Wide-angle chromatic aberration corrector for the human eye

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The human eye is affected by large chromatic aberration. This may limit vision and makes it difficult to see fine retinal details in ophthalmoscopy. We designed and built a two-triplet system for correcting the average longitudinal chromatic aberration of the eye while keeping a reasonably wide field of view. Measurements in real eyes were conducted to examine the level and optical quality of the correction. We also performed some tests to evaluate the effect of the corrector on visual performance. © 2007 Optical Society of America

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1. INTRODUCTION

The eye as an optical system suffers from both longitudinal chromatic aberration (LCA) and transverse chromatic aberration (TCA). For monochromatic objects, the LCA means a shift in the emmetropic state and the TCA a change in the visual axis. Consequently, these aberrations could theoretically be compensated with the eye's accommodation and by changing the direction of sight, respectively. However, in the presence of polychromatic light, these two types of chromatic aberration have an effect on the retinal image. Studied in isolation, both the LCA and the TCA have been shown theoretically to be a major optical factor limiting the retinal image quality.[1–4] This effect is reduced by the presence of monochromatic aberrations, which tend to equalize the image quality across wavelengths.[5] However, some improvement in retinal image quality can be achieved by correction of the chromatic aberrations both for vision and for retinal imaging, especially in combination with the correction of monochromatic high-order aberrations.

Both types of chromatic aberration in the eye have been extensively studied in the literature.[6–14] The foveal TCA has been assessed only by subjective techniques,[3,13,14] and it has been shown to be subject dependent, with a value distributed around 0. This behavior remains a subject for study.[14] The intersubject variability of the foveal TCA prevents the design of a general average correction device for this aberration, since the individual data should be collected and taken into account. In contrast, the LCA, which can be easily measured using both objective and subjective methods,[3,5–11] has been found to be fairly constant across subjects, with a value around 2 D in the visible spectrum. In addition, it remains constant with age;[15] this is not the case for monochromatic aberrations, which are known to increase with normal aging.[16] Accordingly, it is feasible to produce a corrector for the eye's LCA, based on average population data, appropriate for most subjects. Although the subjects with large amounts of foveal TCA would experience no benefit, this kind of universal LCA-only correction device could be useful both for retinal imaging and for improved vision for the average subject.

Chromatic aberrations arise from the dispersive nature of the eye's media. The amount of LCA is basically determined by the power of the eye, which varies only marginally among "normal" subjects, and by the refractive index of the ocular media, whose main constituent is water. As a consequence, a very simple schematic eye consisting of a medium of water with only one spherical refractive surface is good enough to describe ocular (chromatic) paraxial optics. Better results are obtained when the refractive index of the internal medium is obtained by fitting and a more general aspherical surface is considered, as proposed by Thibos *et al.*[17] Not only does this model account well for the on-axis variations of focus found in the literature for the visible spectrum, but it can also be extended into the near-infrared region.[18,19] However, a more

realistic eye model is necessary to predict monochromatic aberrations and off-axis behavior. We have selected a wide-angle eye model,[20] based on anatomical data that predict some simple average monochromatic aberrations of the eye in reasonably good agreement with experimental data for a wide field.

Lenses for correcting the chromatic difference of refraction have been proposed before.[3] The first design to our knowledge was a symmetrical triplet proposed by van Heel[21] based on the data in three subjects[6] and correcting only for three colors. Bedford and Wyszecki[8] systematically measured the LCA across the visible spectrum for 12 subjects and used the experimental curve to design another symmetrical triplet with external flat surfaces. Lewis *et al.*[22] proposed yet another triplet, also providing a good on-axis LCA correction. All of these triplet-type designs present a limited effective field of view since the eccentric TCA rapidly increases with the incidence angle, producing color fringing. A more sophisticated solution was offered by Powell,[23] who proposed an air-spaced triplet–doublet system, which performed much better off axis. However, the alignment of this system has been proved to be an extremely critical factor. Any small decentration induces a TCA proportional to the amount of decentration,[24] which eventually reduces the benefit of the LCA correction. This problem is shared by all the LCA correcting devices designed to date, including the one presented here, since the misalignment data have not been considered in the design stage. Very recently, the topic of ocular achromatization has been revisited by some research teams. For example, Díaz *et al.*[25] have proposed a hybrid diffractive–refractive doublet design for the visible range, and Fernández *et al.*[26] have developed a triplet correcting the ocular LCA in the near infrared for retinal imaging applications in a work related to ours.

Since the LCA can be related directly to a chromatic difference of magnification,[3,27] we looked at the possibility of a system having the opposite external magnification. Such systems were designed in astronomy before. Roddier *et al.* built one for interferometry,[28] and Wynne suggested a system made of two air-spaced triplets to correct the dispersion effect in speckle interferometry.[29] The latter consisted of two triplets made of two glasses having the same refractive index for one primary wavelength. The surfaces facing the air are flat. Therefore, the system is afocal and free of aberrations for the primary wavelength. On the other hand, dispersion differences make the beam convergent for longer wavelengths and divergent for shorter wavelengths, so the corrected system, a telescope in Wynne's case, had a unit magnification. The principle of this design can be used to correct chromatic aberrations of optical systems in general.

We propose here an innovative design of achromatizing lens, based on Wynne's system for the particular case of the eye. The parameters of the design were obtained by software optimization, including a wide-angle schematic eye model.[20] The theoretical performance of the system was compared with previous designs of achromatizing lenses, and the effect of tilt and decentration was simulated. Making use of the design parameters, a corrector was manufactured to examine its optical effect on real eyes. The optical quality of the system was checked, and a psychophysical experiment was performed to test the potential benefit of LCA correction on visual acuity (VA). The results show a good correction of the eye's LCA, although with limited effect on visual performance.

2. METHODS

A. Design of the Corrector
We designed a two-triplet air-spaced system, using glasses for the range of 405–1060 nm as provided in the optimization software (ZEMAX Development Corporation). The wide-angle eye model was added to the simulation, and optimization was performed to obtain a minimum LCA without introducing additional monochromatic aberrations, while keeping a reasonably wide field of view. The variables for the optimization were the optical parameters of the two materials, the internal curvature and thickness of the triplets, and the distance between the two triplets. Each triplet was symmetric with external flat surfaces. A practical advantage of this design is that each of the triplets is symmetric, so flipping an element does not change the optics of the system.

Since it was our intention to eventually implement our corrector design into an actual device, there were manufacturing hardware constraints that slightly changed the parameters of the final design. The outcome of the optimization procedure for the optical parameters was compared with the optical material catalogs to find the closest available materials. Then the geometrical parameters were refined in another partial optimization loop. Table 1 lists the parameters of the proposed corrector, and Fig. 1 shows a layout of the final design together with the wide-angle eye model. After obtaining a satisfying correction of LCA, with unit magnification in combination with the eye for all wavelengths, we examined the optical quality of the corrector in combination with the wide-angle eye model. Figure 2 shows the theoretical residual chromatic refractive error of the corrector–eye system as provided

Table 1. Parameters of the Final Corrector Design

Surface	Glass	Radius (mm)	Thickness (mm)
1	N-LaF21	∞	5.00
2	SF56A	26.58	10.00
3	N-LaF21	−26.58	5.00
4	Air	∞	16.00
5	N-LaF21	∞	6.56
6	SF56A	−13.60	5.00
7	N-LaF21	13.60	6.56
8	Air	∞	17.00

Note: N-LaF21 glass parameters: refractive index in d-light=1.78800; Abbé number=47.49. SF56A glass parameters: refractive index in d-light=1.78470; Abbé number=26.08. d-light wavelength=587.5618 nm.
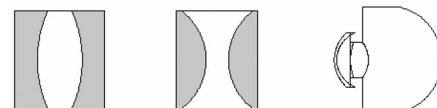

Fig. 1. Schematic diagram of the corrector and the wide-angle eye model used for the optimization process.
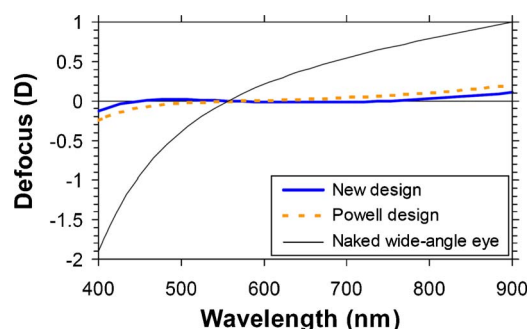
Fig. 2.   (Color online) LCA for the naked wide-angle eye model (thin solid curve) and theoretical residual LCA for the coupling of the wide-angle eye and the two-triplet achromatizing system (thick solid curve). For comparison purposes, we show the theoretical residual LCA for the coupling of the wide-angle eye with Powell's achromatizing lens (dotted curve) for the same eye relief (17 mm). In all cases, the reference wavelength was 555 nm.
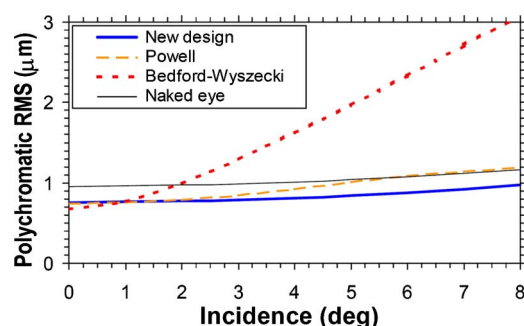

Fig. 3.   (Color online) Theoretical polychromatic RMS[30] as a function of the angle of incidence for the combination of the wide-angle schematic eye and different LCA correctors: Bedford–Wyszecki's design (dotted curve), Powell's corrector (dashed curve), or the design presented here (thick solid curve). The pupil size for the calculation was 6 mm, and the reference wavelength was 555 nm. The eye relief for the previous corrector designs was also 17 mm. For comparison purposes, the polychromatic RMS as a function of the angle of incidence for the naked wide-angle eye model has been plotted (thin solid curve).
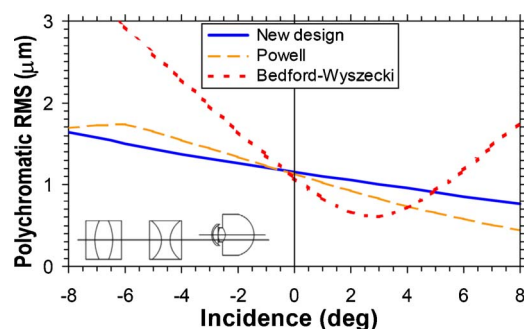

Fig. 4.   (Color online) Theoretical effect of 1 mm of lateral decentration on the polychromatic RMS for the combination of the wide-angle schematic eye and different LCA correctors: Bedford–Wyszecki's design (dotted curve), Powell's corrector (dashed curve), or the design presented here (solid curve). Vignetting effects can be seen for Powell's corrector below ±6°. The origin for the incidence angle is the corrector optical axis.

by ZEMAX after optimization. It can be compared with that for the naked wide-angle eye model and also with the residual chromatic refractive error for Powell's corrector. Although a similar LCA correcting performance can be achieved on axis, the design presented here performs better for eccentric objects as a consequence of the use of a wide-angle eye model in the optimization procedure. To illustrate this point, Fig. 3 shows the effect of eccentricity on the size of the white-light point-spread function, quantified by the polychromatic root mean square (RMS)[30] computed for the combination of the wide-angle eye model and our chromatic corrector. For comparison purposes, results for two other previously proposed correctors are presented: Bedford–Wyszecki's[8] and Powell's.[23] The former is a triplet, and it produces a rapid increase in the eccentric TCA. As a consequence, it produces some advantage only in terms of polychromatic retinal image size for a field of view of around ±2°. Powell's design is an evolution of Bedford–Wyszecki's. A doublet is added to compensate the lateral chromatic spread of the triplet in order to increase the field of view. However, the polychromatic RMS can be seen to become similar to or even bigger than that for the naked eye for incidence angles above 6°. The new design takes advantage of the inclusion in the design stage of a wide-angle eye model that realistically predicts the eccentric TCA of the eye. Consequently, the polychromatic retinal image size is improved for the whole effective field of view.

It is a well-known fact that alignment is a critical issue for LCA correction.[24] Although the compensation of the chromatic defocus would not be noticeably affected, a lateral misalignment or a tilt between the eye and the corrector would induce TCA, and the potential advantage in the polychromatic image quality may be easily lost. Figures 4 and 5 address this problem from a theoretical point of view. Figure 4 shows the effect of 1 mm of lateral displacement on the polychromatic RMS as a function of the incidence angle. The on-axis polychromatic image quality is affected in a similar way for all three designs analyzed. Off axis, the behavior is asymmetrical, since the radial symmetry is broken. However, it is worth noting that this asymmetry is less pronounced for the new corrector design. In Fig. 5, the consequences of angular misalignment are shown for a 1° tilt. Again, a slight asymmetry can be seen, with the new design producing the flattest curve.

B. Experimental Testing of the Corrector
Using the specifications obtained in the design stage, an actual two-triplet system was built. The aperture of the
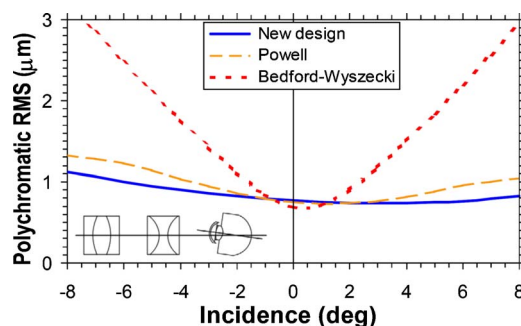

Fig. 5.   (Color online) Theoretical effect of 1° of tilt on the polychromatic RMS for the combination of the wide-angle schematic eye and different LCA correctors: Bedford–Wyszecki's design (dotted curve), Powell's corrector (dashed curve), or the design presented here (solid curve). The origin for the incidence angle is the corrector optical axis.
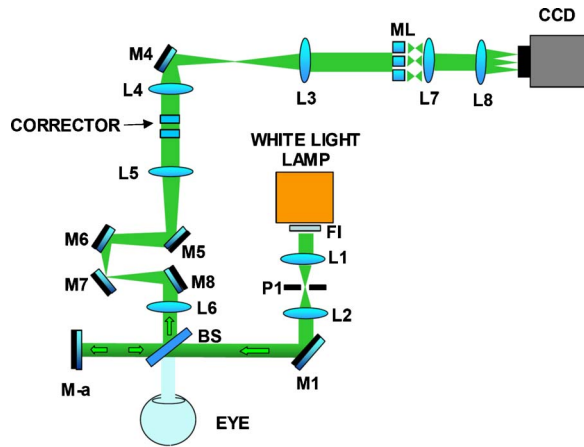
Fig. 6. (Color online) Experimental apparatus for measuring the monochromatic aberrations introduced by the device for different wavelengths. L1, L2, L3, L4, L5, L6, L7, and L8, achromatic doublets; M1, M-a, M4, M5, M6, M7, and M8, mirrors; FI, filter holder for the 10 nm bandwidth interference filters; P1, 1 mm stop; BS, beam splitter; ML, microlens array.

two triplets was 22 mm. Considering the distances involved (see Table 1) and a pupil size of 6 mm for the wide-angle model eye, the total field of view has a radius of 13.5° with no vignetting for incidence angles below 8°.

As a preliminary test, we evaluated the possible astigmatism and high-order aberrations induced by the device in the visible range. We used a white-light wavefront sensor described in detail elsewhere.[31] The experimental setup is shown schematically in Fig. 6. The system is based on a Hartmann–Shack wavefront sensor[32] modified for measuring aberrations at different visible wavelengths.

In summary, the Hartmann–Shack sensor consisted of a short-focal-length microlens array (ML), a high-sensitivity CCD camera (Q-imaging Retiga 1300i), and a telescopic relay system (lenses L7 and L8). The illumination source was a white-light xenon lamp (Hamamatsu L2274). The monochromatic aberrations for different wavelengths were measured by inserting the appropriate 10 nm bandwidth interference filter (FI) in front of the lamp (wavelengths, 440, 488, 532, 633, and 694 nm). A telescopic system (L1 and L2) with a 1 mm stop (P1) was used to produce a nearly collimated beam, which was directed toward the corrector placed on a pupil conjugate plane between lenses L5 and L4. The path between mirror M1 and lens L5 contained a beam splitter (BS) and a motorized defocus corrector (mirrors M5, M6, M7, and M8) not required for this measurement. They were included to allow subjective LCA and VA measurements with minor modifications as described in the next section.

C. Longitudinal Chromatic Aberration Measurement Procedure
Subjective measurements of the eye's LCA were performed, with and without the corrector. The setup used in the experiments is shown in Fig. 7, which is based on the apparatus in Fig. 6, with some modifications. For these measurements, mirror M1 is used to allow the subject to fixate on a target slide with high spatial-frequency features. This slide is illuminated with different wave-

lengths by means of the xenon white-light lamp and the set of interchangeable interference filters. A pair of linear polarizers placed between the xenon lamp and the filter holder is used to control the output intensity. To approximately equalize the target luminosity for the different wavelengths, the angle between the two polarizers can be varied. The subject's task is to bring the target to the best subjective focus for each wavelength by using the motorized defocus corrector system, which consists of lenses L5 and L6 with four mirrors between them. Mirrors M5 and M8 are fixed, while the pair M6 and M7 are mounted on a computer-controlled stage and slide together to produce changes in vergence. The subject has direct control on the motorized defocus corrector through a keyboard, and the focus search is done in 0.1 D steps. The differences in the best focus position for each wavelength are an estimate of the subject's LCA. The same procedure is repeated with the two-triplet system placed in front of the subject's eye to evaluate the residual LCA after correction. All the experiments were performed with natural unparalyzed accommodation. The subjects were instructed to relax accommodation, and the search for the best focus was started from beyond the far point.

D. Visual Acuity Testing Procedure
For VA testing, mirror M-b in Fig. 7 is tilted to present the subject with a stimulus displayed on the monitor. The custom procedure to measure VA was developed using the libraries provided by Cambridge Research Systems, Inc., together with the VSG2/5 graphic card. The stimuli are presented on a Sony Trinitron GDM-F520 monitor. Basically, the test consists of a forced-choice tumbling E test with random letter size. The subject's task is to determine the letter orientation using a keypad. Five different letter sizes are presented, uniformly distributed in a range around a central value, previously obtained using a calibration test where the subject subjectively determines the threshold size. The success percentage values are fitted to a sigmoidal function, and the VA is estimated from the
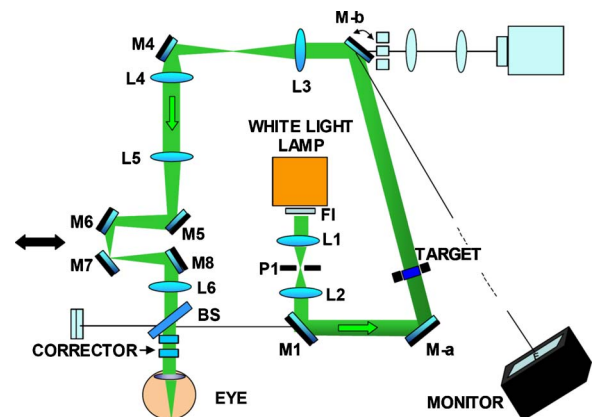

Fig. 7. (Color online) Experimental apparatus for measuring the ocular LCA and performing VA tests with and without the corrector. The elements removed from the apparatus in Fig. 6 are presented in light gray (blue online). Other differences are as follows: Mirrors M1 and M-a illuminated the target for LCA measurements; a monitor for VA tests was included; tilting of mirror M-b allowed switching between tasks. Additionally, mirrors M6 and M7 are mounted on a motorized stage that is computer controlled by the subject to adjust the best focus (Badal scheme).

letter size corresponding to 62.5%. For each experimental condition, six runs were averaged. The VA was measured with and without the corrector in front of the eye using black E letters on a white background (124.0 cd/m^2 of luminance). This will be referred to as the polychromatic case, and it provides information about the potential benefit of correcting the LCA. Additionally, as a control experiment, VA with and without corrector was also measured in quasi-monochromatic light, consisting of black E letters on a green background (green phosphor of the monitor; 84.3 cd/m^2 of luminance; $\sim$75 nm FWHM of spectral bandwidth). Although the contrast sensitivity has been found to be slightly better for monochromatic light than for white light, VA has been reported to remain practically unaffected.[33] Additionally, the difference in luminance between the polychromatic and the monochromatic conditions can be expected to produce a slight decrease in VA[34] (around −0.03) that can be neglected in practice.

In total, the experiment included four different conditions and took around one hour for each subject to complete. The subjective best focus was fine tuned for each condition. Since the alignment of the corrector is known to be a critical factor,[24] the experiment sequence consisted of the two VA measurements for the naked eye followed by those with the two-triplet system in front of the eye in order to keep the same corrector position for both of them. The alignment of the corrector was carefully controlled using an additional monitoring path.

3. RESULTS

A. Corrector Calibration

The amount of monochromatic aberrations introduced by the corrector as a function of wavelength is presented in Fig. 8, where the Zernike coefficients up to fifth order are plotted for a 5.5 mm pupil, together with the combined RMS excluding defocus. The defocus term (C_4) is the only Zernike coefficient with significant values (note that it has been plotted on a different scale), and its behavior is appropriate to compensate the ocular LCA. Excluding this term, values of higher-order RMS around 0.1 μm are found, which can be neglected when compared with the typical ocular aberrations. Furthermore, every individual coefficient (excluding defocus) was smaller than $\lambda/5$ for every wavelength, and no systematic aberration pattern is introduced. Finally, the wrapped wavefront maps displayed in Fig. 9 show peak-to-valley values lower than or around one wavelength in every case.

B. Longitudinal Chromatic Aberration Correction

The LCA of the naked eye, and with the corrector, was measured subjectively for the five wavelengths in the visible range. Three young subjects with normal vision (PA, PP, YB) participated in the experiment. Each subject was presented with the high spatial-frequency target sequentially illuminated with the selected wavelengths and was instructed to find the best focus for each case by means of the defocus corrector system. The experiment was performed both with the corrector in front of the subject's eye and with the naked eye. Figure 10 presents the differences in focus with respect to a reference wavelength
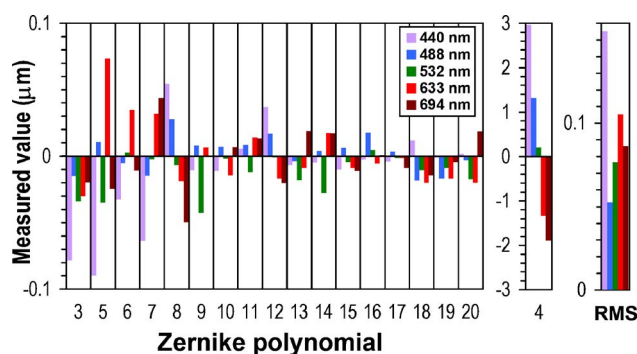

Fig. 8. (Color online) Zernike coefficients (OSA standard order) of the corrector aberrations over a 5.5 mm pupil for a series of wavelengths. The defocus term is presented separately due to the different scale. The last column represents the RMS of the corrector calculated from the set of Zernike coefficients, excluding the defocus. The average standard deviation for individual coefficients (including defocus) was 0.01 μm and for the total RMS was 0.02 μm.
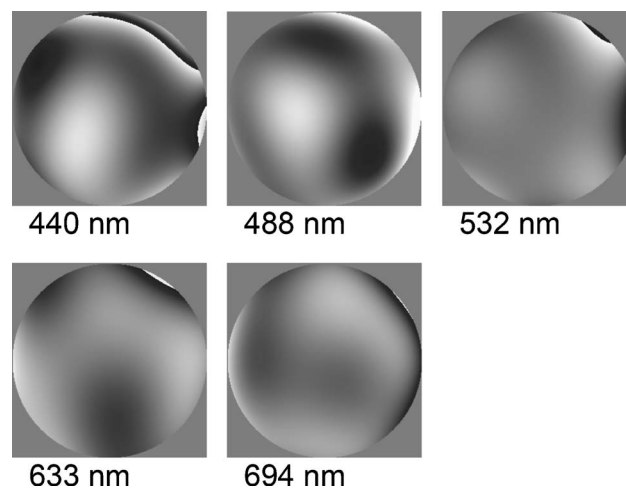

Fig. 9. Phase maps of the corrector aberrations excluding defocus, wrapped between 0 (black) and 2π radians (white) for the five selected wavelengths. In all cases the peak-to-valley values can be seen to be less than or around 1 λ.
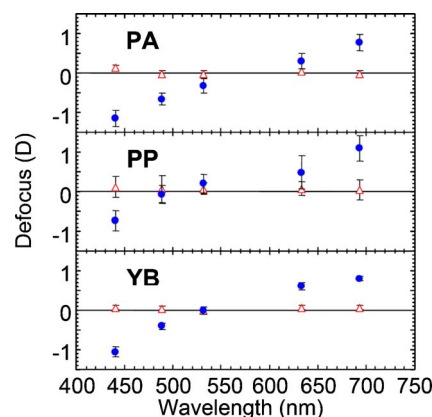

Fig. 10. (Color online) Longitudinal chromatic aberration for the naked eye (circles) and after LCA correction with the two-triplet system (triangles) for three subjects.

Table 2. Decimal Visual Acuity Values for SM and YB, without and with the Corrector, for Monochromatic and Polychromatic Light[a]

Subject	Without Corrector		With Corrector	
	Monochromatic	Polychromatic	Monochromatic	Polychromatic
SM	1.32 ± 0.13	1.22 ± 0.06	1.53 ± 0.15	1.41 ± 0.07
YB	1.69 ± 0.26	1.35 ± 0.04	1.60 ± 0.17	1.55 ± 0.05

[a]Each value is the average of six runs. The error is the standard deviation.

(532 nm), which can be taken as an estimate of the subject's LCA. All three subjects show similar behavior for the naked eye, in good agreement with the data found in the literature.[10] Furthermore, the corrector is found to effectively correct the eye's LCA in all cases. This result confirms the convenience of the design based on population data proposed here.

C. Visual Acuity Measurements

To evaluate the potential benefit of LCA correction on visual performance, a VA test was conducted on two young normal subjects, SM (−3 D) and YB (−3.5 D), through the system with and without the corrector in place. To isolate the effect of LCA correction from other potential effects produced by the introduction of the device, the test was performed both in polychromatic (black letters on white background) and monochromatic (black letters on green background) illumination.

The VA estimates for the two subjects can be seen in Table 2 and graphically in Fig. 11. Without the corrector, the monochromatic VA is slightly better than the polychromatic VA for both subjects. Although these differences are statistically significant only for subject YB ($p=0.01$ for YB and $p=0.11$ for SM), this effect can be produced by the chromatic aberrations (both LCA and TCA) of the eye and may indicate that there is room for some improvement in visual performance by correction of the LCA.

This improvement may be showing for both subjects, as they exhibit a statistically significant ($p < 0.001$) increase in the polychromatic VA. However, the monochromatic VA presents a different behavior for each subject. For subject YB, the monochromatic VA remains basically unchanged, suggesting that the improvement observed for polychromatic light can be attributed to the correction of the LCA. Conversely, for subject SM, the monochromatic VA experiences a statistically significant increase ($p=0.02$) with the introduction of the LCA corrector, leaving the difference between monochromatic and polychromatic VA practically constant. This result is difficult to explain from the point of view of chromatic aberration correction and suggests some other, unknown origin for the increase in VA observed for this subject.

There are a series of effects reported in the literature that could explain these differences in behavior. One is the combination of the chromatic aberrations with the subject's actual monochromatic aberrations, which has been reported to reduce the effect of chromatic aberrations.[5] Correction of the LCA alone could, therefore, improve polychromatic retinal image quality in some subjects and present no benefit in others. This could also be the case for subjects with large values of foveal TCA,
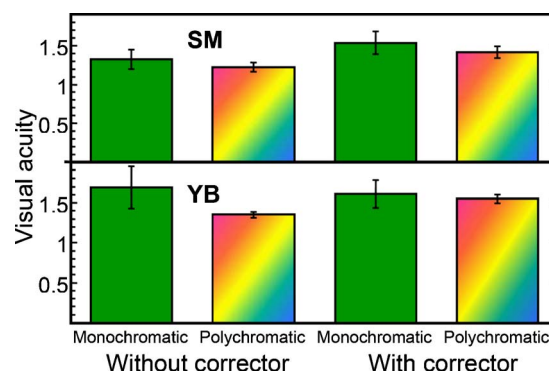

Fig. 11. (Color online) Monochromatic (green light) and polychromatic (white light) visual acuity estimates for two subjects, SM (−3 D) and YB (−3.5 D), with the eye naked and wearing the LCA corrector. The error bars are the standard deviation.

since the spread in the polychromatic retinal image caused by this aberration may be the most important chromatic effect.[11] These two factors would have a direct effect on the use of the LCA corrector for both retinal imaging and improved vision. For the latter application, which is the one discussed in this paper, there are some other aspects that could affect the potential benefit of chromatic aberration correction, such as neural adaptation[35] or the use of the chromatic differences as an accommodation cue.[36]

Despite these considerations, the use of a LCA correcting device, such as the one presented here, could be of interest in some subjects both to increase resolution in retinal imaging systems and to improve vision. It should be pointed out that in this work we have studied only VA, but there are some other aspects of visual performance, such as contrast sensitivity, that could profit from LCA correction. Furthermore, the potential benefits would be more readily expected when the corrector is used in combination with an adaptive optics system or any other device for compensation of the eye's monochromatic aberrations.

4. CONCLUSIONS

An innovative design of an achromatizing correcting lens optimized for a wide field has been presented. Theoretical analysis of the design predicts a good chromatic aberration correction and a potential improvement of retinal image quality for polychromatic light. The use of a wide-angle model in the design stage is expected to produce a better behavior for eccentric incidence, theoretically increasing the effective field of view of the device as compared with previous designs. The effect of tilt and decen-

tration has been simulated, and the system presented in this work appears to be more robust than other previously proposed schemes. Based on the optimization data, an actual device was built to experimentally check the theoretical predictions. The optical quality of the corrector alone was tested for different wavelengths with a Hartmann–Shack wavefront sensor, showing only small amounts of aberrations. The performance of the device for LCA correction was checked on three subjects and is in agreement with the predictions. The impact of the corrector on VA was tested in two subjects. One of the subjects showed an improvement in polychromatic VA that can be attributed to the correction of LCA, while for the other subject the results were not clear. The potential benefits of chromatic aberration correction alone can be thwarted by the interaction with monochromatic aberrations and, therefore, will probably be more apparent when the corrector is used as an element of a system for global compensation of both monochromatic and chromatic aberration such as an adaptive optics apparatus.

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