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Title: **Diurnal variations in ocular aberrations of human eyes**

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ABSTRACT

Purpose: To investigate the diurnal variations in ocular wavefront aberrations over two consecutive days in young adult subjects.

Materials and methods: Measurements of both lower-order (sphero-cylindrical refractive powers) and higher-order (3^{rd} and 4^{th} order aberration terms) ocular aberrations were collected for 30 young adult subjects at ten different times over two consecutive days using a Hartmann-Shack aberrometer. Fifteen subjects were myopic and 15 were emmetropic. Five sets of measurements were collected each day at approximately 3 hourly intervals, with the first measurement taken at ~9 am and the final measurement at ~9 pm.

Results: Spherical equivalent refraction (p = 0.029) and spherical aberration (p = 0.043) were both found to undergo significant diurnal variation over the two measurement days. The spherical equivalent was typically found to be at a maximum (i.e. most hyperopic) at the morning measurement, with a small myopic shift of 0.37 ± 0.15 D observed over the course of the day. The mean spherical aberration of all subjects (0.038 ± 0.048 μm) was found to be positive during the day and gradually became more negative into the evening, with a mean amplitude of change of 0.036 ± 0.02 μm. None of the other considered sphero-cylindrical refractive power components or higher-order aberrations exhibited significant diurnal variation over the two days of the experiment (p>0.05). Except for the lower-order astigmatism at 90/180 deg (p = 0.040), there were no significant differences between myopes and emmetropes in the magnitude and timing of the observed diurnal variations (p>0.05).

Conclusions: Significant diurnal variations in spherical equivalent and spherical aberration were consistently observed over two consecutive days of measurement. Research and clinical applications requiring precise refractive error and wavefront measurements should take these diurnal changes into account when interpreting wavefront data.

Keywords: Diurnal variations; ocular aberrations; spherical equivalent refraction; spherical aberration; myopia.

INTRODUCTION

Wavefront sensors allow comprehensive measurements of the optical quality of the eye that provide the quantification of both lower-order and higher-order ocular monochromatic aberrations.[1] Such measurements of the eye's optical quality are important for a range of research and clinical applications. Measurements of the eye's wavefront optics have improved our understanding of the optical quality of normal eyes,[2] of eyes with refractive errors,[3-6] and of clinical conditions such as dry eye,[7,8] keratoconus,[9,10] cataract,[11] as well as the changes in optical quality associated with corneal refractive surgery,[12-14] contact lenses[15,16], orthokeratology,[17,18] and intraocular lenses.[14]

A range of previous studies have investigated the cross-sectional characteristics,[19-23] and longitudinal changes in optical aberrations for both normal eyes[24] and in eyes following refractive surgery.[12] However, there have been only a limited number of investigations into the natural diurnal variations occurring in the wavefront aberrations in human subjects. Knowledge of such diurnal variations in the eye's optics is important for the reliable interpretation of clinical and research findings, particularly for applications requiring highly precise determination of wavefront aberrations (e.g. wavefront guided refractive surgery and customised refractive corrections), and in the assessment of longitudinal changes in ocular aberrations.

Two previous studies using a Tscherning-type aberrometer,[25] and a Hartmann-Shack aberrometer[26] have reported that diurnal fluctuations in most of the higher-order (third and fourth order Zernike) aberrations are relatively small in magnitude (~ 0.01 – 0.03 µm), and are clinically insignificant. Mierdel et al (2004)[25] only found a statistically significant change in the higher order aberration term, vertical secondary astigmatism (C_4^2) during the day. These previous studies have examined the diurnal changes in ocular aberrations over a single day only, and have not involved measurements extending past 6:00 pm.[25,26] A study by Cheng and associates[24] also reported upon significant temporal variability in Hartmann-Shack derived ocular aberrations, in serial measurements of a small number of subjects collected over seconds, hours, days, months and one year.

It is known that the two major contributors to the overall aberrations in the human eye are the anterior surface of the cornea and the crystalline lens.[27,28] Therefore, the changes in ocular wavefront aberrations could be modulated by optical changes in the cornea, crystalline lens or from a combination of changes in both of these ocular components. Previous studies have reported significant diurnal variations in anterior corneal aberrations,[29] but the presence of significant diurnal change in the eye's internal optics is not known. One additional factor that could potentially influence the dynamics of wavefront aberrations (in particular the defocus term) is the diurnal variation in axial length.[30-32] Alternatively, diurnal variations in ocular optics could potentially influence axial length, given that recent research shows that optical defocus can influence axial length in humans subjects.[33] However, no previous study has examined the potential association between the diurnal changes in eye length and ocular optics of the human eye.

A large body of research work has been carried out over the years to understand the potential role of wavefront aberrations in development of myopia in humans.[3-6,23,34] Although some previous authors have found the magnitude of higher-order aberrations to be greater in myopic eyes compared to emmetropic eyes[4,5] that increased with increasing levels of myopia,[5] others have reported no significant differences in the magnitude of higher-order aberrations between refractive error groups.[20,35,36] A recent study examining a large clinical population noted significant associations between spherical refractive error and certain higher order aberrations such as spherical aberration and horizontal coma.[23] Whether the magnitude and timing of diurnal variations in ocular aberrations differ between myopic and emmetropic subjects however has not been investigated previously. The presence of significant diurnal variations in ocular optics, or differences in the magnitude of these variations associated with refractive error could potentially account for some of the inconsistencies between the findings of previous cross-sectional studies.

In this study, we sought to investigate whether lower-order and higher-order ocular optical aberrations undergo significant diurnal variation in young adult emmetropes and myopes over two consecutive days using a Hartmann-Shack aberrometer. To shed light on the potential mechanisms underlying diurnal variations in ocular optics, we also examined the relationship between variations in ocular optics and the changes in related ocular biometric parameters over the course of the day.

MATERIALS AND METHODS

Subjects and procedures

Thirty young adult subjects (17 myopes, 13 emmetropes) aged between 18 to 30 years (mean age ± standard deviation (SD), 25.16 ± 3.32 years) participated in this study. Seventeen of the subjects were male. Subjects were primarily recruited from the students and staff of our university. All participants were free of any ocular or systemic disease, and had no history of significant ocular trauma or surgery. Before the study, each subject underwent an initial ophthalmic screening to ensure good ocular health, rule out any ocular pathology and to determine their refractive status. Subjects were classified according to their spherical equivalent refraction (SE) as either emmetropes (SE +0.50 to -0.50 D, mean -0.06 ± 0.21 D) or myopes (SE < -0.50 D, mean -3.57 ± 1.70 D). The mean cylindrical refraction across all the subjects ranged from 0.00 to -1.25 D (-0.12 ± 0.24 D and -0.57 ± 0.37 D for the emmetropes and myopes respectively). All of the subjects had normal logMAR visual acuity of 0.00 or better (mean -0.05 ± 0.05). No subject exhibited an intraocular difference (anisometropia) greater than 1.00 D.

As contact lens wear can influence anterior eye parameters such as corneal thickness,[37] three myopic soft contact lens wearers were asked to discontinue contact lens wear for one week before the study and to abstain from lens wear for the duration of the study. No rigid gas permeable (RGP) contact lens wearers were included in the study. Approval from the university human research ethics committee was obtained, and all subjects gave written informed consent. All subjects were treated in accordance with the Declaration of Helsinki.

To investigate the diurnal changes in ocular optics, a series of measurements of ocular wavefront aberrations were obtained over two consecutive days. On each day, 5 measurement sessions were carried out approximately every 2.5 to 3 hours, with the first measurement taken at approximately 9 am and the final measurement at approximately 9 pm. One emmetropic subject was unable to attend session 3 on the first day of measurements. Each session took approximately 10 minutes to complete all the measurements, with subjects undertaking their regular daily activities between the measurement sessions.

The Complete Ophthalmic Analysis System (COAS, AMO Wavefront Sciences) wavefront aberrometer was used to measure the eye's total wavefront aberrations at each session. This instrument uses the Hartmann-Shack principle and has been found to be highly accurate and reliable over a range of lower-order and higher-order ocular aberrations.[38] The wavefront aberrations of the eye were defined in the form of Zernike polynomials[39] and expressed in the OSA double index form.[40]

For each measurement, the fellow (left) eye was occluded, and each subject was instructed to fixate upon the centre of the instrument's internal fixation target. During the measurement, the fixation target is automatically fogged by the instrument in order to control accommodation. Fogging procedures have been shown to assist in the relaxation of accommodation during objective refraction measurements.[41] The wavefront measurements were performed without the use of any eye drops, under natural pupil and accommodation conditions. Given that the quality of tear film could influence the measurement of optical aberrations,[7,42-44] subjects were instructed to blink normally, and the measurements were collected 1 – 2 seconds after the blink to ensure a smooth, stable tear film during the measurement.

Four measurements, each consisting of 25 continuous frames (4×25 frames, multibuffer acquisition) were obtained at each measurement session. The raw wavefront aberration data were fit with Zernike polynomials up to the eighth radial order and exported from the instrument for further analysis. A Matlab-based algorithm was used to detect artifacts (due to factors such as blinking or poor tear film quality) in the Zernike polynomial fit coefficients and then to remove these data before averaging.[45] Although all measurements were collected under natural pupil conditions, the average wavefront was calculated across a fixed 5 mm pupil diameter for each subject at each session using custom written software.

At each measurement session, various ocular biometric parameters [including, central corneal thickness (CCT), anterior chamber depth (ACD), vitreous chamber depth (VCD) and axial length (AL)] were also assessed using the Lenstar LS900 optical biometer.[46,47] The average of seven biometry measures were determined at each session for each subject.[48] The average anterior corneal curvature measurements (i.e. the mean of the steep and flat keratometry values) from the biometer were also recorded (Lenstar LS 900; Haag–Streit AG, Koeniz, Switzerland).[49] The keratometry measurements with the Lenstar have been found to be highly precise,[46] and to correlate closely with manual keratometry, corneal topography and other biometry devices such as the IOL master.[50] Given the evidence of small variations in corneal topography associated with the changes in tear film after blinking,[51,52] subjects were asked to blink immediately before measurements were taken in order to spread a smooth tear film over the cornea.

Data analysis

Studies have shown that optical aberrations up to the fourth order in normal subjects typically exhibit the largest magnitude, and are generally regarded as the major contributors to the total aberrations of the human eye.[21,53,54] Our analysis therefore concentrated upon investigation of diurnal variations in the lower-order (sphero-cylindrical refractive powers) and the 3rd and 4th order aberration terms; along with the higher-order root mean square (derived from the sum of 3rd through to the 8th order aberration terms).

Following data collection, the average of all the Zernike polynomials for each subject at each measurement session was calculated. To provide an estimate of each subject’s lower-order optics, the average wavefront was converted into refractive power,[55] and the best sphero-cylinder was fit to this dioptric power map.[56] The resultant sphero-cylinder was then transformed into power vector components M (the spherical equivalent refraction), J0 (astigmatism at 90°/180°) and J45 (astigmatism at 45°/135°).[57] The amplitude of change (the difference between the maximum and minimum) on days 1 and 2 and the average amplitude were also calculated for each measured Zernike coefficient and power vector.

A repeated measures analysis of variance (ANOVA) with two within-subjects factors (time of day and day of measurement) and one between-subjects factor (refractive error) was performed to investigate for significant diurnal changes in each of the optical aberration parameters and for any significant differences between the refractive error groups. Additionally, to investigate any significant association between the changes in ocular wavefront aberrations and changes in ocular biometry and anterior corneal curvature, an analysis of covariance (ANCOVA) was carried out for the analysis of repeated measures.[58]

RESULTS

Diurnal variation in lower-order optics

Table 1 displays the mean values and diurnal amplitude of change observed in the sphero-cylinder power vectors for emmetropes, myopes and all subjects. Significant diurnal variation was observed in refractive power vector M (spherical equivalent refraction), (repeated measures ANOVA, p = 0.029) (Figure 1). The mean spherical equivalent of all subjects was -2.28 ± 2.21 D, with mean amplitude of change of 0.37 ± 0.15 D (range, 0.70 - 0.12 D) over the measurement period. Power vector M was typically observed to be at a maximum (i.e. most hyperopic) at the morning measurement, with a small myopic shift observed over the course of the day. The mean spherical equivalent was significantly different (p<0.0001) between myopes (-3.79 ± 1.73 D) and emmetropes (-0.31 ± 0.63 D). However, the changes in power vector M did not exhibit a significant time by refractive error interaction (p = 0.430, repeated measures ANOVA), indicating a similar timing and amplitude of diurnal variation in the spherical equivalent refraction in the myopic (mean amplitude 0.30 ± 0.13 D) and emmetropic (mean amplitude 0.46 ± 0.14 D) subjects over the two days of measurement. Repeated measures ANOVA revealed no significant diurnal variation (p>0.05) in power vector J0 (astigmatism at 90/180 degree) or in power vector J45 (astigmatism at 45/135 degree) (Figure 1). Power vector J0 did exhibit a significant time by refractive error interaction (p = 0.040). Pairwise comparisons for J0 revealed that the only significant difference between the myopes and emmetropes occurred between the first and second measurement sessions, where the myopes exhibited a significant increase in J0 (i.e. a small increase in the magnitude of with-the-rule astigmatism) between these two sessions (mean change +0.036 ± *0.034* D, p = 0.009), but the emmetropes did not exhibit a significant change (mean change -0.01 ± 0.035 D, p>0.05). No significant time by refractive error interaction was observed for power vector J45 (p = 0.182). Repeated measures ANOVA revealed a significant effect of measurement day for power vector J0, as the mean power vector J0 on day 2 was 0.01 ± 0.004 D greater than that on day 1 (p = 0.016). Neither of the other sphero-cylindrical power vectors (M and J45) exhibited a significant time by day interaction (p>0.05).

Diurnal variation in higher-order optics

The mean values and amplitude of diurnal variation in the individual 3rd and 4th order aberration terms and the higher order RMS for emmetropes, myopes and all subjects are displayed in Table 2. Spherical aberration (C_4^0) was found to undergo statistically significant diurnal variation on repeated measures ANOVA (p = 0.043) (Figure 2). Spherical aberration was found to be positive during the day (reaching its peak in the late morning/early afternoon) and gradually became more negative towards the later afternoon/evening, with a mean amplitude of change of 0.036 ± 0.02 µm (range, 0.012 - 0.119 µm). Spherical aberration did not exhibit any significant difference in mean amplitude of change between myopic (0.029 ± 0.010 µm) and emmetropic (0.045 ± 0.027 µm) subjects (time by refractive error interaction, p = 0.486). None of the other measured 3rd or 4th order aberration terms exhibited significant diurnal variation over the two days of measurement (p>0.05 for all terms), or a significant time by refractive error interaction (p>0.05 for all terms). Additionally, no significant diurnal variations were found in the higher-order RMS (p = 0.364). The mean amplitude of change in higher-order RMS was 0.076 ± 0.06 µm, which was not significantly different between the two refractive error groups (p = 0.263). Repeated measures ANOVA also revealed that none of the higher-order aberration terms exhibited a significant effect of measurement day or significant time by day interaction (p>0.05).

Corneal curvature

Significant diurnal variations in anterior corneal curvature ($p<0.001$) were observed over the two days of measurement (Figure 3). The cornea was typically observed to be flattest in the morning (session 1, mean time, 09:17) and gradually became steeper throughout the day, with the steepest corneal curvature typically observed in the evening between the third (mean time, 15:20) and fourth measurement session (mean time, 18:15). Repeated-measures ANOVA revealed that the mean corneal curvature (43.41 ± 1.49 D) was not significantly different between the myopic and emmetropic subjects ($p = 0.462$). The mean amplitude of change in corneal curvature 0.24 ± 0.13 D (range, 0.05 – 0.49 D) did not exhibit a significant time-refractive error interaction ($p = 0.278$, repeated-measures ANOVA), indicating similar timing and amplitude of diurnal corneal curvature changes between the refractive error groups.

Association between variables

The diurnal variations observed in the measured ocular biometric variables (i.e. CCT, ACD, VCD and AL) over the two consecutive days have been previously reported in detail.[41] ANCOVA for repeated measures was performed to examine any significant association between the changes in optical aberrations and the other biometric variables measured at each session. A weak negative correlation was found between the changes in power vector M and the anterior corneal curvature, however this did not reach statistical significance (slope = -0.177; $r^2 = 0.01$, $p = 0.10$). Additionally, none of the other measured ocular biometric variables (i.e. CCT, ACD, VCD and AL) showed a significant association with the changes in power vector M or spherical aberration ($p>0.05$).

DISCUSSION

In this study, we have examined the diurnal variation in a range of ocular lower-order and higher-order aberrations over two consecutive days in young adult myopic and emmetropic subjects. Significant diurnal variations were observed in the spherical equivalent refraction (power vector M) and in spherical aberration (C_4^0), whereas the other optical components examined did not exhibit consistent diurnal changes over the two measurement days. The diurnal variations observed in power vector M and C_4^0 also appeared to exhibit similar amplitude across the two consecutive days of testing (M vector, day 1 = 0.37 ± 0.20 D and day 2 = 0.35 ± 0.24 D, and C_4^0 day 1 = 0.037 ± 0.022 µm and day 2 = 0.035 ± 0.025 µm). Although Figures 1 and 2 suggest slight differences in the pattern of diurnal variations in both power vector M and C_4^0 between the two measurements days, no significant time by day interaction was observed in the diurnal variation of these parameters (p>0.05). This is likely due to the relatively high variability between subjects observed in the diurnal change in both parameters at each measurement session (as illustrated by the vertical error bars in Figures 1 and 2). Although the measurement and analysis protocol was designed to reduce the influence of tear film changes on the results, changes in wavefront aberrations due to small changes in tear film integrity throughout the day is one potential cause of the between subject variability observed in the study. Previous studies investigating diurnal fluctuations in ocular wavefront aberrations have only assessed variations over a single day, and have not involved measurements extending past 6:00 pm.[25,26] Therefore, the exact pattern of diurnal change in ocular aberrations, and their relative consistency between days, has not previously been clearly defined. In this study, the collection of wavefront data over a 12 hour period across each of two consecutive days allowed the consistent diurnal variation in these ocular optical parameters to be detected.

One important finding from this study is the significant diurnal variation noted in the spherical equivalent refraction (power vector M). Diurnal variation in ocular refraction has been previously documented in normal eyes.[59-61] The mean amplitude of change in spherical equivalent (0.37 ± 0.15 D) in our population is within the range of previously reported average magnitude of diurnal change in eye's refraction.[60,61] We found a significant myopic refractive shift in spherical equivalent refraction later in the day. Previous studies have also reported a myopic shift in automated objective refraction over the course of the day for normal eyes.[60] The magnitude of change that we observed in ocular spherical refraction were on average greater than 0.25 D, and therefore will potentially influence clinical measures of refraction. Clinicians requiring precise refraction measures should be aware of the potential for diurnal changes to influence refraction measures, and can take these diurnal changes into account when interpreting measured changes in ocular refraction.

We have previously reported that the axial length of the subjects in this study underwent significant diurnal variation, with the longest axial length typically occurring during the day, and the shortest at night.[48] If the changes in spherical equivalent were occurring solely as a result of the diurnal variations in the eye's axial length, then the refraction would be expected to be more hyperopic (by ~0.083 D) in the evening when the axial length is at its shortest.[48] However, this was not the case, as the spherical equivalent refraction was actually found to be more myopic later in the day (mean diurnal change, 0.37 ± 0.15 D) compared to the morning. This apparent paradoxical relationship between the fluctuations in axial length and spherical refraction, and the fact that no significant association was found between the changes in these two variables ($p>0.05$) suggests that changes in other ocular optical components (such as the cornea or crystalline lens) are playing a greater role in the diurnal changes in ocular refraction compared to the axial length. Previous animal studies have also observed a similar paradoxical relationship between the diurnal variations in axial length and ocular refraction.[62]

The general pattern and magnitude of diurnal change that we have observed in anterior corneal curvature are consistent with previous investigations.[29,63-65] The cornea was observed to be flattest in the morning, and became gradually steeper throughout the day (mean diurnal change, 0.24 ± 0.13 D) leading to a significant myopic shift in the corneal refractive power over the course of the day. The diurnal changes in corneal power over the day were of similar magnitude to, and appeared to be consistent with the pattern of change observed in the spherical equivalent refraction, that was also most hyperopic in the morning and became more myopic over the course of the day. However, the changes in anterior corneal curvature were not significantly associated with the changes in ocular spherical refraction ($p>0.05$), which suggests that diurnal fluctuations in the other optical components of the eye, such as curvature of the crystalline lens or posterior cornea (or variations in the corneal or crystalline lens refractive index), could also be involved in the changes observed in the overall ocular refraction. Diurnal fluctuations in the gradient refractive index of the crystalline lens have been observed in other species,[66-68] and have been shown to be related to variations in retinal dopamine levels, however diurnal changes in the refractive index of the human crystalline lens have not previously been examined. A limitation of the measurements in our current study is that the spherical refraction data was analysed over a 5 mm pupil, but the anterior corneal keratometry values reflect only the central 2-3 mm of corneal curvature, which may have influenced the strength of the correlation observed between these variables. Future research utilising measures of ocular aberrations combined with corneal optics from videokeratoscopy (that provides a more complete assessment of corneal optics over a wider region of the cornea compared to keratometry) is required to more comprehensively investigate the physiological basis and underlying causes of diurnal variations in the spherical equivalent refraction of human eyes.

We have also shown that spherical aberration (C_4^0) undergoes significant diurnal variation. In two earlier studies, both Mierdel[25] and Srivannaboon[26] did not find significant diurnal variations in C_4^0. This difference between the studies may result from a range of factors including; differences in the timing of measurements, the instruments used,[25] analysis procedure (RMS of individual higher-order Zernike polynomials calculated),[25] accommodative state used for measurements (cycloplegic aberrometry)[26] and pupil size used for analysis (6.0 mm pupil used).[25,26] Spherical aberration is typically one of the larger magnitude higher-order aberrations in human eyes, with an average absolute magnitude of approximately 0.05 - 0.1 µm for a 5 mm pupil in young normal eyes.[22,69] The mean amplitude of change in C_4^0 of 0.036 ± 0.02 µm in the current study equates to 69% of the mean absolute value of C_4^0 (i.e. 0.052 ± 0.032 µm). Given that the magnitude of diurnal fluctuations in C_4^0 could be greater than 50% of the mean absolute level of the aberration present in the eye, it is important to consider the potential for diurnal changes in this aberration term for reliable interpretation of various clinical and research measures. Research applications investigating longitudinal changes in wavefront aberrations, or clinical applications requiring precise wavefront measurements (e.g. wavefront-guided refractive surgeries for correcting higher-order wavefront errors) should take this within day variability into account while interpreting the wavefront data, to avoid confounding of results.

In the current study, we found no evidence of significant differences between the diurnal variations in both lower-order (except for the refractive power vector J0) and higher-order wavefront aberrations in our population of myopic and emmetropic subjects, which suggests that the daily fluctuations in the ocular optics are similar between myopes and emmetropes. Although statistically significant, the difference between the refractive error groups in terms of the daily changes in astigmatism power vector J0, was only significant at one time point during the day and was of only small magnitude and would not be considered clinically significant (mean difference, ~0.04 D at this time point). Some earlier studies have reported significant differences in the total higher-order RMS,[4,5] or individual higher-order aberrations[5] between the myopic and emmetropic eyes. In contrast, a range of other studies[20,35,36] found no strong evidence for individual or total higher-order RMS to be greater in myopes than those in emmetropes. In two earlier studies, both He[4] and Paquin[5] found that the RMS of spherical aberration is significantly greater in myopes than emmetropes. Future cross-sectional studies investigating wavefront aberration in different refractive error populations should take diurnal changes in aberrations into account when interpreting differences in ocular aberrations between refractive error groups.

In conclusion, spherical equivalent refraction (power vector M) and spherical aberration (C_4^0) both underwent significant diurnal variations that were consistently observed over two consecutive days of measurement. Except for the lower-order astigmatism at 90/180 deg (power vector J0), there were no significant differences in the magnitude and timing of diurnal variations in ocular aberrations associated with refractive error. Research and clinical applications requiring precise wavefront measurements should take these diurnal changes into account when interpreting the wavefront data.

DECLARATION OF INTERESTS

Ranjay Chakraborty: None

Scott A. Read: None

Michael J. Collins: None

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TABLES

Table 1: Mean values and amplitude of change for emmetropes, myopes and all subjects over two days and p-values from repeated measures ANOVA investigating the within-subjects effects of time, day, and the time by day interaction, the between-subjects effect of refractive error and the time by refractive error interaction for lower-order (sphero-cylindrical refractive power vectors M, J0 and J45). Significant p values (p<0.05) are highlighted in bold.

Type	Variables	Mean ± SD			Mean amplitude of change ± SD			p values from repeated measures ANOVA				
		Emmetropes (n = 13)	Myopes (n = 17)	All (n = 30)	Emmetropes (n = 13)	Myopes (n = 17)	All (n = 30)	(Time)	(Day)	(Time by day)	(Time by refractive error)	(Refractive error)
Spherocylindrical data, refractive power data (D)	M Vector (spherical equivalent refraction)	-0.31 ± 0.63	-3.79 ± 1.73	-2.28 ± 2.21	0.46 ± 0.14	0.30 ± 0.13	0.37 ± 0.15	**0.029**	0.372	0.718	0.430	**<0.0001**
	J0 Vector (astigmatism at 90/180 deg)	0.04 ± 0.18	0.16 ± 0.29	0.11 ± 0.25	0.16 ± 0.04	0.07 ± 0.04	0.11 ± 0.04	0.318	**0.016**	0.306	**0.040**	0.083
	J45 Vector (astigmatism at 45/135 deg)	0.02 ± 0.12	0.02 ± 0.25	0.02 ± 0.20	0.07 ± 0.04	0.08 ± 0.06	0.08 ± 0.05	0.168	0.79	0.673	0.182	0.388

Table 2: Mean values and amplitude of change for emmetropes, myopes and all subjects over two days and p-values from repeated measures ANOVA investigating the within-subjects effects of time, day, and the time by day interaction, the between-subjects effect of refractive error and the time by refractive error interaction for 3rd and 4th higher-order optics (oblique trefoil (C_3^{-3}), vertical coma (C_3^{-1}), horizontal coma (C_3^{1}), horizontal trefoil (C_3^{3}), oblique quatrefoil (C_4^{-4}), 45/135 deg secondary astigmatism (C_4^{-2}), spherical aberration (C_4^{0}), 90/180 deg secondary astigmatism (C_4^{2}), and quatrefoil (C_4^{4}) along with root mean square (RMS) for the higher-order aberrations. Significant p values (p<0.05) are highlighted in bold.

Types	**Variables**	**Mean ± SD**			**Mean amplitude of change ± SD**			**p values from repeated measures ANOVA**				
		Emmetropes (n = 13)	**Myopes (n = 17)**	**All (n = 30)**	**Emmetropes (n = 13)**	**Myopes (n = 17)**	**All (n = 30)**	**(Time)**	**(Day)**	**(Time by day)**	**(Time by refractive error)**	**(Refractive error)**
Third-order aberrations (µm)	**Oblique trefoil (C_3^{-3})**	-0.079 ± 0.071	-0.059 ± 0.050	-0.068 ± 0.060	0.059 ± 0.052	0.063 ± 0.037	0.061 ± 0.043	0.670	0.227	0.633	0.388	0.380
	Vertical coma (C_3^{-1})	0.026 ± 0.127	0.020 ± 0.089	0.022 ± 0.105	0.068 ± 0.054	0.065 ± 0.033	0.066 ± 0.043	0.138	0.272	0.249	0.622	0.622
	Horizontal coma (C_3^{1})	-0.007 ± 0.034	-0.002 ± 0.057	-0.004 ± 0.048	0.042 ± 0.018	0.044 ± 0.025	0.043 ± 0.022	0.059	0.892	0.409	0.468	0.685
	Horizontal trefoil (C_3^{3})	0.009 ± 0.077	0.039 ± 0.069	0.026 ± 0.073	0.043 ± 0.027	0.046 ± 0.024	0.044 ± 0.025	0.420	0.453	0.345	0.089	0.399
Fourth-order aberrations (µm)	**Oblique quatrefoil (C_4^{-4})**	0.015 ± 0.022	0.013 ±0.021	0.014 ± 0.021	0.030 ± 0.019	0.025 ± 0.019	0.027 ± 0.019	0.354	0.257	0.634	0.200	0.687
	45/135 deg secondary astigmatism (C_4^{-2})	-0.010 ± 0.016	-0.007 ± 0.019	-0.008 ± 0.017	0.024 ± 0.014	0.021 ± 0.013	0.023 ± 0.013	0.218	0.136	0.332	0.150	0.464
	Spherical aberration (C_4^{0})	0.043 ± 0.052	0.034 ± 0.047	0.038 ± 0.048	0.045 ± 0.027	0.029 ± 0.010	0.036 ± 0.020	**0.043**	0.898	0.169	0.486	0.795
	90/180 deg secondary astigmatism (C_4^{2})	0.012 ± 0.036	0.009 ± 0.036	0.010 ± 0.035	0.044 ± 0.028	0.034 ± 0.011	0.038 ± 0.020	0.115	0.261	0.845	0.531	0.875
	Quatrefoil (C_4^{4})	0.011 ± 0.023	0.003 ± 0.034	0.006 ± 0.029	0.039 ± 0.024	0.034 ± 0.015	0.036 ± 0.019	0.327	0.546	0.863	0.419	0.320
Higher-order RMS	**Higher-order RMS**	0.250 ± 0.056	0.207 ± 0.053	0.225 ± 0.057	0.086 ± 0.077	0.068 ± 0.044	0.076 ± 0.060	0.364	0.481	0.204	0.263	0.056

FIGURE LEGENDS

Figure 1: Mean change in lower order optics; power vector M (spherical equivalent refraction) (top), J0 vector (astigmatism at 90/180 deg) (middle) and J45 vector (astigmatism at 45/135 deg) (bottom) for all subjects (n=30) over two consecutive days. All values are normalised to the mean of the ten sessions across the two measurement days. Repeated measures ANOVA revealed significant diurnal variations in power vector M (p = 0.029). Vertical error bars are standard error of the mean (SEM). Horizontal error bars are standard error in the mean time that the measurement was taken at each session (in hours).

Figure 2: Mean change in spherical aberration (SA, C_4^0) for all subjects (n=30) over two consecutive days. All values are normalised to the mean of the ten sessions across the two measurement days. Repeated measures ANOVA revealed significant diurnal variations in C_4^0 (p = 0.043). Vertical error bars are standard error of the mean (SEM). Horizontal error bars are standard error in the mean time that the measurement was taken at each session (in hours).

Figure 3: Mean change in anterior central corneal curvature for all subjects (n=30) over two consecutive days. All values are normalised to the mean of the ten sessions across the two measurement days. Repeated measures ANOVA revealed significant diurnal variations in corneal curvature (p<0.001). Vertical error bars are standard error of the mean (SEM). Horizontal error bars are standard error in the mean time that the measurement was taken at each session (in hours).