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Impact of longitudinal chromatic aberration on through-focus visual acuity

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Abstract: An enhanced adaptive optics visual simulator (AOVS) was used to study the impact of chromatic aberration on vision. In particular, through-focus visual acuity (VA) was measured in four subjects under three longitudinal chromatic aberration (LCA) conditions: natural LCA, compensated LCA and doubled LCA. Ray-tracing simulations using a chromatic eye model were also performed for a better understanding of experimental results. Simulations predicted the optical quality of the retinal images and VA by applying a semi-empirical formula. Experimental and ray tracing results showed a significant agreement in the natural LCA case ($R^2 = 0.92$). Modifying the LCA caused an impairment in the predictability of the results, with decreasing correlations between experiment and simulations (compensated LCA, $R^2 = 0.84$; doubled LCA, $R^2 = 0.59$). VA under modified LCA was systematically overestimated by the model around the best focus position. The results provided useful information on how LCA manipulation affects the depth of focus. Decreased capability of the model to predict VA in modified LCA conditions suggests that neural adaptation may play a role.

1. Introduction

The dispersion of the ocular media produces a significant amount of chromatic aberration in the eye [1]. Typically, chromatic aberration is divided into longitudinal chromatic aberration (LCA), and transverse chromatic aberration (TCA). LCA results in a wavelength-dependent change of refractive power [2], while TCA produces a wavelength-dependent change in the magnification of extended, or off-axis, images [3]. TCA has a high individual variability in the human eye [4], while LCA is usually considered to be similar among eyes. Difference between objective and subjective LCA was previously shown [5], with one study demonstrating a difference of up to 0.5 D within the visible spectrum [6]. In contrast, a more recent study has shown a difference of approximately 0.1 D between psychophysical and and objective LCA [7]. In this study we will use a model from Atchison and Smith [8] for a comparison and modeling. Some studies have also suggested that LCA is age-dependent [9], although the change in its amplitude is insignificant. It has been also shown that LCA affects accommodation [10,11].

The correction of the LCA in the eye has been previously accomplished in a number of studies [1,12–16], with some using intra-ocular lenses (IOLs) as correctors [17,18]. The visual benefit associated with the correction of the ocular LCA significantly varies across different studies. Some studies have shown an increase in visual acuity and contrast sensitivity when LCA was eliminated [14,16]. However, there are a few additional factors to be considered. In both cases, a significant difference in visual performance was achieved only when monochromatic aberrations were corrected in addition to the LCA, either low-order and full wavefront [14], or only spherical aberration [16]. Additionally, in the study by Yoon and Williams, LCA was eliminated by selecting a narrow band of the spectrum using an interference filter. An achromatizing lens

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was used in that study during preliminary experiments, but a smaller benefit was achieved [14]. However, from a point of view of perception, it is important to distinguish between the elimination of LCA by a narrow band-pass filter and the correction of LCA in polychromatic light.

A number of studies did not show a significant improvement in visual performance when LCA was compensated either by achromatic lenses [12,19–21], or a diffractive phase plate [15]. In these cases, the lack of expected improvement can be attributed to imperfect correction methods. Aside from possible optical aberrations introduced by imperfections of the lenses, their alignment is very critical, as any deviations would introduce extra TCA [13,22]. The question remains, whether the lack of visual improvement is due to the methodology of the experiments or due to possible neural factors.

In this context, exploring the effect of correcting (or in general manipulating) ocular LCA on through-focus visual performance would allow to shed some light on LCA's impact on vision. There were studies about the influence of LCA correction on the optical quality through depth of focus when combined with IOLs [17,18], with one showing that there is a certain relation between modified LCA and spherical aberration [18]. However, those studies ignored the visual responses, which might play a role for LCA. It can be noted that under normal conditions, subjects do not complain about color halos or other chromatic effects, despite the LCA spanning 2 D across visible spectrum [20]. There must be an adaptation or a filtering mechanism ameliorating the polychromatic retinal images. This problem may also be of practical interest since a total or partial correction of the LCA can be incorporated in IOLs. In this scenario, the manipulation of LCA could eventually serve to expand depth of field, which is of importance for the presbyopic eye.

In this study, an adaptive optics visual simulator (AOVS) [23] was used to measure VA through-focus under modified chromatic conditions. AOVS has proved to be a useful tool to study vision under controlled optical conditions. For example, AOVSs have been used to study the visual effect of correcting monochromatic aberrations [24–32], or the impairment on vision produced by individual aberrations [33–35], as well as correcting LCA [15,16]. AOVSs have also allowed to evaluate the ability of the visual system to adapt to monochromatic aberrations [36–39].

Previous measurements with LCA compensation in the eye employed achromatizing lenses [12,15,21], diffractive phase elements [16], or a multi-channel approach for each wavelength [7]. The AOVS used in this work [23] employs a recently reported method to control LCA [40]. For the experiment, three different LCA conditions were considered: natural LCA (1.2 D of chromatic shift for the given spectrum), compensated LCA (0 D of chromatic shift), and doubled LCA (2.4 D of chromatic shift). Ray-tracing simulations were also performed for modeling the impact of the chromatic conditions on VA [41], and for a comparison with the experimental results.

2. Methods

2.1. Experimental setup

The instrument and its calibration have been described in detail elsewhere [23]. The experimental setup is depicted in Fig. 1. It is an adaptive optics visual simulator which incorporated an electrically tunable lens (TL), (Optotune EL-16-40-TC-VIS-20D, Optotune Switzerland AG, Dietikon, Switzerland) and a liquid crystal on silicon spatial light modulator (LCoS-SLM), (PLUTO-VIS-014, Holoeye Photonics AG, Berlin, Germany).

Visual stimuli were presented by a digital light processing (DLP) projector (DLPDLCR4710 EVM-G2, Texas Instruments, Texas, USA) with a micromirror array with a resolution of 1920 x 1080. The device emitted a luminous flux up to 600 lm at a refresh rate of 60 Hz. Three light-emitting diodes (LEDs), corresponding to RGB channels, illuminated the micromirrors. The projector allowed to manipulate the emitted spectrum by controlling each RGB channel

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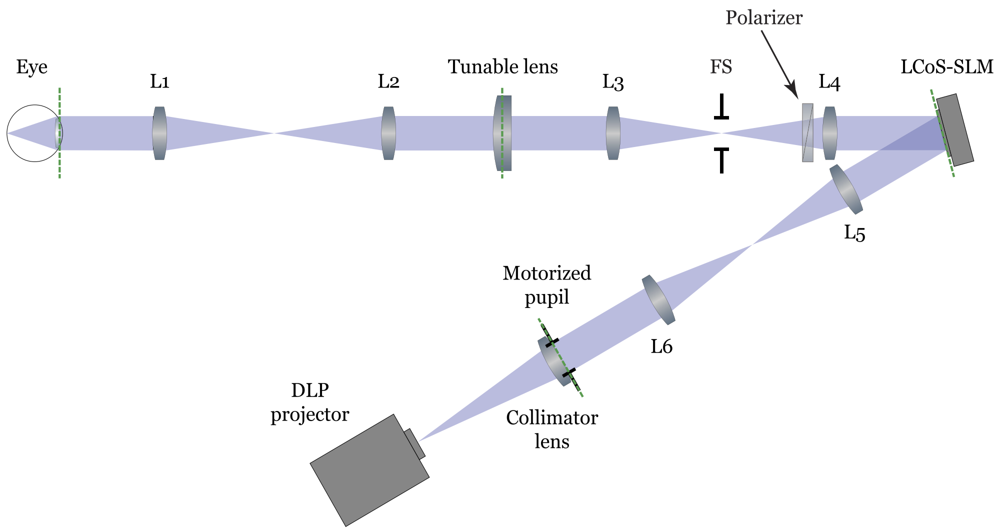

Fig. 1. Schematic of the AOVS system. Lenses L1 to L6 – achromats with focal lengths of 100 mm. Planes conjugated to the entrance pupil of the system are shown with a green dotted line. Further explanation is given in text.

individually. An achromatic doublet with a focal length of 200 mm was used for setting the stimuli at an infinite distance. Motorized diaphragm (8MID8.2-0.8-N, Standa Ltd, Vilnius, Lithuania) placed next to the collimating lens acted as the entrance pupil of the system. The pupil diameter was set to 4.5 mm during the experiment.

A telescope (L5 and L6 in Fig. 1) conjugated the entrance pupil onto the LCoS-SLM plane. The modulator's resolution was 1920 x 1080, with a pixel pitch of 8 μm, and a fill factor of 93%. The LCoS-SLM was calibrated and linearized for 543 nm wavelength [42]. A second telescope (L3 and L4 in Fig. 1) relayed the modulator's plane onto the TL plane. A field stop placed between lenses L3 and L4 limited the field to 3.1 x 1.7 degrees while filtering out parasitic diffraction orders produced by the discrete pixel structure of the LCoS-SLM. Defocus modulation range of the TL was -12 D to 10 D. A third telescope (formed by L1 and L2 in Fig. 1) relayed the conjugated plane to the pupil of the subject. The control software of the system was developed in the laboratory using C++.

2.2. Control of the chromatic aberration and white light generation

The phase modulator was used to control the chromatic aberration experienced by an observer looking through the simulator. The effective chromatic aberration was the combination of the one generated by the system and that from the observer's eye [8]. The method to manipulate the chromatic aberration by using an LCoS-SLM was described in a previous work [40]. Briefly, the method takes advantage of 2π phase wrapping on the LC-SLM when modulating defocus. The wrapped profile is equivalent to a continuous one only for the design wavelength, while other wavelengths result in a multi-focal lens, with most of the energy being in the first diffraction order for the visible spectrum. The optical power of the first diffraction order is proportional to the used wavelength. Thus, when LCoS-SLM is illuminated with polychromatic light, in addition to the modulated defocus, a linear dispersion is produced, which is then used to manipulate the LCA perceived by the eye.

The defocus introduced by the diffractive lens for the design wavelength was then compensated by the TL, which exhibited a neglectable chromatic dispersion. The manufacturer has specified an Abbe number of 108.49 for the fluid within the TL. As an example of its chromatic aberration, a programmed defocus of 3.4 D generated a chromatic shift of 0.035 D across the visible range. In the experiment, the visible spectrum was constrained to the range of 450 to 630 nm [43]. Three chromatic conditions were tested: natural LCA of the eye (1.2 D of chromatic shift on the observer's retina for the selected spectrum [8]), compensated LCA (all wavelengths focused on the observer's retina), and doubled LCA (chromatic shift of 2.4 D).

The spectral irradiance of the stimuli was manipulated in order to produce a flatter illuminance curve on the observer's retina. The red and blue channels in the DLP projector were raised by a factor of two compared to the green one, which resulted in a white stimulus with a slight magenta tint. Illuminance at the eye's entrance pupil was maintained at 100 cd/m^2. The normalized spectral illuminance, depicted in Fig. 2, was estimated by Eq. (1):

$$E(\lambda) = L_n(\lambda) \cdot T_n(\lambda) \cdot S_n(\lambda), \tag{1}$$

where $L_n(\lambda)$ is normalized spectral irradiance of the source, $T_n(\lambda)$ is the normalized ocular transmittance [44], and $S_n(\lambda)$ is the photopic spectral sensitivity of the eye [43].

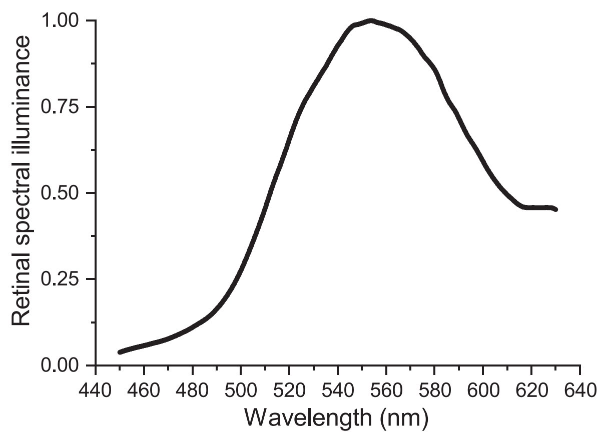

Fig. 2. Retinal spectral illuminance estimated for the experiment

As the precise control of LCA depended on the phase profile introduced by the LCoS-SLM, astigmatism and high order aberrations of participating subjects were left uncorrected. Defocus was always controlled by the TL.

2.3. *Subjects and characterization of visual quality*

Four adults (26, 42, 45, and 44 years old) with normal vision participated in the measurements. All of them were experienced subjects in visual testing. The mean spherical refractive error for the group was −0.3 ± 1.67 D (mean ± SD), and the average astigmatism was −0.5 ± 0.12 D, where the standard deviation was taken as the uncertainty range on both cases. Cycloplegics were instilled in the right eye to paralyze accommodation. The subjects were informed about the purpose of the experiment, following the tenets of the Declaration of Helsinki. Once aligned at the exit pupil of the instrument, the subjects were stabilized to the system by their dental impression.

For each condition, before the testing, subjects found their best subjective focus position by changing the TL's defocus. A black Maltese cross subtending 1 degree and surrounded by concentric circles on a white background served as the monocular focusing target.

Visual acuity (VA) was estimated by using the Freiburg test [45]. An E letter of variable size was displayed on the DLP for 4 orientations. Each VA value was calculated from the results

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obtained from 90 trials. Each trial corresponded to a given orientation and size of the E letter. The participants used a keyboard to indicate the orientation of the letter while looking through the system. The responses of the subjects were fitted to a Boltzmann sigmoid function, with the VA threshold set at 75% of correct answers.

2.4. Eye modeling and theoretical estimation of the visual acuity

A chromatic eye was modeled in ray-tracing software (Zemax, LLC, Washington, USA) for studying the effects of LCA manipulation through-focus on the retinal images. The eye model was based on a previous work [17], with geometrical parameters optimized to produce diffraction-limited images on the fovea at the 550 nm wavelength. Polychromatic light was modeled to follow the curve in Fig. 2 by weighting individual wavelengths. The eye model provided realistic LCA on-axis. The geometrical parameters of the eye model are shown in the Table 1. A pupil diameter of 4.5 mm was used in the simulations, mimicking the experimental conditions.

Table 1. Parameters of eye model. Unit for radius, thickness and semi-diameter is mm.

Surface	Radius	Thickness	Refractive index	Abbe number	Semi-diameter	Conic constant
Anterior cornea	7.77	0.55	1.3766	55.7029	5	−0.708
Posterior cornea	6.4	3.16	1.3375	50.6963	5	−0.6
Iris	Infinity	—	—	—	2.25	—
Anterior lens	10.2	4	1.4201	50.7824	5	−3.132
Posterior lens	−6	16.503	1.3361	53.5626	5	−1
Retina	−12	—	—	—	—	—

The Stiles-Crawford effect (SCE) of the first kind [46,47] was incorporated in the eye model, as it was shown that it might impact VA [48]. The SCE was modeled by applying a Gaussian apodization over the pupil of the eye model [49]. Eq. (2) shows the applied apodization factor A_G, provided that the maximum intensity η_{max} occurred at the center of the pupil:

$$A_G(x,\ y) = e^{-2} \cdot \eta_{edge}(x,\ y)/\eta_{max}, \tag{2}$$

where $\eta_{edge}(x,\ y)$ is the intensity at the edge of the pupil, derived from the SCE directionality parameter ρ.

The SCE ρ directionality parameter was 0.055 [50]. The different chromatic conditions of the experiment (natural, compensated and doubled LCA) were simulated by using 2 triplets, T_{comp} and T_{doub}, in front of the eye model. Those were specifically designed for modeling purposes. The parameters of the triplets are presented in the Table 2. The triplets were diffraction limited at 550 nm.

Table 2. Parameters of achromatizing triplets. Unit for radius, thickness and semi-diameter is mm.

Surface	Radius		Thickness	Refractive index	Abbe number	
	T_{comp}	T_{doub}			T_{comp}	T_{doub}
1	Infinity	Infinity	0.9	1.61	36.4	28.3
2	14.085	−14.085	5.2	1.61	57.0	39.2
3	−14.085	14.085	0.9	1.61	36.4	28.3
4	Infinity	Infinity	—	—	—	—

The retinal images retrieved from the eye model served to estimate VA as a function of the different chromatic conditions. For this purpose, a semiempirical formula was applied. The formula was devised in the context of through-focus VA using real data [41]. The mathematical expression is given in the Eq. (3):

$$VA_{dec}(wMTFa) = 10^{-(a \cdot wMTFa^{b}+c)}, \tag{3}$$

where VA_{dec} is decimal VA, and the semiempirical parameters: $a = 1.9793$, $b = -0.8$, $c = -0.18$ were estimated from real data obtained in 243 subjects.

The function *wMTFa* stands for the weighted modulation transfer function (MTF) area, in the form:

$$wMTFa = \sum_{f=1}^{150/d} \frac{d}{150} MTF(fd)CSF(fd), \tag{4}$$

where d is sampling size of the spatial frequency f, $MTF(fd)$ is the optical MTF, $CSF(fd)$ is the contrast sensitivity function (CSF) of the eye.

The CSF used here was taken from the work of Campbell and Green [51]. MTFs were estimated from the retinal images obtained in the eye model for the different chromatic and focusing conditions.

3. Results

3.1. Focusing on monochromatic stimulus under modified chromatic conditions

In the first experiment, subjects found their best focus under natural LCA, compensated LCA, and doubled LCA conditions at certain wavelengths. Interference filters of 10 nm bandwidth were incorporated in the system centered at 450, 550 and 630 nm. The purpose of these measurements was to assure that the method of LCA manipulation did not any introduce collateral effects (scattering, halos, diffraction ghosts, etc.) which might alter the ability to focus correctly.

The average results from the 4 subjects together with the standard deviation are presented in Fig. 3. In the figure, the theoretical focal shift for the visible range is also shown as solid lines for each chromatic case. These curves were estimated by combining a typical LCA [8] with chromatic shift generated by the phase modulator.

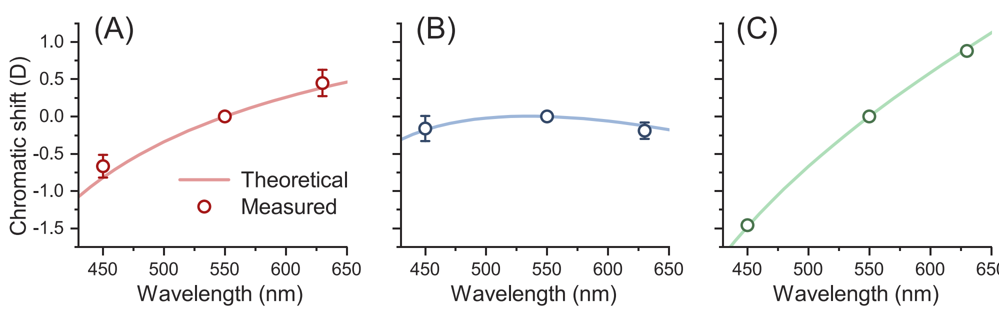

Fig. 3. Averaged chromatic shifts under monochromatic stimuli from the four subjects for chromatic conditions: Natural LCA (A); Compensated LCA (B); and Doubled LCA (C). Error bars represent standard deviation, omitted when too small for the figure scale.

The results were shifted in every case to place the chromatic shift at 0 D for the 550 nm wavelength. In some cases, the error bars are within the symbols.

3.2. Through-focus VA under modified chromatic conditions

VA in white light under the modified chromatic conditions was obtained for every subject. The through-focus range was from −1.5 to 1.5 D, around the best focus position obtained individually for every subject and condition. Through-focus VA was estimated in steps of 0.3 D, resulting in a total of 11 VA measurements for every chromatic condition.

The average results from the four subjects are shown in Fig. 4. Each point corresponds to the mean VA, the error bars are the standard deviations. The correction of the LCA did not produce an increase in the VA for the best focus (blue line) as compared to the natural case (red color), which remained the situation presenting the highest VA. The compensation of LCA sharpened the through-focus curve, indicating a higher sensitivity to variations in defocus. Doubling the LCA flattened the through-focus curve (green line), which reversely shows a decrease in the ability to discern across defocused stimuli.

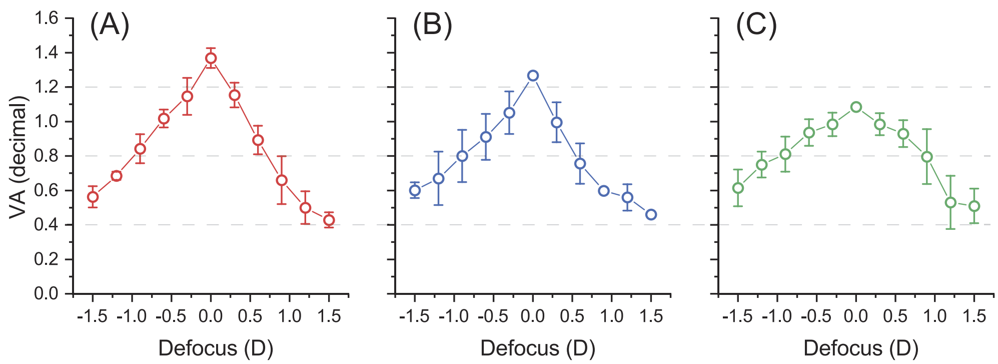

Fig. 4. Average through-focus VA from the four subjects for chromatic conditions: Natural LCA (A); Compensated LCA (B); and doubled LCA (C). The solid lines connecting experimental points were obtained from a cubic splines interpolation.

Maximum VA values were found to be: 1.37 ± 0.06 for natural LCA; 1.27 ± 0.02 for compensated LCA; and 1.08 ± 0.04 for doubled LCA. The depth of focus at VA of 0.8 was calculated from a cubic spline interpolation, with a value of 1.7 D for natural LCA, 1.44 D for compensated LCA, and 1.8 D for doubled LCA.

3.3. Through-focus optical and visual metrics

The experimental chromatic conditions were replicated for the eye model by modeling the triplet lenses. The same retinal illuminance was considered, and through-focus ray-tracing was done within the range of -1.5 to 1.5 D. The chromatic shifts from the ray tracing simulation are presented in Fig. 5.

The polychromatic point spread function (PSF) was retrieved for each chromatic condition. The associated MTF was obtained through Fourier transform. The area under the MTF within the range of spatial frequency relevant for the eye (from 0 to 150 cycles/mm) was calculated for each focus position and chromatic condition. The results are presented in panel A of Fig. 6. The MTF exhibited significant differences in both shape and amplitude depending on the chromatic condition. As expected, the maxima of the MTF areas were found at the best focus.

The area under the MTF was subsequently employed in the estimation of the VA using Eqs. (3)–(4). The results are presented in the right panel of Fig. 6. In all the cases the same CSF was used.

The increase in the area under the MTF is almost twofold when comparing compensated LCA to natural LCA. However, when converted into VA, the predicted benefit is only 3.2%. Conversely, doubling the LCA produced a reduction in the area of the MTF of 32% regarded the natural case. The reduction of predicted VA for this condition was only of 4.2%.

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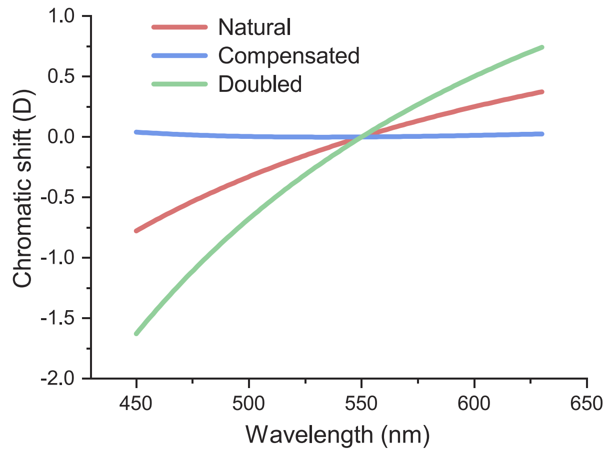

Fig. 5. Chromatic shift (D) at the retina calculated from the eye model for natural, compensated, and doubled LCA.

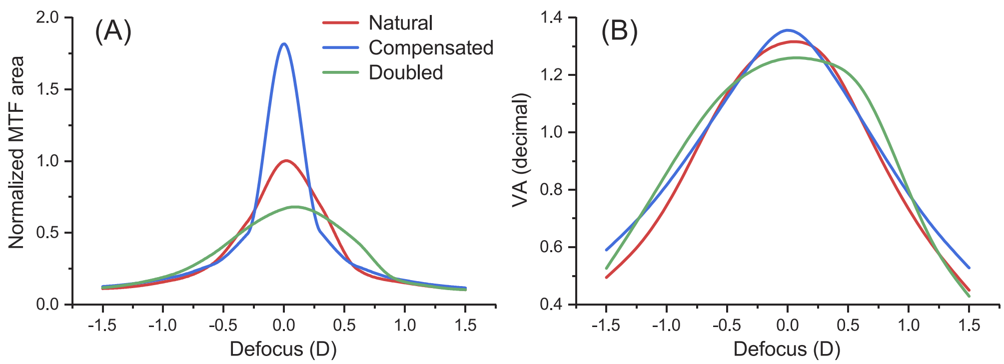

Fig. 6. (A) MTF area (normalized for the natural LCA) through-focus for natural (red line), compensated (blue line) and double (green line) LCA. (B) Theoretical estimation of the decimal VA associated with the conditions natural (red line), compensated (blue line), and double (green line) LCA.

4. Discussion

Modifying the chromatic conditions did not affect the ability to correctly focus on monochromatic stimuli. Despite individual variability, and possible depth of focus effects associated with the pupil of 4.5 mm, measured LCA curves followed the theoretical ones.

The compensation of the LCA did not produce an improvement of VA around the best focus position compared to the natural case under the experimental conditions, in a photopic regime with luminance of 100 cd/m^2. Through-focus VA curve for the corrected LCA exhibited a slight decrease compared to the natural case, though it was not statistically significant when the pairs of through-focus points were confronted. Doubling the LCA showed a clear impairment of the VA around the best focus position.

Previous studies on the visual effect of LCA compensation at best focus have shown contradictory results. To the best of our knowledge, we expanded this topic to through-focus vision. While some studies suggested that compensating of LCA provided an increase of VA [14,16], some others were inconclusive [15], and others presented no change of VA [12,19–21]. It is important to take into account that while the high-order aberrations (HOA) of subjects were low (young adults and 4.5 mm pupil size), leaving HOA uncorrected may diminish the visual effect of correcting LCA [52–54]. Previous studies which provided an increase of VA, did so (with a statistical significance) when aberrations of the eye were corrected in addition to LCA, in one case either low-order or full wavefront correction [14], in other – correction of spherical aberration [16]. Although the LCA itself has been shown to be almost independent of HOA [6,7], effects of its correction seem to be dependent on the optical quality. The root mean square error of the wavefronts of subjects was 0.21 ± 0.05 μm (mean ± SD). This was a limitation of our experimental setup, as the HOA had to be left uncorrected in order to not interfere with the chromatic modulation by the LCoS-SLM. An additional phase modulator should be incorporated to account for HOA. Similarly, astigmatism was not corrected, although subjects exhibited small values.

When considering mesopic or scotopic vision, the effect of LCA modulation may be different, so future works might explore other luminance conditions. It was noted earlier [55] that the chromatic axis and its location regarding the pupil may affect the visual performance significantly. However, when the achromatic axis position was measured for the 4 subjects, the displacement between the center of the pupil and chromatic axis was below 0.2 mm, and it did not produce different VA values.

Theoretical modeling was done to better understand the impact of the different chromatic conditions on the optical and visual performance. The chromatic conditions were simulated in the eye model [17]. The model and the semiempirical formula for transitioning from optical quality to visual performance permitted theoretically to attain an estimation of the expected VA. The model included SCE of the first kind. As the directionality parameter of the SCE depends on the wavelength, a value of ρ equal to 0.075 [56] was tested as well. The MTF areas for two different directionalities were compared, and the maximum difference was below 0.2%. Due to this, for further ray-tracing simulations, the directionality parameter was assumed to be independent of wavelength, similar to other studies [48].

The results of the simulations and the experimental VA are shown together in Fig. 7. Experimental and simulation results were correlated. Natural LCA case produced R^2 of 0.92; compensated LCA – R^2 of 0.84; doubled LCA – R^2 of 0.59. The semiempirical formula for VA estimation through-focus predicted the experimental results with distinct success depending on the chromatic condition. When considering modified chromatic conditions, the VA prediction declined, especially for the doubled LCA case. This method to estimate VA was proved to be reliable in a larger population, and natural chromatic aberration [41]. The factor to be tuned for matching the experimental results in the model is the CSF. Different CSF should be applied to the formula for different chromatic conditions. Nevertheless, obtaining the precise CSF sampled at a significant number of frequencies involves a massive set of experimental data, for the CSF must be estimated for every chromatic condition.

Experimental limitations of the LCA correction method have to be considered. The method of controlling the LCA using diffractive phase masks was previously proved to be working correctly [40], and validated again in this study, when used in an AOVS, both objectively and subjectively. The limitation of the method comes from the diffractive nature of the masks used for LCA control. For any wavelength different from the one used for calculating the phase masks, multiple diffractive orders occur, splitting the energy between them, thus reducing the contrast. Due to this factor, it was decided to not use any CS testing for this study. However, for VA testing, a moderate contrast drop does not affect the VA values [57]. The contrast drop was measured for the case of compensated LCA using a camera in an intermediate image plane. For a tumbling E letter corresponding to VA of 1 acting as a stimulus, the drop in contrast equaled 8%, down from 98% to 90% in polychromatic light. VA at contrast of 90% would be indistinguishable from VA at contrast of 98% [57]. As an extra subjective test, VA for one of the subjects was measured using a 450 nm (which is the wavelength with worst performance, as at this wavelength

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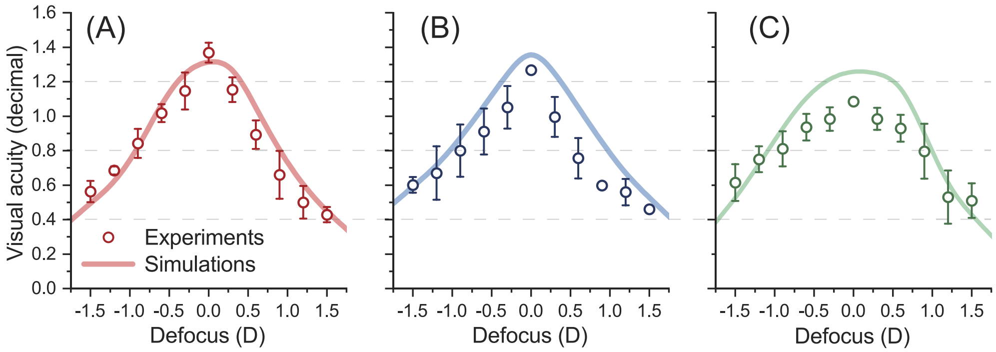

Fig. 7. Visual acuity from simulations and experimental measurements. (A) natural LCA; (B) compensated LCA; (C) doubled LCA. Error bars represent standard deviation

the energy of the first diffractive order is the lowest – at 70%, resulting in the lowest contrast) interference filter for two conditions: with the phase mask corresponding to compensated LCA (case 1), and with no modulation of LCA (case 2), leaving LCoS-SLM free. This way the negative influence of parasitic diffractive orders was isolated from the chromatic state. VA in case 1 was 1.33 ± 0.12, while in case 2 it was 1.31 ± 0.17. This result suggests that the observed difference in the VA curves is due to the chromatic modulation and not due to the limitations of the method. Compared to the previously described methods [1,12–16], the LCA modulation is done in a pupil-conjugated plane, which prevents possible misalignment issues. A method dividing the spectrum into separate wavelengths, each with its own path [7] may be superior, although significantly more complex, but it has yet to be implemented in a visual simulator.

Ideally, the correction of LCA, based solely on optical metrics, should have produced an increase of the visual quality at best focus, as well as considerably change the depth of focus, as can be seen in panel A of Fig. 6. When the optical quality is weighted by the standard CSF [19], the difference between the conditions becomes less severe. Given that the limitations of the method used in this paper were proven to be insignificant for vision, it suggests that the difference is due to a change in neural part of the CSF, which is yet to be characterized in future experiments.

5. Conclusions

VA exhibits a robust response under modified chromatic conditions. The degradation of the retinal image induced by doubling the LCA did not manifest into a proportional impairment of VA and depth of focus. This might simplify ophthalmic design, relaxing the LCA constraints. On the other hand, correcting the LCA did not improve VA, under the photopic conditions of the experiment. Through-focus response was not raised by correcting LCA either. Doubling the LCA might not be an effective way to extend the depth of focus for ophthalmic solutions (under photopic conditions). In general, when manipulating the LCA for modifying the depth of focus, possible neural factors should be considered. The expected benefit might arise when luminous flux is compromised, under mesopic or scotopic conditions. The change in CSF might explain these results, leading to possible neural and, perhaps, adaptation effects. Those could be responsible for the lack of visual benefit when correcting LCA. Further studies including long periods of exposure to modified chromatic conditions can help to solve the question.

The comparison between predicted and obtained VA suggested that a certain neural tuning mechanism associated with the chromatic condition might exist. This idea is in line with some facts associated with color perception. It is well known that the neural system affects the perception of light of a certain chromatic state. For example, it has a significant effect on

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accommodation [10,11,58,59] and color perception [60]. It has also been shown that the human eye can adapt to sinusoidal gratings of certain colors [61]. Accordingly, the neural aspects of chromatic vision should be taken into account. Considering the ability of the visual system to adapt to monochromatic aberrations [36] and to color gratings [61], there might be a possibility it can also adapt to different LCA conditions.

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