

# The Influence of First Near-Spectacle Reading Correction on Accommodation and Its Interaction with Convergence

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**PURPOSE.** Accommodation and convergence can adapt to blur and disparity stimuli and to age-related changes in accommodative amplitude. Does this ability decline with age? The authors investigated short-term adaptation to first near-spectacle reading correction on the accommodative-stimulus response (ASR) function, accommodative amplitude (AA), AC/A, and CA/C ratios in a pre-presbyopic and an incipient presbyopic population and determined whether changes in these functions recovered after discontinuation of the use of near spectacles.

**METHODS.** Thirty subjects with normal vision participated; their ages ranged from 21 to 30 years ( $n = 15$ ) and 38 to 44 years ( $n = 15$ ). Oculomotor functions were measured before and after single-vision reading spectacles were worn for near tasks over a 2-month period and then 2 months after the use of near spectacles was discontinued.

**RESULTS.** The slope of the ASR function and the AC/A and CA/C ratios did not change significantly after near spectacles were worn. There was a hyperopic shift of the ASR function that significantly reduced the near point of accommodation (NPA) and lowered the far-point refraction. These changes were age invariant and did not recover after 2 months of discontinuation of near spectacle wear.

**CONCLUSIONS.** These results imply that the NPA may be enhanced normally by tonic bias of accommodation that elevates the entire ASR function and produces myopic refraction bias. When this bias relaxes after reading spectacles are worn, there is a hyperopic shift of the refractive state and a reduction of the NPA, specified from optical infinity. (*Invest Ophthalmol Vis Sci.* 2009;50:4215–4222) DOI:10.1167/iovs.08-3021

Difficulty in focusing near material within arm's reach usually first occurs in the fourth decade of life. This condition, known as presbyopia, results from a longstanding but gradual loss of accommodative amplitude with increasing age.<sup>1</sup> The most prominent age-related lenticular changes that limit accommodative amplitude include progressive hardening of the lens,<sup>2,3</sup> increase in lens friction (viscosity)<sup>4,5</sup> and stiffness (1/compliance),<sup>5-7</sup> and geometric changes such as increases in thickness and convexity.<sup>8,9</sup> Increased lens stiffness also influ-

ences cross-link interactions between accommodation and convergence. Accommodation responds directly to perceived distance<sup>10</sup> and retinal image defocus and indirectly to binocular disparity through the convergence-accommodation cross-link whose gain is described by the CA/C ratio (accommodation [diopters (D)] associated per unit change in convergence [meter angle (MA)]). The vergence system responds directly to perceived distance<sup>11</sup> and to binocular disparity and indirectly to retinal image defocus via the accommodation-convergence cross-link<sup>12-14</sup> whose gain is described by the AC/A ratio (convergence [MA] associated per unit accommodation [D]). As the lens hardens with age, the CA/C ratio declines steadily,<sup>13,15</sup> from 1 D/MA at approximately 12 years of age to 0 D/MA at 62 years.<sup>13</sup> This illustrates that the coupled innervation between convergence and accommodation becomes less effective with age to drive the stiffening ocular lens. Interestingly, the AC/A ratio does not change until 40 years of age,<sup>16-18</sup> either because the AC/A cross-link has adapted to increased efforts of accommodation or because separate efferent signals could be associated with direct-defocus and indirect-convergence stimuli to accommodation, and only the direct signals have been adjusted for lens stiffness. These studies on cross-link gains and age indicate that the direct neural drive for accommodation is perhaps under some form of adaptive regulation that offsets the age-related increased stiffness of the ocular lens and that adaptation slows down the gradual reduction of accommodative amplitude. They also illustrate that accommodative convergence and convergence accommodation adapt differently to age-related increases in lens stiffness.

Reading spectacles or plus lenses are prescribed for presbyopia to reduce the near stimulus to accommodation. If the accommodative amplitude is sustained in part by neural adaptation to age-related increases in lens stiffness, do reading spectacles reduce the adaptation response? If aftereffects to reading spectacles were long term, they could accelerate the progression of incipient presbyopia. Moreover, if accommodative convergence adapted to reduced efforts of accommodation while reading spectacles are worn, the near spectacles could influence the AC/A ratio when removed. Indeed, changes in the AC/A ratio have been reported when refractive correction of previously uncorrected myopes were first prescribed.<sup>19</sup>

We investigated the influence of reading spectacles on static accommodation and its cross-link interactions with convergence to reveal adaptive mechanisms that normally respond to the age-related increases in lens stiffness. Although reading spectacles are prescribed for most people older than 40 years of age, the effect of reading spectacles on accommodative amplitude and its interaction with convergence has not been well documented. This study was a direct test of adaptability of the amplitude of accommodation and the AC/A and CA/C cross-link interactions to first reading spectacles in a pre-presbyopic and an incipient presbyopic population. Specifically, the following questions were asked: Is the AC/A ratio altered after reading spectacles are worn (treatment) for a short time? Do persons with incipient presbyopia lose some of their re-

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TABLE 1. Subject Demographics for the Two Age Groups

Subject Group	Age (y)	Right Eye (SE) Diopters	Left Eye (SE) Diopters	Left Eye (AA1) Diopters	Left Eye (AA2) Diopters	Near Phoria Prism D
Young	25.13 ± 3.2	-1.59 ± 2.37	-1.73 ± 2.21	10.15 ± 3.39	7.33 ± 1.13	-0.13 ± 3.52
Old	40.27 ± 1.87	-1.04 ± 1.9	-1.05 ± 1.63	6.79 ± 2.54	4.17 ± 0.89	-1.88 ± 1.97

Data are mean ± SD. SE, spherical equivalent; AA1, accommodative amplitude (AA) by push-up technique; AA2, AA by minus lens to blur method; phoria, negative sign denotes exophoria measured using the Von Graefe technique.

maining accommodation ability after treatment? Will accommodative amplitude and the interactions between accommodation and convergence return to the pretreatment state after reading spectacles are discarded? Are there differences in adaptability of these functions between younger and older subjects?

## METHODS

Thirty subjects in two different age groups, 21 to 30 years ( $n = 15$ ) and 38 to 44 years ( $n = 15$ ) completed the study. All subjects gave informed consent before participation. The research protocol followed the tenets of the Declaration of Helsinki and was approved by the Committee for Protection of Human Subjects at the University of California at Berkeley. Subjects were given a comprehensive eye examination. All subjects habitually wore distance refractive corrections and had best-corrected visual acuity of 20/20 or better, gradient estimate of the stimulus AC/A ratio lying between 2/1 to 6/1, anisometropia 1 D or less, and normal ocular health and eye alignment. None of the subjects had astigmatism greater than  $-1.25$  D. Subjects with spherical refractive errors greater than  $\pm 4.5$  D were excluded except for three subjects with longstanding myopia who wore  $-6.0$  D ( $n = 1$ ) and  $-5.5$  D ( $n = 2$ ) contact lens correction. Thirteen subjects had myopia (refractive error  $\geq -0.50$  D), of whom only one had myopia of late onset (after 15 years of age and progressive myopia). Fifteen subjects had emmetropia ( $+0.50$  to  $-0.25$  D), and two had hyperopia ( $>0.5$  D). In the younger group, seven subjects had myopia, seven had emmetropia, and one had hyperopia. In the older group, six subjects had myopia, eight had emmetropia, and one had hyperopia. Subjects in the older group were included only if they had accommodative amplitudes of at least 3 D, determined by monocular minus lens to blur method. Only those subjects who had not yet obtained reading spectacles were included in the older group. Subject demographics are given in Table 1.

Qualified subjects were prescribed  $+1.50$  D single-vision reading additions over their distance refractive corrections to ensure compliance during reading tasks. Subjects who used contact lens correction for distance vision wore the reading spectacles over their contact lenses. If bifocals had been prescribed, some subjects could have used the distance portion of the spectacle correction for near viewing. Subjects were asked to wear the reading spectacles for a minimum of 3 hours per day for all near vision tasks, such as computer use and reading, for 2 months. On average, younger and older subjects wore the reading spectacles for  $3.5 \pm 1.42$  and  $3.47 \pm 1.54$  hours per day (based on daily log), respectively. Accommodative stimulus-response function (ASR),<sup>20,21</sup> response AC/A ratio, and CA/C ratio were measured on three occasions: before treatment or baseline, before reading spectacles were worn; after treatment, immediately after reading spectacles were worn for 2 months; and recovery, 2 months after use of the reading spectacles was discontinued. Subjects wore their distance refractive correction during these measurements.

A Wheatstone-mirror haploscope that housed a pair of Badal-otometer stigmascopes, one before each eye, was used to obtain the subjective estimates of convergence and accommodation (Fig. 1). The stigmascopes viewed by the left eye was used to measure accommodative responses.<sup>22</sup> The stigmascopes consist of a 10 D Badal lens system, which images a variable focus stigma (0.5-mm point source of light).

The secondary focal point of the Badal lens coincides with the anterior focal point of the eye, thereby allowing changes in dioptric vergence of the stigma without altering its magnification.<sup>23</sup> A small depth of field of the stigma (0.125 D) was produced by a crosshair placed within the pinhole aperture. It appeared focused when it was optically conjugate to the retina  $\pm 0.125$  D. The stigma was superimposed with a beam splitter on an accommodative stimulus consisting of a text target ( $\sim 6/9$  print size). Accommodation of the left eye was stimulated monocularly with the right eye occluded. Subjects were instructed first to fixate and focus on the center of the text target placed 1 m from the spectacle plane and then to adjust the distance of the left eye stigma from the Badal lens by turning a knob until the crosshair was in sharp focus. The distance between the stigma/crosshair and Badal lens was used to compute the accommodative response. A range of negative lenses was used to increment the accommodative stimulus to the left eye in 0.5- or 1-D steps for the older and younger subject groups, respectively, until maximum minus lens stimulus to accommodation was reached. Because the text target was at a distance of 1 m and was a 1-D stimulus to accommodation, a  $+1$ -D lens was used to produce 0.0 D accommodative stimulus condition.

## AC/A Ratio Measurement

The gradient response AC/A ratio was measured with the right stigmascopes; an occluder was positioned on the far side of the beam splitter before the right eye so that the view of the accommodative stimulus could be occluded while the right stigma was allowed to remain visible. The left eye viewed both the left stigma and the accommodative stimulus (Fig. 1). Because the right eye was occluded, there was no disparity stimulus to convergence (open-loop disparity condition), whereas the text target provided monocular blur feedback to accommodation (closed-loop condition). The measurement of AC/A ratio

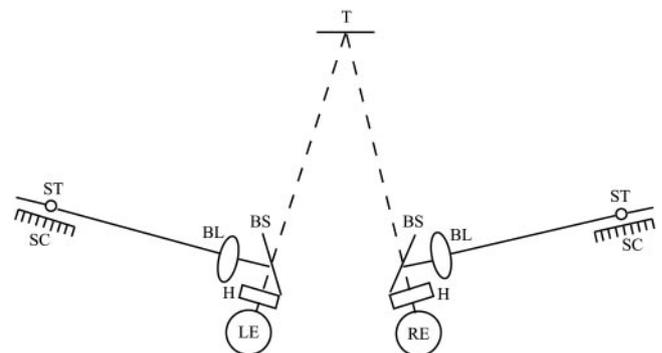


FIGURE 1. Schematic of two stigmascopes built into a Wheatstone-mirror haploscope to subjectively measure closed-loop accommodative response and open-loop accommodative-convergence response. The left stigma (ST; point source of light) visible to the left eye (LE) was imaged on a target (T) viewed by that eye through a beam splitter (BS). The subject adjusted the focus of the stigma by moving it toward or away from the 10-D Badal lens (BL) while fixating at target (T). The stigma is focused when it is optically conjugate with the retina, and the scale reading (SC) is converted to accommodation in diopters. Lenses of different powers were placed on the lens holder (H) to induce a range of accommodative stimuli.

began with focusing each of the stigmas (and crosshairs), as described, with no lens stimulus. Subjects were then instructed to fixate and focus on a letter seen by the left eye at the center of the text target. Accommodation response measurements were obtained from the left eye with the right eye occluded, as described. Convergence associated with changes in accommodation was measured with a dichoptic Vernier alignment task. The subject rotated the arm of the right haploscope to adjust the perceived direction of the right stigma so that it was perceived in the same visual direction as the left stigma, which appeared centered on the text chart (Nonius technique). Binocular fusion of the right and left eye stigmas was prevented by vertical displacement of the right stigma so that the two stigmas appeared vertically aligned with the fixated letter in the Vernier task. The rotation angle of the right haploscope arm was taken as the measure of convergence. The haploscope arm rotates about a pivot point coincident with the eye's center of rotation, thereby preventing retinal image translation of the stigma caused by right eye rotation during accommodative convergence. Accommodation was stimulated with ophthalmic lenses placed before the left eye over a range of dioptric powers: +1 D to -5 D in 1-D steps in the younger group and +1 D to -3 D in 0.50-D steps in the older group.

### CA/C Ratio Measurement

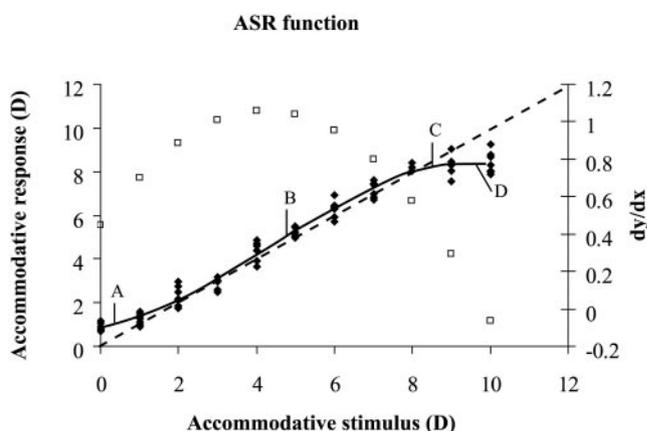
The gradient CA/C ratio was measured with a convergence stimulus that eliminated blur as a stimulus to accommodation using a large depth of field. The convergence target was a low pass-filtered Difference of Gaussian (DoG) that had a center spatial frequency of 0.2 cpd. The DoG was presented binocularly, and it served as a binocular fusion stimulus (closed-loop disparity stimulus), whereas accommodation was open-loop.<sup>24</sup> Subjects were instructed to fuse the DoG target while the binocular disparity stimulus to convergence was varied with ophthalmic prisms placed before both eyes over a range -1 to +4 MA in 1-MA steps. Accommodative responses associated with convergence responses to the varying prism stimuli were measured in the left eye using the stigma-bracketing technique. Convergence responses were assumed to be within a few minutes of arc of the vergence stimuli as long as the DoG target could be fused.<sup>25,26</sup> Previously, we have shown that the vergence error to this stimulus is less than 0.25°. <sup>27</sup>

Sufficient test trials were conducted (training) for each task before the final data set was recorded. The sequence through which ophthalmic lenses varied the stimulus to accommodation was randomized to reduce the adaptation of resting levels of accommodation to a given stimulus magnitude. Similarly, magnitudes of prism-disparity stimuli were randomized to avoid adaptation of resting convergence. Seven measurements were obtained for each magnitude of the defocus or disparity stimuli levels.

### Computation of Steady State Parameters

**Accommodative Stimulus Response Function.** The ASR function is a plot of accommodative response as a function of accommodative stimulus, and the resultant function conforms to a sigmoid curve that behaves according to a cubic function.<sup>28</sup> Four parameters were estimated objectively from the ASR data with the use of a computer algorithm: the slope of the ASR function (estimates the closed-loop gain of the accommodation system), the  $y$ -intercept (estimates the distance accommodative state and refractive error at zero D stimulus), the zero derivative point at the peak of the ASR function (estimates the near point of accommodation, as described), and the soft saturation (transition) zone<sup>29</sup> at the peak of the ASR curve. Although a single index approach<sup>30</sup> to describe the static accommodation response has been proposed by some researchers, we did not use this because it is not applicable to nonlinear regions of the ASR curve (Fig. 2).

Data of a representative subject are shown by the solid curve in Figure 2. The linear portion of the ASR curve was used to determine the slope and the intercept. An objective method was used to determine the linear portion of the function instead of relying on visual



**FIGURE 2.** The ASR function of a representative young subject is illustrated by the *solid curve*. Accommodation response is plotted as a function of accommodative stimulus. The first derivative (*open squares*) of a third-order polynomial fit (*black solid line*) to the raw data is shown. The *dashed line* indicates the 1:1 line where the accommodation responses equal the stimuli. The ASR curve can be divided into four sections describing different response characteristics.<sup>29</sup> A, initial nonlinear region; B, linear region; C, soft saturation zone; D, NPA (or hard saturation region).

inspection. A third-order polynomial was fit to the data, and the first derivative was computed (Fig. 2, open squares). The ASR data range, which yielded slope values greater than 0.40, was considered linear. Fitting higher order polynomials to this linear data did not produce better fits than the linear regression line. Therefore, the slope and intercept of this straight line estimated the gain and bias of the accommodation response. The distance in diopters between the data corresponding to the 0.40 derivative point and the zero derivative point at the peak of the ASR function was taken as a measure of the dioptric width of the soft saturation zone. The near point of accommodation (NPA; maximal accommodation) was estimated by the accommodation response corresponding to a derivative of zero at the peak of the ASR function. Pretreatment, posttreatment, and recovery data were analyzed separately.

**AC/A and CA/C Ratios.** The AC/A ratio was estimated from open-loop vergence responses, plotted as a function of closed-loop accommodation responses, to a range of accommodative stimuli that were within the linear range of accommodation of each subject. Plots were of absolute values of accommodation and convergence with reference to primary position and the distance refractive correction. Linear regression lines were fit to the linear portion of the data, and the slope of the straight line quantified the AC/A ratio (expressed in MA and D). CA/C ratios were estimated from the open-loop accommodation responses, plotted as a function of convergence, for prism stimuli over the range -1 to 4 MA. A linear regression line was fit to the linear portion of the data, and the slope quantified the CA/C ratio (D/MA). Linearity was assessed by visual inspection, because a single objective criterion could not be applied to determine linearity resulting from the variability in the data. Fitting higher order polynomials to the linear portion of the data did not improve the fit, suggesting that the data do not violate the linearity assumption.

Biases (phorias) of convergence and accommodation were estimated indirectly from the  $y$ -intercepts of the straight line plots of AC/A and CA/C data, respectively. Convergence bias indicates the open-loop convergence response when the accommodation response is zero. Similarly, the accommodation bias indicates the open-loop accommodation response when the convergence response is zero.<sup>31</sup> Pretreatment, posttreatment, and recovery data were analyzed separately.

### Statistical Analysis

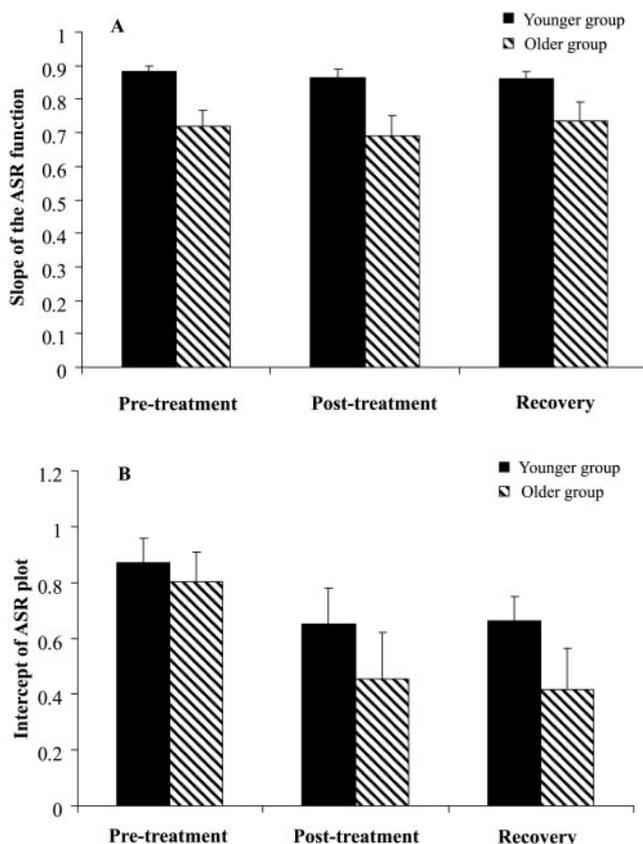
Independent sample  $t$ -tests ( $P < 0.025$ ) were used to compare pretreatment data between the two groups. Two-way ANOVA ( $P < 0.025$ ;

Bonferroni corrected for multiple comparisons) was then applied by which the within-subjects factor (three levels) describes the changes after treatment from baseline and recovery. The between-subjects factor was the subject group (two levels, younger and older age groups). A significant interaction effect between the two factors suggested that the changes from pretreatment data are different in the two groups. An absence of significant interaction effect and within-subjects effect indicated that reading glasses did not change the baseline data in either group. Correlation between variables was examined using Pearson product-moment correlation coefficients ( $P < 0.05$ ). A sample size of 15 per group was chosen based on computations using pilot results. For an assumed alpha value of 0.05 and a power of 0.80, a minimum sample size of 14 per group was required for an anticipated mean difference in the change in accommodative amplitude between groups of 0.38 D and an overall variability of 0.35 D.

## RESULTS

### Accommodative Stimulus-Response Function

We observed that the pretreatment slopes of the ASR function were significantly higher in the younger age group than the older group (unpaired,  $P < 0.025$ ), consistent with the results of Radhakrishnan and Charman.<sup>32</sup> Inverse transformation was required to achieve variance homogeneity before ANOVA was run on slope data. ASR slopes did not change significantly with treatment in both groups (ANOVA;  $P > 0.025$ ; Fig. 3A). On the other hand, the ASR intercept showed a posttreatment hyperopic shift that did not recover after near spectacle use was



**FIGURE 3.** (A) The slope of the ASR function (mean  $\pm 1$  SEM) before treatment, after treatment, and at recovery are shown for the younger (black solid bar) and the older (hatched bar) subject groups. (B) Mean ( $\pm 1$  SEM) ASR intercepts before treatment, after treatment, and at recovery are plotted for the younger (black solid bar) and the older (hatched bar) subject groups.

discontinued for 2 months ( $F_{(2,56)} = 4.24$ ;  $P < 0.025$ ; Fig. 3B). Interaction between the changes with treatment and the subject group was not significant ( $P > 0.025$ ), indicating that the magnitudes of hyperopic shift were similar in the two age groups. There was no difference in the pretreatment ASR intercept values between the two groups (unpaired;  $P > 0.025$ ). As with the slope data, there were no statistical changes in the widths of the soft saturation zone and the linear portion of the ASR curve after treatment with reading spectacles (ANOVA;  $P > 0.025$ ). ASR slope estimates and sensitivity were similar with both 1- and 0.5-D step sizes during accommodation measurements in young subjects ( $n = 3$ ), suggesting that the choice of a relatively large step size (1 D) did not affect the estimates.

### Accommodative Amplitude

Accommodative amplitude, defined as the dioptric difference between NPA and the far point of accommodation (FPA; empirically measured minimum accommodation response, which invariably occurred for a 0-D accommodative stimulus), did not change with treatment in both groups (ANOVA;  $P > 0.025$ ). Pretreatment amplitudes were significantly greater in the younger than the older age group (unpaired;  $P < 0.025$ ). Interestingly, after treatment with reading spectacles, both groups showed similar magnitudes of hyperopic (plus) bias of the empirically measured far point of accommodation ( $F_{(2,56)} = 5.09$ ;  $P < 0.025$ ), as would be predicted by the hyperopic shifts of the  $y$ -intercept of the ASR function.

Accommodative amplitude was also defined with respect to true optical infinity (NPA-0 D; i.e., FPA = 0 D). The hyperopic bias of the ASR reduced the accommodative amplitude defined this way, and the amplitudes did not revert to pretreatment values 2 months after reading spectacle use was discontinued ( $F_{(2,56)} = 8.93$ ;  $P < 0.025$ ) (see Figs. 4A, B). The interaction effect was not significant ( $P > 0.025$ ), suggesting that the magnitudes of the reduction in the accommodative amplitude were similar in the two groups. This result was not attributed to one or two aberrant subjects. Twelve of 15 of the younger subjects and 14 of 15 subjects in the older groups displayed a reduction of accommodation. Average changes in accommodative amplitude (posttreatment) were 0.65 D and 0.7 D in the younger and the older group, respectively. Because the adaptive changes to reading spectacles were age-invariant, the accommodative amplitude data of the two age groups were combined for further analysis. Interestingly, the magnitudes of reduction of amplitude determined with respect to infinity and the shifts in ASR intercepts after treatment were found to be similar in myopes and emmetropes (unpaired;  $P > 0.025$ ).

### AC/A Measures

Figure 5A shows the mean AC/A ratios at baseline, after treatment, and at recovery. Pretreatment AC/A ratios were not significantly different between the two age groups (unpaired;  $P > 0.025$ ). AC/A ratios did not change significantly with treatment in either group (ANOVA,  $P$ -values  $> 0.025$ ). Mean differences between the pretreatment and posttreatment AC/A ratios were 0.03 and 0.09 in the younger and older groups, respectively. The correlation between the baseline AC/A ratios and the magnitudes of posttreatment changes in AC/A did not reach statistical significance ( $n = 30$ ;  $r = 0.33$ ;  $P > 0.05$ ), suggesting that the posttreatment changes in AC/A ratios were not dependent on the baseline measures. The open-loop vergence bias (phoria, indicated by the  $y$ -intercept of the AC/A plot) before treatment, after treatment, and at recovery are shown in Figure 5B. Pretreatment vergence biases were similar in the two groups ( $P > 0.025$ ), and although there was a trend toward increased esophoria after treatment in the older group,

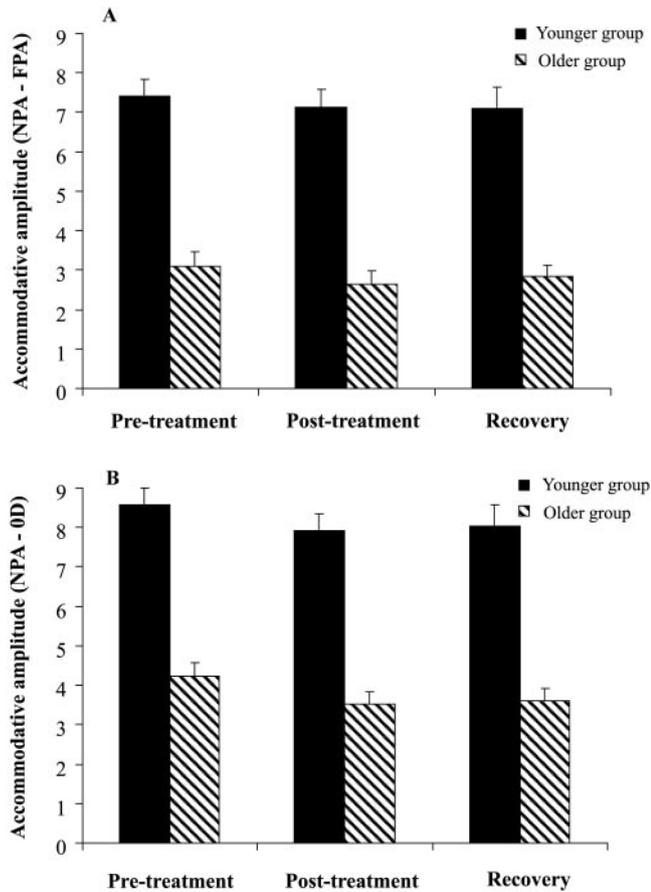


FIGURE 4. (A) Accommodative amplitude/range (defined as the difference between the near point and the far points of accommodation) before treatment, after treatment, and at recovery are plotted for the younger (black solid bar) and the older (hatched bar) subject groups. Error bars represent ±1 SEM. (B) Accommodative amplitude (estimated with respect to optical infinity [NPA - 0 D]) before treatment, after treatment, and at recovery are plotted for the younger (black solid bar) and the older (hatched bar) subject groups. Error bars represent ±1 SEM.

the biases remained unaltered with treatment (ANOVA;  $P > 0.025$ ) in both groups.

**CA/C Measures**

Figure 6A shows the mean CA/C ratios at baseline, after treatment, and at recovery. Pretreatment CA/C ratios did not differ between the two groups (unpaired;  $P > 0.025$ ). Consistent with our AC/A results, the changes in CA/C ratios (average changes, 0.04 and 0.03 in the younger and older groups, respectively) with treatment did not reach statistical significance (ANOVA;  $P > 0.025$ ). However, the correlation between baseline CA/C ratios and magnitudes of posttreatment changes in CA/C ratios was significant ( $n = 30$ ;  $r = 0.64$ ;  $P < 0.05$ ). Figure 6B plots the open-loop accommodation bias (accommodation phoria, indicated by the  $y$ -intercept of the CA/C plot) before treatment, after treatment, and at recovery. Pretreatment accommodation biases were similar between the two age groups ( $P > 0.025$ ). As can be predicted from the hyperopic shift of the ASR intercept with treatment (Fig. 3B), accommodation bias showed a trend toward less myopia, though statistical significance was not reached (ANOVA;  $P > 0.025$ ).

**DISCUSSION**

The impact of short-term use of reading spectacles on accommodative amplitude and the interactions between accommodation and convergence were studied in pre-presbyopia and incipient presbyopia. The main findings are that wearing single-vision reading spectacles for 2 months induced distal shifts of the near and far points of accommodation without changing the range of accommodation in both groups. The receded NPA did not recover to baseline after 2-month use of reading spectacles was discontinued, and this effect was independent of the age of the subjects studied. The evidence was insufficient to suggest adaptation of the cross-links between accommodation and vergence.

**Adaptation of the Accommodation Stimulus-Response Function**

The ASR function depicted in Figure 2 illustrates that an increase or a decrease in accommodative amplitude can result primarily from vertical shifts (biases) of the accommodative response for distance (0 D) stimuli, increases or decreases in the linear portion of the ASR function, changes in the slope of the ASR curve, or a combination of all three. The results demonstrate that the accommodative amplitude estimated with respect to optical infinity declined after treatment with reading spectacles. Mean decreases in the amplitudes were 0.65 D and 0.7 D in the younger group and the older group, respectively. It is apparent from the results that the slope of the

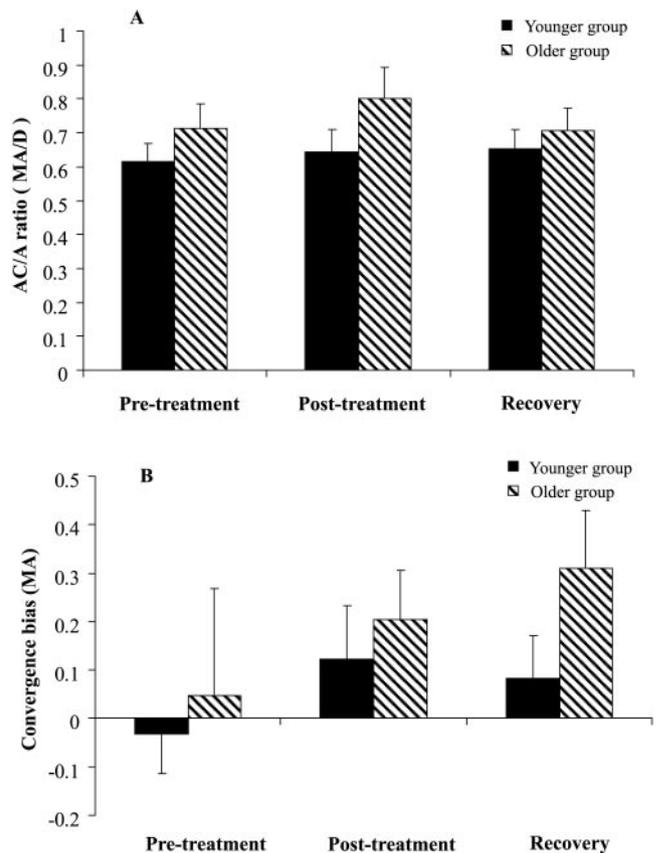
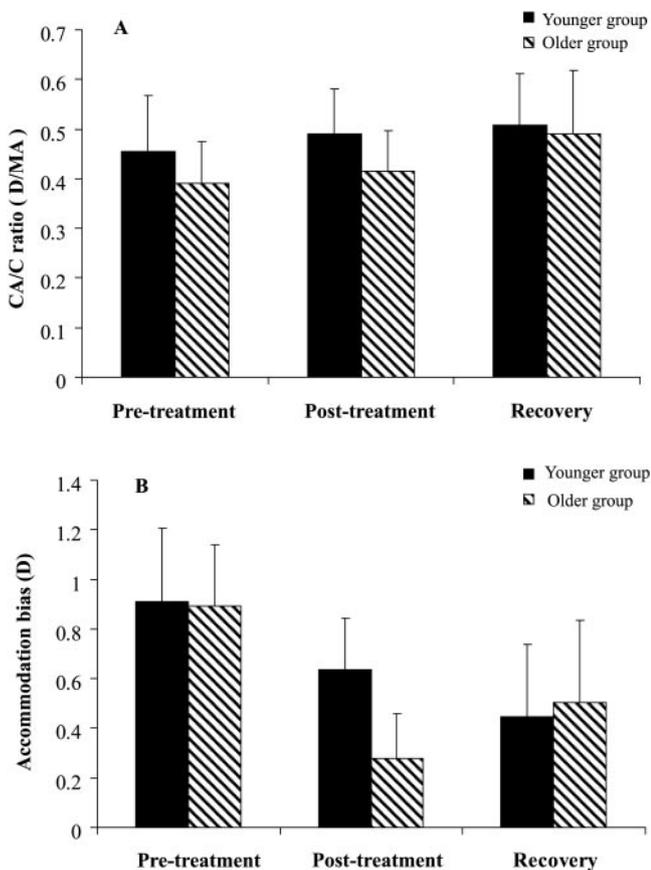


FIGURE 5. (A) AC/A ratios (mean ± 1 SEM) before treatment, after treatment, and at recovery are shown for the younger (black solid bar) and the older (hatched bar) subject groups. (B) Mean (±1 SEM) convergence bias (indicated by  $y$ -intercept of the AC/A plot) before treatment, after treatment, and at recovery are shown for the younger (black solid bar) and the older (hatched bar) subject groups.



**FIGURE 6.** (A) CA/C ratios (mean  $\pm$  1 SEM) before treatment, after treatment, and at recovery are shown for the younger (black solid bar) and the older (hatched bar) subject groups. (B) Mean ( $\pm$  1 SEM) convergence-accommodation bias (indicated by  $y$ -intercept of the CA/C plot) before treatment, after treatment, and at recovery are shown for the younger (black solid bar) and the older (hatched bar) subject groups.

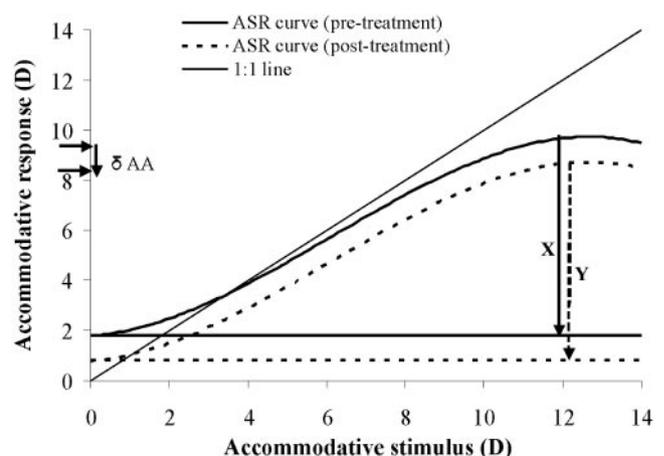
ASR function did not change in either group after reading spectacles were worn (Fig. 3a). However, the  $y$ -intercepts of the ASR function and the near point of accommodation were reduced after treatment in both groups. The mean amplitude of the linear range of accommodation was constant after treatment in both groups. Therefore, by elimination, the main factor that appears to contribute to the decline in the accommodative amplitude of the two groups is the hyperopic shift of the ASR curve after treatment. Figure 7 is a diagrammatic representation of the adaptive changes to the ASR curve after treatment. We propose that the NPA may normally be enhanced by a tonic bias of accommodation that elevates the entire ASR function and produces a myopic refraction bias. When this bias relaxes after the use of near spectacles, a hyperopic shift in the refractive state occurs, as does a reduction in NPA, specified from optical infinity, but the accommodative amplitude specified from the empiric far-point refraction is unaffected. That there exists a tonic bias of accommodation is well established, as is its amenability to adaptation.<sup>33-39</sup>

An alternative explanation to consider for hyperopic shifts is that the magnitude of the depth of focus increased with treatment and resulted in a large lag of accommodation. Exposure to myopic defocus with plus lenses during distance fixation increases the subjective tolerance level to blur.<sup>40</sup> According to the established models of accommodation, an increase in depth of focus (tolerance to blur) would decrease the blur-driven accommodation response, thereby increasing the ac-

commodative lag.<sup>14,21</sup> Laboratory studies indicate that an increase in the accommodative lag (or hyperopic defocus) during near vision is a precursor to axial myopia.<sup>41</sup> However, this is an unlikely explanation for our results because subjects only wore plus lenses for near tasks. Normally, presbyopic eyes show gradual hyperopic shifts, perhaps because of an age-related decrease in the gradient refractive index of lens.<sup>42</sup> The present results indicate that wearing of reading glasses may contribute in part toward this normal hyperopic drift.

As shown by the error bars in Figure 3B, there was inter-subject variability in the amounts of the hyperopic shifts, and this perhaps could be attributed to the differences in the baseline tonic innervation between subjects<sup>34,35</sup> or to the differences in the number of hours of near spectacle lens wear between subjects. It is also evident from our results that the NPAs receded by the same magnitude in emmetropes and myopes after treatment. McBrien and Millodot<sup>34</sup> studied the adaptation of tonic accommodation in four different refractive groups. They found that subjects with late-onset myopia experienced large increases in tonic levels after a 15-minute period of sustained near activity, subjects with hyperopia experienced large counteradaptive effects (opposite in sign to the accommodative stimulus), and subjects with emmetropia and early-onset myopia fell in the middle and behaved in a similar manner. In the present study, 92.3% of subjects with myopia had early-onset myopia; therefore, the absence of a difference between these subjects and those with emmetropia are in line with previous research.

A striking feature of the present study is that we found no age-dependent adaptability of accommodative amplitude to reading spectacles. We also found that the decline in accommodative amplitude (NPA - 0 D) did not regress to baseline even after reading spectacle use was discontinued for 2 months. What implications do these findings have for the progression of presbyopia? If increased tonic activity of accommodation is not sustained during the wearing of reading spectacles, it could result in a reduction of NPA and the amplitude of accommodation. The results also suggest that a myopic shift may normally slow down the progression of presbyopia by increasing the near point of accommodation.



**FIGURE 7.** Summary of the changes of the ASR function produced by wearing reading spectacles. Solid curves and dashed curves represent the pretreatment and post-treatment ASR functions, respectively. The two horizontal arrows along the  $y$ -axis represent the dioptric pre-treatment and post-treatment NPAs. The accommodative amplitude estimated with FPA at infinity declines with treatment (shown as  $\delta AA$ ), but the accommodative range pre-treatment (X) and post-treatment (Y) remains unaltered (i.e., X = Y).

## Adaptation of the Accommodation and Vergence Cross-Links

Large conflicts in stimuli between accommodation and vergence can produce adaptive changes in AC/A ratio. AC/A ratios can be elevated, and CA/C ratios can be reduced in response to a telestereoscope, which optically widens the effective interocular separation to increase the convergence stimulus approximately 2.6 times compared with a given accommodative stimulus.<sup>43</sup> Plasticity of the cross-links has also been demonstrated by decreasing the effective interocular separation (which reduces the convergence stimulus compared with the accommodative stimulus),<sup>44</sup> stimulating dynamic vergence responses without changing the accommodative stimulus using a virtual reality stimulus,<sup>45</sup> visual fatigue,<sup>46</sup> pharmacologic agent,<sup>47</sup> and orthoptics.<sup>48</sup> In the present study, although stimulus conflicts were introduced by decreasing the accommodative stimulus (with +1.5 D readers) relative to the convergence stimulus, we found no adaptive changes of the cross-link gains.

Of related interest here is a study by Flom,<sup>49</sup> in which the AC/A ratio and baseline phoria of one adult subject was measured before and immediately after discontinued use of a pair of single-vision +1.50-D readers worn continuously for 30 waking hours. Treatment resulted in an increase in the AC/A ratio. Flom<sup>49</sup> also observed a high AC/A ratio immediately after undercorrected myopia was corrected with minus spectacle lenses. After the refractive correction was worn for some time, the AC/A ratios were found to regress toward normal values.<sup>19</sup> Subjects with undercorrected myopia have in-built near additions equal to the magnitude of undercorrection, and prescribing full minus correction to these subjects has the same effect as discontinuing the in-built reading spectacles. In the present study, subjects wore the reading spectacles only for near work so that conflicts between accommodative and convergence stimuli were not present when the reading glasses were not worn. There was no objective way to monitor the number of hours of eyeglass wear. We might have found adaptive changes in the cross-links between accommodation and convergence if our subjects had used the reading spectacles continuously for longer durations. Nevertheless, our results suggest that there is no long-term impact of wearing the reading spectacles intermittently for a short-term on the accommodation and vergence cross-links; this was true for both subject groups.

## CONCLUSIONS

The results demonstrate that static accommodative response can be adapted in response to short-term treatment with reading spectacles. The unique feature of this work is the finding of age invariance of this effect. Our results showed that the near and far points of accommodation recede after reading spectacles are worn and do not recover after 2 months of discontinued treatment. If these distal shifts transferred to persons with presbyopia, they would report more dependence on reading spectacles, and clinicians would find a more rapid reduction in the clinical measures of accommodative amplitude that assume the far point to be set at infinity. In practical terms, our results suggest that to preserve the remaining range of focusing ability in incipient presbyopia, it would be beneficial to delay the prescription of reading spectacles unless the hyperopic refractive shift is also corrected.

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