The relationship between CA/C ratio and individual differences in dynamic accommodative responses while viewing stereoscopic images

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The oculomotor synergy as expressed by the CA/C and AC/A ratios was investigated to examine its influence on our previous observation that whereas convergence responses to stereoscopic images are generally stable, some individuals exhibit significant accommodative overshoot. Using a modified video refraction unit while viewing a stereoscopic LCD, accommodative and convergence responses to balanced and unbalanced vergence and focal stimuli (BVFS and UBVFS) were measured. Accommodative overshoot of at least 0.3 D was found in 3 out of 8 subjects for UBVFS. The accommodative response differential (RD) was taken to be the difference between the initial response and the subsequent mean static steady-state response. Without overshoot, RD was quantified by finding the initial response component. A mean RD of 0.11 ± 0.27 D was found for the 1.0 D step UBVFS condition. The mean RD for the BVFS was 0.00 ± 0.17 D. There was a significant positive correlation between CA/C ratio and RD (r = +0.75, n = 8, p < 0.05) for only UBVFS. We propose that inter-subject variation in RD is influenced by the CA/C ratio as follows: an initial convergence response, induced by disparity of the image, generates convergence-driven accommodation commensurate with the CA/C ratio; the associated transient defocus subsequently decays to a balanced position between defocus-induced and convergence-induced accommodations.

Keywords: accommodation, convergence, stereoscopic image, stereo-display, convergence-induced accommodation, defocus-induced accommodation

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Introduction

Generally stereoscopic vision occurs when the visual system has disparity information. Disparity information can arise from two viewing positions in a natural scene, or when each eye views a different image. The latter condition can induce uncoupling of normal yoked accommodation and vergence responses as the accommodation response bias will be toward the screen position whereas the convergence response bias will be driven by the disparity specified location in space of the stereoscopic image. The resulting conflict between accommodation and vergence responses has been identified as a potent cause of visual fatigue and eyestrain (Emoto, Niida, & Okano, 2005; Hoffman, Girshick, Akeley, & Banks, 2008; Kuze & Ukai, 2008; Ukai & Howarth, 2008; Yano, Emoto, & Mitsuhashi, 2004; Yano, Ide, Mitsuhashi, & Thwaites, 2002). The range of vergence and accommodative responses that can be achieved without discomfort is referred to as the "zone of comfort," which is narrower than the "zone of clear single binocular vision" (Howard, 2002).

Shibata et al. (2005) developed a stereoscopic display that incorporated an optical correction to compensate for accommodative error. Recently Akeley, Watt, Girshick, and Banks (2004) have developed a novel 3-dimensional display that presents focus cues that are correct or nearly correct for the depicted scene. Hoffman et al. (2008) used this

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volumetric stereoscopic display to evaluate the influence of focus cues on perceptual distortions, fusion failures, and fatigue. The display was distinctive in that it retained the ability to render view-dependent lighting effects and used conventional graphics hardware while minimizing the conflict between simulated cues and focus cues. Correct or nearly correct focus cues were shown to improve stereoacuity, to reduce the time required to identify a stereoscopic stimulus, and to reduce viewer fatigue and discomfort; concomitantly, performance in a time-limited task was increased.

Thus, visual fatigue caused by viewing a stereoscopic display can be attributed, at least partly, to an imbalance between stimulus to the accommodation and vergence systems although the mechanism for the relationship between the imbalance and fatigue is ill-defined. This is a highly complex problem because fatigue itself is not an objectively observable phenomenon.

The present study is part of a sequence of studies, the aim of which is to provide objective bases for the assessment of visual fatigue that some observers experience when viewing displays where convergence and accommodation stimuli are unbalanced (Hoffman et al., 2008). We have previously reported on the effect of these viewing conditions on static accommodation responses in the presence of different target spatial characteristics (Okada et al., 2006) and demonstrated the substantial inter-subject variation that can occur when accommodation and convergence are uncoupled (Torii, Okada, Ukai, Wolffsohn, & Gilmartin, 2008). In the present study we explore the degree to which these inter-subject variations are attributable to inter-subject variations in the CA/C ratio.

The neural mechanisms underpinning the quick and accurate cross-links between accommodation and vergence are of course well documented (Ciuffreda & Kenyon, 1983; Semmlow & Hung, 1983) and generate inter-individual variations in, for example, AC/A and CA/C ratios.

An accommodative response to a stimulus in the absence of a stimulus to convergence, such as when one eye is occluded, will elicit a concurrent convergence response termed accommodative convergence. The ratio of accommodative convergence to the unit of accommodation (i.e., the AC/A ratio) is an index of the degree of accommodative convergence. Similarly, a convergence response to a stimulus will, in the absence of a stimulus to accommodation, elicit a concurrent accommodation response termed convergence accommodation. The ratio of convergence accommodation to the unit of convergence (i.e., the CA/C ratio) is an index of the degree of convergence accommodation. Semmlow and Wetzel (1979) have shown fusional vergence and accommodative convergence to be additive in nature based on the experiments comparing vergence only stimuli (i.e., accommodation open loop) and balanced vergence and accommodation stimuli. Vergence responses to step stimuli were shown to be initiated by fusional vergence and followed by accommodative convergence; the AC/A ratio was used to calculate additivity. Measurements of CA/C are experimentally more difficult than those for AC/A as generally open-loop accommodation responses are harder to achieve experimentally than open-loop convergence responses. One solution was the use of low-pass filtered images (Tsuetaki & Schor, 1987).

More recently Ukai and Kato (2002) have utilized a parallax-barrier LCD display and a modified video refraction unit to measure accommodation and convergence simultaneously while viewing stereoscopic images. They found that unstable oscillations in accommodation and vergence responses were elicited under certain conditions. To explore further the findings of Okada et al. (2006), Torii et al. (2008) and Ukai and Kato (2002) demonstrated that the demand of defocus-driven accommodation was reduced by blurring, that is by reducing the higher spatial frequency components of the target, and consequently, the remaining low spatial frequency components were less affected by defocus, and inaccurate accommodation was tolerated.

Torii et al. (2008) used video refraction to measure dynamically accommodative and convergence responses to stepped changes in convergence stimuli with unchanged accommodative stimuli, i.e., unbalanced vergence and focal stimuli (UBVFS) and compared these responses to those for balanced vergence and focal stimuli (BVFS). A transient accommodative overshoot was demonstrated in 4 out of 7 subjects but only for unbalanced stimuli.

In the present study we hypothesize that the transient accommodation responses to step UBVFS described qualitatively by Torii et al. (2008) are initiated by convergence-driven accommodation and subsequently followed by slower fine-tuning of the accommodation response modulated by the amount of blur. We examine whether the accommodative overshoot is attributable to an initial phase of substantial convergence-induced accommodation generating subsequent blur-induced accommodation (relative to the steady-state static response), the decay of which prolongs the overall accommodative response. In addition, we examine inter-individual variations (Torii et al., 2008) in dynamic responses to UBVFS.

Methods

Apparatus

Stereoscopic images were presented on a liquid crystal display (LL-151D, Sharp, Osaka, Japan) that was placed at a distance of 33 cm from the observer's eye as shown in Figure 1 (Torii et al., 2008). Three stimulus conditions were used: two where convergence (in meter angles, MA) and accommodative (in diopters, D) stimuli are balanced (i.e., BVFS 3.0 MA–3.0 D, 2.0 MA–2.0 D) and one where convergence and accommodative stimuli are unbalanced (UBVFS 3.0 MA–2.0 D); both MA and D being the

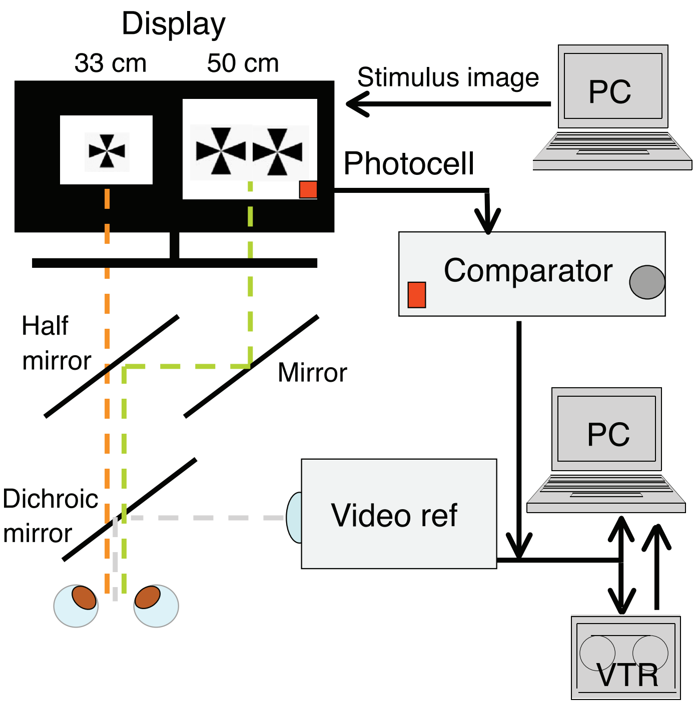


Figure 1. Schematic drawing of the apparatus.

reciprocal of stimulus distance in meters. The display has a parallax barrier (a series of 60-μm width slits) for generating the stereoscopic image pairs presented to each eye. The parallax barrier used in this display is uncommon as it is composed of a second liquid crystal panel, which has periodically transmitting and non-transmitting stripes. This is a useful feature because the non-transmitting parts of the liquid crystal panel can be switched to transmitting mode by an electrical signal such that the parallax barrier can be extinguished to allow the display to operate as conventional LCD (Jacobs et al., 2003). In the present study the stereoscopic display mode was used for all stimulus conditions.

The position of the liquid crystal parallax barrier is different from the conventional parallax barrier as it is set between the main LCD screen and the illumination system instead of being set in front of the main display. Although it has a similar operation to the conventional parallax barrier, the contrast of the stripes observed by the subjects is reduced. The parallax barrier is a series of 60-μm width slits covering one of the RGB subpixels. Subpixels for one pixel pair are arranged in the order Rr, Gl, Br, Rl, Gr, Bl, where RGB indicates Red, Green, and Blue, and rl indicates images for right and left eyes, respectively. The size of the LCD is 307 $\times$ 230 mm, which corresponds to 35 $\times$ 26 and 53 $\times$ 39 degrees of visual angle at 50 and 33.3 cm, respectively. The resolution of the display was 1024 $\times$ 768 pixels for conventional display mode and 512 $\times$ 768 pixel pairs for stereoscopic mode. Pixel pitch for stereoscopic mode is 4 and 6 min arc and subpixel pitch is 0.67 and 1.0 min arc at 50 and 33.3 cm, respectively. The parallax barrier, in which a stripe covers a subpixel every two subpixels, was very fine and could not be seen by the subject. The calculated spatial frequency is 44.2 and 29.5 cpd at 50 and 33.3 cm visual distance, respectively. With very careful observation some subjects could discern a contrast, not parallax, grating. Darker blue subpixels comprise a vertical grating of 14.7 and 9.8 cpd at 50 and 33.3 cm, respectively. With this spatial frequency subjects do not see a chromatic grating but a luminance grating. Due to low contrast sensitivity to the grating frequency, the grating fails to initiate an accommodative response. Although crosstalk was not reported by subjects any opportunity for crosstalk was minimized by careful positioning of the subject's head within the head restraint.

Targets were presented in a 3.0-D plane through a half-mirror (red dashed line in Figure 1) or a 2.0-D plane using the combination of a mirror and half mirror (green dashed line in Figure 1, see also Figure 4).

A high contrast (≈95%) black Maltese cross was displayed against a white background (34 cd m^{-2}) as shown in Figure 2a. The Maltese cross subtended an angle of 6.11 degrees in both width and height.

Accommodative and convergence responses were measured dynamically (see gray dashed line in Figure 1) at a rate of 30 Hz using a modified commercially available video refraction unit (PR-1000, TOPCON, Tokyo, Japan). Image analysis was carried out using virtual instrument software (LabVIEW 7.0 with vision development tool 7.0, National Instruments, Austin, Texas, USA). Details have been described previously (Torii et al., 2008).

When a stimulus is shown on the display a bright marker is simultaneously displayed. A photocell was attached to the display and the marker was detected. Another marker was superimposed on the measurement video image on the video refraction unit such that the timing could be analyzed to the nearest 25 ms by image analysis software. This is useful because both the online measurements and measurements using the image recorded on videotape can be time-locked with the stimulus.

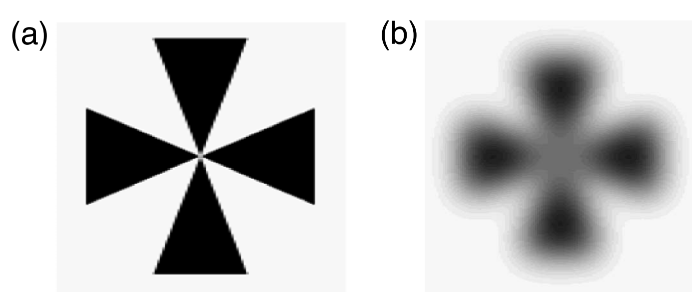


Figure 2. (a) A high contrast Maltese cross target was used for measurements of AC/A ratio and dynamic responses of accommodation and convergence. (b) The blurred Maltese cross target (which initially comprised higher spatial frequency components) was used for the measurement of CA/C ratio.

Measurements of AC/A and CA/C ratios

Response AC/A and response CA/C ratios were measured using the same instruments as those used to measure dynamic responses (see Figure 3), i.e., stimuli were presented on the stereoscopic LCD display and measurements were recorded by the modified video refraction unit. Accommodative and convergence responses were measured and averaged for a minimum of 3 s with at least 5 s elapsing between changes in the stimulus arrangements described below.

The CA/C ratio was measured by stimulating convergence while simultaneously opening the accommodative feedback loop and was calculated as the convergence accommodation divided by the convergence. Opening the accommodative feedback loop was performed using a blurred stimulus as shown in Figure 2b. The CA/C ratio indicated the degree of convergence-driven accommodation. The difference between the convergence stimuli was a 1.0-MA, from 2.0 MA to 3.0 MA, stepwise change of stereoscopic stimulus. The accommodative stimulus was presented using a Gaussian low-pass filter, generated by retouch software (Adobe Photoshop, Adobe System Incorporated, San Jose, CA, USA) to open the accommodative control loop. The Gaussian blur was produced by convolution of a target pattern with a Gaussian function to produce 32 minutes of arc (min arc) represented by the radius of half-width at half-height of the Gaussian form. This was the methodology adopted by Tsuetaki and Schor (1987) and utilized by Okada et al. (2006).

The AC/A ratio was measured by stimulating accommodation while simultaneously opening the convergence loop and calculated as the accommodative convergence divided by the accommodative response. The AC/A ratio indicates the degree of accommodative-driven convergence. The convergence loop was opened by covering one eye using a near infrared transmitting filter, blocking visible light without interfering with the operation of the video refraction unit. Change in the accommodative stimulus was a 1.0-D, from 2.0 D to 3.0 D, stepwise change of stimulus. The measurement of response AC/A used in the present study shows the actual strength of mutual coupling between accommodation and vergence control systems. In contrast stimulus AC/A is an approximation of the strength of coupling used in clinical binocular vision assessment.

Measuring dynamic responses of accommodation and convergence for BVFS and UBVFS target motions

Two conditions for target change, both controlled by animation software (Flash MX, Macromedia, San Francisco, CA, USA), were used as shown in Figure 4.

BVFS motion condition. Natural target conditions were used both before and after the stepwise motion such that the target moved successively in a step-wise manner from the combination of a 2.0 MA–2.0 D demand to a 3.0 MA–3.0 D demand.

UBVFS motion condition. The target at 3.0 MA was a stereoscopic image. The disparity of the target was changed successively from 2.0 MA to 3.0 MA while the accommodative stimulus was maintained at a constant 2.0 D, i.e., the location of the screen surface.

Procedure

Following initial baseline measures of AC/A and CA/C, dynamic responses to BVFS and UBVFS target motions were recorded. Subjects were instructed to try to fuse the

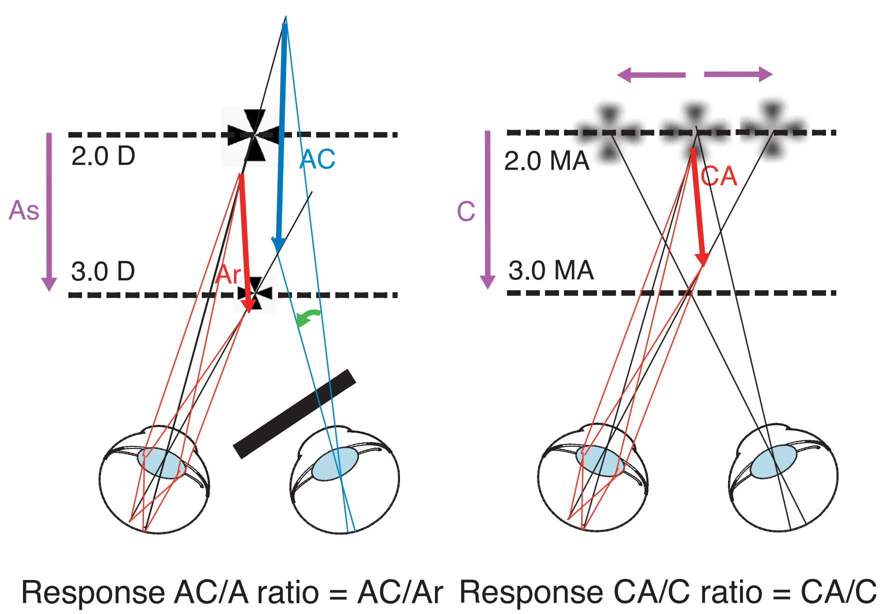
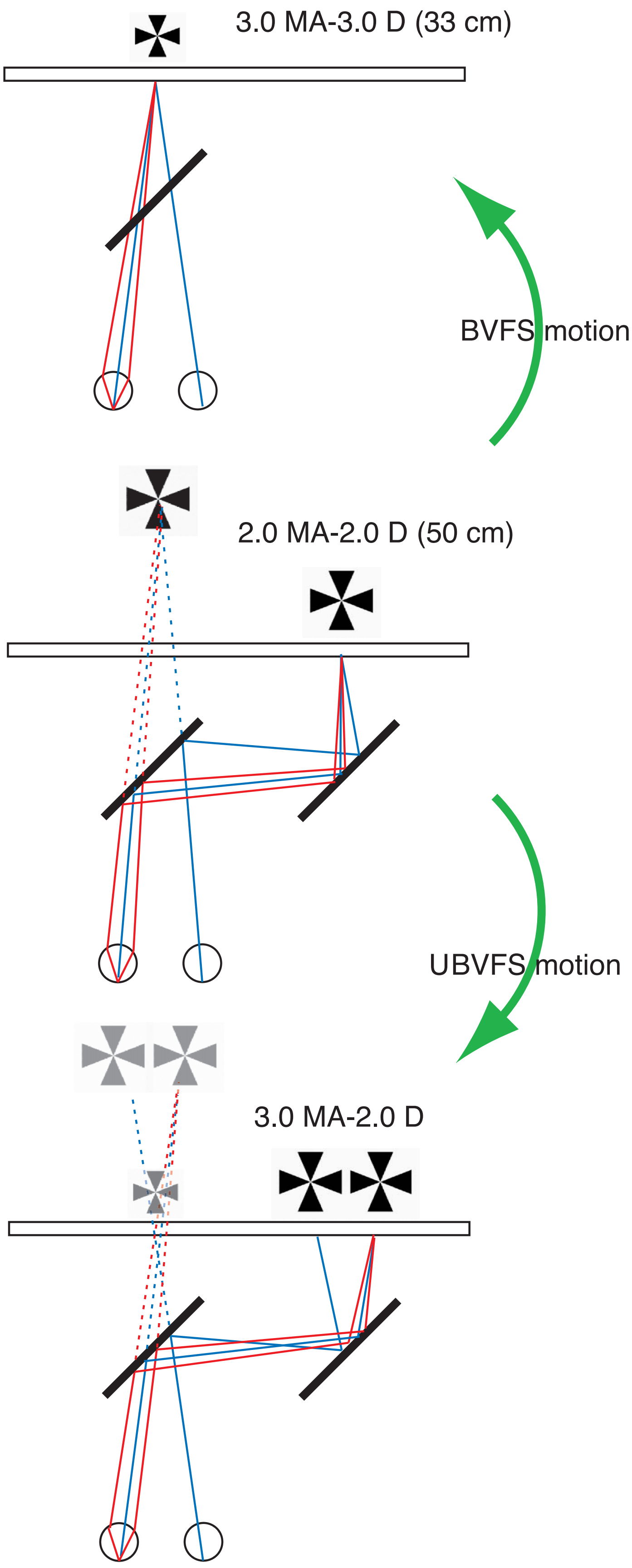


Figure 3. Measurement of AC/A and CA/C ratios (As: accommodative stimulus, Ar: accommodative response, AC: accommodative convergence, C: convergence, CA: convergence accommodation).



target while maintaining optimum clarity. The accommodative and convergence responses were measured for 20 trials per subject per condition.

Subjects

Eight subjects (6 males and 2 females) were employed for the measurement of AC/A, CA/C, and dynamic responses. The mean age of subjects was 22.8 ± 0.9 years (average ± *SD*; range 22 to 24 years). Additional eight subjects (7 males and 1 female) were employed solely for the calculation of AC/A and CA/C ratios. The mean age of the whole group of 16 subjects was 22.9 ± 1.0 years (range 22 to 25 years). All participants were emmetropes with normal vision bar two who had low-level myopia correctable to normal levels with ophthalmic lenses. All participants had normal oculomotor functions including accommodative amplitude.

Analyses

Various indices were used to characterize the accommodation response to a step stimulus as shown in Figure 5. The "static response" was defined as the difference between the average response from −0.5 s to 0.0 s before stimulus onset ("response at onset") and the average response from +2.5 s to +3.0 s after stimulus onset ("response at 3 s"). To measure the amount of overshoot in accommodation responses, the "initial response" was defined by the difference between the response at onset and the first local maximum to occur 0.25 s after stimulus onset. This criterion is based on convergence latency (0.2 s in Schor's model (Schor, 1992)). The "initial response" is considered to be a transition point whereby the initial accommodation component is switched to successive components; when there is no accommodative overshoot the index represents the initial component. The "response differential" was taken as (initial response − static response). If the response differential is positive, accommodative overshoot is observed.

Indices were calculated by 2 methods for each subject and for each condition. The first is "analysis after averaging," that is, 20 recordings were averaged and indices were then analyzed for an averaged waveform. This method minimizes noise and hence analysis can be carried out using a smoother waveform. The second is "averaging after analysis," that is, indices were analyzed for each recording and then averaged.

Figure 4. Measurement procedure for dynamic responses of accommodation and convergence. The images generated by the display occur for balanced vergence and focal stimuli (BVFS, i.e., conditions 3.0 MA–3.0 D and 2.0 MA–2.0 D) and unbalanced vergence and focal stimuli (UBVFS, i.e., condition 3.0 MA–2.0 D).

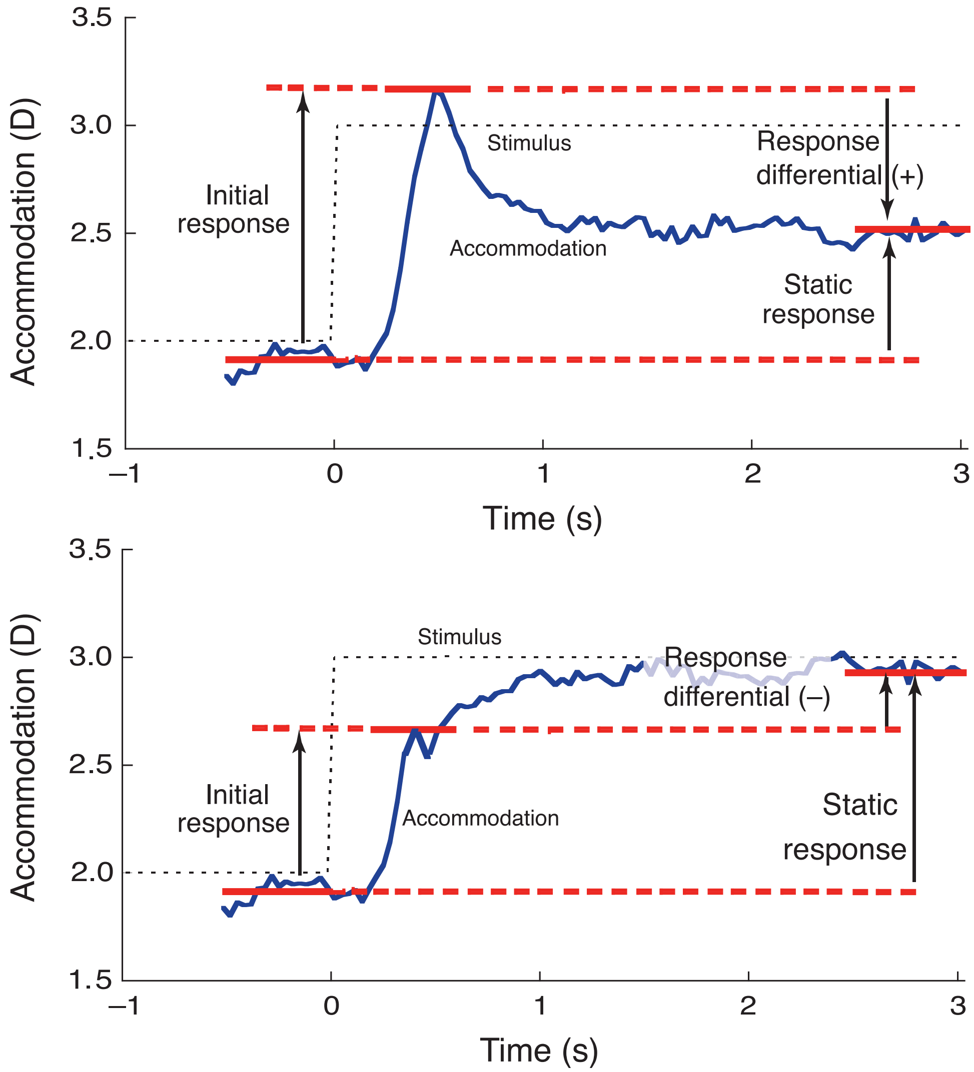


Figure 5. The response differential was defined as (response differential) = (initial response) − (static response).

This method provides an estimate of variability of the indices. Initial responses occur at slightly different times and therefore each trial and associated averaged values may not coincide when calculated by the two different methods. Response differentials have similar characteristics but indices obtained using the two methods for the response at onset, response at 3 s, and for the static response coincide, because timing of the data is fixed.

Results

AC/A and CA/C ratios

The relationship between AC/A ratio and CA/C ratio obtained from 16 subjects is shown in Figure 6. The results show that mean ± *SD* values of AC/A and CA/C ratios were 1.71 ± 0.84 MA/D and 0.55 ± 0.24 D/MA, respectively. The negative correlation between CA/C and AC/A ratios was significant ($r = -0.92$, $n = 16$, $p < 0.001$). The values for 8 subjects providing dynamic responses were: 1.78 ± 0.67 MA/D and 0.54 ± 0.22 D/MA for AC/A and CA/C ratios, respectively. The negative correlation between ratios was significant ($r = -0.84$, $n = 8$, $p < 0.01$; see Table 2).

Dynamic responses

Dynamic accommodative responses for all 8 subjects are shown in Figure 7.

Figures 7a–7c show overshoot accommodation responses (positive response differentials) for UBVFS target motion. The accommodative overshoot was greater for the UBVFS condition but relatively absent for the BVFS target motion. No overshoot was present in convergence for both target motions. Figure 7h illustrates a subject with almost absent accommodative overshoot. Of note is that Figures 7b, 7c, and 7h demonstrate that static responses were greater for BVFS target motion than for UBVFS target motion.

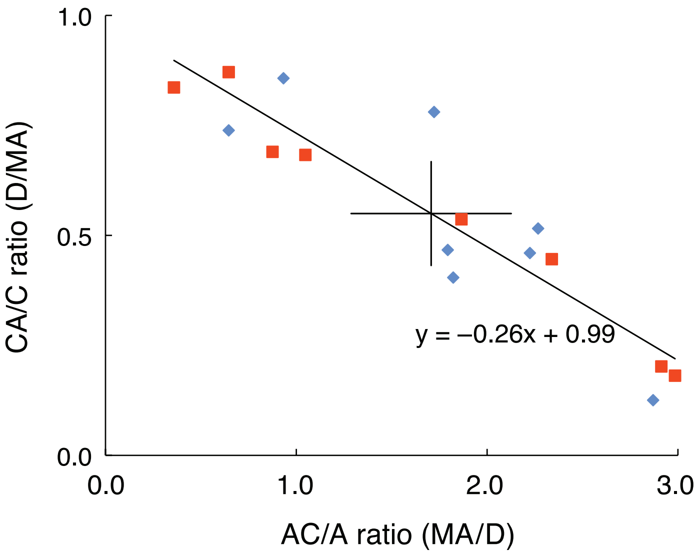


Figure 6. The relationship between AC/A and CA/C (n = 16). Diamond (blue) plots (n = 8) indicate subjects who participated in the subsequent motion experiments, and square (red) plots (n = 8) indicate subjects who participated in only in AC/A and CA/C measurement. The regression line is based on data for all 16 participants. The cross bar = *SD*.

Figure 7a shows responses for subject AY where, similar to data in Figures 7b and 7c, accommodative overshoot was observed for UBVFS target motion but not for BVFS target motion; convergence being equivalent for both target motions. However, for subject AY static accommodative responses coincide for both target motions, a feature not apparent in other subjects. Figure 7g shows an example of minimal overshoot for both conditions, which may be attributable to the atypical situation where the static response was present for the UBVFS condition but relatively absent for the BVFS target motion condition.

Calibration of convergence recording was based on each subject's inter-pupillary distance. None of the subjects reported diplopia or difficulty in fusing the images.

Analyses

Results of analyses are shown in Table 1. Indices for each subject analyzed for averaged waveforms (i.e., "analysis after averaging") are displayed in the left half, and averaged indices analyzed from each waveform (i.e., "averaging after analysis") are listed with standard deviations (*SD*s) in the right half.

Inter-subject variations were calculated using "analysis after averaging" data. Means ± *SD* values (D) in 8 subjects for initial response, static response, and response differential were, for BVFS, respectively, 0.58 ± 0.21, 0.58 ± 0.20, and 0.00 ± 0.17; for UBVFS, respectively, 0.64 ± 0.24, 0.53 ± 0.26, and 0.11 ± 0.27. Response differentials following "analysis after averaging" are also shown in Figure 7 with averaged responses.

Figure 8a shows the relationship between response differential and CA/C ratio for the BVFS motion condition. CA/C and response differential calculated by "analysis after averaging" were not significantly correlated (r = 0.50, n = 8, p = 0.21). Figure 8b shows the relationship between response differential and CA/C ratio for the UBVFS motion condition. CA/C and response differential calculated by "analysis after averaging" were significantly correlated (r = 0.75, n = 8, $p < 0.05$; see Table 2). The abscissas of Figures 8a and 8b have the same scale to facilitate comparison between individual response differential for UBVFS and BVFS conditions.

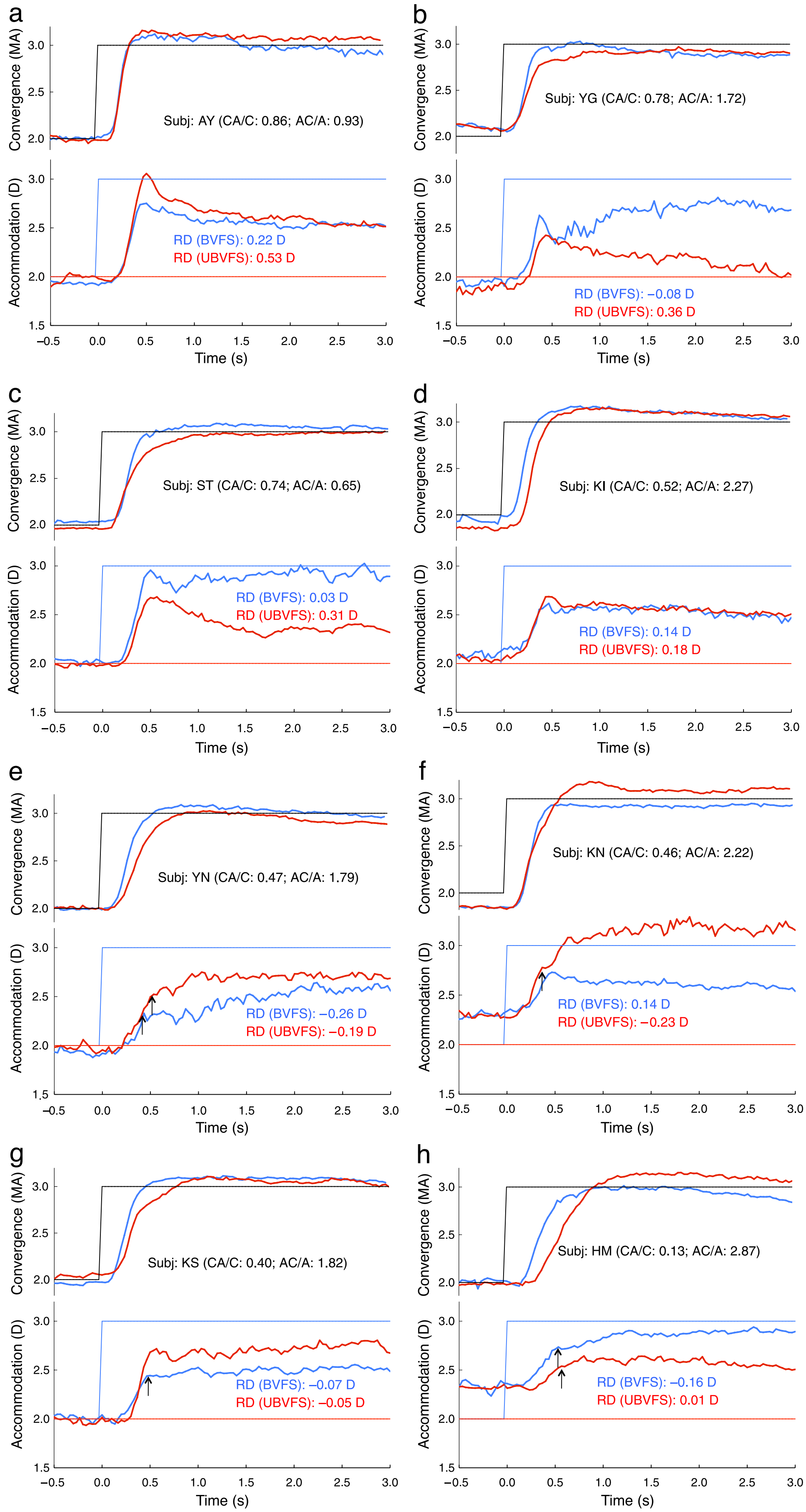
Data calculated by the "averaging after analysis" method are also displayed in Figure 8 with error bars. In Table 2, correlations for "analysis after averaging" indices were similar to those found for "averaging after analysis" indices.

A correlation matrix for 5 indices, i.e., AC/A ratio, CA/C ratio, initial responses, static responses, and response differentials for BVFS and UBVFS motions, is shown in Table 2. Dynamic accommodative response data for the UBVFS target motion shows a significant positive correlation between CA/C ratio and response differential as indicated above, whereas the static response does not correlate with either CA/C or response differential. Dynamic accommodative response data for the BVFS target motion shows a significant correlation between initial response and both CA/C (positive) and AC/A (negative) ratios.

Discussion

The presence of overshoot in accommodation responses in some subjects might indicate the existence of two or more components in accommodation response with the

Figure 7. Convergence and accommodation responses to BVFS and UBVFS target motions. Responses were averaged from 20 recordings for each condition. Blue lines represent responses to BVFS target motion, red lines to UBVFS target motion. Panels (a) to (h) are arranged in descending order of CA/C ratio. Upward arrows indicate the initial accommodative responses, when clear peaks were absent. (a) Example of a pronounced accommodative overshoot for UBVFS target motion, minimal overshoot for BVFS target motion, and equivalent static responses for both conditions. (b, c) Examples of two accommodation overshoot responses to UBVFS target motion in the presence of approximately equivalent convergence responses; the overshoot is more pronounced in (c) with a more rapid decay to the steady-state static response than (b). No overshoot was evident in convergence for UBVFS or BVFS target motion. (e–h) Examples of absence of accommodative overshoot.


a
Subj: AY (CA/C: 0.86; AC/A: 0.93)
RD (BVFS): 0.22 D
RD (UBVFS): 0.53 D
b
Subj: YG (CA/C: 0.78; AC/A: 1.72)
RD (BVFS): −0.08 D
RD (UBVFS): 0.36 D
c
Subj: ST (CA/C: 0.74; AC/A: 0.65)
RD (BVFS): 0.03 D
RD (UBVFS): 0.31 D
d
Subj: KI (CA/C: 0.52; AC/A: 2.27)
RD (BVFS): 0.14 D
RD (UBVFS): 0.18 D
e
Subj: YN (CA/C: 0.47; AC/A: 1.79)
RD (BVFS): −0.26 D
RD (UBVFS): −0.19 D
f
Subj: KN (CA/C: 0.46; AC/A: 2.22)
RD (BVFS): 0.14 D
RD (UBVFS): −0.23 D
g
Subj: KS (CA/C: 0.40; AC/A: 1.82)
RD (BVFS): −0.07 D
RD (UBVFS): −0.05 D
h
Subj: HM (CA/C: 0.13; AC/A: 2.87)
RD (BVFS): −0.16 D
RD (UBVFS): 0.01 D
Convergence (MA)
Accommodation (D)
Time (s)

Subject	Analysis after averaging: Static (D)	Analysis after averaging: Response differential (D)	Analysis after averaging: Initial response timing (s)	Averaging after analysis: Static (D)	Averaging after analysis: Response differential (D)	Averaging after analysis: Initial response timing (s)
(a) BVFS						
AY	0.59	0.22	0.50	0.59 ± 0.24	0.22 ± 0.42	0.45 ± 0.07
YG	0.77	−0.08	0.37	0.77 ± 0.29	−0.09 ± 0.44	0.37 ± 0.07
ST	0.90	0.03	0.50	0.90 ± 0.34	0.02 ± 0.33	0.50 ± 0.09
KI	0.39	0.14	0.47	0.39 ± 0.26	0.17 ± 0.31	0.39 ± 0.08
YN	0.65	−0.26	0.47	0.65 ± 0.35	−0.33 ± 0.32	0.34 ± 0.06
KN	0.29	0.14	0.47	0.29 ± 0.23	0.06 ± 0.24	0.39 ± 0.09
KS	0.51	−0.08	0.50	0.51 ± 0.19	−0.19 ± 0.65	0.46 ± 0.12
HM	0.56	−0.16	0.53	0.56 ± 0.38	−0.24 ± 0.32	0.52 ± 0.09
(b) UBVFS						
AY	0.55	0.53	0.50	0.55 ± 0.22	0.53 ± 0.41	0.53 ± 0.07
YG	0.19	0.36	0.43	0.19 ± 0.32	0.43 ± 0.30	0.43 ± 0.11
ST	0.39	0.31	0.57	0.39 ± 0.24	0.33 ± 0.27	0.51 ± 0.09
KI	0.46	0.18	0.47	0.46 ± 0.24	0.16 ± 0.39	0.41 ± 0.12
YN	0.73	−0.19	0.53	0.73 ± 0.42	−0.38 ± 0.40	0.35 ± 0.09
KN	0.87	−0.23	0.53	0.87 ± 0.32	−0.25 ± 0.44	0.40 ± 0.11
KS	0.79	−0.05	0.57	0.79 ± 0.51	−0.11 ± 0.57	0.50 ± 0.11
HM	0.21	0.01	0.57	0.21 ± 0.25	−0.06 ± 0.38	0.40 ± 0.14

Table 1. Indices for each subject calculated by 2 methods. (a) BVFS. (b) UBVFS. Indices analyzed from averaged waveforms are displayed in the left half, and averaged indices analyzed from each waveform are listed in the right half.

maximum point of overshoot being considered as a transition point where the respective dominancy of components is switched.

Accommodative responses without overshoot may also have these components. To measure the first component we analyzed response waveforms using the criterion of the first local maximum to occur 250 ms after stimulus onset. This criterion is based on convergence latency (200 ms in Schor's model (Schor, 1992)). Thus we searched for the first zero velocity point from 250 ms after stimulus onset separately for each response trace and then averaged the data (i.e., "averaging after analysis"). A zero point could be located for all traces and consequently the level of inherent variability in responses could be calculated (see Table 1). These data were generally found to be consistent with the "analysis after averaging" method (with or without overshoot) and both methods yielded similar plots and correlation coefficients as indicated, respectively, in Figure 8 and Table 2. Table 1 also shows that the initial responses for "analysis after averaging" generally occur slightly later than those calculated by "averaging after analysis" as individual zero velocity points in the latter method may be detected earlier owing to inherent response fluctuations.

The high correlation found between AC/A ratio and CA/C ratio is consistent with previous reports (e.g., Bruce, Atchison, & Bhoola, 1995; Fincham & Walton, 1957; Rosenfield, Ciuffreda, & Chen, 1995). Although the relationship is well documented, confirmation of the correlation using 16 subjects verified that the methods of measuring the ratios were robust and hence that the subset of 8 subjects used for dynamic response measurements was representative of the population (see Figure 6). Data presented are consistent with the qualitative observations reported previously by Torii et al. (2008), that is, accommodative overshoot (positive response differential) is a characteristic response in around 50% of subjects when perceiving UBVFS target motion. The mean response differential was 0.11 ± 0.27 D in the 8 subjects used with 3 subjects exhibiting at least 0.3-D overshoot. Data presented in Table 2 and Figures 7a–7c and 8b are clearly indicative of the contribution of CA/C ratio to the initial phase of accommodative response to UBVFS target motion and specifically demonstrate that the response differential is larger in subjects with higher CA/C ratios, suggested by the correlations in Table 2, the positive correlations between CA/C ratio and initial responses are found both in BVFS and UBVFS target motions.

For the UBVFS motion condition, we propose that the initial accommodative response is convergence-driven, which in turn generates defocus of the UBVFS image. Figures 7a–7c demonstrate generally that this initial response is transient in nature and followed by relatively slow, presumably defocus-driven, decay to a baseline steady-state static response level. Thus the locus of accommodative overshoot is comprised of a transient, ascending convergence-driven accommodation phase and a descending defocus-driven accommodative phase.

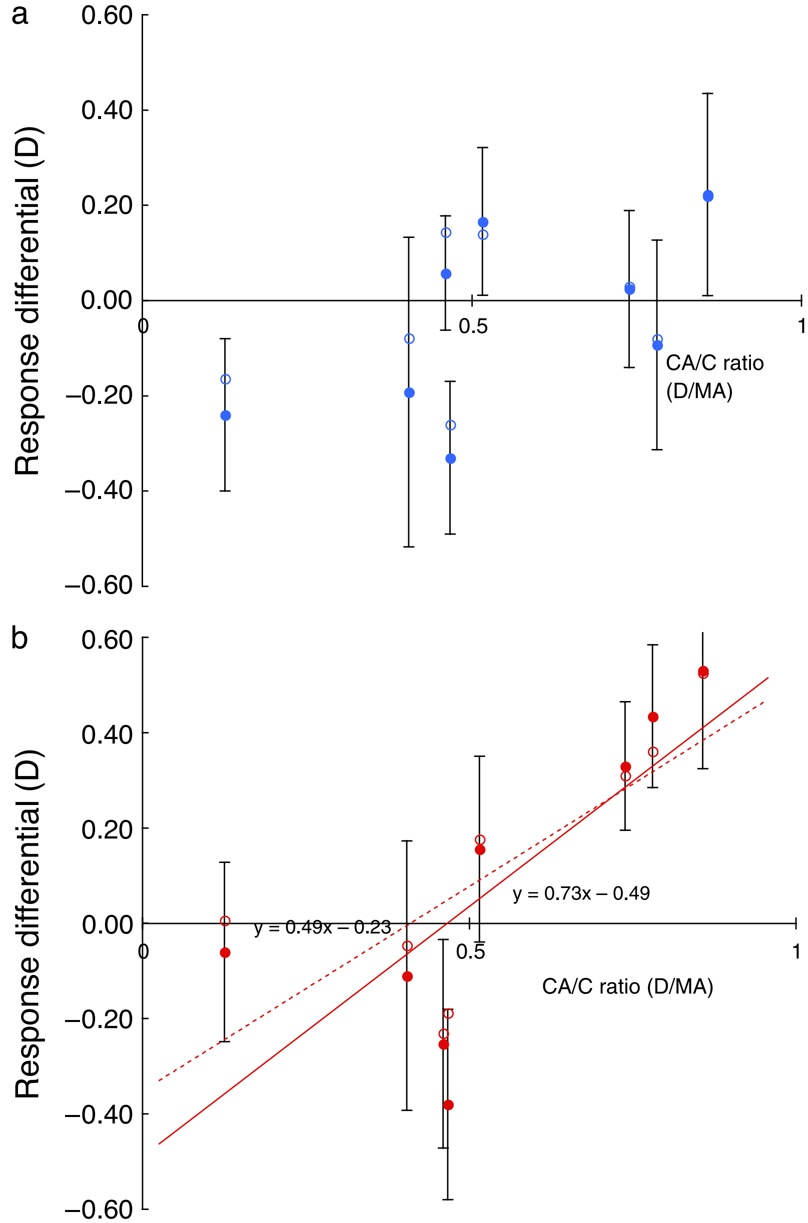


Figure 8. The correlation between accommodation response differential and CA/C ratio for the (a) BVFS motion condition and (b) UBVFS motion condition; the response differential was accentuated by the higher CA/Cs and resulted in significant positive correlation ($p < 0.05$). Filled circles with error bars and solid lines indicate "averaging after analysis" data. Error bars show 1 *SD*. Open circles and dotted lines indicate "analysis after averaging" data.

	Response differential (D)	Static response (D)	Initial response (D)	CA/C (D/MA)
AC/A (MA/D)	−0.32 (−0.38)	−0.64	−0.87** (−0.81*)	−0.84**
	−0.61 (−0.57)	−0.05	−0.74* (−0.74*)	
CA/C (D/MA)	0.50 (0.59)	0.47	0.84** (0.85**)	
	0.75* (0.75*)	−0.10	0.75* (0.82*)	
Initial response (D)	0.47 (0.63)	0.67 (0.62)		BVFS
	0.50 (0.66)	0.40 (0.21)		UBVFS
Static response (D)	−0.35 (−0.22)	−0.59 (−0.60)		

Table 2. Matrix of correlation coefficients (n = 8). Values in brackets indicate indices "averaging after analysis." *Note*: *$r > 0.707$ ($p < 0.05$), **$r > 0.834$ ($p < 0.01$).

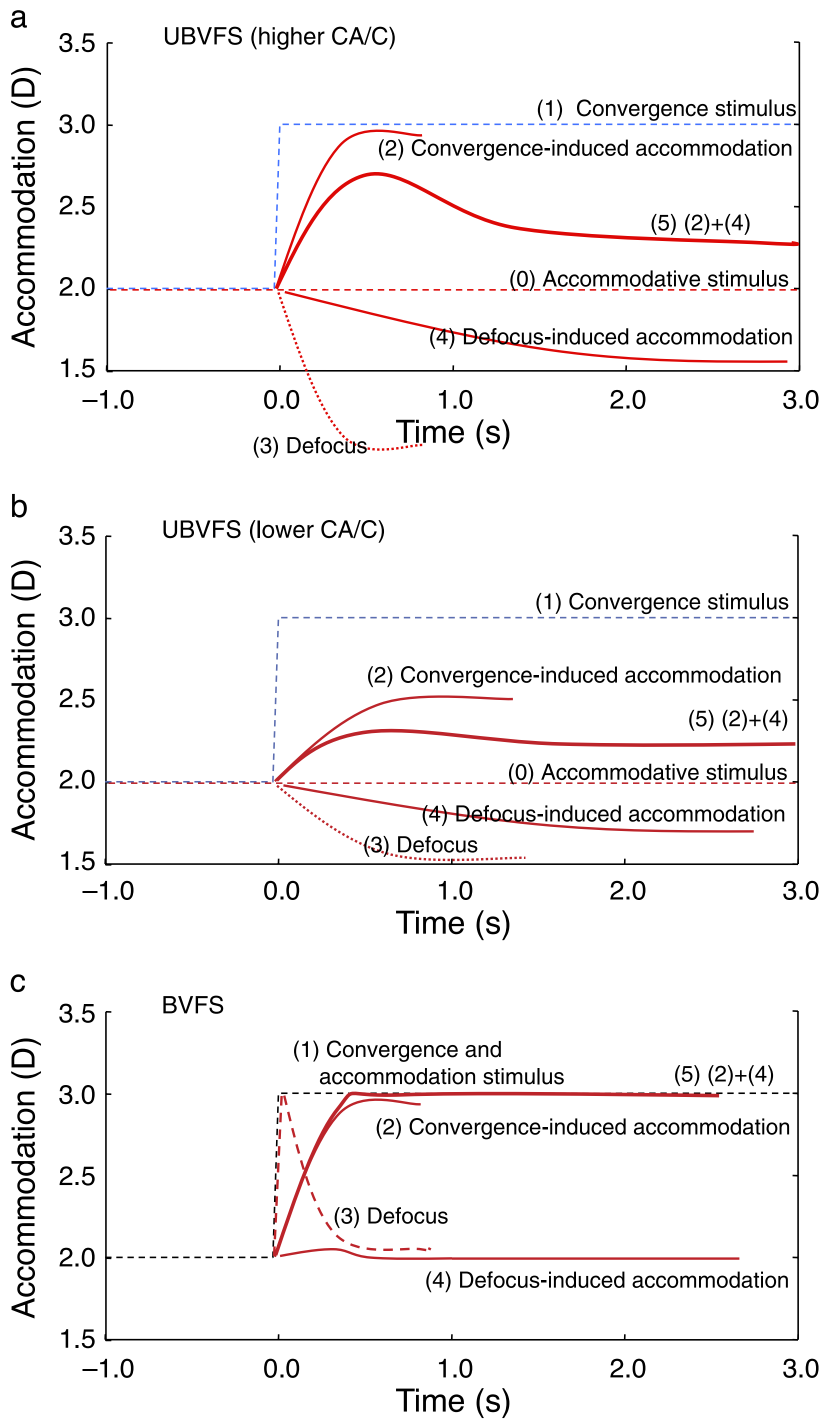


Figure 9. (a) The properties of convergence-induced accommodation predominate in the aggregate response to UBVFS motion to produce accommodative overshoot. (b) The properties of defocus-induced accommodation predominate in the aggregate response to UBVFS motion and mask accommodative overshoot. (c) Normal synkinesis between accommodation and convergence occurs with BVFS motion and is unimpeded by convergence-induced accommodation.

In Figures 7b and 7c initial accommodative responses are smaller for UBVFS target motion than for BVFS target motion, which suggests that defocus-induced accommodation to the static baseline level intervenes before completion of the initial convergence-induced transient accommodation. If the overriding effect of defocus-induced accommodation to baseline is sufficiently large, then this may account for the effect illustrated in Figure 7a: here the ascending convergence-mediated phase of the response appears to be masked by the descending defocus-driven phase of the response. Thus we propose that the effect of UBVFS motion on the subsequent locus of accommodative response will be determined by an aggregate of the gain and temporal properties specific to the convergence and defocus-driven components of that response. The proposal is illustrated schematically in Figure 9. The corollary is that if the target is artificially blurred, overshoot will be diminished because defocus-induced accommodation will be minimized. The effect is in fact evident in Figure 2a of Torii et al. (2008), where it can be seen that the amount of overshoot is decreased as target blur increases; future work is necessary for this relationship to be confirmed.

Mutual crosstalk between accommodation and vergence control systems is velocity sensitive (Schor & Kotulak, 1986) and hence convergence-induced accommodation is determined by a combination of the velocity of convergence and CA/C ratio. Under static zero-velocity conditions the static accommodation response to the UBVFS image will be an amalgam of steady-state convergence-induced accommodation and defocus-induced accommodation (Okada et al., 2006).

Clearly not all the data presented are consistent with the proposal. For example, as shown in Figures 7e and 7f, accommodation responses differ for subjects YN and KN despite both having similar CA/C and AC/A ratios. That CA/C ratio is a predominant factor in determining how individuals respond to the UBVFS condition will be examined further with reference to well-documented simulation models (Hung, 1998; Schor, 1992; Schor, Alexander, Cormack, & Stevenson, 1992).

In summary, we propose that inter-subject variation in accommodative overshoot is influenced by the CA/C ratio as follows: an initial convergence response, induced by proximity of the UBVFS image, generates convergence-driven accommodation commensurate with the CA/C ratio; the associated transient defocus subsequently decays to a balanced position between defocus-induced and convergence-induced accommodations. Thus when the three conditions of UBVFS, relatively high CA/C ratio, and non-blurred target (needs future confirmation) are combined, overshoot accommodative responses are observed.

Figure 7 indicates that, although convergence responses to BVFS and UBVFS target motions are very similar, most subjects showed small response latencies for the UBVFS condition. The latencies may be a consequence of a reduction in convergence induced by negative defocus-induced accommodation elicited after positive convergence-induced accommodation. Semmlow and Wetzel (1979) previously compared vergence responses elicited by coordinated fusional and accommodative stimulation to those elicited by fusional only stimulation and showed that the former is faster than the latter, with the most pronounced differences occurring toward the late stage of the movements. They also suggested that this difference may vary with the subject's AC/A ratio. The present observation on vergence responses is similar to Semmlow and Wetzel's (1979) observation.

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