



Fatigue reduces tonic accommodation

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Summary

Ocular accommodation adopts a mean baseline response level of approximately 1.0 D in the absence of blur feedback (open-loop state). This baseline or tonic accommodation (TA) can be elevated following a sustained monocular accommodative response to a dioptric stimulus (lens adaptation) that exceeds the baseline open-loop level of TA. The accommodative response to the lens persists in the open-loop state (accommodative hysteresis), and eventually decays to a stable end-point. Interestingly, if the baseline TA is high, the monocularly adapted accommodative state can decay to an end-point that is below the initial pre-adapted baseline level of the TA (counter-adaptive response) (McBrien, N.A. and Millodot, M., (1988). Differences in adaptation of TA with refractive state. *Invest. Ophthalmol. Vis. Sci.*, **29**, 460–469).

We have investigated the possible contribution of accommodation fatigue to the counter-adaptive change in baseline TA following sustained accommodation. Two fatigue procedures were used while viewing a target at 66 or 33 cm. In a monocular condition, accommodation was stimulated for 3 min with lens values alternating from -1.5 to $+1.5$ D at a rate of 0.25 Hz. In the binocular condition, convergence was stimulated with alternating prism values from 9 prism diopters (PD) base-out to 9 PD base-in. Both monocular and binocular tasks resulted in a significant reduction of TA.

These results suggest that previously reported reductions of baseline TA following sustained monocular accommodation or binocular convergence could have resulted from fatigue of the accommodative system. Accommodative fatigue could be responsible for the lower values of TA observed in counter-adaptive responses to sustained accommodative or convergence effort.
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Introduction

Tonic accommodation (TA) refers to an intermediate accommodative state in the absence of an adequate visual stimulus such as darkness (dark focus) (Leibowitz and Owens, 1975), ganzfeld (empty field) (Whiteside, 1953; Schor *et al.*, 1984), low contrast targets (Luckiesh and Moss, 1937) and reduced visual acuity (Heath, 1956), a low spatial frequency target (Kotulak and Schor, 1987), or pinhole (open-loop condition) (Malmstrom and Randle, 1976; Roscoe and Benel, 1978; Rosenfield and Ciuffreda,

1991). Under these conditions the eye assumes an intermediate response of approximately 0.75–1.5 D (Leibowitz and Owens, 1975; Gilmartin *et al.*, 1984; Schor *et al.*, 1984; McBrien and Millodot, 1987). TA is influenced by a variety of factors including age (Whitefoot and Charman, 1992; Mordi and Ciuffreda, 1998), duration of open loop state (Rosenfield and Gilmartin, 1989), cognitive demand (Malmstrom *et al.*, 1980; Bullimore and Gilmartin, 1987; Jaschinski-Kruza and Toenies, 1988), or proximity of visual and non-visual stimuli (McLin *et al.*, 1988; Rosenfield and Gilmartin, 1990; Rosenfield and Ciuffreda, 1991; Winn *et al.* 1991).

TA is believed to be an aggregate response to a variety of stimuli (Rosenfield *et al.*, 1993). These include intrinsic innervation from the sympathetic and parasympathetic branches of the autonomic nervous system (Gilmartin and Hogan, 1985; Rosenfield *et al.*, 1990) responses to spatio-topical cues such as perceived size and distance (Schor *et al.*,

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1992), and extraretinal cues from tactile, auditory, vestibular and efference signals of extraocular muscle activity. Stimulus conditions that influence any of these variables would be expected to influence the magnitude of TA.

Innervation to accommodation is composed of two dynamic components. One is a fast phasic component that initially responds to changes in accommodative stimuli (both retinotopic and spatiotopic) (Schor *et al.*, 1992). The other is an adaptable tonic component that gradually replaces the phasic response (Schor and Kotulak, 1986). In addition, there is a static component described as a baseline innervation level or bias (Hung and Semmlow, 1980). The adaptable dynamic tonic component has a persistent aftereffect or hysteresis that discharges slowly in darkness (Roscoe and Benel, 1978; Ebenholtz, 1983; Schor *et al.*, 1984). The magnitude of the aftereffect is proportional to the magnitude of the dioptric stimulus vergence (Ebenholtz, 1983; Owens and Wolf-Kelly, 1987), which equals the sum of the lens and reciprocal of the viewing distance in meters. When varying viewing distance alone, far distances result in reductions of TA (Ebenholtz, 1983; Fisher *et al.*, 1987; McBrien and Millodot, 1988) and near distances result in increases of TA (Schor *et al.*, 1984; McBrien and Millodot, 1988; Bullimore and Gilmartin, 1989).

The combination of dynamic tonic aftereffect and static bias, measured under open-loop conditions (e.g. darkness) can be described by the following equation

$$K e^{-at} + C$$

where K equals the total amount in diopters that TA decays during the open-loop measure when projected to a time of infinity, a is the reciprocal of the decay time constant (the time taken for 63% of the decay to occur), t equals time, and C is the change of the static baseline from pre-adapted TA that remains following complete discharge of the aftereffect. The total shift of TA observed when the accommodative loop is first opened equals $K + C$. The time course for the recovery of the fatigue effect is quantified by a . Measures of time-constant vary from 1.5 to 25 min (Wolf *et al.*, 1987; Ebenholtz, 1983; Schor *et al.*, 1984; Wolf and O'Connell, 1987; Rosenfield and Gilmartin, 1989) depending on the duration of the adaptation stimulus and the method of measurement. Any of these dynamic and static components can contribute to the open-loop measures of accommodation. Most of the intrinsic innervation for TA is attributed to the static accommodative bias. However, it is possible that the phasic responses to spatiotopic cues (proximal accommodation) and adaptable tonic components could also contribute to measures of TA. All measures of TA are preceded by a history of some form of visual stimulation. Even when alert subjects have been kept in darkness for some period of time, they are stimulated by a variety of non-visual spatial cues for distance or proximity (Rosenfield and Gilmartin, 1990). Persistent accommodative responses

(hysteresis) to these prior conditions could contaminate subsequent measures of TA under open-loop conditions. Accommodative hysteresis can be disabled following performance of a fatigue task such as accommodative facility training (Schor and Tsuetaki, 1987).

The term fatigue refers to reduced performance. For the purpose of this paper, fatigue will be defined as a transient reduction of TA that follows performance of accommodation and convergence tasks. Fatigue differs from accommodative hysteresis in that the reduction of TA is unrelated to the sign of the task. For example, tasks stimulating either increases or decreases of accommodation could cause a reduction (fatigue) or shift in TA towards the far point. Previously, the term fatigue has been used to partially explain the results of studies that found counter-adaptive TA shifts after 2 h of VDU usage (Ostberg, 1982). Ostberg (1982) showed that 2 h of uninterrupted work at various distances led to subjects becoming more myopic for distant stimuli (adaptive response) and more hyperopic for near stimuli (counter-adaptive response), referenced to their pre-work accommodation level. The change in TA could be considered to consist of two components, one being adaptation of TA to the near task (accommodative hysteresis), and the other being fatigue of the system caused by excessive use.

In the current study, we have estimated the degree to which fatigue of accommodation contributes to estimates of TA by comparing measures of TA before and after performing a fatigue task. The fatigue task consisted of either monocularly stimulated changes of accommodation from near to far, or binocularly stimulated changes of convergence from near to far every 2 s for a period of 3 min. This task is analogous to accommodative and convergence facility training (Schor and Tsuetaki, 1987). Since our task is dynamic, and stimulates both increases and decreases of response level, we can be reasonably convinced that the effect of hysteresis on TA will be minimized. Given this, we observed that fatigue produced by either monocular stimulation of accommodation, or binocular stimulation of vergence, reduced the magnitude of TA below its habitual level (negative or hyperopic shift). These results have important implications concerning the interpretation of studies of accommodative aftereffects produced by lenses and prisms and the role of fatigue produced by adaptation tasks on the magnitude of both adaptive and counter-adaptive responses. They also suggest that accommodative fatigue contributes to the measures of TA.

Methods and subjects

Subjects

Sixteen subjects (11 males, five females) participated, all of whom were staff or students in the School of Optometry, University of California at Berkeley. We excluded myopic

Table 1. Subject characteristics ($n = 16$)

Subjects	Age (years)	Refractive error (diopters)	Phoria (far/near) (prism diopters)	Mean tonic accommodation (diopters)
M.H.	24	2.0	0/0	1.2
E.G.	24	0.2	2E/0	1.2
J.S.	30	0.0	8X/16X'	0.7
M.S.1	23	0.0	0/0	2.1
J.G.	18	0.0	0/0	0.8
C.B.	24	-0.6	12X/12X'	1.4
M.E.	35	-0.7	0/0	1.6
X.O.	22	-1.8	0/10X'	1.5
L.D.	23	-2.1	0/0	3.0
H.R.	19	-2.7	0/2X'	0.6
J.H.	30	-3.2	0/0	0.8
W.A.	27	-3.8	0/0	3.1
P.Y.	23	-5.1	0/0	0.6
S.H.	38	-5.5	8X/0	0.7
W.S.	18	-7.1	8X/16X'	0.4
M.S.2	32	-8.8	12X/12X'	0.3
Median	24	-2.0		1.0

subjects who had an onset after 15 years of age (late-onset myopia) from this study, because they were reported to exhibit differences in adaptation of TA to a sustained visual task (McBrien and Millodot, 1988; Gilmartin and Bullimore, 1991). Subject characteristics are summarized in *Table 1*. The mean (\pm SD) age of the group was 26.1 ± 6.2 years (median; 24 years, range; 18–38 years). Spherical equivalent refractive error ranged from +2.0 to -8.8 D (median; -2.0 D) and any astigmatism did not exceed 1.0 D. All subjects had corrected distant visual acuity of at least 6/6 (20/20). No subject had any major oculomotor imbalance, i.e. heterotropia, uncompensated heterophoria, asthenopic symptom, or known ocular pathology. Each subject was informed of the nature of the procedure, and their informed consent was obtained prior to their participation in the study.

Measurement of accommodation

The accommodation response was measured objectively using the Grand Seiko WV-500 infrared autorefractor (Grand Seiko Co., Fukuyama, Japan). This autorefractor is similar to the Canon R-1. It has an open-field of view and computes the spherocylindrical refractive error at a precision of 0.12 D, once per second by projecting a near infrared (IR) circular beam on the retina and processing the size and shape of the image. The refraction data was stored on a micro-computer, Dimension XPS R9012 (Dell Co., USA) and analyzed offline. All measures of accommodation were taken from the right eye, and the reading was analyzed as a spherical equivalent, i.e. sphere + half-cylinder power.

The subject's head was stabilized with a forehead rest and a dental compound mouth-bite.

Opening accommodation and vergence loops

During the measurement period, having subjects view a fixation target monocularly through a 0.5 mm pinhole opened the vergence and accommodation loops. The pinhole was drilled into a Kodak Wratten 87 gelatin filter (Eastman Kodak Co., USA) and was placed 12 mm from the corneal apex. A Wratten 87 filter transmits the IR light used in the recording system of the autorefractor, allowing measurements to be taken through the subject's whole pupil, but it filters out all visible light, thus restricting the subject's view to the 0.5 mm aperture. It has been shown previously that a 0.5 mm pinhole pupil is sufficient to open the accommodative feedback loop. Under these conditions, the slope of the stimulus-response function is less than 0.1 for stimuli ranging from 0 to -4.5 D (Ward and Charman, 1987).

The fixation target for the open-loop measurement consisted of a 10×4 matrix of letters (12-point font), placed at a viewing distance of 33 cm. A target luminance of 400 cd/m^2 was provided by a light source that was suspended 10 cm above the target, making the target luminance well above threshold photopic levels when viewed through the pinhole.

Use of lens and prism flippers

Fatigue was induced during the task period with lens and prism flippers. The flippers consisted of two vertically offset

lenses, or prisms, of opposite sign (e.g. ± 1.5 D) in two pairs of lens wells held by the subject in front of their eyes. This orientation allows the subject to selectively view the target through one lens (monocularly) or a pair of prisms (binocularly) at a time. At the sound of a tone, the subject flipped from one lens or prism pair value to the other, alternating in step changes every 2 s (0.25 Hz). For the above example, the accommodative target was placed at 66 cm, so that the effective accommodative demand, target distance plus lens, ranged from 0 to 3 D. Five conditions were used, consisting of three different flipper tasks and two controls: Condition 1—monocular, ± 1.5 D lens-flipper at 66 cm; Condition 2—monocular, ± 1.5 D lens-flipper at 33 cm; Condition 3—binocular, 9 prism diopters (PD) base-out/base-in prism-flipper at 66 cm; Condition 4—monocular control (static viewing) at 66 cm without the flipper; and Condition 5—binocular control (static viewing) at 66 cm without the flipper. The near lens-flipper (Condition 2), stimulated a range of 4.5–1.5 D that was nearer than the median pre-task TA level of our subjects (1 D). Conditions 1 and 2 were compared to investigate the combined contribution of fatigue and the accommodative hysteresis to the near-viewing task compared with fatigue in the far-viewing task on post-task measures of TA. The fixation target for these tasks consisted of a text paragraph in 12-point font, high contrast (90%) letters viewed through natural pupils and refractive corrections. A target luminance of 50 cd/m^2 was provided by ceiling lights.

Experimental procedure

Experiment 1. Before each measurement session the far point of each subject was obtained objectively with the autorefractor and a Snellen chart. The test chart was then placed at the subject's far point.

First, the subject wore translucent goggles in a lighted room for 5 min without refractive corrections, to allow TA to stabilize in a uniformly lit field. After this period, the subject, still without refractive correction, was instructed to bite the bite-block and to look at the monocular fixation target through the pinhole. Measurements of accommodation were taken once per second for 90 s.

Second, subjects performed either one of the three different flipper tasks or one of the two control tasks described above for 180 s. Subjects wore refractive corrections during this task period. Subjects were instructed to keep an accurate focus throughout this task period.

Finally, immediately after completion of the task, the subject returned to the bite-block, and the post-task TA was measured for 90 s using the same method as in the pre-task measurement. All measures of TA were taken without spectacle lenses.

Experiment 2. This experiment characterized the persistence of the fatigue effect under open-loop conditions. Six subjects participated in fatigue Condition 1 (± 1.5 D

at 66 cm). Following the fatigue exercise they remained in the bite-block with both the accommodation and vergence loops open. TA change was monitored three times every minute for 15 consecutive minutes following the post-task measurement of 90 s. As a control, five of our six subjects participated in the same experiment with Condition 4 (monocular viewing at 66 cm).

The order of the experimental sessions was randomized, and each session was separated by a period of at least 6 h in both experiments.

Data analysis

The pre-task TA level was determined by subtracting the mean pre-task measures of TA from the far point. It has been reported that any distance-dependent aftereffect dissipates approximately 45 s after opening the accommodation loop (Roscoe and Benel, 1978; Gilmartin and Bullimore, 1987; Rosenfield and Gilmartin, 1988b). Accordingly, post-task TA was determined by subtracting the averaged value of measures taken during the latter half of the measurement period (45–90 s) from the far point. Thus a TA value of zero represents the far point of the eye. Post-task shifts in TA were computed by subtracting the pre- from the post-task TA. The significance of the differences in means between the pre- and post-tasks for each condition, as well as the significance of the post-task differences found between the task and control conditions were evaluated using three separate multivariate analyses of variance (MANOVA). This analysis allowed the accurate calculation of *p*-values for multiple concurrent tests, while accounting for the non-independence among the repeated measurements of a single group of subjects under different experimental conditions. The first MANOVA looked at the significance between the pre- and post-task TA means for the binocular control condition (Condition 5) and the binocular prism condition (Condition 3), as well as the differences in the post-task TA shift between task and control conditions. A second MANOVA tested for significance between the pre- and post-task TA means for the monocular control condition (Condition 4) and the monocular far task condition (Condition 1), as well as the differences in the post-task TA shift between task and control conditions. A third MANOVA looked at the significance between the pre- and post-task TA means for the monocular far task condition (Condition 1) and the monocular near task condition (Condition 2), as well as the differences in the post-task TA shift between far and near task conditions.

In Experiment 2, the decay of the post-task shift was quantified with an exponential fit using three parameters ($K e^{-at} + C$). The first parameter, *K*, represents the total amount (in diopters) that the fatigue effect decayed as time goes to infinity. The second parameter, a time constant ($t(1/a)$), represents the temporal duration or time in seconds at which 63% of the post-task TA decay had occurred. The

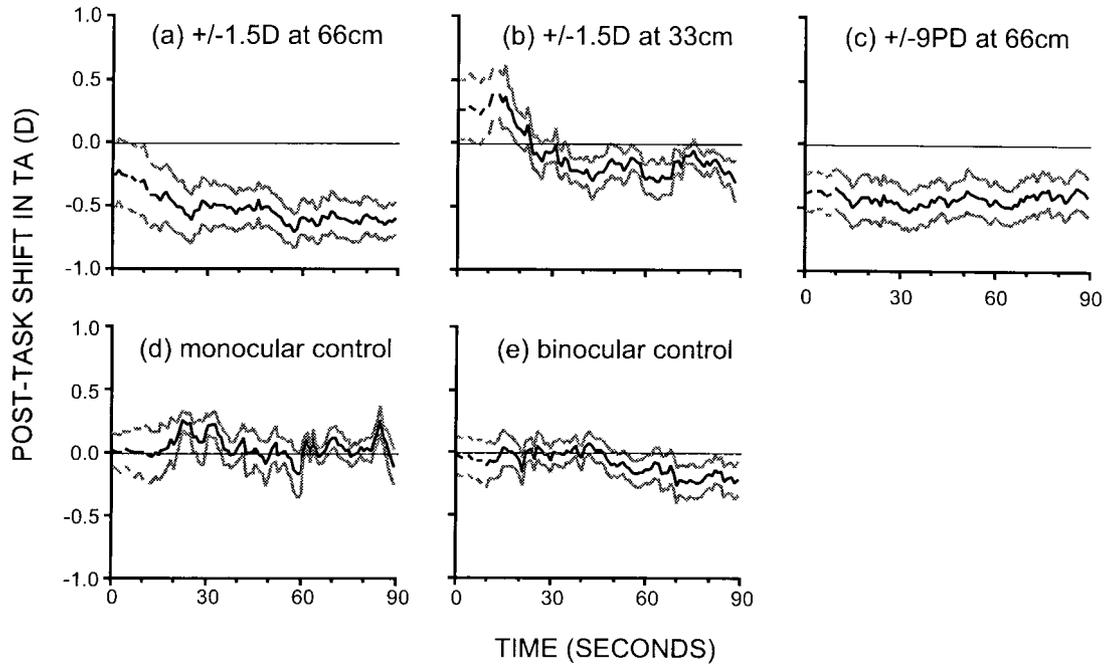


Figure 1. Post-task shift in TA for the three flipper task and two control conditions. Shown are means and standard errors, calculated for every data point, for the post-task TA shift (post-task TA value minus pre-task TA level) for all 16 subjects. The horizontal axis represents time (s) of the post-task period. Positive values along the vertical axis indicate more accommodation (diopters), and zero represents pre-task TA level. Dashed sections at the beginning of the traces indicates a lack of data at all test intervals. Under both of the lens-flipper conditions (Conditions 1 and 2), mean TA decreased with time and decayed below the pre-task level. Under the prism-flipper condition (Condition 3), TA remained below the pre-task level throughout the measurement period. No change in TA was observed for the monocular control condition (Condition 4), and a small negative shift was found for the binocular control condition (Condition 5).

third parameter, a constant (C), represents the persistent shift of post-task TA (in diopters) from the pre-task level. Thus, the total post-task shift of TA observed when the accommodative loop is first opened is the sum of the constants K and C .

Results

Experiment 1

The averaged responses (± 1 SE) of all 16 subjects for Conditions 1 and 2 (± 1.5 D lens-flipper at 66 cm and at 33 cm, monocularly) are shown qualitatively in *Figure 1a* and *b*. The zero reference describes the pre-task TA value. Inspection of the figure reveals that TA decreased with time and converged to a value below that of the pre-task TA level. As an interesting sidelight, the near viewing after-effect can be seen by comparing the initial, more myopic values of Condition 2 (33 cm flipper) with that of Condition 1 (66 cm flipper).

In Condition 3 (± 9 PD prism-flipper at 66 cm, binocularly), TA was continuously below the zero level throughout the post-task measurement period (*Figure 1c*). For Condition 4 (monocular control), no change was

observed between pre- and post-task TA, as shown in *Figure 1d*. A small change was found between the pre- and post-task TA for Condition 5 (binocular control), as shown in *Figure 1e*.

A more detailed analysis of the results is depicted in *Figure 2*. The mean (\pm SE) post-task reduction of the TA for Condition 1 (± 1.5 D at 66 cm) was 0.51 ± 0.09 D. Condition 2 (± 1.5 D at 33 cm) had a TA reduction of 0.15 ± 0.07 D, and Condition 3 (± 9 PD at 66 cm) had a TA reduction of 0.42 ± 0.14 D.

As mentioned above, significance for the different conditions was evaluated using three separate multivariate analyses of variance (MANOVA). The first MANOVA described the analyses performed on the differences in the binocular control and task conditions. The first variable, the difference between the pre- and post-task means for the binocular task condition (Condition 4), was found to be significant, $F(2, 14) = 10.26$, $p = 0.0064$. The second variable, the difference between pre- and post-task means in the binocular control condition (Condition 5), was not found to be significant, $F(2, 14) = 2.11$, $p = 0.1687$. The third variable in the analyses, the difference between the post-tasks shifts found between the binocular task and control

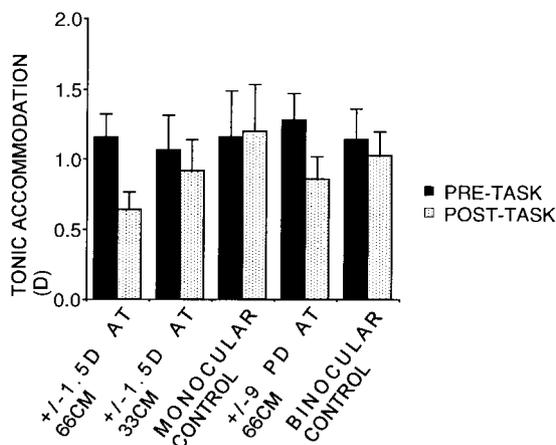


Figure 2. Pre- versus post-task TA, post-task change of TA and normalized post-task change of TA fatigue data ($n = 16$) is represented by comparing the pre-task TA (solid bars) with the post-task TA (open bars). Positive values along the vertical axis indicate more accommodation (diopters). The significance for the difference in means was tested using three separate multivariate analyses of variance (MANOVA); see text for complete description and p -values.

conditions, was found to be significant, $F(2, 14) = 8.29$, $p = 0.0121$.

The second MANOVA described the analyses performed on the differences between the monocular far task (Condition 1) and the monocular control condition (Condition 4). The comparison between pre-task and post-task means for the monocular far task (Condition 1) showed significance, $F(2, 13) = 25.90$, $p = 0.0002$. Comparing the pre-task and post-task means for the monocular control condition (Condition 4) showed no significance, $F(2, 13) = 0.07$, $p = 0.8004$. The difference between the post-task shifts of the control and task conditions showed significance, $F(2, 13) = 17.92$, $p = 0.0010$.

Our third MANOVA tested for differences between the monocular far condition (Condition 1) and the monocular near condition (Condition 2). The comparison between pre-task and post-task means for the monocular far task (Condition 1) showed significance, $F(2, 10) = 18.82$, $p = 0.0015$. The difference between the pre- and post-task means for the monocular near condition (Condition 2) did not meet the $p = 0.05$ level of significance, $F(2, 10) = 4.10$, $p = 0.0704$. The difference between the post-task shifts of the far and near task conditions showed significance, $F(2, 10) = 8.47$, $p = 0.0156$.

These results indicate that fatigue produced by the flipper tasks, i.e. the rapid alternating stimulation to increase and decrease accommodation or convergence, caused a small but significant reduction of TA for two of our three task conditions. A small reduction of TA in our third task condition, the near flipper task (Condition 2), did not reach significance. Neither the monocular

control or binocular control condition showed a significant post-task shift in TA.

Since a range of pre-task TA levels was observed among our subjects (mean \pm SD; 1.25 ± 0.85 D, median; 1.0 D, range; 0.3–3.1 D), we analyzed the correlation between the pre-task TA level and the post-task reduction in TA using regression coefficients. The results of the three flipper-task conditions revealed a moderate negative correlation between the two variables ($R = 0.53$, $y = -0.32x + 0.01$), such that post-task TA was reduced more for subjects with large (rather than small) pre-task levels of TA. The moderate correlation coefficient (0.53) indicates that the amount of post-task reduction of TA was not easily predicted from the pre-task TA. Four of our subjects had nearly 100% reduction of post-task TA, such that their post-task TA equalled their individual far point. The results for the control conditions illustrate that post-task TA remained near zero, or at the pre-task TA level ($R = -0.47$, $y = -0.08x + 0.08$), and only one subject showed a post-task TA reduction greater than 0.5 D.

Post-task shift in TA was also analyzed as a function of refractive error. A weak negative correlation was observed between refractive error and the post-task TA reduction for the flipper-task condition ($R = -0.39$, $y = -0.06x - 0.54$) such that the post-task reduction of TA decreased with degree of myopia. Although there is a negative correlation between refractive error and reduction of TA, because of the small sample size, we are not able to conclude that hyperopic subjects had significantly greater reductions of TA than myopes. However it should be noted that with a larger sample size, McBrien and Millodot (1987) reported greater TA in hyperopes than myopes, and they also report that the magnitude of negative shifts of counter-adaptive TA increased with positive signs of refractive error (McBrien and Millodot, 1988). There was no correlation between these two parameters for our control conditions ($R = -0.13$, $y = -0.01x - 0.09$).

Experiment 2

The subsequent decay of the induced post-task shift of TA is shown in *Figure 3*. The x -axis represents time (s) for the 15 min period of measurement. Zero along the y -axis represents pre-task TA. Positive and negative values represent increases and decreases of TA, respectively. The left columns represent post-task shifts of TA following Condition 1 (monocularly ± 1.5 D at 66 cm) and the right columns represent post-task shifts of TA following Condition 4 (monocular control at 66 cm). In all subjects, Condition 1 caused an initial reduction of TA followed by a gradual rebound or increase toward pre-task TA. The rebound fell short of the baseline level in four of the six subjects, and in two others (C.B. and H.R.) TA rose to a level above the pre-task level of TA. In contrast, the shifts of TA for control Condition 4, shown in the right columns,

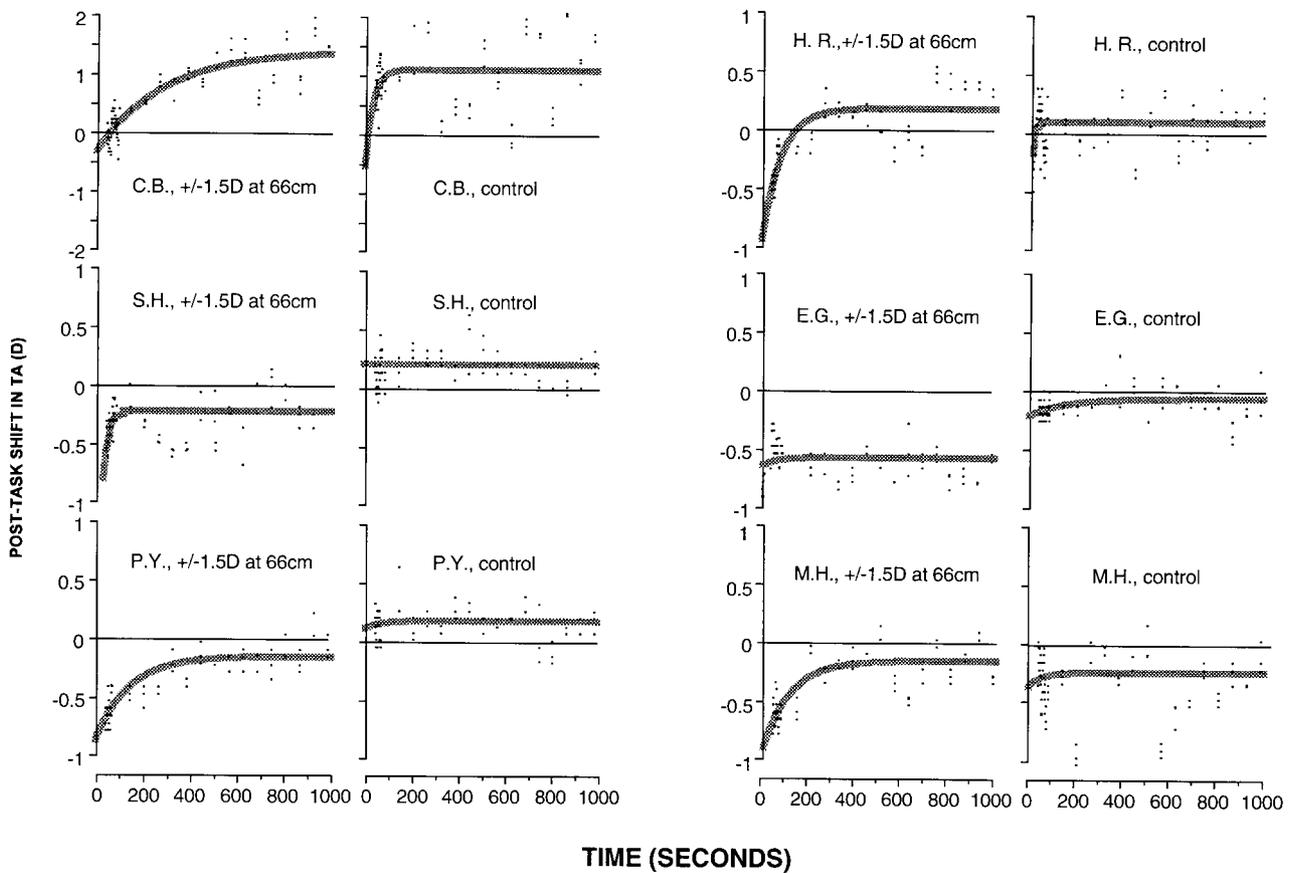


Figure 3. Persistence of the fatigue effect upon TA. Shown are data from six subjects whose TA was measured under open-loop conditions consecutively at 20 s intervals for 15 min after completion of Condition 1 (+/- 1.5 D at 66 cm) (left column) and control Condition 4 (monocular viewing at 66 cm). Positive values along the vertical axis indicate greater post-task than pre-task TA. Left columns demonstrate that post-task TA increased over time (left columns) from the initial reduced post-task TA level to approximate their respective pre-task levels. Control data in the right columns demonstrate a fixed post-task TA that is approximately equal to pre-task TA. Fitting the recovery data to an exponential function ($K e^{-at} + C$) shows a mean K of -1.13 D, a mean time-constant ($1/a$) of 162 s and a mean residual post-task effect C of 0.08 D. Subject C.B. had greater values for C in both Conditions 1 and 4 for post-task than pre-task TA.

remained constant at a level equal to the end-point described by the constant, C , of Condition 1.

The data describing the recovery from fatigue was fit to an exponential function of the form $Ke^{-at} + C$. The mean (\pm SE) values for K and time-constant T , ($T = (1/a)$), were -1.13 ± 0.27 D (median; -0.93 D, range; -2.11 to -0.34 D) and 162 ± 73 s (median; 100 s, range; 3–462 s), respectively. The amount of the post-task shift of TA that remained is characterized by a constant, C . The mean value of C was 0.08 ± 0.28 D (median; -0.10 D, range; -0.62 to $+1.39$ D) indicating that in most cases, the post-task TA decayed to pre-task levels in the 15-minute period. The time period for the TA level to return to baseline may depend on the duration and activity level of the fatigue task. Prolonged visual stress, caused by mismatches between stimuli for accommodation and convergence, could cause long-term reductions of TA.

The subject C.B. showed excessive over-correction during recovery of TA in the task condition compared with the pre-task TA level. However, the subject also showed a similar increase of TA during the recovery period in the control condition. Increasing TA over time has been reported previously for several healthy subjects in total darkness (Krumholz *et al.*, 1986). Perhaps these increases are the result of idiosyncratic proximal responses of accommodation in darkness.

Discussion

Influence of fatigue on measures of accommodative aftereffects and baseline TA

Accommodative aftereffects or hysteresis can be produced by stimulating accommodation monocularly

with lenses (Roscoe and Benel, 1978; Ebenholtz, 1983; Schor and Kotulak, 1986), or binocularly with prisms via convergence accommodation (Schor and Kotulak, 1986; Wolf and O'Connell, 1987; Kran and Ciuffreda, 1988). Both classes of adaptive stimuli have been shown to produce a negative shift of baseline TA following the decay of the accommodative aftereffect. Negative shifts of TA produced by monocular lens adaptation (McBrien and Millodot, 1987, 1988; Rosenfield and Gilmartin, 1988a,b, 1989; Gilmartin and Bullimore, 1991) range from 0.12 to 0.25 D with the magnitude of the hyperopic shift depending upon refractive error and viewing distance (McBrien and Millodot, 1988; Gilmartin and Bullimore, 1991).

A study that compared the magnitude of the negative baseline shift of TA following adaptation to lenses and prisms (Rosenfield and Gilmartin, 1988b) reported that greater negative shifts result from binocular adaptation to convergence stimuli (0.25 D) than to monocular accommodation stimuli (0.12 D). Their small negative shift found with lenses is significant with the sign test (consecutive measures are below pre-task TA), and it is consistent with results from six additional studies of monocular accommodation (cited above), all of which report the negative shift effect. Rosenfield and Gilmartin (1988b) interpret the greater effects on the negative shift of TA caused by convergence stimuli as evidence in support of a model of cross-link interactions between accommodation and convergence in which the cross-links are driven by the sum of tonic and phasic components.

With this model, the hyperopic shift of TA caused by convergence results from negative feedback in the closed accommodative loop during adaptation. This model predicts that the negative shifts of TA would not be expected to occur following monocular adaptation of accommodation. In addition, our combined base-out to base-in prism fatigue exercise would not be expected to produce a negative shift of the baseline TA because prism flippers stimulated both increases and decreases of convergence accommodation. One could postulate that the negative aftereffect of TA resulted from adaptation to one component of the flipper stimulus. This would require a selective adaptation response to plus lenses and base-in prism. However this is unlikely because adaptation is more robust in response to increases in accommodation (Schor *et al.*, 1984) and to base-out prism (Schor, 1979). Alternative models of cross-link interactions presented by Schor and Kotulak (1986) propose that the main inputs to the cross-links are the phasic components, with the tonic components providing no direct cross-link input. This alternative model is supported by Jiang (1996) who found that accommodative vergence was reduced after accommodation adapted to a portion of the accommodative stimulus. This observation indicates that the cross-link was driven by the phasic but not the tonic component. The negative shift of TA found by Rosenfield and

Gilmartin (1988b) could have resulted from fatigue of accommodation caused by their base-out fusion stimulus in the absence of an equivalent accommodative demand (Schor and Tsuetaki, 1987).

The contribution of adaptable accommodation to open loop measures of TA

Both accommodative hysteresis and fatigue appear to influence measures of TA produced by the near monocular flipper task (Condition 2 monocular, ± 1.5 D lens-flipper at 33 cm). TA was reduced more at the far 66 cm-task distance of Condition 1 than in the near 33 cm-task distance of Condition 2. Remote viewing distances are less likely to produce accommodative hysteresis than are near ones (Schor *et al.*, 1984) such that fatigue would be the main factor affecting TA in Condition 1 while a combination of fatigue and accommodative hysteresis could have altered TA in Condition 2. The negative shift of TA caused by fatigue would be reduced at the near viewing distance by an increase of accommodation caused by an adaptive hysteresis.

There may also be a hysteresis contributing to the reduction of TA following the far viewing task. The observed reduction in TA quantified above as $K e^{-at} + C$ cannot be entirely explained by the dynamic component of adaptable accommodation, characterized by our constant K . The remaining change in TA, constant C , indicates that initial bias of the accommodative system, or TA, can be decreased by fatigue or decreased by long duration hysteresis stimulated by the far viewing distance. This poses an interesting problem for modelers, because it suggests that tonic accommodative bias is not a constant (Ostberg, 1982). One could argue that the apparent change in accommodative bias is the result of either fatigue or hysteresis of accommodation. Hysteresis could be evoked by distal stimuli during the far task which would persist during open loop measures of TA. Either of these mechanisms could account for the observations by Rosenfield and Gilmartin (1988b).

Relation between the post-task negative shift of TA and (1) pre-task magnitude of TA and (2) refractive error

Prior studies of accommodative hysteresis indicate that the rate of decay of accommodative aftereffects ($1/a$) and the magnitude of counter adaptive or negative shift of tonic accommodative aftereffects (reduction of TA) increase with the positive sign of refractive error (McBrien and Millodot, 1988). In response to monocular accommodation, hyperopes show larger negative shifts of TA than emmetropes, and emmetropes show less positive shifts than do late onset myopes. As stated by McBrien and Millodot, these results could be confounded by unknown effects that previous spectacle-wearing history might exert. While

participating in these prior studies, all subjects wore refractive corrections so that differences in accommodative demand would not occur between the various refractive groups. However many subjects did not wear their refractive corrections while not participating in laboratory studies, particularly hyperopes (McBrien and Millodot, 1987), and more accommodative effort would be required and more fatigue would occur for uncorrected hyperopes than emmetropes, and for emmetropes than uncorrected myopes. If persistent, the resulting fatigue could contribute to the differences in accommodative hysteresis and TA following adaptation in laboratory experiments.

Another contributing factor to the relation between TA and refractive error is the magnitude of the baseline TA. If fatigue reduces TA by some proportion of the baseline, then larger reductions of baseline TA would be expected in cases where the pre-adapted measure of TA was high compared with low. Interestingly, there is a tendency for corrected hyperopes to have the highest dioptric value of TA and corrected late-onset myopes have the lowest dioptric values with emmetropes in between these values (McBrien and Millodot, 1987). Thus all groups could fatigue equally during the adaptation training period, but the effects of fatigue on the negative shift would be greatest on the group that had the largest amount of TA to lose (i.e. hyperopes).

It is possible that a dual-tonic adaptive mechanism could provide an alternative explanation to the fatigue model of the negative shift of TA following monocular and binocular near tasks. The initial positive aftereffects of negative lens and base-out prism stimuli could result from an increased activity of one tonic adapter, and the negative aftereffect that occurred later could result from the decreased activity of another tonic adapter. The decay time constant of the first adapter would need to be shorter than that of the second adapter to account for the biphasic nature of the hysteresis (a positive aftereffect followed by a small negative one). Both the dual-tonic adaptation model and the fatigue model predict that negative shifts in TA can result from monocular stimulation of accommodation and that the negative shift observed in the binocular prism task does not necessarily imply a specific organization of cross-link binocular interactions between accommodation and convergence.

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