Research Article | Vol. 28, No. 25 / 7 December 2020 / Optics Express 37450

Optics EXPRESS

# Adaptation to the eye's chromatic aberration measured with an adaptive optics visual simulator

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**Abstract:** Some aspects of vision after correcting the longitudinal chromatic aberration (LCA) of the eye are not yet completely understood. For instance, correcting the LCA notably alters the through focus visual acuity (VA) curve, but it does not improve the best VA obtained for the natural case. In this work, vision with corrected LCA is further investigated by using an adaptive optics visual simulator (AOVS). VA was measured continuously during 20 minutes in 5 subjects under both natural and corrected LCA conditions to explore possible adaptation effects. Low contrast VA as a function of time exhibited a consistent and significant boost of 0.19 in decimal scale after an average time of 10.9 minutes of continuous testing. For high contrast, only one subject showed a similar increase in VA. These results suggest that some LCA neural adaptation may exist, particularly for low contrast. This adaptation impacts the performance of vision under corrected LCA, and possibly prevents measurement for immediate visual benefit. The results have practical implications for the design and visual testing of optical aids, especially those correcting, or altering, the LCA.



## 1. Introduction

The human eye exhibits a significant chromatic aberration due to the dispersion of the ocular media [1,2]. Typically, the chromatic aberration is separated in two components for its study and characterization: the transverse chromatic aberration (TCA); and the longitudinal chromatic aberration (LCA). The former manifests in a change of magnification over the extended image as a function of wavelength. The LCA produces a shift in the focal plane depending on the wavelength. The TCA shows significant individual variations in the human eye [3,4]. Conversely, the LCA is usually taken as a predictable function [5,6], barely changing with age [7]. This is advantageous for the eventual correction of LCA in the eye, which has been explored in several studies [5,8–18]. Interestingly, the visual benefit associated with the correction of the ocular LCA significantly varies across different works. Some studies have shown an increase in visual acuity (VA) and contrast sensitivity when LCA was compensated [13,16,17,19]. In some of these studies, a significant difference in visual performance was achieved only when monochromatic aberrations were corrected in addition to the LCA, either low-order or full wavefront [13], or only spherical aberration [17]. In some cases, the visual performance under LCA correction was experimentally tested by using monochromatic illumination [13], which should be taken with caution from a point of view of perception. On the other hand, some studies have even found no clear benefits from correcting LCA [5,11,20–22]. In this context, we investigated in a previous work the performance of vision under different chromatic conditions with an adaptive optics visual simulator (AOVS) endowed with enhanced capabilities [22]. In particular, the

#404296 https://doi.org/10.1364/OE.404296
Journal © 2020 Received 30 Jul 2020; revised 12 Nov 2020; accepted 14 Nov 2020; published 30 Nov 2020

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natural through focus VA was confronted with the cases of vision with LCA correction, and twice the normal LCA. Theoretical simulations were also conducted to understand the experimental results. It was obtained that simulations predicted the results in the natural case with high accuracy. Nevertheless, when the LCA was modified, either corrected or doubled, the validity of the simulations declined. This fact suggested that some extra neural, or perceptual, phenomena must be accounted to complete the puzzle of vision through different LCA conditions. Another intriguing result was that once the LCA was modified, including the case of correction, the VA did not exceed the VA obtained under natural vision. In the aforementioned work, this result could not be attributed to a shift in the best focus position, for the VA was obtained through focus. Consequently, any displacement in the VA peak within the range would have been detected, which was not the case in the any of the subjects.

Some works have proposed physiological and optical mechanisms for the compensation of the LCA [23,24], so that its negative impact on vision is ameliorated. An interesting question is whether correcting the LCA might disturb such, or others, adaptation mechanisms in a way that it could eventually mask the potential benefits, even producing the reversal effects in some cases. That could explain to a certain extent some of the paradoxical results around the correction of LCA and its impact on visual performance. Whether any type of adaptation mechanism exists, it seems possible that after some time of vision under modified chromatic conditions, eventual adaptation processes could re-tune the visual system, perhaps improving it. Here we investigated these possible phenomena with the help of an AOVS capable to manipulate the LCA [22,25]. The VA was measured continuously for 20 min under natural and corrected LCA, for low and high contrast stimuli to explore possible adaptational changes.

## 2. Methods

A schematic diagram of the setup is presented in Fig. 1. The setup employed an electrically tunable lens (TL) (Optotune EL-16-40-TC-VIS-20D, Optotune Switzerland AG, Dietikon, Switzerland) for independent defocus control. A liquid crystal on silicon spatial light modulator (LCoS-SLM) (PLUTO-VIS-014, Holoeye Photonics AG, Berlin, Germany) was incorporated for phase modulation, and the subsequent chromatic aberration manipulation. Visual stimuli were displayed by a digital light processing (DLP) projector (DLPDLCR4710EVM-G2, Texas Instruments, Texas, USA), shown as DLP projector in Fig. 1. The spectral luminance of the projector was digitally controlled from the computer providing the stimuli. The shape of the emitted white light spectrum has been described elsewhere [22], covering the entire visible range.

An achromatic doublet (f' = 200 mm, collimator lens in Fig. 1) produced an image of the projector at infinite distance, with angular pixel size of 6 arc-seconds at the entrance pupil. A telescope composed of two achromatic doublets (L5 and L6, both f' = 100 mm) was used to optically conjugate the entrance pupil plane with the plane of the LCoS-SLM. A rectangular field stop placed in the intermediate image plane between lenses L3 and L4 (both f' = 100 mm) constrained the field of view to 3.1 by 1.7 degrees (horizontal and vertical direction, respectively). The telescope formed by lenses L3 and L4 conjugated the plane of the LCoS-SLM to the TL, which allowed for an LCoS-SLM-independent defocus manipulation. The TL allowed to correct subjects' equivalent sphere. A linear thin film polarizer exhibiting high acceptance angles of ±30° was placed in front of the lens L4 selecting horizontal polarized light. Other types of polarizers should be placed at a different location, assuring normal incidence. The polarizer assured that only the light that was phase-modulated by the LCoS-SLM would pass through to the eye. An additional telescope, consisting of lenses L1 and L2 (both f' = 100 mm), relayed the plane of the TL to the pupil's plane of the subject. The design and components of the system, using achromatic doublets, guaranteed a neglectable LCA when compared with the amplitude of the LCA of the human eye. The TL did not introduce a significant LCA either [22]. The fluid within the TL exhibited an Abbe number of 108.49, as specified by the manufacturer.

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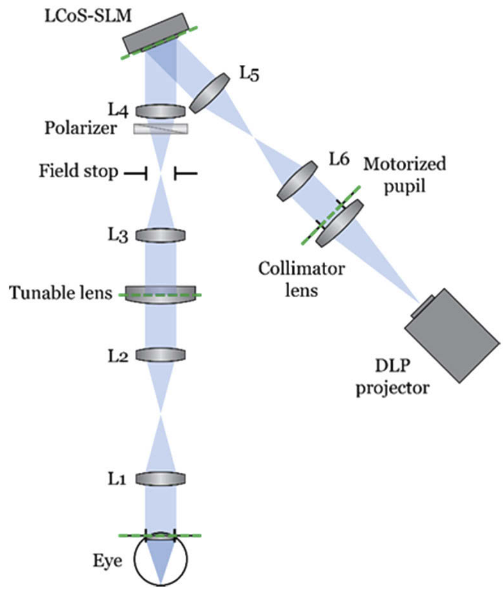


**Fig. 1.** Schematic of the experimental setup. Dashed green line shows the optically conjugated planes.

The manipulation of the LCA was accomplished by introducing defocus phase profiles on the LCoS-SLM as previously described [26]. Briefly, the method benefitted from the diffraction dispersion collateral to discrete phase wrapping under white light illumination in the SLM. When a defocus value is programmed on the SLM, the so-generated LCA is predictable by a model. The carrier defocus can be then accurately compensated by the TL, so that the requested LCA is introduced in the system. The phase mask used for the correction of ocular LCA was a diffractive lens of 3.4 D designed for a reference wavelength of 540 nm. This resulted in a chromatic shift of -1.2 D for the spectral range of 450 to 630 nm, compensating the average natural LCA of the eye. The TL was modulating -3.4 D of defocus to keep the image at 540 nm in focus.

Five subjects participated in the experiment, all of them nearly emmetropic healthy adults (mean refraction of -0.7 ± 1.3) and subclinical astigmatism below 0.65 D. The experimental protocol included paralyzing the accommodation of the subjects' right eyes. Subjects were stabilized to the system by using their dental impression mold. The centering of the eye's pupil was continuously monitored in real time during the measurements to prevent misalignments which could introduce additional chromatic effects. Best focus position was measured for every subject and condition for a Maltese cross, surrounded by 2 concentric rings, subtending 1'. VA was then obtained with E letters of variable size and 4 possible orientations presented on the projector for 0.3 s, using the Freiburg VA Test [27]. The VA estimate was obtained following 90 trials, distributed in 3 runs of 30 trials each. The average value from the 3 runs was adopted in every case. Each trial displayed certain size and orientation for the E letter. The subjects indicated the orientation by using a dedicated keyboard while they were watching the letter through the AOVS. The responses were later processed and fitted to a Boltzmann sigmoid function. The value of the VA can be directly retrieved from the Freiburg VA Test with similar performance. The detection threshold for VA was set to 75% of correct answers instead the more widely adopted value of 62.5%, corresponding to the middle point of the sigmoid. The impact of a superior threshold is just a shift in the final values of VA. The astigmatism was not corrected during the experiment.

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The subjects played 4 complete runs for high contrast VA estimation before the start of the series to be recorded. After that, 10 consecutive measurements of VA were obtained, each taking an average time of 1.88 ± 0.07 min (mean ± SD), corresponding to approximately 20 min for the full set of measurements. They were initially obtained for natural vision. Immediately after completing the measurements, a subsequent set of other 10 runs were taken under corrected LCA condition. The procedure was repeated for both high contrast and low contrast (10%) conditions.

## 3. Results

The results are summarized in Fig. 2, where the evolution of VA as a function of time is presented for different conditions. The top panels (A and B) present the low contrast VA. High contrast VA is shown in the bottom panels (C and D) of the figure. The left column corresponds to results under natural vision, while the right column shows the results obtained with corrected LCA. The individual VA evolution for every subject is presented with different color and shape. The average results are shown with larger black circles, that include the error bars accounting for the dispersion of the samples.

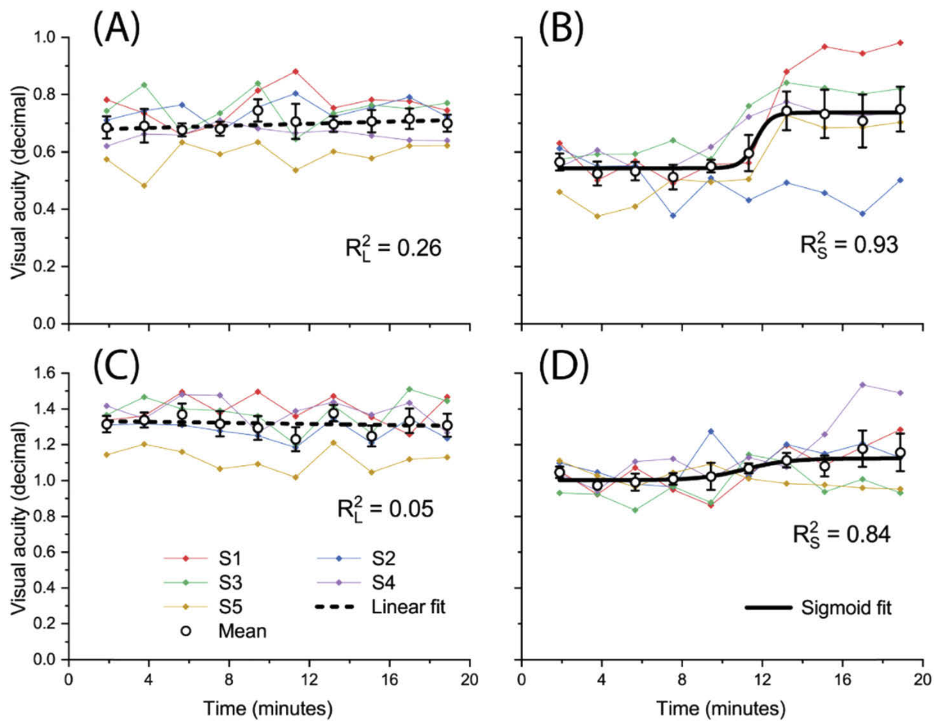


**Fig. 2.** Visual acuities (VA) measured continuously. Low contrast measurements are shown in the top row, with natural LCA (A) and corrected LCA (B). High contrast measurements are shown in the bottom row, with natural LCA (C) and corrected LCA (D). The vertical scale is different for each condition. Each VA measurement on average took 1.88 ± 0.07 (mean ± SD) minutes. The SD of X axis values is not shown on the graph for clarity. In natural LCA cases (A and C), a linear fit for the mean data is shown. In corrected LCA cases, a sigmoid fit for the mean data is shown. $R_L{}^2$ and $R_S{}^2$ show the fit quality for the linear and sigmoid fits, respectively.

For low contrast and natural vision results (A), a linear fit was first performed. The fitting produced for the average data a low correlation coefficient $R^2$ of 0.26, with a slope of 0.002, indicating lack of VA changes with time. The linear fitting in the case of LCA correction (B) produced an $R^2$ of 0.75. A similar analysis was performed for the set of data corresponding to high contrast (C and D). The linear fit of the mean VA values under natural vision and high contrast produced a low coefficient of correlation $R^2 = 0.005$, indicating that VA did not significantly evolved with time. A similar linear analysis for the case of LCA correction and high contrast (panel D) revealed a $R^2 = 0.74$, this time depicting certain evolution of VA with time.

Once identified the set of data presenting a statistically significant evolution, the curves underwent an additional fitting. A Boltzmann sigmoid function was fitted to every subject's data as well as to the average data. The fitting was accomplished by using the Levenberg Marquardt algorithm, setting all parameters free, as shown in Eq. (1):

$$y = A_1 + \frac{A_1 - A_2}{1 + \exp\left(\frac{x_0 - x}{\Delta}\right)}, \tag{1}$$

with $x$ as the independent variable, being $A_1$, $A_2$, $x_0$ and $\Delta$ the parameters to be estimated by the fitting. $A_1$ and $A_2$ correspond to the maximum and minimum value of the curve, respectively. The parameter $x_0$ is the mean point in the transition between $A_1$ and $A_2$, being the inflexion point of the curve. Finally, $\Delta$ is the slope of the transition between asymptotic the values $A_1$ and $A_2$.

A summary of the results estimated from the curve fittings are shown in the Tables 1 and 2. VA is expressed in decimal units, while time parameters are expressed in minutes. VA gain was defined as the difference between the horizontal asymptotes of the sigmoid ($A_1$ - $A_2$). Latency was calculated as the time from the origin up to the beginning of the sigmoid's slope. Adaptation time, AT in the tables, was obtained as the projection of the curve between $A_1$ and $A_2$ on the time axis. The average or mean results in both the curves and the tables were obtained averaging first the experimental points corresponding to the VA values.

**Table 1. Responses to corrected LCA in low contrast**

| Subject | Gain | AT | Latency | $R^2$ |
|---|---|---|---|---|
| S1 | 0.41 | 1.56 | 11.89 | 0.966 |
| S2 | — | — | — | 0.417 |
| S3 | 0.23 | 0.62 | 11.09 | 0.971 |
| S4 | 0.18 | 2.28 | 8.79 | 0.944 |
| S5 | 0.25 | 0.64 | 11.23 | 0.912 |
| Mean | 0.19 | 1.48 | 10.93 | 0.931 |

**Table 2. Responses to corrected LCA in high contrast**

| Subject | Gain | AT | Latency | $R^2$ |
|---|---|---|---|---|
| S1 | — | — | — | 0.637 |
| S2 | — | — | — | 0.491 |
| S3 | — | — | — | 0.412 |
| S4 | 0.45 | 0.37 | 14.83 | 0.920 |
| S5 | — | — | — | 0.408 |
| Mean | 0.17 | 8.82 | 8.53 | 0.846 |

The sigmoid function fitted to the mean and individual data for LCA correction in low contrast produced significant correlation coefficients for the fitting in most of the subjects: S1, S3, S4 and S5 showed correlations coefficients above 0.91. Only S2 did not show sigmoidal evolution. The average data resulted in a $R^2 = 0.93$.

The mean VA gain was $0.21 \pm 0.13$ decimal (mean ± standard deviation), with adaptation time of $1.27 \pm 0.7$ minutes and with a delay of $10.75 \pm 1.17$ minutes.

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Average VA with natural LCA in low contrast was 0.67 (decimal scale). The correction of LCA caused an initial drop of VA to 0.54. After approximately 10 minutes of continuous vision under LCA correction, VA increased to 0.73, surpassing the initial value measured in the natural LCA case.

The analysis of the fits under LCA correction in high contrast in the Tab. 2 shows that the tendency of the average values in this case was heavily skewed by the response of subject S4. That subject was the only one showing a significant sigmoidal response according to the correlation coefficient $R^2$.

The VA increase under continuous vision with corrected LCA exhibited significant individual variations, as it has been described by the sigmoid curves. Subject S2 raised his VA in neither high nor low contrast conditions. On the contrary, subject S4 was the only one showing a clear boost in VA under both contrast conditions. Low contrast measurements showed four out of five subjects experiencing the raise of VA under LCA correction.

## 4. Discussion and conclusions

The higher prevalence of the VA evolution under low contrast conditions could be understood in terms of the higher sensitiveness to blur of the visual system. This fact has been shown before, for instance in the work of Johnson et al. [28], where VA was tested for different amounts of blur. Specifically, VA obtained with low contrast targets exhibited a faster decline with defocus in the range 0 to 2 D as compared with that measured with high contrast targets [28].

The perception of color is also known to change under different LCA conditions [29]. Adaption to sinusoidal gratings of certain colors has also been reported [30]. Studies on color perception could benefit from the new findings on adaptation by introducing the variable time in revisited or new experiments, allowing the subjects to repeat the task under modified LCA conditions looking for eventual evolution. Another visual function affected by the LCA is accommodation [31–33], which in view of the results obtained could be also exhibit certain changes when the subjects can look through modified LCA conditions for a sufficiently long lapse of time.

Changes in VA over time, in the direction of enhancing performance, have been reported in the context of perceptual learning [34–38]. The magnitude of our results, in terms of the amplitude of the enhancement, is comparable with the ranges found in other studies [39,40]. However perceptual learning requires of several sessions and training blocks, which were not programmed in the reported experiment. In some works, perceptual learning is demonstrated with reduced training time [41,42], only requiring several blocks of above 40 runs each. The presented experiment did not incorporate such a possibility, not even providing any kind of feedback from the response of the subject. In addition, one of the subjects (S3) underwent the experimental protocol 3 times within a time frame of 3 months, obtaining the same trend for the evolution of the VA curve at every run. Perceptual training produces a quite permanent effect once acquired, which remains relatively steady along time, contrary to what was found in subject S3. In addition, there were no changes in high contrast VA with time. Accordingly, we can conclude that the contribution of perceptual learning to the results is likely neglectable.

The reduced, or lack of, impact of the correction of LCA on vision has been found previously in other works and it has been explained from different perspectives. None has considered the possibility of adaptation, and a subsequent increase in the visual performance after some time. For instance, in the work of Howarth and Bradley the authors suggested a deficient estimation of the LCA as the cause of the lack of benefit on vision following its correction [5]. They hypothesized an over correction of the LCA to occur, therefore compromising the resulting visual performance. In the AOVS with capabilities for manipulating the LCA we have used [22], the subjects performed a best focus search task under monochromatic illumination, while the conditions of the LCA were altered. The results, summarized on the Fig. 3 of Suchkov et al. [22], showed that neither an ill estimation of the LCA nor a failure in the experimental apparatus

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performance were affecting the outcomes. Another reference tackling the problem of failing to enhance vision from the LCA correction is the work of Bradley et al. 1991 [11]. In this work, the authors suggested that the effective depth of field might be below the benefit of correcting chromatic aberration. They also discussed the effects of lateral color, which could be largely increased when achromatizing lenses are used in combination with the eye. The problem of concomitant lateral color induced by the chromatic correctors becomes important as the size of the image increases [21]. Conversely, for small objects and misalignments this circumstance barely affects. VA measures should not significantly contribute in our case. The nature of the task guarantees that the stimuli were always small and close to detection thresholds. The problem of centering is surpassed with the employed AOVS setup by using the phase diffraction dispersion method to generate chromatic aberration [22,26]. The absence of improvement in VA when the LCA is corrected has been also explained in terms of photometric reasons: when the polychromatic illumination is weighted with the spectral response of the retina the impact is low [20]. In the model developed in our previous study [22], the prediction of visual performance including these photometric considerations was capable to describe the results with fidelity for the natural case. The method showed a decreasing fidelity as manipulated LCA conditions were considered.

Within this context, we hypothesize that the new VA boosting effect can be related to certain visual adaptation to the LCA, in a similar way that adaptation occurs for monochromatic aberrations [43–47]. Previous existing literature shows controversial results on the visual benefits of the LCA correction. Our results introduce an additional factor to account for in future works: LCA adaptation. We have measured a raise of visual performance after some time of exposure to LCA correction in young subjects, particularly when performing under low contrast. The astigmatism was not corrected in this experiment due to its modest value and subclinical nature in all cases. It could be eventually the responsible for part of the variability found across subjects. It should be accounted in future works to expand the results to larger populations. We are convinced that these results are relevant for a better understanding of the human vision, along with some practical applications. For instance, optical aids incorporating LCA correction as intraocular lenses [18,48] should be tested in protocols enabling the detection of benefits. Our experiment also opens new questions about the nature of the LCA adaptation, for instance about the temporal frame where the phenomenon manifests. The boost in VA for high contrast letters, only found in one of the subjects, might occur preferably for enlarged sessions, so longer periods of adaptation might be required. Another interesting question is whether the age can be a factor for this adaptation effect, as well as the refraction. These and other questions can be explored in the future with the new generation of AOVS capable of LCA manipulation together with visual testing [49].

## Funding

Agencia Estatal de Investigación (PID2019-105684RB-I00); Fundación Séneca (19897/GERM/15, 20513/PDC/18); H2020 Marie Skłodowska-Curie Actions (675137).

## Disclosures

Two of the authors (EJF & PA) holds patents on adaptive optics visual simulators.

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