Optical Quality of the Eye in Subjects with Normal and Excellent Visual Acuity

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Purpose. To study the relationship between visual acuity (VA) and the eye's optical quality in subjects with normal and excellent spatial vision. VA ranged from decimal values of 1.0 (20/20) to 2.0 (20/10) when defocus and astigmatism were carefully corrected.

Methods. In 60 eyes of young subjects, visual and optical performance with the natural pupil were measured. A forced-choice procedure was used to measure tumbling-E high-contrast VA (HCVA) and low-contrast VA (LCVA). Wavefront aberration (WA) was measured using a Hartmann-Shack sensor. The associated point-spread function (PSF) and modulation transfer function (MTF) were also estimated. High-order aberrations (HOA) and several image quality parameters were represented as a function of VA. Subjects were classified into three groups according to their VA, and average optical parameters were calculated.

Results. Coma and trefoil vary between 0 and 0.5 μm, and spherical aberration ranges from -0.40 μm to $+0.45$ μm, with an average value of approximately zero. LCVA is not correlated with any of the aberration terms. Coma and spherical aberration are not correlated with HCVA. However, eyes with trefoil equal to or higher than 0.25 μm have an HCVA less than 1.5. The average optical quality in eyes with HCVA greater than 1.4 is slightly better than in eyes with normal VA. However, some eyes had relatively poor image quality and excellent VA.

Conclusions. No significant correlations were found between VA measurements and the optical quality of the eye in young subjects with normal or excellent spatial vision. Some subjects with normal degrees of aberrations attained excellent VA. (*Invest Ophthalmol Vis Sci.* 2008;49:4688–4696) DOI:10.1167/iovs.08-2316

The optical quality of the human eye imposes a fundamental physical limit to visual performance. The eye, like any other optical instrument, is affected by aberrations that blur the retinal image.[1,2] Subjects with eyes affected by large amounts of aberrations have poor spatial vision.[3] However, the impact of the eye's optical quality in subjects with excellent vision is not well understood. We may anticipate different possible scenarios: one is the idea that perfect diffraction-limited optics (limit zero aberrations) would produce the highest visual acuity (VA). In addition, it has been also speculated that some aberration patterns are best suited to produce good visual performance. Another option, supported by recent results showing a neural adaptation to the aberrations,[4] would be that the subject's own aberrations provide the best performance. It should be pointed out that the nature and magnitude of the neural adaptation is still controversial, with a recent study[5] suggesting a limited impact (approximately 12%) to the amount of higher-order aberration correction that produces the best subjective image quality.

The relationship between optical quality and visual performance has been studied in the past using computationally aberrated letters in the context of defining image quality metrics[6] and measuring VA as a function of defocus.[7] The use of adaptive-optics visual simulators provides a powerful tool to better understand this problem. The complete correction of high-order aberrations (HOA) significantly improves visual performance.[8,9] Correction of some particular aberration terms, in particular spherical aberration, also produces improvement in visual acuity and contrast sensitivity.[10,11]

These previous studies using adaptive optics seem to indicate that subjects with better than normal spatial vision should have eyes with nearly perfect ocular optics (negligible amounts of aberrations). However, we reported (Artal P, et al. *IOVS* 2005;46:ARVO E-Abstract 3615) that most subjects with excellent natural VA had normal amounts of HOA and even small amounts of astigmatism. Levy et al.[12] measured HOA in young subjects with natural uncorrected VA equal to or better than 20/15 through a dilated pupil, finding values of HOA similar in magnitude to those reported for myopic eyes. Applegate et al.[13] estimated several optical metrics in subjects with high-contrast VA better than 20/17. The population in their study covered a large range of ages (22–63 years) and refraction (sphere and cylinder ranges: -6.25 D to $+3.00$ D and -5.00 D to 0.00 D), and measurements were taken through dilated pupil. Their results showed that retinal image quality metrics did not predict well the high-contrast VA for photopic conditions, but predictions were better for lower contrast and luminance values.

Here, we report data on the relationship between optical and visual performance in young near-emmetropic subjects with visual acuity between 20/20 and 20/10. We have performed this study to determine the eye's optical quality in subjects with good VA to be compared with subjects with normal VA. Optical and visual measurements were taken with natural pupil diameters at best focus and with astigmatism corrected with a crossed-cylinder device (Villegas EA, et al. *IOVS* 2006;47:ARVO E-Abstract 1173).

Methods

Subjects

To identify subjects with excellent natural VA, we organized a competition among the students of our university to find those with the highest VA. We performed a screening test for a group of young subjects with decimal high-contrast VA (1/minimum angle of resolution [1/MAR]) better than 1.0. In addition, two refractive conditions had to be fulfilled: defocus within -1 and $+1$ D and astigmatism equal

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to or lower than 0.5 D. We found 60 eyes of 45 subjects with VA uniformly distributed from 1.0 (20/20) to 2.0 (20/10) when defocus and astigmatism were corrected. They had normal results on a standard ophthalmologic examination, and their ages ranged from 19 and 35 years (average, 25 ± 4 years). All measurements were obtained under natural viewing conditions (ie, accommodation was not paralyzed, and the pupil was not dilated). 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.

Wave-Aberration Measurements

Wave-aberration (WA) was measured using a near-infrared Hartmann-Shack (HS) sensor developed in our laboratory[14] and adapted to the clinical environment. This system has more than 220 microlenses for a 5-mm diameter pupil (the size of each microlens on the eye's pupil is 0.3 mm). The HS images were recorded in a dark room, allowing a natural pupil diameter larger than in the visual measurements. From these HS images, we computed the WA and its root mean square (RMS) for the pupil diameter used during the VA measurements. The eye's point-spread function (PSF) and modulation transfer function (MTF) were estimated from the WA at best focus. Because of residual accommodation, small defocus differences between HS and VA measurements could occur. We calculated the PSF for three different conditions of defocus: maximizing image quality, set to zero, and adjusted to minimize the RMS. Several image quality metrics were calculated for each eye: the Strehl ratio as the quotient between the intensity peak in the system's PSF and the diffraction-limited PSF, the logarithm of the Strehl ratio (lnSR), and the logarithm of visual Strehl ratio (lnVSX) that incorporates a neural weighting function.[15]

Crossed-Cylinder Device to Correct Astigmatism

The small amounts of astigmatism appearing in the subject's eye were carefully corrected before VA was measured. We designed and built a simple device to correct astigmatism consisting of two rotating 0.25-D cylindrical lenses that change cylindrical power from 0 D to 0.5 D, depending on the angle between the lenses. The whole device is rotated to adjust the axis of the astigmatism. Both cylindrical lenses have the same power ($C_{\rm com}$), and their combination with a relative angle (α) provides an effective cylindrical power ($C_{\rm eff}$), with its axis equidistant to both axes. This combination produces a residual defocus ($D_{\rm res}$) corrected with a Badal optometer before VA measurements. The effective cylindrical power and the residual defocus are given by the following equation:

$$C_{\rm eff} = 2C_{\rm com}\cdot\cos\alpha;\ D_{\rm res} = C_{\rm com}\cdot(1-\cos\alpha). \qquad (1)$$

We checked that the cross-cylinder corrector does not introduce any significant HOA by measuring in some subjects the WA with and without the corrector. The residual values of astigmatism after correction, measured with the wave-front sensor, were lower than 0.10 D in all subjects.

Visual Acuity Measurements

Figure 1 shows a schematic of the setup used to measure the VA. The crossed-cylinder corrector device, previously adjusted using the HS system, is placed in front of the eye. A Badal optometer[16] (L1 and L2) is used to correct defocus with an accuracy equal to or better than 0.1 D. A computer monitor with an average luminance of 100 cd/m^2 was placed 8 m from the subject. A forced-choice procedure with a tumbling E letter was used to estimate VA. The letter size was reduced up to the smallest letter the subject could see in best focus. In addition to this reference size, four more sizes were randomly presented to the subject in four different orientations (right, left, up, down). Decimal VA (i.e., inverse of 1/MAR) was estimated from a psychometric function (four-parameter sigmoidal fit) of correct responses for different letter sizes. The setup would allow measuring VA as high as 3 with good accuracy, although the highest measured value was approximately 2. High (100%) and low (20%) contrast letter acuity were measured.

VA was measured monocularly while the fellow eye was kept open under a cover patch. Before the test, best focus was determined subjectively with the Badal optometer, by moving the lens L2 from a myopic position for minimizing the possible residual accommodation (Fig. 1), while the subject was looking for a tumbling E measuring 2.5 min arc. The subject's head was stabilized by a chin rest attached to a three-axis positioner. The front of the eye was illuminated by an array of infrared LEDs, and a CCD video camera monitored the centering and the size of the natural pupil. Pupil size was measured during each VA measurement, and the average value was used to estimate the WA. Large intersubject variability from 5 to 8 mm (average, 6.5 ± 0.9 mm) was observed in the pupil diameters.

Standard deviations of WA and VA were calculated from the series of three measurements. All measurements were obtained with natural pupil and accommodation. We were interested in the relationship between monochromatic aberrations and VA measured in white light. We assumed that chromatic aberration is constant through subjects[17] and that its impact on VA is limited.[18]

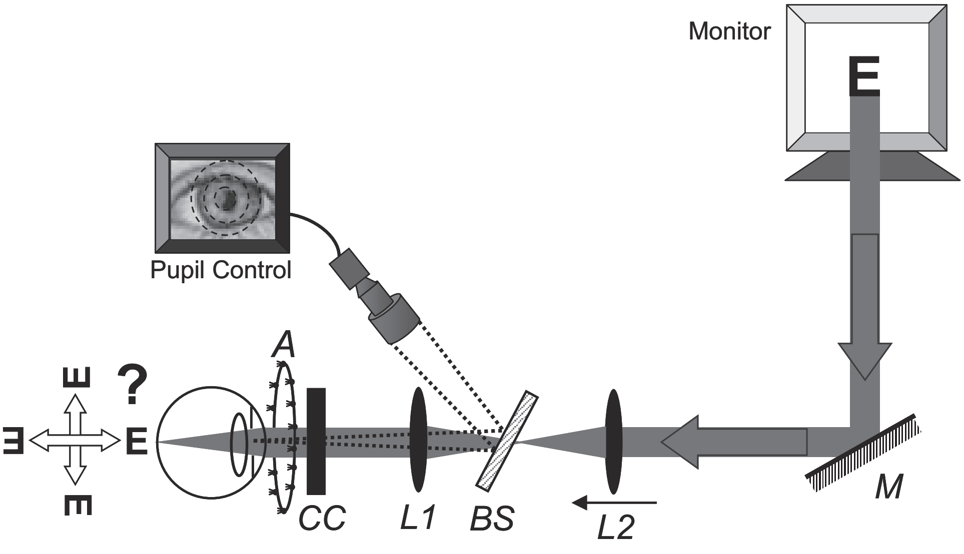

Figure 1. Schematic diagram of the setup used to measure VA. A mirror (M) is used to reach 8 m from the monitor to the eye. Astigmatic and spherical refractive errors were corrected with the cylinder corrector (CC) and with the Badal optometer consisting of two lenses, L1 and L2, with 100-mm focal distances. An array of infrared light-emitting diodes (A) and a pellicle beam splitter (BS) permit control of the centering and the size of the pupil using a CCD video camera. The "tumbling E" was randomly presented in four different orientations for different sizes. From a psychometric function, we obtained the decimal VA (1/MAR).

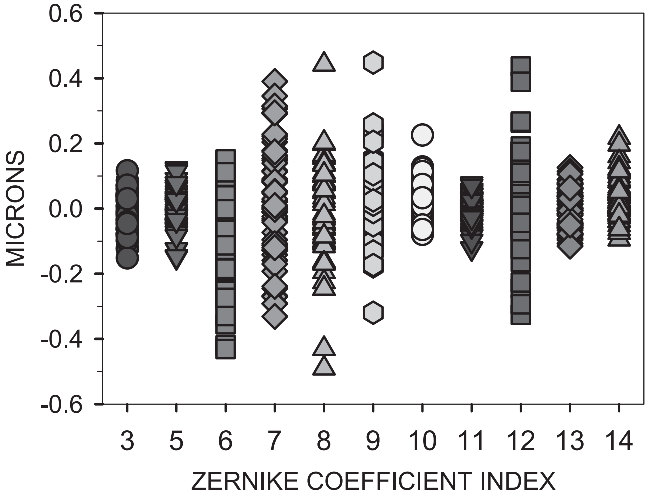

FIGURE 2. Zernike coefficients when astigmatism is corrected with the crossed-cylinder device. Residual astigmatism is approximately or less than 0.15 µm. If all values of astigmatism are translated to diopters ($C = 9.8$ µm/r^2, where C and µm are the astigmatism in diopters and in microns respectively, and r is the pupil radius), all these are below 0.1 D. In addition to spherical aberration (coefficient 12), the other two predominant terms are the vertical trefoil and coma (coefficients 6 and 7).

RESULTS

Figure 2 shows the Zernike coefficients for all tested eyes, with astigmatism corrected (residual values for astigmatic terms 3 and 5 are also presented) and for the natural pupil diameter in each eye. In all subjects, the Zernike coefficients of coma, trefoil and spherical aberration range between −0.50 and +0.50 µm. The rest of the high-order aberrations terms are below 0.2 µm. Residual values of astigmatism are under 0.15 µm (lower than 0.10 D). As an example, Figure 3 shows the WA and PSF maps of two subjects with their natural astigmatism (0.47 and 0.33 D, respectively) and after astigmatism correction. The RMS and the Strehl ratio are indicated for each condition. Optical quality results as a function of VA for every eye tested are presented. VA values were uniformly distributed from 1.0 to 2.0 for high-contrast and from 0.5 to 1.1 for low-contrast letters.

Figure 4 shows the RMS of HOA as a function of VA for high-contrast (a) and low-contrast (b) letters. The amount of HOA varies between 0.1 and 0.7 µm across subjects with a large range of VA. Subjects with the highest VA do not necessarily have the lowest amount of aberrations. In our group, we found a low correlation between HOA and high contrast VA (HCVA; $R^2 = 0.13$; $P = 0.004$) or low-contrast VA (LCVA) ($R^2 = 0.04$; $P = 0.15$). However, most eyes with HCVA greater than 1.6 had RMS values lower than 0.4 µm, whereas most eyes with RMS higher than 0.4 µm had HCVA below 1.3. Figure 5 shows the amount of third-order aberrations (coma and trefoil) as a function of VA. The values of coma and trefoil were calculated as modulus from the Zernike coefficients 7, 8 and 6, 9, respectively. The magnitudes of both coma and trefoil ranged between 0 and 0.50 µm, and the average values were 0.21 ± 0.12 µm and 0.18 ± 0.13 µm, respectively. We found a very low correlation between coma and HCVA ($R^2 = 0.09$; $P = 0.02$) or LCVA ($R^2 = 0.03$; $P = 0.17$). Some subjects with coma greater than 0.25 µm had high VA values. The situation with trefoil is slightly different. We found some correlation between the amount of trefoil and HCVA ($R^2 = 0.23$; $P = 0.001$), though this was not so clear for LCVA ($R^2 = 0.09$; $P = 0.02$). Every eye with trefoil equal to or higher than 0.25 µm had HCVA lower than 1.5. In addition to magnitude, it is important to evaluate the orientation of these aberrations. Figure 6 shows the orientation of coma (Fig. 6a) and trefoil (Fig. 6b) as functions of HCVA in those subjects with magnitude, coma, or trefoil higher than 0.1 µm. We did not find a preferred orientation of coma that could be associated with higher VA. This result does not support some ideas suggesting that subjects with vertical coma could have better VA. The values of the wavefront pattern in trefoil are repeated every 120° and are represented accordingly in the polar plots (i.e., each is repeated three times). For most subjects and independently of their VA, vertical trefoil 90° to 210° to 330° (corresponding to negative values of coefficient 6 and small values of coefficient 9) is predominant.

Figure 7 shows the values of spherical aberration as a function of HCVA (Fig. 7a) and LCVA (Fig. 7b). Spherical aberration ranges from −0.40 to +0.45 µm, with an average value of +0.04 ± 0.18 µm. Neither HCVA ($R^2 = 0.04$; $P = 0.13$) nor LCVA ($R^2 = 0.06$; $P = 0.07$) is correlated with spherical aberration.

To better evaluate the impact of different aberration terms, we separated the subjects into three groups according to their VA, and the average values of the aberrations were calculated. Figure 8 shows the average values of HOA-RMS, coma, and trefoil for the three ranges of VA: normal VA (1.0–1.4 in high contrast; 0.5–0.7 in low contrast), good VA (1.4–1.7 in high contrast; 0.7–0.9 in low contrast), and excellent VA (1.7–2.0 in high contrast; 0.9–1.1 in low contrast). As in the previous

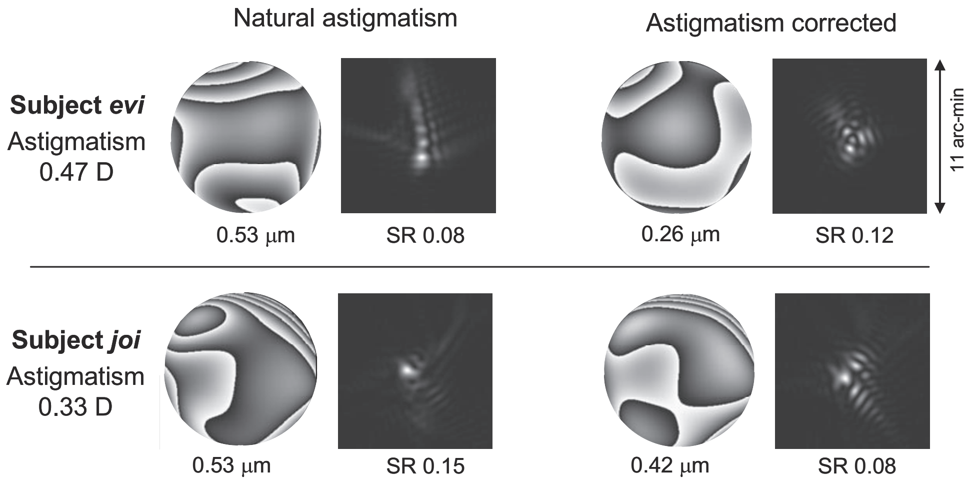

FIGURE 3. Examples of WA and PSF maps of two eyes with natural and corrected astigmatism.

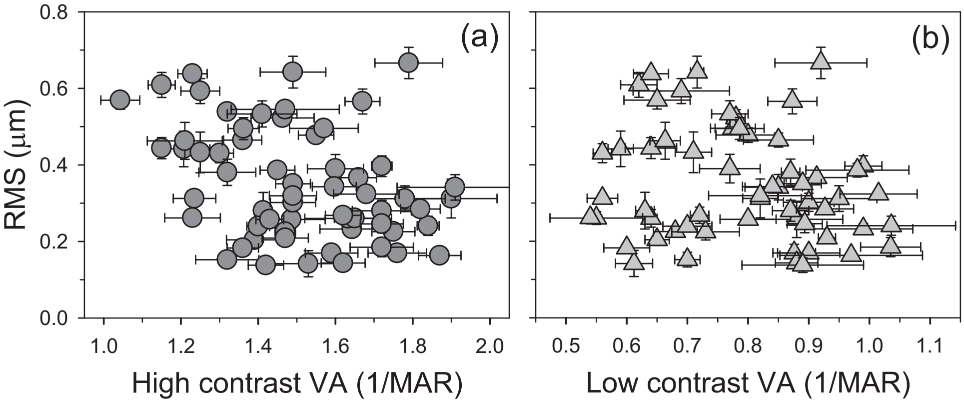

FIGURE 4. High-order RMS as a function of VA, for high (**a**) and low (**b**) contrast. Errors bars are the SD from three experimental measurements.

figures, the RMS values were obtained for the natural pupil diameter. For HCVA, the average values of HOA, coma, and trefoil decrease from the subjects with normal VA to those with excellent VA. This aberration reduction is mainly the result of a decrease in trefoil (0.24–0.14 μm). In the case of LCVA, the average values of HOA, coma, and trefoil are similar in the three groups.

Figure 9 shows the same type of results for spherical aberration. In this case, we also added the average spherical aberration for a fixed pupil diameter (5 mm), together with the values for natural pupil (range, 5–8 mm; average, 6.5 ± 0.9 mm). For the fixed 5-mm pupil diameter, the mean values of spherical aberration were close to zero (approximately +0.03 μm) and did not depend on the values of VA. Spherical aberration increases with age,[19] and Figure 10 shows the values of spherical aberration for a 5-mm pupil diameter as a function of age (19–35 years) in those subjects whose HCVA was better than 1.4. In the younger subjects in our group (19–25 years), spherical aberration had an average value of approximately zero (+0.02 ± 0.05 μm), whereas it tended to slightly positive values in subjects 25 to 35 years of age (average, +0.05 ± 0.04 μm).

On the other hand, accommodation errors may affect the eye's aberrations[20,21] and, in particular, may induce negative spherical aberration. We calculated the approximate values of the accommodation shift as the difference between the defocus value obtained from subjective refraction (during VA measurements) and those obtained directly from the HS measurements (using a chromatic difference value of 0.72 D[22]). An average defocus difference of 0.6 ± 0.5 D was found. These values are too small to induce significant changes in aberration.

Parameters in the pupil plane, such as wavefront RMS or individual aberrations, are not the best image quality metrics. Therefore, we studied two additional metrics calculated in the retinal plane: lnSR and lnVSX. For both high- and low-contrast VA, we also found very low correlation values of lnSR (R^2 = 0.05–0.15; P = 0.10–0.002) with defocus either set to zero or optimized. For the three focus conditions considered, we did not find correlation between lnVSX and VA ($R^2 < 0.04$; $P >$ 0.15). As an example, Figure 11 shows these two image quality parameters for the defocus values that maximize them as a function of HCVA and LCVA. In most eyes with HCVA lower than 1.3, the lnRS was smaller than −2.0 (SR < 0.14) and the lnVSX was lower than −1.25 (VSX < 0.3). For subjects with

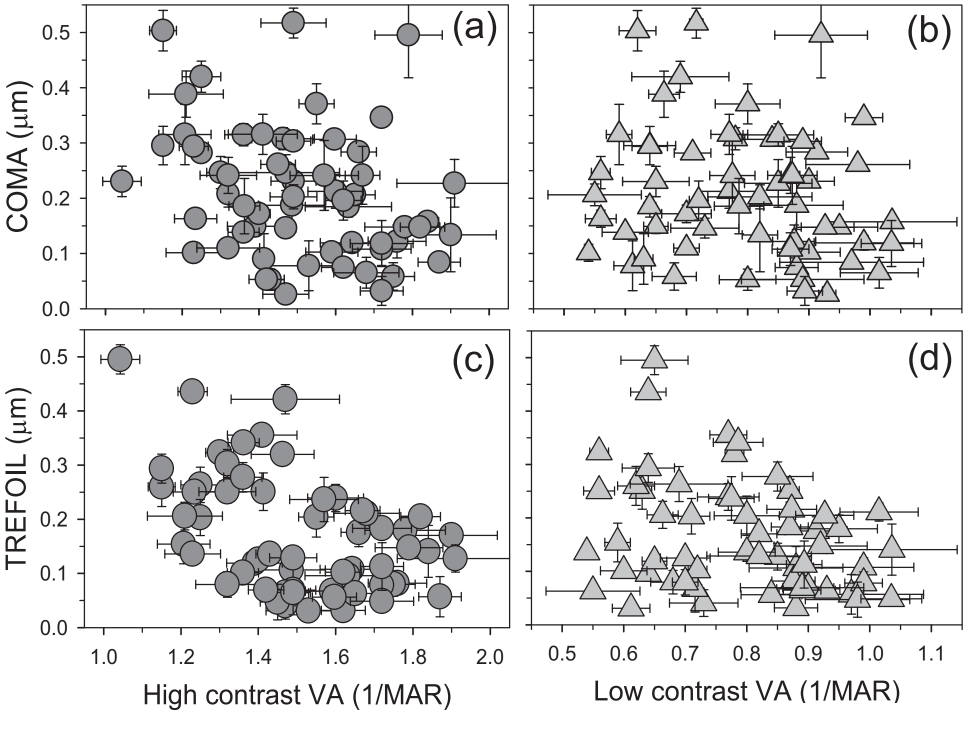

FIGURE 5. Modulus of coma and trefoil as a function of VA. (**a**, **c**) Results with high-contrast letters. (**b**, **d**) Results with low-contrast letters, for coma and trefoil. respectively.

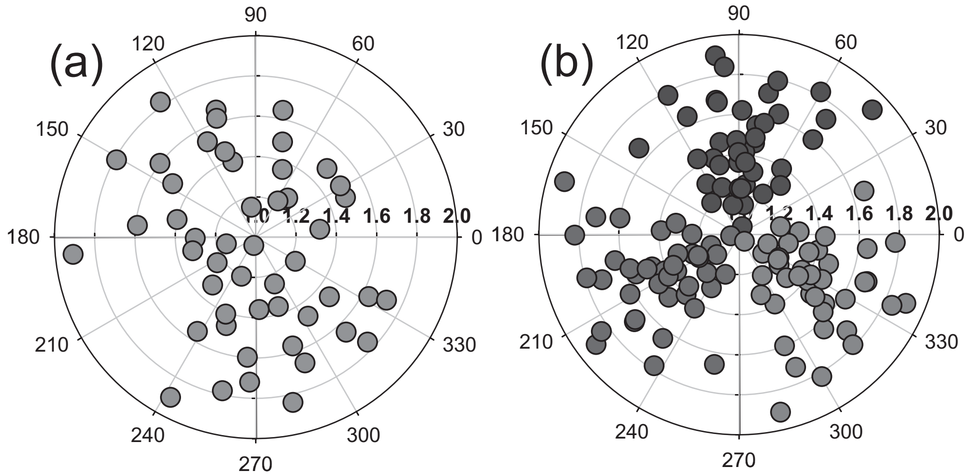

FIGURE 6. Polar plots showing the orientation of coma (**a**) and trefoil (**b**), when their values are higher than 0.1 μm. Radius represents the values of HCVA.

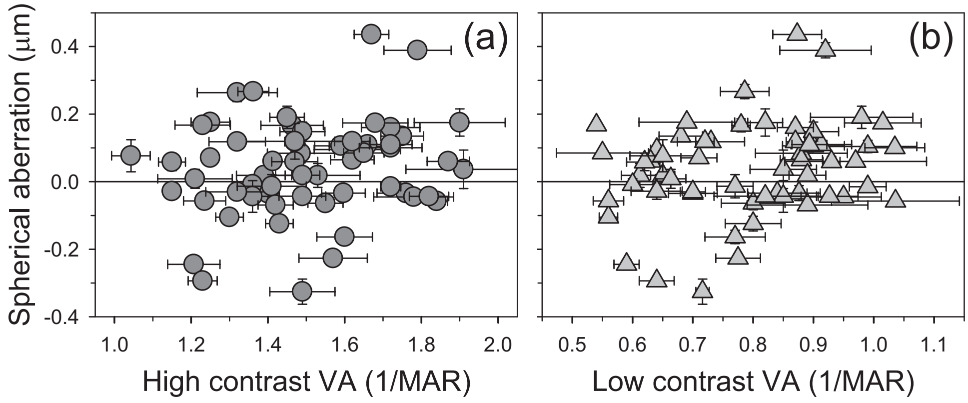

FIGURE 7. Spherical aberration (Zernike coefficient 12) as a function of VA for high (**a**) and low (**b**) contrast.

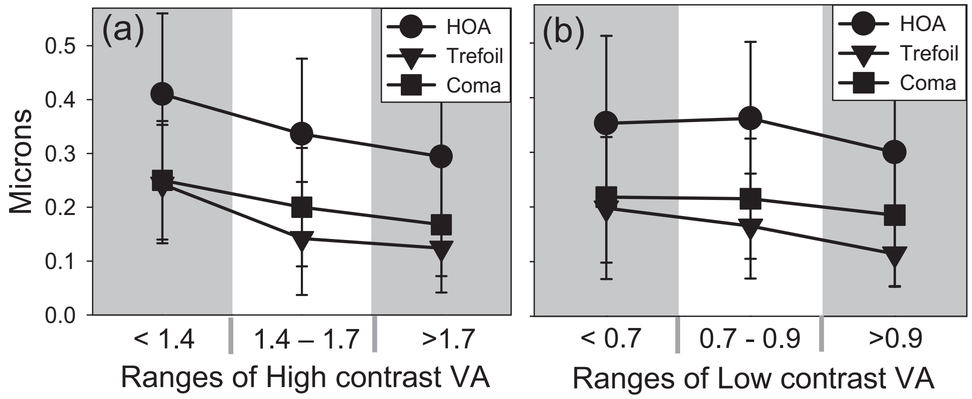

FIGURE 8. Average values of HOA RMS, coma, and trefoil for eyes grouped in three subgroups for high-contrast (**a**) and low-contrast (**b**) VA.

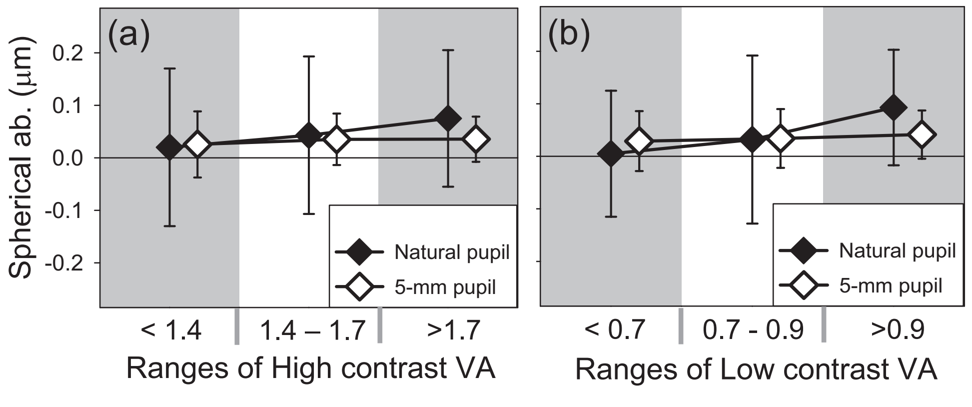

FIGURE 9. Average values of spherical aberration with both natural and 5-mm pupil size, for eyes grouped in three subgroups of high (**a**) and low (**b**) contrast VA.

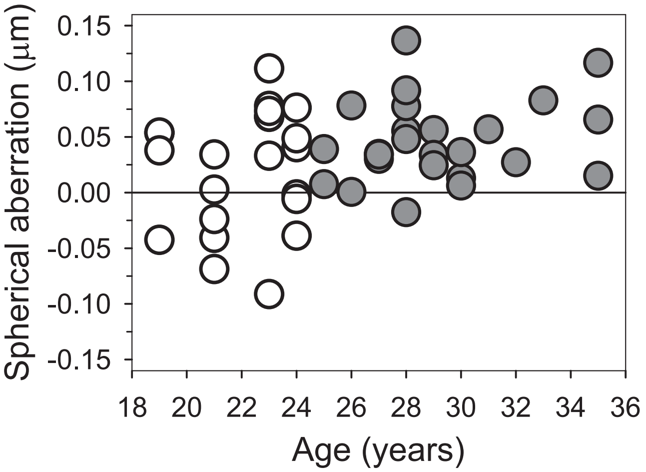

FIGURE 10. Spherical aberration of subjects with HCVA higher than 1.4 as function of age for 5-mm pupil diameter. *White circles* and *gray circles* represent subjects younger and older than 25 years, respectively.

better visual performance, the lnRS and the lnVSX varied randomly; actually, some subjects with lnRS below −2.0 and lnVSX below −1.25 had VA better than 1.7. The average values of lnSR and lnVSX for the three groups are shown in Figure 12. In all graphs, the mean values were slightly better in the group with the highest VA. All the mean values of lnSR were between −2.33 and −1.94 (SR, 0.10–0.14), except in the group with the lowest HCVA, which had a mean lnSR of −2.56 (SR, 0.077). The average lnVSX varied from −1.31 to −1.12 (VSX, 0.27–0.33).

The average MTF in the three intervals of VA are shown in Figure 13, for defocus adjusted to the center of least confusion. There were no differences in the MTF curves for the LCVA ranges. The mean MTF for the high HCVA were slightly better than for the group of lower VA in the frequency range between 15 and 35 cycles per degree. It is also illustrative to show the WA and PSF maps of eyes within the selected VA ranges (Fig. 14). Interestingly, it was not necessary to have a flat WA—i.e., a concentrated PSF—to get an excellent VA. The opposite is also true: some eyes with nearly flat WA may have VA in the lower range.

DISCUSSION

The main objective of this study was to explore the potential relationship between the number of monochromatic aberrations and VA measured in white light in young subjects with normal or better than normal (excellent) VA. A relatively large screening of subjects with normal VA allowed us to select a group covering the range of VA from 1.0 to 2.0. This group of subjects represents a representative young population. We considered VA less than 1.4 as normal, in agreement with previous studies[23] reporting that more than 50% of young subjects had a VA below that value based on a standard chart for measurements. It should be noted that VA data determined with our forced-choice procedure tends to be lower than standard estimates. Although most subjects had low refractive errors, we carefully corrected defocus and astigmatism during the study. All measurements were performed under natural viewing conditions, without paralyzing accommodation. Because we were interested in the impact of aberrations, relatively large natural pupils were favored during the measurements, which were performed in a dark environment with a screen luminance of 100 cd/m^2, subtending 3.9° × 2.3° of the visual field. Subjects had an average pupil diameter of 6.5 mm (range, 5–8 mm. We measured 60 eyes in 45 subjects. Accordingly, 15 pairs of fellow eyes, sharing brain processing and with significant correlations between optical aberrations,[24] were measured. However, we have not found a significant correlation between VA in fellow eyes, with differences ranging from 0 to 0.61. Despite this fact, we recalculated the correlation between every optical parameter and VA with only 45 independent eyes, and the results were similar to those obtained with the 60 eyes of 45 subjects.

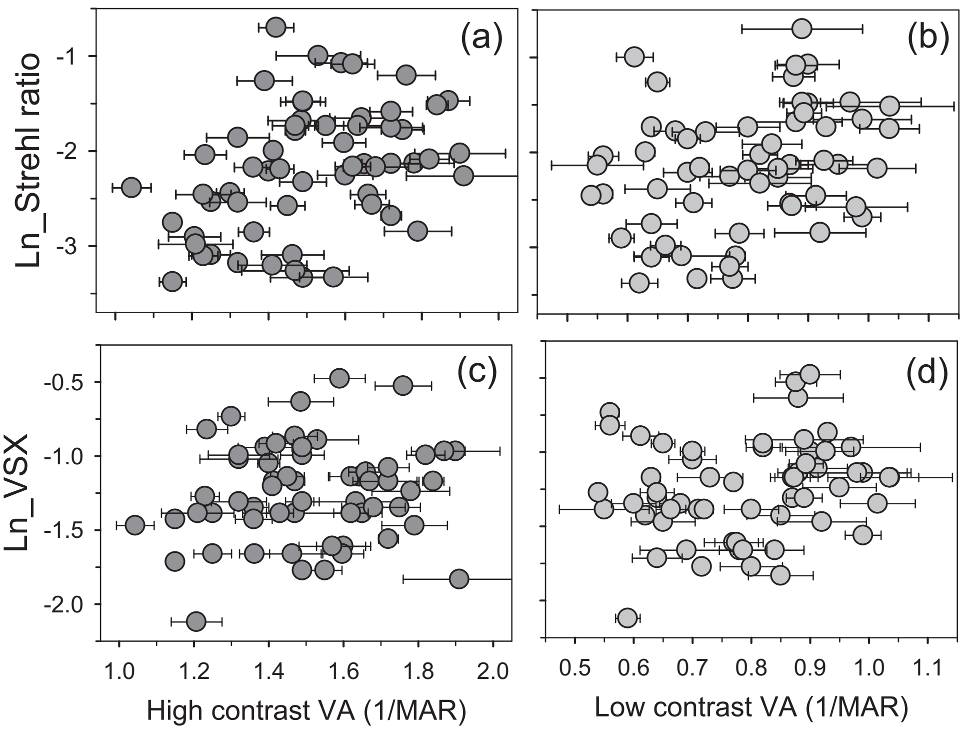

FIGURE 11. Image metrics (natural logarithm of lnSR and lnVSX) as a function of VA, for high and low contrast, with focus adjustments that maximize them.

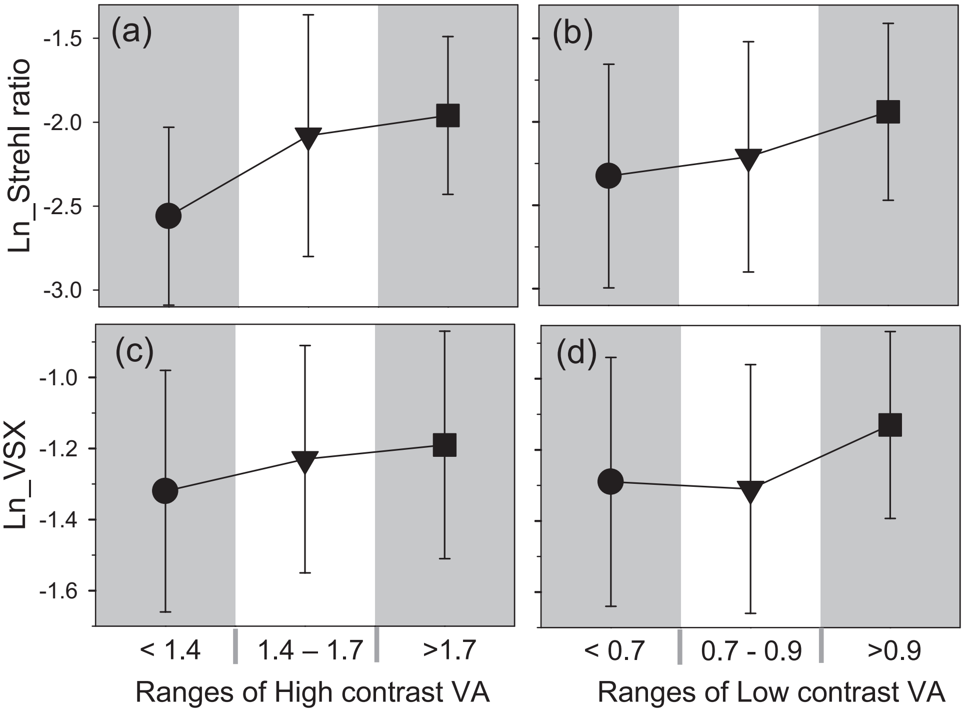

Figure 12. Average values of image metrics (lnSR and VSX) for eyes grouped in three ranges of high- and low-contrast VA.

VA was measured in white light, whereas aberrations were obtained in monochromatic light (for a near infrared wavelength). Although chromatic aberrations could affect VA data, some recent experiments[18] showed a limited impact in VA when chromatic aberrations were corrected using achromatizing lenses. This result induced us to measure VA with a higher luminance (using the full spectrum of the monitor) instead of reducing the luminance condition with pseudomonochromatic light.

The predominant high-order aberrations are coma, trefoil, and spherical aberration. Although these aberrations can reach values of 0.5 μm, most of the tested eyes had amounts of coma, trefoil, and spherical aberration below 0.35 μm. HOA varied widely among subjects; the average RMS values of coma and trefoil was approximately 0.20 μm. These relatively small values of coma are caused by the mechanism of compensation of the aberrations of the cornea by the lens.[25] Spherical aberration is either positive or negative, and the average value is near zero. Porter et al.[26] measured the aberrations in a large population for a 5.7-mm pupil diameter. They found mean values of approximately 0.15 μm for coma and trefoil and 0.12 μm for spherical aberration. This is consistent with our data, considering the differences in pupil diameter and the subject's refraction range. Another study[12] reported average values of 0.14, 0.27, and 0.11 μm for coma, trefoil, and spherical aberration, respectively, for a pupil diameter of 6 mm.

We did not find correlations in the tested group of eyes among optical parameters and low- and high-contrast VA. Despite important methodological differences, our results are in agreement with a recent study[13] in a group of subjects with VA better than 20/17 that showed low predictions of high- and low-contrast VA (11%) in photopic conditions.

In particular, subjects with excellent VA had normal amounts of aberrations. A detailed analysis of some of the most relevant aberration terms did not show any significant effect. Subjects with excellent vision did not exhibit some particular aberration pattern, in magnitude or in orientation. However, it is important to point out that under normal conditions, the coupling of different aberration terms may play an important role.[27] Beyond the well-known coupling between spherical aberration and defocus, the appropriate combination of trefoil and coma may also improve the retinal image (Villegas EA, et al. *IOVS* 2007;48: ARVO E-Abstract 1509). Our results seem to indicate that some specific aberration terms do not provide better performance. For example, the orientation of coma is random and without correlation with visual performance. With

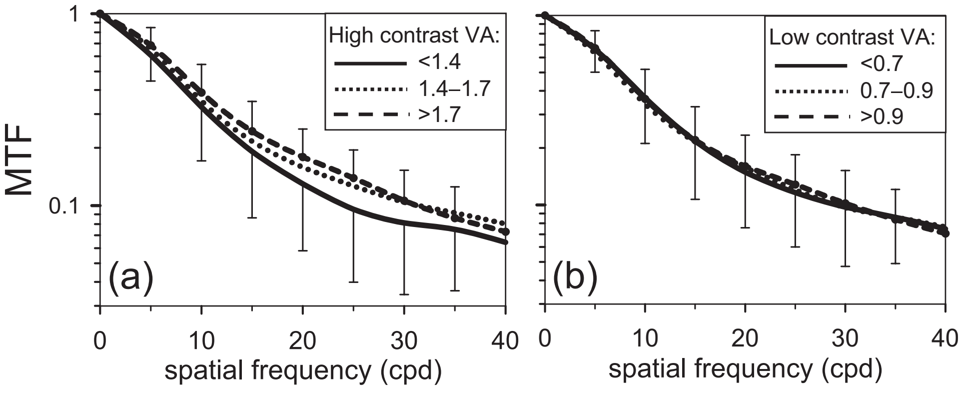

Figure 13. Average MTF in three subgroups of high-contrast (**a**) and low-contrast (**b**) VA, with focus adjusted to the circle of least confusion.

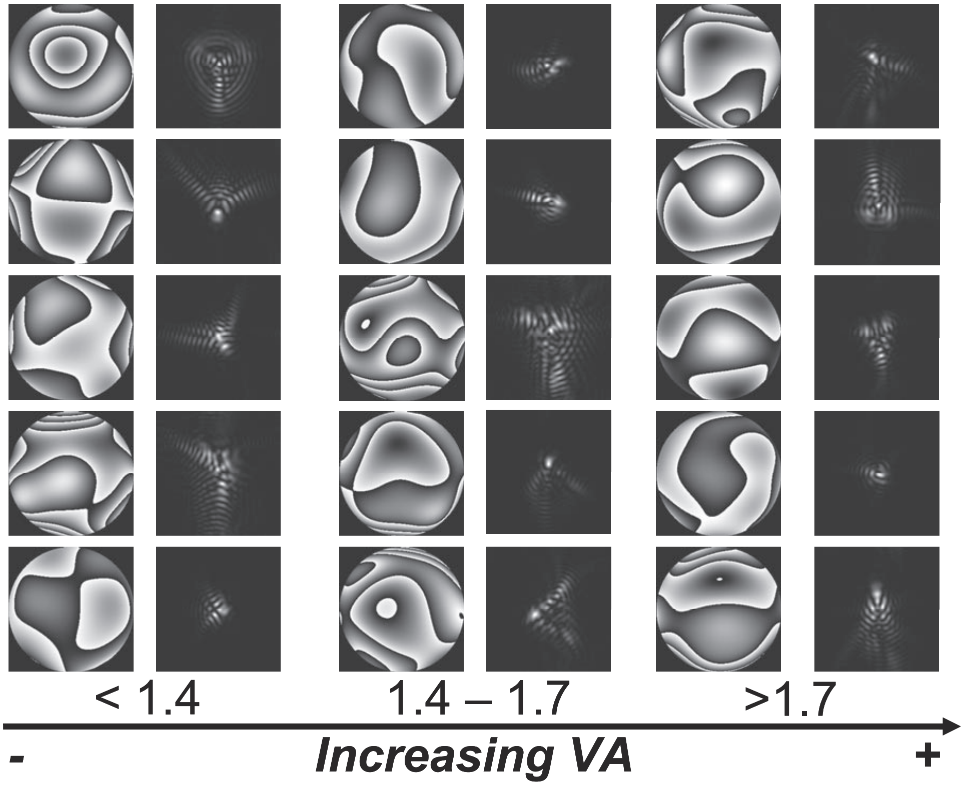

FIGURE 14. Representative examples of WA maps and associated PSF for the three subgroups of high-contrast VA.

regard to overall retinal image quality, we did not find any significant correlation with VA. Subjects' eyes showed a large variety of optical quality without a clear relationship with acuity. In addition, subjects with the best acuity did not necessarily have the best optical quality by any metrics.

These results are not in contradiction to the idea that the correction of aberrations improves visual performance. For example, for most of our subjects we probably would be able to improve performance to some extent by adequate correction of the remaining aberrations. In addition, it is obvious that bad optics beyond a certain level will degrade visual performance. In this context, it is important to determine the normal level of aberrations that can be tolerated without degrading VA.

An important related question is why similar amounts of aberrations produce such different values of visual acuity. The answer could be that, in addition to optical aberrations, many factors—among them intraocular scatter, cone density, ganglion cell density, and cortical processing—can limit visual acuity. The combination of all those factors in a complicated fashion set the actual resolution of the visual system. In this complex scenario, optical aberrations alone are a not a good predictor of visual performance.

It should be noted that we concentrated our study on the relationship between aberrations and forced-choice tumbling-E VA for fast stimulus presentation, avoiding potentially temporal summation effects. It is possible that a different type of relationship can be found if different visual tasks or different conditions are compared. For example, Applegate et al.[13] found a significant relationship between standard VA data without duration limit under mesopic conditions. It may be that specific visual tests other than what we used are more sensitive to changes in optical quality.

Neural adaptations to blur[28] and to aberrations[4,5] have been previously demonstrated. Our results somehow support those findings. If subjects adapt to their specific aberration patterns, it is reasonable that the amount of aberrations would have a smaller effect on vision. Although the effect of neural adaptation is probably not too large, it may contribute to the robustness of the visual system, leading to similar performance for a large range of ocular optics quality.

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