Binocular visual performance with aberration correction as a function of light level

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The extent to which monocular visual performance of subjects with normal amounts of ocular aberrations can be improved with adaptive optics (AO) depends on both the pupil diameter and the luminance for visual testing. Here, the benefit of correction of higher order aberrations for binocular visual performance was assessed over a range of luminances for natural light-adapted pupil sizes with a binocular AO visual simulator. Results show that binocular aberration correction benefits for visual acuity and contrast sensitivity increase with decreasing luminances. Also, the advantage of binocular over monocular viewing increases when visual acuity becomes worse. The findings suggest that binocular summation mitigates poor visual performance under low luminance conditions.

Introduction

From our daily experience we know that visual performance decreases under low luminance conditions. A considerable amount of literature has been published on this topic. Koenig provided a very complete study of this phenomenon over a large range of luminances as early as 1897 (Koenig, 1897). Results show that visual acuity (VA) increases as a sigmoidal function of the logarithm of luminance, with a steep linear increase for intermediate light levels between -2.5 and 0.5 log cd/m^2. Similarly, contrast sensitivity decreases with decreasing luminance (van Meeteren & Vos, 1972). In the intermediate luminance range, the relationship between visual performance and stimulus luminance is mainly due to two reasons. On the one hand, neural performance falls off when retinal illuminance is reduced (Coletta & Sharma, 1995; van Nes & Bouman, 1967). On the other hand, pupil diameters (Leibowitz, 1952), and with them aberrations (Artal & Navarro, 1994; Liang & Williams, 1997), increase for lower light levels and reduce the optical quality of the eye.

With the availability of adaptive optics (AO) instruments for visual testing (Fernández, Manzanera, Piers, & Artal, 2002) several studies investigated the benefit of monocular AO aberration correction at differing light levels. Yoon and Williams (2002) found a significant increase in VA when correcting monochromatic aberrations for a fixed pupil size of 6 mm in a group of subjects. Thus, the AO benefit was higher for a low luminance stimulus (2 cd/m^2) than for a bright stimulus (20 cd/m^2). A later study confirmed this behavior over a wider luminance range of two log-scales for VA (Marcos, Sawides, Gambra, & Dorronsoro, 2008). However, for similar light levels and the same pupil size, AO benefits derived from contrast sensitivities (CS) decreased when stimulus luminance was decreased (Dalimier, Dainty, & Barbur, 2008). Moreover, Dalimier and colleagues found that the slope of AO benefit versus light levels became shallower with decreasing pupil diameters. Based on the results, the AO benefit for a natural light-adapted pupil size was estimated to range from 1 to 1.4, depending on the luminance condition.

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While the studies mentioned above were performed with induced cycloplegic-mydriatic drugs and fixed artificial pupil sizes, pupil diameters increase with decreasing ambient luminance under normal conditions (Winn, Whitaker, Elliott, & Phillips, 1994). Furthermore, the research to date has tended to focus on monocular vision. An AO instrument was also used to study magnitude and underlying causes of a phenomenon often called night myopia, that is, the refractive defocus shift as a function of luminance (Artal, Schwarz, Cánovas, & Mira-Agudelo, 2012).

Under normal conditions, binocular viewing leads to an increase in visual performance compared to monocular viewing. Binocular advantage is commonly quantified by the binocular summation ratio, defined as the ratio of binocular performance and monocular performance of the better performing eye. The ratio is known to be greater for detection tasks at threshold than for discrimination tasks that are performed above threshold (Blake & Fox, 1973; Legge, 1984a, 1984b). For high luminance stimuli and best corrected refraction, contrast sensitivity measurements revealed a binocular summation ratio of about 1.4 over a wide range of spatial frequencies (Campbell & Green, 1965), whereas visual acuity resulted in a ratio of about 1.1 (Cagenello, Arditi, & Halpern, 1993).

In part, binocular advantage is due to optical factors. In binocular viewing, natural pupil sizes are smaller than in monocular viewing under the same luminance conditions (Doesschate & Alpern, 1967). While smaller pupil sizes reduce the amount of aberrations of the eye and extend the depth of focus (Guirao, Porter, Williams, & Cox, 2002), retinal illuminance is reduced. Leibowitz and Walker (1956) observed a minor nonsignificant effect on binocular summation of suprathreshold stimuli when reducing retinal illuminance by three log scales. Additionally, fixation and accommodation might differ under monocular and binocular conditions. However, summation is also observed when optical factors are kept constant. Stimuli viewed binocularly appear brighter than stimuli viewed monocularly. Binocular brightness summation was shown to depend on the stimulus size. Ganzfeld conditions caused summation by a factor of 2, whereas a 2° field failed from evoking binocular summation (Bolanowski, 1987). Home (1978) investigated the way that binocular summation of visual acuity and contrast sensitivity with natural pupil sizes and accommodation is affected by reduced stimulus luminance. His main findings were that binocular summation stays relatively constant over a wide luminance range and that binocular summation mainly happens in the contrast domain. That is to say, larger low-contrast letters evoke more summation than smaller high-contrast letters, since the task is basically that of contrast detection. In line with this theory, a recent study showed that binocular summation was higher when both eyes' optical quality was reduced by adding a defocus (Plainis, Petratou, Giannakopoulou, Atchison, & Tsilimbaris, 2011). To what extent visual performance with best corrected refraction, under binocular viewing conditions and at low luminance, can be improved by correcting higher order aberrations still remains to be investigated. The best achievable performance could then be regarded as neural limit to performance.

Recently, binocular AO visual simulators have been introduced (Fernandez, Prieto, & Artal, 2010; Fernández, Prieto, & Artal, 2009). These instruments permit binocular visual testing of subjects while aberrations of both eyes are measured and modified with AO (Sabesan, Zheleznyak, & Yoon, 2012; Schwarz, Cánovas, et al., 2014; Schwarz, Manzanera, Prieto, Fernández, & Artal, 2014; Zheleznyak, Sabesan, Oh, MacRae, & Yoon, 2013), and are thus suitable to address this knowledge gap.

In an effort to better understand natural binocular vision under varying luminance conditions, this study investigates monocular and binocular visual performance with or without AO correction over a range of light levels. Correction benefits and binocular summation ratios are deduced and interpreted.

Methods

Experimental setup

A binocular AO visual simulator was used for the study. Similar versions of the setup have been reported elsewhere (Fernández et al., 2009; Schwarz, Prieto, Fernández, & Artal, 2011). Figure 1 shows the layout of the binocular AO system. While typical AO systems are constructed to measure and manipulate aberrations of a single eye, the instrument employed here provides aberration measurement and modulation of both eyes simultaneously with a single Hartmann-Shack sensor (HSS) and a single liquid crystal on silicon spatial light modulator (LCoS-SLM). Each lenslet of the HSS has an effective diameter of 400 μm and a focal length of 6 mm. The spot image is projected onto a CCD camera with enhanced sensitivity in the near infrared (C5999; Hamamatsu Photonics, Hamamatsu, Japan). Aberrations are measured at a wavelength of 780 nm. The LCoS-SLM (PLUTO-VIS, Holoeye, Berlin, Germany) features Full HD (1920 × 1080) resolution with a pixel pitch of 8 μm. For pupil diameters of 7 mm (i.e., the largest pupil size the system permits in the current configuration), one pupil is sampled by more than half a million pixels for phase modulation. Another liquid crystal device (LC-SLM) working in transmission (LC2002; Holoeye, Berlin, Germany) is used to create

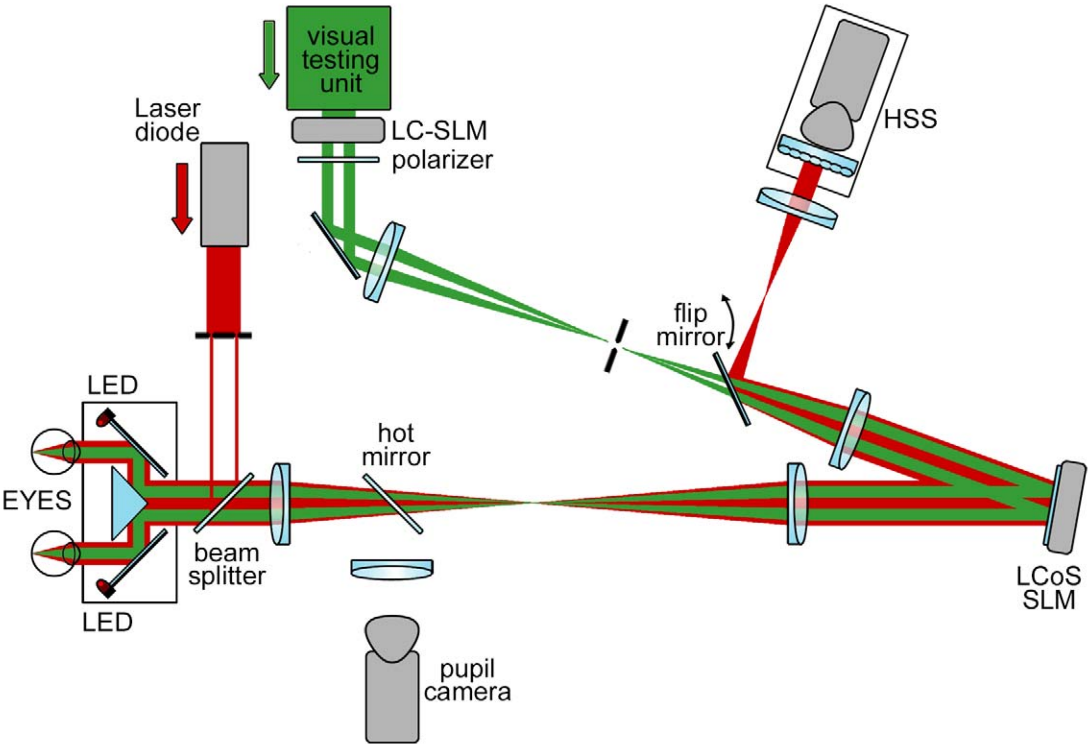

Figure 1. Optical layout of the binocular adaptive optics visual simulator.

both artificial pupils. A microdisplay (MPro 120; 3M, St. Paul, MN, USA) in combination with a 40 nm FWHM bandpass filter centered at 550 nm allows for presenting visual stimuli at optical infinity. Aberration modulation is performed at a wavelength of 543 nm, being the peak wavelength of the measured display spectrum. The subjects' position with respect to the AO simulator's entrance pupils can be monitored via a pupil camera (Manta G-145 NIR; Allied Vision Technologies GmbH, Stadtroda, Germany) featuring high sensitivity in the infrared spectrum. During pupil monitoring, the subjects' pupils were illuminated with LEDs emitting light around 900 nm.

Subjects

Three experienced subjects, aged 51, 40, and 28, participated in the study. All of them have normal binocular vision and no history of ocular disease. The subjects are mild myopes with refractive errors between –1 and –3 D; Subject 1 is a presbyope. Table 1 provides the subjects' aberration data for a 5 mm pupil and the dominant eye is marked with an asterisk. Table 2 lists the subjects' average pupil diameters when fixating a stimulus with different background luminances under binocular viewing conditions. Eye dominance was determined by the Miles test (Miles, 1929).

All subjects provided informed consent after the nature of the study and possible consequences had been explained to them. The research followed the tenets of the Declaration of Helsinki.

Optical quality simulations

For every subject, the theoretical monocular AO benefit was computed by visual quality simulations. Since there was only a small increase in pupil diameter with decreasing stimulus luminance, simulations were performed for the highest and the lowest stimulus luminance. We used the radially average MTF between 0 and 60 cpd at best focus as optical quality metric. Simulations took into account the spectral bandwidth of the stimulus display, the luminous efficiency function of the human eye, the subject's pupil size and aberration pattern, and the Stiles-Crawford effect. Since in this study we tested foveal vision which only involves cones, the photopic spectral luminous efficiency function was used for visual quality simulations at the highest and lowest stimulus luminance.

Figure 2 shows the area under the rMTF at best focus for the dominant eyes of the three subjects. Metrics for a stimulus luminance of 2 cd/m^2 are shown on the left and for 0.002 cd/m^2 on the right. According to the simulations, Subject 2, who has the highest amount of higher order aberrations, is supposed to benefit the most from AO correction. Subject 3, who presented the lowest amount of higher order aberrations, is expected to have the least benefit.

Subject	Age (y)	Eye	Subjective refraction (D)	RMS (μm)	HOA-RMS (μm)
#1	51	OS	−2.46 −0.57 × 68°	0.39	0.15
		OD*	−2.40 −1.01 × 92°	0.68	0.22
#2	41	OS	−2.40 −0.90 × 63°	0.62	0.24
		OD*	−3.02 −0.38 × 86°	0.32	0.20
#3	28	OS*	−0.93 −0.45 × 110	0.30	0.10
		OD	−1.01 −0.30 × 59	0.22	0.12

Table 1. Ocular data and aberrations for 5 mm pupils of subjects involved in the study. The asterisk marks the dominant eye.

Measurement of visual performance

Throughout the experiment, artificial pupils were set to 7 mm. The subjects' pupils were not dilated and they were able to accommodate normally. Astigmatism and higher order aberrations (HOA) of the subjects were corrected statically according to HSS measurements for the largest available pupil size while the subject was looking at the stimulus with the lowest luminance level tested. In case a subject did not reach a pupil diameter of 7 mm and aberrations were measured for a smaller pupil size, we expanded the wavefront map to a diameter of 7 mm. In this way, the wavefront map was not altered for the measured pupil and did not suffer abrupt changes in case the pupil dilated to a diameter larger than the one during aberration measurement.

The experiment involved VA and CS testing in quasi-monochromatic (green) light for four different stimulus luminances in an otherwise dark room. The visual test field subtended a visual angle of 1°. The maximum stimulus luminance measured through the AO system was 2 cd/m^2. Stimulus luminance was then reduced by placing neutral density filters with optical density 1, 2, and 3 (log units absorptance) in front of the microdisplay, so that the effective stimulus luminances were 0.2 cd/m^2, 0.02 cd/m^2, and 0.002 cd/m^2, respectively. Visual testing was performed with best corrected refraction, with or without additional static HOA correction. After adaptation to the screen luminance under test, subjects adjusted their best-focus position subjectively in increments of 0.1 D. In this way, subjects were able to correct for the possible relative myopic shift due to night myopia which was expected to occur under low luminance conditions (Artal et al., 2012). Therefore, they were given control over the defocus term induced by the wavefront modulator in such a way that, by scrolling a mouse wheel, the best-focus position could be modified. This procedure was performed monocularly for either eye while the fellow eye was occluded with an eye patch. Subsequently, in case of binocular testing, subjects were allowed to fine-adjust the best-focus position while fixating the target binocularly. The average of three adjustments was taken as final value.

	Stimulus luminance			
Subject	2 cd/m^2	0.2 cd/m^2	0.02 cd/m^2	0.002 cd/m^2
#1	6.7 ± 0.3	6.7 ± 0.2	6.7 ± 0.3	6.9 ± 0.4
#2	6.3 ± 0.5	6.4 ± 0.6	6.6 ± 0.5	6.5 ± 0.5
#3	6.4 ± 0.4	6.3 ± 0.5	6.0 ± 0.4	6.2 ± 0.6

Table 2. Average pupil diameters for every subject while fixating stimuli of different background luminances under binocular viewing.

VA was tested under monocular and binocular viewing. Monocular performance was only tested in the dominant eye. After the subject performed an initial adjustment of the letter size to the approximate threshold, a four-alternative forced-choice test was initiated. Stimuli were high-contrast tumbling E letters that were presented for 300 ms in one of four possible orientations. Seven letter sizes distributed in steps of 0.13 arcmin around the previously adjusted value were presented per series of the forced-choice test. One series consisted of 42 stimulus presentation (6 repetitions per letter size). The subjects' task was to determine the orientation of the letter E. VA was defined as the letter size for which 62.5% of the orientations were correctly discriminated.

For CS measurements, the same display was used as for high-contrast VA measurements. CS was obtained in binocular viewing conditions. Stimuli were vertical Gabor patches with a carrier frequency of 6 cpd. Gabor patches consisted of sinewave gratings with a Gaussian envelope function, so that the effective stimulus size was 0.8°. Stimuli were presented for 300 ms, followed by a 500 ms interstimulus interval. The subject's task was to decrease the contrast of the Gabor grating from a clearly visible contrast to the threshold. Contrast could be modified in increments of 0.4%. The average of three consecutive adjustments was taken as final CS for a given optical condition.

Subsequently, the binocular AO benefit was calculated as ratio between binocular visual performance (VA and CS) with AO correction and without AO correction. Monocular AO benefits were derived accordingly as ratios between monocular VA with AO correction and monocular VA without AO correction. The binocular summation ratio (BSR) was determined by dividing binocular VA by monocular VA.

Statistical analysis was performed with multifactorial ANOVAs (categories: subjects, stimulus luminance, aberration correction, and in case of VA data binocularity) and paired student's *t* tests. Results were considered significant when $p < 0.05$.

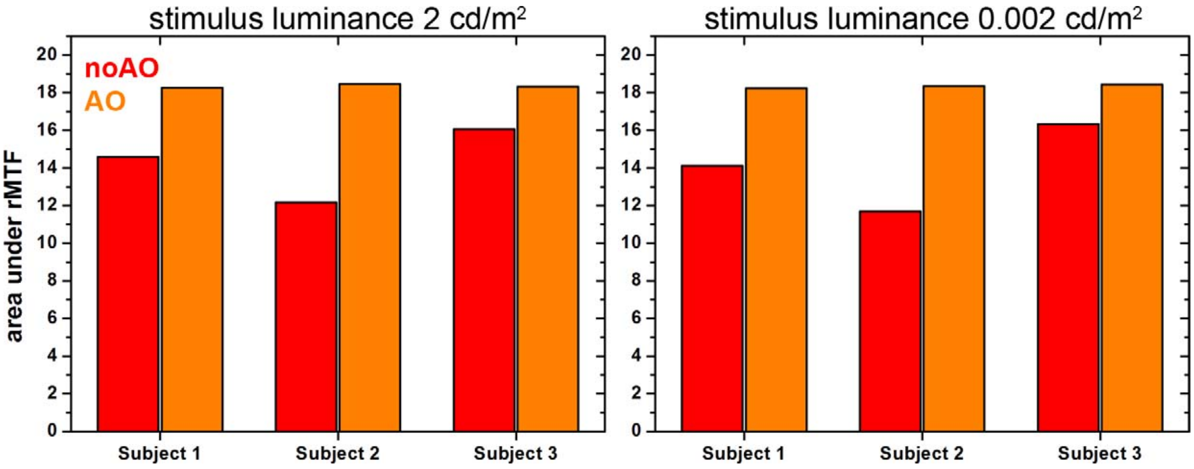

Figure 2. Theoretical optical quality simulations for the three subjects. Left and right panels show the area under the radially averaged modulation transfer function (rMTF) between 0 and 60 cpd at a stimulus luminance of 2 and 0.002 cd/m^2. Metrics computed with and without the subjects' higher order aberration pattern are illustrated in red and yellow.

Results

Table 2 lists the subjects' average pupil diameters when fixating a stimulus with different background luminances under binocular viewing conditions. No significant difference in pupil diameter could be observed under monocular and binocular viewing conditions. A nonsignificant increase in pupil diameters was observed as stimulus luminance was reduced. The small difference in pupil size between viewing conditions is due to our small visual test field of 1° (Watson & Yellott, 2012). No significant effect of dark vergence could be observed.

Subjects demanded on average a higher myopia correction as stimulus luminance decreased. However, no substantial amount of night myopia could be observed. Between the highest and the lowest stimulus luminance, the subjective defocus shift without AO correction was 0.2 ± 0.2 D and with AO correction 0.1 ± 0.2 D. This effect was not statistically significant.

The left panel of Figure 3 shows the average VA across the three subjects as a function of light level. Typical standard deviations between subjects were about 15% of the average VA. Typical within-subject standard deviations were about 10% of the individual average VA. Monocular VAs were omitted for the lowest stimulus luminance without AO correction, since for two of the subjects, the stimulus luminance was too faint to search for the best-focus position. Average VA decreased with decreasing luminance, no matter if measured monocular, binocular, with baseline correction (no AO) or HOA correction (AO).

The ANOVA revealed significant effects of subjects ($p = 0.021$), stimulus luminance ($p < 0.001$), aberration correction ($p < 0.001$), and binocularity ($p = 0.001$) but

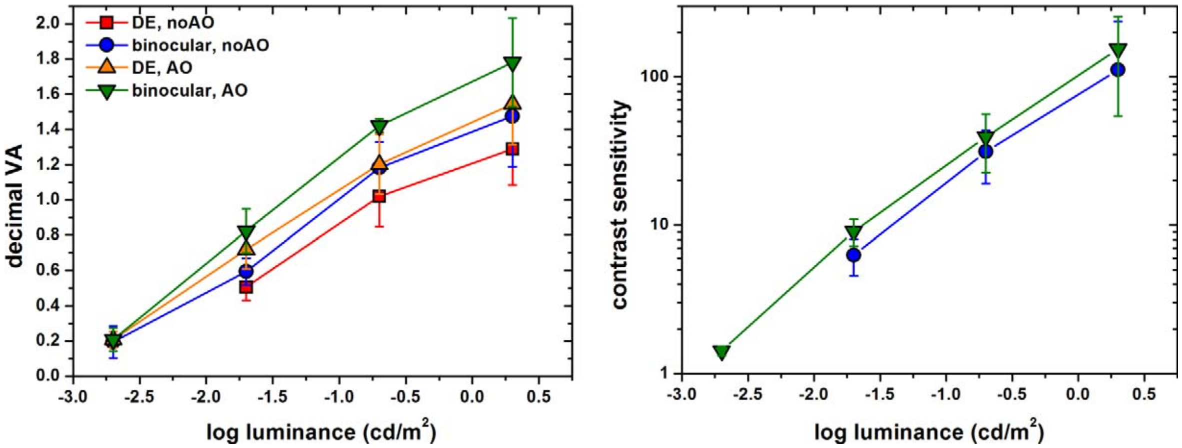

Figure 3. Average decimal visual acuity (VA) and contrast sensitivity across the three subjects versus log luminance. Visual performance was measured for the dominant eye (DE) or binocular, with or without adaptive optics correction (AO and noAO, respectively). Error bars are standard deviations.

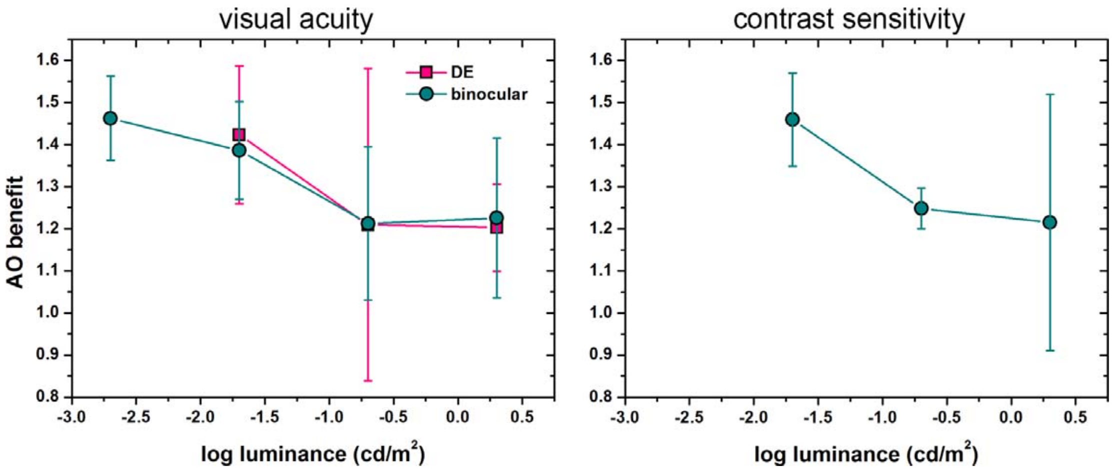

Figure 4. Average adaptive optics (AO) visual benefit as a function of stimulus luminance under monocular viewing with the dominant eye (DE) and under binocular viewing. Left and right panels show AO benefits derived from visual acuities and contrast sensitivities. Error bars are standard deviations.

no interaction between these factors. For all luminance conditions, average binocular VA was greater than average monocular VA under that same correction mode. For monocular and binocular VA without AO correction, a significant difference was found at all stimulus luminances where a comparison was possible (2 cd/m^2: $p = 0.034$; 0.2 cd/m^2: $p = 0.036$; 0.02 cd/m^2: $p = 0.023$). For monocular and binocular VA with AO correction, a significant difference was found for stimulus luminances of 0.2 cd/m^2 ($p = 0.012$) and 0.02 cd/m^2 ($p = 0.013$). Moreover, for all luminance conditions, average VA assessed during AO correction was always greater than average VA with baseline correction only. Statistically significant differences between monocular VA with and without AO correction was found for stimulus luminances of 2 cd/m^2 ($p = 0.041$) and 0.02 cd/m^2 ($p = 0.023$). Binocular VA with and without AO correction was found to be statistically significantly different for the two lowest stimulus luminances (0.02 cd/m^2: $p = 0.018$; 0.002 cd/m^2: $p = 0.038$).

Curves for which average VAs were obtained over all stimulus luminances, were fit with linear regressions. For monocular AO corrected VAs, a slope of 0.43 ± 0.10 was found. In case of binocular VAs, the slope was 0.44 ± 0.08 when HOA were not corrected, and 0.51 ± 0.06 with AO correction. The difference in slopes failed to be statistically significant.

In the right panel of Figure 3, average binocular CS across the three subjects versus log luminance is shown. Standard deviations between subjects were about 80% of the average CS for the highest luminance but decreased as luminance was decreased to 40%, 20%, and 10%. Typical within-subject standard deviations were about 20% of the individual average CS. CS measurements for the lowest stimulus luminance without AO correction were omitted due to the faintness of the stimulus. Average CS decreased with decreasing luminance. This was valid for measurements with AO correction as well as without AO correction. Slopes of binocular CSs without and with AO correction versus log luminance were 0.5 ± 0.2 and 0.5 ± 0.1. The ANOVA revealed significant effects of subjects ($p = 0.040$) and stimulus luminance ($p < 0.001$) but not aberration correction ($p = 0.081$). No interactions between these factors were found. For all luminance conditions, average binocular CS assessed during AO correction was greater than average binocular CS with baseline correction only. A statistically significant difference was only found for the lowest comparable stimulus luminance of 0.02 cd/m^2 ($p = 0.030$).

Figure 4 shows average AO benefits versus stimulus light levels. Typical standard deviations measured about 0.15. Ratios derived from monocular and binocular VAs are presented on the left, whereas ratios derived from binocular CS are illustrated on the right. AO benefits increased with decreasing luminance and were similar under monocular and binocular visual conditions. A statistical significant effect with stimulus luminance was only found for benefits derived from VAs. The monocular AO benefit was significantly higher with respect to the highest stimulus luminance of 2 cd/m^2 at 0.02 cd/m^2 ($p = 0.012$). Binocular AO benefits were significantly higher with respect to the highest stimulus luminance of 2 cd/m^2 at the two lowest luminances of 0.02 cd/m^2 ($p = 0.041$) and 0.002 cd/m^2 ($p = 0.030$).

Figure 5 shows BSR derived from VAs as a function of luminance. Standard deviations measured about 0.05. Without AO correction, the curve shows a slight, though not significant increase. With AO correction, the BSR was significantly greater for the lowest light level compared to the brightest stimulus luminance ($p =$

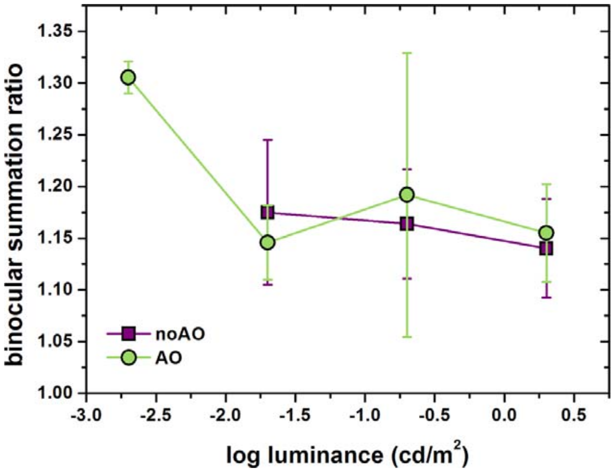

Figure 5. Average binocular summation ratio across the three subjects derived from visual acuities versus log luminance for uncorrected (noAO) and corrected (AO) higher-order aberrations. Error bars are standard deviations.

0.04). Over the three highest luminances, in contrast, BSRs with and without AO correction were similar with an average value of 1.16 ± 0.02.

Figure 6 shows binocular VAs versus monocular VAs for individual subjects. The diagonal black line marks equal VA for monocular and binocular vision. All of the measurement points lie above the black line, meaning that binocular summation occurred. A linear regression with the equation $VA_{binocular} = 1.13 \cdot VA_{DE} + 0.04$ fitted the data well ($R^2 = 0.994$, $p < 0.001$).

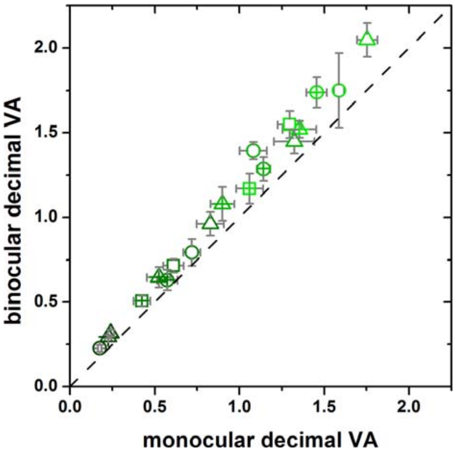

Figure 6. Binocular decimal visual acuity versus monocular decimal visual acuity for individual subjects (coded by symbol shapes). Crossed symbols represent measurements without AO correction; open symbols represent measurements with AO correction. Stimulus luminance is color-coded, where the lightest shade of green stands for the 2 cd/m^2 and the darkest shade for 0.002 cd/m^2. Error bars are standard deviations.

Discussion

The aim of this study was to measure the benefit of correction of higher order aberrations for binocular visual performance over a range of luminances for natural light-adapted pupil sizes. Both effects, aberration correction and binocular summation, increase as stimulus luminance is decreased. Binocular vision is of particular advantage in low luminance conditions. Correcting aberrations of both eyes can further improve visual performance.

We measured binocular and monocular visual performance over the range of luminances for which changes in performance are known to be greatest (Koenig, 1897). In accordance with Koenig's work, VA versus log luminance curves flatten noticeably for the highest luminance measured in this experiment, and slopes of linear regressions fit to the data were found to be steeper than reported elsewhere for higher light levels (Marcos et al., 2008). To the best of our knowledge, this is the first study that reports visual performance with AO correction at a stimulus luminance as low as −2.5 log cd/m^2. Comparisons to other studies can therefore only be made for the highest stimulus luminance measured here of 0.5 log cd/m^2. Nevertheless, monocular and binocular VA measurements at lower stimulus luminance without AO correction are in line with previous reports (Home, 1978; Johnson, 1976; Koenig, 1897) when differences between experimental conditions (stimulus spectrum, stimulus contrast, compensation for night myopia, etc.) are considered. Also, binocular CSs are largely in line with monocular and binocular measurements in previous studies (Coletta & Sharma, 1995; Home, 1978; van Nes & Bouman, 1967). Slopes of binocular CSs versus log luminance agreed well with the slope of 0.5 of the DeVries-Rose law, meaning that for low luminances sensitivity is limited by photon noise (de Vries, 1943; Rose, 1948). Effects of stimulus luminance on AO benefits derived from CSs were not statistically significant, probably due to the adjustment method used to obtain the thresholds.

We found that AO correction improves binocular VA over a range of luminance conditions with vision through natural pupil diameters. The monocular AO benefit derived from VAs for the highest stimulus luminance of 1.2 is broadly in line with previous studies (Marcos et al., 2008; Yoon & Williams, 2002), although subjects and optical conditions differed between the studies. On the one hand, VA measurements were obtained here with natural light-adapted pupils that were even slightly bigger than artificial 6 mm pupils in other studies. On the other hand, the stimuli were presented in quasi-monochromatic light, hence reducing the effect of chromatic aberration. Both factors are expected to influence the AO benefit (Liang &

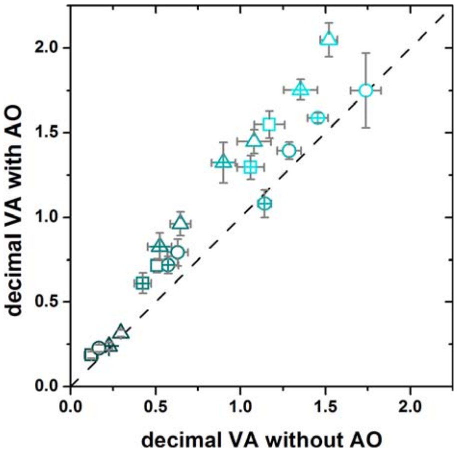

Figure 7. Decimal visual acuity with aberration correction versus decimal visual acuity without aberration correction for individual subjects (coded by symbol shapes). Crossed symbols represent monocular measurements; open symbols represent binocular measurements. Stimulus luminance is color-coded. The lightest shade of blue stands for the 2 cd/m^2 and dark blue for 0.002 cd/m^2. Error bars are standard deviations.

Williams, 1997; McLellan, Marcos, Prieto, & Burns, 2002). Monocular AO benefits measured with natural pupil diameters increase with decreasing light levels from 1.2 to 1.4. Dalimier and colleagues (2008) predicted a similar range of AO benefits with natural light-adapted pupils for CSs. We could confirm the prediction by Dalimier et al. that a difference in the trend of AO benefit as a function of retinal illuminance exists for experiments where pupil size is fixed as compared to experiments where the pupil diameter can adjust normally to stimulus luminance (compare their table 1 and figure 8, as well as Figure 3 of this article), although average pupil diameters in this study only increased by 0.1 mm when stimulus luminance was decrease from the brightest to the dimmest condition.

The binocular AO benefit shows a similar course and increases for the lowest luminance to about 1.5. Since at this lowest luminance the natural pupil diameters were similar to the limiting artificial pupil diameters, the binocular AO benefit found here, can be taken as benefit occurring under natural pupil conditions for our group of subjects. Thereby, the factor depends on both the amount of aberrations and the natural light-adapted pupil diameter of the subjects.

In a previous experiment with fixed artificial pupils and intermediate contrast letters (Schwarz, Cánovas, et al., 2014), the monocular aberration correction benefit was found to be greater than the binocular correction benefit. In the current experiment, one might expect a similar or even stronger effect considering the reduced pupil size, and thus, a smaller amount of aberrations, when viewing a stimulus of equal brightness under binocular instead of monocular conditions. However, a negligible difference in monocular and binocular AO benefit was found, not revealing a consistent trend. There are several possible explanations for this result. For the small visual test field of 0.95° used here, monocular and binocular pupil diameters are assumed to differ little (Watson & Yellott, 2012). Additionally, in contrast to the previous study, visual tests employed high contrast letters which are less affected by HOA as is generally known. For a vision test employing a larger visual test field and low contrast letters, probably a greater difference in monocular and binocular AO benefit can be observed.

Most importantly, over the whole range of stimulus luminances tested, monocular and binocular VA could be improved by correcting for the imperfect optics of the eye. That is to say, under no circumstances spatial vision was limited by neural performance (Applegate, 2000; Charman & Chateau, 2003). Figure 7 illustrates this statement graphically. The figure shows AO corrected VAs versus uncorrected VAs. The diagonal black line in the graph marks the equal visual acuity line. Nearly all the measurement points lie above the diagonal black line.

AO corrected VAs agreed well with previously reported neural limits to performance, such as twice the cut-off frequencies of the CS curves reported by Coletta and Sharma (1995) and van Nes and Bouman (1967). Even better visual performance could be expected for visual testing with a smaller spectral bandwidth. However, an interesting observation was that for our experimental conditions optical quality simulations were bad predictors for the AO benefit of individual subjects. Although all subjects benefitted from AO correction, the subject with the least amount of aberrations benefitted most, whereas the subject with the highest amount of aberrations benefitted least. Further research is necessary to explain this discrepancy.

The BSR was calculated here as the ratio between binocular VA and monocular VA of the dominant eye. In other studies, BSR is defined as the ratio between binocular VA and monocular VA of the better performing eye. Although our definition could result in higher BSRs, the difference should be minor (<0.1), since all subjects had normal vision (i.e., no signs of amblyopia), similar perceived brightness between both eyes, and the amount of HOA was similar between both eyes of individual subjects, as can be seen in Table 1. Average BSR for the highest stimulus luminance was calculated as 1.14 ± 0.05 when HOA were present and 1.16 ± 0.05 when HOA were corrected. Both values accord with earlier reports for BSRs derived from VAs (Cagenello et al., 1993; Plainis et al., 2011; Sabesan et al., 2012).

With respect to dependence on luminance, we found that binocular summation averaged across subjects increased with decreasing light levels. However, BSRs were similar for both aberration correction conditions.

The current study estimates the visual benefit when HOA are corrected under natural binocular visual conditions. Successful HOA correction presents a major advantage under low luminance conditions in monocular and binocular viewing. The study provides additional evidence to the ameliorating effect of binocular compared to monocular vision when optical quality is reduced.

Conclusions

Visual performance as a function of luminance was measured in a small group of normal subjects with and without correction of aberrations either under monocular or binocular vision. Spatial vision deteriorates for low luminance conditions, but the correction of the eye's aberration significantly increases performance under binocular conditions. In addition, the binocular advantage increases with decreasing luminances. This indicates that binocular summation tends to mitigate the poor visual performance under low luminance conditions. These results may have some potential implications for activities that require vision at low luminance. In those cases, in addition to good correction of refractive errors, aberration correction could show some practical benefit.

Keywords: binocular vision, optical aberrations, low luminance

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