OPO OPHTHALMIC AND PHYSIOLOGICAL OPTICS
THE JOURNAL OF THE COLLEGE OF OPTOMETRISTS

Ophthal. Physiol. Opt. 2009 **29:** 264–271

Changes of ocular aberrations with gaze

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Abstract

The dependence of the ocular aberrations on gaze has been studied in three eyes using a fast-acquisition, Hartmann–Shack wavefront sensor. Although there were some trends in the change of some aberration terms with gaze, the changes of most Zernike coefficients were smaller than their variability at each individual gaze position, due to the combined effects of microfluctuations of accommodation, eye movements, tear film dynamics, and measurement noise. For our particular experimental dataset, the confidence level at which the null hypothesis (i.e. that the aberrations do not change significantly with gaze) can be rejected is very low. Further advances in the study of the dependence of eye aberrations with gaze will require a tighter control of the sources of aberration variability at each individual gaze position.

Keywords: eye movements, oblique viewing, ocular aberrations, physiological optics

Introduction

Several instruments have been used to measure the aberrations of the living eye, either subjectively (Smirnov, 1961; Howland and Howland, 1977; Webb *et al.*, 1992) or objectively by, e.g. calculations from retinal images of a point source (Santamaría *et al.*, 1987; Iglesias *et al.*, 1998), laser ray tracing (Navarro and Losada, 1997) and the widely-used Hartmann–Shack (H-S) wavefront sensor (Liang *et al.*,1994; Prieto *et al.*, 2000). Using these instruments, studies have been carried out to explore several aspects of the ocular aberrations: the dependence of the on-axis eye's aberrations on age (Artal *et al.*, 2002), accommodation (Atchison *et al.*, 1995; Fernández and Artal, 2005; Zhu *et al.*, 2006), temporal dynamics (Hofer *et al.*, 2001; Li and Yoon, 2006), and cardiopulmonary rhythms (Zhu *et al.*, 2004; Hampson *et al.*, 2005), among others.

Received: 7 November 2008
Revised form: 9 January 2009
Accepted: 13 January 2009

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There is, however, a related issue which has received less attention: how do on-axis eye aberrations change with gaze? In principle, it can be expected that the stresses exerted on the eyeball by the extraocular muscles, especially in extreme gaze positions, should affect the ocular shape to a greater or lesser extent, inducing changes in the aberration pattern of the eye. Apart from providing interesting data related to ocular biomechanics, the answer to this question should give some insights into the significance of aberrations in binocular vision, since changes in gaze and vergence should give rise to related but unequal behaviours in the two eyes. The assessment of whether the change of aberrations with gaze can be measured in a small sample of normal eyes, using a state-of-the-art research prototype Hartmann–Shack wavefront sensor, is the main aim of this paper.

Some preliminary work in this field has been done by Buehren *et al.* (2003), who measured the corneal aberrations in people who had been reading. They found significant changes in aberrations after one hour of reading, especially in primary astigmatism (a_5), primary vertical coma (a_7) and trefoil 30° (a_9). The notation used is according to the standard of the Optical Society of America (Thibos *et al.*, 2000). Moreover, some subjects showed statistically significant changes of the local

doi: 10.1111/j.1475-1313.2009.00652.x

refractive power of particular regions of the pupil. These refractive changes were mostly located in the upper and/or the lower pupil areas, and were probably due to eyelid pressure. The approach of our study differs from Buehren's in two main points: we have measured the global eye aberration, not only the corneal one, and we have searched for short-term aberration changes, immediately after changes in gaze, taking measurements in these different positions of gaze as well as in the primary position.

On the other hand, the recent work published by Radhakrishnan and Charman (2007) shows high levels of intersubject variability for the refractive changes with gaze. Only a few subjects showed some evidence of small systematic trends in the dependence of refraction error with gaze, especially in the temporalward direction. These trends, however, are not apparent in higher-order aberrations.

In this study we have taken into account horizontal ductions from the primary position of gaze. In abductions (horizontal eye movements toward temple) the lateral rectus muscle contracts and the medial rectus relaxes, while in adductions (horizontal eye movements towards nose) the opposite holds, that is, the medial rectus contracts and the lateral rectus relaxes. More information about the extraocular muscles and their insertions in the orbit can be found in Tunnacliffe (1993).

These extraocular muscles exert their action over the eyeball and it seems reasonable to expect that if there is any distortion in the eyeball shape, it should produce some amount of astigmatism and coma-like aberration terms with axes oriented along the direction of the resulting stresses. With the aim of checking this assumption, we have analyzed the changes in individual Zernike aberration terms caused by changes in horizontal gaze direction, testing their statistical significance within complete series of real-time measurements.

Methods

Experimental setup

The instrument used to measure the ocular aberrations, which is schematically shown in *Figure 1*, is a laboratory version of a fast H-S wave-front sensor for the eye, equipped with a speckle-reduction approach. A high-speed CCD camera together with the appropriate frame grabber and software are used to record H-S images at 200 Hz. A loudspeaker emitting white noise induces vibrations in a pellicle beam splitter (BS) placed in front of the eye, removing speckle in the H-S images, and increasing the signal-to-noise ratio. Two optical relays (lenses L1-L2 and L3-L4) conjugate the CCD camera, the microlens array and the eye pupil planes. The illumination source is a collimated near-infrared (780 nm) laser diode that at the same time is used as the fixation target. Subjects used a bite-bar mounted on a rotary stage that allows the subject's head to be turned while he or she keeps fixating on the target and the H-S data are collected.

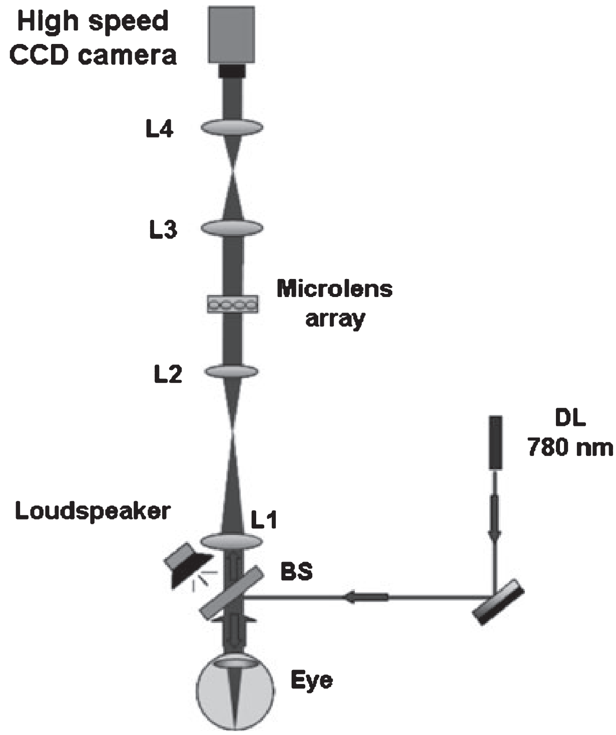

Figure 1. Schematic diagram of the high speed Hartmann–Shack wave-front sensor used to measure the ocular wave aberrations at different gaze positions.

Measurement protocol

Three eyes (OD) of three normal subjects were measured: PA (myopic, 1.5 D, 46 years); AM (27 years) and PP (25 years), both of them emmetropes. The H-S images were recorded with natural pupil diameters and the aberrations reconstructed for a 4 mm diameter pupil (natural pupil diameter was larger under the illumination conditions used in this experiment). Five positions of gaze were analyzed following this order: primary position (0°); adduction positions at 15 degrees nasal (15° N) and 30 degrees nasal (30° N); and abduction positions at 15 degrees temporal (15° T) and 30 degrees temporal (30° T). The eye pupil was kept in the plane conjugate to the microlens array for all gaze positions. Four series of 200 images were taken at each gaze position and each set took about 1 s. Between any two series of measurements, the subject had a rest, closing his/her eyes when the series were taken in a fixed gaze position, and moving out of the system when the consecutive series belong to different positions of gaze. We centred the subject's pupil in the reference system of the microlens array, with an estimated error of pupil position of about 200 μm. The four series of measurements in each position of gaze were completed in about 2 min. For each subject, the total of 20 series of measurements were taken in approximately 30 min.

The H-S images were processed to find the spot centroids, whose displacements from the reference position are proportional to the wavefront aberration derivatives. If we express the wavefront aberration *W(x,y)* as a sum of *M* Zernike polynomials (Z_i), the aberration coefficients vector **a** can be linearly estimated from the measurements vector **m** as

$$W(x,y) = \sum_{i=1}^{M} a_i Z_i(x,y) \qquad \mathbf{a} = \mathbf{Rm}, \tag{1}$$

where **R** is the (least-squares) reconstruction matrix (Prieto *et al.*, 2000). In our case we fitted $M = 35$ Zernike terms (up to the seventh order) to the sensor measurements.

Results

With the aim of determining whether the Zernike coefficients change with gaze direction, we calculated their mean values and their standard deviation at each particular gaze position, using the data of all measurement series, as:

$$a_{ik} = \frac{1}{SN}\sum_{s=1}^{S}\sum_{n=1}^{N} a_{iksn} = \langle a_{iksn} \rangle_{sn}, \tag{2}$$

$$\sigma_{ik} = \sqrt{\frac{1}{SN-1}\left[\sum_{s=1}^{S}\sum_{n=1}^{N}\left(a_{iksn} - \langle a_{iksn} \rangle_{sn}\right)^2\right]}, \tag{3}$$

where the subscript *i* is the index of the corresponding Zernike mode, $k = 1,...,5$ represents the five positions of gaze analyzed in our work (from 30°N to 30°T respectively), *s* is the index labelling each series of aberrations measurements ($s = 1,...S$, with $S = 4$) and *n* is the index labelling each measurement inside each series ($n = 1,\ldots N$, with $N = 200$). The brackets notation '$\langle\ \rangle_{pq}$' indicates 'averaging on the variables *p* and *q*'. Although we only show in this paper the behaviour of the Zernike coefficients from a_3 to a_{14} (up to the fourth order), we have found that higher-order coefficients follow similar trends.

Each row of data in *Figure 2* shows the evolution of the mean value, *Equation 2*, of the corresponding Zernike coefficient across the five gaze positions. The error bars correspond to one standard deviation of the data, computed according to *Equation 3*.

Changes in the Zernike coefficients across gaze position are apparent in these graphs (see, e.g. the behaviour of defocus, a_4). However, the variability of the Zernike coefficients at each individual gaze position

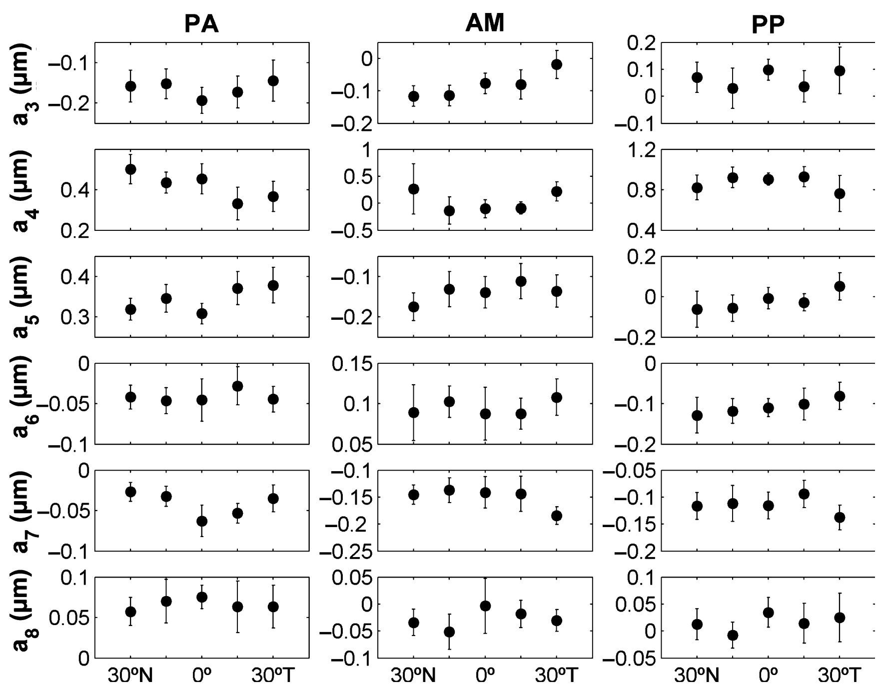

Figure 2. Mean values of the Zernike coefficients of modes $i = 3$–14 for five different positions of gaze (30°N, 15°N, 0°, 15°T, 30°T) of the eyes of PA, AM and PP. Error bars correspond to one standard deviation of the data.

is relatively high. In order to assess quantitatively the significance of these differences, we applied a chi-square test to each coefficient (Frieden, 1991). The initial hypothesis stated the constancy of the ocular aberrations among positions and its magnitude, which was taken as equal to the average (across positions) of the means calculated by Equation (2). Using the brackets notation described above, the χ_i^2 parameter of the *i*-th Zernike coefficient is given by:

$$\chi_i^2 = \sum_{k=1}^{K} \frac{(<a_{iksn}>_{sn} - <<a_{iksn}>_{sn}>_k)^2}{\sigma_{ik}^2}, \quad (4)$$

with $\nu = K-1$ degrees of freedom, since the hypothetically constant value of the coefficient is calculated as the average of the input data. *Figure 3* shows the values of χ_i^2 for modes $i = 3,...14$. The horizontal lines correspond to χ_c^2, the critical χ^2 above which a coefficient can be considered to change significantly between gaze positions for a given confidence level *p*. We plotted the χ_c^2 for the confidence levels at which it could be considered that at least a few coefficients reject the constant-value hypothesis. As it can be seen, these confidence levels are too low (about $p = 0.60$ for PA and AM and $p = 0.20$ for PP) for it to be possible to accept that any significant change has been detected. We also computed the χ^2 for the total and higher-order *rms* (HO) of the subjects' aberration, obtaining the results presented in *Table 1*: again confidence levels are generally low.

Although the existence of real changes is of course not excluded, the χ^2 results indicate that the observed differences of the Zernike coefficients and *rms* between gaze positions could also be due to purely random effects arising from the variability showed at each gaze position.

We also studied the variability of the aberration coefficients between the measurement series taken at a fixed gaze position, for instance at the primary position of gaze (0°). The mean value of the *i*-th coefficient averaged over all data of the *s*-th series and the corresponding standard deviation of the data are computed in this case as

$$a_{i0^\circ s} = \frac{1}{N}\sum_{n=1}^{N} a_{i0^\circ sn} = <a_{i0^\circ sn}>_n, \quad (5)$$

$$\sigma_{i0^\circ s} = \sqrt{\frac{1}{N-1}\left[\sum_{n=1}^{N} (a_{i0^\circ sn} - <a_{i0^\circ sn}>_n)^2\right]}, \quad (6)$$

and the χ^2 parameter across the *S* series ($\chi_{i0^\circ}^2$), for the initial hypothesis that the *i*-th coefficient equals its average value between series and does not change across them, is given by

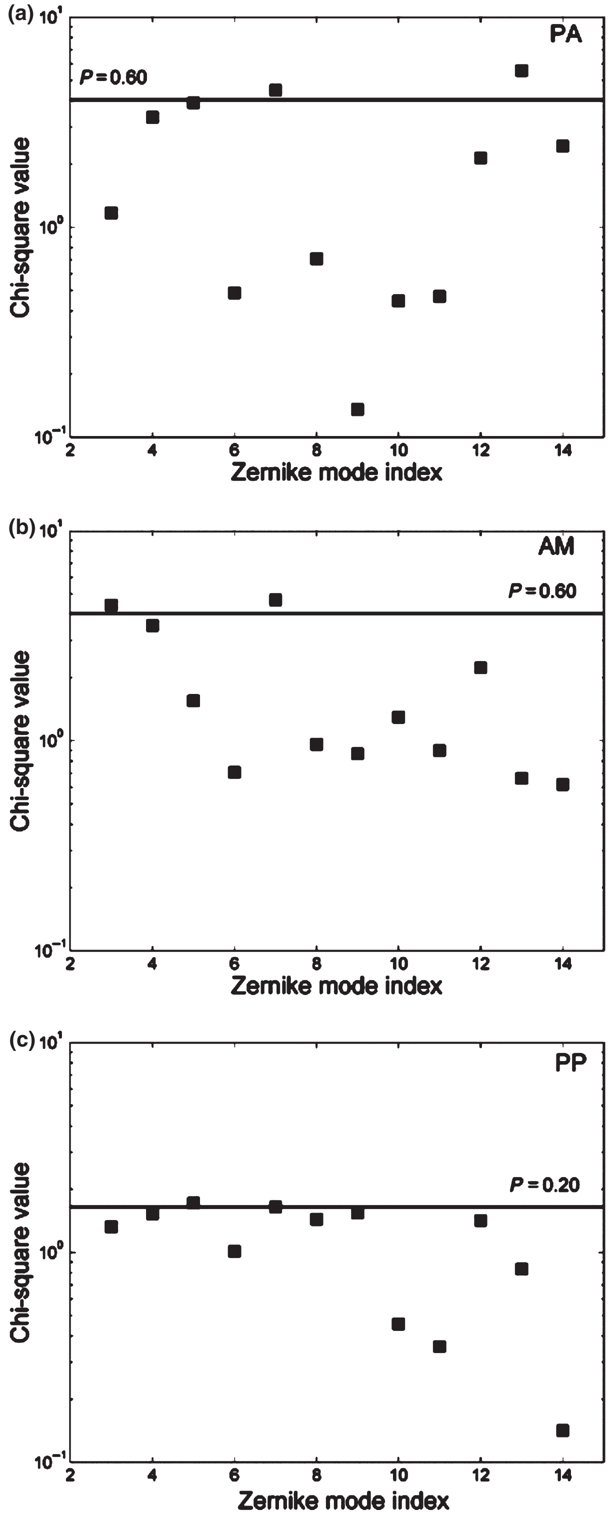

Figure 3. χ_i^2 value for each Zernike coefficient across the five gaze positions analyzed in this work. The solid line corresponds to χ_c^2 value for the degree of confidence *p* indicated in each case.

$$\chi_{i0^\circ}^2 = \sum_{s=1}^{S} \frac{(<a_{i0^\circ sn}>_n - <<a_{i0^\circ sn}>_n>_s)^2}{\sigma_{i0^\circ s}^2}, \quad (7)$$

Table 1. Chi-square and confidence level for the total and high order (HO) rms of each subject's aberrations

	Chi-square rms	Confidence level (*p*)	Chi-square HO rms	Confidence level (*p*)
PA	1.6605	0.23	1.6983	0.23
AM	6.9374	0.86	0.8753	0.09
PP	1.2496	0.12	0.4090	0.02

Figure 4 shows the mean values, *Equation 5*, of the different modes for the four measurement series ($S = 4$) taken at the primary gaze position. The uncertainty bars are equal to one standard deviation of the data, computed according to *Equation 6*. *Figure 5* displays the corresponding chi-squared values, $\chi^2_{i0^\circ}$, for the initial constant hypothesis. The horizontal lines correspond to the critical χ^2_c above which the coefficients may be considered to change significantly, for the confidence level p. As before, we plotted χ^2_c for the level p at which one or a few coefficients may be considered to reject the constant hypothesis. Note that, in this case, for all the eyes analyzed, some coefficients reject that hypothesis at a meaningful 99% confidence level.

Discussion

Some mean values of estimated Zernike coefficients apparently show some trends of change with gaze (see *Figure 2*): defocus (a_4), primary astigmatism (a_5) and primary vertical coma (a_7) in PA; defocus (a_4), primary astigmatism (a_3 and a_5) and primary vertical coma (a_7) in AM; and primary astigmatism (a_5) in PP. In the analyzed eyes, a_5 seems to change with a common trend, whereas other coefficients change with gaze following different trends for different eyes. It is worth mentioning that Buehren *et al.* (2003) found significant changes in the coefficient a_5 too. But they found differences that we have not observed in the terms a_7 and a_9.

The small sample size is a limitation of the present study. Even so, our findings basically agree with the results of Radhakrishnan and Charman (2007). They support that, on average, shifts in refraction with short-term changes in gaze direction are very small. Moreover, the averages of the RMS monochromatic aberrations (third to seventh order), third-order coma and fourth-order spherical aberration, showed no significant differences between the central and oblique viewing conditions.

We have found that the measured changes have little statistical significance, since the variability of the Zernike coefficients at each definite position of gaze is of the same or higher order than the change across positions. This variability at a fixed position of gaze stems from two different kinds of source: there is an intrinsic variability due to microfluctuations in accommodation, tear film dynamics and possible medium- to long-term aberration drifts (Kotulak and Schor, 1986; Hofer *et al.*, 2001; Iskander *et al.*, 2004). There is also an extrinsic fluctuation contributing to the measured changes, due to random eye movements, different initial pupil positioning between measurement series (Davies *et al.*, 2003),

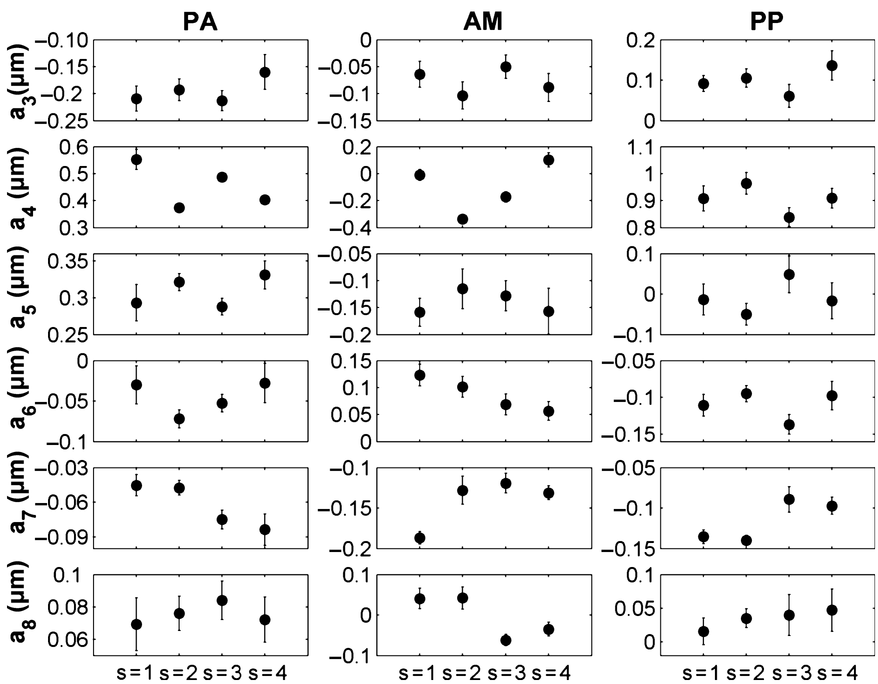

Figure 4. Mean values of the Zernike coefficients for the four series taken at the primary position of gaze (0°) for subjects PA, AM and PP. Error bars represent one standard deviation of the data.

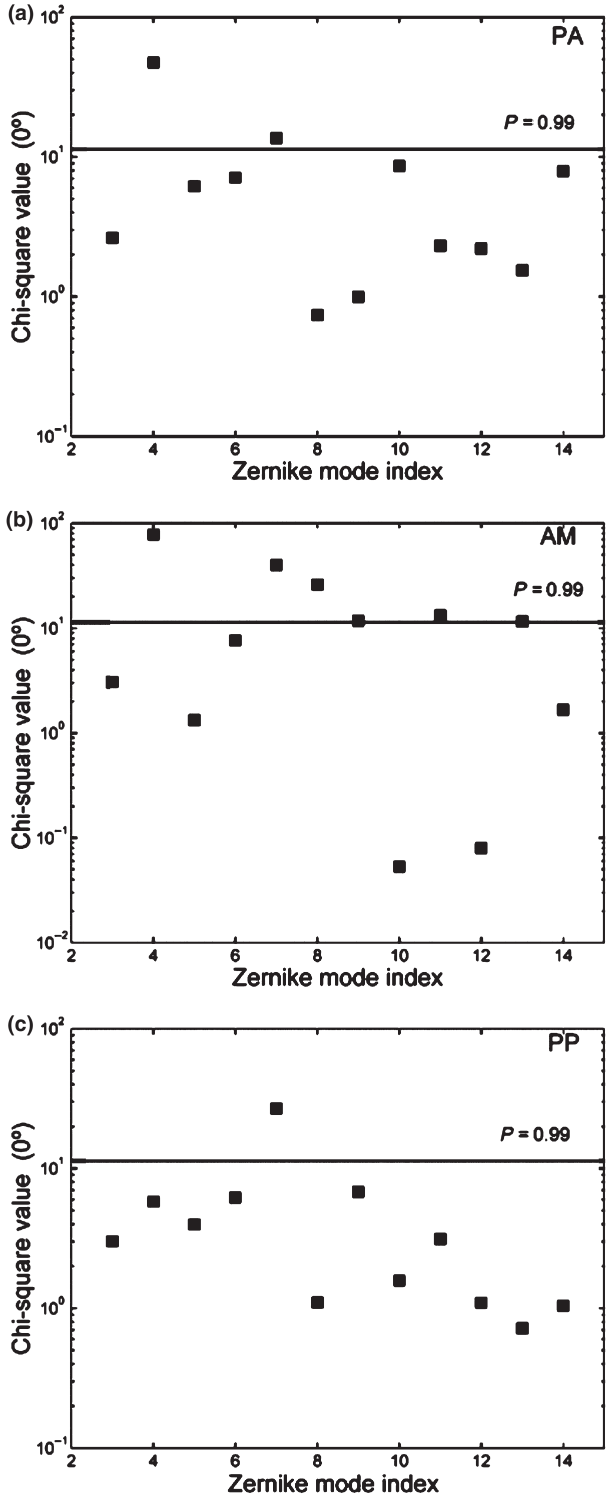

Figure 5. $\chi^2_{i0^\circ}$ values for each Zernike coefficient across the four series in primary gaze position, for subjects PA, AM and PP. The solid line corresponds to the χ^2_c value for the degree of confidence *p* indicated in each case.

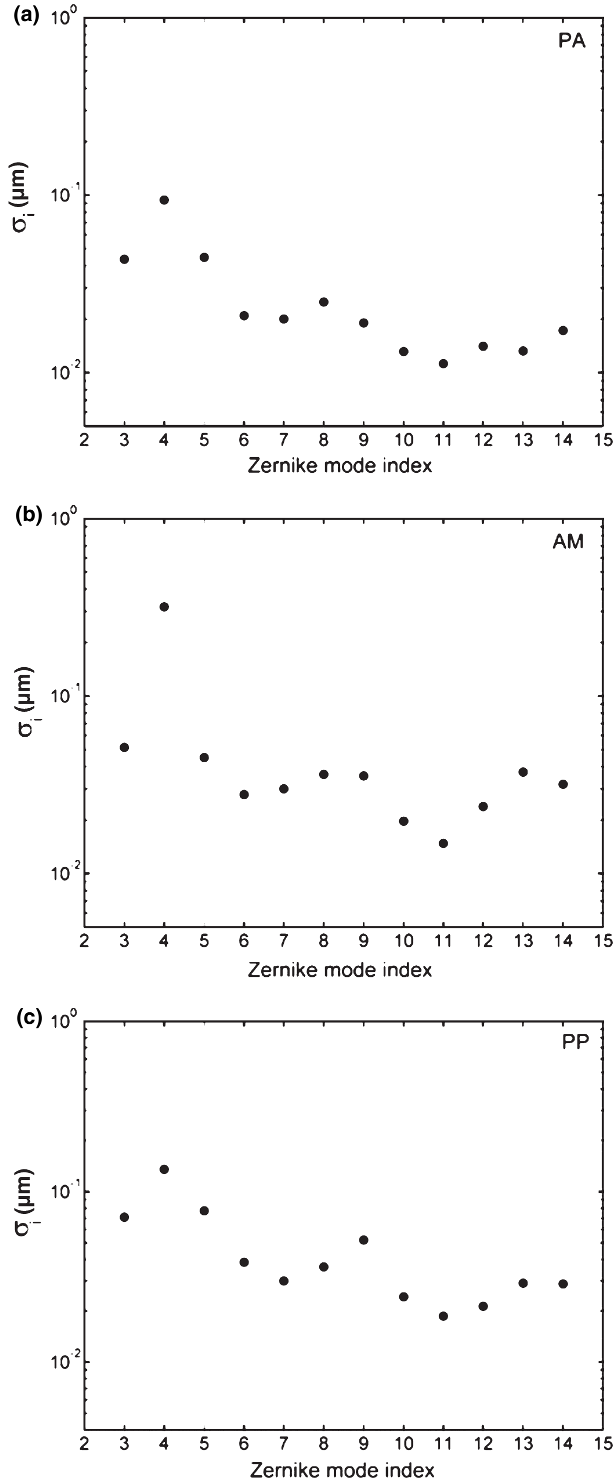

Figure 6. Upper bound of standard deviation for each aberration coefficient across the five gaze positions, for PA, AM and PP.

and measurement noise due to the centroiding algorithms and the detector noise (Ares and Arines, 2001, 2004). Our results (see *Figures 4 and 5*) show that there is a high inter-series variability of aberrations for a fixed gaze, which diminishes the signal-to-noise ratio for the detection of gaze-related aberration changes. Since the changes of aberrations with gaze can be considered - in a first approximation - as statistically independent from the changes due to other sources of variability, an upper bound for the σ_{ik} gaze-related change of each aberration coefficient is just the σ_{ik} of the set of its (mean) values at the five gaze positions, see *Equation 3*. *Figure 6* displays these σ_{ik} upper bounds for modes i = 3–14 of the three subjects. Their magnitude is higher for lower-order modes, and ranges from 0.4 to 0.01 μm. The variability at each individual gaze position should be of smaller magnitude than the changes across positions, in order for the latter to be considered statistically significant. This result provides a guideline for the design of the next generation of experiments, which should aim to reduce the overall (intrinsic plus extrinsic) variability at each gaze position by a factor of at least four, with respect to the present performance.

Conclusions

We have found that the changes of aberrations with gaze are smaller than the overall variability measured at each individual position. Although the analysis of the mean value of the ocular aberrations for the different gaze positions suggests the possibility that some aberrations might change with gaze direction, the confidence level at which we can state that the wavefront aberrations change with gaze is very low. From these results, the eye appears to cope reasonably well with the differential stresses produced by the extraocular muscles when turning to different gazes, at least within the range from 30° temporal to 30° nasal studied in this work. We have also shown that the wavefront aberration variability at each gaze position should be reduced at least by a factor of four in order to determine with more confidence the change of the ocular aberrations with gaze.

Acknowledgements

The wavefront sensor used in this study was developed in collaboration with Ralf Blendowske. This work has been supported by the Spanish Ministerio Educación y Ciencia, grants FIS2005-05020-C03-02, FIS2004-02153, FIS2007-64765, and 'Fundación Séneca', Murcia, Spain, grant 04524/GERM/06. A Mira-Agudelo acknowledges the financial support from 'COLCIENCIAS' Colombia and 'Universidad de Antioquia' Colombia. Justo Arines' permanent address: Departamento de Fisica Aplicada (área de Óptica), Universidad de Zaragoza, Zaragoza (Spain).

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