Influence of adaptive-optics ocular aberration correction on visual acuity at different luminances and contrast polarities

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We evaluated the visual benefit of correcting astigmatism and high-order aberrations with adaptive optics (AO) on visual acuity (VA) measured at 7 different luminances (ranging from 0.8 to 50 cd/m^2) and two contrast polarities (black letters on white background, BoW, and white letters on black background, WoB) on 7 subjects. For the BoW condition, VA increased with background luminance in both natural and AO-corrected conditions, and there was a benefit of AO correction at all luminances (by a factor of 1.29 on average across luminances). For WoB VA increased with foreground luminance but decreased for the highest luminances. In this reversed polarity condition AO correction increased VA by a factor of 1.13 on average and did not produce a visual benefit at high luminances. The improvement of VA (averaged across conditions) was significantly correlated (p = 0.04) with the amount of corrected aberrations (in terms of Strehl ratio). The improved performance with WoB targets with respect to BoW targets is decreased when correcting aberrations, suggesting a role of ocular aberrations in the differences in visual performance between contrast polarities.

Keywords: adaptive optics, ocular aberrations, psychophysics, visual acuity, luminance, contrast polarity

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Introduction

Understanding the limits to spatial vision has been for decades one of the most fascinating questions in visual science. The visual image is first degraded by the optics of the eye, followed by the cone mosaic sampling and neural factors that limit the finest resolvable detail. Recently, stimulated with the potentials of customized refractive surgery and high-order aberration correcting intraocular, contact or ophthalmic lenses, the debate on the visual benefits of achieving a perfect optics has been reopened.

Several studies have studied relationships between optical aberrations and visual performance in normal eyes (Applegate, Ballentine, Gross, Sarver, & Sarver, 2003; Applegate, Marsack, & Thibos, 2006; Jimenez, Ortiz, Hita, & Soler, 2008; Levy, Segal, Avni, & Zadok, 2005; Marsack, Thibos, & Applegate, 2004). While it is true that highly aberrated eyes show poorer performance (Marcos, 2001; Sabesan et al., 2007), particularly if appropriate retinal-image based optical quality metrics are chosen to describe the optics of the eye, high-contrast visual performance appears to be uncorrelated with retinal image quality in a normal population (Applegate et al., 2006). Correlation of absolute magnitudes of visual acuity and retinal image quality across subjects may be masked by the limits imposed by further stages in the visual process. However, the question of whether inducing changes in the optics of the eye has an impact on visual performance (Applegate et al., 2000; Atchison, Marcos, & Scott, 2003; Marcos, 2001; Sabesan et al., 2007) is in fact more relevant when considering the possibility of altering

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high-order aberrations (with lenses or surgery) of individual subjects (Barbero & Marcos, 2007; MacRae, Schwiegerling, & Snyder, 2000; Yoon, Jeong, Cox, & Williams, 2004).

Adaptive optics is an ideal technique to manipulate the retinal image quality of the eye (Liang, Williams, & Miller, 1997). Correcting high-order aberrations in fundus imaging devices has been shown to improve the imaging capabilities of the eye, so that images of retinal structures with unprecedented resolution and contrast can be achieved (Burns, Marcos, Elsner, & Bará, 2002; Hermann et al., 2004; Liang et al., 1997; Roorda et al., 2002). In combination with a psychophysical channel adaptive optics has become a useful tool to simulate visual experience with new lens designs, before the lens is implanted or even manufactured (Manzanera, Prieto, Ayala, Lindacher, & Artal, 2007; Piers, Manzanera, Prieto, Gorceix, & Artal, 2007). Despite the increasing popularity of adaptive optics, few studies have addressed the changes in visual performance with correction of high-order aberrations, particularly in extended range of conditions (luminance and contrast polarity). Artal, Chen, Manzanera, and Williams (2004), in a study on three subjects, found a decrease of the minimum angle of resolution (MAR) for polychromatic high-contrast targets (by a factor of 1.16) when correcting high-order aberrations with respect to the natural aberrated condition. When MAR was compared for two conditions with similar amount of aberrations (natural wave aberration and a rotated version of this map) MAR was always best for the natural aberrations, suggesting neural adaptation effects (Artal, Chen, Fernández, et al., 2004). A later work studied the effects of correcting aberrations in peripheral visual acuity (Lundstrom et al., 2007). Yoon and Williams (2002) found a significant decrease in the logMAR by a factor of 1.2 for high luminance (~20 cd/m^2) polychromatic targets and of 1.6 for dim (~2 cd/m^2) monochromatic light (using an interference filter) in a group of 7 subjects. Rossi, Weiser, Tarrant, and Roorda (2007) used targets directly projected on the retina using an Adaptive Optics Scanning Laser Ophthalmoscope to explore potential differences in visual performance with adaptive-optics-corrected aberrations between emmetropes (n = 9) and low myopes (n = 10) and found a lower benefit in the myopic group, despite the fact that both groups were left with negligible residual aberrations. Most of these studies used relatively high luminances and black targets on a bright background. Relative measurements of the contrast sensitivity function in the same subject after a change in the optics reveal larger effects for higher spatial frequencies and for low-contrast than for high-contrast targets, in good agreement with the changes of the optical modulation transfer function (Atchison, Woods, & Bradley, 1998). The difference in the benefits of correcting aberrations (with adaptive optics) on visual performance as a function of light level has been stressed by Dalimier, Dainty, and Barbur (2007). However, they measured contrast thresholds using a relatively large target (15 arc min Landolt C) rather than targets in the spatial resolution limit. For their experimental conditions they found that for lower luminances, the drop in neural sensitivity limits the impact that increased optical degradations have on vision. In their study, visual benefits ranged between 1 and 1.7, across the three subjects and luminances.

Most studies use black letters on a white background. However, the effects of ocular aberrations are more usually subjectively experienced in nighttime conditions (large pupils) and bright targets on dark backgrounds (street lights, the moon, etc.). The intrinsic difference of measuring visual acuity with white targets on a black (WoB) background as opposed to the more standard measurement using black targets on a white background (BoW) has been addressed in very few studies (Pointer, 2001; Westheimer, 2003; Westheimer, Chu, Huang, Tran, & Dister, 2003; Wilcox, 1932). Westheimer's (2003) predictions that WoB targets would produce better visual performance than BoW were supported experimentally by psychophysical measurements using Landolt C on 4 subjects and clinical measurements using conventional and reversed Snellen charts on 108 patients of different ages. He attributed the differences observed in visual resolution by reversing contrast polarity to changes in the effective retinal contrast of the target. Scattering and aberrations cause flattening and broadening of the point-spread function, affecting BoW targets more than WoB targets. If this hypothesis is correct, the relative advantage of WoB targets over BoW targets should decrease when aberrations are corrected and therefore possibly tested using adaptive optics.

The relative impact of optical, pre-neural and neural factors in the change of visual resolution with luminance has been previously discussed on both real and ideal observers (Banks, Geisler, & Bennett, 1987; Campbell & Green, 1965; Losada, Navarro, & Santamaría, 1993; Marcos and Navarro, 1997). Recently, models incorporating optical and neural filtering, neural noise, and decision rules have been even implemented to simulate a visual acuity task (Watson & Ahumada, 2008). While these models are able to reproduce measured visual performance for a set of optical aberrations, whether they can be extrapolated to other conditions of luminance or contrast remains to be explored. Previous studies show that neural constraints on foveal spatial vision are relatively low, although they cannot alone explain the decrease of visual acuity and contrast sensitivity with decreased luminance (Banks et al., 1987; Campbell & Green, 1965; Losada et al., 1993). The relative impact of the optics of the eye and non-optical pre-neural factors (quantal fluctuations, photoreceptor aperture and quantum efficiency) can be investigated by assessing the effect on visual acuity of correcting aberrations at various luminances, particularly for large pupil sizes, so that diffraction plays a limited role.

This study will investigate the benefit of correcting high-order aberrations at various conditions, by measuring high-contrast visual acuity as a function of luminance in the mesopic and photopic range, using standard and reversed-contrast polarity targets, under natural aberrations and adaptive-optics-corrected aberrations.

Method

Adaptive-Optics setup

Figure 1 shows a view of the adaptive-optics setup that we have developed for this study. The primary components of the system are a Hartmann–Shack wave front sensor (composed by a matrix of 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. The performance of this mirror has been extensively evaluated by Fernandez et al. (2006). Illumination comes from a SuperLuminescent Diode (SLD) coupled to an optical fiber (Superlum, Ireland) emitting at 827 nm. The beam is collimated and enters the eye with a diameter of 1 mm and with an irradiance of 6.95 μW on the cornea. The beam is slightly (1 mm) off-centered with respect to the pupil center to avoid a corneal reflex in the Hartmann–Shack images. Light reflected off the retina passes a Badal system, the deformable mirror, and is focused on the CCD camera by the microlens array. The Badal system compensates for spherical error and is mounted on a motorized stage. The deformable mirror is conjugated to the pupil by a pair of relay lenses (focal length = 50 mm and 100 mm) with a ×2 magnification factor from the pupil to the mirror. The microlens array is conjugated to the pupil by a pair of relay lenses (focal length = 200 mm and 50 mm) with a ×0.5 magnification factor from the pupil to the microlens array. A cold mirror behind the wavefront sensor allows inserting a visual stimulus channel in the deformable mirror path, so that the subject can perform psychophysical tasks under controlled optical aberrations. 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). The minidisplay is placed at the focal length of a 200-mm achromatic lens, i.e., at optical infinity to the observer, and therefore subtended 2.58 deg on the retina. 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. Subjects are aligned to the system (using a $x-y-z$ stage) using the line of sight as a reference. The Badal system and pupil camera monitoring are automatically controlled using custom-built software programmed in VB.Net 2005 (Microsoft). The Hartmann–Shack system, deformable mirror, and closed-loop correction are controlled with the software provided by the manufacturer.

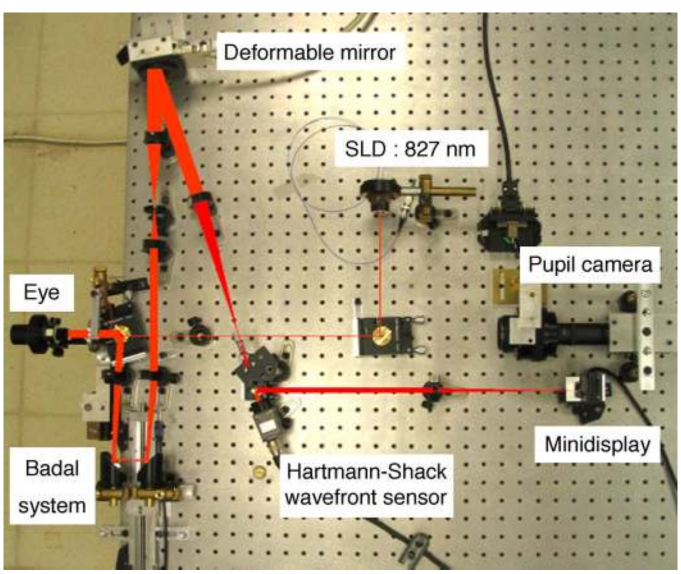

Figure 1. Adaptive-optics system optical set-up.

The performance of the wave front sensor was validated using artificial eyes with known high-order aberrations (as calibrated from the manufactured and also measured by a Laser Ray Tracing system in our laboratory; Llorente, Barbero, Cano, Dorronsoro, & Marcos, 2004; Llorente, Diaz-Santana, Lara-Saucedo, & Marcos, 2003). Discrepancies in the measured aberrations were typically less than 5% with respect to nominal values (Gambra, Sawides, Dorronsoro, Llorente, & Marcos, 2008).

Correction of ocular aberrations

The calibration of the deformable mirror was performed using an artificial eye (consisting of a doublet—focal length = 35 mm—and a rotating diffuser as an artificial retina). A modal control was used. Each actuator of the deformable mirror is pushed or pulled (±0.2 V applied) and the wavefront for each actuator state measured to build an interaction matrix, and the deformable mirror command control matrix, which accounts for the voltage that should be applied to each actuator to generate (or correct) a certain amount of wave aberration. As some aberrations were inherent to the system and the deformable mirror in the flat state (RMS = 0.11 mm for 6.5-mm pupil, excluding tilt and defocus), those were measured and corrected using a closed loop. The state of the mirror that compensates for the system's aberrations is saved and applied when measurements are performed under natural aberrations. The wave aberration of the eye is measured with the wavefront sensor and kept as a reference file (tilt and defocus are measured but kept free). In a closed-loop correction, the residual wavefront is continuously measured and command controls are continuously sent to the deformable mirror to keep the correction of the aberrations in real time (15 Hz). To perform a static correction, we stop the loop when the RMS (excluding tilt and defocus) does not longer decrease, and we save the deformable mirror state with the voltage applied to each actuator for a future use.

Psychophysical measurements

VA was measured using a four alternative choice procedure with high-contrast tumbling Snellen E letters. The thickness of the lines and gaps of the E letter were one-fifth of their total size. Subjects were asked to identify the orientation of the illiterate letter E (pointing right, left, up, or down) that was displayed on the minidisplay. Each run consisted on 50 trials presented during 0.5 seconds with no feedback to the subject. A QUEST algorithm was programmed in Psychtoolbox (Brainard, 1997) to select the size of each stimuli and optimize the estimation of the spatial resolution threshold. Experiments were done for white E letters on a black background and black E letters on a white background. The effective luminance of the minidisplay at the pupil plane was 50 cd/m^2. This value was estimated taking into account the light losses in the system. Measurements were performed for different luminances (50, 25, 16, 5, 2.5, 1.6, and 0.8 cd/m^2) in the photopic and mesopic range, achieved by placing neutral density filters of appropriate optical density in a filter holder in front of the display. Luminances are specified in terms of the white area of the display. This refers to the background in the BoW experiments and the foreground on the WoB experiments.

Experimental protocols

A total of 42 conditions were tested on each subject, corresponding to seven luminances, two aberration states (natural aberrations and AO-corrected aberrations), two contrast polarities (WoB and BoW), and two pupil dilation states. Measurements with WoB targets were done under undilated and dilated conditions, and measurements with BoW targets were done for dilated conditions only. Experiments were conducted on three sessions on two different days, each typically lasting around two hours.

The subject's pupil was aligned to the system, using a bite bar and the pupil was centered and focused. The subject was then asked to adjust the best subjective focus (starting from a myopic defocus) controlling the Badal system with a keyboard while looking at a high-contrast Snellen E (0.3 decimal VA). Wave aberrations were measured and a closed-loop adaptive-optic correction aiming at cancelling all aberrations except for tilt and defocus was applied. Given the chromatic difference of focus between the infrared aberration-measurement channel and the visible psychophysical channel, defocus was left uncorrected with the mirror, and the Badal system was used instead. The subject was asked again to adjust the Badal system position that provides the best subjective focus for this AO-corrected condition. An AO correction was deemed satisfactory if the residual aberration was <0.2 μm. In most cases the residual was $\sim$0.1 μm (RMS error correction of 67–95%). Only one subject (with low natural aberrations) did not achieve these thresholds after AO correction. A closed-loop correction (at a rate of 15 Hz) was typically achieved in 10 iterations (less than 1 second). Psychophysical measurements were performed under static corrections of aberrations, as continuous dynamic correction would have involved continuous viewing of the spot test and discomfort to the subject (particularly given the relatively long duration of the test). Pupil monitoring and aberration measurements were performed immediately before and after each visual acuity measurement to ensure proper centration and AO correction. A closed-loop AO correction was performed if the percentage of correction had fallen from the initial values.

The first session of measurements was always conducted with undilated pupil and WoB targets. In the undilated condition, the pupil diameter ranged between 5.7 ± 0.8 mm and 4.7 ± 0.7 mm on average, for the lowest luminance the pupil diameter was up to 6.6 mm in certain subjects (AF and LS), and for the highest luminance it was down to 4.1 mm in certain subjects (LR, NC, SB, SM). The second session involved WoB and BoW targets under pupil dilation with 1% tropicamide. An artificial pupil of 6-mm diameter was projected onto the eye's pupil, in the dilated measurements only. All patients dilated up to 6-mm or more, so that the effective pupil diameter was always 6 mm in the dilated condition.

For each condition, VA was measured for ascending level of luminance to minimize the time required for dark adaptation. For the undilated pupil condition this also guaranteed that the aberration measurement and correction were performed for the largest pupil. Subjects were allowed to adapt to the light of each condition by looking at a BoW or WoB square before starting the experiment. For each luminance, VA acuity measurements were performed with natural aberrations and corrected aberrations in random order (with the corresponding defocus correction in each condition). Subjects were allowed to rest whenever required, and they were never informed on the correction-state at which they were performing the test in each moment.

Subjects

Seven young subjects aged 25 to 35 years (29.5 ± 4.4) participated in the experiment. Spherical errors ranged between 0 and −5.75 D (−2.21 ± 2.22 D). Cylinder was ≤0.5 D in all cases. Astigmatism accounted for less than

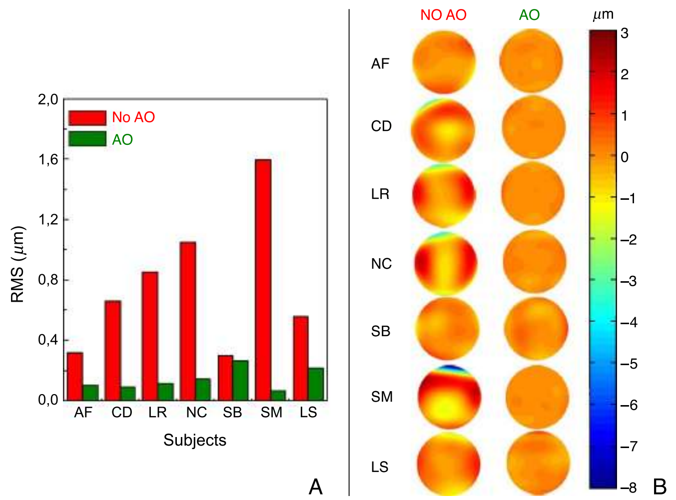

Figure 2. (A) RMS wave front error (excluding tilt and defocus) for all seven subjects before and after AO correction. (B) Wave aberrations maps before and after closed-loop AO correction. Data are for 6-mm dilated pupil diameters.

26% of the RMS (excluding defocus and tilt). 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. The subjects were three of the authors and other four naive subjects.

Data analysis

Visual resolution thresholds were estimated in terms of minimum angle of resolution (MAR), in pixels, converted to arcmin taking into account the focal length of the collimating lens in front of the display (0.026 arcmin/pixels). Visual acuity (VA) will be given in terms of decimal visual acuity (inverse of MAR). The threshold usually converges to the final value in less than 30 trials. At the end of the 50-trial run, the threshold is checked to be stable over the last 10 trials and the VA is obtained as the average of these 10 last visual thresholds.

Wave aberrations were fitted by 7th-order Zernike polynomial expansions. Tilt and the residual defocus term in the Zernike polynomial expansion (consistent with longitudinal chromatic aberration between visible and IR light; Llorente et al., 2003) were set to zero. Optical quality was evaluated in terms of root mean square wave front error (excluding tilt and defocus) and volume under the modulation transfer function (MTF), normalized to the diffraction-limited MTF volume, assuming a homogeneous pupil. Modulation for spatial frequencies beyond 100 c/deg was not considered in the computation (Marcos, Burns, Moreno-Barriuso, & Navarro, 1999). This metric (or equivalent as the Strehl ratio) has been shown to be better correlated with visual function than the RMS (Marsack et al., 2004) and to provide good estimates of refractive error (Guirao & Williams, 2003; Thibos, Hong, Bradley, & Applegate, 2004). Through-focus estimates of the MTF (shifting the defocus term between −1 and 1 D) were computed to assess through-focus optical quality (in terms of Strehl ratio) and the best objective focus position.

Results

Best corrected ocular aberrations and defocus

Figure 2A shows RMS wave front error (excluding tilt and defocus) for all seven subjects before and after correction of aberrations with adaptive optics (for 6-mm pupil diameters). Each bar corresponds to the average of wave aberrations measured throughout the experiment with dilated pupils (average of at least 12 measurements for the corrected state and 4 for natural state). On average, RMS (excluding tilts and defocus) decreased from 0.76 to 0.14 μm, with an average correction of 81%. The AO correction is illustrated in the wave aberration maps in Figure 2B.

Figure 3 shows through-focus Strehl for all subjects with natural and AO-corrected aberrations. Strehl ratios have been computed for a 2-D range around zero defocus (Z_2^0 term). Except for subject SB, there is a dramatic difference in through-focus optical quality between both conditions. In all cases, there is a shift of best objective focus position (more negative in the natural

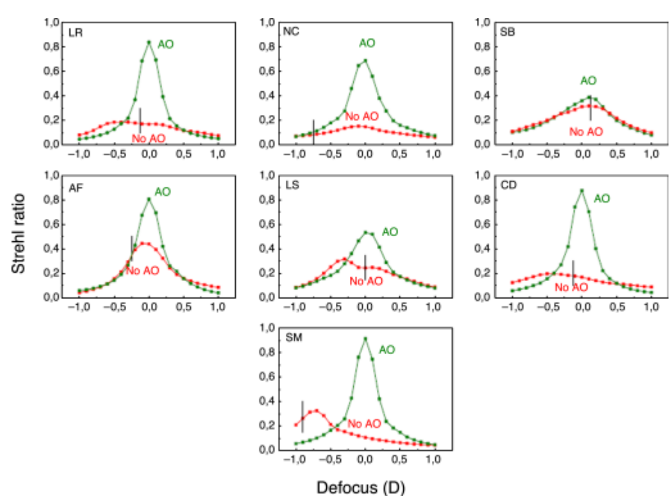

Figure 3. Through-focus Strehl ratio computed from natural and AO-corrected wave aberrations in all subjects (6-mm pupils). The vertical line indicates the subjective best focus as chosen by the subject for the natural aberration condition (with respect to the best focus in the AO condition). Defocus is referred to Z20 = 0. Data are for 6-mm pupils.

aberration condition). Except for subject NC, this shift is in general agreement with the subjective focus shift performed by the subject between conditions (indicated by a vertical line in the graphs). The focus shift is particularly relevant for the subject with larger amount of aberrations (SM, RMS = 1.59 μm), with a focus shift of 0.75 D (Strehl) or 0.9 D (subjective) between the aberrated and AO-corrected condition, illustrating positive interactions of defocus and high-order aberrations (Applegate, Marsack, Ramos, & Sarver, 2003; McLellan, Prieto, Marcos, & Burns, 2006). Comparisons of Strehl ratio for natural and AO-corrected aberrations will be performed for the maximum values of the through-focus curves in Figure 3.

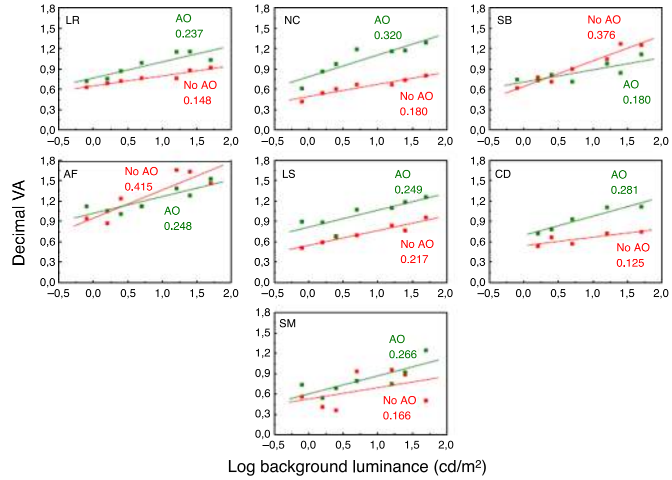

Figure 5. Decimal visual acuity as a function of log background luminance for BoW targets for all eyes, with dilated pupil (6-mm diameter). Data have fitted to linear regressions to the decimal VA vs. logL function (the slope is indicated by the number above each line). Except for in AF and SB, there is an increase in the slope of the regression with correction.

Visual acuity under natural and AO-corrected aberrations as a function of luminance (BoW targets)

There is a consistent average increase of VA with background luminance in both the natural aberrations and AO-correction conditions and a mean improvement of VA at all luminances with AO correction, as shown in Figure 4 (A–C for individual eyes and D for the average across all eyes). The mean increase of VA is fairly constant across luminances, although this varied across individuals. All subjects except for AF and SB showed a significant increase of VA with AO correction. These two subjects showed the lowest RMS before AO correction and the highest VA under natural aberrations.

Figure 5 shows data for all subjects plotted in VA vs. logL form. The numbers on the graphs show the slope of linear regressions to the data. In all eyes (except for AF and SB) there is not only an increase of VA with AO correction but also an increase in the slope of the VA vs. logL function (by a factor of 1.35 on average).

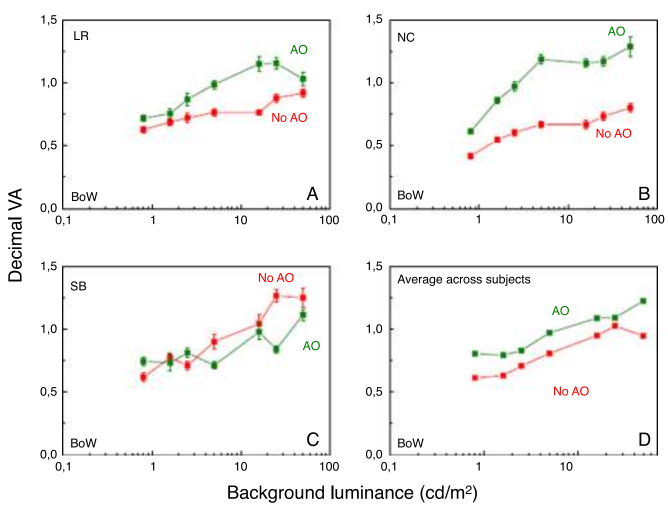

Figure 4. Decimal visual acuity as a function of background luminance (in a log-linear scale) for BoW targets, with dilated pupil (6-mm diameter). (A–C) Examples for three subjects. Error bars stand for standard deviation (of at least ten stabilized threshold estimates). (D) Average across 7 eyes.

Visual acuity under natural and AO-corrected aberrations as a function of foreground luminance (WoB targets)

Figure 6 shows decimal visual acuity as a function of foreground luminance for WoB targets. Figures 6A and 6B are examples for two subjects (for dilated pupils), Figure 6C shows the average across all 7 eyes of the study for dilated pupils, and Figure 6D shows the average across all 7 eyes of the study for undilated pupils. Unlike in Figure 4 (BoW targets) where a systematic increase in VA with luminance was found, curves in Figure 6 show a systematic inverted U shape (i.e., visual acuities are higher for intermediate luminances than for low and high luminances). AO correction of aberrations produced a leftward displacement of the curve, and a significant increase of VA for low and intermediate luminances, but not for the highest luminances tested. Those subjects that did not benefit from AO correction for BoW targets (AF and SB) did not benefit from correction for WoB targets.

Under undilated condition, pupils varied from 5.7 ± 0.8 to 4.7 ± 0.7 mm with increasing foreground luminances (WoB targets). For the natural aberration condition results are similar with dilated and undilated conditions. However, AO correction increases performance less with undilated than with dilated pupils at the lowest luminances.

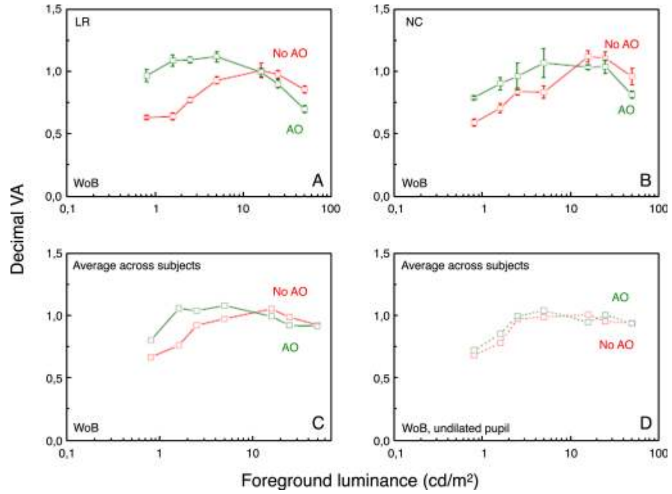

Figure 6. Decimal visual acuity as a function of foreground luminance (in a log-linear scale) for WoB targets. (A–B) Examples for two subjects, with dilated pupil (6 mm). Error bars stand for standard deviation (of at least ten stabilized threshold estimates). (C) Average across 7 eyes, dilated pupil (6 mm). (D) Average across 7 eyes, undilated pupil.

Differences BoW and WoB

We have evaluated the visual benefit of the AO correction of astigmatism and high-order aberrations for all conditions in terms of VA ratios (AO-corrected/natural aberrations) as shown in Figure 7. The benefit is largest for BoW targets than WoB targets (at all luminances except for 1.6 cd/m^2). There is a significant benefit for WoB targets (dilated condition) for low and intermediate luminances, but the ratio falls below 1 for luminances 16 and 25 cd/m^2. The benefit for WoB targets (undilated condition) is very modest, and the ratio falls below 1 at 16 cd/m^2.

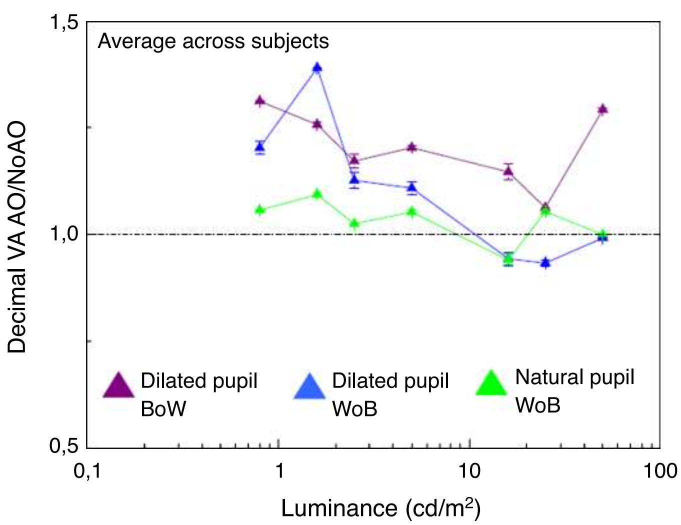

Figure 7. Decimal VA ratios (AO-corrected/natural aberrations) as a function of luminance, in a log-linear scale (background luminance in the BoW condition and foreground luminance in the WoB condition) for all conditions tested: BoW targets (dilated), WoB targets (dilated), WoB targets (undilated), averaged across subjects. Error bars stand for standard deviations.

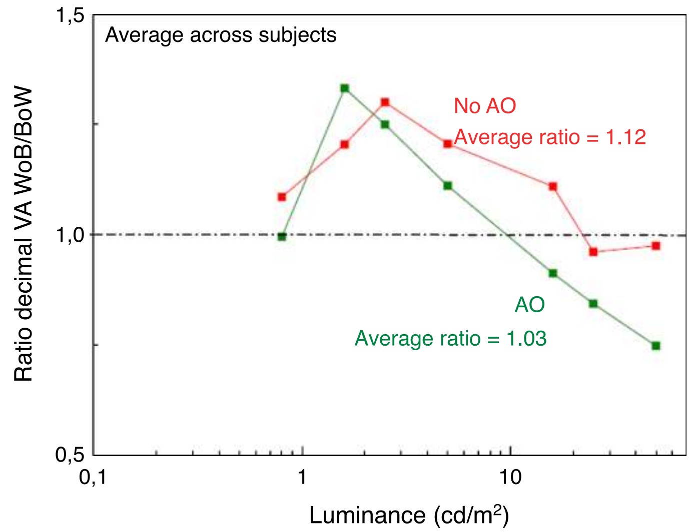

Figure 8. Decimal VA ratios (WoB target/BoW target) as a function of luminance (in a linear-log scale), with natural and AO aberration correction, for dilated pupils (6 mm).

We compared visual performance between standard and reversed contrast polarity targets for the same foreground/background luminances and both natural and AO-corrected aberrations (Figure 8). When the natural aberrations are present, the use of WoB targets produces significantly higher visual performance than BoW targets at least for luminances below 25 cd/m^2. When aberrations are corrected, the relative benefit of using WoB targets is reduced, and except for one luminance (1.6 cd/m^2) WoB/BoW ratio is lower for the AO correction than natural aberrations conditions, and WoB targets only produced higher visual performance than BoW targets (WoB/BoW > 1) for the lowest luminances.

Visual acuity versus optical quality: AO-correction benefit

With natural aberrations, subjects with larger amounts of ocular aberrations tend to have lower VA. Figure 9 shows mean VA (across luminances and contrast polarities) as a function of Strehl ratio at best focus, with dilated pupils (6 mm). The correlation is significant (p = 0.037) when the Strehl ratio metric is used. Our sample included subjects with a large range of natural aberrations and VAs. When subject AF (with highest Strehl and VA) was not included, the correlation did not reach statistical significance (p = 0.11), when the mean decimal VA (across conditions) was used. The correlation was also disrupted when aberrations are corrected (p = 0.582). With AO correction, the functions are displaced toward higher

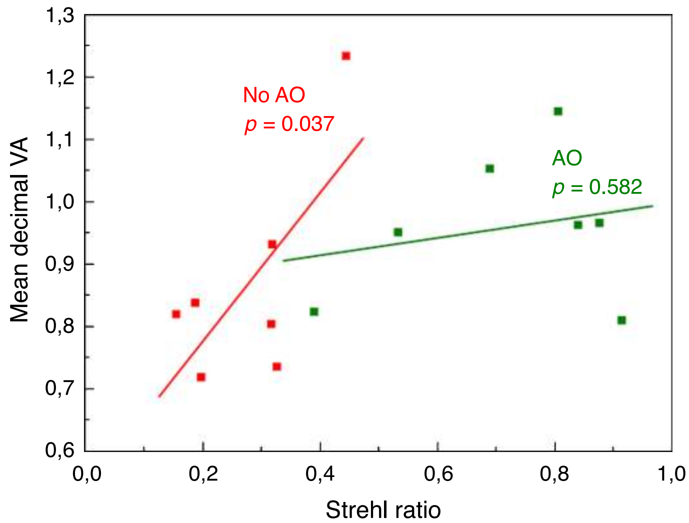

Figure 9. Mean decimal VA versus Strehl ratio for all eyes, for natural aberrations and AO-corrected aberrations. Mean VA is the average across luminances and contrast polarities (for dilated pupils, 6 mm). Strehl ratio is the maximum value of curves of Figure 3 (i.e., Strehl ratio at best focus).

Strehl values and higher VA. Mean decimal VA (across conditions) was not significantly correlated with RMS, neither for natural aberrations nor for AO correction. We performed a similar analysis of VA versus optical quality for each luminance and target-type individually. We found better correlations for BoW than WoB targets. For natural aberrations, correlations were statistically significant for BoW targets at 25 cd/m^2 (p = 0.05), 16 cd/m^2 (p = 0.0005), and 5 cd/m^2 (p = 0.0038) using Strehl ratio and at 50 cd/m^2 (p = 0.009), 2.5 cd/m^2 (p = 0.0046), and 1.6 cd/m^2 (p = 0.0186) using RMS. All of these correlations still held when subject AF was excluded (except at 25 cd/m^2). For WoB targets, correlations were statistically significant only for 5 cd/m^2 (p = 0.036 and p = 0.045 for Strehl and RMS, respectively) and 0.8 cd/m^2 (p = 0.034 and p = 0.048 for Strehl and RMS, respectively). For AO-corrected aberrations, none of the correlations were significant.

We found that subjects that experienced larger amounts of optical corrections also experienced a larger increase in VA. This is shown in Figure 10A by correlations of the mean VA AO/no AO ratios (across luminances and contrast polarities) with Strehl AO/no AO ratios at best focus (for dilated pupils). The correlation was significant (p = 0.04), but not when RMS AO/no AO ratio was used as a metric (p = 0.14). The same analysis was performed individually for each luminance and contrast polarity, using both Strehl AO/no AO and Strehl AO–no AO as metrics. We did not find any systematic trend with luminance for AO benefit in relation to amount of optical correction.

We also found that subjects that experienced a larger amount of optical correction showed a larger increase in the slope VA vs. logL (with BoW targets, see Figure 5). This is shown in Figure 10B, which shows the correlation between the mentioned slope AO/no AO ratio and the Strehl AO/no AO ratio (p = 0.0092).

Discussion

We found that correcting aberrations produced an increase in high-contrast visual acuity in normal eyes under a range of conditions of luminance and target contrast polarity. The maximum increase of decimal VA was by a factor of 2.5 for the subject with the highest amount of ocular aberrations, BoW targets, and the highest luminance (50 cd/m^2). In general, the increase in VA was more modest for WoB targets (by a factor of 1.13, averaged across luminances and subjects) than for BoW targets (by a factor of 1.29). For WoB targets there was no improvement in VA at the highest luminances.

Previous studies had shown an increase (of similar order of magnitude) of high-contrast visual acuity in normal eyes (typically for high luminance and BoW targets) when aberrations had been corrected with adaptive optics (Artal, Chen, Fernández, et al., 2004; Yoon & Williams, 2002) or phase plates (Yoon et al. 2004). Others had shown that increasing the RMS error decreased VA (Applegate, Ballentine, et al. 2003). We have demonstrated that the improvement of VA is actually correlated with the amount of aberrations corrected in normal eyes. It is also interesting that in the presence of aberrations VA appears correlated with optical quality, indicating that aberrations impose a major limit in spatial resolution. The fact that the

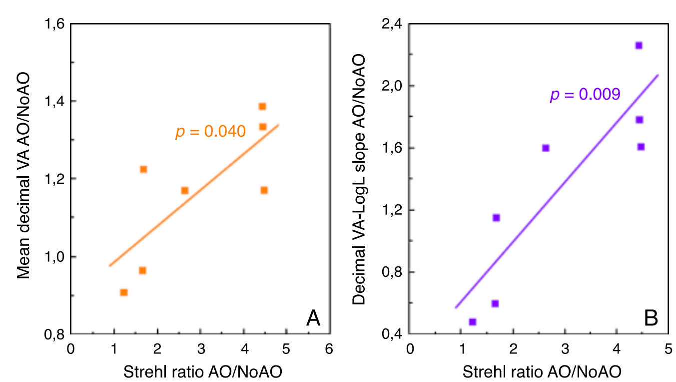

Figure 10. (A) Ratio of mean VA (corrected/natural aberrations) versus Strehl ratio (corrected/natural aberrations) from data shown in Figure 9. (B) Ratio of slope VA vs. LogL functions (corrected/natural aberrations) versus Strehl ratio (corrected/ natural aberrations) using data from Figures 3 and 5. Linear regression to the data (and the corresponding p values) is also shown, indicating a significant correlation between visual and optical improvement (A) and between increase in the rate of change of VA with log luminance and optical improvement (B).

correlation gets disrupted when aberrations are corrected agrees with previous literature that found that in eyes with high visual acuity, photopic high-contrast logMAR acuity is insensitive to variations in retinal image (Applegate et al., 2006), and it is indicative of the limiting effects of other non-optical factors when aberrations are corrected. As the sample was small and most of the subjects were emmetropes, we did not attempt to correlate these findings with refractive error, as the study by Rossi et al. (2007) had done.

The change of VA with luminance and target contrast polarity and how these functions change upon correction of aberrations may give new insights into the physical limits of visual spatial resolution. While it has been shown for more than a century that visual acuity increases with increasing luminance in normal foveal vision (Ferree & Rand, 1932; Riggs, 1965), the relative contribution to visual resolution of optical aberrations, pre-neural factors (quantal fluctuations in the stimulus, transmittance of the optical media, aperture, quantum efficiency, and spatial distribution of foveal photoreceptors), and neural factors for different luminances is not fully established. We have shown that correcting aberrations (for BoW targets) improves VA on average at all luminances, but the increase of VA with luminance also occurs in close to diffraction-limited conditions, indicating that quantum catch properties are a major factor in the effect. The effect of artificial blurring in the retinal image (with trial lenses) on the acuity vs. logL slope had been investigated before (Sloan, 1968). That study aimed at testing the hypothesis that the increase in acuity with luminance results from a decrease in the size of the retinal area that acts as a single photoreceptor unit. We found that similarly to defocus, the blur produced by high-order aberrations also produce a decrease in the slope of the acuity vs. logL.

While the change in visual acuity with luminance has been extensively studied in previous literature for BoW targets, there are scarce data in the literature with WoB targets, and very few have looked at changes with luminance (Wilcox, 1932). It is interesting that VA with BoW targets does not increase steadily with luminance, but following an initial increase for lower and intermediate luminances, decreases for higher luminances. This inverted “U shape” behavior agrees with that reported by Wilcox (1932). This effect may be related to that described as “irradiation” in old literature (Walls, 1943; Wilcox, 1932), i.e., when the brightness of narrow lines on dark field (as in the WoB letter targets) is increased, angular resolution is compromised as the perceived gap is filled in with light. When aberrations are corrected the function seems to be shifted leftwards, as if this phenomenon started to occur at lower luminances. Whatever the origin, there appears to be a benefit of correcting aberrations at low and intermediate luminances, but not at higher luminances for WoB targets. It should also be noted that the state of dark adaptation is different for the same condition of background or foreground luminance. We found slightly poorer benefit of AO correction at the lower luminances under undilated pupil compared to the dilated conditions (WoB targets). This may indicate that, at least with natural aberrations, the pupil miosis provides optimal aperture for visual acuity at each luminance (Campbell & Gregory, 1960). However, differences in the pupil diameter between these dilated and undilated conditions (6 vs. 5.17 ± 0.87 mm at 1.6 cd/m^2, for which the largest difference in VA occurs) cannot account for the difference in visual performance. Also a stable correction may be more challenging under free accommodation and dim illumination (dim targets on black background), which may result in lower VA than with dilated conditions.

Previous literature suggests better visual performance for WoB targets than BoW targets, the magnitude of the effect varying across studies, experimental conditions, and age of the population (Pointer, 2001; Westheimer, 2003; Westheimer et al., 2003). Westheimer (2003) argued that even for identical targets but of reversed polarity, contrast is different because the background light level, which is a dividing factor in the contrast calculation, is much less when only the letters are bright. As contrast is the limiting factor in visual acuity, reversed contrast (WoB) would be expected to be better and more in eyes where aberrations and light scatter widen the point-spread function. We have found (Figure 8) that for a wide range of luminances (particularly low and intermediate luminances) performance with WoB targets exceeds BoW under natural aberrations, and that this advantage significantly decreases when aberrations are corrected. The presence of scattering may explain that even with AO-correction VA with WoB targets still exceeds BoW at low-intermediate luminances.

Conclusions

In summary we have seen that correcting aberrations results in an overall improvement in visual acuity under a range of conditions, particularly in eyes with significant amounts of aberrations. Comparing the effect of correcting aberrations as a function of luminance and contrast polarity has allowed us to test hypothesis on physical limits to spatial vision. However, it remains to be seen to which extent those benefits are of clinical importance could the same amounts of corrections (70% on average) be achieved with customized lenses or surgery. Comparisons of results with dilated and undilated pupils show that the benefits are reduced under undilated conditions. On the other hand, we have used high-contrast targets and polychromatic light. It is likely that higher benefits would have been achieved for low-contrast targets and monochromatic light. Undergoing experiments in our laboratory aim at testing change in visual performance when aberrations are corrected using complex, natural targets and real world tasks.

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