

Visual effect of the combined correction of spherical and longitudinal chromatic aberrations

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Abstract: An instrument permitting visual testing in white light following the correction of spherical aberration (SA) and longitudinal chromatic aberration (LCA) was used to explore the visual effect of the combined correction of SA and LCA in future new intraocular lenses (IOLs). The LCA of the eye was corrected using a diffractive element and SA was controlled by an adaptive optics instrument. A visual channel in the system allows for the measurement of visual acuity (VA) and contrast sensitivity (CS) at 6 c/deg in three subjects, for the four different conditions resulting from the combination of the presence or absence of LCA and SA. In the cases where SA is present, the average SA value found in pseudophakic patients is induced. Improvements in VA were found when SA alone or combined with LCA were corrected. For CS, only the combined correction of SA and LCA provided a significant improvement over the uncorrected case. The visual improvement provided by the correction of SA was higher than that from correcting LCA, while the combined correction of LCA and SA provided the best visual performance. This suggests that an aspheric achromatic IOL may provide some visual benefit when compared to standard IOLs.

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1. Introduction

The optics of the eye degrades the retinal image and limits spatial vision. Different studies have measured the monochromatic aberrations in a large population of normal eyes [1,2]. These studies concluded that the values of each aberration term are subject-dependent and are distributed around zero, except for spherical aberration (SA), which has an average positive value that tends to increase with age [3]. This fact has recently motivated designs for ophthalmic devices that correct ocular SA. In particular intraocular lenses (IOLs) were the natural candidates for the practical implementation of SA correction.

In recent years, the optics of the pseudophakic eye has been further studied [4]. On average, the cornea exhibits positive spherical aberration [5,6]. Different IOL models induce different types of aberration patterns. Like the crystalline lens in the elderly eye, spherical IOLs have positive spherical aberration, and thus cause an increase in the ocular spherical aberration of the average cataract patient. The Tecnis IOL (AMO, Santa Ana, CA) was designed with aspheric optics to correct for the average corneal SA of the pseudophakic eye [7–9]. Postoperative studies carried out on patients implanted with this lens showed an improvement in contrast sensitivity (CS) [10–12]. Additionally, Zhao and Mainster [13] have shown that reducing chromatic aberration (CA) of an IOL by using a material with a high Abbe number also improves overall pseudophakic optical performance. The benefit of the correction of SA on visual performance was previously studied [14] using an adaptive optics visual simulator [15]. In that study, the improvement in performance when SA was corrected both in monochromatic and polychromatic (white) light was measured. When SA was corrected in monochromatic light the measured improvement was higher than that found in polychromatic light. This suggests that further improvement could be provided by the combined correction of SA and LCA.

The dispersive nature of the ocular media induces two types of CA: longitudinal chromatic aberration (LCA) (wavelength-dependent position of the image plane as a function of wavelength), and transverse chromatic aberration (TCA) (wavelength-dependent differences in image location or magnification). Many studies have measured both the LCA [16–20] and the TCA [21,22] in the human eye. While the TCA shows a high inter-subject variability, the LCA is nearly constant across subjects making it feasible to design standard correctors for the general population.

When one considers the large values of LCA measured in the eye (approximately 2 D in the visible range), it seems logical that its correction would have some impact on spatial vision. However, Campbell and Gubisch [23] found a small improvement in CS measured in monochromatic light as compared with white light, and only for small pupil diameters. For a 4 mm pupil diameter they did not find any change in CS when CA was removed. They explained this result to be due to the presence of SA in the eye. The higher-order monochromatic aberrations may attenuate the negative effects of CA [24,25] as well as the possible benefits of its correction [26]. The potential benefit of correcting CA is also attenuated by other mechanisms of the visual system, the most important of which is the eye's lower sensitivity to light at the extremes of the visible spectrum, where the effects of LCA play the largest role.

Refractive chromatic correctors composed of groups of lenses have been proposed in the past [27–29], while more recently, a hybrid diffractive-refractive doublet design [30] and a wide-angle corrector [31] were proposed. Due to their size, these correctors are not suitable for implementation in IOLs. Pure diffractive designs seems to be best suited for a chromatic aberration correcting IOL [32,33].

Different studies relating the effect of CA to visual outcomes have been performed [34]. Lopicque [35] calculated the combined effect of diffraction, SA, and CA on the retinal image. Assuming zero SA, he found only a slight improvement in optical quality, in comparison with

that achieved when removing CA, and concluded that this is the most significant aberration in white light. Van Heel [27] used a SA corrector composed of two cemented lenses to search for an improvement in visual performance when SA was corrected, using monochromatic light to avoid the effects of CA. The subjects in his study didn't report better visual acuity (VA). More recently, Yoon and Williams [26] performed a similar experiment using adaptive optics to correct all higher-order monochromatic aberrations and monochromatic light to remove the effects of CA. In this case, a clear improvement in visual quality was reported when the effects of both monochromatic and chromatic aberrations were removed.

However, to our best knowledge, a study of the visual impact of the correction of SA combined with the true correction of LCA, by means of a device that allows vision in white light, has not been performed yet. In this study, we use a diffractive LCA corrector in combination with the correction of the SA with adaptive optics.

2. Methods

2.1. Subjects

Three normal subjects (PA, SM and HW) took part in the experiment: PA and SM were both myopic (1.5 and 2.5 D respectively) while HW was an emmetrope. For alignment purposes, the subjects' heads were stabilized with a bite bar. The study adhered to the tenets of the Declaration of Helsinki, and informed consent was obtained from each subject after the nature and all possible consequences of the study had been explained. Two drops of 1% tropicamide were instilled before the experiments to initiate cycloplegia and mydriasis.

2.2. Spherical aberration correction

We used an adaptive optics instrument to control and manipulate high-order aberrations while visual testing was performed. The instrument was similar to those previously described [14,15,36]. A schematic diagram of the complete system is shown in Fig. 1. A near-infrared (780 nm) diode laser (DL) illuminated the eye after reflection in a beam-splitter (BS) placed in front of the eye. The eye's pupil plane was imaged onto the corrector device (MDM) by a telescopic relay composed of lenses L1 to L4, and onto the wave-front sensor plane by lenses L5 to L8. The corrector device was a Xinetics, 97-actuator deformable mirror (Xinetics Inc, Devens MA, USA), and the wave-front sensor was of a Hartmann-Shack (H-S) type [37]. The sensor measured the ocular aberrations and those induced by the MDM, and working in closed-loop the sensor and the MDM set the target wavefront-aberration. This wave-aberration can be expressed in terms of the Zernike polynomials modes, and the system is able

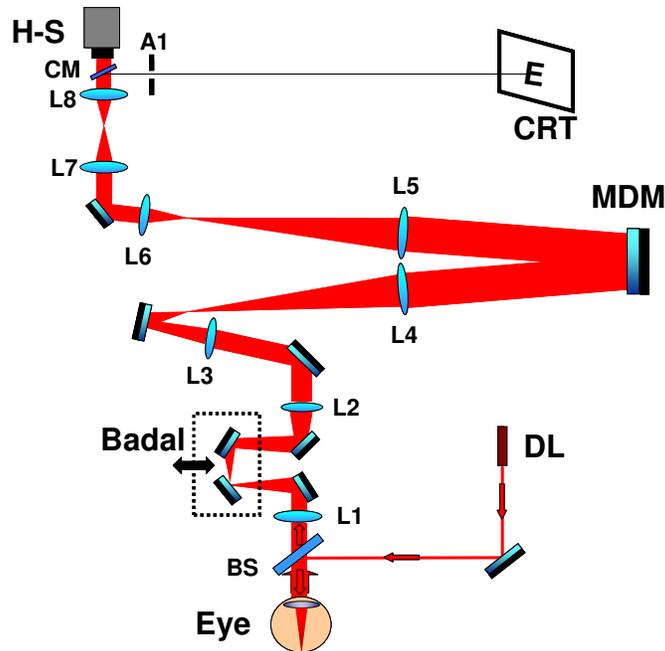


Fig. 1. Schematic diagram of the adaptive optics system. A near infrared diode laser illuminates the eye and a set of telescopic relays imaged the eye pupil plane onto the membrane deformable mirror (MDM) and the H-S sensor. Both elements working in closed-loop set the target wave aberration. At the same time, the subject can perform visual tests through the modified aberrations using the CRT monitor with the vision limited to an artificial pupil, due to aperture A1. A motorized Badal optometer allows changing the focus in the system.

to reach a final wavefront-aberration composed of any possible combination of values of these modes allowed by the MDM stroke ($4 \mu\text{m}$). In this experiment, the adaptive optics system was used to modify only the SA term, while holding the rest of the aberration modes constant. To achieve this, the system initially measured the aberrations of the eye and set these values to the target aberration values, except for SA, which was set to either zero or $0.149 \mu\text{m}$ for a 4.8 mm pupil. This last value was based on the SA measured in the pseudophakic population of eyes implanted with spherical control lenses and from the corneal spherical aberration found in older eyes.

2.3. Chromatic aberration correction

To evaluate the effects of LCA correction on visual quality, a diffractive optical element on a PMMA plate was produced based on a design that could be implemented in an IOL. This is a diffractive element designed to correct the typical chromatic aberration in the eye, but with a chromatic behavior different from standard diffractive lenses [38]. To simulate a behavior similar to that within the eye, the device was immersed in water and placed in front of the eye. A cuvette with plano-parallel plates was built to house the diffractive element immersed in water. A white-light H-S wave-front sensor was included in the experimental system in order to characterize the LCA of the eyes being measured with and without the diffractive element in place. This white-light (or wavelength-tunable) wave-front sensor has recently been described elsewhere [39]. The instrument was composed of a Xe-lamp, a set of interference filters (10 nm bandwidth) for the illumination path and the H-S sensor. The selected filter was placed at the output of the lamp in order to set the wavelength at which the eye is illuminated and the wavefront-aberration measured. Figure 2 illustrates this instrument that was integrated in

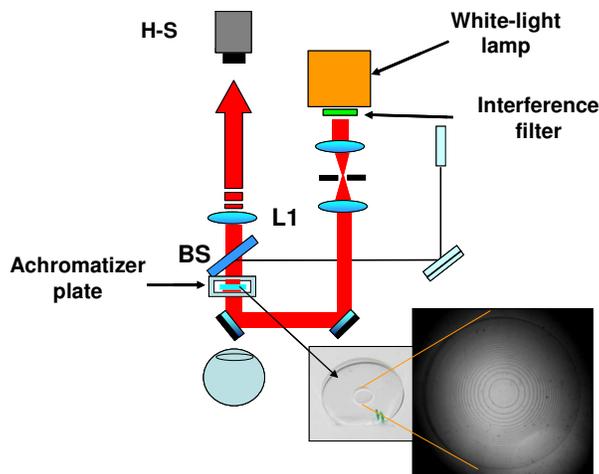


Fig. 2. Schematic diagram of the optical setup used to objectively measure the chromatic aberration induced by the LCA corrector. For simplicity, most of the optical system shown in Fig. 1, is omitted. A wavelength tunable wavefront sensor is implemented on the adaptive optics system. The Xe-lamp and the set of interference filters illuminate the achromatizer plate at different wavelengths in the visible range. A detailed view of the achromatizer plate and its diffractive structure is also shown

the adaptive optics system of Fig. 1. To measure the aberrations induced by the diffractive corrector element alone, it was placed in the location of the eye's pupil plane and illuminated with light from the Xe-lamp, using the auxiliary mirrors shown in the diagram. The wavefront-aberrations were measured for 440, 488, 532, 633 and 694 nm. The corresponding wave-aberration maps for the corrector isolated (without eye) are shown in Fig. 3. It is apparent that the corrector induces only defocus, with negligible amounts of

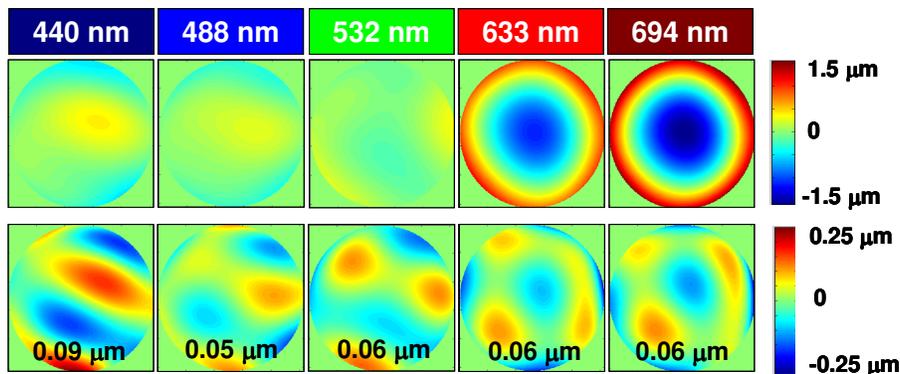


Fig. 3. Wave aberrations at different wavelengths of the LCA corrector, measured by means of the white-light H-S sensor. In the upper row is shown the whole aberration, including defocus, for each wavelength. In the lower row only the higher-order terms, with the corresponding RMS for a 5.5 mm pupil, are shown.

higher-order aberrations. As the test to assess visual quality after LCA correction was performed by the subject through the corrector and the optical setup, the LCA corrector was designed so that the combined LCA of the optical setup and the corrector itself was opposite to that of the average eye. By means of the white-light H-S sensor, the total LCA of the system and corrector was determined from the defocus term of the measured wavefront-aberration. Figure 4 shows the measured LCA of the system plus corrector and the ocular LCA

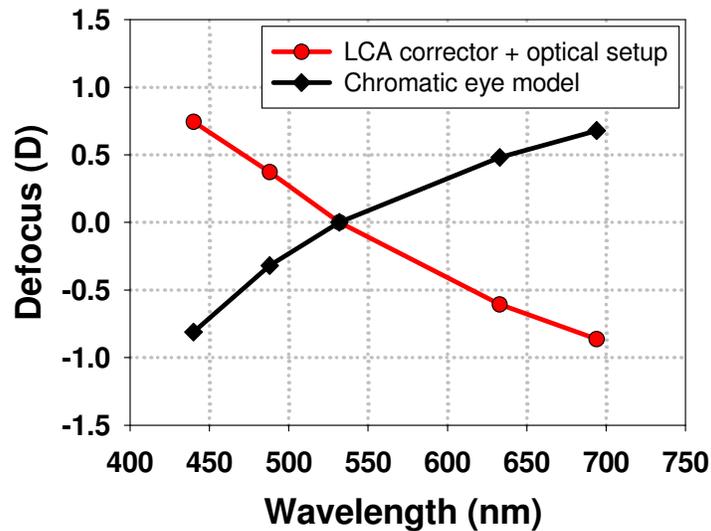


Fig. 4. LCA induced by the achromatizer plate and the optical setup through which the visual test was performed later. It is compared with the LCA predicted by the Chromatic Eye model, showing that, as expected in the design stage of the achromatizer prototype, both chromatic aberrations are opposite.

predicted by a chromatic eye model [40], showing that, as expected from the design stage, the value of the chromatic aberrations were essentially equal and opposite. Moreover, the important issue to be tested was how well LCA in real eyes is corrected by the diffractive element. In principle, the measurement of the chromatic aberration correction in real eyes could have been performed objectively by means of the white-light H-S sensor, with minor modifications to the setup shown in Fig. 2. However the position of the transparent cuvette holding the corrector in front of the eye caused experimental issues. In the first pass, when the eye was illuminated by the lamp, the H-S images were affected by reflections caused by the cuvette surfaces and the corrector plate. In addition, in the second pass, the light intensity coming from the retina was reduced due to the reflections in the cuvette. These issues were particularly important when measuring in the blue part of the spectrum. This problem was addressed by measuring the LCA using a standard subjective technique. Figure 5 shows the modifications in the original optical setup in order to allow the subject to view a slide object test through the combination of the optical system and the CA corrector plate. Using the white-light lamp and the interference filters, this slide was illuminated at different wavelengths and for each wavelength the subject used the motorized Badal optometer to modify the focus of the system to obtain the sharpest image of the slide. The subject performed three measurements of their best focus position for each wavelength and the average was taken as the final defocus value at each wavelength. The LCA was obtained from the chromatic difference of focus. As an initial test of the procedure, the natural LCA (without the chromatic corrector) of the three subjects was measured. Using the same procedure, but with the corrector in front of the eye, the residual LCA was also measured for the same three subjects. These results are presented in Fig. 6. The LCA is well corrected over most of the visible range. It should be noted that the curves from each subject in this figure were shifted to have zero defocus at 532 nm to represent the relative change in defocus as a function wavelength.

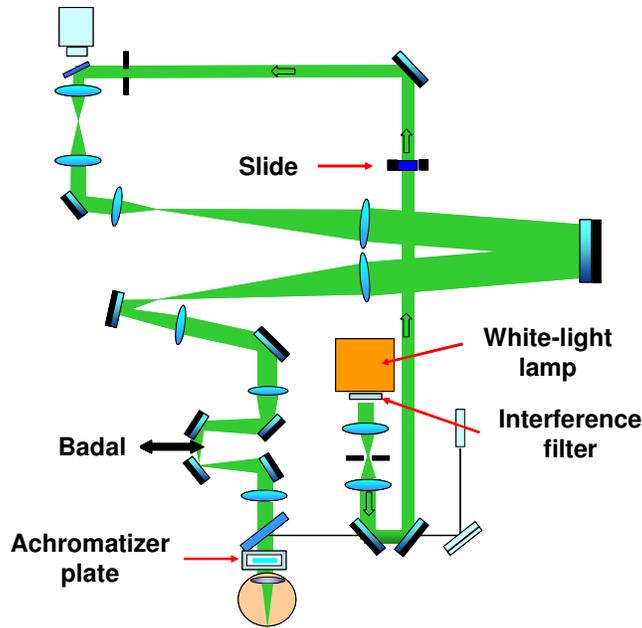


Fig. 5. Diagram of the changes introduced in the adaptive optics system for measuring the quality of the LCA correction in real eyes. The white-light lamp and the interference filters are used to illuminate at different wavelengths a slide that is seen by the subject through the achromatizer plate. The subject, for each wavelength, must bring in focus the image in the slide, using the Badal optometer. From the different Badal positions for each wavelength, the total LCA is obtained.

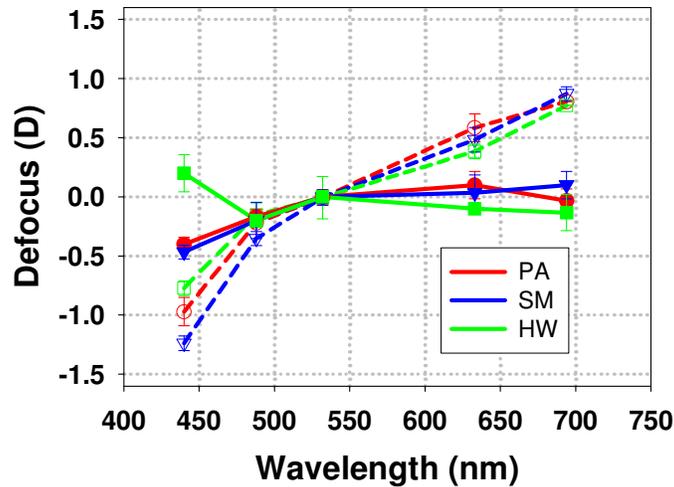


Fig. 6. LCA (with and without the corrector) in three subjects (PA, SM and HW). Dashed lines with open symbol represent the measured natural LCA, and solid lines with filled symbols the corrected LCA. Curves were shifted to cancel out defocus at 532 nm.

2.4. Measurements of visual performance

To perform visual testing through the modified ocular aberrations, an additional path was incorporated into the instrument (Fig. 1) composed of a distant CRT monitor, where the optotypes are displayed, a cold mirror (CM), that allows the subject to see the test through the

optical setup, and a circular aperture (A1) that was conjugate with the pupil plane of the eye, and used as artificial pupil. This aperture was projected onto the eye's pupil and properly centered on the achromatic axis. A motorized Badal optometer allowed each subject to find their best-focus position. For all cases, astigmatism was corrected with the MDM.

Once the spherical and chromatic aberrations were controlled, the visual performance of the subjects under four different conditions was measured. These conditions were the combination of two chromatic aberration states (natural and corrected) and two SA values (0 and 0.149 μm). The case where the subject looked through a SA value equal to 0.149 μm and their natural LCA was used as a reference measurement. Partial corrections were then performed by removing first the LCA and then the SA. Finally LCA and SA were simultaneously corrected.

To measure the visual performance, for each of the cases mentioned above, the closed-loop adaptive optics system first set the SA (0 or 0.149 μm) and astigmatism values through which the subject performed the visual test, and in the cases where the LCA effects were to be removed, the chromatic corrector was placed in front of the eye. Each subject then made use of the motorized Badal optometer to search for their best-focus position while viewing a target displayed on the monitor. The search was carried out changing the focus in steps of 0.05 D, and the process was repeated three times, using the average value as the final best focus position. VA (tumbling 'E') and CS, for 6 cycles/degree, using a QUEST forced choice procedure [41], were measured. This spatial frequency was chosen because it is near the peak of the CS function for normal healthy eyes [42]. A more in-depth description of the procedure used can be found in Piers et al. [14] Testing was performed in white light for a fixed pupil of 4.8 mm, using the corresponding artificial pupil (A1). To avoid any potential learning or adaptation [43] effects, the sequence of the different cases were performed in a random order and subjects were not aware of the particular condition of correction.

3. Results

The VA measured in each subject under the four different correction conditions is shown in Fig. 7, together with the average value for all three subjects. Results of CS, at 6 cycles/degree, for the same conditions are presented in Fig. 8. These figures show a tendency for an improvement in the visual quality of the subjects relative to the normal case when either LCA or SA is corrected. The visual quality is highest when both chromatic and spherical aberrations are simultaneously corrected.

A statistical analysis consisting of a Student's two-sided t-test considering multiple comparisons with the Bonferroni correction was carried out for all the measured differences between optical conditions. For VA this analysis shows that the differences are statistically significant for the following comparisons: (no SA and no CA) vs (SA and CA) ($p < 0.001$), (no SA and no CA) vs (SA and no CA) ($p < 0.01$) and (no SA and CA) vs (SA and CA) ($p < 0.05$). For the measurements of CS only the comparison (no SA and no CA) vs (SA and CA) ($p < 0.05$) is statistically significant.

The combined correction of both aberrations provides the best visual quality, with an average relative improvement of 1.4 to the uncorrected case. The average decimal VA increased from 1 (SD = 0.04) to 1.4 (SD = 0.08) and CS from 17.5 (SD = 2.9) to 25.1 (SD = 4.6).

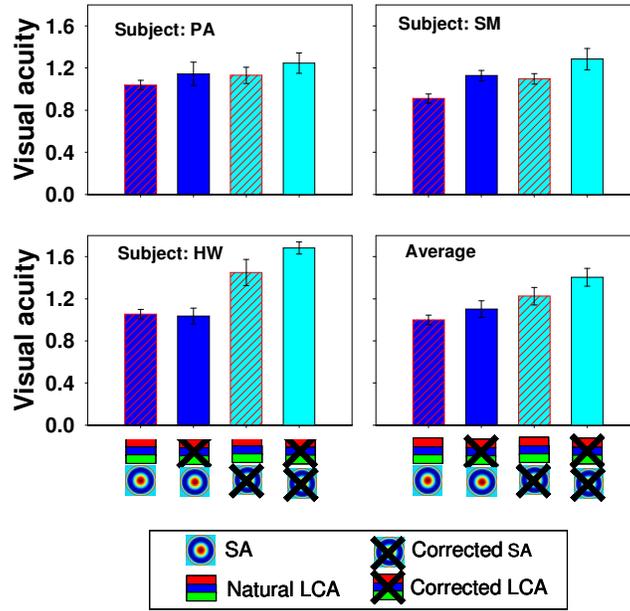


Fig. 7. VA of the subjects PA, SM, HW and the average across them with spherical aberration and chromatic aberration similar to that of the average pseudophakic patient's eye, corrected spherical aberration, corrected chromatic aberration and corrected spherical and chromatic aberration. (Error bar represents standard deviations).

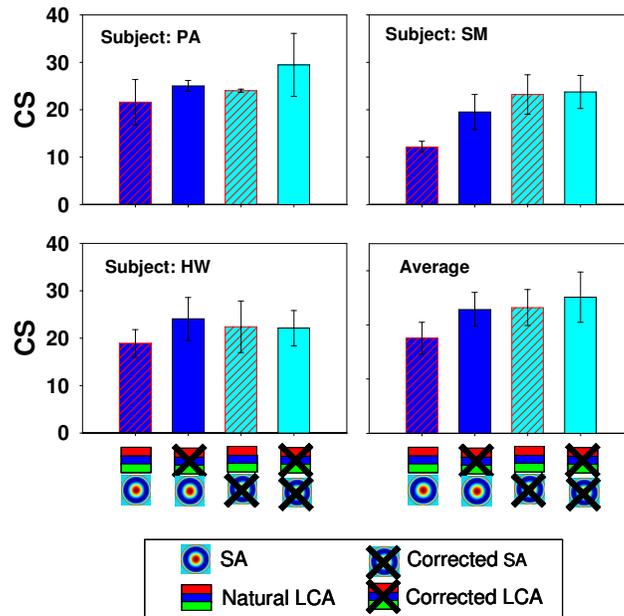


Fig. 8. CS at 6 cycles/degree for subjects PA, SM, HW and the average across them with spherical aberration and chromatic aberration similar to that of the average pseudophakic patient, corrected spherical aberration, corrected chromatic aberration and corrected spherical and chromatic aberration. (Error bar represents standard deviations).

4. Discussion

The correction of SA alone provides a larger impact than LCA in contrast vision. This could be due to the pupil diameter selected for the experiments: a relatively large 4.8 mm pupil. For smaller pupil diameters, LCA correction alone could have a superior impact than correcting SA. Chromatic and spherical aberrations depend differently on the pupil diameter. The wavefront error of the SA depends on the fourth power of the radius, while LCA depends as defocus does (as a function of squared radius). The advantage of the combined correction of spherical and chromatic aberration is to provide superior performance for a larger range of pupil diameters. For the smaller pupil range, LCA would do more, while SA would have a smaller impact and for larger pupils the opposite situation would occur.

When considering a lens that corrects ocular LCA outside of the eye, it is well known that the improvement provided in visual performance is particularly susceptible to alignment errors. In particular a decentered LCA corrector would add significant amount of TCA [44]. Misalignments of the optical axis of the lens with respect to the visual axis leads to chromatic parallax which reduces the quality of vision measured through such a lens. Additionally, it is well known that when the monochromatic aberration of the eye is corrected with an IOL, the patient's optical performance depends on the degree of misalignment of the lens [4]. A recent study of tilt and decentration of foldable IOLs have found average decentration values of 0.19 mm and 0.37 mm and average tilts of 2.85 degrees and 2.89 degrees [45]. Within this range of tilt and decentration found in the pseudophakic population, an aspheric-achromatic lens would outperform lenses that do not correct monochromatic and chromatic aberrations [4].

One issue related with the correction of aberrations is a possible reduction of depth of focus. In an optical system affected only by spherical and chromatic aberration, their correction would severely reduce depth of focus. However, in real eyes affected by many other aberrations terms [46,47], the actual reduction of depth of focus after partial correction of the aberrations would be limited [4]. Another relevant related issue is the relative importance of residual refractive errors when SA and LCA are corrected. Under normal conditions, the benefit reported here would be reduced and would vanish completely if the patients have significant defocus and astigmatism. The correction of aberration would produce visual improvements in those cases where refractive errors are low.

In this study, all measurements were performed with a 4.8-mm artificial pupil in place. In older subjects (typical cataract patients), the average pupil under photopic conditions is around 3.5-mm while the average pupil size under mesopic conditions is 5-mm [48]. Therefore, the pupil size used for this study is considered to be a realistic pupil size for cataract patients. The potential benefits associated with the correction of aberrations are increased when the pupil is larger. As a result, the improvement in visual performance would be larger in younger patients where the pupil is larger than 4.8-mm, or in situations where the pupil is dilated due to low-light conditions. As discussed, the combined correction of SA and CA may extend the benefit for a larger range of pupil diameters.

Three normal subjects were evaluated in this study. This relatively small number was favored because the large duration and complexity of the performed experiments. It should be pointed out that this laboratory results set a baseline on the maximum visual improvement that can be attained after correcting chromatic and spherical aberrations. In real clinical conditions, the benefit would be lower due to many different factors, including the different amount of other aberrations present in pseudophakic eyes.

The premise of the experiments described in this paper was that an adaptive optics system, combined with a diffractive phase plate, should simulate the simultaneous correction of SA and LCA with an IOL. Several disparities are present in the system used that could lead to differences when such an IOL is ultimately tested in a clinical environment. The subjects were all tested in the presence of their natural crystalline lens. As a result, each subject would have a different level of wavelength-dependent light transmission. When an IOL replaces the natural lens, transmission variability between subjects would not be as significant. Additionally, in the simulator, light is lost due to reflections in the system. Another difference,

as was mentioned above, is the fact that correction of LCA outside the eye is more sensitive to misalignment due to the introduction of chromatic parallax. It should be noted though that due to the presence of a pupil camera and the diffractive rings on the phase plate the centration of the phase plate was well controlled during the visual performance measurements. Moreover, while in this experiment we corrected the complete LCA of the eye, when such a corrector would be implemented in an IOL, the target LCA to be induced should be that of a typical aphakic eye. On the other hand, the stimulus generator used to perform the visual experiments was a CRT monitor, with the effective spectrum being the superposition of the spectrums from the blue, green and red phosphors; that is, three broad peaks around 440 nm, 532 nm and 630 nm respectively [49].

5. Conclusions

We evaluated how spatial vision is affected after correcting spherical and longitudinal chromatic aberrations. In addition to the basic understanding of this problem, our motivation was to establish, under controlled laboratory conditions, the benefit of implementing these corrections in IOLs. An adaptive optics system combined with a diffractive chromatic corrector was used to simulate the different optical conditions.

Following the combined removal of SA and LCA, VA and CS improved in white light, relative to the normal case. This suggests that an IOL that corrects both SA and LCA by combining aspheric and diffractive elements may have the potential to provide an improvement in the quality of vision in pseudophakic patients. An additional advantage of the combined correction of these two aberrations is to preserve the visual benefit for a larger range of pupil diameters.

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