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# Measuring and compensating for ocular longitudinal chromatic aberration: supplementary material

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**This document provides supplementary information to "Measuring and compensating for ocular longitudinal chromatic aberration," https://doi.org/10.1364/OPTICA.6.000981. We describe the method to assess the sensitivity of the objective LCA measurement from an adaptive optics scanning laser ophthalmoscope. Next, we describe subjective and objective LCA estimation at 2.5° eccentricity with 470 nm wavelength.**

## 1. SENSITIVITY OF THE OBJECTIVE LCA MEASUREMENT

Given that the objective LCA measurements were estimated from focused foveal cone images, the depth of field (DOF) of imaging determined the sensitivity of this measurement. To assess the sensitivity of the objective LCA measurement, a set of through-focus foveal cone images were obtained at 543 nm imaging wavelength.

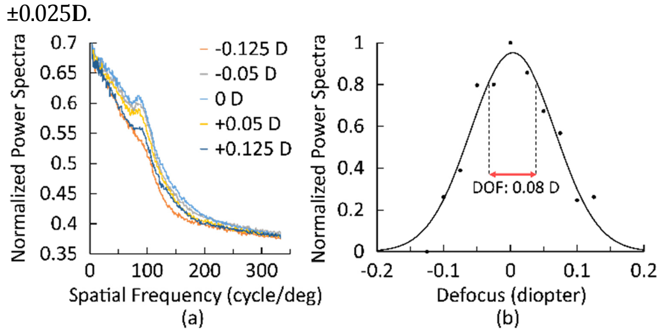
### A. EXPERIMENT PROTOCOL

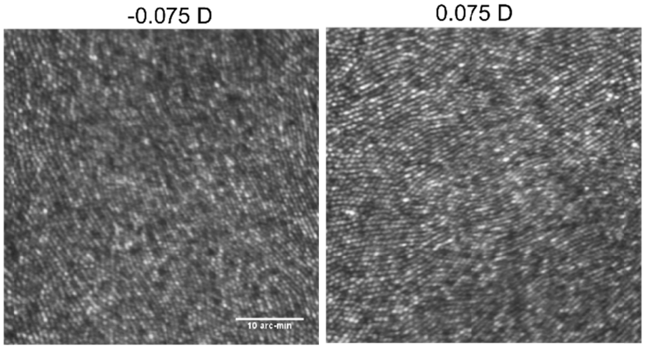
The filter-based Badal LCA compensator was first adjusted to find the best focused foveal cone image with the AO loop closed. Next, a set of through-focus images were obtained with the filter-based Badal LCA compensator's focus adjusted from -0.125 D to + 0.125 D in 0.025 D steps. Ten-second videos were recorded at each vergence position and were registered offline to provide higher fidelity images upon averaging. While quantifying and comparing sharpness across images is not trivial, we chose to proceed with computing the Fourier spectra to compare the through-focus images for its simplicity and physical significance. Power spectra were computed from the images by a Fast Fourier Transform (FFT) and radially averaged to obtain 1-D power spectra. The radially averaged power spectrum at the peak spatial frequency corresponding to the best cone mosaic image was plotted as a function of defocus. The full width at 80% of the maximum value of a fitted Gaussian was used as the criteria to assess the depth of field and accordingly, the sensitivity of the objective LCA estimation.

### B. SENSITIVITY OF THE OBJECTIVE LCA MEASUREMENT

The 1-D power spectra for 5 (out of 11 total) through-focus images (-0.125 D to +0.125 D) are plotted in Fig.S1a. From these power spectra, the peak corresponding to the cone mosaic is plotted as a function of defocus (black dots) and fitted into a Gaussian curve (black solid line) in Fig.S1b after normalization. The peak of the image quality metric at 0 D is consistent with the best-focused image while a fall-off in image quality with increasing defocus is expected. An implicit assumption here is that the depth of field thus calculated follows a symmetric fall-off defined by a Gaussian. However, this does not account for asymmetries in the amount of light scattered from different retinal depths. A metric of spatial frequency content in the image as the one we employed though remains relatively immune to such intensity variations.

The theoretical axial resolution with a 1.8 Airy disk diameter was estimated to be about ~0.18[1] when using the FWHM of the axial intensity profile. The images at -0.075 and 0.075 D (0.15D in total) were obviously blurred when inspected visually (Fig.S1c). Here we used a criterion of 80% of the peak value in Fig.S1b to estimate the depth of field[2] The depth of field thus obtained was 0.08 D (±0.04D). Upon visual inspection, trained experimental operators can at times pick out subtle image quality degradations caused by as little as ±0.025D.






(c)

**Fig.S1.** (a) Normalized 1-D radial averaged power spectra for 5 through-focus images; (b) Normalized power spectra at the corresponding peak in (a) as a function of the defocus are plotted and fitted with a Gaussian curve. The full width at 80% of the maximum height of the Gaussian fit yielded a DOF of 0.08 D (±0.04D); (c) Images obtained at ±0.075 D on either side of best focus indicating an obvious blurred appearance necessitating a stricter criteria for depth of field. All images are taken with 543 nm wavelength and 0.8° FOV.

## 2. COMPARING OBJECTIVE AND SUBJECTIVE LCA MEASURES AT 470nm

In the main article, we report the comparison of subjective and objective estimates of foveal LCA using pyschophysics and AO retinal imaging of cone photoreceptors in the range between 520 - 640nm. High macular pigment density[3] creates a fundamental impediment in generating an estimate of foveal cone-image based objective LCA for wavelengths in the blue region of the spectrum with safe light levels at the cornea. Imaging at lower light levels in the fovea with blue light is possible, although only by sacrificing axial resolution and using a large confocal pinhole, preventing a sensitive measure of LCA. However, by 2.5 deg eccentricity, macular pigment density reduces to about 10% its value at the fovea. Furthermore, Rynders et al. [4] showed that LCA is nearly identical at these parafoveal eccentricities. Therefore, we sought to characterize the objective and subjective LCA between our shortest wavelength of 470nm with 543nm as reference via imaging and psychophysics respectively at 2.5deg.

### A. EXPERIMENT PROTOCOL

Three of the same subjects (S2, S3, and S4) from the main article were involved in this experiment. For objective assessment, through-focus retinal images at 2.5 deg. temporal eccentricity and 1.2 deg. field of view were obtained with AOSLO at 470nm and 543nm. For subjective assessment, due to poorer overall acuity at 2.5 deg., subjects found it difficult to reliably optimize focus and find their best image quality. Therefore, we measured through-focus tumbling 'E' visual acuity (30 trial QUEST staircase) with AO correction and picked the maximum acuity as the point of best subjective focus at both 470nm and 543nm. The acuity measurements were conducted in the AOSLO, using same hardware described in the main article.

### B. OBJECTIVE vs. SUBJECTIVE LCA MEASURES

Best-focus cone photoreceptors images from S3 obtained with 470 and 543nm wavelengths at 2.5° temporal eccentricity are shown in Fig.S2 as an example. Note the similar overlying vessel structure accentuated by strong absorption at these wavelengths.

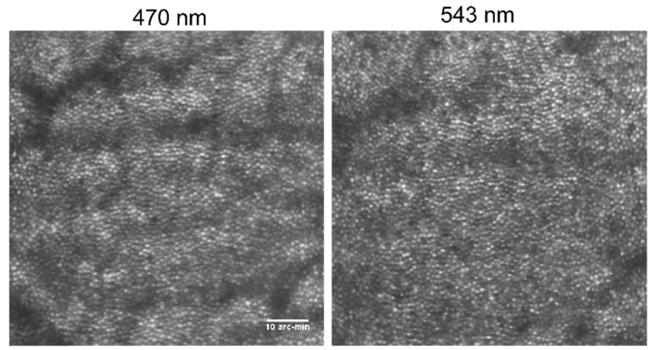



**Fig.S2**. Cone images at 2.5° temporal eccentricity obtained with 470 and 543nm wavelength illumination demonstrating sufficient cone structure to assess LCA objectively.

At this eccentricity, sufficient image fidelity and sensitivity is available to assess LCA objectively. At the same eccentricity, the mean AO-corrected best-focus visual acuity was 20/28 (1.4 arc-min) for both wavelengths, consistent with previous reports[5], indicating optimal correction of LCA for subjective assessment. The objective and subjective estimates of LCA measured at 2.5° T are compared in Table.S1. The average LCA across subjects of -0.59 ±0.09 D and -0.60±0.06 D for subjective and objective cases respectively was not significantly different. ($p$ = 0.32). Given the consistency in both, we conclude that the inferences drawn at the longer wavelengths (520-640nm) with regards to objective vs. subjective LCA remain the same at wavelengths as short as 470nm.

**Table.S1** LCA between 470 and 543 nm at 2.5° temporal eccentricity

| Subjects | Subjective LCA | Objective LCA |
|---|---|---|
| S2 | -0.60 D | -0.58 D |
| S3 | -0.49 D | -0.55 D |
| S4 | -0.67 D | -0.67 D |
| Average ± SD | -0.59 ± 0.09 D | -0.60 ± 0.06 D |

## References

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