Published in final edited form as:

Optom Vis Sci. 2011 May ; 88(5): 593–600. doi:10.1097/OPX.0b013e3182112d99.

Accommodation to Wavefront Vergence and Chromatic Aberration

Yinan Wang, MD, MS, Philip B. Kruger, OD, PhD, FAAO, James S. Li, OD, Peter L. Lin, OD, and Lawrence R. Stark, BAppSc(Optom), PhD, FAAO

Vision Sciences, State University of New York, State College of Optometry, New York, New York (YW, PBK, JSL, PLL), and Southern California College of Optometry, Fullerton, California (LRS)

Abstract

Purpose—Longitudinal chromatic aberration (LCA) provides a cue to accommodation with small pupils. However, large pupils increase monochromatic aberrations, which may obscure chromatic blur. In the present study, we examined the effect of pupil size and LCA on accommodation.

Methods—Accommodation was recorded by infrared optometer while observers (nine normal trichromats) viewed a sinusoidally moving Maltese cross target in a Badal stimulus system. There were two illumination conditions: white (3000 K; 20 cd/m²) and monochromatic (550 nm with 10 nm bandwidth; 20 cd/m²) and two artificial pupil conditions (3 mm and 5.7 mm). Separately, static measurements of wavefront aberration were made with the eye accommodating to targets between 0 and 4 D (COAS, Wavefront Sciences).

Results—Large individual differences in accommodation to wavefront vergence and to LCA are a hallmark of accommodation. LCA continues to provide a signal at large pupil sizes despite higher levels of monochromatic aberrations.

Conclusions—Monochromatic aberrations may defend against chromatic blur at high spatial frequencies, but accommodation responds best to optical vergence and to LCA at 3 c/deg where blur from higher order aberrations is less.

Keywords

accommodation; blur; focus; longitudinal chromatic aberration; wavefront aberration

The conventional view of reflex (blur-driven) accommodation control is that luminance contrast of the retinal image provides an even-error stimulus without directional information. The eye accommodates to reduce myopic or hyperopic defocus blur and maximize luminance contrast of the retinal image, and in this systems control model, negative feedback from changes in luminance contrast is essential. Contrary to the conventional view, Fincham¹ proposed odd-error signed stimuli for accommodation including an achromatic signal from wavefront vergence extracted by the Stiles–Crawford effect and a chromatic signal from the effect of longitudinal chromatic aberration (LCA).

At spatial frequencies above approximately 0.5 cycles per degree (c/deg), longitudinal chromatic aberration (LCA) of the eye from the dispersion of white light by the ocular media alters ocular focus as a function of wavelength. Short wavelength light focuses

anterior to long wavelength light, producing approximately 2 D chromatic difference of focus between 400 and 700 nm²⁻⁵ and significantly different contrasts for spectral waveband components of the retinal image.^{6, 7} Numerous studies have demonstrated that LCA provides an important directional stimulus to reflex accommodation.⁷⁻²³

Monochromatic higher-order (HO) aberrations of eyes affect retinal image quality, provide a potential odd-error signal to accommodation, and interact with chromatic aberrations.²⁴⁻³² In theory, even-order aberrations like second order astigmatism and fourth order spherical aberration can provide the sign of defocus, but odd-order aberrations like third order coma and trefoil cannot.^{24,28} This theory has empirical support.²⁸ However, the potential role of the HO aberrations in accommodation control is not consistent across all studies.^{26, 27, 29, 30, 32} In particular, some individuals appear to use monochromatic aberrations, while others do not.^{26, 29, 30}

Besides their effects on accommodation and resolution of fine detail, HO aberrations interact with chromatic aberration of the eye. McLellan *et al.*³¹ used the modulation transfer function (MTF) of the eye to evaluate retinal image quality for a model eye with LCA but no other aberrations, and also for real eyes with both LCA and monochromatic wavefront aberrations. For the model eye with LCA alone, MTF was degraded distinctly for 450 nm light, which is defocused substantially as a result of LCA, compared with the MTF for 550 nm light which is in focus on the retina. On the other hand, for a real eye with both LCA and monochromatic aberrations, the MTF is very similar for 450 nm and 550 nm light. This result suggests that monochromatic aberrations decrease the difference in MTF across wavelengths that results from LCA alone. The MTF for long-wavelength sensitive cones (L-cones), middle-wavelength sensitive cones (M-cones), and short-wavelength sensitive cones (S-cones) computed separately in real eyes are more similar to each other than in the model eye with LCA alone. While monochromatic wavefront aberrations degrade the retinal image at a single wavelength, McLellan *et al.*³¹ concluded that monochromatic aberrations also attenuate the effects of LCA and thus help the eye defend against chromatic blur.

Previous experiments in our laboratory show that LCA increases dynamic accommodation gain significantly for normal subjects, suggesting that LCA provides an effective directional signal that specifies wavefront vergence.^{7, 9, 11-14, 16-19, 33} The previous experiments all simulated 3 mm artificial pupils to minimize HO wavefront aberrations of the eye, since at the pupil size of 3 mm, the monochromatic aberrations of the eye have minimal effects on the retinal image quality.^{34, 35} Thus the relatively small pupil size may have influenced the previous results. Following McLellan *et al.*³¹ the increase in monochromatic aberrations at large pupil sizes may obscure the effects of LCA, and thus LCA would not provide such a substantial cue at large pupil sizes.

To examine the effect of pupil size and HO aberrations on accommodation, we compared dynamic gain with and without the normal LCA of the eye in observers while they viewed through 3 mm and 5.7 mm diameter artificial pupils.

METHODS

Subjects

Fifteen volunteers (subjects) were involved in this study, which was approved by the Institutional Review Board (IRB) of the College. All subjects gave informed consent. Three were investigators and the others were naive to the purpose of the study. All subjects were visually normal and had no history of strabismus, amblyopia, binocular vision problems, or significant ocular injury, surgery, or disease. Refractive errors were corrected by the subjects' own contact lenses or by trial lenses. Distance refractive states and near point of

accommodation were measured for all subjects. Two subjects were excluded for poor accommodation to a stationary target during the optometer calibration procedure (described below). One subject was excluded for accommodative spasm (severe over-accommodation) and three for excessive blinking during trials. Thus, nine normal trichromatic subjects ranging from 21 to 31 years of age participated in this experiment. Three out of nine are male.

Apparatus

Dynamic accommodation was monitored continuously (100 Hz) with a high-speed infrared optometer³⁶ and the pupil was monitored by video-camera (30 frames/s) while the subject viewed a high contrast Maltese cross target presented in non-Maxwellian view through a Badal stimulus system. The Badal optical system keeps the visual angle subtended by the target constant despite changes in target distance.¹¹ The Badal stimulus system used in this study was similar to the non-Maxwellian arm of the stimulus system described by Kruger *et al.*³⁷ Two artificial pupils (3 mm and 5.7 mm in diameter) were used in the experiment. Figure 1 is a schematic illustration of the apparatus used in the experiment.

Procedures

Preliminary Examinations—During a preliminary session, case histories and Snellen acuities were measured for each subject, and color vision was tested by Nagel anomaloscope (mean of five measurements) and Farnsworth D-15 panel test. Monochromatic wavefront aberration and distance refractive error were measured by clinical aberrometer (COAS, Wavefront Sciences). The subject was directed to focus on a stationary white “ships wheel” target in the aberrometer positioned at five stimulus levels between 0 D and 4 D while wavefront aberration was measured. The subject’s refractive state was measured with the eye accommodating for a far distance. These measurements were taken with subjects’ natural (large) pupils in a dark room. Near point of accommodation was measured monocularly by standard push-up technique.

Subjects’ Calibration—During the accommodation trials, the subject was positioned in front of the apparatus on a chin and forehead rest, which kept the subject still. The left eye of each subject was tested and the right eye was patched. The subject’s refractive error was corrected by the subject’s own contact lenses or by trial lenses, and the room was kept dark so that the subjects’ pupil sizes were always larger than the artificial pupil in use in each trial. The subject’s pupil was monitored by video-camera (30 frames/s) and the image of the pupil was viewed on a video display so that the investigators could adjust the position of the subject’s eye continuously during the experiment.

The IR optometer was calibrated for each subject’s eye using a method of bichromatic stigmatoscopy¹⁷ that includes both objective and subjective measurements of accommodation at five stimulus levels: 0 D, 1 D, 2 D, 3 D, and 4 D.

Experimental Trials—During experimental trials, the Maltese cross target moved sinusoidally toward and away from the subject’s eye between 1 D and 3 D at 0.2 Hz with a mean level of 2 D. The subject was instructed to “concentrate on the center of the target and to keep the target clear using the same amount of effort as reading a book”. There were two illumination conditions: white light (3000 K; 20 cd/m²) to include normal chromatic aberration of the eye, and monochromatic green light (550 nm with 10 nm bandwidth; 20 cd/m²) to eliminate chromatic aberration. There were two artificial pupil diameters: 3 mm and 5.7 mm. Thus there were four conditions in total (two illumination conditions and two pupil conditions). For each subject, six trials were conducted for each condition, randomized in blocks, giving 24 trials in total. To limit subject fatigue, the 24 trials were run separately in

two experimental sessions. Each trial lasted 40.96 s with a break of approximately 1 min between trials.

Analysis

Blinks were removed manually from each accommodation trial before analysis. Trials with more than 14.65% blinks were discarded.³⁷ Data were scaled according to the subject's calibration and analyzed using a fast Fourier transform to extract dynamic gain and temporal phase-lag at the stimulus frequency (0.2 Hz). Data from the six trials for each condition were vector averaged to determine mean gain and temporal phase-lag of accommodation for each condition. In addition, mean accommodation response was calculated for each trial, and means for the six trials were averaged for each condition.

To determine whether chromatic aberration and monochromatic HO wavefront aberration improve or impair the accommodative response, comparisons were made between the accommodation responses in the two illumination conditions and also between the accommodation responses to the two pupil size conditions for the subjects. A non-parametric alternative to multivariate analysis of variance was used.^{38, 39} The following accommodative parameters were tested: (1) the vector gain of dynamic accommodation, a multivariate point (real, imaginary) that can be determined by plotting each subject's gain and phase in rectangular coordinates; (2) gain ratios.

For each subject root-mean-square (RMS) HO aberrations were calculated by the aberrometer for 3 mm and 5.7 mm pupil diameters (COAS, Wavefront Sciences). For these measurements the aberrometer target was moved to a near distance so that the subject was accommodating approximately the same amount as the mean accommodation level measured during the dynamic accommodation trials (white light, large pupil condition). RMS HO aberrations for two pupil diameters were compared for each subject.

RESULTS

Inter-Individual Variation in Accommodation

Each subject's mean dynamic gains and phase-lags for the four conditions (6 trials per condition) are summarized in Table 1 and Figure 2. All the means are vector means. Mean gain varied widely among the observers for the four conditions, indicating large individual differences in the sensitivity to vergence and LCA among subjects. Among the nine subjects, some had very low dynamic gains such as Subject 1 (S1) whose mean gains were 0.14, 0.26, 0.03, and 0.01 for the four conditions. Other subjects like S3 had very high gains, which were all above 1 for the four conditions.

Effect of Chromatic Aberration and Pupil Size on Accommodation

Prior to formal statistical analysis we made informal inspections of plots of the data. On inspection of Figure 2, it appears that eight of the nine subjects showed reduced dynamic gains in monochromatic light at both small and large pupil sizes. Only one (S3) had slightly decreased accommodative responses in white light compared with monochromatic light with a small pupil, and gains were approximately the same in white and monochromatic light with the large pupil. This suggests that the subjects (except S3) were sensitive to the effect of LCA. Eight of the nine subjects showed increased dynamic gains with large pupils in monochromatic light, while in white light, five subjects showed increased dynamic gains with large pupils.

Figure 3 shows data from a typical subject under each of the four experimental conditions. The top trace is the stimulus and the four traces below are the responses in each condition.

The amplitude of response increased in white light for both pupil sizes, and the amplitude of response increased with pupil size in both white and monochromatic light.

To investigate the effect of chromatic aberration and pupil size on accommodation, gain ratios were calculated for each subject for two pupil sizes (3 mm pupil, 5.7 mm pupil) and for two illumination conditions (monochromatic, white), and box plots of the gain ratios were used to summarize the distribution of the gain ratios among the subjects. Figure 4 shows the box plots of the subjects' gain ratios for different conditions. The top figure shows the ratio of gain in monochromatic light to gain in white light for two pupil sizes. For both pupil sizes, most subjects' gain ratios are less than 1, which means that the amplitude of their accommodation responses is smaller in monochromatic light than in white light. The bottom figure plots the ratio of the gain with small pupil to the gain with large pupil in white and monochromatic light. In monochromatic light, most subjects' gain ratios are less than 1, which means their accommodation responses are reduced with small pupils. However, in white light the gain ratios do not follow this pattern.

Statistical analysis (geometric test) results were in agreement with the box plots. The vector gains improved significantly from monochromatic light to white light at both 5.7 mm ($p = 0.004$) and 3 mm ($p = 0.02$) pupil sizes. The vector gains also increased significantly with larger pupils in monochromatic light ($p = 0.005$), but the pupil size had no significant effect on dynamic accommodation in white light ($p = 0.12$).

The monochromatic to white gain ratio was not significantly different between the two pupil sizes ($p = 0.0746$). Thus, LCA still provides a useful signal to accommodation at large pupil sizes, which is not significantly attenuated by the presence of HO monochromatic aberrations.

Effect of Pupil Size on RMS HO Aberrations

Figure 5 shows the RMS HO aberrations for 9 subjects with two pupil sizes. RMS HO aberrations increased with pupil size for all 9 subjects ($0.21 \mu\text{m}$ for 3 mm pupil and $0.47 \mu\text{m}$ for 5.7 mm pupil), and for the group, HO aberrations doubled with the larger pupil. Subjects' pupils were always larger than the artificial pupil in use during each trial, except for one subject (S6) who showed oscillations of pupil diameter between approximately 4.2 mm and 5.0 mm at the temporal frequency (0.2 Hz) of the stimulus and in synchrony with the accommodation response.

DISCUSSION

The present results show that LCA continues to provide a directional signal for accommodation at large pupil sizes despite higher levels of monochromatic aberrations. The results also show that large individual differences in accommodation to wavefront vergence and to LCA are a hallmark of accommodation in normal trichromatic observers, which agrees with previous findings.

In the present study we used sinusoidally moving targets rather than stationary targets to reduce voluntary behaviors that can mask the cues to accommodation when the target is stationary. Voluntary accommodation can mask the effects of spatial frequency, contrast, chromatic aberration and defocus when the target is stationary.¹¹ In addition, we instructed the subjects to "concentrate on the center of the target and to keep the target clear using the same amount of effort as when reading a book" rather than to "focus the target as hard as you can" or "use as much effort as you can". This type of instruction in conjunction with the moving target is intended to enhance reflex blur-driven accommodation by minimizing prediction and voluntary behaviors.¹¹ 40 41

Individual Differences among Observers

In the current experiment, we found that the observers showed large individual differences in dynamic gain to both wavefront vergence and LCA (Figure 2). This confirms the results of previous accommodation experiments that wide variation among individuals in sensitivity to both vergence and LCA is typical.^{1, 7, 11, 14, 16–19, 33, 42} One possibility is that subjects who respond poorly or who do not respond at all to optical vergence and/or chromatic aberration have not developed the physiological mechanisms to detect effects of chromatic aberration and/or optical vergence. Studies suggest that the signal from LCA is analyzed by comparing L-cone and M-cone contrasts.^{7, 10, 12, 13, 15, 17–19, 22, 43} Some observers who cannot detect color signal from LCA may not develop the neurophysiology to measure contrast separately by cone type, and/or the neurophysiology to then compare L- and M-cone-contrasts to derive the directional signal to drive accommodation. Other observers do develop strong neural mechanisms for detecting these color signals. Inter-subject variation in detecting optical vergence signals might result from variation in the Stiles-Crawford effect (pointing direction) of individual cones and small subgroups of cones that sample from different parts of the pupil.⁴⁴ Proposed mechanisms for optical vergence detection have been summarized in our previous papers,^{32, 45} including modal patterns in cones, and subgroups of cones that sample from slightly different areas of the pupil. Development of these mechanisms may vary widely among subjects. In the current study, all the subjects except S3 used LCA as a directional cue for reflex accommodation. This confirms that most subjects are sensitive to LCA and individuals like S3 are unusual.

Pupil Size and HO Aberrations

We found that LCA continued to provide a useful signal to accommodation at large pupil sizes despite the increased monochromatic aberrations. Yet McLellan *et al.*³¹ concluded that monochromatic aberrations attenuate the effects of LCA and help the eye defend against chromatic blur. Monochromatic aberrations may defend against chromatic blur at high spatial frequencies, but the effects of LCA are most effective for reflex accommodation at intermediate spatial frequencies between 3 and 5 c/deg.^{41, 46, 47} Defocus and other aberrations of the eye reduce retinal image contrast as a function of spatial frequency, and the effect is most prominent at high spatial frequencies (> 30 c/deg) and minimum at very low spatial frequencies (< 0.3 c/deg). But at intermediate spatial frequencies (0.5–8 c/deg), defocus and LCA have moderate effects on image contrast, and dynamic accommodative gain is maximum at around 3 c/deg. HO aberrations have minimal effect on contrast of the retinal image at 3 c/deg, where defocus and LCA are the principal cause of retinal blur. The target in the present experiment was a Maltese cross with broadband spatial frequency content. Thus HO aberrations may reduce chromatic blur at high spatial frequencies,³¹ but they do not attenuate the effects of LCA when the target includes intermediate spatial frequencies even at large pupil sizes. When pupil diameter was reduced from 5.7 mm to 3 mm, accommodative gain decreased significantly in monochromatic light, but not in white light. In monochromatic light the reduced gain could result from a larger depth of focus as well as from a smaller directional signal from HO aberrations when the pupil is small. Besides effects of blur and depth of focus, smaller artificial pupils reduce the change in angle of incidence of light across edges blurred by defocus compared to larger pupils, and thus might impair retinal mechanisms that monitor wavefront vergence. In white light, LCA provided a strong directional signal at both pupil sizes and gain did not decrease significantly when pupil size was reduced.

CONCLUSIONS

In summary, large individual differences in accommodation to wavefront vergence and to LCA are a hallmark of accommodation in normal trichromatic observers. The present

findings support the view that blur from aberrations especially defocus and chromatic aberration specifies wavefront vergence at intermediate spatial frequencies and drives accommodation. 1· 41· 43· 46–49

Acknowledgments

The research was supported by grants from the National Eye Institute of NIH (2R01-EYO5901) to Philip B. Kruger, and Minnie Flora Turner Memorial Fund for Impaired Vision Research to Yinan Wang.

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Figure 1.

Badal stimulus system: The illumination system is in dashed lines and the target system in solid lines. S, tungsten-halogen light source; CL1, collimating lens; IF, interference filter; ND, neutral density filter; D1 & D2, opal diffusers; IB, integrating bar; L1, L2, L3, L4, achromatic lenses; M, front-surface mirror; T, Maltese cross target photographic transparency; A, artificial pupils; P1 & P2, prisms with mirrored surfaces; T', target image; E, eye.

Figure 2. Mean gain for nine subjects under four stimulus conditions. Error bars represent 1 SEM for six experimental trials per condition.

Figure 3.

Typical accommodation data from one subject for four stimulus conditions. The top trace is the accommodative stimulus and the four traces below are the accommodative responses for each of the four conditions. Each trace is for one 40-sec trial.

Figure 4.

Box plots of gain ratios (monochromatic/white) for two pupil sizes and gain ratios (3 mm pupil/5.7 mm pupil) for two illumination conditions. Gain ratios are given on the y-axis, and different conditions on the x-axis. The boxes represent the inter-quartile range. The upper and lower edges of the boxes indicate the 75th and 25th percentile. The horizontal line in the box represents the median value. The ends of the vertical lines indicate the minimum and maximum values. The box and the whiskers together indicate the area within which all data are found.

Figure 5.
RMS HO aberrations for 9 subjects for two different pupil analysis sizes. Gray bars are for 3mm pupil and hatched bars are for 5.7mm pupil.

Table 1

Each subject's mean dynamic gains and mean phase-lags (degree) for the four conditions ($N = 6$ per condition).

Subject	White + 5.7mm			White + 3mm			Mono + 5.7mm			Mono + 3mm		
	Mean gain	mean phase lag (Degree)	Mean gain	mean phase lag (Degree)	Mean gain	mean phase lag (Degree)	Mean gain	mean phase lag (Degree)	Mean gain	mean phase lag (Degree)	Mean gain	mean phase lag (Degree)
1	0.14	-60	0.26	-56	0.03	-77	0.01	-4	0.01	-4	0.01	-4
2	0.45	-37	0.36	-47	0.36	-60	0.12	-75	0.12	-75	0.12	-75
3	1.26	-24	1.01	-32	1.23	-33	1.10	-40	1.10	-40	1.10	-40
4	0.73	-42	0.58	-49	0.59	-49	0.50	-57	0.50	-57	0.50	-57
5	0.15	-56	0.17	-59	0.05	-50	0.01	12	0.01	12	0.01	12
6	0.26	-64	0.16	-70	0.11	-72	0.09	-84	0.09	-84	0.09	-84
7	0.52	-92	0.63	-128	0.42	-110	0.44	-141	0.44	-141	0.44	-141
8	0.41	-69	0.53	-63	0.34	-92	0.21	-87	0.21	-87	0.21	-87
9	0.33	-64	0.27	-66	0.17	-84	0.04	-62	0.04	-62	0.04	-62
Average	0.44	-49	0.38	-60	0.32	-59	0.23	-65	0.23	-65	0.23	-65

Bold letters are the vector averages of all subjects' mean gains and mean phase-lags.