Modeling Accommodation Control of the Human Eye: Chromatic Aberration and Color Opponency

Agostino Gibaldi, Steven A. Cholewiak, Martin S. Banks - University of California, Berkeley

Accommodation is the process by which the eye lens changes optical power to maintain a clear retinal image as the distance to the fixated object varies. Although luminance blur has long been considered the driving feature for accommodation, it is by definition *unsigned* (*i.e.*, there is no difference between the defocus of an object closer or farther than the focus distance). Nonetheless, the visual system initially accommodates in the correct direction, implying that it exploits a cue with sign information. Here, we present a model of accommodation control based on such a cue: *Longitudinal Chromatic Aberration* (LCA). The model relies on color-opponent units, much like those observed among retinal ganglion cells, to make the computation required to use LCA to drive accommodation.

Longitudinal Chromatic Aberration

Color vision derives from differential responses among three classes of cone photoreceptors; the different classes respond predominantly to long (red), medium (green), and short (blue) wavelengths. The eye's refracting elements have different refractive indices with respect to wavelength, producing chromatic aberration [7]. Short wavelengths are refracted more than long, so when a broadband image is "in focus", the blue and red images are focused in front of and behind the retina, respectively. Therefore, objects farther vs nearer than current focus create different chromatic effects in the retinal image (Fig. 1). LCA is used to determine if the eye is well focused and, if it is not, in which direction it should accommodate to restore sharp focus [5]. LCA also affects perceived depth [8]. However, it is not clear how the visual system implements this cue in accommodative control.

Color Opponency

While photoreception in the retina is trichromatic, the signals are subsequently transformed into color-opponency [6]. Color-opponent retinal ganglion cells signal Blue-Yellow (BY) differences and Red-Green (RG) differences (and of course luminance). Their receptive fields have a central area with positive/negative response to a color and a surround with the opposite response to another color (*e.g.* Fig. 1C). Such a unit is effectively modeled by Difference of Gaussian (DoG) receptive fields, where the *on* and *off* Gaussian kernels represent different color channels. These computational units provide a physiological response to wavelength changes.

Considering LCA, it is interesting for accommodative control to notice how RG channel has a stronger response when red wavelengths are sharp on retina, and besides BY channel has a stronger response when blue wavelengths are sharp.

The Accommodation Control Model

Similarly to vergence eye movements [2, 3], accommodation control is applied in closed-loop negative feedback that drives lens power. The model arranges the BY and RG color-opponent channels in a push−pull fashion, in order to balance their response. The control is obtained by:

$$AC = \alpha\left((E[BY^2] - E[BY]^2) - \gamma(E[RG^2] - E[RG]^2)\right)$$

where E is the expected value, γ balances the contribution of the two channels, and α acts as control gain. Given an initial defocus, the control gradually changes the lens power in a closed-loop that tends towards a steady-state where the control itself goes to zero (Fig. 1A). With such a configuration, the steady-state accommodative response has a similar amounts of defocus for short (positive defocus) and long (negative defocus) wavelengths, while medium wavelengths are in-focus.

The model has been implemented using receptive-field sizes of $0.5°$, $1.0°$ and $2.0°$, in multi-scale fashion. The relation between the *on* and *off* spatial envelopes is held constant at $1/4$. The model parameters have been tuned to resemble the behavior of human accommodation control.

Experimental Procedures

To test the model, we used a stimulus-generation method that incorporates the viewers optics, yielding retinal images close to those in natural viewing [1]. The generated retinal images simulate a fronto-parallel surface with a pink noise texture (Fig. 1A) and different magnitudes of defocus (Fig. 1B). These stimuli drive accommodation quite effectively [1]. We presented these stimuli to the accommodation control model and examined the temporal evolution and gain of the response (Fig. 1) to various magnitudes and signs of focus error.

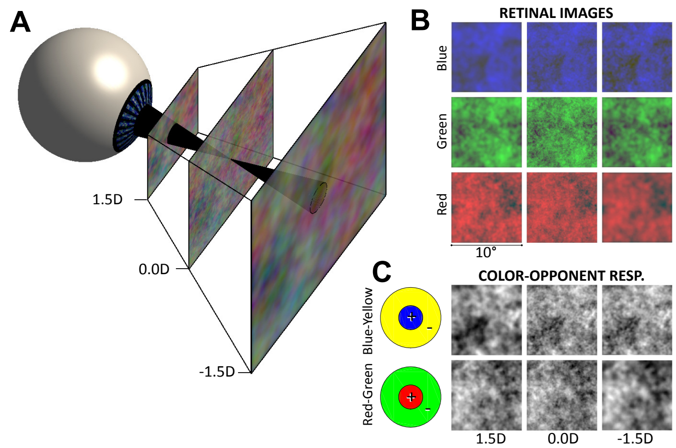

Figure 1: **A.** Longitudinal chromatic aberration (LCA), and **B.** the associated retinal images with positive, zero, and negative defocus, together with **C.** the Blue-Yellow and Red-Green color-opponent responses.

Results

The model's responses provides a control characterized by an odd-symmetry and a zero crossing at about zero diopters (Fig. 2B). These two characteristics ensure the control to effectively drive the accommodation of the lens to obtain a sharp retinal image. Interestingly, responses are slightly faster for positive than for negative accommodation, as is observed in humans [4]. Moreover, responses tend to undershoot the optimal value as is also observed in humans [4].

Conclusion

We implemented a biologically plausible model for accommodative control that is based on longitudinal chromatic aberrations instead of luminance blur. The model correctly yields the direction the lens should accommodate to restore sharp focus in a fashion that is qualitatively consistent with human accommodative behavior. Because the model is based on balancing blur at short and long wavelengths, it does not necessarily yield the sharpest retinal image. This behavior is actually consistent with human accommodation suggesting a primary role for chromatic aberration [1].

References

[1] S.A. Cholewiak, G.D. Love, and M.S. Banks. Rendering correct blur. In *Visual Sciences Society (VSS) Annual Meeting*, May 2017.

[2] A. Gibaldi, M. Chessa, A. Canessa, S.P. Sabatini, and F. Solari. A cortical model for binocular vergence control without explicit calculation of disparity. *Neurocomputing*, 73(7), 2010.

[3] A. Gibaldi, M. Vanegas, A. Canessa, and S.P. Sabatini. A portable bio-inspired architecture for efficient robotic vergence control. *International Journal of Computer Vision*, 2016.

[4] J.C. Kotulak and C.M. Schor. Temporal variations in accommodation during steady-state conditions. *JOSA A*, 3(2):223–227, 1986.

[5] P.B. Kruger, S. Nowbotsing, K.R. Aggarwala, and S. Mathews. Small amounts of chromatic aberration influence dynamic accommodation. *Optometry & Vision Science*, 72(9), 1995.

[6] R. Shapley and M.J. Hawken. Color in the cortex: single-and double-opponent cells. *Vision Research*, 51(7):701–717, 2011.

[7] L.N. Thibos, M. Ye, X. Zhang, and A. Bradley. The chromatic eye: a new reduced-eye model of ocular chromatic aberration in humans. *Applied Optics*, 31(19):3594–3600, 1992.

[8] M. Zannoli, G.D. Love, R. Narain, and M.S. Banks. Blur and the perception of depth at occlusions. *Journal of Vision*, 16(6):17–17, 2016.

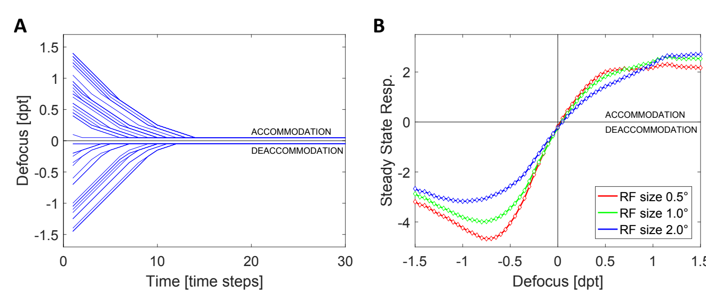

Figure 2: **A.** The temporal evolution of model's response, starting from different stating defocus values. **B.** The model's response with respect to defocus for different receptive-field sizes ($0.5°$, $1.0°$ and $2.0°$).