Impact of positive coupling of the eye's trefoil and coma in retinal image quality and visual acuity

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When the eye's higher-order aberrations are measured and reported, as important as the magnitude of each individual term are the possible combinations between them, which may change the overall retinal image quality and therefore visual performance. We have evaluated the relationships among different aberration terms in the human eye—coma, trefoil, and spherical aberration—and their effects on both retinal image quality and visual acuity (VA). In a group of normal young subjects with normal to excellent vision, we measured the eye's aberrations and high contrast VA under natural conditions after carefully correcting defocus and astigmatism. Among the different combinations of aberration terms, we only found a significant negative correlation ($r2 = 0.30$) between the vertical coefficients of trefoil $C(3,-3)$ and coma $C(3,-1)$. This is a positive coupling that produces a better retinal image quality than any of the other possible combinations of these terms. However, this improvement in image quality is limited by the presence of other aberrations. Only in a few eyes that presented the larger values of coupled vertical trefoil and coma appeared a significant improvement of image quality. Although we did not find a clear correction between the coma-trefoil vertical coupling and VA, most eyes with large amounts of aberrations (RMS > 0.4 μm) have these terms coupled, keeping decimal acuity around 1.2 or higher. © 2012 Optical Society of America

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1. INTRODUCTION

The optical quality of the human eye imposes a fundamental limit to spatial vision. In recent years, the eye's optics has been characterized by measuring the wave-aberrations, expressed as expansion of Zernike polynomials, and its statistical properties have been determined in different studies [1–5]. While low-order aberrations, defocus and astigmatism, are the predominant terms, third-order aberrations (coma and trefoil) and spherical aberration may represent around 6% and 2%, respectively, of the total wave-aberration variance. The relative amounts of aberrations in groups of normal eyes were found to be similar in the different studies, but the type and nature of the correlation between them is still a controversial issue. Cagigal *et al.* [3] suggested that the human eye may follow the Kolmogorov model of a statistically homogeneous medium. Two previous works [1,4] obtained a random variation in the ocular aberrations of a large population, although a correlation between terms $C(3,-3)$ (trefoil) and $C(3,-1)$ (coma) was found in both studies. McLellan *et al.* [5] suggested that the eye's aberrations terms were not independent and their natural interactions actually improve the eye's modulation transfer function (MTF) with respect to random combinations of terms. On the other hand, in the statistical analysis of the ocular aberrations using Zernike coefficients, fictitious correlations may appear due to the estimation process [6]. It is important to emphasize that although it may be of practical interest, considering aberration terms independently can be erroneous, leading to inaccurate retinal image quality predictions. What actually matters is the overall impact of the aberrations on the retinal image quality, and this will surely be affected by different interactions among individual terms.

The total aberrations of the eye are the result of the combination of those produced mainly by the cornea and the lens. Several previous studies suggested that corneal aberrations are partially compensated by those of the internal media of the eye [7,8]. Horizontal coma is compensated mostly in hyperopic eyes due to their larger kappa angle [9,10]. However, despite this compensation mechanism, third-order aberrations may still present significant values in many eyes.

The eye's retinal image limits visual performance, but the exact relationship between optics and vision is not completely well determined yet. In order to predict the visual performance from the eye's optical measurements, in the last few years, several studies explored the relationships among optical and visual parameters. Some authors evaluated the correlation between visual acuity (VA) measured with computationally aberrated letters and optical metrics derived from wavefront aberrations [11]. In some previous studies, we proposed the use of the logarithm of the retinal image spread to predict VA [12,13]. However, the relationship between aberrations and visual performance can actually be quite complex due to neural adaptation effects [14,15]. For example, we showed recently that many subjects with excellent VA had normal levels of aberrations, while other subjects with near to diffraction-limited eyes simply reached standard values of VA, far from the subjects with excellent VA [16].

In this study, we used the dataset of aberrations and VA from [16] to further study how the different aberration terms are related and specifically how aberration terms coupling, in particular combinations of trefoil and coma, may affect retinal image quality and VA.

2. METHODS

We measured 60 eyes of 45 young subjects with age ranged between 19 and 35 years (average of 25 ± 4). Astigmatism and defocus were lower than 0.5 and 1.0 D, respectively. In every case, we measured both the optical aberrations and VA. All measurements were obtained for far vision under natural viewing conditions; that is, no drugs were used to either paralyze accommodation or dilate the pupil. The study followed the tenets of the Declaration of Helsinki, and signed informed consent was obtained from the subjects after the nature and all possible consequences of the study had been explained.

In each eye, the wavefront aberrations were measured using a custom-made Hartmann–Shack (HS) sensor [17]. From the images of the spots, we computed the Zernike coefficients (following the OSA standards [18]) and the root mean-squared (RMS) of the wave-aberration for the natural pupil size. The modulus and the direction of third-order aberrations were calculated from coefficients $C(3,-3)$ and $C(3,3)$ for trefoil, and $C(3,-1)$ and $C(3,-1)$ for coma. The orientation of third-order aberrations was considered as the vector with origin at the center and direction towards the positive increment of the wave-aberration. For example, if $C(3,-1)$ is zero and $C(3,-1)$ is positive, the orientation of coma is 270°. For trefoil, if $C(3,-3)$ is zero and $C(3,-3)$ is positive, the trefoil orientation will be 30°.

The associated point-spread function (PSF) was also calculated for each eye by setting defocus (coefficient $C(2,0)$) to zero. The Strehl ratio was determined as the quotient between the intensity peak in the eye's PSF and the diffraction-limited PSF, and used as an image quality metric. For each subject, astigmatism was measured with the HS sensor and then corrected using a custom device, consisting of two rotating 0.25 D-astigmatic lenses with variable cylindrical power from 0 to 0.5 D depending on the angle between the lenses. The residual (uncorrected) values of astigmatism were in all cases lower than 0.1 D, as measured with the HS sensor.

The series of VA measurements was obtained with both astigmatism and defocus corrected in each subject. A Badaloptometer permitted us to subjectively adjust the focus, starting from a myopic position to minimize the effect of accommodation, while the subject was looking a Snellen letter of 2.5 arcmin in size. VA was measured using a forced-choice procedure with Snellen letters being presented on a white-light screen, located at a distance of 8 m from the subject, with an average luminance of 100 cd/m^2. The pupil size was measured with an auxiliary CCD camera during each series of VA measurements (i.e., six times), and the average value was used to estimate the wave-aberrations. All measurements were obtained with natural pupil diameters, which vary from 5 to 8 mm. The subject's head was stabilized by a chin rest. Additional details on the experimental procedure and subjects details are in [16].

3. RESULTS

For the eyes of all subjects, the orientations of trefoil and coma as a function of their modulus are presented as a polar diagram in Fig. 1. Although in the case of trefoil, each wavefront value is repeated three times adding 120°, to allow an

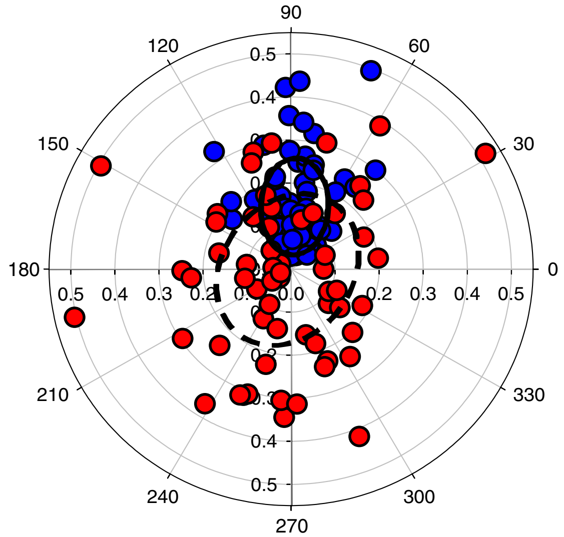

Fig. 1. (Color online) Polar plot of the orientation of trefoil (gray circles) and coma (white circles) as a function of modulus values of these aberrations, and confidence ellipses for trefoil (solid line) and coma (dashed line).

easier representation, only the values in the vertical component are shown. Confidence ellipses for both trefoil and coma are also included. For values of trefoil larger than 0.1 μm, the vertical direction of 90–210–330° is clearly predominant. This orientation is due to negative values of the term $C(3,-3)$ and smaller values of $C(3,3)$. Although the orientation of coma is more randomly distributed, the vertical orientation, especially to 270°, is more frequent than the horizontal direction. It is produced by small values of horizontal coma term $C(3,1)$ in relation to vertical coefficient $C(3,-1)$.

We explored the possible correlations among coma, trefoil, and spherical aberration. Figure 2 shows the relationship between horizontal coma and trefoil (A), between spherical aberration and coma (B) and trefoil (C). We did not find any correlation (R-squared values below 0.04 and p-values higher than 0.11) for any of these combinations. However, there was a significant negative correlation (R-squared 0.30, and p-value <0.0001) between vertical trefoil ($C(3,-3)$) and coma ($C(3,-1)$), as shown in Fig. 3. In many eyes, negative trefoil term $C(3,-3)$ was combined with a positive coma term $C(3,-1)$. In particular, this coupling is more evident in 18 eyes (30% of tested eyes), which have vertical terms of trefoil and coma with opposite sign and magnitude higher than 0.1 μm.

In order to better understand the effects of the terms coupling in the retinal image, we simulated retinal images for different combinations of coma and trefoil. Figure 4 shows examples with the combination between vertical terms of trefoil and coma and the situation with coma rotated 180°. The wave-aberrations and the associated PSF produced by a $C(3,-3)$ of -0.2 μm and a $C(3,-1)$ of $+0.2$ μm, both individually and in combination, are shown in Fig. 4(a). The black vectors depicted on the aberration maps indicate the orientation of coma and trefoil. When trefoil and coma have opposite orientation, their combination provides a beneficial effect that improves the image quality. The Strehl ratio is higher in the combination (0.29) than for each isolated term (0.14 and 0.17), although the RMS is higher for the combination (0.28 μm). The combination of terms $C(3,-3)$ and $C(3,-1)$ with the same sign

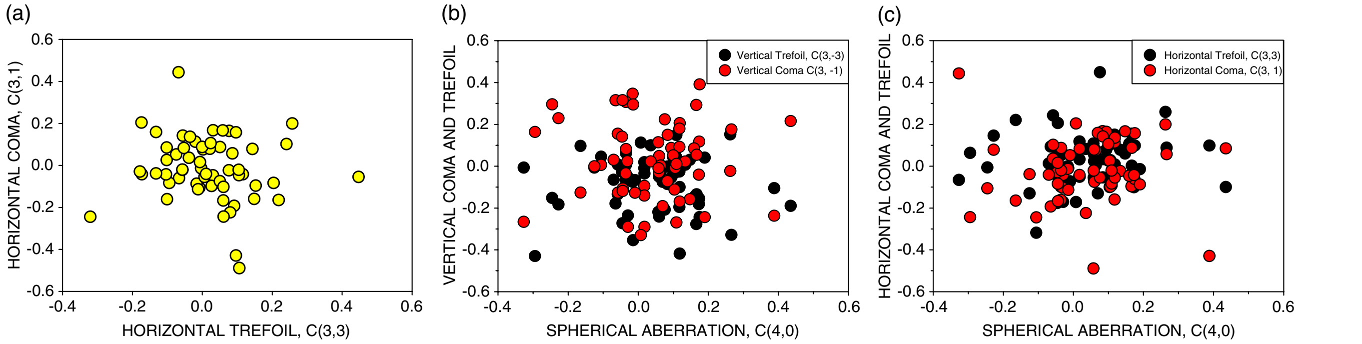

Fig. 2. (Color online) Relationship between (a) horizontal terms of trefoil $C(3,3)$ and coma $C(3,1)$, (b) spherical aberration, $C(4,0)$, with vertical coma, $C(3,-1)$, and trefoil, $C(3,-3)$, (c) spherical aberration, $C(4,0)$, with horizontal coma, $C(3,1)$, and trefoil, $C(3,3)$. In all these graphs, R-squared <0.04, p-values >0.11.

is occurring less frequently in the eye, especially for large magnitudes. The simulated images for this case are shown in Fig. 4(b) for values of −0.2 μm. This combination produces a reduction of Strehl ratio with respect to each isolated coefficient, from 0.09 to 0.14 and 0.17, respectively. Thus, when trefoil and coma have the same orientation, negative coupling degrades the retinal image quality.

The vertical terms of coma and trefoil appear coupled in many eyes. These eyes should have a better image quality than others with a similar amount of aberrations. Figure 5 shows the relationship between image quality expressed by Strehl ratio and the amount of high-order aberrations expressed by RMS of all tested eyes distributed in three groups depending on the combination between terms $C(3,-3)$ and $C(3,-1)$: one or both terms below 0.1 μm (a), both terms larger than 0.1 μm with positive (b), and negative coupling (c). Most eyes with higher values of total RMS (>0.4 μm) have vertical terms of coma and trefoil higher than 0.1 μm, 16 of 19 eyes (84%), and the majority of them, 14 of 16 eyes, have these terms coupled. However, in only four of these cases, the Strehl ratio is maintained in similar values (>0.07) to the other ones with lower values of RMS (<0.4 μm). In the rest of eyes with coupling, the Strehl ratio decreases as RMS increases up to 0.4 μm, and then up to 0.7 μm, the Strehl ratio is stabilized around 0.05. In addition, the two eyes with uncoupled terms $C(3,-3)$ and $C(3,-1)$ and RMS larger than 0.4 μm also have similar values of Strehl ratio, around 0.05.

Figure 6 shows the VA as a function of RMS, for the three groups with different combinations of terms $C(3,-3)$ and $C(3,-1)$. In eyes with vertical coupling of coma and trefoil, VA decreases as RMS increases (linear correlation: $R\text{sqr} = 0.41$, $p\text{-value} = 0.004$). In the group of eyes with coma-trefoil coupling, two of them have an RMS below 0.35 μm and high values of VA (around 1.9); however, there is a great variability in the VA (from 1.0 to 1.7) in the cases with RMS between 0.35 and 0.60 μm, and for higher values of RMS (>0.60 μm), VA is around 1.2.

Table 1 and Fig. 7 show three examples of eyes with similar values of total RMS but with different combinations of vertical coma and trefoil. The first one (geld) has a significant coupling between these terms and low values of the rest of aberrations, which provides good retinal image quality, and a Strehl ratio of 0.13. In the second one (sgmd), the effect of coupling in the image quality is limited by the presence of other high-order aberrations, especially by $C(3,3)$, $C(4,-4)$, and $C(4,0)$, and the Strehl ratio is low, 0.03. In the last case (nhmi), $C(3,-3)$ and $C(3,-1)$ have the same sign with a small impact of other high-order aberrations, and the image quality is degraded, with a Strehl ratio of 0.04. It is interesting to note that in these three eyes, there were no correlation between optical quality

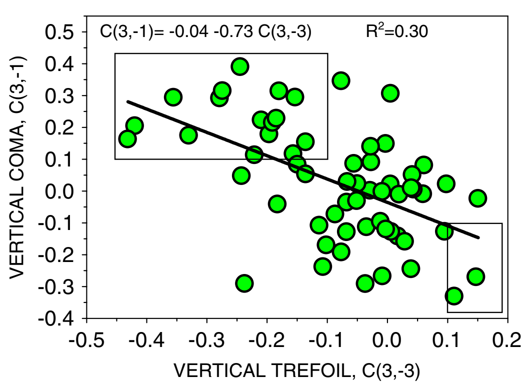

Fig. 3. (Color online) Correlation between vertical terms of trefoil $C(3,-3)$ and coma $C(3,-1)$. Squares include vertical terms of trefoil and coma opposite in sign and higher than 0.1 μm.

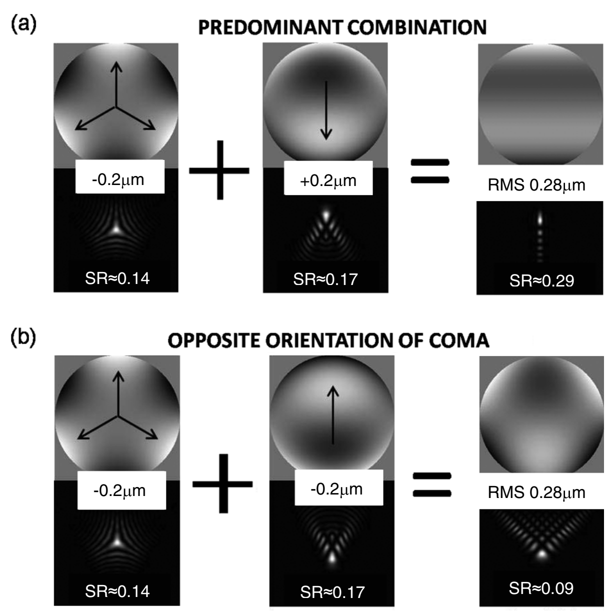

Fig. 4. Simulated examples of wave-aberrations and associated PSF for (a) predominant combination between vertical terms of ocular trefoil and coma and (b) for coma with opposite orientation.

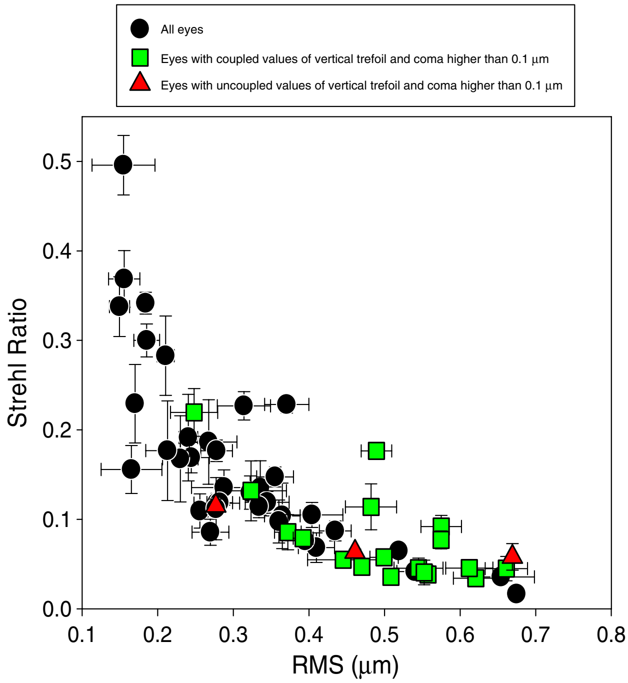

Fig. 5. (Color online) Retinal image quality (Strehl ratio) as a function of total amount of aberrations (RMS) of all tested eyes, with vertical terms of coma or trefoil below 0.1 μm (black circles), with terms over 0.1 μm: coupled (white squares) and uncoupled (gray triangles).

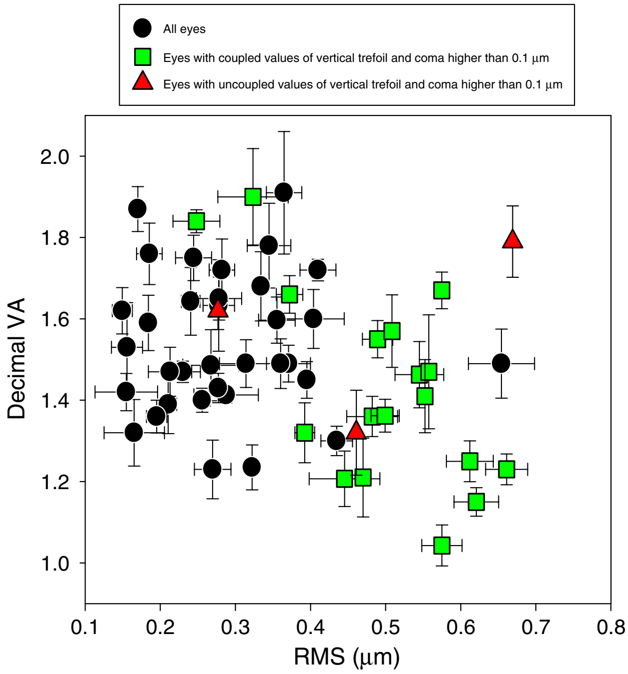

Fig. 6. (Color online) VA as a function of RMS of all tested eyes, with vertical terms of coma or trefoil below 0.1 μm (black circles), with terms over 0.1 μm: coupled (white squares) and uncoupled (gray triangles).

and VA. While the values of RMS were similar, between 0.46 and 0.51 μm, VA was different, 1.36, 1.57, and 1.15 (Strehl ratios were 0.13, 0.03, and 0.04, respectively). We have only studied the coupling between the vertical terms of coma and trefoil, but it can be interesting also to explore the level of coupling between total (modulus) values of coma and trefoil. To quantify this, we calculated a coupling factor (CF) that consists of relating the natural image quality with respect to that calculated with coma rotated to the opposite direction. The image quality is evaluated using the natural logarithm of the Strehl ratio (lnSR). The CF is given by expression [1], corresponding to a positive coupling (improving the retinal image) for values larger than 1 and a negative coupling (degrading the retinal image) for values lower than 1, respectively. When CF is equal to lower than 1, the ocular trefoil and coma are not coupled. For example, if the case of Fig. 4(a) would correspond to a real eye and Fig. 4(b) is the same eye but with coma rotated to opposite direction, the ln_SR of natural WA is −1.6, and with rotated coma is −2.8, giving a CF of 1.95.

Table 1. Wavefront Aberrations, Optical Parameters (RMS and Strehl Ratio) and VA of Three Representative Eyes with Different Scenarios of Combination Between Coefficients $C(3,-3)$ and Coma $C(3,-1)$

		Eyes					
		geld		sgmd		nhmi	
		Mean	SD	Mean	SD	Mean	SD
Zernike coefficients	3	−0.02-0.02	0.08	−0.06	0.02	0.12	0.02
	5	−0.07	0.12	−0.08	0.06	0.04	0.02
	6	**−0.27**	0.03	**−0.18**	0.02	**−0.24**	0.03
	7	**0.31**	0.02	**0.23**	0.06	**−0.29**	0.03
	8	0.01	0.00	0.08	0.03	−0.04	0.02
	9	0.00	0.06	0.14	0.05	−0.17	0.00
	10	0.08	0.00	0.23	0.03	−0.02	0.03
	11	−0.03	0.01	−0.05	0.02	0.00	0.02
	12	−0.04	0.05	−0.23	0.01	−0.03	0.02
	13	−0.05	0.04	0.00	0.01	0.06	0.03
	14	0.11	0.00	0.09	0.01	0.08	0.00
RMS		0.48	0.03	0.51	0.00	0.46	0.02
Strehl ratio		0.13	0.03	0.03	0.00	0.04	0.00
VA		1.36	0.05	1.57	0.09	1.15	0.10

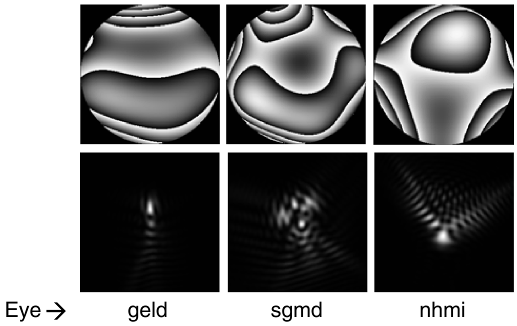

Fig. 7. Wavefront aberration maps and associated PSFs of three representative eyes (optical and VA data in Table 1).

$$\mathrm{CF} = \frac{\ln \mathrm{SR}_{\mathrm{OPPOSITE\,COMA}}}{\ln \mathrm{SR}_{\mathrm{NATURAL}}} \quad \begin{array}{l}\mathrm{CF} > 1 \rightarrow \mathrm{POSITIVE\ COUPLING} \\ \mathrm{CF} < 1 \rightarrow \mathrm{NEGATIVE\ COUPLING}\end{array}. \tag{1}$$

Figure 8 shows the CF values for all tested subjects as a function of their VA. In many eyes with VA below 1.5, there are important changes in image quality when coma is rotated, but in both directions improving and degrading, which does not indicate a predominance of positive coupling between modulus of coma and trefoil. Most eyes with VA higher than 1.5 have a CF value around 1. This is due to the small values of trefoil and coma in the majority of subjects with high values of VA. The natural combination between modulus of coma and trefoil provides a random image quality, due to no-coupling of horizontal terms and the presence of other high-order aberrations. In general, eyes with positive coma-trefoil coupling do not present better VA.

4. DISCUSSION

We have explored the relationship among some specific aberration terms (trefoil, coma, and spherical aberration) present in the eyes of a group of normal subjects and their VA. What really matters to impact vision is the overall combination of the different terms to form the final retinal image. When considered isolated, the magnitude of the aberrations terms can be misleading. Interestingly, we identified subjects that, in spite of having relatively large aberrations, still reported a good VA. In those cases, vertical terms of trefoil and coma were the predominant aberrations and they were negatively correlated. This type of positive coupling produces an improved retinal image quality. However, we found that the beneficial effect of this positive coupling mechanism is reduced by the presence of the other high-order aberrations. In agreement with previous studies, our results further support that the eye's RMS is a poor descriptor of the quality of vision. Two eyes having a similar RMS may have a different type of coupling among terms resulting in a distinct retinal image.

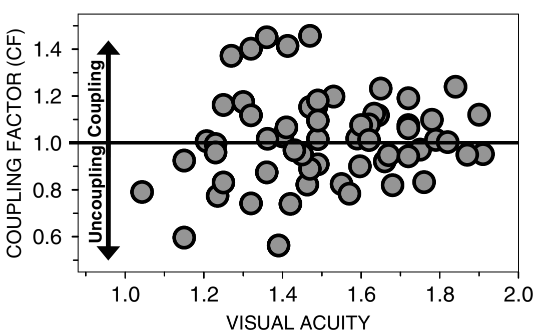

Fig. 8. CF (ratio between natural image quality and that calculated with coma rotated to the opposite direction) with respect to the VA.

The compensation mechanism between cornea and internal media [7,8] optimizes the total optical quality of the human eye for some of the predominant aberrations (astigmatism, spherical aberration, and horizontal coma). However, the vertical components of trefoil and coma seem to not be affected by this type of mechanism [19,20]. However, these terms are not random since in many eyes it appears that vertical trefoil is coupled with coma. In a previous study, Thibos *et al.* [4] also reported a similar negative correlation (R-squared of 0.28) of these aberration terms.

Although this coupling produces an improved retinal image quality, this is not apparent in most eyes due to the influence of the other higher-order aberrations.

Moreover, we did not find a clear correction between the coma-trefoil vertical coupling and VA, but most eyes with large amounts of aberrations ($\mathrm{RMS} > 0.4\ \mu\mathrm{m}$) have these terms coupled, keeping decimal acuity around 1.2 or higher. In eyes with large values of RMS, although the image quality is deteriorated, the VA is maintained in normal values. The positive coupling of some terms could provide some protective mechanism to maintain a good retinal image quality in those cases where some terms are larger than normal. Based on our current results, this is, however, a mere speculation and the reason could be due to the eye's biomechanics. Previous studies [2] reported on the high correlation between aberrations of fellow eyes. In our work, we measured 60 eyes of 45 subjects (15 fellow eyes), and it could have implications in the relationship between vertical components of coma and trefoil. However, in 45 independent eyes, we obtained a very similar negative correlation between $C(3,-3)$ and $C(3,-1)$ (R-squared 0.29, and p-value <0.0001).

An additional important issue to be explored is the underlying reasons within the eye structures that produced the observed coupling between these terms. This could have some practical implications to design both ophthalmic elements and refractive surgery procedures that could maintain or enhance the positive coupling of some of the aberrations. For example, progressive power lenses could be designed to couple their third-order aberrations [21] in combination with those of the eye, or presby-LASIK procedures could be enhanced by fine tuning the patient's natural coma and trefoil.

In conclusion, we found that in young subjects with normal and excellent VA, there was a significant positive coupling between the vertical terms of trefoil and coma. We did not find any significant correlation among the other different measured aberration terms. In absence of other aberrations, the positive coupling of coma and trefoil produces a better retinal image quality. In most normal eyes with high values of aberrations (RMS), vertical terms of trefoil and coma are the predominant aberrations. The influence of the other aberrations limits the effect of the coupling on the image quality, but the VA remains in normal values.

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