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Combining coma with astigmatism can improve retinal image over astigmatism alone

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ABSTRACT

We demonstrate that certain combinations of non-rotationally symmetric aberrations (coma and astigmatism) can improve retinal image quality over the condition with the same amount of astigmatism alone. Simulations of the retinal image quality in terms of Strehl Ratio, and measurements of Visual Acuity under controlled aberrations with adaptive optics were performed, varying defocus, astigmatism and coma. Astigmatism ranged between 0 and 1.5 D. Defocus ranged typically between −1 and 1 D. The amount of coma producing best retinal image quality (for a given relative angle between astigmatism and coma) was computed and the amount was found to be different from zero in all cases (except for 0 D of astigmatism). For example, for a 6 mm pupil, in the presence of 0.5 D of astigmatism, a value of coma of 0.23 μm produced (for best focus) a peak improvement in Strehl Ratio by a factor of 1.7, over having 0.5 D of astigmatism alone. The improvement holds over a range of >1.5 D of defocus and peak improvements were found for amounts of coma ranging from 0.15 μm to 0.35 μm. We measured VA under corrected high order aberrations, astigmatism alone (0.5 D) and astigmatism in combination with coma (0.23 μm), with and without adaptive optics correction of all the other aberrations, in two subjects. We found that the combination of coma with astigmatism improved decimal VA by a factor of 1.28 (28%) and 1.47 (47%) in both subjects, over VA with astigmatism alone when all the rest of aberrations were corrected. Nevertheless, in the presence of typical normal levels of HOA the effect of the coma/astigmatism interaction is considerably diminished.

1. Introduction

In recent years, the availability of wavefront sensors and the renewed interest in understanding the sources and effects of aberrations on optical quality and vision, have motivated studies aiming at understanding the interactions between aberrations. Several studies have demonstrated the interactions between low and high order aberrations (HOA) (Applegate, Ballentine, Gross, Sarver, & Sarver, 2003; Thibos, Hong, Bradley, & Applegate, 2004). In particular, adding spherical aberration to defocus can improve retinal quality over defocus alone, indicating that cancelling defocus in the wave aberration Zernike polynomial expansion does not necessarily produce the best optical quality. As a consequence, the contribution of spherical aberration to the refraction needs to be considered (Cheng, Bradley, & Thibos, 2004; Guirao & Williams, 2003). Favorable interactions between other high order aberrations (HOA) must also be present. McLellan et al. showed that the actual combination of HOA found in eyes produced typically better Modulation Transfer Function (MTF) than most combinations of equal amounts of aberrations and random signs (McLellan, Prieto, Marcos, & Burns, 2006). Chromatic and monochromatic aberrations seem also to interact favorably: the relative degradation produced by longitudinal and transverse chromatic aberration of the eye on the MTF at short wavelengths with respect to the MTF at higher wavelengths is much higher in diffraction-limited eyes than in eyes with natural monochromatic aberrations (McLellan, Marcos, Prieto, & Burns, 2002).

The use of adaptive optics has opened the possibility to test vision under minimized, corrected or manipulated aberrations. Adaptive Optics has demonstrated that visual performance increases when correcting the aberrations of the eye (Dalimier, Dainty, & Barbur, 2008; Fernandez & Artal, 2003; Liang, Williams, & Miller, 1997; Marcos, Sawides, Gambra, & Dorronsoro, 2008; Sawides, Gambra, Pascual, Dorronsoro, & Marcos, 2010; Yoon & Williams, 2002). It also allows to manipulate the optics to study the effect of aberrations on accommodation (Chen, Kruger, Hofer, Singer, & Williams, 2006; Fernandez & Artal, 2005; Gambra, Saw-

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ides, Dorronsoro, & Marcos, 2009), to test the impact of certain aberrations such as spherical aberration on visual performance (Artal et al., 2004; Chen, Artal, Gutierrez, & Williams, 2007; Piers, Manzanera, Prieto, Gorceix, & Artal, 2007) or to test potential neural effects on visual performance (Artal et al., 2004; Chen et al., 2007; Piers et al., 2007; Sawides et al., 2010).

Besides defocus, astigmatism is one of the most frequent, and important aberrations of the eye (Vitale, Ellwein, Cotch, Ferris, & Sperduto, 2008), followed by coma (Castejon-Mochon, Lopez-Gil, Benito, & Artal, 2002; Howland & Howland, 1977; Thibos, Hong, Bradley, & Cheng, 2002). Apart from the natural astigmatism and coma that can be present in an eye on-axis, astigmatism and coma increases off-axis (Charman & Atchison, 2008; Gustafsson, Terenius, Buchheister, & Unsbo, 2001; Navarro, Moreno, & Dorronsoro, 1998). Certain pathologies increase progressively corneal astigmatism and coma (e.g. keratoconus) (Barbero, Marcos, Merayo-Lloves, & Moreno-Barriuso, 2002). Ophthalmic lenses may induce astigmatism and coma (Villegas & Artal, 2003). Some surgical procedures induce astigmatism and HOA, such as the corneal incision in cataract surgery (Marcos, Rosales, Llorente, & Jimenez-Alfaro, 2007).

While the management of astigmatism is in many cases straightforward with cylindrical or toric lenses, the understanding of potential interactive effects of astigmatism and coma is crucial. In many situations, the correction must come with complex optical designs (i.e. lenses aiming at reducing off-axis aberrations; progressive lenses, etc.). In other cases (i.e. cataract surgery) surgeons may play with the incision location to maximize optical quality. In customized corneal ablation procedures the surgeon may have the option of selectively correcting aberrations, and decoupling astigmatism and coma may be detrimental. Furthermore, the use of aberrometry for the measurement of astigmatism $\left(Z_2^{-2}\text{ and }Z_2^2\right)$ may not be optimal if interactions of coma and astigmatism are present.

In this study, we test the potential interactive effects of astigmatism $\left(Z_2^{-2}\text{ and }Z_2^2\right)$ and coma $\left(Z_3^{-1}\text{ and }Z_3^1\right)$ using computer simulations of retinal image quality and measurements of VA in subjects under controlled aberrations. We will demonstrate that optical/visual quality in the presence of astigmatism can be improved by adding coma (and vice versa).

2. Methods

2.1. Optical quality computer simulations

Point Spread Functions (PSFs) were computed for different combinations of astigmatism, coma and defocus using standard Fourier optics. The Strehl Ratio (SR) was used as an optical quality metric. Two dimensional maps of SR for fixed amounts of astigmatism and coma were generated, as a function of the orientation of astigmatism and coma ranging between 0° and 90° (at 3° steps).

SR was computed for astigmatism ranging from 0 to 1.50 D (1.38 μm) at 0.05 D steps and angles ranging from 0° to 90°. For a fixed amount of astigmatism, the amount of coma (and relative angle) that optimized SR was estimated. Coma values ranging from 0 to 1 μm were tested (at 0.02 μm steps). The simulations were done for different amounts of defocus, typically ranging from −1 to 1 D (at 0.02 D steps). Unless otherwise noted, the computations were performed for 6-mm pupil diameters, and λ = 555 nm. Simulations were performed setting all HOA to zero, and repeated for the natural HOA of two subjects (see Section 2.2), where coma and astigmatism were replaced by those of the conditions under test.

2.2. Experimental measurements

Measurements of Visual Acuity (VA) were performed on two subjects for different combinations of coma, astigmatism and defocus. The aberrations were manipulated using an adaptive optics system.

2.2.1. Experimental set up

We used an adaptive optics system developed at the Visual Optics and Biophotonics Laboratory (Instituto de Optica, CSIC, Madrid) and described in detail in previous publications (Gambra et al., 2009; Marcos et al., 2008; Sawides, Gambra, et al., 2010). The primary components of the system are a Hartmann–Shack wavefront sensor (composed by 32 × 32 microlenses, with 3.6-mm effective diameter and a CCD camera; HASO 32 OEM, Imagine Eyes, France) and an electromagnetic deformable mirror (MIRAO, Imagine Eyes, France) with 52 actuators, a 15-mm effective diameter and a 50-μm stroke. Illumination comes from a Super Luminescent Diode (SLD) coupled to an optical fiber (Superlum, Ireland) emitting at 827 nm. A 12 mm × 9 mm SVGA OLED minidisplay (LiteEye 400) is used to project high-contrast targets. The minidisplay has a nominal luminance of 100 cd/m^2, with a black level < 0.2 cd/m^2 (as calibrated using a ColorCal luminance meter/colorimeter, Cambridge Research Systems). A Badal system (mounted on a motorized stage) compensates for spherical error. A pupil monitoring channel, consisting of a CCD camera (TELI, Toshiba) conjugate to the pupil, is inserted in the system by means of a plate beam-splitter and is collinear with the optical axis of the imaging channel. The Hartmann–Shack system, deformable mirror, and closed-loop correction are controlled with custom software in C++ specifically designed for the current study. The routines control the generation and error measurement of the mirror states and the Badal system. They also control a subroutine in Matlab to perform the VA measurements. The process is fully automated, so that once one mirror state is created, no further interaction from the experimenter is required to load the mirror, check its performance, measure VA, check the validity of the VA measurements, and measure the aberrations after the VA measurement.

Wave aberrations were fitted to 7th order Zernike polynomials. We used the OSA convention for ordering and normalization of Zernike coefficients (Thibos, Applegate, Schwiegerling, Webb, & Members, 2000).

2.2.2. Subjects

The experiments were performed in the right eye of two male subjects. Subject CDD was 37 years old, with a refraction of +1.5 D sphere. Subject ANC was 30 years old and emmetrope. Both subjects had an ophthalmological evaluation before performing the experiments. Accommodation was paralyzed and the pupil was dilated with 1% tropicamide. Subjects signed a consent form approved by the institutional review boards after they had been informed on the nature of the study and possible consequences. All protocols met the tenets of the Declaration of Helsinki.

2.2.3. Experimental protocol

Visual Acuity (VA) was measured in two subjects for astigmatism alone (0.5 D), with and without coma, and with and without the HOA of the subject.

The measurements were repeated for different amounts of defocus: −0.6, −0.2, 0, 0.2, and 0.6 D, with respect to the best subjective focus (which may change across conditions). All defocus conditions were achieved by moving the Badal system. Spherical refraction was compensated by means of the Badal system. The experiments were performed under dilated pupils, with an artificial pupil of 6-mm placed in a plane conjugate to the pupil in the psychophysical channel.

A total of five series of through-focus VA measurements were performed on each subject in different conditions: (1) 0.5 D of astigmatism, all HOA corrected. (2) A combination of 0.5 D of astigmatism and 0.23 μm of coma (best combination predicted by simulations in absence of HOA), all other HOA corrected. (3) 0.5 D of astigmatism, 0 μm of coma and all the rest of HOA set to their natural values. (4) Natural aberrations replacing the natural astigmatism by 0.5 D and the natural coma by 0.23 μm. (5) Natural aberrations replacing the natural astigmatism by 0.5 D and the natural coma by the best coma parameters predicted for each subject's aberrations.

The angle of both astigmatism and coma was 45° (relative angle 0°), except in condition (5), where both angles (of astigmatism and coma) where the ones providing the best predicted optical combination with each subject's aberrations. Coma and astigmatism at a certain angle was achieved by combinations of Z_{3-1} and Z_{31} for coma and Z_{2-2} and Z_{22} respectively. Besides the through-focus series, two control measurements were performed in focus: All natural aberrations corrected and all natural aberrations uncorrected.

The tests were conducted in two different sessions. The first session involved the conditions with all HOA corrected and the second one involved the cases in which natural aberrations were present. Conditions within each session were randomly tested.

Decimal VA was measured using a four alternative choice procedure with high-contrast tumbling Snellen E letters. Subjects were asked to identify the orientation of the letter E (right, left, up, or down) that was displayed on the minidisplay, using a keyboard. The introduction of astigmatism at 45° in most experiments helps to minimize differences in blur for each of the four letter orientations. Each run consisted on 50 trials presented during 0.5 s with no feedback to the subject. A QUEST algorithm was programmed in Psychtoolbox (Brainard, 1997) to select the size of each stimulus and optimize the estimation of the spatial resolution threshold. Experiments were done for black E letters on a white background. The VA measurement was deemed satisfactory if the standard deviation of at least the 8 last trials (from a sequence of 50 trials) was less than 0.06 arcmin. Otherwise the VA measurement was considered incorrect and repeated. Typically, the standard deviation for repeated measurements of VA was 0.02–0.05 decimal VA. The effective luminance of the minidisplay for the subject was 25 cd/m^2. This value was estimated taking into account the light losses in the system.

The mirror state was achieved after a closed-loop of 40 iterations. Experiments were performed under a static state of the mirror, but the wave aberrations were periodically monitored to ensure that the deviations from the desired wave aberration pattern was achieved and used during the measurement. The aberrations of the eye + mirror were measured just before and after each VA run. If the amount of coma or astigmatism differed from the expected value by more than 0.10 μm (on average the discrepancy was 0.04 μm), the closed-loop operation to achieve the desired mirror state was performed again and the VA measurement repeated. The centration of the pupil was monitored just before, in the middle and after the VA run.

In summary, the procedure sequence of the experiment for each condition was: (1) refractive correction with the Badal system; (2) measurement of ocular aberrations with the Hartmann-Shack sensor; (3) closed-loop to set the mirror status (aberration correction + specific astigmatism/coma combination); (4) subjective focus setting with the Badal system; (5) repeat steps 2 and 3; (6) measurement of eye + mirror aberrations; (7) measurement of VA; and (8) measurement of eye + mirror aberrations.

3. Results

3.1. Optical quality simulations

The different combinations of astigmatism and coma produce significant changes in Strehl Ratio (SR), which depend on the relative angle between both, and the amount of defocus. Fig. 1 shows 2-D SR maps for fixed amounts of astigmatism and coma, at different angles. Each panel in the upper row represents a different amount of defocus (from −0.5 to 0.5 D). The rest of the HOA aberrations are assumed to be zero. The symmetry of the maps allows

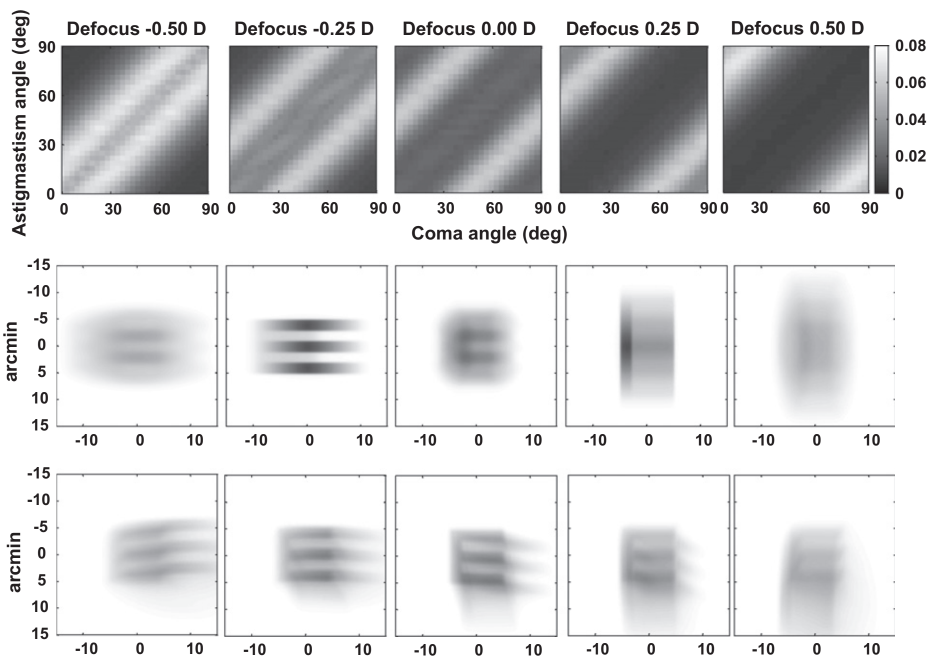

Fig. 1. Upper row represents Strehl Ratio maps for combinations of 0.5 D of astigmatism with 0.23 μm of coma, as a function of angle of coma and astigmatism. Each panel represents a different amount of defocus, ranging from −0.5 D to 0.5 D in steps of 0.25 D. The vertical axis represents angle of astigmatism. The horizontal axis represents angle of coma. Middle and bottom rows represent convolved letters for five different amounts of defocus, ranging from −0.5 D to 0.5 D in steps of 0.25 D. Middle row show convolved letters for astigmatism values of 0.5 D. Bottom row represents the condition of 0.5 D of astigmatism + 0.23 μm of coma for a relative angle of 45°. Pupil size 6 mm. Letter size is 10 arcmin.

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reducing the description in terms of relative angle, and each sequence of images can be summarized into one single 2-D plot. Convolved images are shown in the middle and bottom row for the same defocus values. The middle row represents the condition of only astigmatism and the bottom row the condition of astigmatism + coma. Legibility of the letters is higher in the condition with combined astigmatism + coma for all the amounts of defocus. In Fig. 2 SR is represented as a function of relative angle and defocus. We observe optimal combinations of relative angle and defocus that maximize optical quality. Alternatively for a fixed amount of astigmatism, one can find the amount of coma that maximizes optical quality through focus. Fig. 3 shows the SR through-focus for 0.5 D of astigmatism, and different amounts of coma. Fig. 3A represents SR for a relative angle of 0°, which is the relative angle that produces the highest SR value (see Fig. 2). Each line on Fig. 3A corresponds to the central horizontal section of a map such as that shown in Fig. 2. Fig. 3B represents the maximum SR at each defocus position, at the best relative angle.

We found that for a significant range of coma (0.15–0.35 μm) and for a relatively wide range of focus (>1.5 D), adding coma to astigmatism improves the optical performance over astigmatism alone (shown in solid black line). The same results stand for negative values of coma, being the SR values equal for any pair of ±μm of coma.

The same calculations were performed for a total of 31 amounts of astigmatism ranging from 0 to 1.5 D (at 0.05 D steps), and for two different pupil diameters (4 and 6 mm). Two dimensional maps of optical quality as a function of coma versus astigmatism were obtained (Fig. 4), for two pupil sizes, 4 mm in A and 6 mm in B. The area under the through-focus SR curves between −0.5 and +0.5 D was chosen as optical quality metric. The dashed red lines show the amount of coma for each amount of astigmatism that maximizes the metric. Combinations between the blue dotted line and the x-axis provide better performance than astigmatism alone (x-axis).

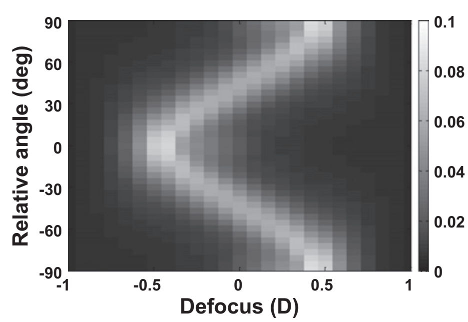

Fig. 2. Strehl Ratio for combinations of 0.5 D of astigmatism and 0.23 μm of coma at different defocus positions and relative angles. This map summarizes an entire sequence of maps like those shown in Fig. 1. Bottom row of convolved figures represent (from left to right) the condition of only 0.5 D of astigmatism for defocus values of −1, −0.5, 0, 0.5 and 1 D.

Fig. 4 shows again that there is a wide range of values of coma that improves optical quality in the presence of astigmatism (i.e. for 1 D of astigmatism and a 4-mm pupil, any value of coma up to 0.5 μm). Optimal combinations of coma and astigmatism (dashed red lines in Fig. 4) can be fitted by linear regressions. The following expressions are linear regressions to the data ($R^2 > 0.98$) and can be used to approximately obtain the optimal amount of coma (or astigmatism) to maximize Strehl Ratio for a given amount of astigmatism (or coma):

$$\text{Astigmatism (D)} = 0.404 \cdot \text{coma } (\mu\text{m}) + 0.040, \quad \text{for 6-mm pupil}$$
$$\text{Astigmatism (D)} = 0.204 \cdot \text{coma } (\mu\text{m}) + 0.013, \quad \text{for 4-mm pupil}$$

When astigmatism is expressed in μm, the slope of the linear fit and therefore the amount of coma that maximizes the metric is approximately ½ of the astigmatism-value for both pupils (slopes of 0.44 and 0.49 for 4-mm and 6-mm pupils respectively).

The simulations above assumed an eye in which only astigmatism and coma were present. We also performed computer simulations of Strehl Ratio using wave aberrations of real eyes (from the two subjects that participated in the experiment, described below). The presence of other HOA breaks the symmetries of Fig. 1, and the description in terms of relative angle is no longer valid. In our subjects, the best combination is provided by an astigmatism angle of 9° and a coma angle of 84° (corresponding to a relative angle of 75°) for subject ANC, and an astigmatism angle of 11° and a coma angle of 63° (relative angle 48°) for subject CDD. Fig. 5 represents the through-focus SR functions for different combinations of astigmatism (0.5 D) and coma (from 0 to 0.61 μm), as in Fig. 3, but in presence of the rest of the natural HOA, for the two subjects (ANC, 3A–C and CDD, 3D–F). The optical quality with the fixed angles providing the best combination for each subject is shown in Fig. 5A and D. Fig. 5B and E shows the SR with the best combination of angles at each defocus position. Fig. 5C and D represents the SR values for fixed angles of astigmatism and coma of 45°, i.e. the ones providing best optical quality in the absence of other HOA.

The improvement of astigmatism by adding coma is still present. For subject ANC, the combination of 0.5 D of astigmatism with 0.11 μm of coma increases performance by a factor of 1.13 (13%), over astigmatism alone, but the defocus range over which this occurs is narrower than in the absence of other HOA (Fig. 3). Furthermore Fig. 5B shows on average higher SR values than Fig. 3B, indicating that natural aberrations + astigmatism + coma can lead to better optical performance than astigmatism + coma + HOA corrected. For subject CDD, the combination of 0.5 D of astigmatism with 0.51 μm of coma increases SR by a factor of 2.44 (144%). In

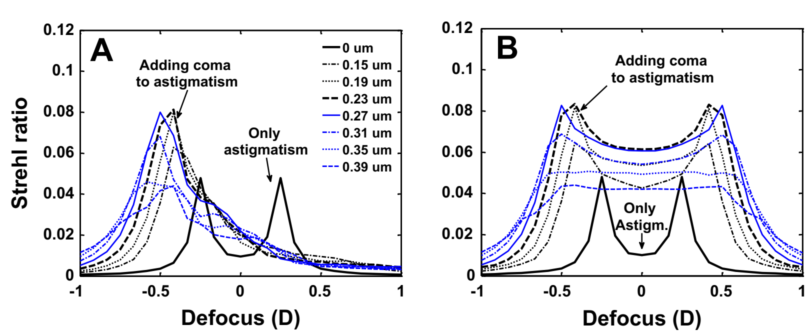

Fig. 3. Strehl Ratio for combinations of 0.5 D of astigmatism and different amounts of coma, ranging from 0 to 0.39 μm. (A) For a fixed relative angle of 0°. (B) For a varying relative angle giving the optimal SR at each defocus. Pupil 6 mm.

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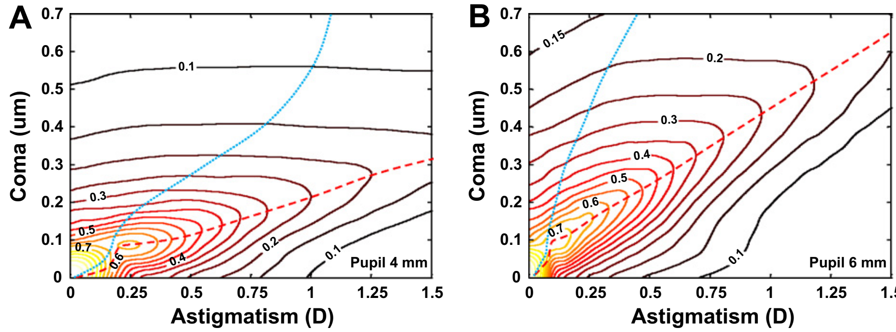

Fig. 4. Two dimensional maps of optical quality as a function of coma versus astigmatism. The height at each point of the map represents the value of the optical quality metric (area under the through-focus SR curves between −0.5 and +0.5 D), normalized to the diffraction limited condition (coma and astigmatism set to 0). The red dashed line represents the optimal combinations of coma and astigmatism that maximizes the area under the Strehl Ratio. Combinations below the blue dotted line provide better performance than astigmatism alone. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

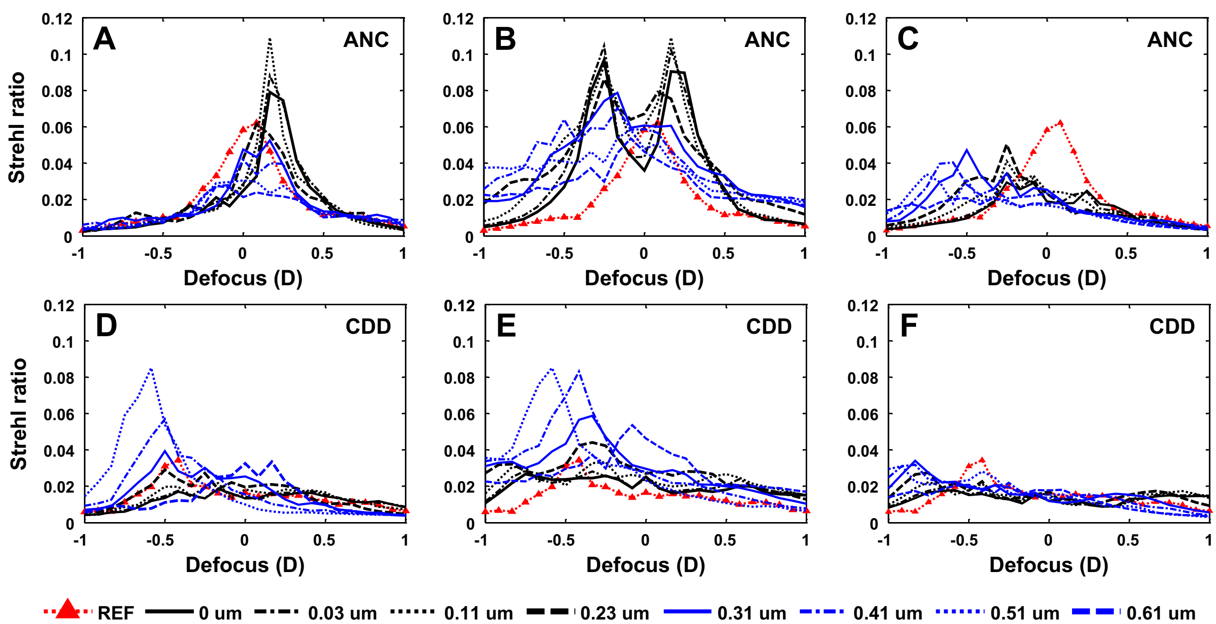

Fig. 5. Through-focus Strehl Ratio with real aberrations (Subject ANC, upper panels, CDD lower panels), in the presence of astigmatism (0.5 D) combined with different amounts of coma. Panels (A) and (D) represent the SR values for a fixed relative angle (75° for ANC and 48° for CDD, see text for details). Panels (B) and (E) represent the best SR values for the optical angles at each defocus position. Panels (C) and (F) represent the SR values for fixed angles of astigmatism and coma of 45°. The red dotted line (triangles – REF) represents the through-focus SR for the subject's own natural aberrations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the presence of HOA, the amount of coma that maximizes SR changes across individuals. For subject ANC, the condition producing the highest SR is 0.2 D of defocus and 0.11 μm of coma (at 84°, with astigmatism at 9°). For subject CDD, the condition producing the highest SR is 0.6 D of defocus and 0.51 μm of coma (at 63° with astigmatism at 11°).

3.2. Optical aberrations induction and correction

ANC had a natural astigmatism of −0.02 D at 160°, a natural coma of 0.10 μm at 60°, and a RMS_{HOA} of 0.214 μm for a 6-mm pupil diameter. CDD had a natural astigmatism of −0.17 D (at 144°), a natural coma of 0.15 μm at 30° and a RMS_{HOA} of 0.454 μm (for 6-mm pupils). The ocular HOA of the subjects were corrected down to 0.072 and 0.048 μm respectively (0 D defocus). The induced combinations of astigmatism and coma deviated from the desired state typically less than 1% (RMS wavefront error, as measured with an artificial eye), and on average 0.04 μm when measured on the subjects' eye.

3.3. VA measurements

Fig. 6 shows through-focus measurements of Decimal VA for a combination of 0.5 D of astigmatism and 0.23 μm of coma, and relative angle of 0°, for the rest of HOA corrected for both subjects. This combination of astigmatism and coma was shown to provide optimal improvement of optical quality in the simulations (with corrected HOA). Decimal VA with astigmatism alone and VA with natural aberrations (at best focus) are also shown as a reference. In the absence of HOA, both subjects show a dramatic improvement of VA when coma is added to astigmatism over at least a 0.5 D interval. When all aberrations are corrected VA is around 1.4. Adding 0.5 D of astigmatism reduces VA to about 0.8. However, adding 0.23 μm of coma increases VA by a factor of 1.25 for ANC and by a factor of 1.33 for CDD in the best focus conditions over the VA with astigmatism alone.

Fig. 7 shows through-focus VA results on the same subjects with natural HOA, for the same amounts of coma and astigmatism, and relative angle than the measurements shown in Fig. 6.

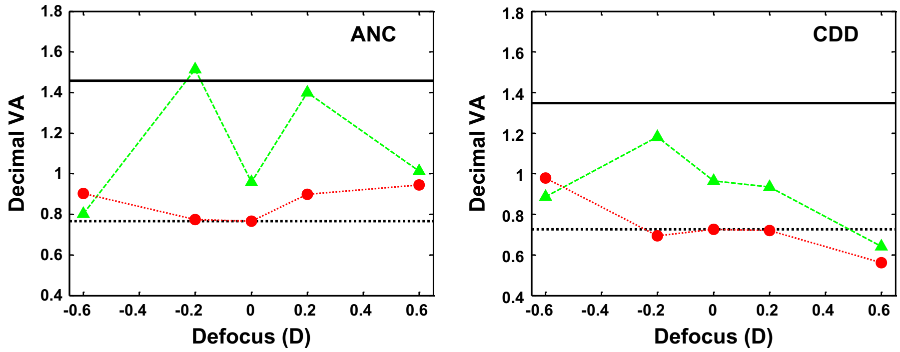

Fig. 6. Through-focus VA for corrected HOA. The green line (triangles) represents VA measurements with a combination of 0.5 D of astigmatism and 0.23 μm of coma, while the red line (circles) VA measurements for 0.5 D of astigmatism. The black solid line represents VA in focus for all aberrations corrected. Black-dotted line represents VA in focus with only 0.5 D of astigmatism (doted-dashed black lines represent its standard deviation values). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

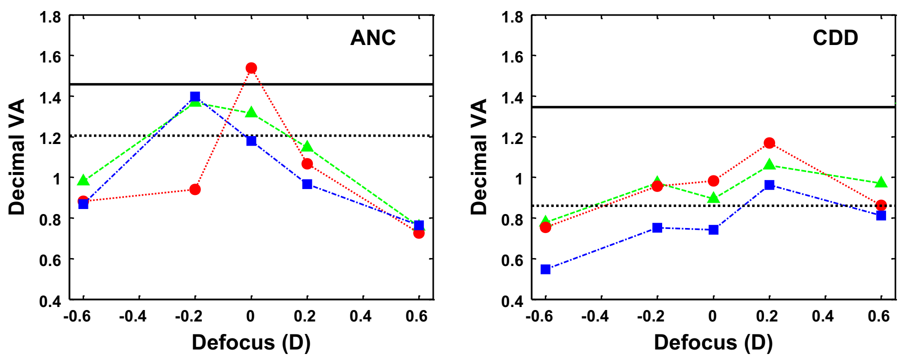

Fig. 7. Through-focus decimal VA for natural HOA. The green line (triangles) represents VA measurements with 0.5 D of astigmatism and 0.23 μm of coma; the red line (circles) represents VA measurements with 0.5 D of astigmatism; the blue line (squares) represents the VA obtained under the best condition obtained on the simulations for each subject with natural aberrations and 0.5 D of astigmatism (astigmatism angle 9° and coma 0.51 μm at 63° for CDD; astigmatism angle 11° and coma 0.11 μm at 84° for ANC). The black solid line represents VA in focus for all aberrations corrected. Black-dotted line represents VA in focus for natural aberrations (doted-dashed black lines represent its standard deviation values). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

VA was also tested under the best possible combination of astigmatism (0.5 D) and coma, (magnitudes and angles) as predicted by the simulations in the presence of the natural HOA of the subjects. Blue line (squares) represents VA values obtained under these optimized conditions.

For ANC, VA for the best combination is 1.40 ± 0.07, for CDD VA for the best combination is 0.96 ± 0.03, not showing improvement over the condition of astigmatism alone.

4. Discussion

We found that adding coma to astigmatism can improve Visual Acuity over the condition where only astigmatism is present. Simulations reveal that Strehl Ratio can be improved by 40% or more when adding coma to 0.5 D of astigmatism. For a 6-mm pupil the improvement hold for a range of at least 1 D of defocus and 0.20 μm of coma. When the natural aberrations were present, this improvement is very dependent on the subject's own aberrations, but there are specific amounts of coma and angles of coma and astigmatism that produce an improvement.

Previous works reported that combinations of certain types of aberrations (in particular symmetric aberrations such as spherical aberration and defocus) can produce higher optical quality than those aberrations individually (Applegate, Marsack, Ramos, & Sarver, 2003). We have demonstrated that the effects happen both optically (measured in terms of Strehl Ratio) and visually (in terms of high-contrast Visual Acuity) for asymmetric aberrations such as coma and astigmatism.

Adaptive Optics has allowed us to manipulate the optics of the eye, and measure visual performance after introduction of desired combinations of coma and astigmatism (either under correction or in the presence of natural aberrations).This approach allows the simulation of aberration patterns which may be adopted in the design of lenses or the simulation of induced aberrations by certain pathologies or surgeries that increase the amounts of aberrations and coma.

While presenting simulated retinal images to the subject has been shown to capture the interactive effects of monochromatic aberrations, and it is an inexpensive and valuable technique, the use of adaptive optics presents some advantages (De Gracia, Dorronsoro, Sawides, Gambra, & Marcos, 2009). First, by removing the natural aberrations of the eye one makes sure that all subjects are exposed to identical aberration patterns, without relying on the use of small pupils. Second, it allows testing directly the effect of correcting or inducing monochromatic aberrations, while maintaining the actual interactions with polychromatic aberrations (McLellan et al., 2002). Third, one does not rely on assumptions inherent to the computations of the retinal images concerning energy distribution and light propagation (Barbero & Marcos, 2008).

The results have important implications in the management of astigmatism correction and the evaluation of the optical aberrations induced by lenses, pathologies or surgery. For example, progressive spectacle lenses, induce astigmatism and coma; progressive corneal diseases such as keratoconus induce astigmatism and coma; astigmatism can be modulated by the incision location and size in cataract surgery, while astigmatism and coma may be modified in refractive surgery.

Our data show that in the presence of astigmatism, having certain amounts of coma improves optical and visual performance very substantially. Alternatively, the presence of coma can be attenuated by astigmatism. In the absence of other HOA the effect is very robust. Other metrics of optical quality where computed: VSOTF (Iskander, 2006; Marsack, Thibos, & Applegate, 2004) and the radial-averaged MTF for frequencies between 5 and 15 Hz ($rMTF_{515}$) (Legras, Chateau, & Charman, 2004). Both of them showed a similar trend and confirmed the beneficial effect of adding coma to astigmatism.

The effect is reduced in the presence of other natural aberrations. The range of conditions in which the improvement is produced by adding coma to astigmatism when natural aberrations are present is more restricted, and larger differences between the optical prediction and the VA might occur if slight discrepancies from the optimal conditions are present.

In our study we focused on fixed amounts of astigmatism and coma, which were varied experimentally with adaptive optics. We found that specific combinations of these aberrations produced optical and visual improvements. An interesting question is whether these optimal combinations may occur naturally. A study by McLellan et al. suggests that this may happen, at least in terms of signs (relative orientation of coma and astigmatism, among others), as the MTF generated by random combinations of signs of the Zernike terms were in general more degraded than that from the natural aberrations of the eye (McLellan et al., 2006). Our results suggest favorable or protective effects of other HOA against astigmatism. In both subjects VA with astigmatism and HOA (see Fig. 7) tends to be higher than VA with astigmatism alone (see Fig. 6).

We have found a relatively good correspondence between the effects revealed by SR and VA when all the natural aberrations are corrected in these two subjects. Additional simulations with residual aberrations predicted lower SR improvement rates than those assuming perfect correction (as considered in the simulations). In addition, it is expected that the SR metric does not capture all the effects as it refers only to contrast degradation, and not phase, which is likely relevant in the presence of asymmetric aberrations. On the other hand VA is affected by neural factors which cannot be captured optically. The difference in VA (see Fig. 6) between subjects under identical optical conditions arises from differences in neural stages of the visual process. Furthermore, neural adaptation may play a role in subjects with significant amounts of natural astigmatism (Webster et al., 2009).

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