The effect of blur adaptation on accommodative response and pupil size during reading

Rongrong Le
Wenzhou Medical College, Wenzhou, Zhejiang, China

Jinhua Bao
Wenzhou Medical College, Wenzhou, Zhejiang, China

Dongyan Chen
Wenzhou Medical College, Wenzhou, Zhejiang, China

Ji C. He
Wenzhou Medical College, Wenzhou, Zhejiang, China, & New England College of Optometry, Boston, MA, USA

Fan Lu
Wenzhou Medical College, Wenzhou, Zhejiang, China

To study the effect of blur adaptation on accommodative variability, accommodative responses and pupil diameters in myopes \((n = 22)\) and emmetropes \((n = 19)\) were continuously measured before, during, and after exposure to defocus blur. Accommodative and pupillary response measurements were made by an autorefractor during a monocular reading exercise. The text was presented on a computer screen at 33 cm viewing distance with a rapid serial visual presentation paradigm. After baseline testing and a 5-min rest, blur was induced by wearing either an optimally refractive lens, or a +1.0 DS or a +3.0 DS defocus lens. Responses were continuously measured during a 5-min period of adaptation. The lens was then removed, and measurements were again made during a 5-min post-adaptation period. After a second 5-min rest, a final post-adaptation period was measured. No significant change of baseline accommodative responses was found after the 5-min period of adaptation to the blurring lenses \((p > 0.05)\). Compared to the pre-adaptation level, both refractive groups had similar and significant increases in accommodative variability right after blur adaptation to both defocus lenses. After the second rest period, the accommodative variability in both groups returned to the pre-adaptation level. The results indicate that blur adaptation has a short-term effect on the accommodative system to elevate instability of the accommodative response. Mechanisms underlying the increase in accommodative variability by blur adaptation and possible influences of the accommodation stability on myopia development were discussed.

Keywords: blur, adaptation, accommodation, accommodative variability, retinal defocus


Introduction

During reading, a clear vision of the text is achieved through accommodation by which refractive power of the eye is increased to the degree required for near reading distance. In most cases, however, the refractive power of the accommodating eye is slightly less than that needed for the reading distance. Thus, it exhibits a small amount of under-accommodative defocus, termed accommodation lag, which slightly degrades the retinal image in the eye. Accommodation lag varies with visual conditions, such as the luminance level (Johnson, 1976; Kotulak & Schor, 1987) and contrast of the reading letters (Heath, 1956; Rosenfield, Ciuffreda, Hung, & Gilmartin, 1994). Even under identical visual conditions, the amount of accommodation lag is not constant for everyone but is different from one person to another. Meanwhile, refractive power of the accommodating eye is by no means constant over time either. Even when staring at a stationary target, refraction fluctuates dynamically around the mean accommodative response within a limited range of about 0.5 diopter (D). These small, rapid changes are termed accommodation microfluctuations, the range of which also varies from individual to individual (Campbell, Robson, & Westheimer, 1959; Charman & Heron, 1988; Collins, 1937; Kotulak & Schor, 1986; Seidel, Gray, & Heron, 2003; Winn, Pugh, Gilmartin, & Owens, 1990).
The optical effect of the accommodation fluctuations on the retinal image is to make the image quality unstable (Langaas et al., 2008).

Thus, both accommodation lag and accommodation fluctuations deteriorate the optical quality of the retinal image. An open question is how the accommodative system tolerates or makes use of the degraded image and effectively controls the accommodative response for achieving clear near vision. A useful approach to address this question is to explore the factors that contribute to individual variation in accommodation lag and fluctuations. This could help understand the necessary information that is processed during accommodation control. Recently, there has been increasing interest to test differences in accommodative behavior among people with different refractions, e.g., myopia vs. emmetropia. Progressive myopes have a larger accommodation lag than do emmetropes (Abbott, Schmid, & Strang, 1998; Gwiazda, Thorn, Bauer, & Held, 1993), although this has not always been found under different experimental conditions (Allen & O’Leary, 2006; Lan, Yang, Liu, Chen, & Ge, 2008). The higher level of accommodation lag in myopes was suggested to be a risk factor for myopia development and progression in schoolchildren (Gwiazda et al., 1993; Gwiazda, Thorn, & Held, 2005). Myopes have larger amounts of accommodation microfluctuations than do emmetropes when a simple visual target is used to induce accommodation (Day, Strang, Seidel, Gray, & Mallen, 2006; Langaas et al., 2008) or during sustained periods of reading (Harb, Thorn, & Troilo, 2006). The elevated level of accommodation microfluctuations in myopes is also believed to be a risk factor for myopia development due to its integrated blur effect on retinal image over time (Harb et al., 2006; Langaas et al., 2008). Determination of the underlying factors that differentiate accommodative behavior in the myopic eye from the emmetropic eye therefore is of interest not only for understanding the accommodative mechanism but also for finding effective intervention to control myopia development and progression.

Visual blurring is a perceptual experience that results partially from optical degradation of the retinal image and partially from prior visual experience due to the adaptive nature of the visual neural system. Previous studies have revealed a change in blur detection for both emmetropes and myopes after exposure to blurred visual stimulation for a period of time (Cufflin, Mankowska, & Mallen, 2007; Wang, Ciuffreda, & Vasudevan, 2006). However, myopes can better detect previously blurred visual targets than emmetropes (Cufflin, Hazel, & Mallen, 2007; George & Rosenfield, 2004). Because blur adaptation improves spatial sensitivity by partially negating blur impact on visual performance, it might influence the processing of defocus blur visual information by controlling the accommodative system. By using blur adaptation as a manipulation on accommodative stimulation, Vera-Diaz, Gwiazda, Thorn, and Held (2004) observed an increase in accommodative response (or decrease in accommodation lag) in myopic eyes after 3-min exposure to a blurred screen during reading. However, the increase in accommodative responses after blur adaptation was not observed for emmetropes. The decrease in accommodation lag after blur adaptation in myopic eyes was thought to be in agreement with blur adaptation linked to improvement in visual performance as observed in previous studies. However, no reduction in accommodation lag after blur adaptation was observed in two other studies when different types of blur stimuli were used (Cufflin, Hazel et al., 2007; George & Rosenfield, 2002). The effect of blur adaptation on accommodation lag is still controversial, and no experiments have been conducted to examine the influence of blur adaptation on accommodation fluctuations during reading. In addition, there have been no studies to determine if there are differences between myopes and emmetropes in the effect of blur adaptation on accommodation variability. The primary aim of this study was to test the influence of blur adaptation on accommodation fluctuations by continuously measuring accommodative responses during reading. We monitored changes in accommodation lag, accommodation variability, and pupil size in myopes and emmetropes before, during, and after exposure to a lens-induced defocus, to determine if there were differences between the two groups.

### Methods

#### Subjects

The research followed the tenets of the Declaration of Helsinki and was approved by the Sciences Ethics Committee of Wenzhou Medical College. The informed consent was obtained from the subjects after explanation of the nature and possible consequences of the study. Forty-one young subjects were recruited from the student cohort of Wenzhou Medical College. All of the subjects voluntarily participated in this study. Refractive errors of all participants were determined by monocular subjective refraction at 5 m. All subjects were free of ocular pathology and had a visual acuity (VA) of 20/20 or better. Those with astigmatism >0.75 D were not included in the study. Among the subjects, emmetropes ($n = 19$) had spherical equivalent (SE, sphere + 0.5×cyl) refractive errors between −0.25 and +0.50 D (Table 1). Myopes ($n = 22$)

<table>
<thead>
<tr>
<th>Myopes</th>
<th>Emmetropes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of subjects</td>
<td>22</td>
</tr>
<tr>
<td>Age (years)*</td>
<td>24.6 ± 2.1</td>
</tr>
<tr>
<td>Male/female distribution</td>
<td>9/13</td>
</tr>
<tr>
<td>Mean SE (D)*</td>
<td>−4.08 ± 1.47</td>
</tr>
</tbody>
</table>

Table 1. Emmetropic and myotropic subject characteristics. Notes: *Values are means ± standard deviation.
had SEs ≤ −0.75 D. Myopes were required to wear trial lenses to best correct their SE for at least 60 min continuously before the start of the experiment.

**Apparatus**

The accommodative response was dynamically measured with an open-field instrument, Grand Seiko Auto Ref/Keratometer WAM-5500 (Grand Seiko, Hiroshima, Japan). In HI-SPEED mode, the autorefractor was connected with a computer to measure refraction and pupil size of the entire meridian every 0.2 s (5 Hz). Validity of the instrument in measuring accommodation dynamically has been confirmed in previous studies (Day, Gray, Seidel, & Strang, 2009; Day, Seidel, Gray, & Strang, 2009; Kimura, Hasebe, & Ohtsuki, 2007; Mallen, Wolffsohn, Gilmartin, & Tsujimura, 2001; Sheppard & Davies, 2010; Wolffsohn, Gilmartin, Mallen, & Tsujimura, 2001). Because we used trial frames and lenses in the experiment, the pupil size of each myopic subject was calibrated later.

**Reading task**

Reading materials were obtained from a translated Chinese version of the Harry Potter stories. A rapid serial visual presentation (RSVP) reading paradigm was employed in this study to avoid influence of saccadic eye movements on accommodation measurement. Characters of the stories were presented one by one at a rate of 150 characters per minute with RSVP software on a 5.6-inch Fujitsu U2010 laptop computer screen (screen resolution of 1024 x 768) with high contrast (95.1%). To make the tested eye to be coincident with the visual axis, the letters were located at the center of the computer screen, and the fellow eye was occluded. The screen was set at a distance of 33 cm from the subject, and the character with a size of 12 pt (42 pixels per character height) formed a visual angle of 0.729°.

**Experimental procedures**

Accommodative responses were measured in three different visual conditions: (i) with optimal correction of SE of refractive error if needed (the control test), (ii) with a +1.0 DS of defocus, and (iii) with a +3.0 DS of defocus. In the (ii) and (iii) conditions, an additional lens (+3.0 DS) over the distance refractive correction were given to each subject to compensate for the required accommodation when viewing a fixed target at 33 cm. The measurement for each blur condition was carried out at least 48 h apart (Rosenfield, Hong, Ren, & Ciuffreda, 2002) and was performed in a randomized order.

For each of the conditions, control, +1.0 DS lens, and +3.0 DS lens, the subject was given a 30 min reading test that was divided into the following six 5-min periods: (Period 1) The accommodative response was measured monocularly while the subjects read through RSVP for 5 min. This was referred to as the “pre-adaptation baseline test.” (Period 2) The subjects were then given a 5-min rest. (Period 3) Afterward, blur was induced by either control lens, a +1.0 DS, or a +3.0 DS lens, and the subjects continued reading for another 5 min. This is referred to as the “5-min blur adaptation test.” As most subjects reported that they could not discriminate the letters of the text during the blur adaptation of +3.0 DS lens, they were asked to stare at the center of the screen. (Period 4) Upon completion of the blur adaptation test, the control or plus lens was removed, and accommodative responses were measured for another 5-min period. This was referred to as the “first post-adaptation test.” (Period 5) Following the fourth period, another 5-min rest was given. (Period 6) Following this rest period, the subjects were asked to read again for another 5 min while the accommodation was measured. This is referred to as the “second post-adaptation test.”

**Data analysis**

All data containing no more than two blinks every 10 s were selected for data analysis. Blinks were removed from the data automatically by the Grand Seiko WAM-5500 software in HI-SPEED MODE. A value of >6 D/s in addition to a change in magnitude of >2 D was considered to be an abnormal steady-state accommodation response (Day et al., 2006). Variability in the accommodative response or pupil size was defined as the standard deviation (SD) of the response across the time period. In our test, the average value and SD of accommodation responses and pupil sizes were examined. Statistical analysis, including two-way ANOVA and t-test, was performed to test differences in accommodative responses between refractive groups and blur adaptation conditions.

**Results**

**Accommodation response**

We measured accommodation responses while the subject was reading text on a computer screen at a viewing distance of 33 cm. For both myopic (Figures 1a and 2a) and emmetropic (Figures 1b and 2b) subjects, the refractive response was about 2.0 D. Thus, the accommodation lag was about 1.0 D because the screen was located at 33 cm from the eye, making a 3.0-D accommodation stimulus. The individual raw data were
divided into 30-s intervals, and the mean was calculated for each of those intervals (Figure 2). The mean accommodation responses for each group were relatively stable with small amounts of fluctuation throughout the whole test period in the control condition (Figure 2). For the +1.0 DS and +3.0 DS blur test conditions, accommodation responses remained relatively steady before and after blur adaptation for both subjects; however, the emmetropic subjects had a relatively higher amount of accommodative response and with more fluctuations than the myopic subjects during the blur adaptation period.

There were no significant differences in the mean accommodation responses of the baseline measurement among the different blur test conditions or different refractive groups (repeated-measures ANOVA, \( p > 0.05 \) for both test conditions and refractive groups, Table 2). For testing the effect of blur adaptation on accommodation, accommodative responses before and after adaptation were compared. A repeated-measures ANOVA analysis failed to show any significant effects for either the myopes or the emmetropes (repeated-measures ANOVA, \( p > 0.05 \) for control, +1.0 DS, and +3.0 DS, and for myopes vs. emmetropes).

When exposed to positive defocus, myopes completely relaxed accommodation while emmetropes did not (Figure 3). Emmetropes had a higher magnitude of accommodative responses than myopes when faced with...
Accommodative variability

Accommodative variability was estimated as the SD of the accommodative responses for every subject over a 30-s period and within a whole test period. Typically, myopic subjects had little change in the accommodation SD during the 5-min blur adaptation test when faced with a +3.0 D blur (Figure 4a). In contrast, for emmetropes, the accommodation SD during that period in response to the same stimulus was much greater (Figure 4b). The subjects in Figure 4 are the same as shown in Figure 1.

The mean accommodation SD of each group was relatively stable at each of the test periods for all three adaptation conditions, except during the period of blur adaptation. At that time, both myopes (Figure 5a) and emmetropes (Figure 5b) had large changes in the accommodation SD.

There were significant differences in the mean accommodation SD between the two refractive groups across the three blur adaptation conditions at each of the test periods (repeated-measures ANOVA, $p < 0.01$ for pre-adaptation, first post-adaptation, and second post-adaptation, Figure 6). Under control conditions, there were no significant changes in mean accommodation SD across the pre-, first post- and second post-adaptation test periods when both refractive groups were tested against the three test periods ($p > 0.05$). However, with the +1.0 DS blur adaptation, there was an overall significant change in the mean accommodation SD across the three test periods ($p < 0.01$). Because there was no significant change between the pre- and 10-min post-adaptation periods (paired t-test, $p > 0.05$), this change occurred mainly at the post-adaptation period (Figure 6). For +3.0 DS blur adaptation, there was a significant increase in mean accommodation SD between the pre- and post-adaptation periods ($p = 0.04$), but the increase disappeared after the 5-min rest period taken before for the final period of testing (paired t-test, $p > 0.05$).

During the period of blur adaptation, changes in accommodative SD were different between myopes and emmetropes. The accommodation SDs for emmetropes at +1.0 DS and +3.0 DS were similar to one another, about 0.33 D (Figure 7, Table 3). Both were significantly larger than the comparable SDs for myopes, which were about 0.19 D (two-way ANOVA, $p > 0.05$ for control, $p < 0.001$).
pupil size during the pre-adaptation period, others were relatively stable (Figure 8). However, almost everyone exhibited a reduction of pupil size during the post-adaptation test period.

There was a significant correlation between time and pupil size at each of the test periods. For myopes, pupil diameter decreased by $0.8 \pm 0.4$ mm, $0.5 \pm 0.4$ mm, $0.4 \pm 0.3$ mm, and $0.3 \pm 0.3$ mm during the pre-adaptation, blur adaptation, first post-adaptation, and second post-adaptation tests, respectively. For emmetropes, the corresponding decreases were $0.3 \pm 0.3$ mm, $0.2 \pm 0.2$ mm, $0.5 \pm 0.2$ mm, and $0.2 \pm 0.1$ mm. We analyzed changes in pupil diameter by the repeated-measures regression model that included pupil size, for both $+1.0$ DS and $+3.0$ DS, Figure 7, Table 3). For the emmetropic subjects, the accommodation $SD$ drastically increased at the onset of defocus. The control accommodation $SD$, $0.13 \pm 0.03$ (Table 3), was significantly smaller than for the $+1.0$ and $+3.0$ DS blurring (two-way ANOVA with post hoc t-test, $p < 0.001$ for control vs. $+1.0$ DS and vs. $+3.0$ DS, $p > 0.05$ for $+1.0$ DS vs. $+3.0$ DS, Table 3).

In contrast, for the myopic subjects, there were no significant differences among the different defocus levels.

**Pupil size**

The change in pupil size varied greatly from one subject to another. While some subjects showed a decrease in pupil size during the pre-adaptation period, others were relatively stable (Figure 8). However, almost everyone exhibited a reduction of pupil size during the post-adaptation test period.

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refractive error, time, and the interaction of time with refractive error. Pupil size decreased with time ($p < 0.001$), and the slopes for myopes were greater than those of the emmetropes during the baseline ($p < 0.01$) and the blur adaptation periods ($p < 0.05$).

All subjects experienced a significant decrease in pupil size after the lens was removed at the end of the 5-min blur adaptation test period (repeated-measures ANOVA, $p < 0.001$, Figure 9). After the second 5-min test period, pupil diameters for both groups and for all test conditions returned to baseline values (repeated-measures ANOVA, $p > 0.05$ for all comparisons).

Discussion

In this study, for the first time we have tested the effect of blur adaptation on accommodative variability for myopes and emmetropes. These tests were run before, during, and after exposure to a +1.0 DS or +3.0 DS lens defocus while the subjects were performing extended reading with an RSVP paradigm. Significant increases in accommodative variability after 5-min blur adaptation to both the +1.0 DS and the +3.0 DS defocus occurred for both myopic and emmetropic groups. The increase in accommodative variability after blur adaptation, however, was a short-term effect because it returned to the pre-adaptation level after the blur defocus was removed for 10 min. The results therefore indicate that blur adaptation has a short-term effect on accommodation fluctuations that increases the instability of the accommodative response. The mean increase in accommodation $SD$ was only about 0.025 D, which seems to be of no clinically importance; however, it was large and of great significance in certain individuals. For all of the subjects, the increase of accommodative $SD$ ranged from 0.09 D to $-0.03$ D, and the average accommodation $SD$ change was almost 17% above the baseline (0.025 D/0.15 D).

Evidence of improvement in visual performance after blur exposure is well documented in the literature (Cufflin, Hazel et al., 2007; Rosenfield & Abraham-Cohen, 1999; Rosenfield et al., 2002; Rosenfield, Hong, & George, 2004), and changes in depth of focus caused by blur adaptation were also reported in previous studies (Cufflin, Mankowska et al., 2007; Wang et al., 2006). In this study, we demonstrated a blur adaptation-linked increase of accommodative variability. This implies that the accommodative system
was recently found to increase accommodation fluctuation (Harb et al., 2006). Introducing more Zernike aberrations higher level of wavefront aberrations in myopic eyes modative fluctuation in myopes might be attributed to a study on this topic is expected. Further results might support the aberration hypothesis. Perhaps, the higher tolerance to defocus blur in myopic eyes contributes to myopia development in emmetropic eyes. It would be interesting to test in a future study whether the increase of accommodation fluctuations that is linked to defocus blurring also contributes to myopia development in emmetropic eyes.

During the period of exposure to lens defocus, our subjects showed different responses in accommodative variability between the two refractive groups. The emmetropes exhibited a big increase of accommodation variation while the variation for myopes was relatively stable. At the same time, the accommodative response of emmetropes, while reduced compared to that at the pre-adaptation period, was still significant. In contrast, there was almost no accommodative response by the myopes. The results could mean that myopes were more tolerant to defocus blur than the emmetropes, as demonstrated in both eye research and clinic practices (Rosenfield & Abraham-Cohen, 1999; Thorn, Cameron, Arnel, & Thorn, 1998). Perhaps, the higher tolerance to defocus blur in myopic eyes made the depth of focus elongated and consequently resulted in accommodation relaxation, while the emmetropes were trying hard to obtain a clear image by stimulating the accommodation system. An alternative explanation for this phenomenon is that the higher accommodative response in emmetropes could be due to a higher level of tonic accommodation (Maddock, Millodot, Leat, & Johnson, 1981; McBrien & Millodot, 1987). While our observation of the differences in accommodative responses between refractive groups during the lens blurring period is very interesting, the mechanistic explanations of the differences will require further study.

Higher level of accommodation fluctuations may be a risk factor for myopia development (Harb et al., 2006; Langaas et al., 2008). In this study, we found elevated accommodative variability during blur adaptation in emmetropic eyes. It would be interesting to test in a future study whether the increase of accommodation fluctuations that is linked to defocus blurring also contributes to myopia development in emmetropic eyes.

### Table 3. Accommodation SD for myopes and emmetropes.

<table>
<thead>
<tr>
<th>Defocus level</th>
<th>Pre-adaptation</th>
<th>Blur adaptation</th>
<th>First post-adaptation</th>
<th>Second post-adaptation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Myopes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>0.16 ± 0.02</td>
<td>0.16 ± 0.03</td>
<td>0.16 ± 0.03</td>
<td>0.16 ± 0.03</td>
</tr>
<tr>
<td>+1.0 DS</td>
<td>0.15 ± 0.03</td>
<td>0.19 ± 0.12**</td>
<td>0.18 ± 0.04**</td>
<td>0.16 ± 0.03</td>
</tr>
<tr>
<td>+3.0 DS</td>
<td>0.15 ± 0.03</td>
<td>0.19 ± 0.06**</td>
<td>0.17 ± 0.04*</td>
<td>0.15 ± 0.03</td>
</tr>
<tr>
<td>Emmetropes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>0.14 ± 0.03</td>
<td>0.13 ± 0.03</td>
<td>0.14 ± 0.03</td>
<td>0.13 ± 0.03</td>
</tr>
<tr>
<td>+1.0 DS</td>
<td>0.14 ± 0.03</td>
<td>0.34 ± 0.21**</td>
<td>0.17 ± 0.05**</td>
<td>0.14 ± 0.03</td>
</tr>
<tr>
<td>+3.0 DS</td>
<td>0.14 ± 0.03</td>
<td>0.32 ± 0.13**</td>
<td>0.15 ± 0.03</td>
<td>0.14 ± 0.03</td>
</tr>
</tbody>
</table>

Notes: Values are means ± SD; *p < 0.05 level and **p < 0.01, comparison between pre- and post-adaptation periods. ▲▲p < 0.01, comparison between myopes and emmetropes.

During the period of exposure to lens defocus, our subjects showed different responses in accommodative variability between the two refractive groups. The emmetropes exhibited a big increase of accommodation variation while the variation for myopes was relatively stable. At the same time, the accommodative response of emmetropes, while reduced compared to that at the pre-adaptation period, was still significant. In contrast, there was almost no accommodative response by the myopes. The results could mean that myopes were more tolerant to defocus blur than the emmetropes, as demonstrated in both eye research and clinic practices (Rosenfield & Abraham-Cohen, 1999; Thorn, Cameron, Arnel, & Thorn, 1998). Perhaps, the higher tolerance to defocus blur in myopic eyes made the depth of focus elongated and consequently resulted in accommodation relaxation, while the emmetropes were trying hard to obtain a clear image by stimulating the accommodation system. An alternative explanation for this phenomenon is that the higher accommodative response in emmetropes could be due to a higher level of tonic accommodation (Maddock, Millodot, Leat, & Johnson, 1981; McBrien & Millodot, 1987). While our observation of the differences in accommodative responses between refractive groups during the lens blurring period is very interesting, the mechanistic explanations of the differences will require further study.

Higher level of accommodation fluctuations may be a risk factor for myopia development (Harb et al., 2006; Langaas et al., 2008). In this study, we found elevated accommodative variability during blur adaptation in emmetropic eyes. It would be interesting to test in a future study whether the increase of accommodation fluctuations that is linked to defocus blurring also contributes to myopia development in emmetropic eyes.
In this study, there was no difference in accommodation lag between the two refractive groups during reading either before or after blur adaptation. This was consistent with other studies (Cufflin, Mankowska et al., 2007; George & Rosenfield, 2002), but not with a decrease in accommodation lag after blur adaptation as reported by Vera-Diaz et al. (2004). The inconsistency might be due to the difference in experimental paradigms. Vera-Diaz et al. used a scatter filter to blur text, while we used lens defocus. Scatter filters do not exhibit spurious resolution.

Figure 9. Dynamic change in mean pupil size of myopes and emmetropes at each period of the blur adaptation tests. Mean diameter changes for (a) myopes and (b) emmetropes for (1) pre-adaptation baseline test, (2) 5-min break, (3) 5-min blur adaptation test followed by lens removal, (4) first post-adaptation test, (5) 5-min break, and (6) second post-adaptation test. The pupil size of both groups decreased continuously. During the baseline and 5-min blur adaptation tests, the pupil size of myopes decreased more rapidly than in the emmetropes. After the second 5-min rest, all pupil diameters returned to the baseline values. Each point represents mean pupil size within a 30-s interval.
and phase shifts, as does defocus, so the optical characteristics of these two blur modalities might be qualitatively different (Pérez, Archer, & Artal, 2010). To determine if accommodative behavior is different for lens blurring and scatter filter blurring, it will require testing of both experimental paradigms on the same subjects. If the type of optical signal plays a role in the mechanism of blur adaptation, then there will be different patterns of change in the magnitude of accommodative microfluctuations. Another fact that might also contribute to the difference between the two studies is that Vera-Diaz et al. displayed the reading text on a large monitor screen, while in our study, single letters were serially presented at the screen center. The difference in visual field size might cause different spatial summation of the effect of blur adaptation, which could therefore produce different influences on accommodation lag after adaptation.

Pupil size was not stable during reading, especially for myopes. Substantial individual variation in the fluctuation of pupil size is a main behavioral characteristic during sustained periods of reading. Most subjects in this study, however, showed a trend of gradual reduction in pupil size with time at each test period. However, we did not find an association of pupil size reduction with changes in accommodative variability. This was probably because the effect of pupil size reduction on depth of focus was balanced by a decrease of aberrations due to the smaller pupil size.

A previous study showed that blur adaptation has no effects on pupil size when pupil size was measured before and after blur adaptation (Cufflin, Hazel et al., 2007). This is inconsistent with our observation of a general reduction in pupil size after blur adaptation as compared to the pre-adaptation pupil size. The difference between the two studies could be due to a difference in test methodology. While we continuously monitored the pupil size during each test period, Cufflin et al. only measured pupil size before and after blur adaptation. Due to the substantial pupil fluctuation, single measurements may not be statistically sufficient to detect significant changes in pupil size. From the results in this study, the general reduction of pupil size after blur adaptation and the gradual reduction at each test period could be due to fatigue effect (Morad et al., 2009; Morad, Lemberg, Yofe, & Dagan, 2000). Future study is required to clarify the underlying mechanisms responsible for the gradual reduction in pupil size.

**Conclusions**

During the period of accommodation to blurring, emmetrope accommodation was more unstable than myope accommodation. After blur adaptation, a systematic increase in accommodative variability occurred compared to baseline level in both myopes and emmetropes, and there was no difference between the two refractive groups. The results suggest that visual experience plays a role in determining accommodation stability. For most of the subjects, pupil sizes decreased with continuous reading, though there was no correlation of pupil size reduction with changes in accommodative variability.

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Commercial relationships: none. Corresponding author: Fan Lu. Email: lufan62@mail.eye.ac.cn; Lufan@wzmc.net. Address: Wenzhou Medical College, 82 Xue Yuan Road, Wenzhou, Zhejiang 325000, PR China.

**References**


