

Effect of the polarization on ocular wave aberration measurements

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Measurement of the eye's wave aberrations has become fairly standard in recent years. However, most studies have not taken into account the possible influence of the polarization state of light on the wave aberration measurements. The birefringence properties of the eye's optical components, in particular corneal birefringence, can be expected to have an effect on the wave aberration estimates obtained under different states of polarization for the measurement light. In the work described, we used a psychophysical aberrometer (the spatially resolved refractometer) to measure the effect of changes in the polarization state of the illumination light on the eye's wave aberration estimates obtained in a single pass. We find, contrary to our initial expectation, that the polarization state of the measurement light has little influence on the measured wave aberration. For each subject, the differences in wave aberrations across polarization states were of the same order as the variability in aberrations across consecutive estimates of the wave front for the same polarization conditions. © 2002 Optical Society of America

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1. INTRODUCTION

The birefringence (i.e., dependence of the refractive index on the polarization state of light) of the whole eye and of its separate elements has been widely studied both *in vitro* and *in vivo* (for a review see Ref. 1). Most studies agree that the cornea contributes substantially to the birefringence of the eye.²⁻⁵ Corneal birefringence seems to arise from both the intrinsic properties of the collagen fibers composing the stroma of the cornea and from their arrangement in oriented layers, but whether it is uniaxial or biaxial is still a matter of discussion.³⁻⁶ Imaging polarimetry, which can be used to obtain spatially resolved Mueller matrices,^{7,8} reveals that corneal birefringence varies locally across the pupil, in a complex pattern that differs among subjects.⁴ Fibers composing the crystalline lens are also birefringent.¹ However, the total lens birefringence appears to be negligible, leading to the conclusion that the spatial arrangement of the lens fibers compensates for their intrinsic birefringence.^{9,10} Finally, the retina itself exhibits complex, inhomogeneous birefringence, dichroism, and depolarization properties.¹

Despite this evidence that the optical elements of the eye are birefringent, the possible effect of polarization is rarely considered in measuring the ocular wave aberrations (WA). When the current techniques are considered,¹¹⁻¹⁸ distinction can be made between those using natural light and those using polarized light. While subjective sensors tend to use natural light, many objective methods make use of cross polarization in illumination and detection pathways to remove corneal reflections. Furthermore, a specific polarization state of

light may be required by the presence of polarization-sensitive elements in the measurement device or in other components of the apparatus (e.g., liquid-crystal devices¹⁹). Nevertheless, all the sensors are assumed to provide estimates of the same WA. However, when interacting with a birefringent material, a light beam can be considered to be composed of two beams with orthogonal polarization states. These components are specific for the material and the propagation direction. Each component travels at a different velocity, meaning that the effective refractive index depends on the polarization state.²⁰ Corneal aberrations, depending on the corneal shape and index, could be expected to introduce polarization-dependent differences in the measured ocular WA, with local variations of corneal birefringence adding further complexity.

To our knowledge, this problem has been studied only in very recent work in which Mueller-matrix imaging polarimetry was used to analyze the effects of the illumination polarization state on the double-pass, modulation-transfer-function (MTF) estimates.²¹ From the small range of variability of the MTF, the authors concluded that the polarization state of the illumination has little effect on the ocular image quality and therefore little effect on the ocular WA. However, this is only an indirect measurement, since different WAs can produce similar MTF radial profiles. For example, rotation of the WA or sign reversals cannot be detected with this kind of analysis.

In this paper we present the results of WA measurements for four subjects and for a series of polarization states. A spatially resolved refractometer was used.²²

This device uses a psychophysical (subjective), single-pass procedure, as opposed to the objective methods that require a double pass through the optics of the eye. Most of the latter techniques measure the WA in the second pass; therefore it is difficult to select a certain polarization state of the measuring light (especially if a constant state across the pupil plane is desired), since it is modified by the first pass, by the retinal reflection, and by the second pass through the optics. Conversely, in the psychophysical method, only one pass through the optics of the eye is involved in the measurement of the ocular aberration. This means that we obtain single-pass estimates of the ef-

fect of the polarization state of the measurement light, which is easily and accurately controlled externally.

2. METHODS

The spatially resolved refractometer is described in detail elsewhere.²³ Briefly, it consists of two illumination channels and an eye monitoring channel that are combined by means of beam splitters. The reference illumination channel consists of a fixation target (composed of a

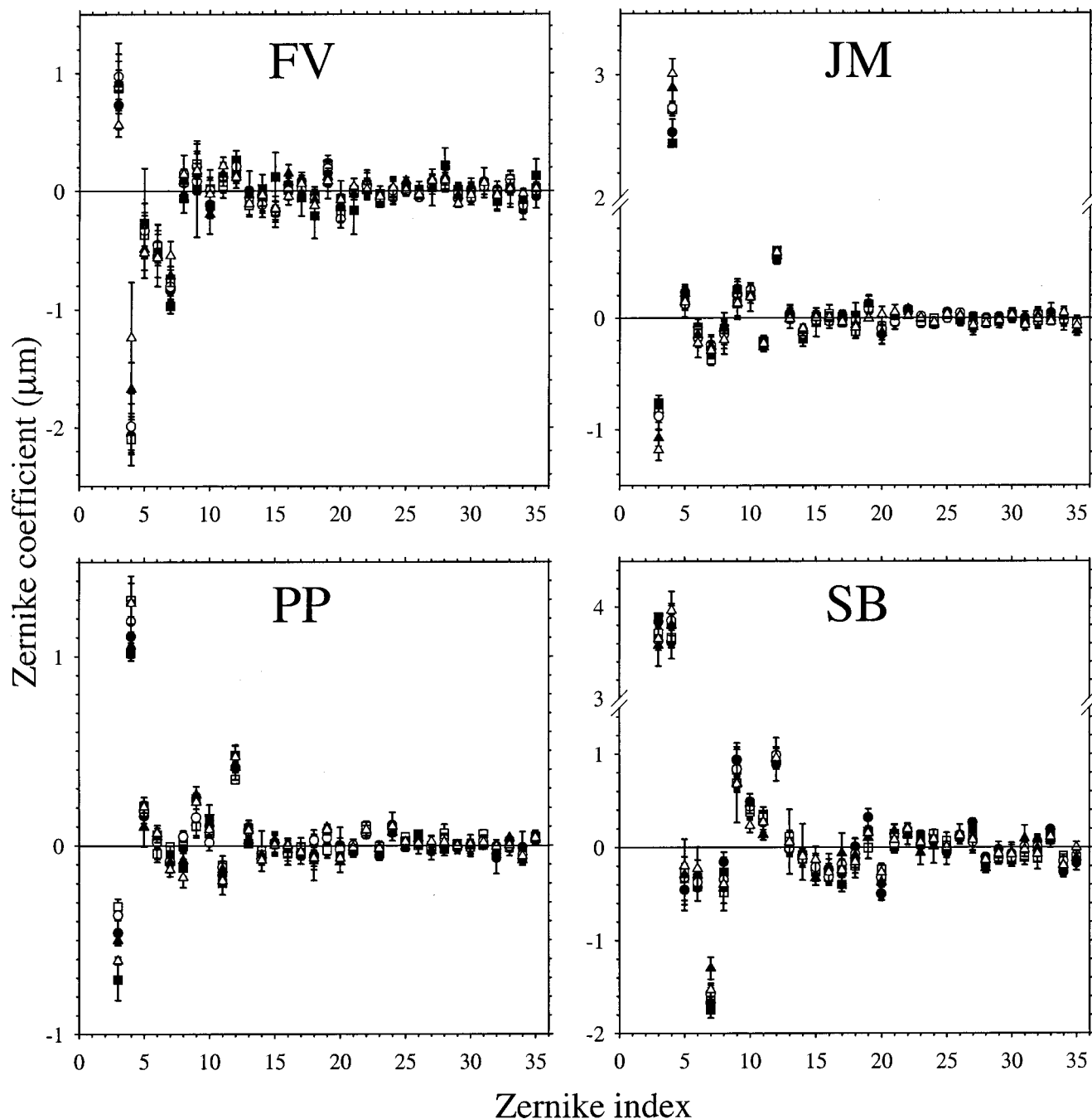


Fig. 1. Zernike coefficients (in OSA standard order) for different polarization states of the illumination light: natural light, solid squares; horizontal linear, solid circles; 45° linear, open squares; vertical linear, open circles; right-hand circular, solid triangles; left-hand circular, open triangles. The error bars represent the standard deviation across the three runs under the same conditions.

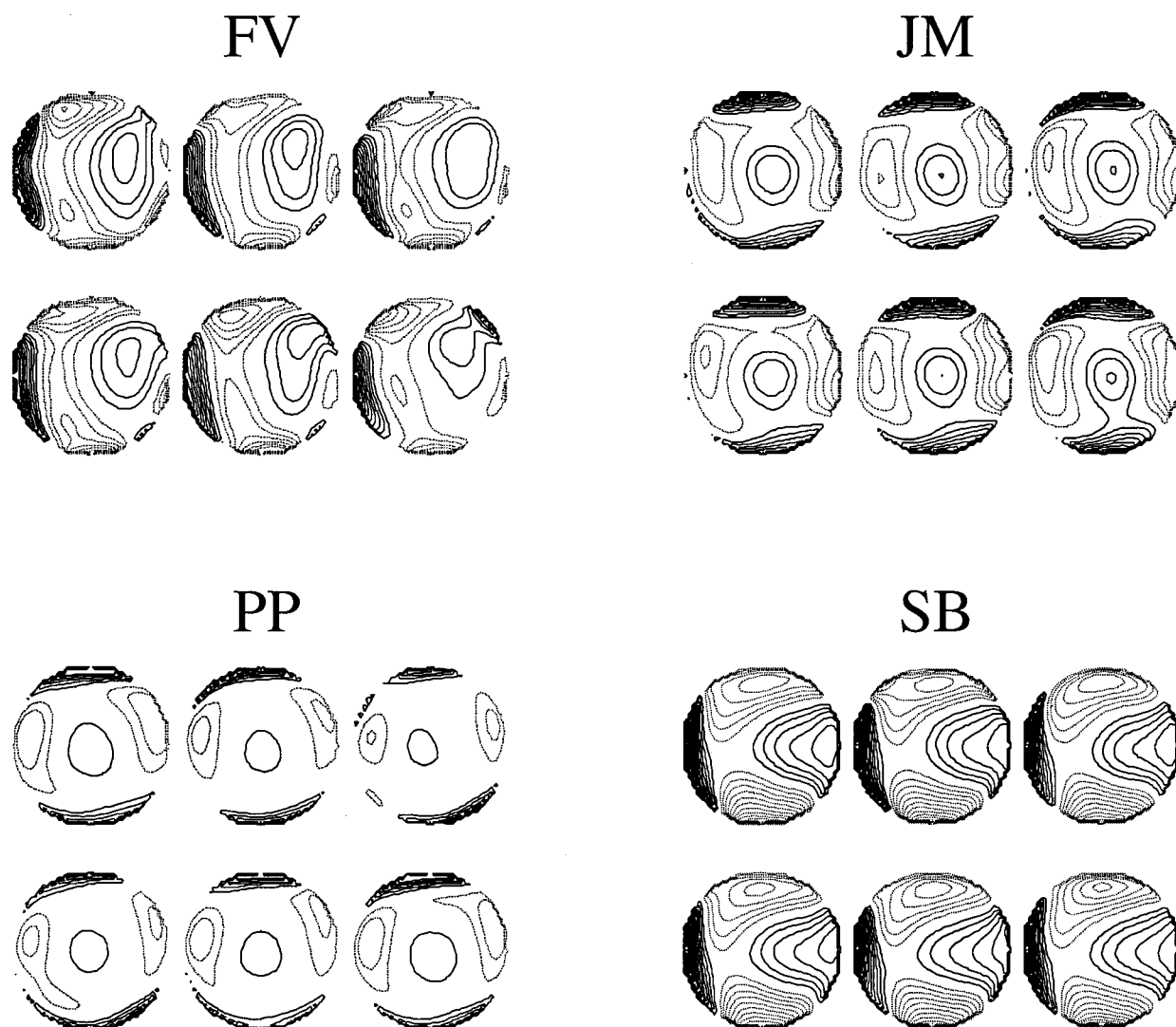


Fig. 2. Wave aberration maps from the Zernike coefficients in Fig. 1. Top row from left to right for each subject: natural, horizontal linear, and 45° linear light; bottom row: vertical linear, right-hand circular, and left-hand circular light. Contour line spacing is $\lambda/2$ except for subject SB (spacing is λ).

crosshair plus a fine structure) that is presented through an aperture centered in the subject's pupil. The test illumination channel consists of a movable spot presented through a small pupil (1 mm in diameter) that scans the subject's pupil (37 locations over a pupil 7.32 mm in diameter). The source for this channel is a broadband CRT monitor filtered by an interference filter (spectral centroid at 530 nm, 10 nm halfwidth, Ditrac Optics). The sources of both illumination channels are optically conjugate, as are the pupils. The monitoring channel is used to image the subject's pupil, and this image is used by the experimenter to align the eye's pupil to the apparatus. A focus corrector, consisting of a Badal system, is used to conjugate the reference crosshair and the test spot with the subject's retina. This is done by subjectively searching for the position of best focus of the fine structure of the reference target when the iris is fully open to reduce the depth of focus. The subject is instructed to align the movable spot with the crosshair for each of the 37 pupil locations. The spot displacement is proportional to the mean local derivative of the wave front (or ray aberration)

in that pupil location. The WA is obtained from this measurement by means of a modal fitting to the Zernike polynomial basis (through seventh order).

To measure the WA under different polarization conditions, a polarization state generator consisting of a linear polarizer and a $\lambda/4$ plate that can be individually rotated is inserted in front of the subject's eye. Polarization states used include natural (unpolarized), linear in several orientations, and circular. Placing the polarization generator after combining the reference and the test channels makes the system insensitive to effects of the polarization on the tip/tilt terms of the WA. However, the alternative locations are discarded because any subsequent reflections can affect the polarization of the light incident on the eye. In the current setup it is straightforward to select a polarization state. Moreover, an informal check of the global tip/tilt effect was performed in three of the subjects by placing a motorized rotating polarizer in the measurement channel before the combining beam splitter, thus leaving the reference channel with natural polarization. The axis of the polarizer was ro-

tated at ~ 1 Hz. Two of the subjects saw no motion of the measurement channel, and the third one saw a very small motion (less than the accuracy of the measurement system). This supports the idea that global tip/tilt effects are not large.

Four healthy male subjects were studied: FV, PP, JM, and SB, ages 30, 33, 36, and 50, respectively. Spherocylindrical refractions were $(+4.5, -0.75)$ for FV, $(-4, 0)$

for PP, $(0, -0.25)$ for JM, and $(-4.5, -2.5)$ for SB. The subject's pupil was dilated with one drop of tropicamide 1%. The WA was measured with natural light and five different states of polarized light: linear horizontal, linear vertical, linear 45 deg, right-handed circular, and left-handed circular. Three runs for each subject at each polarization state were averaged to increase the statistical accuracy of the method.

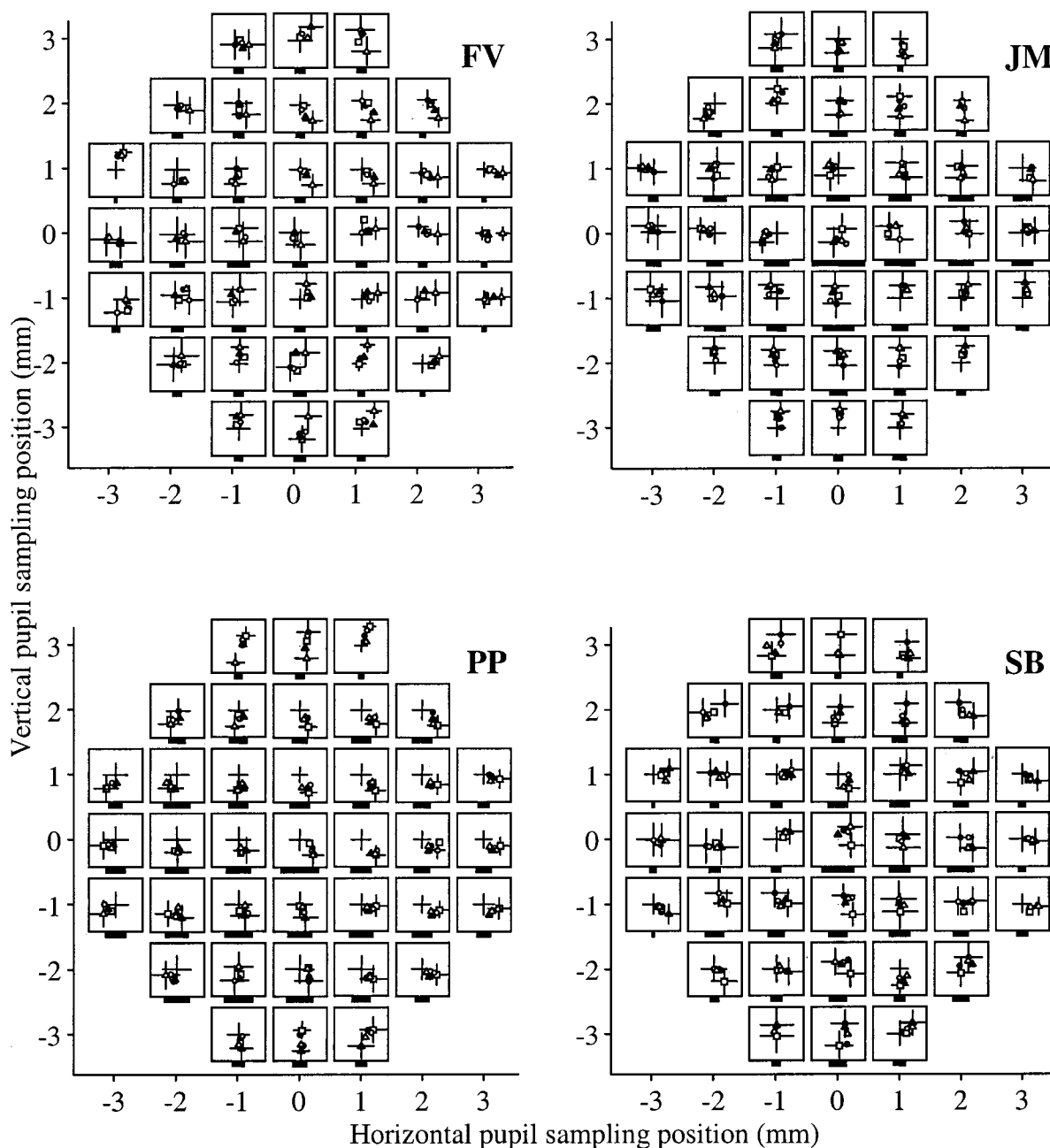


Fig. 3. Effects of the polarization on the ray aberration for each pupil location. In each case the center of the cell represents the natural light ray aberration, which is taken as the origin. Differences in the ray aberrations for other polarization states are represented by the positions of the symbols: solid circles, horizontal linear; open circles, vertical linear; open squares, 45° linear; closed triangles, right-hand circular; open triangles, left-hand circular. Scale in each cell is different to make more visible the polarization effects. The thick line below each cell represents a normalized 1-mrad segment for comparison purposes. Crosses centered on two of the symbols in each cell represent the normalized 95% confidence interval for the ray aberration on the corresponding pupil location. Confidence intervals have been represented only for the two extreme polarization effects, i.e., for the two symbols farthest apart in each cell.

3. RESULTS

In Fig. 1 the series of Zernike coefficients obtained for each subject with the different polarization states are plotted with error bars. Changes in the polarization state used for measuring the WA produce changes in the Zernike coefficients similar to or smaller than the typical variability of our measuring system, which is comparable with that of other current devices.²⁴

In Fig. 2 the corresponding WA maps are displayed. The WA shape is affected little by changes in the polarization state of the illumination light. Furthermore, the changes observed are similar to those reported for consecutive measurements for the same subject under the same conditions²⁵ and are assumed to come from slight dynamic changes of the WA.²⁶

One of the advantages of using a modal approach for WA reconstruction is that the spatial averaging improves the robustness of the findings in the presence of local noise. In this case, this means that the results displayed in Figs. 1 and 2 do not rule out the possibility that the polarization produces random, local changes in the WA. To address this issue, we examined the polarization effects for each pupil entry location. There were slight changes in the ray aberrations for some pupil locations with changes in the polarization of the illumination light. To emphasize these changes, we have calculated the differences between each polarization ray aberration and the natural light wave aberration for each pupil location and plotted them in Fig. 3. We have plotted these differences using the center of the corresponding cell as the origin for each sampling position.

For each pupil position and polarization state, the statistical accuracy of our system can be estimated by calculating the standard deviation of the WA derivative in the three runs. However, assuming the same kind of variability for the set of measurements for each point, a better estimate of the accuracy is obtained by averaging the standard deviation across polarization states. To compare the polarization effects with the precision of our measuring system, the 95% confidence intervals, calculated from the mean standard deviation for each pupil position, have been included in Fig. 3 for the two points with the largest distance between them.

Both the differences in the ray aberration and the confidence intervals tend to be smaller for central pupil locations than for eccentric ones. To clarify the differing polarization effects for different pupil positions, we have scaled these two angular variables, usually expressed in milliradians, differently for each panel in Fig. 3, making use of as much of the corresponding area as possible. A normalized 1-mrad segment has been included below each subpupil to allow comparison between the scales for the different panels.

In Fig. 3 it can be seen that in most cases, the two confidence intervals displayed clearly overlap. Since these two represent the extreme polarization effects with all the other data points scattered between them, we can conclude that individual polarization effects are usually below the accuracy of our measurement method.

It has to be pointed out that owing to the size of the entry pupil used in our spatially resolved refractometer (1

mm in diameter), the WA derivatives displayed in Fig. 3 actually correspond to a spatial average over the sampling pupil area. As a consequence, our system presents a limited spatial resolution, since any potential polarization effects at a smaller scale would be averaged.

4. SUMMARY

A single-pass measurement technique has been used to test for possible effects of corneal birefringence on estimates of the WA of the human eye calculated over a 7.32-mm-diameter pupil. No detectable differences have been found between the WA estimates obtained with natural light and those for different states of linearly and circularly polarized light. Furthermore, the differences in the local WA derivative measurements at each sampling point for each subject were either smaller than, or on the order of, the statistical accuracy of our experimental procedure. In conclusion, WA estimates obtained with different apparatus can be safely compared regardless of the polarization state of the illumination light they use.

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