Retinotopic Accommodation Responses in Myopia

Dirk Seidel, Lyle S. Gray, and Gordon Heron

Purpose. A reduced sensitivity to retinal image blur has been reported in myopes. Diminished blur detection reduces the error signal to the retinotopic (blur-induced) accommodation system and results in impaired accommodation responses under retinotopic conditions. This study was conducted to investigate retinotopic accommodation responses in emmetropia and myopia under dynamic conditions.

Methods. Static accommodation responses to a blur-only target with vergences of 0 to 4.5 D were measured with an optometer. Microfluctuations of accommodation were recorded with the subject viewing the target at a vergence of 4 D, and dynamic step responses were measured for step stimuli from 2.5 to 3.5 D and 2.0 to 4.0 D, with the optometer in dynamic recording mode. Measurements were obtained from a group of 32 visually normal emmetropes (EMMs) and subjects with progressing myopia.

Results. Stimulus–response curves were not significantly different between the refractive groups. Subjects with late-onset myopia (LOMs) demonstrated significantly larger accommodation microfluctuations compared with emmetropes and subjects with early-onset myopia (EOMs). Fourier analysis revealed that the increase in the magnitude of the fluctuations was mediated by the low-frequency components. Accommodation step responses revealed longer reaction times in LOMs. Further analysis showed that LOMs responded to accommodation step stimuli only between 43% and 64% of the time. In contrast, the other groups showed a response rate of almost 100%.

Conclusions. The experiments demonstrate a reduction in retinotopic processing in LOMs, which results in an increased variability in their dynamic accommodation response to stationary near targets and reduced performance for dynamic step tasks. The results demonstrate a reduced blur appreciation under dynamic conditions in these refractive groups that may lead to periods of retinal image blur of varying magnitude during near work. (*Invest Ophthalmol Vis Sci.* 2003;44:1035–1041) DOI:10.1167/iovs.02-0264

Depending on the characteristics of the target, the accommodation system uses different stimuli to guide its response. Accommodation responses can be characterized as either spatiotopic, which respond to body-referenced stimuli and are coarse, or retinotopic, which respond to eye-referenced stimuli and are very accurate.[1]

The former include perceptual cues, such as relative size, texture, perspective, and position of the object in space, and can be controlled voluntarily. The latter elicit reflex accommodation responses and mainly respond to blur, which is the primary retinotopic stimulus. Both types of stimuli have distinct operating ranges (i.e., retinotopic ≤1.5 D and spatiotopic >1.5 D), with a complementary zone that lies approximately between 1 and 2 D.[1]

Perceptual spatiotopic cues are derived from the object's perceived position in space and provide optimal stimuli to initiate accommodation and vergence responses of large magnitudes. Because of the coarse characteristics of these cues, the spatiotopic system tends to respond inaccurately (over- or undershooting) to purely spatiotopic cues. The retinotopic system then acts as the fine-focus control, continually monitoring and responding very finely to small alterations in retinal image contrast.[1,2]

Blur is regarded as the primary drive of the accommodation system. It has been demonstrated that blur is a sufficient stimulus to accommodation alone and that the system can still produce adequate responses, even when other cues are eliminated.[3,4] Blur is therefore also regarded to be the primary retinotopic stimulus, which is of particular importance for maintaining focus on stationary targets and initiating small step responses when spatiotopic information is minimal or absent.[2]

Several investigators[2,5,6] have found that accommodation always responds with a change in the correct direction to small amounts of blur (≤1.5 D). If the blur stimulus exceeds this limit, the response is in error 50% of the time (i.e., random) for a blur-only stimulus. Because it can be appreciated that blur alone can provide information only about the size of the accommodative error, not about its direction (odd-error cue) a combination of different spatiotopic and retinotopic stimuli must assist the accommodation system during step changes. It has been suggested that these include aspects of the retinal image from which the system can derive directional information to guide the response—for example, chromatic aberration, spherical aberration, and consequences of the Stiles-Crawford effect.[7]

Collins[8] was the first to note that the accommodation response is in constant variation around a mean level (microfluctuations) during steady state viewing. The characteristics of these microfluctuations have been extensively examined,[9–14] and it has been established that their magnitude is quite small (≤0.5 D) and they are dominated by two characteristic frequencies: a high-frequency component (HFC; approximately 1.0–2.3 Hz) and a low-frequency component (LFC; <0.6 Hz). For a long time there has been controversy about whether these fluctuations simply reflect noise in the system or whether any functional role can be attributed to them (for review see Refs. 15–17). Winn et al.[18] established that the HFC is an artifact correlated with arterial pulse. It was later shown that the LFC assists the system in controlling the response to stationary targets.[19] The amplitude of the fluctuations has approximately the size of the perceptual depth-of-focus (DoF), which enables the accommodation system to start a response before the object becomes perceptually blurred.[20] The magnitude of the fluctuations tends to increase under conditions in which the DoF enlarges—that is, in lower levels of illumination.[12] Gray et al.[11] demonstrated that systematic changes in the fluctuations with increasing DoF are mediated by the LFC.

There is evidence that the DoF varies across different refractive groups. Rosenfield and Abraham-Cohen[21] measured the DoF in a groups of myopes and emmetropes and demon-

From the Department of Vision Sciences, Glasgow Caledonian University, Glasgow, Scotland, United Kingdom.

Submitted for publication March 14, 2002; revised July 22 and August 23, 2002; accepted August 30, 2002.

Commercial relationships policy: N.

The publication costs of this article were defrayed in part by page charge payment. This article must therefore be marked "*advertisement*" in accordance with 18 U.S.C. §1734 solely to indicate this fact.

Corresponding author: Dirk Seidel, Department of Vision Sciences, Glasgow Caledonian University, Cowcaddens Road, Glasgow G4 0BA, Scotland, UK; d.seidel@gcal.ac.uk.

strated significantly larger values in myopes. Although it is known that magnitude of the DoF varies with contrast, target size, illumination, and color, the DoFs obtained seem rather low, especially for perceptual measurements (±0.19 D in the myopes and ±0.11 D in the emmetropes, despite the use of a 2-mm pinhole pupil) compared with other studies.[22] It was concluded that myopes are generally less sensitive to retinal image blur, which could explain why larger accommodative errors have been reported in the past in this refraction group.[23,24]

Several studies investigating steady state accommodation have demonstrated that myopes tend to underaccommodate to near targets. McBrien and Millodot[25] measured accommodation stimulus–response curves (ASRCs) for stationary targets ranging from 0 to 6 D. They found that subjects with late-onset myopia (LOMs; onset after 15 years of age) exhibited the highest lags followed by those with early-onset myopia (EOMs; onset before 15 years of age) and emmetropes (EMMs).

Gwiazda et al.[26] demonstrated extremely shallow ASRCs in children with myopia when the dioptric vergence of a distant target was varied by the introduction of minus lenses. The subjects were all aged between 6 and 18 years (presumably, most were EOMs). In a more recent study Abott et al.[27] replicated the experiments of Gwiazda et al.[26] in an adult population, who found that the presence of myopia reduced only the accuracy of the accommodation response significantly in subjects with progressing refractive errors. The age of onset had no significant effect on the accommodative performance. Conditions in which a real target was presented or when the target was viewed through plus lenses of decreasing power did not produce differences in accommodation responses. Abbott et al.[27] attributed this to proximal accommodation induced by the close position of the target in the plus lens condition and perceived distance when the target was real, respectively. The findings led them to the conclusion that steady state accommodation does not significantly differ among EOMs, LOMs, and EMMs. If the myopia is progressive, however, it impairs accommodative accuracy. It was therefore suggested that it might be more appropriate to classify myopia according to the rate of progression rather than the age of onset. Despite methodological differences (e.g., monocular versus binocular; differences in data analysis and target presentation), all these studies have in common that they demonstrate higher lags of accommodation in myopes.

Measuring the accommodation response under purely static conditions gives only a partial representation of the near response. Natural visual tasks (e.g., deskwork and the use of visual display units) require constant head and eye movements and frequent alterations in target distance, which result in numerous relatively small changes in contrast of the retinal image, for which the accommodation system must persistently and accurately compensate.

A comprehensive picture of the accommodation mechanism in myopia requires an examination of the dynamics of the response. Culhane and Winn[28] investigated closed-loop accommodation step responses in EOMs, LOMs, and EMMs after a period of sustained near fixation. The results demonstrated significantly longer accommodation response times for near-to-far (N-F) steps in LOMs, which increased as the near-fixation period before the step was extended. Further evidence that myopes are more susceptible to near-work aftereffects than other refractive groups has also been provided by Ciuffreda and Wallis.[29]

The present experiments were conducted to investigate both the static and dynamic aspects of the retinotopic accommodation response in progressive myopia.

Methods

Thirty-two subjects (mean age ± SD: 21.4 ± 3.9 years) with a corrected visual acuity of at least 6/6, less than 0.75 D of astigmatism, and no ocular or systemic disease took part in the study. All participants gave written consent, and the study complied with the tenets of the Declaration of Helsinki.

Fourteen subjects were EOMs (refractive correction [Rx]: +0.05 ± 0.15 D), 10 subjects were EOMs (Rx: −3.75 ± 1.5 D), and 8 subjects were LOMs (Rx: −1.56 ± 0.71 D). Axial refraction was established by noncycloplegic autorefraction. All subjects answered a questionnaire before taking part in the experiment, which revealed the following: All subjects with myopia had progressive myopia, with mean progression rates of −0.49 ± 0.30 D (range, 0.25–1.00) in the EOMs and −0.47 ± 0.16 D (range, 0.25–0.75) in the LOMs during the previous 12 months. It can be noted that the EOMs had more than twofold the myopia of the LOMs but mean rate and range of progression were similar in both randomly selected groups. However, more subjects with more rapidly progressing myopia were found in the EOM group (SD of 0.3 D compared with 0.16 D).

Ninety percent of the EOMs wore glasses or contact lenses all the time, compared with only 50% of the LOMs. Subjects who wore their Rx constantly also used it for reading, whereas the others did not read with their Rx. Fifty percent of the EMMs, all the EOMs, and 20% of the LOMs stated that they had at least one parent with myopia. The mean age of onset for the EOMs was 9.9 ± 2.13 years (range, 7–13) and 16.2 ± 1.7 years (range, 15–18) for the LOMs.

During the experiment, all subjects with myopia had vision corrected with ultrathin soft contact lenses (Acuvue; Vistakon, Johnson & Johnson Vision Care, Inc., Jacksonville, FL). Every few minutes, a lubricant (HECL 44; Chauvin Pharmaceuticals Ltd., Romford, UK) was applied to both eyes to prevent dehydration and warping of the contact lens. A headrest and dental bite were used to minimize the effects of head and eye movements.

A black high-contrast (80%) Maltese-cross target (angular subtense: 15°) was carefully aligned in a Badal lens system (+5 D). This configuration allowed changes in stimulus vergence without changing the apparent size of the target or perceived distance of the object. Thus, bringing the target closer toward the subject's eye changed the object's vergence, inducing a blur-only stimulus.

Monocular accommodation responses of the subject's right eye were measured objectively with an infrared optometer (modified Autoref R-1; Canon Europa, Amstelveen, The Netherlands), which can be used in either static or dynamic mode.[30] Pupil size was monitored at the same time on a calibrated scale on the alignment monitor, which provides an enlarged view (8.2×) of the pupil and iris. This ensured that the subject's pupil size was within the limit for which the instrument allows accurate recordings.

In static mode the Canon R-1 has a resolution of 0.12 D and can take a measurement every 1 to 2 seconds. It has been evaluated elsewhere.[31] Stimulus-response curves were measured for stimulus vergences ranging from 0.0 to 4.5 D in steps of 0.5 D. Ten static measurements were taken at each stimulus level and a mean response calculated.

During continuous recording, the analog output from the optometer was fed into a digital storage oscilloscope (model 1604; Gould, Cleveland, OH), which was connected to a computer (model PC-XT; Epson Seiko Corp., Nagano, Japan) through an interface (IEEE-488 general purpose interface bus [GPIB]), where the traces were stored and analyzed. This setup permitted continuous recording of accommodation at a sampling rate of 102.4 Hz with a frequency resolution of 0.1 Hz.

Ten continuous 10-second accommodation responses to a stationary target at 4-D vergence were recorded. For each subject, 10 power spectra obtained by fast Fournier transformation were averaged[32] and included in the analysis. Dynamic accommodation responses to step changes in target vergence were then recorded for a subgroup of 22 randomly selected observers (8 EMMs, 7 EOMs, 7 LOMs whose refrac-

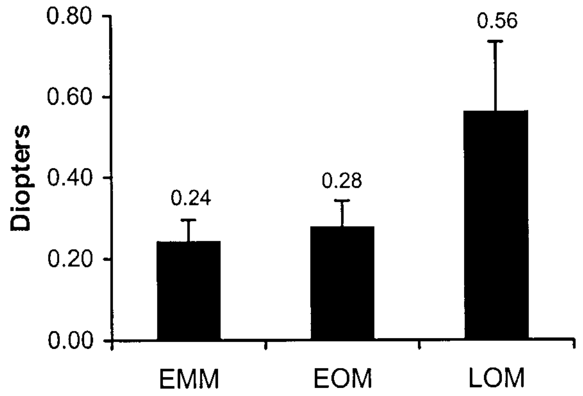

FIGURE 1. Mean RMS values of the microfluctuations of accommodation for a near object at a vergence of 4 D (error bars, SD).

tive errors, myopia progression rate, reading habits, and static accommodation responses matched those of the rest of the group) for two different conditions, a 2-D (2–4 D) and a 1-D (2.5–3.5 D) accommodation step. A stimulus generator was used to create square waves that randomly modulated the target's movement in the Badal system using an x–y plotter at a mean frequency of 0.06 Hz. Ten near-to-far (N-F) and 10 far-to-near (F-N) step responses per step modulation were recorded. The recording order was randomized, and measurements were taken over several sessions, each one lasting for no more than 1 hour, to avoid fatigue. The sessions for any one subject took place within the space of approximately 1 month and at the same time of the day (normally early morning). The subjects were told not to read before the experiment and were given 5 minutes in the dark to dissipate the effects of any previous near work.

Reaction and response times for these steps were calculated by determining the period between a change in stimulus vergence and an actual change in accommodation response level, using previously established methods.[33,34]

During the collection of the step data, it was noticed that a high number of the subjects with myopia did not make full accommodation steps. Some of the responses were incomplete, sometimes no apparent change in response level occurred at all. To account for these observations, accommodation was quantified according to the number of correct responses for a given number of stimulus changes. The following algorithm was used: An accommodation step is normally finished in roughly 1 second (reaction plus response time).[34] We obtained and compared the mean response levels before the stimulus changed and 1.5 seconds after the change in stimulus vergence had occurred. If the mean response level differed by more than 2 SDs from the initial mean level after the stimulus change, the step was counted as a "correct response." If the response level did not reach the 2-SD mark, it was recorded as a "null response." This ensured that the change in accommodation level truly represented a response to the change in target vergence rather than an increase in the amplitude of the accommodative microfluctuations. This was applied to all responses regardless of whether their initial direction was correct.

RESULTS

Stimulus–Response Curves

The mean ± SD gradients for the accommodative stimulus–response function, calculated by fitting least-squares regression lines, were: EMM, 0.81 ± 0.06; EOM, 0.81 ± 0.09; and LOM, 0.80 ± 0.07. There was no significant difference between any of the groups (EMM versus EOM, t = 0.14, P = 0.88, df = 22; EOM versus LOM, t = 0.07, P = 0.94, df = 16; EOM versus LOM, t = 0.07, P = 0.94, df = 16).

It was noted that in some individual subjects with myopia, the variability of the response was much greater than it was in the emmetropic group. Mean standard deviations averaged for all 10 stimulus levels were 0.19 D (range, 0.12–0.24) in the EMMs, 0.25 D (0.11–0.47) in the EOMs, and 0.28 D (range, 0.15–0.50) in the LOMs. The mean difference was significant between the EMMs and LOMs (t = 2.17, P = 0.04, df = 18) but not between any of the other groups.

Fluctuations of Accommodation

The mean root mean square (RMS) of the fluctuations of accommodation to the 4-D target can be seen in Figure 1. The EMMs (0.24 ± 0.05 D) and EOMs (0.28 ± 0.07 D) demonstrated significantly smaller fluctuations than the LOMs (0.56 ± 0.17 D); EMM versus LOM (t = 5.37, P < 0.001, df = 19); EOM versus LOM (t = 4.17, P = 0.001, df = 14).

Figure 2 is an example of steady state response traces of a typical EMM, EOM, and LOM, showing clearly the large drift in the LOM's response. In the corresponding power spectrum (Fig. 3) this drift shows up as an increase in the RMS for frequency components below 0.6 Hz.

Power spectrum analysis revealed that these differences were due to a significant increase in the LFCs (0–0.6 Hz) of the power spectrum in the LOMs compared with the EMMs (t = 5.26, P < 0.001) and EOMs (t = 4.17, P = 0.001). The HFCs (high-frequency peak plus the two adjacent bins) were similar in all groups (Fig. 4).

Reaction and Response Times

Mean reaction and response times for EMMs, LOMs, and EOMs under both step conditions are shown in Table 1. A three-factor

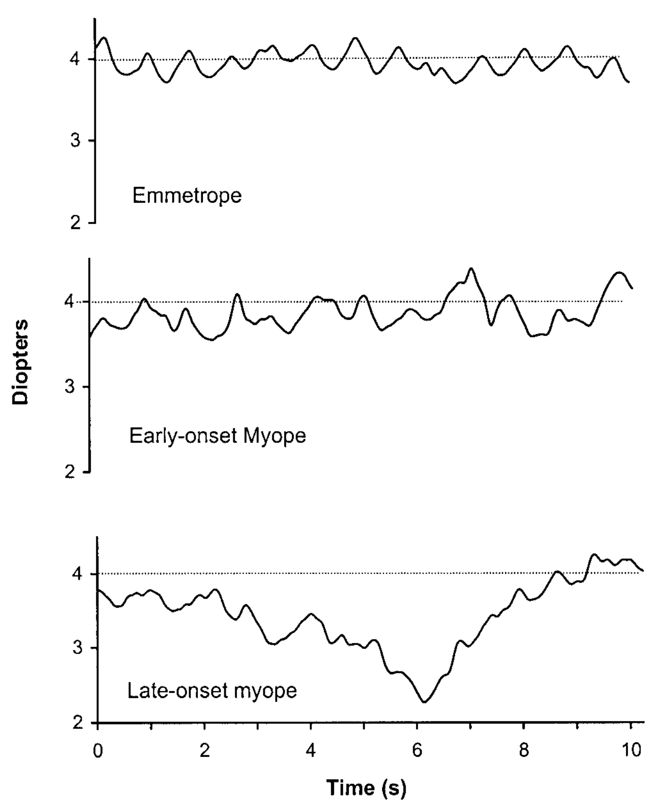

FIGURE 2. Ten seconds of continuous accommodation response to a stationary near target at 4-D vergence by an EMM (Rx: +0.12 D), EOM (Rx: −4.25 D, progression −0.38 D/y) and LOM (Rx: −1.12 D, progression −0.50 D/y)

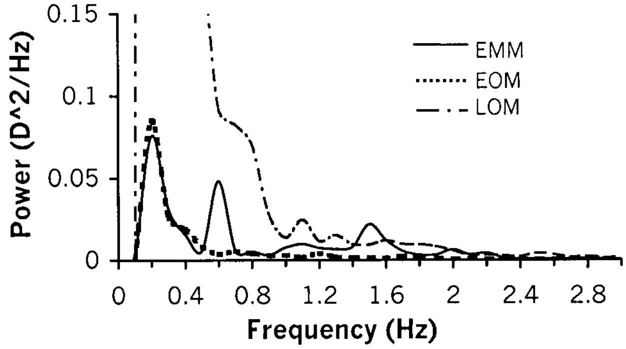

FIGURE 3. Mean power spectra for the subjects in Figure 2.

ANOVA model (refractive group, step size, step direction) showed that reaction times were significantly affected by the refractive group (F = 6.32, $P = 0.003$), but not by the direction of the vergence change (F = 0.34, $P = 0.56$), step size (F = 1.12, $P = 0.29$), or any combination of the three factors ($P >$ 0.2). Pair-wise comparison revealed that LOMs differed significantly from both the EMM ($P = 0.002$) and the EOM ($P =$ 0.002) groups.

Accommodation response times were found to be significantly affected by step size (F = 7.61, $P = 0.007$) but not by refractive group (F = 2.97, $P = 0.058$), step direction (F = 0.33, $P = 0.57$), or any combination of the factors ($P > 0.68$). A post hoc Scheffé F-test revealed increased pooled mean response times for the EOM group compared with the EMMs ($P = 0.048$).

Percentage of Correct Responses for Accommodation Steps

The percentage of correct responses to changes in target vergence is illustrated in Figure 5. A three-way ANOVA, with the same factors and interactions used as for reaction–response times, showed that the correctness of a response was highly dependent on the type of myopia of the subject (F = 23.05, $P < 0.001$). Neither step direction (F = 1.81, $P = 0.18$) nor step size (F = 0.24, $P = 0.62$) nor any of their interactions ($P >$ 0.48) influenced the percentage of correct responses. LOMs made significantly less correct responses than EMMs ($P <$ 0.001) and EOMs ($P < 0.001$), but EOMs were not different from EMMs ($P = 0.335$).

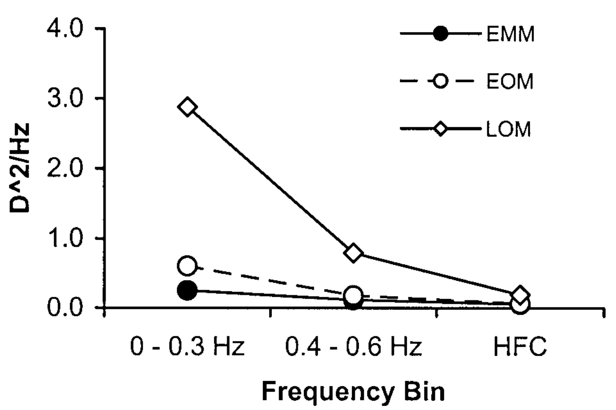

FIGURE 4. Distribution of mean power (RMS) for three different frequency bins in the power spectrum. The HFC occurred at approximately 1 to 1.5 Hz in all subject groups.

TABLE 1. Reaction and Response Times for Emmetropes and Myopes under the Different Experimental Conditions

Step	Time	EMM	EOM	LOM
2–4D				
Far-near	Reaction	0.31[a] ± 0.06	0.29[b] ± 0.07	0.45[ab] ± 0.15
	Response	0.53 ± 0.16	0.65 ± 0.28	0.62 ± 0.31
Near-far	Reaction	0.31[c] ± 0.12	0.27[d] ± 0.07	0.42[cd] ± 0.19
	Response	0.55 ± 0.16	0.78 ± 0.25	0.59 ± 0.23
2.5–3.5 D				
Far-near	Reaction	0.28 ± 0.08	0.29 ± 0.10	0.39 ± 0.18
	Response	0.39 ± 0.14	0.50 ± 0.24	0.45 ± 0.19
Near-far	Reaction	0.28 ± 0.13	0.32 ± 0.11	0.32 ± 0.10
	Response	0.36 ± 0.11	0.56 ± 0.18	0.48 ± 0.24

a,b,c,d, Statistical significance at $P < 0.05$.

DISCUSSION

The results indicate a deficit in retinotopic (blur-induced) control of accommodation in subjects with progressing late-onset myopia, leading to increased variability in the steady state response and reduced performance at dynamic tasks.

The slope of the stimulus–response curves was found to be similar in all refractive subgroups. Statistically significant differences in static accommodation responses between emmetropes and myopes have been shown (with infrared optometers) under conditions in which high accommodative demands (>5 D) were required[25] or when accommodation to a distant target was stimulated with minus lenses. Plus lenses or "real" targets in free space produced identical lags for different refractive groups.[26,27]

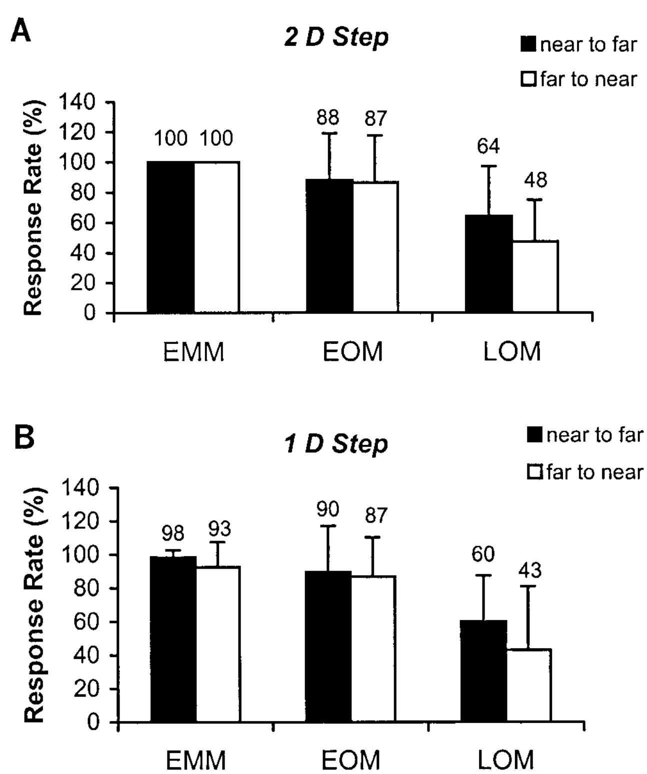

FIGURE 5. Response rate for the three groups of subjects for the 2-D (**A**) and the 1-D (**B**) step stimulus. A step response was regarded as a "true response" if the mean response level differed by more than 2 SD from the initial accommodation level within 1.5 seconds after a stimulus change. (■) versus (□) indicates the direction of the vergence change.

Gwiazda et al.,[26] using 6/30 letters, reported lags of 2 D or sometimes larger in children with myopia, which increased with the use of 6/9 letters, but were much smaller when proximity and size cues were added. Abbott et al.[27] and McBrien and Millodot[25] presented 6/9 letters and found accommodative errors in the range of up to 1 D in adult myopes, by using blur-only and free-space stimulation, respectively. If the target is very large and does not require accurate accommodation to resolve it, instructing the subject becomes very important. It may well be that myopes with a reduced blur sensitivity, exhibit high lags of accommodation if they can see the target without the need for accurate accommodation. In contrast, emmetropes may always adjust their accommodation for maximum retinal image clarity. Despite similar static mean accommodation responses, the myopic groups in the present study, particularly the LOMs, exhibited greater variability in their static responses. It has been demonstrated that voluntary and proximal accommodation can be relatively precise[35] and if the observer is experienced, might be powerful enough to produce accurate accommodation responses, even in the absence of any other cues. Future studies must show whether myopes, whose accommodation response is sluggish, have learned to use proximal stimuli and voluntary accommodation to a greater extent to enhance their static response.

The Maltese cross used in our study provided high spatial frequencies to stimulate accommodation adequately as well as gross structures to support accurate fixation. As this stimulus was presented in the Badal lens system, size cues were eliminated, but proximal input was still present to the accommodation system, because the setup allowed the subjects to be aware that the target was located at an intermediate distance. This arrangement creates a situation similar to that when the target is viewed through plus lenses of decreasing power, the method of stimulating accommodation used by Abbott et al.[27] We consider our findings therefore to be in agreement with previous experiments.

There was a significantly higher RMS for the fluctuations in the LOM subjects with most of the power in the LFCs. Winn et al.[20] were the first to demonstrate that the portion of the low frequencies (e.g., frequencies below 0.6 Hz) more than span the DoF and that they can assist the accommodation system in controlling the steady state response. Under conditions in which the DoF enlarges (e.g., small pupil diameters or low luminances) the RMS of these components increases.[11,12,17] LOM subjects may require larger microfluctuations to guide their accommodation response across their enlarged DoF. Pupil diameter was monitored and found to be greater than 3.5 mm in all subjects at any time during the experiment. Therefore, pupil size would not account for any change in the size of the DoF.[22] An increase in the low frequencies (e.g., ≈0.2 Hz) of the fluctuations is also an indication of drift in the response. Many of the subjects with myopia demonstrated such behavior, in that the lag of accommodation became more variable and the accommodation response exhibited large fluctuations.

The HFCs, which have been shown to arise from the effects of arterial pulse within the ciliary muscle, reflect noise rather than serve any purpose in the control of accommodation[10,17,36] and were not significantly different between the refractive subgroups in the present study.

Rosenfield and Abraham-Cohen[21] demonstrated recently that the perceptual DoF is enlarged in myopes. In our experiments the LOMs demonstrated a significantly greater variation in the accommodation response to a stationary near object.

If the accommodation response, scanning across the DoF to detect and rectify image defocus before it becomes perceptually visible, is in greater variation, this suggests that the objective blur threshold must also be increased in these subjects.

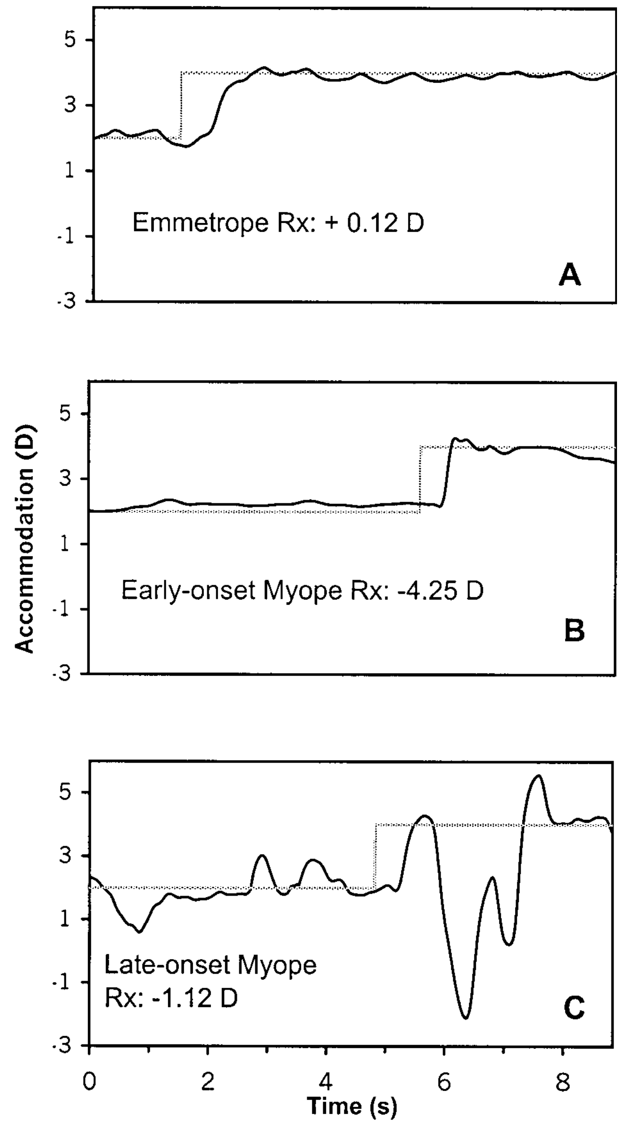

FIGURE 6. Sample traces of a 2-D accommodation step by an EMM (**A**), EOM (**B**; progression 0.38 D/y), and LOM (**C**; progression −0.50D/y). *Dotted line*: the stimulus.

A reduced retinotopic control of accommodation, needed to fine tune accommodation step responses, also affected the system's performance at dynamic tasks. The subjects had to make accommodation step responses of two different magnitudes: a 1-D step, which is well within the range of the retinotopic system and a 2-D step, which is thought to represent the upper end of the retinotopic range and may even be outside retinotopic limits.

The step–response data revealed that there was a clear difference in how individual subjects with myopia accommodated for step changes in target vergence. It appeared that with both step sizes, LOMs tended to perform noticeably poorer than EOMs, who seemed to perform the tasks with the same accuracy and ease as the emmetropic group. Frequently, LOMs started a response but were unable to find or maintain the new stimulus level, especially for the larger 2-D steps. This can be seen in Figure 6, where a normal step response for an emmetrope and an EOM are shown in A and B and an LOM's response is shown in C, exhibiting large fluctuations to hunt for the new stimulus (2-D step), which she finds after several attempts. For the 1-D steps LOMs frequently seemed to scan between the two stimulus levels, trying to respond to small accommodative stimuli. It can be appreciated that these subjects experience considerable amounts of retinal defocus over several seconds. However, most of the LOM subjects reported only very short periods of target blur with the 2-D steps, even when the objective accommodation data showed that their response was 1 D or more in error. For the 1-D steps, most LOM subjects did not report any blur, even when their accommodation system did not respond at all.

A poor response by the retinotopic system affects the response to targets within the retinotopic range. However, it appears also to be critical toward the end of the retinotopic limit, as the low response rate for the 2-D steps suggests. In contrast, both EMMs and EOMs responded very well to step changes nearly 100% of the time, regardless of the size and direction of the step. It was also observed that they were able to recognize the sign of a blur change instantly, whereas LOMs quite often went in the opposite direction of the vergence stimulus.

The mean reaction time for accommodation step responses ranged between 0.28 and 0.32 seconds for EMMs and EOMs, which is in the range previously reported[33,37] and was not different under the various experimental conditions. However, LOMs took, on average, 150 ms longer before starting a 2-D step. Clearly, if the DoF of the eye is enlarged, the reaction time of the accommodation controller is increased, because it takes longer to detect the blur signal.

In the 1-D stimulus condition, there seems to be no apparent difference in reaction times between the LOMs and the other groups, because the number of LOMs who were actually able to make adequate step responses was lower with the 1-D than with the 2-D step condition.

Accommodation response times were found to be longer in the myopic groups for some viewing conditions than in the emmetropic group. These times have been shown to be extended for LOMs after a sustained near task.[28] It has been suggested that as a result of near-vision adaptation effects in LOMs, their ability to relax accommodation is reduced, which leads to a delayed N-F response.[29,38] Although the conditions in our experiments did not deliberately include prior near adaptation, myopes generally demonstrated slightly longer response times for the N-F and the F-N step conditions. It has been suggested before that an explanation for this could lie in a difference in the elastic properties of the myopic crystalline lens and/or ciliary body.

LOMs seemed to have shorter response times than EOMs, particularly for the 2-D steps, but this also occurred for some of the 1-D steps—an artifact that occurred as a result of the low response rate and reduced gain in the LOMs. If a subject makes a response, which, for example, is only half the size of the stimulus demand, the new accommodation level is reached in a much shorter time. In contrast EOMs who almost always made full steps took longer to complete the full step response.

Because all our subjects with myopia had progressive disease, we cannot draw conclusions about differences in accommodation depending on the stability of refraction. It seems, however, that not all those subjects responded in the same manner. LOMs showed a higher accommodative variability and performed notably poorer at dynamic tasks, whereas EOMs performed very similarly to EMMs. This implies that that accommodation performance especially for dynamic tasks is not related to the magnitude of the refractive error. LOMs, who generally have lower refractive errors, demonstrate more sluggish accommodation responses than do EOMs, whose axial refraction tends to be larger. An explanation for this may be that LOMs frequently do not wear their Rx for near work (see the Methods section) and that the onset of myopia is more recent. EOMs who usually wear their Rx all the time and have had myopia for a number of years may have blur detection similar to EMMs or may use visual cues unrelated to blur more efficiently.

Our findings indicate that the objective blur threshold for accommodation was greater in myopes, particularly LOMs, and led to a failure of retinotopic processing in these subjects, which affected both their ability to maintain an accurate steady state response and their responses to step targets. As a consequence, LOM subjects experienced retinal image blur of continuously varying magnitude when performing near tasks.

The results may have implications for our understanding about accommodation as a possible trigger mechanism for the development of myopia. Animal studies have shown that optical defocus, if present over longer periods, can influence eye growth.[39-41] It has been argued that hyperopic defocus blur associated with close work could therefore be a causative factor in progression of myopia. Our results demonstrate that the amount of defocus present on the retina was in constant variation rather than steady when viewing stationary or dynamic objects and may be much larger than expected in subjects with myopia.

References

1. Schor CM, Alexander J, Cormack L, Stevenson S. Negative feedback control model of proximal convergence and accommodation. *Ophthalmic Physiol Opt.* 1992;12:307–318.
2. Phillips S, Stark L. Blur: a sufficient accommodative stimulus. *Doc Ophthalmol.* 1977;43:65–89.
3. Kruger PB, Pola J. Stimuli for accommodation: blur, chromatic aberration and size. *Vision Res.* 1986;26:957–971.
4. Kruger PB, Pola, J. Dioptric and non dioptric stimuli for accommodation: target size alone and with blur and chromatic aberration. *Vision Res.* 1987;27:555–567.
5. Fincham EF. The accommodation reflex and its stimulus. *Br J Ophthalmol.* 1951;35:381–393.
6. Stark L, Takahashi Y. Absence of an odd-error signal mechanism in human accommodation. *IEEE Trans Biomed Eng.* 1965;12:138–146.
7. Kruger PB, Pola J. Changing target size is a stimulus for accommodation. *J Opt Soc Am A.* 1985;2:1832–1835.
8. Collins G. The electronic refractionometer. *Br J Physiol Opt.* 1937; 1:30–42.
9. Campbell FW, Robson JG, Westheimer G. Fluctuations of accommodation under steady viewing conditions. *J Physiol.* 1958;145: 579–594.
10. Collins M, Davis B, Wood J. Microfluctuations of steady-state accommodation and the cardiopulmonary system. *Vision Res.* 1995; 35:2491–2502.
11. Gray LS, Winn B, Gilmartin B. Accommodative microfluctuations and pupil diameter. *Vision Res.* 1993;33:2083–2090.
12. Gray LS, Winn B, Gilmartin B. Effect of target luminance on microfluctuations of accommodation. *Ophthalmic Physiol Opt.* 1993;13:258–265.
13. Heron G, Schor C. The fluctuations of accommodation and aging. *Ophthalmic Physiol Opt.* 1995;15:445–449.
14. Miege C, Denieul P. Mean response and oscillations of accommodation for various stimulus vergences in relation to accommodation feedback control. *Ophthalmic Physiol Opt.* 1988;8:165–171.
15. Charman WN, Heron G. Fluctuations in accommodation: a review. *Ophthalmic Physiol Opt.* 1988;8:153–64.
16. Winn B, Gilmartin B. Current perspective on microfluctuations of accommodation. *Ophthalmic Physiol Opt.* 11992;12:252–256.
17. Winn B. Accommodative microfluctuations: a mechanism for steady-state control of accommodation. In: Franzen O, Richter H, Stark L, eds. *Accommodation and Vergence Mechanisms in the Visual System*. Basel, Switzerland: Birkhauser-Verlag; 2000;129–140.
18. Winn B, Pugh JR, Owens H. Arterial pulse modulates steady-state ocular accommodation. *Curr Eye Res.* 1990;9:971–975.

19. Gray LS, Winn B, Gilmartin B. Microfluctuations of accommodation below 0.6 Hz are likely to contribute to the maintenance of sustained accommodation [ARVO Abstract]. *Invest Ophthalmol Vis Sci.* 1993;34(4):S1307. Abstract nr 2972.
20. Winn B, Charman WN, Pugh JR, et al. Perceptual detectability of ocular accommodation microfluctuations. *J Opt Soc Am A.* 1989; 6:459–462.
21. Rosenfield M, Abraham-Cohen JA. Blur sensitivity in myopes. *Optom Vis Sci.* 1999;76:303–306.
22. Tucker J, Charman WN. The depth-of-focus for the human eye for Snellen letters. *Am J Optom Physiol Opt.* 1975;52:3–21.
23. McBrien NA, Millodot M. Amplitude of accommodation and refractive error. *Invest Ophthalmol Vis Sci.* 1986;27:1187–1190.
24. Gwiazda J, Bauer J, Thorn F, Held R. A dynamic relationship between myopia and blur-driven accommodation in school-aged children. *Vision Res.* 1994;35:1299–1304.
25. McBrien NA, Millodot M. The effect of refractive error on the accommodative response gradient. *Ophthalmic Physiol Opt.* 1986; 6:145–149.
26. Gwiazda J, Thorn F, Bauer J, Held R. Myopic children show insufficient accommodative response to blur. *Invest Ophthalmol Vis Sci.* 1993;34:690–694.
27. Abbott ML, Schmidt KL, Strang NC. Differences in the accommodation stimulus response curves of adult myopes and emmetropes. *Ophthalmic Physiol Opt.* 1998;18:13–20.
28. Culhane HM, Winn B. Dynamic accommodation and myopia. *Invest Ophthalmol Vis Sci.* 1999;40:1968–1974.
29. Ciuffreda KJ, Wallis DM. Myopes show increased susceptibility to nearwork aftereffects. *Invest Ophthalmol Vis Sci.* 1998;39:1797–1803.
30. Pugh JR, Winn, B. Modification of the Canon Auto Ref R 1 for use of a continuously recording infra-red optometer. *Ophthalmic Physiol Opt.* 1988;8:460–464.
31. McBrien NA, Millodot M. Clinical evaluation of the Canon Autoref R-1. *Am J Optom Physiol Opt.* 1985;62:768–792.
32. Pugh JR, Eadie AS, Winn B, Heron G. Power spectrum analysis in the study of ocular mechanisms. *Ophthalmic Physiol Opt.* 1987; 7:321–324.
33. Tucker J, Charman WN. Reaction and response times for accommodation. *Am J Optom Physiol Opt.* 1979;56:490–503.
34. Charman WN. Retinal image in the human eye. *Prog Retinal Res.* 1982;2:1–50.
35. Ciuffreda KJ, Kruger PB. Dynamics of human voluntary accommodation. *Am J Optom Physiol Opt.* 1988;65:365–370.
36. van der Heijde GL, Beers APA, Dubbelman M. Microfluctuations of steady-state accommodation measured with ultrasonography. *Ophthalmic Physiol Opt.* 1996;16:216–221.
37. Heron G, Winn B. Binocular accommodation reaction and response times for normal observers. *Ophthalmic Physiol Opt.* 1989; 9:176–183.
38. Strang NC, Winn B, Gilmartin B. Repeatability of post-task regression accommodation in emmetropia and late-onset myopia. *Ophthalmic Physiol Opt.* 1994;14:88–91.
39. Schmid KL, Wildsoet CF. The sensitivity of the chick eye to refractive defocus. *Ophthalmic Physiol Opt.* 1997;17:61–67.
40. Diether S, Schaeffel F. Local changes in eye growth induced by imposed local refractive error despite active accommodation. *Vision Res.* 1997;37:659–668.
41. Meyer C, Mueller MF, Duncker GIW, Meyer HJ. Experimental animal myopia models are applicable to human juvenile-onset myopia. *Surv Ophthalmol.* 1999;44(suppl 1):S93–S102.