affect refraction during oblique viewing conditions. In Experiment 2, it is important to consider the duration over which the data were collected; only three measurements of refractive error and ocular aberrations were obtained, and the data collection in each position of gaze took no longer than 60 s. The data in Experiment 1 were collected for a period of 3 min at each position of gaze, and the results (Figure 1) show that the

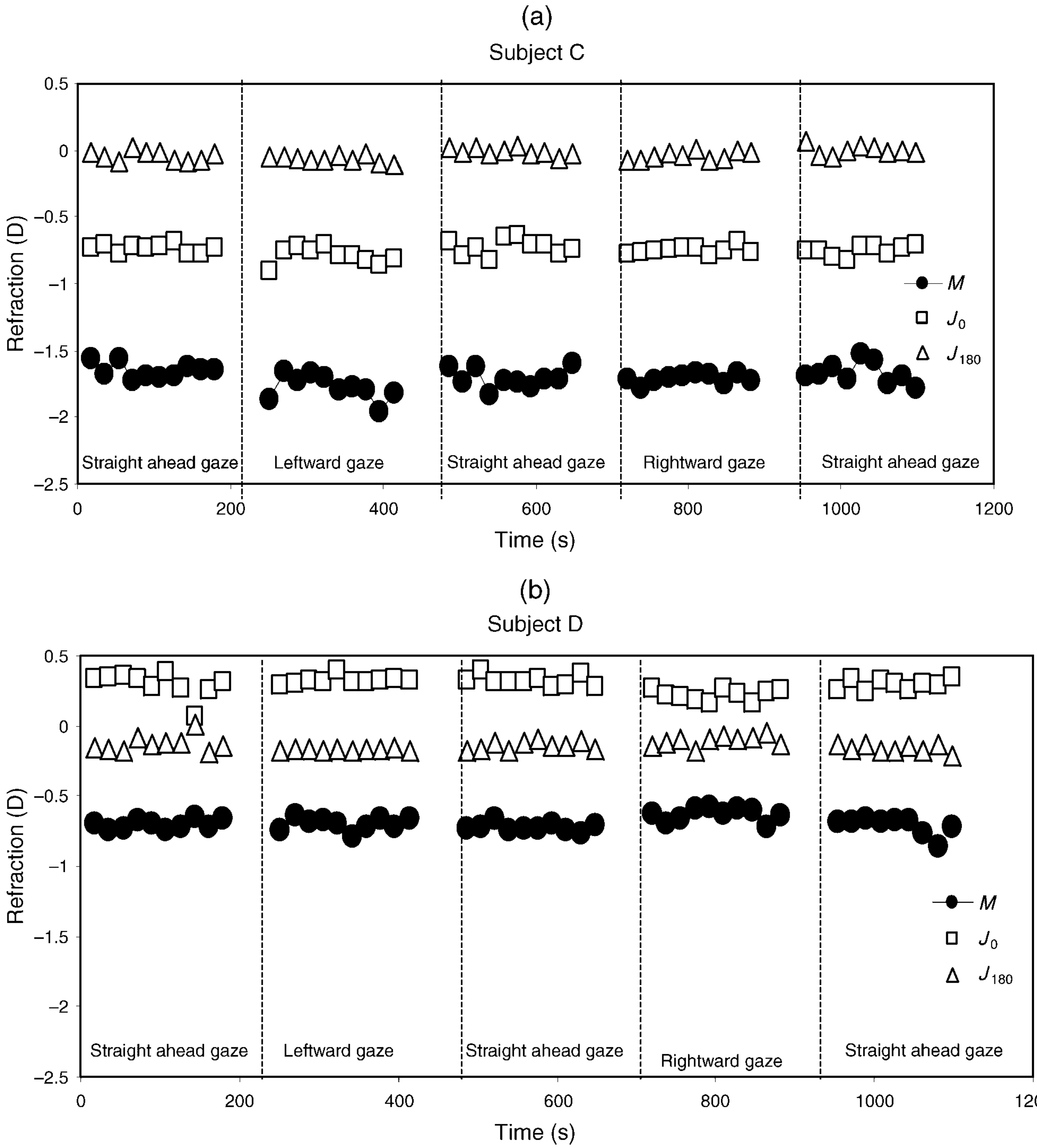

Figure 9. Changes in the refractive components *M*, J_0, and J_{45} with time for two subjects under cycloplegia during straight-ahead and oblique gazes.

changes in refraction started to occur after approximately 1.5–2 min of oblique viewing. This may suggest that the refractive shifts increase with the duration and frequency of oblique viewing.

Overall, we feel that the data support the view that, at least in some individuals, short-term pressures from structures external to the eye may affect its axial refraction if oblique viewing is maintained for a considerable length of time. Whether such effects, if occurring regularly, may contribute to a permanent long-term change in refraction remains to be demonstrated. The pressures exerted by the extraocular structures during short periods of reading appear to have no significant effect on axial refractive error.

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