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Vision Research 46 (2006) 1959–1972
Vision Research
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Initial destination of the disaccommodation step response

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Received 12 July 2005; received in revised form 14 November 2005

Abstract

Peak velocity and peak acceleration of disaccommodation step responses remain invariant of response magnitude for a constant starting position and they increase linearly with proximity of starting position. This suggests that disaccommodation response is initiated towards an initial (default) destination and is switched mid-flight to attain the desired final destination. The dioptric location of initial destination was estimated from the *x*-intercept of regression of peak velocity on response starting position. The *x*-intercept correlated well with subject's cycloplegic refractive state and poorly with their dark focus of accommodation. Altering the dark focus by inducing fatigue in the accommodative system did not alter the *x*-intercept. These observations suggest that cycloplegic refractive state is a good behavioral correlate of initial destination of disaccommodation step responses.

Keywords: Accommodation; Cycloplegia; Disaccommodation; Dynamics; Fatigue; Initial destination; Peak velocity; Peak acceleration; Dark focus; Step response

1. Introduction

Ocular disaccommodation refers to the reduction of the accommodative response from a near target to a far target. The first- and second-order dynamics of disaccommodation step responses exhibit two characteristics that depend on starting position (Bharadwaj & Schor, 2006; Kasthurirangan & Glasser, 2005). First, for a given starting position, the peak velocity and peak acceleration of disaccommodation remain invariant of the response magnitude (Figs. 1A, C, and E). Second, both peak velocity and peak acceleration of disaccommodation increase linearly with proximity of the starting position (Figs. 1B, D, and F). Based on these results we postulated that, for a given starting position, the same relaxation force is applied by the ciliary muscle to initiate all disaccommodation responses towards an initial (default) destination, irrespective of the magnitude of the final response. Initially, the disaccommodation response is under open-loop control (without feedback) and subsequently it is switched mid-flight to closed-loop control to attain the desired final position (Bharadwaj & Schor, 2006; Schor & Bharadwaj, 2006). Peak acceleration and peak velocity describe the dynamic properties of the initial open-loop component. The linear increase in peak velocity and peak acceleration with proximity of starting position suggests that the initial open-loop component of all disaccommodation responses could have a common initial destination. The main aim of this paper was to estimate the dioptric location of the initial destination of the disaccommodation step response. A secondary aim was to obtain a behavioral correlate for the initial destination of disaccommodation.

In a study of the role of defocus as an odd-error cue to accommodation, Yamada and Ukai (1997) observed that the initial trajectories of disaccommodation step responses from different starting positions were on the "same path" and were initiated towards a common destination. They estimated the location of the initial destination by fitting exponential functions to the "first half" of the disaccommodation step responses. The location of the initial destination was indicated by the final steady-state position of the exponential function. They observed in two of the three subjects

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doi:10.1016/j.visres.2005.11.029

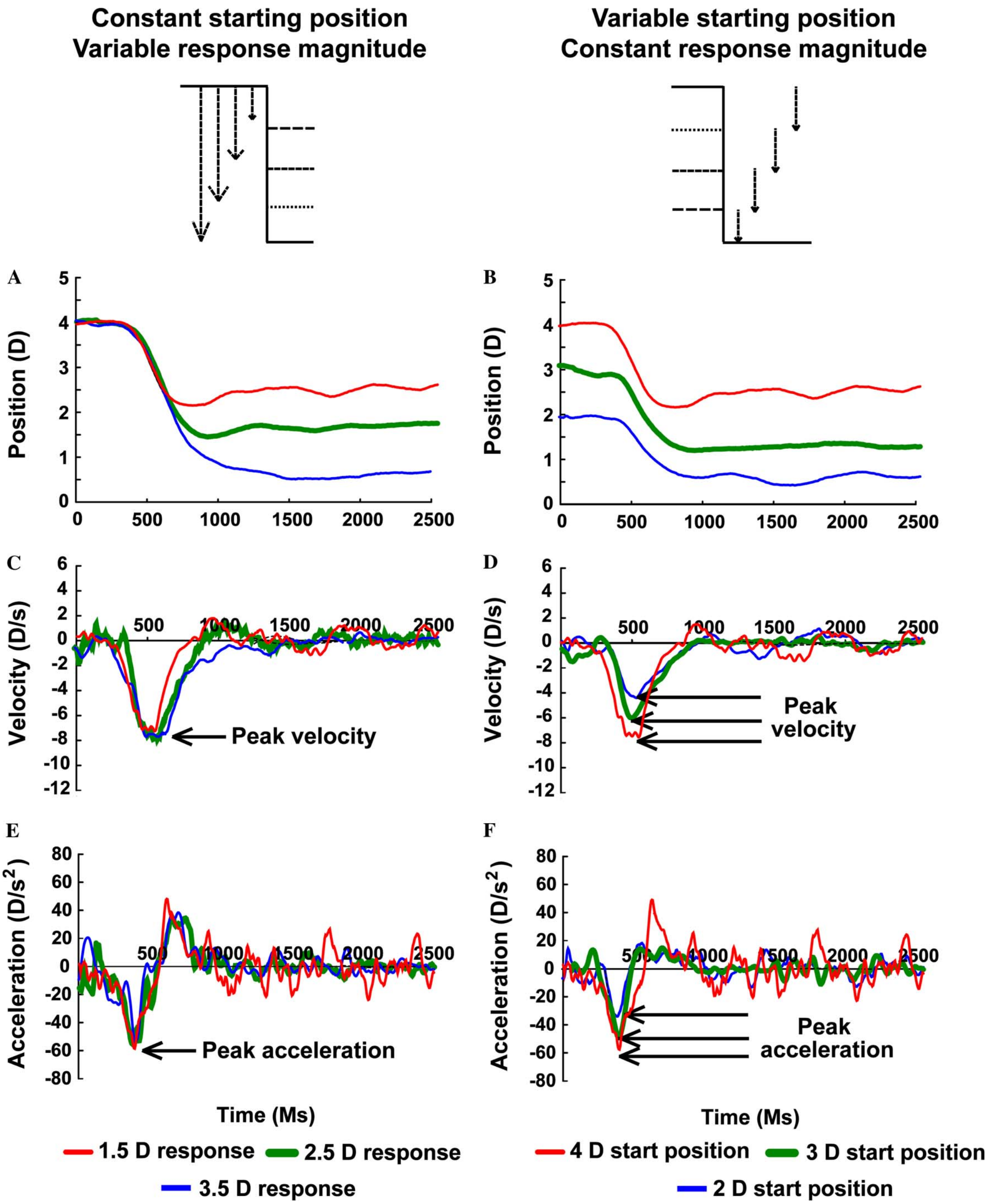

Fig. 1. Position (A and B), velocity (C and D) and acceleration (E and F) profiles of disaccommodation plotted as a function of time for one representative subject. Profiles shown in the left-hand column belong to different response magnitudes from a constant starting position (4 D). Profiles shown in the right-hand column belong to similar response magnitudes (1.5 D) from three-different starting positions (4, 3, and 2 D). Disaccommodation position profiles were collected using the SRI-dynamic infrared optometer, in response to step changes in optical defocus. Response profiles were differentiated and smoothed to compute velocity and acceleration profiles. A detailed account of the data collection and data analysis techniques can be found in Bharadwaj and Schor (2006).

that the initial destination was close to the dark focus of accommodation (Leibowitz & Owens, 1975, 1978; Rosenfield, Ciuffreda, Hung, & Gilmartin, 1993). However, as discussed in detail later (Section 6.2); estimates of initial destination were based on the incorrect assumption that an exponential function was a good fit to the initial step response. Hence we found it necessary to re-examine the location of the initial destination of disaccommodation using a different analytical technique.

Here, we estimated the dioptric location of the initial destination from the x-intercept of the regression of peak velocity on starting position of disaccommodation. We assume that the peak velocity of disaccommodation is proportional to the dioptric difference between the starting position and the initial destination of disaccommodation (Bharadwaj & Schor, 2006; Yamada & Ukai, 1997). This assumption predicts that the peak velocity decreases as the dioptric difference between the starting position and initial destination decreases and that the peak velocity is reduced to 0 D/s when the starting position equals the initial default destination. Thus, the x-intercept of the linear regression of peak velocity on starting position would estimate the dioptric location of the initial destination. To obtain a behavioral correlate of the estimated initial destination, we measured the correlation between x-intercept and either the dark focus of accommodation or the cycloplegic refractive state[1].

Parts of this research were presented in the abstract form at the Association for Research in Vision and Ophthalmology (ARVO) conference (Bharadwaj, Kim, & Schor, 2005).

2. Methods

2.1. A total of 11 subjects took part in the experiment

Ten subjects were naïve to the aims of the experiment and they were inexperienced observers. One of the authors (SRB) was the eleventh subject and he was aware of the aims of the experiment. Data for subject SRB were analyzed separately for reasons discussed below. None of SRB's data has been included with the analyses of other subject's, however they are shown for comparison purposes in Figs. 2, 4 and Table 1. The subjects' ages ranged from 21 to 34 yrs. Their refractive errors, as denoted by the spherical equivalent of refraction, ranged from −3.75 to +0.50 D (Table 1). The first- and second-order dynamic characteristics of their disaccommodation step responses were similar to those described in an earlier paper (Bharadwaj & Schor, 2006). Overall, peak velocity and peak acceleration of all 11 subjects were invariant with response magnitude of disaccommodation from a constant starting position and peak velocity and peak acceleration of disaccommodation increased with the proximity of the starting position.

The peak velocity of disaccommodation was plotted separately for 10 subjects as a function of the starting positions of disaccommodation step responses and best-fit linear regression equations were fit to these plots to calculate the x-intercepts (Fig. 2). In 10 subjects, the relationship between the peak velocity and response starting position was described by a single linear regression equation. The robustness of the linear regression fit was assessed by computing the ±95% confidence intervals (Devore & Peck, 1993a). The x-axis zero-crossings of the confidence intervals provided the range of initial destination estimates permitted by the confidence intervals.

Prior to the measurement of the dark focus, subjects were seated in a dark room for approximately 5 min to allow any residual accommodation to decay (Fisher, Ciuffreda, Levine, & Wolf-Kelly, 1987; Wolf, Ciuffreda, & Jacobs, 1987). Following this, subjects were instructed to focus on a dark screen while their accommodation was measured using the Grand Seiko open-field binocular auto-refractor (Hiroshima, Japan) (Schor, Kotulak, & Tsuetaki, 1986; Westheimer, 1957; Whiteside, 1953). The dark screen (field of view: 47.48°; mean luminance: 0.52 cd/m^2) was devoid of any accommodative stimuli and hence provide a good viewing condition to measure the open-loop dark focus of accommodation (Schor et al., 1986; Westheimer, 1957; Whiteside, 1953). Fifteen measurements of the dark focus were obtained from the left eye of each subject and they were averaged to obtain the mean dark focus. The right eye was occluded during all the measurements. Subsequently, correlation between the dark focus and the initial destination, estimated from the x-intercept of the regression analysis using the Pearson's sample correlation coefficient (Devore & Peck, 1993b), was tested.

The cycloplegic refractive states were measured on 10 subjects (except subject AB who was not available for the experiment) on a separate day after the dynamic properties of the disaccommodation step responses were determined. Cycloplegia was achieved 20–30 min following instillation of 2–3 drops of 1% Tropicamide (Gettes & Belmont, 1961; Lovasik, 1986; Michaels, 1985). Cycloplegia was verified two ways. First, as a cursory check on the accommodative ability of the subject, a high contrast near-acuity card was slowly and progressively brought closer or moved away from the subject (push-up test; Grosvenor, 1996). The dioptric equivalent of the nearest distance where the subject could not read the smallest line of letters in the card was considered the maximum amplitude of accommodation. Maximum amplitude of accommodation of less than 0.5D was considered as full cycloplegia (Lovasik, 1986). Once an accommodative amplitude of less than 0.5 D was observed using the push-up test, the subjects were aligned in the SRI optometer and were asked to focus on a black and white Maltese cross that was optically defocused (step changes of 1–4 D) using the SRI stimulating optometer and accommodation was measured using the SRI recording optometer. The absence of any significant accommodation response to these step changes in optical defocus indicated full cycloplegia. Following this, the cycloplegic refractive states were measured fifteen times on each subject using the Grand Seiko open-field binocular auto-refractor (Hiroshima, Japan) and these measurements were averaged to obtain the mean cycloplegic refraction. Only the left eye was cyclopleged while the right eye was occluded during all the measurements. Subsequently, the cycloplegic refractive states were correlated with initial destinations as estimated from the x-intercept of the regression analysis using the Pearson's sample correlation coefficient (Devore & Peck, 1993b).

The data presented in this paper have taken into account each subject's distance refractive error that was measured and corrected in the aforementioned measurements. The results are normalized with respect to refractive error so that 0 D indicates the accommodative response at which the conjugate focus equaled the subject's far point. As a convention, positive values of cycloplegic refraction and dark foci indicated refractions closer than optical infinity (myopic refractions) and negative values of cycloplegic refraction and dark foci indicated refractions beyond optical infinity (hyperopic refractions).

3. Results

Data from 10 of the 11 subjects (except SRB) were analyzed together. Data of subject SRB will be described separately in Section 4. Peak velocities of disaccommodation for the 10 subjects increased significantly with the response starting position (Figs. 2A–E) (P value: <0.001). This relationship was well described by the linear regression equations shown in Figs. 2A–E suggesting that a default position could be used to describe the initial destination of disaccommodation. The slopes of the linear regression equations ranged from 0.82 to 2.04 s^{-1} and the y-intercepts ranged from −1.35 to +4.30 D/s across the 10 subjects (Table 1). Among the 10 subjects, the x-intercepts had negative values (range: −0.45 to −2.48 D) in nine subjects, implying that the initial destination of disaccommodation was located beyond optical infinity (Figs. 2A–D Table 1). In the tenth subject (KS), the x-intercept had a positive value (+0.92 D), implying that the initial destination was located closer than optical infinity (Fig. 2E, Table 1). The range of x-intercepts permitted by ±95% confidence intervals is shown in Table 1 for each subject. This range varied from ±0.19 to ±1.22 D across the 10 subjects.

[1] Cycloplegia is a clinical term that refers to a complete relaxation of accommodation (Giles, 1965; Michaels, 1985; Pragnen, 1931) and it occurs as a result of blocking the parasympathetic innervation (paralysis) to the ciliary muscle (Mitchell, 1960).

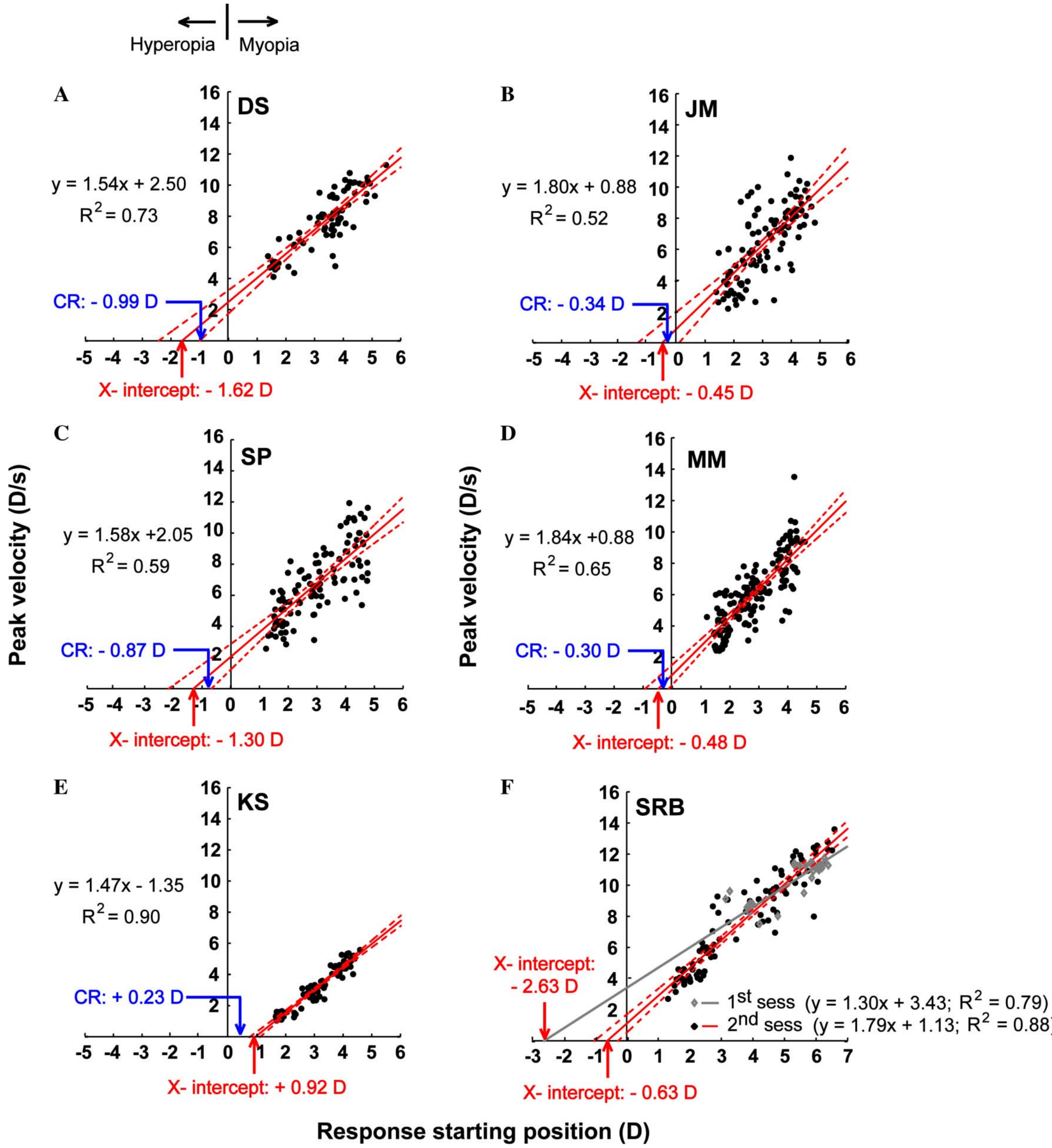

Fig. 2. Peak velocity of disaccommodation plotted as a function of response starting position for five representative subjects (A–E) and for subject SRB (F). The solid red lines in each figure represent the linear regression equation fit to the data and the dashed red lines indicate the ±95% confidence intervals. The *x*-intercept indicates the estimated initial destination of disaccommodation and the zero-crossings of the confidence intervals indicated the range of *x*-intercepts permitted by the confidence intervals. For subject SRB, two separate linear regression equations were computed, one for the first session (open squares, gray solid and dashed line) and the other for the second session (filled circles, red solid and dashed line). The *x*-intercept for the first session was more distal than the *x*-intercept for the second session. In figures A–F, the dioptric location of *x*-intercept is identified by the red arrowhead and the dioptric location of the cycloplegic refraction (CR) is identified by the blue arrowhead. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this paper.)

Fig. 3 shows representative traces of accommodation responses to step changes in optical defocus (1–4 D) prior to- and following complete cycloplegia. The response trace prior to cycloplegia illustrated clear accommodation and disaccommodation step responses whose amplitudes were correlated with the step changes in stimulus defocus (Fig. 3). In contrast, the response traces following cycloplegia for accommodation or disaccommodation did not change significantly with stimulus defocus (Fig. 3). The post-cycloplegic responses also had a significant shift towards a negative (hyperopic) refraction (Fig. 3). The mean cycloplegic refractive state was hyperopic (range: −0.297 to −1.811 D) in nine of the 10 subjects (Fig. 4A, Table 1), showing that the cycloplegic refractive state of accommodation was located beyond optical infinity. For the tenth subject (KS), the mean cycloplegic refractive state was positive (+0.228 D), showing that the cycloplegic refractive state was located closer than optical infinity

Table 1
Distance refractive errors, linear regression equation of plot of peak velocity as a function of response starting position, initial destination estimated from x-intercept, mean cycloplegic refraction and dark focus of accommodation for all subjects

Subject	Refractive error (D)	Peak velocity vs. starting position regression equation	Estimated initial destination (D)	Cycloplegic refractive state (D)	Dark focus of accommodation (D)
KS	−3.75	$y = 1.47x - 1.35$	+0.915 ± 0.19	+0.228 ± 0.08	+1.388
ER	+0.50	$y = 0.82x + 1.74$	−2.129 ± 0.94	−1.811 ± 0.100	+0.250
JM	0.00	$y = 1.80 + 0.80$	−0.446 ± 0.72	−0.343 ± 0.115	+0.575
MM	0.00	$y = 1.84x + 0.88$	−0.477 ± 0.41	−0.297 ± 0.267	+0.505
DS	+0.50	$y = 1.54x + 2.50$	−1.620 ± 0.72	−0.995 ± 0.103	+1.043
SP	−3.25	$y = 1.58x + 2.05$	−1.299 ± 0.75	−0.870 ± 0.210	+0.785
MT	−2.50	$y = 1.92x + 2.67$	−1.240 ± 1.05	−0.760 ± 0.127	+1.315
SL	−0.37	$y = 1.91x + 4.08$	−2.136 ± 0.57	−0.870 ± 0.130	+0.880
KY	−0.25	$y = 1.58x + 1.17$	−0.745 ± 0.80	−0.87 ± 0.210	+0.063
AB	−2.50	$y = 0.89x + 2.16$	−2.418 ± 1.22	—	+0.808
SRB I	−1.50	$y = 1.30x + 3.43$	−2.630	—	—
SRB II	−2.25	$y = 1.79x + 1.13$	−0.630 ± 0.38	−1.58 ± 0.268	+0.113

The refractive errors in column 1 indicate the spherical equivalent of refraction. The ± errors in column 3 indicate the range of x-intercepts permitted by the ±95% confidence intervals. The ± errors in other columns indicate 1 SD from the mean.

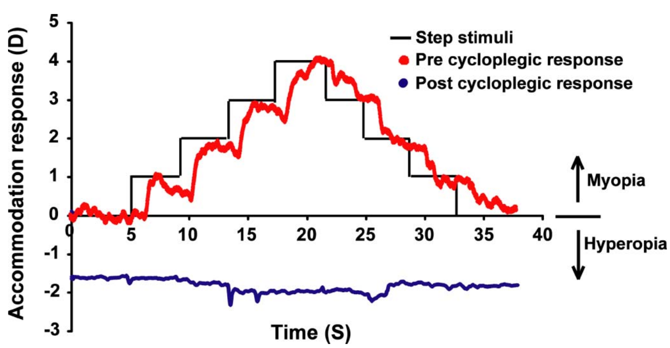

Fig. 3. Representative accommodation and disaccommodation responses to step changes in optical defocus (1–4 D in 1 D steps; solid black line) prior to- and following cycloplegia. The response trace prior to cycloplegia (solid red trace) showed clear accommodation and disaccommodation step responses that were correlated with the step changes in stimulus defocus. The response trace following cycloplegia (solid blue trace) showed no significant changes in accommodation and disaccommodation response. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this paper.)

(Fig. 4A, Table 1). The mean dark focus of accommodation (range: +0.11 to +1.39 D) were positive (myopic refractive state) for all 10 subjects (Fig. 4A, Table 1). This illustrates that the dark focus of accommodation were located closer than optical infinity in all 10 subjects. The cycloplegic refractive state measured in nine subjects (except AB), was well correlated with the estimated initial destination of disaccommodation ($y = 0.54x - 0.13$; r^2: 0.81) (Fig. 4B) while the dark focus of accommodation, measured in 10 subjects, were poorly correlated with the estimated initial default destination of disaccommodation ($y = 0.09x + 0.87$, r^2: 0.05) (Fig. 4C).

4. Effects of training on the dynamics of disaccommodation: Methods and results

Disaccommodation step responses for subject SRB were collected on two occasions (first session and second session), separated by a one-year period. Effects of training on the dynamics of disaccommodation were illustrated by different dynamic properties on the two occasions. A detailed account of the changes in his dynamics can be found in Bharadwaj and Schor (2006). Overall, in the first session, SRB's dynamic disaccommodation responses had the same pattern as for the other subjects: peak velocity increased with starting position, irrespective of response magnitude. In the second session, the pattern was different: peak velocity of his disaccommodation response increased with response magnitude from a common starting position, demonstrating a different control strategy than used by the other subjects or in the first session (Schor & Bharadwaj, 2006). Linear regressions of peak velocity on response starting position were compared for both sessions. Because peak velocity in the second session increased with response magnitude from a fixed starting position, only those data points that corresponded to responses to the far point were used to fit the regression equation. ±95% confidence intervals were computed only for the data of the second session. The x-intercepts of the linear regression equations for both sessions had a negative value implying that the initial destination of disaccommodation was located beyond optical infinity. The x-intercept was located more distally in the first session (−2.63 D) than in the second session (−0.63 D) (Fig. 2F, Table 1). In retrospect, it would have been ideal to measure changes in the dark focus of accommodation and the cycloplegic refraction in the first session along with the changes in the dynamic trends of disaccommodation. However, the observed change in the dynamic strategy of disaccommodation in the second session was serendipitous and was not being predicted. Hence the dark focus and the cycloplegic refractive state are only reported for the second session. The mean dark focus of accommodation for his second session was +0.113 D. The mean cycloplegic refractive state was −1.578 ± 0.27 D after his second session.

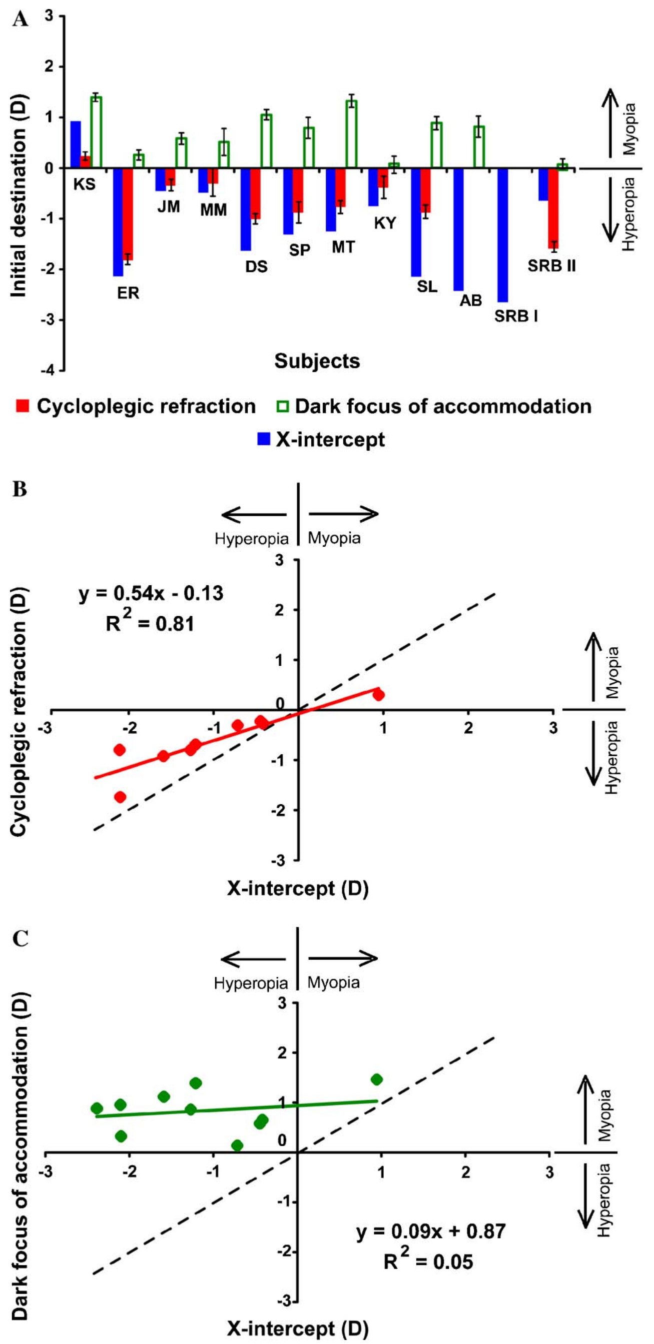

Fig. 4. (A) Bar graphs of initial destination of disaccommodation, estimated from x-intercepts of Fig. 2, cycloplegic refractive state and dark focus of accommodation for all subjects. Since the cycloplegic refractive state and dark focus measurements for subject SRB were made after the second session, they are shown along with the estimated initial destination from the second session. Positive values of the ordinate indicate refractions closer than optical infinity (myopia) and negative values of the ordinate indicate refractions beyond optical infinity (hyperopia). (B) Cycloplegic refraction is plotted for nine subjects as a function of estimates based on x-intercepts of their initial destination of disaccommodation. The cycloplegic refractions were well correlated with the x-intercept estimates of the initial default destination of disaccommodation (r^2: 0.81). (C) Dark focus of accommodation plotted for 10 subjects as a function of the x-intercept estimates of initial destination of disaccommodation. The dark focus was poorly correlated with the initial default destination of disaccommodation (r^2: 0.05). The dashed line in figures (B) and (C) is the 1:1 line that indicates perfect correspondence between the parameters in the abscissa and ordinate.

5. Effect of altering the dark focus of accommodation on the dynamics of disaccommodation

Yamada and Ukai (1997) proposed that the peak velocity of disaccommodation was determined by the dioptric difference between the response starting position and the dark focus of accommodation. This proposition was tested by changing the dark focus and its dioptric difference from the starting position. This should result in predictable changes in the peak velocity of responses toward the initial destination of disaccommodation. Shifting the dark focus in the myopic direction should reduce the dioptric difference between start position and initial destination. This should decrease the peak velocity and peak acceleration of disaccommodation (Fig. 5A). Conversely, shifting the dark focus in the hyperopic direction should, increase the dioptric difference and increase the peak velocity and peak acceleration of disaccommodation (Fig. 5A). We tested this prediction by shifting the dark focus of accommodation in the hyperopic direction and concurrently measuring its influence on the peak velocity and peak acceleration of disaccommodation. Hyperopic shifts in the dark focus were produced by fatiguing the accommodative system using repeated optical stimulation of accommodation and disaccommodation step responses (Hasebe, Graf, & Schor, 2001).

A subset of the subjects who took part in the main experiment also took part in this control experiment. Subjects were corrected for their distance refractive error and aligned in the SRI dynamic optometer (Crane & Steele, 1986) after their left eye was dilated with 2.5% Phenylephrine hydrochloride eye drops. Once the calibration routine was completed (Bharadwaj & Schor, 2006, 2005), pulse changes in optical defocus were presented repeatedly with the SRI stimulus optometer while the subjects maintained focus a black and white Maltese cross. Ideally, to study if the x-intercept described earlier is influenced by the hyperopic shift of the dark focus, peak velocity of disaccommodation from multiple starting positions should be assessed. However, considering the cumbersome nature of the experiment, the peak velocity from only two starting positions (4 and 2 D) were studied. The two disaccommodation stimuli were presented as two different pulse stimulus configurations. In the first configuration, the pulse stimulus had a magnitude of 4 D and duration of 6 s (Fig. 5B). In the second combination, the pulse stimulus had a magnitude of 2 D and duration of 4 s (not shown). The ascending limb of the pulse (0–4 or 0–2 D) stimulated accommodation responses and the descending limb of the pulse (4–0 or 2–0 D) stimulated disaccommodation responses (Fig. 5B). Both the pulse stimulus configurations had a duty cycle of 0.8, where the duty cycle was defined as the ratio of the sum of all pulse durations during the experimental session to the total duration of the experimental session. This resulted in total durations of 25 and 17 min for the first and second configurations, respectively. Pulse stimuli with a similar duty cycle have been used before to induce fatigue in the

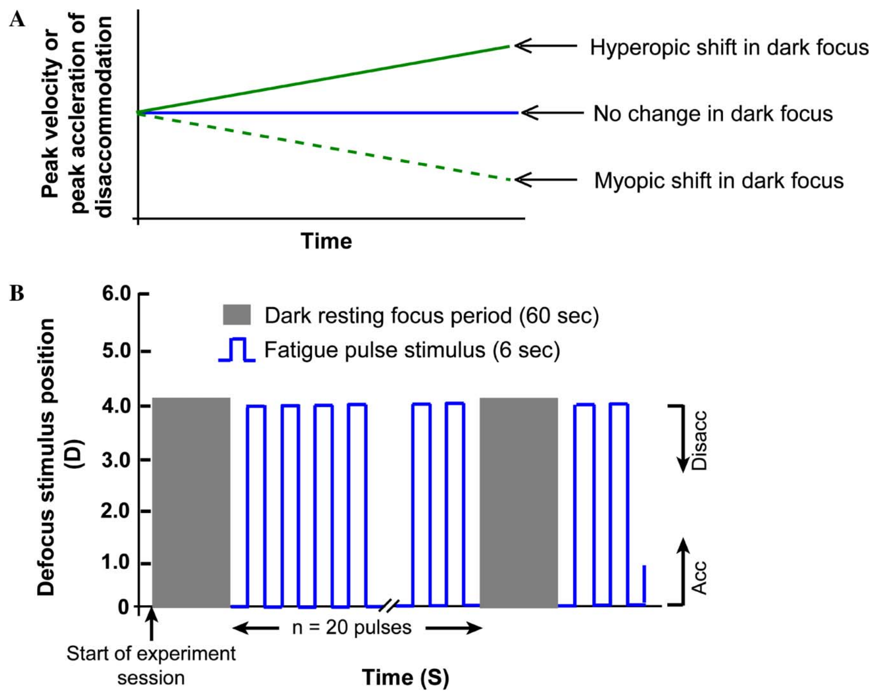

Fig. 5. (A) Hypothetical changes of peak velocity or peak acceleration of disaccommodation during changes of dark focus produced by fatigue. The initial destination of disaccommodation is assumed to correspond to the dark focus of accommodation. Peak velocity or peak acceleration increase with fatigue duration when the dark focus of accommodation shifts in a hyperopic direction (solid green line). Peak velocity or peak acceleration decrease with fatigue duration when the dark focus of accommodation shifts in a myopic direction (dashed green line). Peak velocity or peak acceleration would not change with time if the dark focus did not change or if the dark focus of accommodation did not correspond to the initial destination of disaccommodation (solid red line). The slopes of the solid and dashed green lines are set to an arbitrary scale. (B) Schematic illustration of the experimental paradigm used to induce fatigue in the accommodation system. The gray rectangles represent periods of complete darkness used to measure the dark focus of accommodation. The red lines represent pulse changes in optical defocus with the ascending limb of the pulse stimulating accommodation and the descending limb of the pulse stimulating disaccommodation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this paper.)

accommodation system (Hasebe et al., 2001; Vilupuru, Kasthurirangan, & Glasser, 2005). In a given experimental session, only one of the two configurations was presented and the two configurations were tested on separate days. Dark focus measurements were obtained for a period of 1 min once before the start of the fatigue session and once after every set of 20 pulse stimuli (Fig. 5B). During measurements of the dark focus of accommodation, the light source illuminating the Maltese cross was turned off to create a completely dark setting. The experimental session was continued for either the entire length (25 or 17 min) or until the subject could no longer sit comfortably inside the instrument. Accommodation and disaccommodation responses to the pulse stimuli and the dark focus measurements were recorded (sampling frequency: 200 Hz) with the SRI recording optometer (Cornsweet & Crane, 1970) and were stored for offline analysis. The peak velocity and peak acceleration of accommodation and disaccommodation were obtained from the ascending and descending limbs, respectively, of the pulse stimulus using the same procedure described by Bharadwaj and Schor (2006). The peak velocity and peak acceleration data from each set of 20 pulse stimuli were grouped and compared for statistical significance using a single-factor ANOVA test. The mean and ±1 SD of peak velocity and peak acceleration of each data group were also computed. Dark focus recordings usually showed a rapid decay in dioptric power until a steady-state was attained. Dark focus of accommodation was defined as the dioptric power of the eye during this steady-state period.

Six subjects (ER, SP, MT, KS, DS, and SL) took part in the experimental session with the first configuration (4 D amplitude and 6 s duration) and three subjects (KS, DS, and SL) took part in the experimental session with the second configuration (2 D amplitude and 4 s duration). Fig. 6 plots the result of the dark focus of accommodation and of the first- and second-order dynamics obtained from the first configuration. Four subjects showed a progressive hyperopic shift in the dark focus of accommodation as the sessions progressed while the fifth subject (ER) did not show any significant shift in his dark focus of accommodation (Fig. 6A, Table 2). Figs. 6B and C illustrate peak velocity of disaccommodation and accommodation, respectively, plotted as a function of session number. None of the subjects showed a significant change in the peak velocity of either disaccommodation (Fig. 6B, Table 2) or accommodation (Fig. 6C) as the sessions progressed. The single-factor ANOVA test did not show a significant change in peak velocity of either disaccommodation or accommodation with session number (P value: >0.5). Similar results were obtained in the data of peak acceleration of disaccommodation (Fig. 6D, Table 2) and accommodation (Fig. 6E).

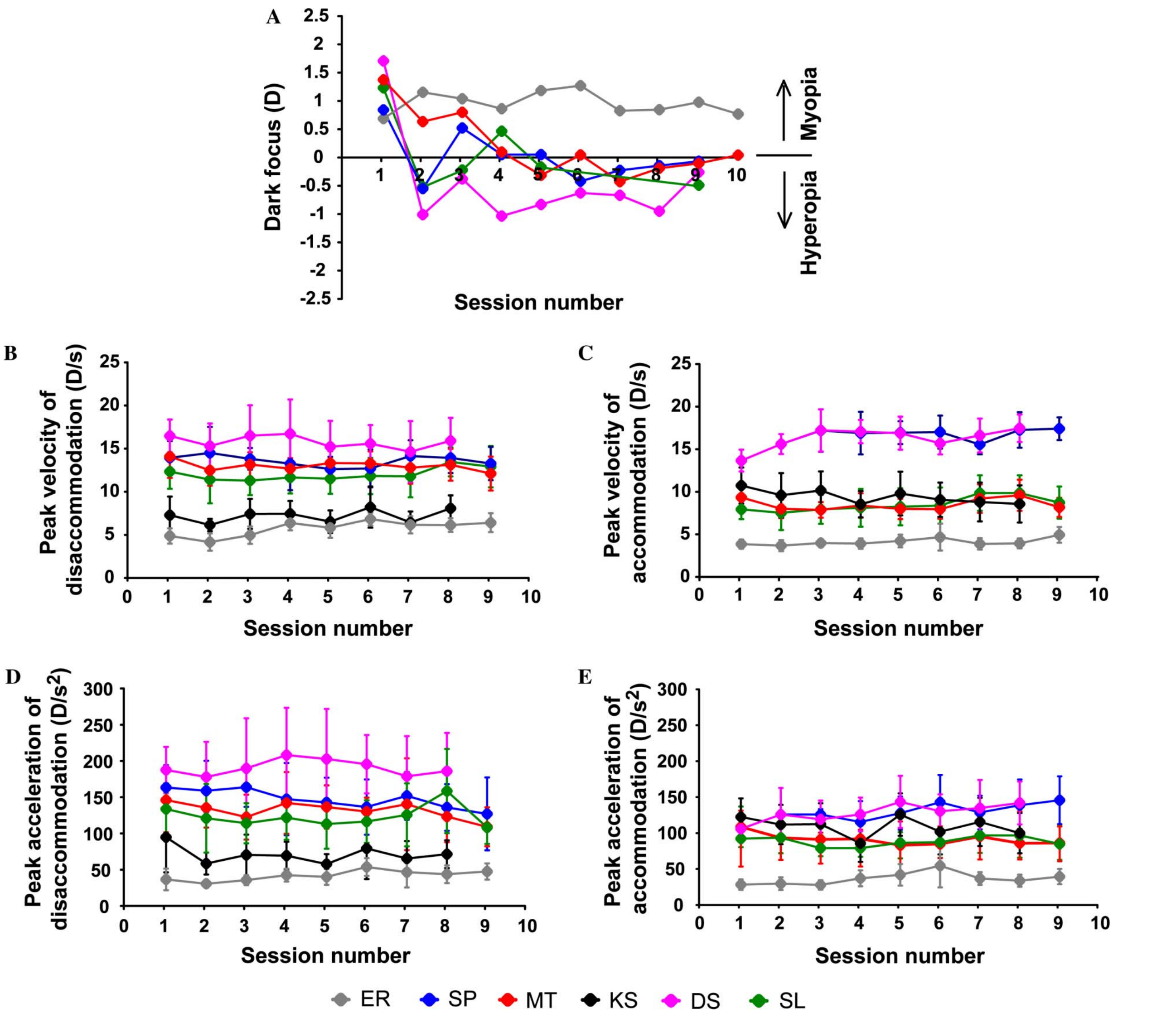

Fig. 6. Results of the fatigue experiment wherein the dark focus of accommodation was shifted in the hyperopic direction inducing 'fatigue' in the system. The peak velocity and peak acceleration of disaccommodation and accommodation were measured concurrently with the dark focus. (A) Dark focus of accommodation plotted as a function of session number for the first configuration (4 D pulse amplitude and 6 s pulse duration).This experiment was run on six subjects but reliable dark focus measurements were obtained only from five subjects. Positive values of the ordinate indicate refractions closer than optical infinity and negative values of the ordinate indicate refractions beyond optical infinity. The first data point for each subject represents the dark focus measurement prior to the start of the 'fatigue' trials and each subsequent data point represents the dark focus measurement made after the end of each session (comprising of 20 trials each). (B and C) Peak velocity of disaccommodation and accommodation plotted as a function of session number, respectively, for six subjects obtained with the first configuration stimulus. (D and E) Peak acceleration of disaccommodation and accommodation plotted as a function of session number, respectively, for six subjects obtained with the first configuration stimulus. In figures B–E, each data point and error bar represents an average and ±1 SD of one session (comprising of 20 trials).

None of the subjects showed any significant change in peak acceleration of either disaccommodation or accommodation with session number (*P* value: >0.5). Results of the experimental session with the second configuration (not shown) were qualitatively similar to the results described above. The dark focus of accommodation showed a hyperopic shift as the sessions progressed. However, this shift in dark focus was not as sustained or robust as those seen with the first configuration. Neither the peak velocity nor the peak acceleration of disaccommodation and accommodation changed significantly with session number (*P* value: >0.5) in the three subjects. As expected (Bharadwaj & Schor, 2006, 2005), the peak velocity and peak acceleration of both accommodation and disaccommodation were smaller in the second configuration than in the first configuration. For example, for subject DS, the peak velocity and peak acceleration of disaccommodation in the first configuration was 15.41 ± 0.73 D/s and 186.28 ± 10.73 D/s^2, respectively (Figs. 6B and C). For the same subject, the peak velocity and peak acceleration of disaccommodation in the second configuration was 5.92 ± 0.86 D/s and 60.97 ± 10.58 D/s^2, respectively. Similarly, for subject DS, the peak velocity and peak acceleration of accommodation in the first configuration was 15.90 ± 1.25 D/s and 123.93 ± 12.31 D/s^2,

Table 2
Dark focus of accommodation (DF), mean peak velocity of disaccommodation (PV) and mean peak acceleration of disaccommodation (PA) measured on six subjects for sessions 1–10 during the fatigue experiment

Subjects	Session type	Session number									
		1	2	3	4	5	6	7	8	9	10
ER	DF	0.63	1.10	0.98	0.81	1.13	1.21	0.77	0.77	0.92	0.71
	PV	4.48 ± 0.88	3.78 ± 1.00	4.58 ± 1.00	5.99 ± 0.86	5.43 ± 1.16	6.44 ± 0.74	5.78 ± 1.00	5.75 ± 0.79	6.02 ± 1.09	
	PA	32.05 ± 14.86	26.01 ± 5.10	31.10 ± 6.85	37.93 ± 8.92	35.51 ± 10.87	49.19 ± 12.25	42.02 ± 21.01	39.20 ± 12.24	43.04 ± 11.17	
SP	DF	0.79	−0.60	0.46	−0.01	−0.02	−0.48	−0.29	−0.20	−0.13	
	PV	13.56 ± 1.93	14.12 ± 3.01	13.44 ± 1.26	12.88 ± 3.08	12.24 ± 1.42	12.32 ± 2.19	13.75 ± 1.84	13.54 ± 1.75	12.89 ± 1.93	
	PA	158.87 ± 30.9	154.42 ± 41.4	159.29 ± 27.0	142.93 ± 49.8	138.34 ± 34.1	131.91 ± 38.2	147.39 ± 32.9	131.38 ± 32.1	122.49 ± 50.2	
MT	DF	1.31	0.58	0.74	0.04	0.37	−0.01	−0.48	−0.25	−0.16	−0.02
	PV	13.70 ± 2.48	12.10 ± 1.78	12.77 ± 1.41	12.29 ± 1.22	12.94 ± 1.38	12.91 ± 1.38	12.41 ± 1.87	12.74 ± 1.85	11.72 ± 1.96	
	PA	141.52 ± 44.5	130.89 ± 27.3	118.03 ± 30.9	137.59 ± 42.6	132.00 ± 29.8	125.64 ± 19.3	135.86 ± 63.4	118.80 ± 35.3	104.62 ± 26.8	
KS	DF	—	—	—	—	—	—	—	—	—	—
	PV	6.90 ± 2.15	5.76 ± 0.71	7.05 ± 1.73	7.07 ± 1.47	6.15 ± 1.30	7.83 ± 2.39	6.05 ± 1.27	7.69 ± 1.50		
	PA	90.35 ± 48.57	53.92 ± 15.15	65.77 ± 28.14	64.85 ± 19.25	53.16 ± 13.87	74.83 ± 24.21	60.83 ± 24.21	66.82 ± 19.09		
DS	DF	1.52	−1.20	−0.56	−1.12	−1.02	−0.81	−0.85	−1.14	−0.45	
	PV	16.10 ± 1.90	14.92 ± 2.61	16.11 ± 3.54	16.34 ± 4.00	14.85 ± 2.99	15.18 ± 2.17	14.26 ± 3.54	15.52 ± 2.66		
	PA	183.05 ± 31.9	173.42 ± 48.6	185.26 ± 69.1	203.61 ± 53.2	198.17 ± 69.3	191.01 ± 40.2	174.35 ± 55.5	181.38 ± 52.8		
SL	DF	0.88	−0.87	−0.57	0.11	−0.52	—	—	—	−0.84	
	PV	11.96 ± 1.99	11.01 ± 2.75	10.90 ± 1.68	11.27 ± 1.85	11.13 ± 1.76	11.44 ± 2.10	11.40 ± 2.44	13.08 ± 1.68	12.52 ± 2.40	
	PA	129.14 ± 35.5	116.46 ± 47.3	109.61 ± 27.7	117.36 ± 30.5	108.59 ± 34.2	111.94 ± 29.4	121.16 ± 43.4	154.03 ± 58.1	103.78 ± 22.8	

The first measurement of the dark focus was made prior to the start of the fatigue sessions. Dark focus is denoted in D, peak velocity is denoted in D/s and peak acceleration is denoted in D/s^2. Positive values of dark focus indicate myopic refractions while negative values of dark focus indicates hyperopic refractions. The ± errors in the PV and PA rows of each subject indicate 1 SD from the mean.

respectively (Figs. 6D and E). For the same subject, the peak velocity and peak acceleration of disaccommodation in the second configuration was 10.41 ± 1.00 D/s and 110.00 ± 9.49 D/s^2, respectively.

6. Discussion

The results of this experiment are summarized by the following four points:

1. The plots of peak velocity as a function of response starting position have negative x-intercepts in nine subjects and a positive x-intercept in the tenth subject (KS). The linear regression fit to these data suggests that the estimated initial destination of disaccommodation is to a position located beyond optical infinity in nine subjects and it is located at a finite distance in front of optical infinity in the tenth subject.
2. Among the nine subjects for whom cycloplegic refractive state was measured, the estimated initial destination correlated well with the cycloplegic refractive state and poorly with their dark focus of accommodation.
3. For subject SRB, the estimated initial destination of disaccommodation was located beyond optical infinity in both sessions. The initial destination was located more distally in the first session and its location moved more proximally in the second session demonstrating a change in the control strategy for dynamic disaccommodation.
4. The peak velocity and peak acceleration of disaccommodation did not change in a subset of six subjects despite a progressive hyperopic shift in their dark focus of accommodation. This finding is contrary to the prediction that, if the dark focus of accommodation is the initial destination of disaccommodation, then a hyperopic shift in the dark focus should result in an increase in the peak velocity and peak acceleration of disaccommodation.

6.1. Dioptric location of the initial (default) destination of disaccommodation and its behavioral correlate

The first- and second-order dynamic properties of disaccommodation from a constant starting position remain invariant of the response magnitude, and they increase linearly with the proximity of the starting position of disaccommodation (Bharadwaj & Schor, 2006). These observations suggest that the disaccommodation responses are initiated towards a constant initial destination and they are switched mid-flight to attain their desired final destination (Bharadwaj & Schor, 2006; Schor & Bharadwaj, 2006; Yamada & Ukai, 1997). In our experiment, the estimated initial destination of disaccommodation was located beyond optical infinity in nine of the 10 subjects. Hyperopic refractions ranging from 0.5 to 1.5 D are often observed in humans (Giles, 1965; Michaels, 1985) and in primates (Gamlin, Zhang, Clendaniel, & Mays, 1994; Westheimer & Blair, 1973) following complete cycloplegia. Since our estimates of the initial destination of disaccommodation (range: -0.45 to -2.58 D) were in the range of hyperopia produced by complete cycloplegia, we conjectured that the subject's cycloplegic refractive state of accommodation was a possible behavioral correlate of the initial destination of disaccommodation.

Yamada and Ukai (1997) however found that the initial destination of disaccommodation of their subjects to corresponded with the dark focus of accommodation. We explored these two possibilities by measuring the cycloplegic refractive states and the dark focus of accommodation and correlating these measurements with the initial destination of disaccommodation that was estimated from the x-intercept of the linear regression of peak velocity and starting position. Across subjects, the x-intercept correlated well with the cycloplegic refractive states (r^2: 0.81) (Fig. 4B) and poorly with the dark focus of accommodation (r^2: 0.05) (Fig. 4C). This illustrates that the cycloplegic refractive state is a better behavioral correlate of the initial destination of disaccommodation than is the dark focus of accommodation. The differences in the results of our experiment and those of Yamada and Ukai could be due to inter-individual variability (Schaeffel, Wilhelm, & Zrenner, 1993) or it could be due to the methodological differences discussed next in Section 6.3.

The cycloplegic refractive state reduces innervation of the ciliary muscle to zero. Good behavioral correlation between the initial destination and the cycloplegic refractive state suggests that disaccommodation step responses from a starting position are initiated towards the cycloplegic refraction state by a reduction of innervation of the ciliary muscle toward zero. However, the linear regression equation ($y = 0.54x - 0.13$) of a plot of cycloplegic refraction as a function of the x-intercept had a non-unity slope (solid line in Fig. 4B), thus raising a possibility that the reduction in ciliary muscle innervation during initiation of the step response is not coincident with the neural correlate of the cycloplegic refraction. While there is no simple behavioral test that would argue for or against this possibility, the non-unity slope could be a result of incomplete cycloplegia. The cycloplegic refractions of all our subjects (except KS) were less hyperopic than the x-intercept (Fig. 4A, Table 1), presumably due to weak cycloplegic effect of 1% Tropicamide. This suggests that the non-unity slope in Fig. 4B could be due to an incomplete relaxation of the ciliary muscle following cycloplegia. Another factor is that the cycloplegic refractions for all our subjects (except SL) lie within the range of x-intercepts permitted by their $\pm 95\%$ confidence intervals (Fig. 2, Table 1). This suggests that estimates of initial destination and cycloplegic refraction are within the range of experimental variability and that the non-unity slope in Fig. 4B could be affected by variability in measures of peak velocity and response starting positions.

6.2. Exponential-fit analysis of initial destination

Yamada and Ukai (1997) estimated the initial destination of disaccommodation by fitting exponential functions

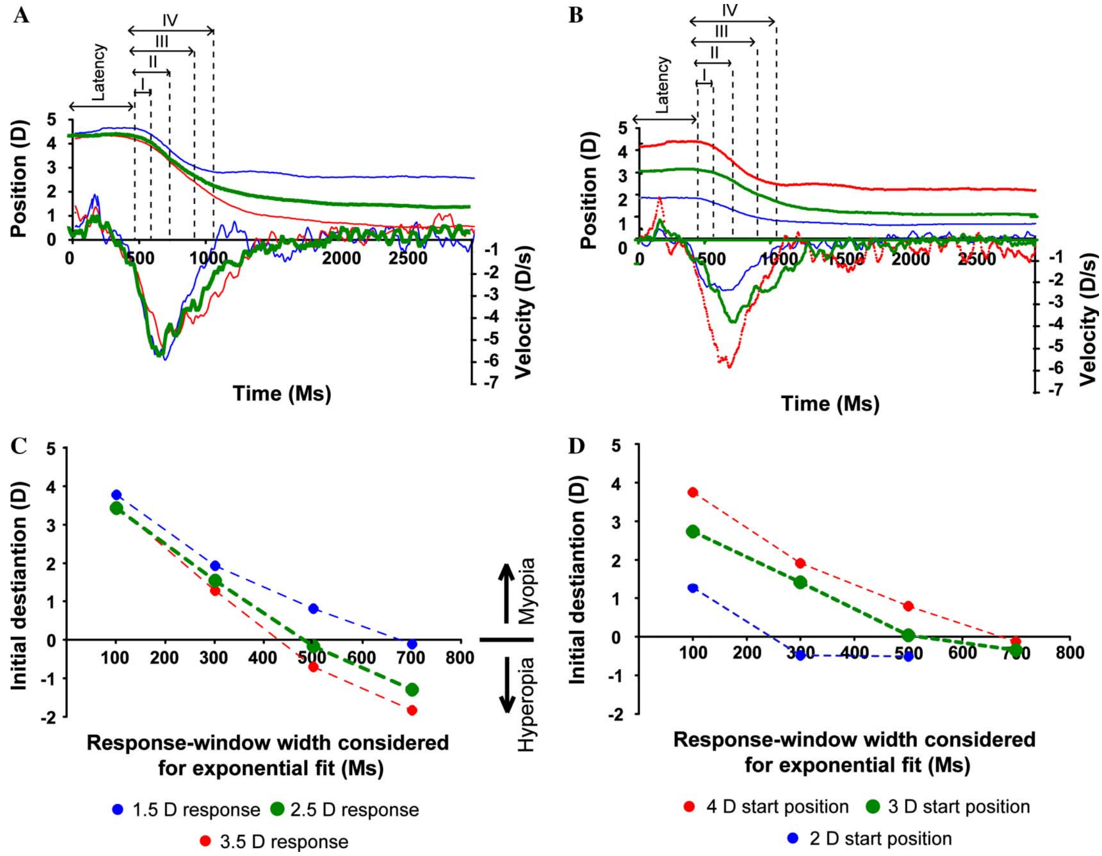

Fig. 7. The initial destination of disaccommodation estimated by fitting exponential functions to responses of different magnitudes from the same starting position (A) and to responses of similar magnitudes from three-different starting positions (B). Five different response-window widths (I: 100 ms, II: 300 ms, III: 500 ms, and IV: 700 ms following the response-latency period) were considered for the exponential curve fitting (dashed-vertical lines in A and B). Estimated initial destination of disaccommodation plotted as a function of response-window width for different magnitude responses from the same starting position (C) and for responses of similar magnitudes from three-different starting positions (D).

of the form $f(t) = a + b * (\exp(-t/\tau))$ to the 'first half' of the disaccommodation response. The coefficient 'a' of the exponential equation indicated the initial destination of disaccommodation when time (t) becomes large. The dioptric value of coefficient 'a' was positive in all their subjects and it corresponded well with the dark focus of accommodation measured in these subjects. To examine if the assumption that an exponential-fit to the 'first half' of the response predicted initial destination, we repeated Yamada and Ukai's analysis on the disaccommodation responses of two of our subjects (Figs. 7A–D). The location of the initial destination was determined for different response magnitudes (Fig. 7A) and for different starting positions (Fig. 7B). We measured the initial destination, estimated from coefficient 'a' of the exponential fit, for five different response-window widths, corresponding to 100, 300, 500, and 700 ms following the response-latency period (Figs. 7A and B). Three significant trends were observed in this analysis. First, the estimated initial destination for all response magnitudes and starting positions shifted systematically towards optical infinity as the analyzed response-window width increased (Figs. 7C and D). Second, for a given response-window width, the estimated initial destination also shifted systematically towards optical infinity as the response magnitude increased (Fig. 7C), except for the 100 ms window where a minimal shift occurred. Third, for a given width of the response-window, the estimated initial default destination shifted towards optical infinity as starting position decreased (Fig. 7D). The distal shift in the initial destination of disaccommodation as width of response-window increased raises the possibility that the response-window width chosen by Yamada and Ukai was too narrow to apply the exponential analysis fit, and this caused the initial destinations to correspond with their subjects' dark focus of accommodation. Had a wider width response-window been chosen for the analysis, the initial destination probably would have been more distal than the dark focus of accommodation. Furthermore, the second and third trends observed in our exponential fit analysis were qualitatively very similar those obtained by Yamada and Ukai (1997) illustrating that when this analysis is based on the first half of the response, it produces results that are neither stable across different response magnitudes nor across different starting positions.

Alternatively, we can estimate the dioptric location of the initial destination of disaccommodation using our analytical technique to calculate the x-intercept of linear regression of peak velocity on response starting position

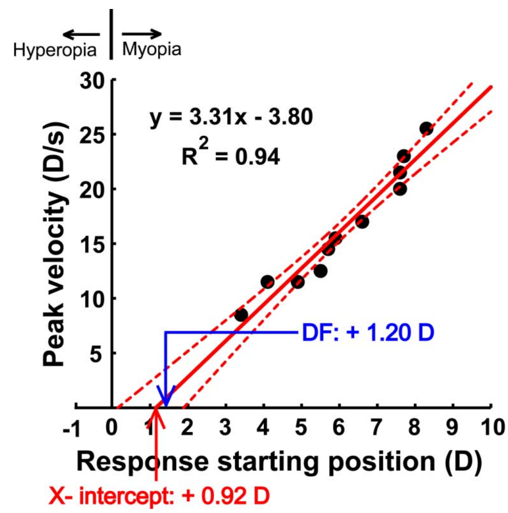

Fig. 8. Initial destination of disaccommodation estimated from a plot of peak velocity as a function of response starting position for one subject who took part in Yamada and Ukai's experiment (Yamada & Ukai, 1997). Raw data of peak velocity and response starting position were obtained from Fig. 3 in their paper. Peak velocity is plotted as a function of response starting position and a best fit-linear regression equation is fit to this data (solid line) along with the ±95% confidence intervals (dashed lines). The initial destination, as estimated from the *x*-intercept of the linear regression fit, was located 1.15 ± 0.87 D proximal to optical infinity. The dioptric location of *x*-intercept is identified by the red arrowhead and the dioptric location of the dark focus (DF) is identified by the blue arrowhead. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this paper.)

from the raw data provided by Yamada and Ukai (Ukai, 2005). We performed our regression analysis on the data of only one subject whose raw data is presented in their paper (see their Fig. 3). Our analysis estimated the initial destination of this subject to be located at 1.15 ± 0.87 D proximal to optical infinity (Fig. 8), which is close to his mean dark focus of accommodation (1.20 D). The authors however did not report their subject's cycloplegic refractive states. Even so, this result is contrary to the results obtained in our experiment. Although no conclusions can be derived from the data of one subject, the result does indicate that the initial destination of disaccommodation could lie close to the dark focus of accommodation in some subjects and that significant inter-individual variability (Schaeffel et al., 1993) could account partially for the difference in the results of the two experiments.

6.3. Influence of shifting the dark focus of accommodation on the dynamics of disaccommodation

If the dioptric difference between the dark focus of accommodation and the starting position of disaccommodation determines the peak velocity of disaccommodation, then the experimentally altered dioptric location of the dark focus should produce predictable changes in the dynamics of disaccommodation. Reducing the dioptric difference (by shifting the dark focus in the myopic direction) should decrease the peak velocity of disaccommodation (Fig. 5A) and increasing the dioptric difference between starting position and dark focus, by shifting the dark focus in the hyperopic direction, should increase the peak velocity of disaccommodation (Fig. 5A). Our fatigue experiment revealed that a significant hyperopic shift in the dark focus (Fig. 6A), induced by fatiguing the accommodation system (Hasebe et al., 2001), had no influence on the peak velocity and peak acceleration of disaccommodation (Figs. 6B and D). No significant change in the peak velocity and peak acceleration of disaccommodation from both the 4 and 2 D starting positions were seen with the hyperopic shift of dark focus. These results indicate that the *x*-intercept (obtained from the linear regression of peak velocity as a function of starting position) did not change with the hyperopic shift of the dark focus and that the dark focus of accommodation is not the initial destination of disaccommodation. Our findings corroborate the results of Vilupuru et al. (2005) for the 5 and 6 D starting positions of disaccommodation. It is possible that neuro-muscular fatigue in the accommodative system and/or a generalized reduction in performance associated with visual fatigue (Hasebe et al., 2001; Owens & Wolf-Kelly, 1987; Takeda, Ostberg, Fukui, & Iida, 1988; Vilupuru et al., 2005) could have masked the enhancement of peak velocity and peak acceleration of disaccommodation that was associated with the hyperopic shift in dark focus. The dynamics of accommodation step responses do not follow an 'initial-destination' strategy (Schor & Bharadwaj, 2006) and hence are unlikely to be affected by changes in the location of the dark focus. Indeed, neither the peak velocity (Fig. 6C) nor the peak acceleration (Fig. 6E) showed any significant reduction in magnitude with fatigue. Overall, our results suggest minimal influence of accommodative and visual fatigue on the dynamics of accommodation and disaccommodation.

We used accommodative fatigue as a technique to alter the dark focus of accommodation. This technique was chosen over more conventional ways of altering the dark focus, such as by using pharmacological agents (Gilmartin, 2000) or by sustained nearwork (Rosenfield, Ciuffreda, Hung, & Gilmartin, 1994), for the following reasons. Pharmacological agents such as timolol maleate or isoprenaline sulphate change the dark focus by intervening with the peripheral autonomic innervation at the level of the ciliary muscle (Gilmartin, 2000). It would thus be contextually inappropriate to employ this technique to assess the relationship between the dark focus and the neural control disaccommodation dynamics.

The myopic shift in the dark focus following sustained nearwork (Rosenfield et al., 1994) could be influenced by both parasympathetic and sympathetic innervations. For example, a sustained nearwork prolongs the duration of disaccommodation step responses in myopes who show diminished sympathetic inhibition (Ciuffreda & Wallis, 1998; Culhane & Winn, 1999; Culhane, Winn, & Gilmartin, 1999; Winn, Culhane, Gilmartin, & Strang, 2002) but it does not influence the response duration in emmetropes (Ciuffreda & Wallis, 1998; Culhane & Winn, 1999).

However, a lack of precise understanding of the interactions between sympathetic and parasympathetic activity that causes the dark focus to shift myopically following sustained nearwork, precludes one from using this technique to study the relationship between dark focus and the neural control strategies of disaccommodation. When compared to pharmacological intervention and sustained nearwork, the use of accommodative fatigue to hyperopically shift the dark focus seems relatively straightforward. Unlike sustained nearwork, accommodative fatigue does not show any refractive-error dependent behavior (Hasebe et al., 2001). Further, repeatedly exercising accommodation and disaccommodation step responses prevents the slow build-up of sympathetic activity (Culhane et al., 1999; Gilmartin, 2000) and is therefore unlikely to interact with the parasympathetic activity in determining the dark focus.

6.4. Variance of estimates of initial destination

In our experiment, the initial destination of disaccommodation was inferred from the x-intercept of the linear regression of peak velocity on response starting position. It is possible that the variability in the measures of response starting position and peak velocity could have influenced the linear regression equation fit, and reduced the accuracy of our estimate of initial destination from the x-intercept. However, the linear regression equations provided good fits (correlation coefficient range: 0.52–0.95) to the data of peak velocity as a function of starting position and the range of initial destinations determined by ±95% confidence intervals of the linear regression equation fit were still within the vicinity of the cycloplegic refractive state. Hence, it is unlikely that our estimates of the initial default destination of disaccommodation were influenced significantly by the variability in the measures of response starting position and peak velocity.

Similar to the increase in peak velocity of disaccommodation with the proximity of starting position, the peak acceleration of disaccommodation also increased with the proximity of the starting position (Bharadwaj & Schor, 2006). Thus, the x-intercept of the regression of peak acceleration of disaccommodation on starting position would have also estimated the initial destination of disaccommodation. However, the relationship of peak acceleration with starting position was more variable than the relationship of peak velocity with starting position. r^2 for peak velocity as a function of starting position was 0.57; while r^2 for peak acceleration as a function of starting position was 0.37 (Bharadwaj & Schor, 2006). Hence, we derived the dioptric location of the initial destination from the plots of peak velocity as a function of starting position.

6.5. The influence of training on the initial destination of disaccommodation

Disaccommodation step responses were collected on subject SRB on two occasions. Data from the first session were collected during initial pilot experiments and data for the second session were collected after a period of 1-year. The trends in his dynamics of disaccommodation changed significantly over the 1-year period of data collection. A detailed account of the changes in his dynamics can be found in Bharadwaj and Schor (2006). Overall, the first- and second-order dynamics of his disaccommodation responses were more sluggish or damped in the second session than in the first session. For a given starting position, the peak acceleration of all responses and the peak velocity of smaller responses were lower in the second session than in the first session (Bharadwaj & Schor, 2006).

We speculate that the reduction in peak acceleration and peak velocity for smaller responses could have resulted in part from a shift in the initial destination of disaccommodation to a more proximal location in the second session. The initial destination of disaccommodation was located more distally in first session (−2.63 D) than in the second session (−0.63 D) (Fig. 2F). The disaccommodation responses in the first session were initiated toward the more distal initial destination and hence traveled with higher peak acceleration and peak velocity. In the second session, the disaccommodation responses were initiated towards a more proximal initial destination and hence traveled with lower peak acceleration and peak velocity than the first session. The proximal shift in the initial destination of subject SRB could have been associated with a proximal shift in his cycloplegic refractive state. However, since the cycloplegic refraction was measured only after his second session, we can only speculate that, like the initial destination, the cycloplegic refractive state may also have shifted from a more distal location in the first session to a more proximal location in the second session. Further experiments that can produce a reliable change in the control strategy for dynamic disaccommodation are required to examine this question in a more systematic fashion.

7. Conclusion

For a constant starting position, the peak velocity and peak acceleration of the disaccommodation step response remains invariant of the response magnitude. The peak velocity and peak acceleration increase linearly with the proximity of starting position. These observations suggest that disaccommodation step responses are initiated towards a constant or default initial destination (Bharadwaj & Schor, 2006). This study further demonstrates that the initial destination of disaccommodation is located beyond optical infinity, close to the cycloplegic refractive state of accommodation. The dioptric difference between the starting position and the cycloplegic refractive state determines the peak velocity and peak acceleration of disaccommodation step response.

Acknowledgments

We thank all our subjects for taking part in the experiments and Young Kim for helping us with the data collection.

We also thank the two anonymous reviewers for providing insightful comments on the manuscript. This research was supported by NIH Grant EYO—3532 to Clifton M. Schor.

References

Bharadwaj, S. R., & Schor, C. M. (2005). Acceleration characteristics of human ocular accommodation. *Vision Research, 45*, 17–28.

Bharadwaj, S. R., & Schor, C. M. (2006). Dynamic control of ocular disaccommodation: First and second-order dynamics. *Vision Research, 46*, 1019–1037.

Bharadwaj, S. R., Kim, Y. S., & Schor, C. M. (2005). Dynamic control of ocular disaccommodation. ARVO supplement (Abstract # 2325).

Ciuffreda, K. J., & Wallis, D. M. (1998). Myopes show increased susceptibility to nearwork aftereffects. *Investigative Ophthalmology and Visual Science, 39*, 1797–1803.

Cornsweet, T. N., & Crane, H. D. (1970). Servo-controlled infrared optometer. *Journal of Optical Society of America, 60*, 548–554.

Crane, H. D., & Steele, C. M. (1986). Generation-V dual-Purkinje image eyetracker. *Applied Optics, 24*, 527–537.

Culhane, H. M., & Winn, B. (1999). Dynamic accommodation and myopia. *Investigative Ophthalmology and Visual Science, 40*, 1968–1974.

Culhane, H. M., Winn, B., & Gilmartin, B. (1999). Human dynamic closed-loop accommodation augmented by sympathetic inhibition. *Investigative Ophthalmology and Visual Science, 40*, 1137–1143.

Devore, J., & Peck, R. (1993a). Simple linear regression and correlation: inferential methods. In J. Devore & R. Peck (Eds.), *Statistics—The exploration and analysis of data* (2nd Ed., pp. 596–656). Belmont: Wadsworth.

Devore, J., & Peck, R. (1993b). Summarizing bivariate data. In J. Devore & R. Peck (Eds.), *Statistics—The exploration and analysis of data* (2nd Ed., pp. 731–802). Belmont: Wadsworth.

Fisher, S. K., Ciuffreda, K. J., Levine, S., & Wolf-Kelly, K. S. (1987). Tonic adaptation in symptomatic and asymptomatic subjects. *American Journal of Optometry and Physiological Optics, 64*, 333–343.

Gamlin, P. D. R., Zhang, Y., Clendaniel, R. A., & Mays, L. E. (1994). Behavior of identified Edinger-Westphal neurons during ocular accommodation. *Journal of Neurophysiology, 72*, 2368–2382.

Gettes, B. C., & Belmont, O. (1961). Tropicamide, comparative cycloplegic effects. *Archives of Ophthalmology, 66*, 336–340.

Giles, G. H. (1965). The use of drugs in ophthalmic optical practice. In G. H. Giles (Ed.), *The principles and practice of refraction and its allied subjects* (pp. 467–479). Philadelphia: Chilton Company.

Gilmartin, B. (2000). Pharmacology of accommodative adaptation. In O. Franzen, H. Richter, & L. Stark (Eds.), *Accommodation and vergence mechanisms in the visual system* (pp. 141–150). Switzerland: Birkhauser Verlag Basel.

Grosvenor, T. (1996). The binocular vision examination. In T. Grosvenor (Ed.), *Primary care optometry. Anomalies of refraction and binocular vision* (3rd Ed., pp. 309–333). Boston: Butterworth-Heinemann.

Hasebe, S., Graf, E. W., & Schor, C. M. (2001). Fatigue reduces tonic accommodation. *Ophthalmic and Physiological Optics, 21*, 151–160.

Kasthurirangan, S., & Glasser, A. (2005). Influence of amplitude and starting point on accommodative dynamics in humans. *Investigative Ophthalmology and Visual Science, 46*, 3463–3472.

Leibowitz, H. W., & Owens, D. A. (1975). Anomalous myopias and the intermediate dark focus of accommodation. *Science, 189*, 646–648.

Leibowitz, H. W., & Owens, D. A. (1978). New evidence for the intermediate position of relaxed accommodation. *Documenta Ophthalmologica, 46*, 133–147.

Lovasik, J. V. (1986). Pharmacokinetics of topically applied cyclopentolate HCl and tropicamide. *American Journal of Optometry and Physiological Optics, 63*, 787–803.

Michaels, D. D. (1985). Drugs in refraction. In D. D. Michaels (Ed.), *Visual optics and refraction* (3rd Ed., pp. 277–297). St. Louis: The C.V. Mosby Company.

Mitchell, D. W. A. (1960). *The use of drugs in refraction* (2nd Ed.). London: Hereford Times pp. 54.

Owens, D. A., & Wolf-Kelly, K. (1987). Near-work, visual fatigue and variations of oculomotor tonus. *Investigative Ophthalmology and Visual Science, 28*, 743–749.

Pragnen, A. D. (1931). What constitutes satisfactory cycloplegia? *American Journal of Ophthalmology, 14*, 665–671.

Rosenfield, M., Ciuffreda, K. J., Hung, G. K., & Gilmartin, B. (1993). Tonic accommodation: a review. I. Basic aspects. *Ophthalmic and Physiological Optics, 13*, 266–284.

Rosenfield, M., Ciuffreda, K. J., Hung, G. K., & Gilmartin, B. (1994). Tonic accommodation: a review. II. Accommodative adaptation and clinical aspects. *Ophthalmic and Physiological Optics, 14*, 265–277.

Schaeffel, F., Wilhelm, H., & Zrenner, E. (1993). Inter-individual variability in the dynamics of natural accommodation in humans: relation to age and refractive error. *Journal of Physiology (London), 461*, 301–320.

Schor, C. M., & Bharadwaj, S. R. (2006). Pulse-step models of control strategies for dynamic ocular accommodation and disaccommodation. *Vision Research, 46*, 242–258.

Schor, C. M., Kotulak, J., & Tsuetaki, T. (1986). Adaptation of tonic accommodation reduces accommodative lag and is reduced in darkness. *Investigative Ophthalmology and Visual Science, 27*, 820–827.

Takeda, T., Ostberg, O., Fukui, Y., & Iida, T. (1988). Dynamic accommodation measurements for objective assessment of eye-strain and visual fatigue. *Journal of Human Ergology, 17*, 21–35.

Ukai, K. (2005). Personal communication.

Vilupuru, A. S., Kasthurirangan, S., & Glasser, A. (2005). Dynamics of accommodative fatigue in rhesus monkeys and humans. *Vision Research, 45*, 181–191.

Westheimer, G. (1957). Accommodation measurements in empty visual fields. *Journal of Optical Society of America, 47*, 714–718.

Westheimer, G., & Blair, S. M. (1973). Accommodation of the eye during sleep and anesthesia. *Vision Research, 13*, 1035–1040.

Whiteside, T. C. D. (1953). Accommodation of the human eye in a bright and empty visual field. *Journal of Physiology, 118*, 65–66.

Winn, B., Culhane, H. M., Gilmartin, B., & Strang, N. C. (2002). Effect of β-adrenoceptor antagonists on autonomic control of ciliary smooth muscle. *Ophthalmic and Physiological Optics, 22*, 359–365.

Wolf, K. S., Ciuffreda, K. J., & Jacobs, S. E. (1987). Time course and decay of effects of near work on tonic accommodation and tonic vergence. *Ophthalmic and Physiological Optics, 7*, 131–135.

Yamada, T., & Ukai, K. (1997). Amount of defocus is not used as an error signal in the control system of accommodation dynamics. *Ophthalmic and Physiological Optics, 17*, 55–60.