Binocular visual acuity for the correction of spherical aberration in polychromatic and monochromatic light

Christina Schwarz
Laboratorio de Óptica, Instituto Universitario de Investigación en Óptica y Nanofísica, Universidad de Murcia, Murcia, Spain

Carmen Cánovas
AMO Groningen B.V., Department of Research and Development, Groningen, Netherlands

Silvestre Manzanera
Laboratorio de Óptica, Instituto Universitario de Investigación en Óptica y Nanofísica, Universidad de Murcia, Murcia, Spain

Henk Weeber
AMO Groningen B.V., Department of Research and Development, Groningen, Netherlands

Pedro M. Prieto
Laboratorio de Óptica, Instituto Universitario de Investigación en Óptica y Nanofísica, Universidad de Murcia, Murcia, Spain

Patricia Piers
AMO Groningen B.V., Department of Research and Development, Groningen, Netherlands

Pablo Artal
Laboratorio de Óptica, Instituto Universitario de Investigación en Óptica y Nanofísica, Universidad de Murcia, Murcia, Spain

Correction of spherical (SA) and longitudinal chromatic aberrations (LCA) significantly improves monocular visual acuity (VA). In this work, the visual effect of SA correction in polychromatic and monochromatic light on binocular visual performance is investigated.
A liquid crystal based binocular adaptive optics visual analyzer capable of operating in polychromatic light is employed in this study. Binocular VA improves when SA is corrected and LCA effects are reduced separately and in combination, resulting in the highest value for SA correction in monochromatic light. However, the binocular summation ratio is highest for the baseline condition of uncorrected SA in polychromatic light. Although SA correction in monochromatic light has a greater impact monocularly than binocularly, bilateral correction of both SA and LCA may further improve binocular spatial visual acuity which may support the use of aspheric-achromatic ophthalmic devices, in particular, intraocular lenses (IOLs).

Introduction

The human eye is affected by both monochromatic and chromatic aberrations. Monocular correction of ocular aberrations leads, in general, to improved visual outcomes (Artal, Manzanera, Piers, & Weeber, 2010; Yoon & Williams, 2002). For normal vision and visual conditions, binocular vision is superior to monocular vision. It can, therefore, be expected that binocular correction of monochromatic and chromatic aberrations leads to improved binocular visual performance.

Citation: Schwarz, C., Cánovas, C., Manzanera, S., Weeber, H., Prieto, P. M., Piers, P., & Artal, P. (2014). Binocular visual acuity for the correction of spherical aberration in polychromatic and monochromatic light. *Journal of Vision*, *14*(2):8, 1-11, http://www.journalofvision.org/content/14/2/8, doi:10.1167/14.2.8.

doi: 10.1167/14.2.8 Received September 25, 2013; published February 11, 2014 ISSN 1534-7362 © 2014 ARVO

Subject	Age (y)	Eye	Sphere (D)	Cylinder (D)	RMS (μm)	HOA-RMS (μm)	SA (μm)
Subject 1	51	OS	2.75	−0.5	0.31	0.14	0.09
		OD*	2.75	−1	0.64	0.13	0.05
Subject 2	39	OS	2.75	−0.75	0.55	0.21	0.04
		OD*	3	−0.5	0.30	0.16	0.01
Subject 3	52	OS*	0	−0.25	0.23	0.18	0.02
		OD	0.25	−0.25	0.22	0.17	0.04

Table 1. Data of the subjects participating in this study for 4.8-mm pupils. The dominant eye of each subject is marked with an asterisk.

In recent years, monochromatic aberrations, especially spherical aberration (SA), have been extensively studied. It has been shown that SA plays a dominant role in visual performance (Castejón-Mochón, López-Gil, Benito, & Artal, 2002; Porter, Guirao, Cox, & Williams, 2001). In addition, it increases with age since the aberration balancing between the cornea and the lens breaks down (Artal, Berrio, Guirao, & Piers, 2002; Artal, Guirao, Berrio, & Williams, 2001). Cataract surgery with aspheric intraocular lenses (IOLs) successfully restores the SA balance in the average old eye and, thus, improves visual quality with respect to cataract surgery with spherical IOLs (Guirao et al., 2002; Holladay, Piers, Koranyi, van der Mooren, & Norrby, 2002; Mester, Dillinger, & Anterist, 2003).

Considering that the longitudinal chromatic aberration (LCA) causes a substantial defocus over the visible range of about 2 D, the additional correction of this aberration should further improve visual quality even considering the protective mechanisms. The longitudinal chromatic aberration (LCA) of the eye is caused by the wavelength dependent refractive index of the ocular media and manifests in image planes at different distances from the retina for different colors. In contrast to monochromatic aberrations, the LCA of the eye does not present any age-dependency and shows very low intersubject variability (Howarth, Zhang, Bradley, Still, & Thibos, 1988). Due to these properties, standard LCA correction based on the population average LCA could be feasible. Chromatic correctors composed of groups of lenses have been proposed in the past (Benny, Manzanera, Prieto, Ribak, & Artal, 2007; Powell, 1981) but due to their size, these are not suitable for implementation in IOLs. Pure diffractive designs seem to be best suited for a chromatic aberration correcting IOL (Piers & Weeber, 2004; Stone & George, 1988), although these are not yet common in clinical practice.

Previous theoretical calculations (Weeber & Piers, 2012) and studies using adaptive optics (AO) (Artal et al., 2010) showed that vision could be improved by simultaneously correcting LCA and SA under monocular conditions. In a recent study (Weeber, Pohl, Mester, & Piers, 2013), subjects were implanted with an IOL correcting both LCA and SA in one eye and an IOL correcting only SA in the fellow eye. Although this study included a small number of subjects, it showed a tendency for better visual performance in the eyes where both aberrations were corrected. Binocular visual quality is more complex, and the amount of binocular gain or loss depends on many factors. In the case of young subjects, binocular vision is in general superior to monocular vision for well-corrected optics (Cagenello, Arditi, & Halpern, 1993; Campbell & Green, 1965). For binocular visual acuity, an improvement of 11% compared to the monocular VA in the best eye was reported by Cagenello et al. (1993). Binocular summation is known to increase with decreasing contrast (Banton & Levi, 1991). Furthermore, it is inversely correlated to the interocular difference in sensitivity (Pardhan & Gilchrist, 1991) and optical quality (Castro, Jiménez, Hita, & Ortiz, 2009; Jiménez, Gonzalez Anera, Jiménez, & Salas, 2003; Jiménez, Castro, Jiménez, & Hita, 2008; Pardhan & Gilchrist, 1990). With binocular performance showing dependence on so many optical factors, it is likely that binocular summation depends on the amount of optical aberration or the level of aberration correction.

In recent years, binocular adaptive optics visual analyzers (BAOVAs) have been introduced, offering the possibility to study binocular vision under carefully controlled optical conditions (Fernandez, Prieto, & Artal, 2010; Fernández, Prieto, & Artal, 2009). These instruments have been used to evaluate presbyopia solutions (Tabernero, Schwarz, Fernández, Artal, & Fernandez, 2011; Zheleznyak, Sabesan, Oh, MacRae, & Yoon, 2013), and to investigate the effect of correcting higher-order aberrations on binocular visual acuity, contrast sensitivity, and stereopsis (Fernandez et al., 2010; Fernandez, Schwarz, Prieto, Manzanera, & Artal, 2013; Sabesan, Zheleznyak, & Yoon, 2012; Vlaskamp, Yoon, & Banks, 2011).

To the best of our knowledge, the effect of the combined correction of SA and LCA has not yet been investigated for binocular visual acuity (VA). In this article, the visual benefit of correcting SA in polychromatic and monochromatic light was assessed under binocular conditions. This result was compared to the expected performance for the typical pseudophakic patient implanted with conventional spherical IOLs.

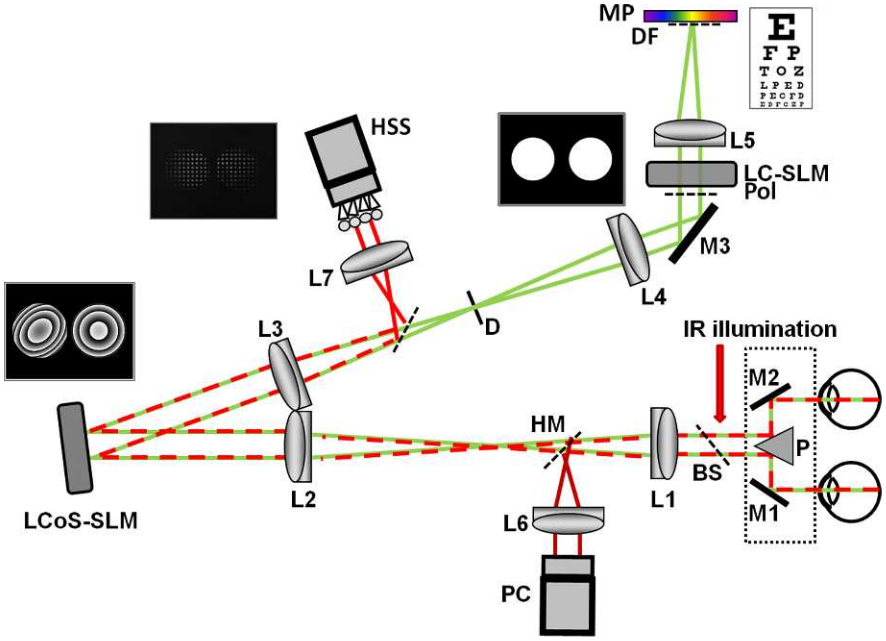

Figure 1. Schematic diagram of the binocular adaptive optics system. A near infrared laser illuminates both eyes. Relay lenses project the eyes' pupil planes onto the wavefront modulator (LCoS-SLM) and the wavefront sensor (HSS). The subject performs visual testing with modified aberrations under binocular vision. Artificial pupils are set via a liquid crystal device (LC-SLM).

Methods

Subjects

The three subjects who participated in this experiment were the same three subjects who took part in a previous monocular study (Artal et al., 2010). Ocular data for these three subjects can be found in Table 1 where aberration data are listed for a 4.8 mm pupil and the dominant eye is marked with an asterisk. Subject ages at the time of the current study were 51, 39, and 52 years. Subjects 1 and 2 are right-eye dominant, and Subject 3 is left-eye dominant. Eye dominance was determined by the "Hole-in-the-hand-test" (Steinman, Steinman, & Garzia, 2000). All subjects reported normal eye health. Subjects 1 and 2 are mild myopes while Subject 3 is a near emmetrope. Astigmatism ranged from 0.25 D to 1 D. The average SA was 0.04 ± 0.03 μm for a 4.8 mm pupil.

For Subjects 2 and 3, accommodation was paralyzed and pupils were dilated with 1% Tropicamide. Subject 1 is presbyopic and his natural pupils were sufficiently large to conduct this experiment.

The experiment was performed in accordance with the tenets of the Declaration of Helsinki. All subjects signed informed consent after they had been informed on the nature of the study and possible consequences.

Experimental setup

The instrument used in this study is a binocular adaptive optics visual analyzer (BAOVA). A schematic diagram of the system is shown in Figure 1. Former versions of the optical setup have been described in detail in previous publications (Fernández et al., 2009; Schwarz, Prieto, Fernández, & Artal, 2011). The binocular system is able to measure and control the monochromatic aberrations of both eyes simultaneously while subjects perform visual testing. The main components are a Hartmann-Shack wavefront sensor (HSS) for measuring both eyes' aberrations, a reflective liquid crystal on silicon spatial light modulator (LCoS-SLM) (PLUTO-VIS, Holoeye, Berlin, Germany), a transmissive liquid crystal spatial light modulator (LC-SLM) (LC2002, Holoeye, Berlin, Germany) for producing both eyes' artificial pupil, and a micro-display (MD) to present visual stimuli. An essential feature of this instrument is that both pupils can be projected side by side onto one single wavefront modulator and one single wavefront sensor, respectively.

The LCoS-SLM offers Full HD (1080 × 1920 pixels) resolution for wavefront control and was calibrated to perform a 2π phase modulation for a wavelength of 543 nm. Due to the high number of independent pixels, the wavefront modulator is able to provide independent correction to both eyes simultaneously. Both SLMs are conjugate to the subject's pupil plane with unity magnification. The HSS consists of a lenslet array with 200 μm lens pitch and a 2/3 in CCD sensor (C5999, Hamamatsu Photonics, Hamamatsu, Japan) and is used in combination with a 780-nm diode laser to illuminate the eye. To fit both pupils onto the sensor chip, a 2:1 telescope is mounted in front of the HSS. A single micro-display (MPro 120, 3M, USA) is used to present stimuli to both eyes. The spectrum of the MD, consisting of the superposition of red, green and blue LEDs, shows peaks at 630 nm, 520 nm, and 455 nm, respectively. A pupil camera (Manta G-145 NIR, Allied Vision Technologies GmbH, Stadtroda, Germany) allowed for continuous pupil monitoring. All the devices were controlled by custom software routines.

In general, efficient phase modulation with liquid crystal devices restricts the use of these instruments to monochromatic light due to the dispersive characteristics of the liquid crystal itself and the application of phase-wrapping. However, by setting the modulating wavefront of the liquid crystal to the central wavefront of the used spectrum, the induced error can be minimized to a maximum phase wrapping error of 6% for the extreme wavelengths to either side of the spectrum when inducing phase maps calculated for a 543 nm wavelength in the LCoS-SLM (Fernández, Prieto, & Artal, 2012). That is to say, when the wavefront modulator induces 3 D of defocus, the system induces an additional chromatic error of about 0.36 D over the visible spectrum from 400 to 700 nm. The effect on visual performance is, however, small because of the spectral luminous efficiency of the eye. To prove this point, high-contrast visual acuity was measured in the DE of Subject 2 (the subject with the greatest refractive error) with the AO system when the subject's refraction was corrected by either trial lenses or the LC device. In quasi-monochromatic (green) light, decimal VA was equal for both correction methods (0.94 ± 0.07 with trial lenses versus 0.94 ± 0.06 with the LCoS-SLM). In polychromatic light, decimal VA was slightly better when refraction was corrected with trial lenses compared with the LCoS-SLM correction (1.31 ± 0.05 vs. 1.29 ± 0.07). Therefore, although the instrument is designed to measure and modify ocular aberrations in monochromatic conditions, it is also able to reliably operate with polychromatic stimuli.

Experimental procedure

The experiment was performed with an artificial pupil diameter of 4.8 mm which is considered to be a realistic pupil size for cataract patients under mesopic luminance conditions (Winn, Whitaker, Elliott, & Phillips, 1994). Wavefront aberrations were measured for a 4.8 mm pupil up to fifth order. Subjects' natural defocus, astigmatism, and SA were statically corrected throughout the experiment. All higher-order aberrations, except SA, were not modified. In the experimental cases where SA was present, the average SA of pseudophakic eyes after spherical IOL implantation was induced by means of the LCoS-SLM. Based on the literature reporting SA in a pseudophakic population implanted with spherical IOLs (Mester et al., 2003) and corneal SA in older eyes (Guirao, Redondo, & Artal, 2000), a value of 0.149 μm for a 4.8 mm pupil was used. LCA effects were removed by performing the testing in monochromatic conditions, placing a 40 nm FWHM band-pass filter centered at 550 nm in front of MD. In order to keep the same retinal illuminance of 2 cd/m^2 for both monochromatic and polychromatic conditions, additional neutral density filters were used under polychromatic conditions.

In the following experiment, the condition in which visual testing was performed in white light inducing 0.149 μm of SA will be considered to be the reference situation because it emulates the vision of a pseudophakic patient implanted with a conventional spherical IOL in a natural (polychromatic) environment.

Visual testing was performed binocularly for four different cases: (a) SA present in polychromatic light (reference condition); (b) SA present in monochromatic light; (c) SA corrected in polychromatic light; and (d) SA corrected in monochromatic light. In order to study the impact of every condition on binocular summation, all four cases were repeated monocularly for the dominant eye. Once an optical condition was set, a target letter with a size corresponding to 1 min of arc was presented on the microdisplay, and the subject was given control over the defocus induced with the wavefront modulator. By scrolling a mouse wheel, the subjective best-focus position could then be adjusted in steps of 0.05 D. This procedure was repeated three times, and the average was taken to be the final best-focus position. For binocular measurements, the best-focus position was adjusted for each eye monocularly while the fellow eye was covered with an eye patch.

Binocular summation is expected to be greater for subthreshold than for threshold tasks. In particular, Sabesan et al. (2012) measured a decrease in binocular contrast sensitivity summation for the baseline aberration correction (correcting only second order aberrations) compared to additionally correcting spherical aberration and higher-order aberration correction, respectively (1.4 vs. 1.3 and 1.3), with the decrease being most pronounced for high spatial frequencies. However, they did not detect a difference in binocular summation when measuring high contrast VA for the aberration correction states mentioned above and found a binocular VA summation ratio of 1.1 for all the cases. In order to investigate the effect of aberration correction, and to increase possible differences in

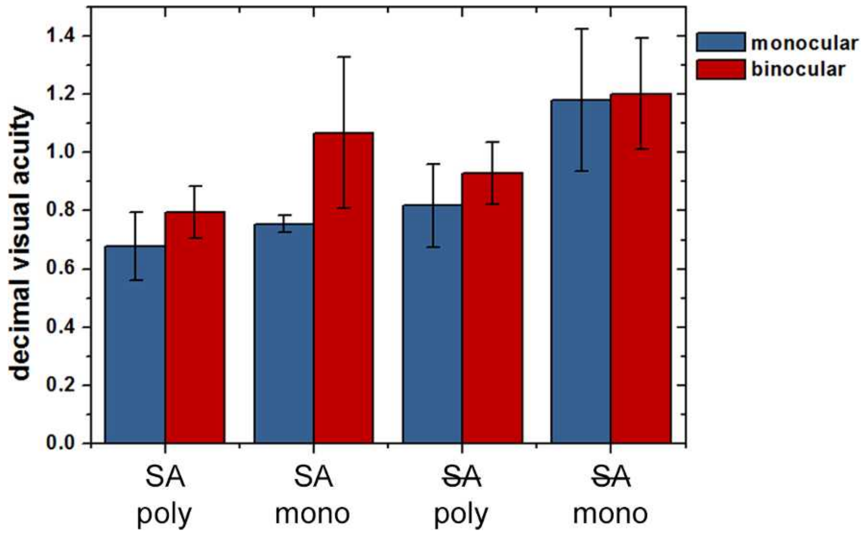

Figure 2. Average monocular and binocular decimal visual acuity (VA) when correcting spherical aberration (SA) in monochromatic (mono) and polychromatic light (poly). Error bars represent standard deviations.

binocular summation, we employed intermediate (30%) contrast letters.

Visual acuity measurements were performed using the illiterate E test. The subject adjusted the letter size to the approximate threshold and, subsequently, a tumbling E four-alternative forced-choice test was initiated. For each studied case, seven letter sizes distributed in steps of 0.13 arcmin around the previously adjusted value were considered for the forced-choice test. Three runs were completed, each consisting of 42 presentations (six per letter size) of a random-size randomly oriented E letter for a duration of 300 ms. The subject was allowed to rest between runs but was given no feedback during the experiment. The averaged correct-response percentages were fit with a sigmoidal function. The acuity threshold was determined to be the letter size where the subject achieves 62.5% correct responses.

From the values obtained for visual acuities, three metrics were calculated. Binocular summation was defined as the ratio between binocular VA and monocular (dominant eye) VA for the same visual condition. Whereas it is common practice to define the binocular summation ratio as the ratio between binocular performance and monocular performance of the better eye, we calculated the ratio between the binocular performance and the monocular performance of the dominant eye. Although the binocular summation ratio may be overestimated using this method, the difference should be considered to be small, due to the fact that all subjects had similar amounts of aberrations and comparable VA in both eyes as can be seen in Table 1.

The binocular correction gain was defined as the ratio between binocular VAs before and after aberration correction. The monocular correction gain was accordingly defined as the ratio between monocular VAs. Once a statistically significant effect for aberration correction conditions was found with an ANOVA test, statistical significance was tested by performing paired student's t tests.

Results

Figure 2 shows the averaged monocular and binocular VAs for the four different cases of aberration correction. Monocular and binocular VAs tended to improve when aberrations were corrected. On average, for the cases in which measurements were performed in monochromatic light or SA was corrected, visual acuity was higher than for the reference case in which LCA effects and SA were present. The best VA for all individuals, both for monocular and binocular vision, was achieved when SA was corrected in monochromatic light.

In order to quantify the improvement in VA due to aberration correction and binocular summation, the ratio (correction gain) between different cases has been calculated. Figure 3 shows monocular and binocular correction gain. The blue bars represent the monocular correction gain. In agreement with previous data, individual correction of either LCA effects or SA produced an improvement in VA, while simultaneous correction of both aberration types further increased VA. The red bars in Figure 3 represent the binocular correction gain. Once again, correction of LCA effects or SA produced an increase in VA, both with the other aberration type present or corrected, with the greatest improvement occurring when both aberrations were corrected simultaneously.

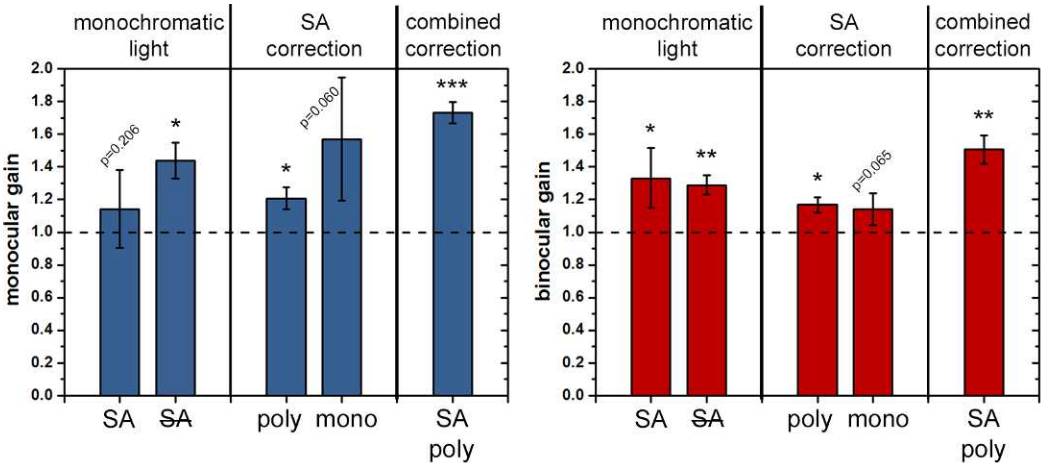

Figure 3. Average gain (i.e., ratio between VAs) for different cases of aberration correction under monocular (left) and binocular (right) vision: reducing LCA effects with SA present (SA) or previously corrected (SA), SA correction in monochromatic (mono) and polychromatic (poly) light, and simultaneous correction of LCA and SA. Each value corresponds to the average across subjects of the individual VA gains. Error bars represent standard deviations. AV gains are tagged with asterisks if statistically significant (*: p value $<$ 0.05, **: p value $<$ 0.01, and ***: p value $<$ 0.005) or with the p value otherwise.

We also determined binocular summation for each aberration correction condition. Figure 4 shows the binocular summation ratio for each case. When SA was present in polychromatic light, there is a statistically significant increase in VA. When VA measurements were performed either in monochromatic light or when SA was corrected, the mean value of binocular summation remains greater than 1 but shows higher variability across subjects. Due to this fact, the improvement in VA is not statistically significant in either case (p value $= 0.104$ and p value $= 0.096$, respectively). When SA is corrected in monochromatic light, binocular summation is very close to one, both on average and for every subject individually.

To further illustrate this point, Figure 5 shows binocular VA versus monocular VA for each subject and aberration condition. The black diagonal marks equality for monocular and binocular VA. In the uncorrected case (blue), the measurement points are located above the diagonal, indicating an improvement

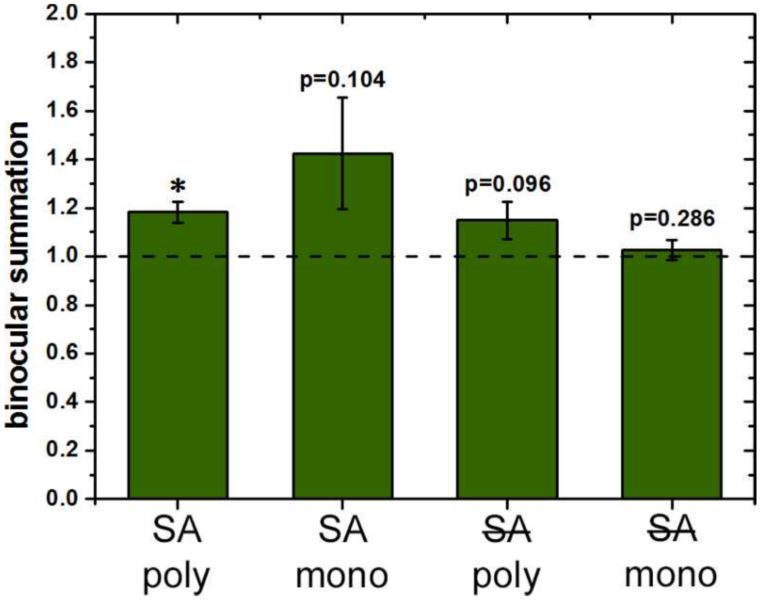

Figure 4. Mean VA gain due to binocular summation (i.e., ratio between binocular and monocular VAs) for different aberration correction conditions. Each value corresponds to the average across subjects of the individual VA gains. Error bars represent one standard deviation. VA gains are tagged with an asterisk if statistically significant (p value $<$ 0.05) or with the p value otherwise.

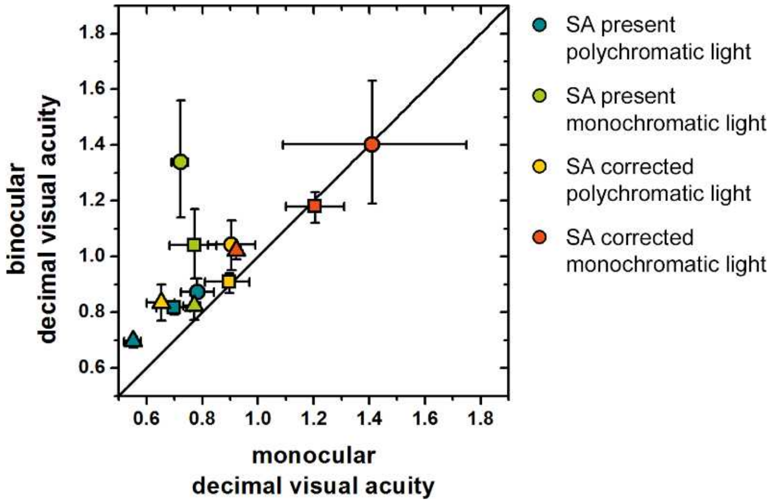

Figure 5. Binocular decimal visual acuity versus monocular decimal visual acuity. Each data point corresponds to an individual measurement for one of the subjects (coded by symbol shapes) under a certain aberration correction condition indentified by color. Error bars correspond to one standard deviation. The black diagonal line marks equality for monocular and binocular data.

in VA due to binocular summation. After correction of either LCA effects (green) or SA (yellow), the measurement points are still above the diagonal but there is a larger variability, especially in the LCA-corrected (monochromatic) case. Finally, when both aberrations are simultaneously corrected, the red measurement points approach the diagonal line, suggesting reduced binocular summation.

Figure 6 compares the three outcome metrics, that is, monocular correction gain, binocular correction gain, and binocular summation, averaged across subjects for three optical conditions: the reference condition, the case when only SA is corrected, and the condition for the combined correction of SA and LCA effects.

Discussion

The main goal of this study was to investigate the effect of the combined correction of spherical and longitudinal chromatic aberrations on binocular vision and to estimate the benefit of bilateral correction. In addition to performing a fundamental vision science study of these effects, we were interested in the potential results of a practical implementation of these types of corrections applied in cataract patients by implanting aspheric-achromatic IOLs. The average spherical aberration of pseudophakic eyes implanted with spherical IOLs was induced or corrected in both eyes with a binocular adaptive optics instrument. The longitudinal chromatic aberration effects were removed by performing measurements in near-monochromatic conditions and comparing this adjustment to polychromatic conditions.

Whereas for 4 mm pupils the effect of spherical and chromatic aberration is approximately equal (Campbell & Gubisch, 1967), monochromatic aberrations have a larger effect for large pupils. Monocular VA measurements averaged across subjects confirm this finding. In the monocular case, the effect of correcting SA only was greater than the effect for reducing LCA effects only. However, under binocular viewing conditions, the behavior was reversed: The effect of correcting SA only was considerably smaller than for reducing LCA effects only. This finding may be due to the large differences between subjects and must be further investigated.

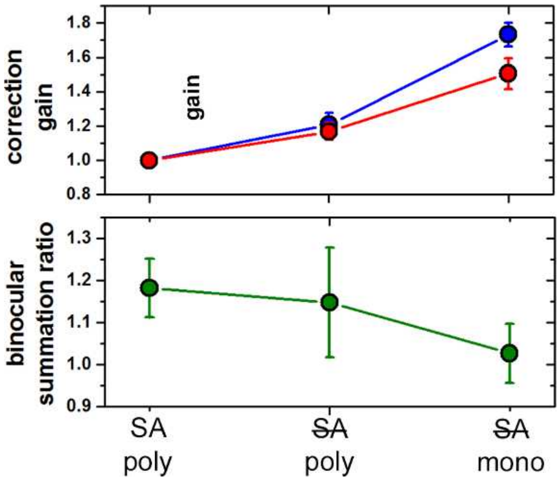

Figure 6. Average outcome metrics for the reference case and the two aberration correction stages that are of interest for IOL design. The blue line represents the VA correction gain under monocular conditions, the red line represents the VA correction gain under binocular conditions, and the green line represents the binocular summation factor for each case. Error bars represent standard deviations.

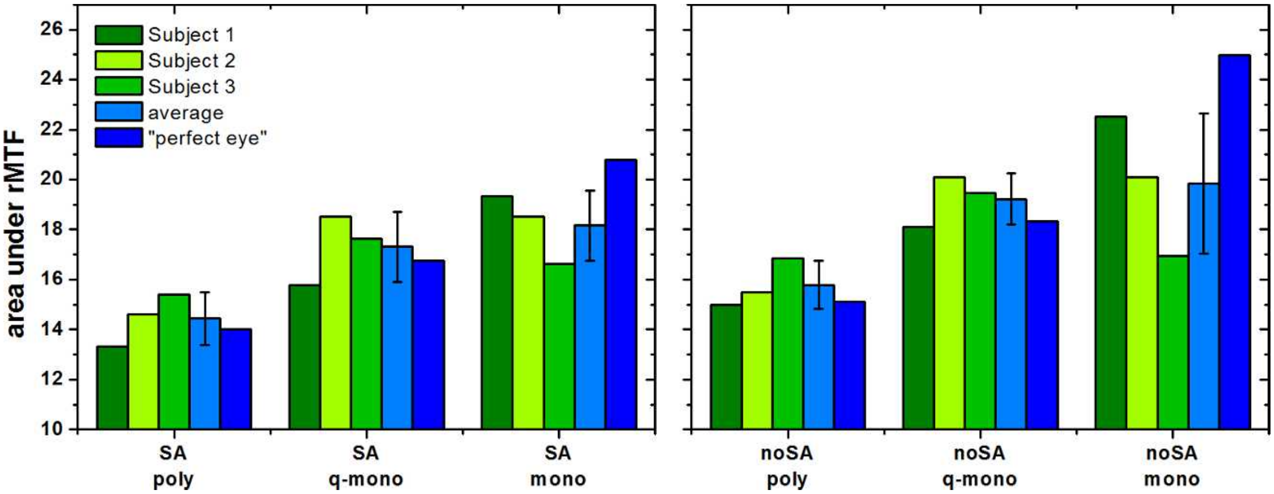

Figure 7. Area under the rMTF at best focus for the different aberration conditions in polychromatic (poly), quasi-monochromatic (q-mono), and monochromatic (mono; 550 nm) light. Data is presented for individual subjects (different shades of green), the average across subjects (light blue), and a perfect eye without any other aberrations than LCA and eventually SA.

VA was higher when aberrations were corrected than when aberrations were present when these cases were averaged across subjects. For binocular as well as for monocular measurements, the highest VA was achieved when SA was corrected in monochromatic light combination. The VAs measured in this study were lower than those measured in the previous monocular study (Artal et al., 2010) (0.7 vs. 1 for the baseline case). However, the monocular aberration correction gain for the combined correction case was greater than in the previous study (1.73 vs. 1.4). This difference may be explained by the decreased luminance of the vision test and the intermediate contrast letters that were employed in the current study.

An interesting finding for monocular VAs was the greater benefit when performing measurements in quasi-monochromatic light with corrected SA compared to the benefit in quasi-monochromatic light when SA was uncorrected. The same behavior was observed when SA was corrected in quasi-monochromatic light compared to SA correction in polychromatic light. These results are in accordance with a previous study by McLellan et al. who found that monochromatic aberrations can mitigate the effect of LCA on visual performance (McLellan, Marcos, Prieto, & Burns, 2002). Correction of monochromatic aberrations in general improves visual performance; however, in some cases the effect of LCA is increased.

To show the potential effect of LCA-correction as a function of the magnitude of other aberrations, monocular through-focus image quality was theoretically simulated for the dominant eye of the three subjects and an eye with perfect optics (apart from LCA and SA). The area under the radially averaged MTF between 0 and 60 cpd was used as an optical quality metric. The ocular polychromatic point-spread function (400–700 nm) was computed for every through-focus position and weighted by the photopic spectral luminous efficiency function V_{λ} of the human eye and the microdisplay's polychromatic or quasi-monochromatic spectrum. The metric took into account the Stiles-Crawford effect (Applegate & Lakshminarayanan, 1993); however, neural factors were not considered. Figure 7 shows the area under the rMTF at best focus for the different aberration conditions in polychromatic, quasi-monochromatic (experimental condition), and monochromatic light. Theoretical simulations show that the benefit of correcting LCA depends on monochromatic aberrations and can be particularly high if SA was previously corrected. The results encourage, therefore, the combined correction of SA and LCA.

The average binocular VA was found to be higher than monocular VA for all correction states. The degree of improvement for binocular vision with regard to monocular vision depended on the optical condition. Binocular VA summation averaged across subjects decreased when increasing the level of aberration correction which is in accordance with findings for contrast sensitivity (Sabesan et al., 2012). Additionally, in the case when only LCA effects were removed, the inter-subject variability was higher than usual. Interestingly, the magnitude of binocular summation was inversely correlated with the theoretical benefit of LCA correction according to optical quality simulations for the three subjects. For simultaneous correction of LCA and SA, binocular VA summation averaged across subjects was very close to 1, suggesting reduced binocular summation compared to the reference condition. Plainis, Petratou, Giannakopoulou, Atchison, and Tsilimbaris (2011) reported a binocular summation of 13% for the case of best spherical correction. When inducing blur by means of spherical lenses, they observed an increase in binocular VA summation. Thinking of aberration correction in terms of improving retinal image contrast and aberration induction in terms of deteriorating image contrast, we believe these experiments are in line with the findings of Banton and Levi's study (1991). Measuring the binocular advantage of vernier acuity limited by contrast, they found that the binocular gain decreased with increasing contrast. While Plainis et al. (2011) related their results to the number of cells involved in the visual process, Banton and Levi (1991) suggested a saturated detection mechanism to be the reason.

In the following paragraphs, some practical implications for aspheric-achromatic IOLs and for patients implanted with this type of IOLs are listed.

In our experiment, we removed chromatic effects by narrowing the spectral range of the test. This rather drastic method not only eliminates LCA but also transverse chromatic aberration (TCA). For pseudophakic patients, LCA may be corrected with IOLs by the use of refractive-diffractive designs. Natural foveal TCA is small in value (Rynders, Lidkea, Chisholm, & Thibos, 1995) and should have small effects on visual quality for most subjects (Simonet & Campbell, 1990). However, induced TCA due to corrector misalignment or chromatic parallax (Zhang, Bradley, & Thibos, 1991) may reduce the advantage of this compensation of the eye's LCA if the IOL is not properly positioned (Tabernero, Piers, Benito, Redondo, & Artal, 2006). Theoretical performance and limits of decentration have been computed based on realistic eye models (Weeber & Piers, 2012). Optical performance with lenses correcting both SA and LCA which are decentered by up to 0.6 mm is still better than that with a spherical control lens. In comparison, IOL decentration in uneventful cataract surgery is approximately 0.2 mm (Baumeister, Bühren, & Kohnen, 2009). The results, thus, indicate that correction of SA and LCA with IOLs is a realistic option with some degree of tolerance.

Another relevant issue patients considering aspheric-achromatic IOLs should be aware of is the possible reduction in depth of focus. Although some level of depth of focus could be beneficial, it should be noted that in the real case of cataract patients, even an optimum correction of the aberrations studied herein would leave the rest of monochromatic aberrations uncorrected and thus provide some tolerance to defocus.

The subjects who participated in this study were relatively young compared to cataract patients. However, for older patients, VA is known to decrease due to age-related changes in the eye. In addition, binocular summation decreases with age, a condition which is attributed to the loss of neurons and receptors in the visual pathway (Pardhan, 1996), and binocular visual performance tends to become closer to the monocular visual performance of the better eye (Rubin, Muñoz, Bandeen-Roche, & West, 2000). Therefore, the binocular VA gains found in this study may be reduced in older subjects studied as well as in cataract patients.

In conclusion, we performed a study to determine the potential improvements in binocular visual acuity following the combined correction of spherical and chromatic aberration. These results may be used to estimate the improvement in visual quality possible when aspheric-achromatic IOLs are implanted in cataract patients.

Keywords: binocular vision, adaptive optics, chromatic aberration, binocular summation

Acknowledgments

This research has been supported by the Spanish "Ministerio de Ciencia e Innovación" (grant FIS2010-14926 and CSD2007-00013), the "Fundación Seneca," Región de Murcia, Spain (grant 04524/GERM/06), EU-FEDER funds, and Abbott Medical Optics, Inc.. P. Artal, C. Schwarz, S. Manzanera, and P. Prieto are all employees of Universidad de Murcia. P. Artal is also a paid consultant for Abbott Medical Optics. C. Canovas, H. Weeber, and P. Piers are employees of Abbott Medical Optics, Inc.

Commercial relationships: Christina Schwarz, Abbott Medical Optics (F); Carmen Canovas, Abbot Medical Optics (E); Silvestre Manzanera, Abbott Medical Optics (F); Henk Weeber, Abbott Medical Optics (E); Pedro M. Prieto, Abbott Medical Optics (F); Patricia Piers, Abbott Medical Optics (F, C).

Corresponding author: Christina Schwarz.
Email: christina.schwarz@um.es.
Address: Laboratorio de Óptica, Instituto Universitario de Investigación en Óptica y Nanofísica, Universidad de Murcia, Murcia, Spain.

References

Applegate, R. A, & Lakshminarayanan, V. (1993). Parametric representation of Stiles-Crawford functions: Normal variation of peak location and directionality. *Journal of the Optical Society of America A, 10*(7), 1611–1623.

Artal, P., Berrio, E., Guirao, A., & Piers, P. (2002). Contribution of the cornea and internal surfaces to the change of ocular aberrations with age. *Journal of the Optical Society of America A, 19*(1), 137–143.

Artal, P., Guirao, A., Berrio, E., & Williams, D. R. (2001). Compensation of corneal aberrations by the internal optics in the human eye. *Journal of Vision, 1*(1), *1*, 1–8, http://www.journalofvision.org/content/1/1/1, doi:10.1167/1.1.1. [PubMed] [Article]

Artal, P., Manzanera, S., Piers, P., & Weeber, H. (2010). Visual effect of the combined correction of spherical and longitudinal chromatic aberrations. *Optics Express, 18*(2), 1637–1648. doi:10.1364/OE.18.001637.

Banton, T., & Levi, D. M. (1991). Binocular summation in vernier acuity. *Journal of the Optical Society of America A, 8*(4), 673–680.

Baumeister, M., Bühren, J., & Kohnen, T. (2009). Tilt and decentration of spherical and aspheric intraocular lenses: Effect on higher-order aberrations. *Journal of Cataract & Refractive Surgery, 35*(6), 1006–1012. doi:10.1016/j.jcrs.2009.01.023.

Benny, Y., Manzanera, S., Prieto, P. M., Ribak, E. N., & Artal, P. (2007). Wide-angle chromatic aberration corrector for the human eye. *Journal of the Optical Society of America A, 24*(6), 1538–1544.

Cagenello, R., Arditi, A., & Halpern, D. L. (1993). Binocular enhancement of visual acuity. *Journal of the Optical Society of America A, 10*(8), 1841–1848.

Campbell, F. W., & Green, D. G. (1965). Monocular versus binocular visual acuity. *Nature, 208*(5006), 191–192.

Campbell, F. W., & Gubisch, R. W. (1967). The effect of chromatic aberration on visual acuity. *The Journal of Physiology, 192*(2), 345–358.

Castejón-Mochón, J. F., López-Gil, N., Benito, A., & Artal, P. (2002). Ocular wave-front aberration statistics in a normal young population. *Vision Research, 42*(13), 1611–1617.

Castro, J. J., Jiménez, J. R., Hita, E., & Ortiz, C. (2009). Influence of interocular differences in the Strehl ratio on binocular summation. *Ophthalmic & Physiological Optics, 29*(3), 370–374. doi:10.1111/j.1475-1313.2009.00643.x.

Fernandez, E. J., Prieto, P. M., & Artal, P. (2010). Adaptive optics binocular visual simulator to study stereopsis in the presence of aberrations. *Journal of the Optical Society of America A, 27*(11), 48–55. doi:10.1364/JOSAA.27.000A48.

Fernández, E. J., Prieto, P. M., & Artal, P. (2009). Binocular adaptive optics visual simulator. *Optics Letters, 34*(17), 2628–2630.

Fernández, E. J., Prieto, P. M., & Artal, P. (2012). Adaptive optics visual analyzer under white-light illumination using liquid crystal on silicon (LCOS) technology. Paper presented at SPIE photonics west, San Francisco, CA.

Fernández, E. J., Schwarz, C., Prieto, P. M., Manzanera, S., & Artal, P. (2013). Impact on stereoacuity of two presbyopia correction approaches: Monovision and small aperture inlay. *Biomedical Optics Express, 4*(6), 822–830. doi:10.1364/BOE.4.000822.

Guirao, A., Redondo, M., & Artal, P. (2000). Optical aberrations of the human cornea as a function of age. *Journal of the Optical Society of America A, 17*(10), 1697–1702.

Guirao, A., Redondo, M., Geraghty, E., Piers, P., Norrby, S., & Artal, P. (2002). Corneal optical aberrations and retinal image quality in patients in whom monofocal intraocular lenses were implanted. *Archives of Ophthalmology, 120*(9), 1143–1151.

Holladay, J. T., Piers, P. A., Koranyi, G., van der Mooren, M., & Norrby, S. (2002). A new intraocular lens design to reduce spherical aberration of pseudophakic eyes. *Journal of Refractive Surgery, 18*(6), 683–691.

Howarth, P. A., Zhang, X. X., Bradley, A., Still, D. L., & Thibos, L. N. (1988). Does the chromatic aberration of the eye vary with age? *Journal of the Optical Society of America A, 5*(12), 2087–2092.

Jiménez Cuesta, J. R., Gonzalez Anera, R., Jiménez, R., & Salas, C. (2003). Impact of interocular differences in corneal asphericity on binocular summation. *American Journal of Ophthalmology, 135*(3), 279–284.

Jiménez, J. R., Castro, J. J., Jiménez, R., & Hita, E. (2008). Interocular differences in higher-order aberrations on binocular visual performance. *Optometry & Vision Science, 85*(3), 174–179.

McLellan, J. S., Marcos, S., Prieto, P. M., & Burns, S. A. (2002). Imperfect optics may be the eye's defence against chromatic blur. *Nature, 417*(6885), 174–176. doi:10.1038/417174a.

Mester, U., Dillinger, P., & Anterist, N. (2003). Impact of a modified optic design on visual function: Clinical comparative study. *Journal of Cataract & Refractive Surgery, 29*(4), 652–660. doi:10.1016/S0886-3350(02)01983-1.

Pardhan, S. (1996). A comparison of binocular summation in young and older patients. *Current Eye Research, 15*(3), 315–319.

Pardhan, S., & Gilchrist, J. (1990). The effect of monocular defocus on binocular contrast sensitivity. *Ophthalmic & Physiological Optics, 10*(1), 33–36.

Pardhan, S., & Gilchrist, J. (1991). The importance of measuring binocular contrast sensitivity in unilateral cataract. *Eye, 5,* 31–35. doi:10.1038/eye.1991.6.

Piers, P., & Weeber, H. (2004). Ophthalmic lens. *US Patent 6830332.*

Plainis, S., Petratou, D., Giannakopoulou, T., Atchison, D. A., & Tsilimbaris, M. K. (2011). Binocular summation improves performance to defocus-induced blur. *Investigative Ophthalmology & Visual Science, 52*(5), 2784–2789, http://www.iovs.org/content/52/5/2784. doi:10.1167/iovs.10-6545. [PubMed] [Article]

Porter, J., Guirao, A., Cox, I. G., & Williams, D. R. (2001). Monochromatic aberrations of the human eye in a large population. *Journal of the Optical Society of America A, 18*(8), 1793–1803.

Powell, I. (1981). Lenses for correcting chromatic aberration of the eye. *Applied Optics, 20*(24), 4152–4155.

Rubin, G. S., Muñoz, B., Bandeen-Roche, K., & West, S. K. (2000). Monocular versus binocular visual acuity as measures of vision impairment and predictors of visual disability. *Investigative Ophthalmology & Visual Science, 41*(11), 3327–3334, http://www.iovs.org/content/41/11/3327. [PubMed] [Article]

Rynders, M., Lidkea, B., Chisholm, W., & Thibos, L. N. (1995). Statistical distribution of foveal transverse chromatic aberration, pupil centration, and angle psi in a population of young adult eyes. *Journal of the Optical Society of America A, 12*(10), 2348–2357.

Sabesan, R., Zheleznyak, L., & Yoon, G. (2012). Binocular visual performance and summation after correcting higher order aberrations. *Biomedical Optics Express, 3*(12), 3176–3189. doi:10.1364/BOE.3.003176.

Schwarz, C., Prieto, P. M., Fernández, E. J., & Artal, P. (2011). Binocular adaptive optics vision analyzer with full control over the complex pupil functions. *Optics Letters, 36*(24), 4779–4781.

Simonet, P., & Campbell, M. C. (1990). The optical transverse chromatic aberration on the fovea of the human eye. *Vision Research, 30*(2), 187–206.

Steinman, S. B., Steinman, B. A., & Garzia, R. (2000). *Foundations of binocular vision: A clinical perspective (p.* 368). New York: McGraw Hill Professional.

Stone, T., & George, N. (1988). Hybrid diffractive-refractive lenses and achromats. *Applied Optics, 27*(14), 2960–2971.

Tabernero, J., Piers, P., Benito, A., Redondo, M., & Artal, P. (2006). Predicting the optical performance of eyes implanted with IOLs to correct spherical aberration. *Investigative Ophthalmology & Visual Science, 47*(10), 4651–4658, http://www.iovs.org/content/47/10/4651. doi:10.1167/iovs.06-0444. [PubMed] [Article]

Tabernero, J., Schwarz, C., Fernández, E. J., Artal, P., & Fernandez, E. J. (2011). Binocular visual simulation of a corneal inlay to increase depth of focus. *Investigative Ophthalmology & Visual Science, 52*(8), 5273–5277, http://www.iovs.org/content/52/8/5273. doi:10.1167/iovs.10-6436. [PubMed] [Article]

Vlaskamp, B. N. S., Yoon, G., & Banks, M. S. (2011). Human stereopsis is not limited by the optics of the well-focused eye. *The Journal of Neuroscience, 31*(27), 9814–9818. doi:10.1523/JNEUROSCI.0980-11.2011.

Weeber, H. A., & Piers, P. A. (2012). Theoretical performance of intraocular lenses correcting both spherical and chromatic aberration. *Journal of Refractive Surgery, 28*(1), 48–52. doi:10.3928/1081597X-20111103-01.

Weeber, H. A., Pohl, R., Mester, U., & Piers, P. A. (2013). Visual performance of pseudophakic eyes corrected for spherical and chromatic aberrations with an achromatic intraocular lens. *Investigative Ophthalmology & Visual Science,* 54, E–Abstract 808.

Winn, B., Whitaker, D., Elliott, D. B., & Phillips, N. J. (1994). Factors affecting light-adapted pupil size in normal human subjects. *Investigative Ophthalmology & Visual Science, 35*(3), 1132–1137, http://www.iovs.org/content/35/3/1132. [PubMed] [Article]

Yoon, G.-Y., & Williams, D. R. (2002). Visual performance after correcting the monochromatic and chromatic aberrations of the eye. *Journal of the Optical Society of America A, 19*(2), 266–275.

Zhang, X. X., Bradley, A., & Thibos, L. N. (1991). Achromatizing the human eye: The problem of chromatic parallax. *Journal of the Optical Society of America A, 8*(4), 686–691.

Zheleznyak, L., Sabesan, R., Oh, J.-S., MacRae, S., & Yoon, G. (2013). Modified monovision with spherical aberration to improve presbyopic through-focus visual performance. *Investigative Ophthalmology & Visual Science, 54*(5), 3157–3165, http://www.iovs.org/content/54/5/3157. doi:10.1167/iovs.12-11050. [PubMed] [Article]