Changes of ocular aberrations with gaze

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Figure 1: Schematic diagram of the high speed Hartmann-Shack wave-front sensor used to measure the ocular wave aberrations at different gaze positions.
149x171mm (600 x 600 DPI)
Figure 2: Mean values of the Zernike coefficients of modes $i=3$ to 14 for five different positions of gaze ($30^\circ N$, $15^\circ N$, $0^\circ$, $15^\circ T$, $30^\circ T$) of the eyes PA, AM and PP. Error bars correspond to one standard deviation of the data.
Figure 3: $\chi^2$ value for each Zernike coefficient across the five gaze positions analyzed in this work. The solid line corresponds to the $\chi^2$ value for the degree of confidence $P$ indicated in each case.
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Figure 5: $\chi^2_{ip}$ 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 $\chi^2_c$ value for the degree of confidence $P$ indicated in each case.
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Abstract

The dependence of the ocular aberrations with 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 aberrations 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 the microfluctuations of the 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: Ocular aberrations; Eye movements; Physiological optics, Oblique viewing

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 like calculations from retinal images of a point source (Santamaria et al., 1987; Iglesias et al., 1998), laser ray tracers (Navarro and Losada, 1997) and the widely used Hartmann-Shack (H-S) wavefront sensor (Liang et al., 1994; Prieto et al., 2000). By using these instruments, different studies have been carried out to explore the dependence of the on-axis eye’s aberrations with age (Artal et al., 2002), accommodation (Atchison et al., 1995; Fernández and Artal, 2005; Zhu
et al., 2006), dynamics (Hofer et al., 2001; Li and Yoon, 2006), and cardiopulmonary rhythms (Hampson et al., 2005; Zhu et al., 2004), among others.

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 bigger or lesser extent, inducing somehow changes in the aberration pattern of the eye. Apart from providing interesting data related with ocular biomechanics, the answer to this question should give some insights about the significance of aberrations in binocular vision, since movements of gaze and vergences should give rise to related but unequal behaviours between both eyes. Assessing 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 change on aberrations after one hour of reading, especially in primary astigmatism ($a_\delta$), primary vertical coma ($a_\gamma$) and trefoil $30^\circ$ ($a_\chi$). 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 refractive power of some particular regions of the pupil. These regions were mostly located in the upper and/or the lower pupil areas, probably due to eyelids 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, not only in 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, 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 microlenses array and the eye pupil planes. The illumination source is a 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 turning the subject's head while he or she keeps fixating on the target and the H-S are collected.

**Measurement protocol**

Three eyes (OD) of three normal subjects were measured: PA (myopic, 1.5 D), AM and PP, both emmetropes. The H-S images were recorded under 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 (0º); adduction positions at 15 nasal degrees (15ºN) and 30 nasal degrees (30ºN); and abduction positions at 15 temporal degrees (15ºT) and 30 temporal degrees (30ºT). The eye pupil was kept in the plane conjugate to the microlenses array for all gaze positions. For each gaze position, four series of 200 H-S images were recorded in one second. Between two series of measurements, the subject had a rest, closing his/her eyes when series were taken in a fixed gaze and out the system when the consecutive series belong to different positions of gaze. We centered the subject’s pupil in the reference system of the microlenses array, with an estimated error of pupils’ position of about 200 µm. The four series of measurements in each position of gaze were taken in about 2 minutes. For each subject, the total series of measurements were taken in 30 minutes approximately.
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 \( (Z) \), the aberration coefficients vector \( \mathbf{a} \) can be linearly estimated from the measurements vector \( \mathbf{m} \) as

\[
W(x, y) = \sum_{i=1}^{M} a_i Z_i(x, y) \quad \mathbf{a} = \mathbf{Rm}
\]  

where \( \mathbf{R} \) 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 to know if there is some trend in the magnitude change of each Zernike coefficients with gaze, we calculated their mean value and their standard deviation at each particular gaze position, using the data of all measurement series, as:

\[
a_{ik} = \frac{1}{SN} \sum_{s=1}^{S} \sum_{n=1}^{N} a_{iksn} = \langle a_{iksn} \rangle_{sn}
\]  

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

where the subscript \( i \) is the index of the corresponding Zernike mode, \( k=1,\ldots,5 \) 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 \( (s=1,\ldots,S, \text{ with } S=4) \) and \( n \) is the index labelling each measurement inside each series \( (n=1,\ldots,N, \text{ with } N=200) \). The brackets notation
"<>_{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, Eq. (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 Eq. (3).

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

\[
\chi^2_i = \frac{\sum_{k=1}^{K} \left( \langle a_{ikSN} \rangle_{SN} - \langle<a_{ikSN} \rangle_{SN} \rangle_k \right)^2}{\sigma_{ik}^2}
\]  

(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 \( \chi^2_i \) for modes
\( i=3,\ldots,14 \). The horizontal lines correspond to \( \chi^2_c \), the critical \( \chi^2 \) above which a coefficient can be
considered to change significantly between gaze positions for a given confidence level \( P \). We
plotted the \( \chi^2_c \) 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) to accept that any significant change 
has been detected. Although the existence of these changes is of course not excluded, the $\chi^2$ 
results indicate that the observed differences of the Zernike coefficients 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 position, for instance at the primary position of gaze ($0^\circ$). 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

$$a_{i0^\circ s} = \frac{1}{N} \sum_{n=1}^{N} a_{i0^\circ sn} = \langle a_{i0^\circ sn} \rangle_n$$

(5)

$$\sigma_{i0^\circ s} = \sqrt{\frac{1}{N-1} \left[ \sum_{n=1}^{N} (a_{i0^\circ sn} - \langle a_{i0^\circ sn} \rangle_n)^2 \right]}$$

(6)

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

$$\chi^2_{i0^\circ} = \sum_{s=1}^{S} \left( \frac{\langle a_{i0^\circ sn} \rangle_n - \langle \langle a_{i0^\circ sn} \rangle_n \rangle_s}{\sigma^2_{i0^\circ s}} \right)^2$$

(7)

Figure 4 shows the mean values, Eq. (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 Eq. (6). Figure 5 displays the corresponding chi-

squared values, $\chi^2_{\text{H_0}}$, for the initial constant hypothesis. The horizontal lines correspond to the
critical $\chi^2_c$ above which the coefficients may be considered to change significantly, for the
confidence level $P$. As before, we plotted $\chi^2_c$ 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 ($a_6$) in PP. In the analyzed eyes, $a_5$ seems to change with the
same 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 can not observe in the terms $a_7$ and $a_9$.

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 kind of sources: there is an intrinsic variability due to microfluctuations in accommodation, tear film dynamics and possible medium to long term aberration drifts (Hofer et al., 2001; Kotulak and Schor, 1986; Iskander et al., 2004) and 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), 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 interseries 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 $rms$ gaze-related change of each aberration coefficient is just the $rms$ of the set of its (mean) values at the five gaze positions. Figure 6 displays these $rms$ upper bounds for modes $i=3$ to 14 of the three subjects. Their magnitude is higher for lower order modes, and ranges from 0.4 $\mu$m to 0.01 $\mu$m. The variability at each individual gaze position should be of smaller magnitude than these changes across positions, in order to these last ones be considered statistically significant. This result provides a guideline for the design of the next generation of experiments, which shall aim to reduce the overall (intrinsic plus extrinsic) variability at each gaze position at least by a factor of 4, 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 shows certain variability, 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 orbit muscles when turning to different gazes, at least within the range from 30 degrees temporal to 30 degrees 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 4 in order to check with more confidence the change of the ocular aberrations with gaze.

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References


Figure captions

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

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

Figure 3. $\chi_i^2$ value for each Zernike coefficient across the five gaze positions analyzed in this work. The solid line corresponds to the $\chi_i^2$ value for the degree of confidence $P$ indicated in each case.

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

Figure 5. $\chi_{iv}^2$ 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 $\chi_i^2$ 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.