Effect of target spatial frequency on accommodative response in myopes and emmetropes

John Taylor
Faculty of Life Sciences, Moffat Building, University of Manchester, Manchester, UK

W. Neil Charman
Faculty of Life Sciences, Moffat Building, University of Manchester, Manchester, UK

Clare O’Donnell
Faculty of Life Sciences, Moffat Building, University of Manchester, Manchester, UK

Hema Radhakrishnan
Faculty of Life Sciences, Moffat Building, University of Manchester, Manchester, UK

This study investigates whether systematic differences exist between the accommodation response/stimulus curves of emmetropes and myopes when the targets are sinusoidal gratings, in particular whether myopic accommodation is relatively less effective when presented with targets of high spatial frequency due to increased tolerance to defocus blur. Ten emmetropes (overall mean sphere +0.19 D, range −0.37 to +1.37 D) and 10 myopes (overall mean sphere −2.89 D, range −1.13 to −6.63 D) viewed Gabor targets with dominant frequencies 1, 4, 8 and 16 c/deg. Maximal grating contrast was 80% and the full, green, stimulus field was 6 deg. Subjects were aged between 18 and 37 years. A further high-contrast 6/30 optotype target was included for comparison purposes. Viewing was monocular, the other eye being occluded. Stimulus demand was varied with trial lenses over the nominal range 0 to 6.0 D and the corresponding accommodation responses were recorded with an open-view, Shin-Nippon SRW-5000 auto-refractor. The resulting accommodation response/stimulus curves were characterized by their slopes over the stimulus range 1.5 to 6.0 D and by an “error index” indicating the extent to which the responses differed from the ideal 1:1 response/stimulus line. No significant differences were found between the mean accommodative behavior of the two refractive groups for any target. There were, however, substantial inter-subject differences. Some subjects in both groups showed more accurate responses with the higher spatial-frequency targets, while others showed optimal response at intermediate frequencies. Although it has been reported in the literature that, in comparison to emmetropes, myopes have reduced sensitivity to blur and response/stimulus curves of lower slope, the present study failed to demonstrate any reduction in their responses to gratings of relatively high spatial frequency. For each target the two refractive groups showed similar accommodative behavior.

Keywords: accommodation, myopia, spatial frequency, response–stimulus curves, auto-refractor


Introduction

Recent decades have seen a rising incidence of myopia, most notably in far eastern countries. Genetic factors undoubtedly play an important role in myopia development, as may nutrition. However, it has long been speculated (e.g. Cohn, 1886; Curtin, 1985; Donders, 1864; Landolt, 1886; Ware, 1813) that environmental factors, particularly near-work, also have a strong influence. As a result, many have suggested that today’s high levels of myopia may be at least partly associated with the increased volumes of educational and occupational near-work that form part of current patterns of life (see, e.g. Goldschmidt, 2003; Mutti, Zadnik, & Adams, 1996; Zadnik & Mutti, 1998 for reviews). If this is true, then a clearer understanding of the mechanisms by which near-work precipitates myopia development in genetically susceptible individuals might allow earlier refractive or other intervention, to minimize any subsequent adverse changes in refractive development. Several candidate mechanisms have been suggested, including the hypothesis that the potentially myopic eye suffers from unusually large levels of higher-order monochromatic aberration. These in turn lead to a less accurate accommodation response, so that the near image suffers from high levels of both aberration and accommodation lag (e.g. Collins, Buchen, & Iskander, 2006; Gwiazda, Bauer, Thorn, & Held, 1995; Gwiazda, Thorn, Bauer, & Held, 1993; He, Gwiazda, Thorn, Held, & Vera-Diaz,
Myopia is then precipitated through a combination of axial form deprivation and hyperopic defocus, both of which stimulate excessive increase in axial length, as demonstrated in animal experiments (see, e.g. Norton, 1999; Smith, 1998; Wildsoet, 1997 for reviews). Alternatively, the aberration of the myopic eye may be normal but some other factor causes large lags in accommodation and this hyperopic defocus leads to axial elongation and myopia.

Current evidence does not favor the concept that the myopic eye has systematically higher levels of aberration (Charman, 2005) but several studies have suggested that myopes have a lower monocular accommodative stimulus–response gradient than emmetropes (e.g. Abbott, Schmid, & Strang, 1998; Gwiazda et al., 1993; McBrien & Millodot, 1986). The largest differences were found for higher accommodative demands (McBrien & Millodot, 1986) and when accommodation was stimulated with negative lenses (Abbott et al., 1998; Drobe & de Saint-André, 1995; Gwiazda et al., 1993, 1995). In contrast, however, no differences in the slope for different refractive groups were found by Ramsdale (1985) when accommodation was stimulated by varying target distance under binocular conditions, by Seidel, Gray, and Heron (2003) for Badal stimuli up to 4.50 D under monocular conditions, or by Seidel, Gray, and Heron (2005) under binocular free-space conditions. In a longitudinal study under free-space binocular conditions, Rosenfield, Desai, and Portello (2002) found slightly lower slopes for stable myopes as compared to stable emmetropes or progressing myopes.

Why might myopes have lower response/stimulus slopes? It has been speculated that larger accommodative lags might be tolerated by myopes, as compared to emmetropes, because of their reduced sensitivity to defocus blur (Collins et al., 2006; Jiang, 1997; Rosenfield & Abraham-Cohen, 1999; Vasudevan, Ciuffreda, & Wang, 2006). This reduced sensitivity is associated with a reduced effect of defocus on visual performance (Thorn, Cameron, Arnel, & Thorn, 1998). Moreover, there is strong evidence for blur adaptation in uncorrected myopes (Rosenfield, Hong, & George, 2004). On the other hand, Schmid, Iskander, Li, Edwards, and Lew (2002) failed to find a statistical difference in the blur detection abilities of myopic and non-myopic children, although myopic children showed greater individual variation. Longitudinal studies comparing the magnitude of initial accommodative near lag with the subsequent myopia progression appear to yield conflicting results (Allen & O’Leary, 2006; Weizhong, Zhikuan, Wen, Xiang, & Jian, 2008).

McBrien and Millodot (1987) found that late-onset myopes had significantly lower levels of tonic accommodation (around 0.5 D) than early-onset myopes or emmetropes (around 0.9 D) (see also, Maddock, Millodot, Leat, & Johnson, 1981; Rosenfield & Gilmartin, 1987). Some studies suggest that, unlike emmetropes, myopes have significantly different sensitivities to positive and negative defocus (Radhakrishnan, Pardhan, Calver, & O’Leary, 2004a, 2004b).

When grating objects are observed, the degrading effect of any given level of defocus blur on the contrast of the retinal image increases with the spatial frequency of the grating, although the exact contrast changes vary with such factors as the pupil diameter, wavelength and ocular aberration (e.g. Atchison, Woods, & Bradley, 1998; Charman, 1979; Charman & Jennings, 1976; Green & Campbell, 1965; Legge, Mullen, Woo, & Campbell, 1987; Marcos, Moreno, & Navarro, 1999). If, then, myopes have a reduced sensitivity to defocus blur and less accurate accommodation responses to targets of broad spatial bandwidth than those of emmetropes, this may be because they place a greater importance on the lower spatial frequency components of the retinal image than on those of higher spatial frequency. If this is true, it might be expected that myopes would have greater problems than emmetropes when asked to accommodate to targets containing mainly high spatial frequencies.

We have therefore studied the form of the monocular response/stimulus curve to grating targets of different spatial frequencies and to a letter target of wider spatial bandwidth in groups of emmetropic and myopic subjects of similar age, to determine whether they show obvious differences in the form of their response curves. The hypothesis was that myopes would show a lower slope than emmetropes when the target was a grating of higher spatial frequency. Accommodation was stimulated monocularly using negative lenses, since earlier studies suggest that these conditions might yield the greatest differences between refractive groups. Under these circumstances, of the components of accommodation identified by Heath (1956a), proximal accommodation is absent (or counter-productive) and there is no convergence-accommodation. Although these monocular, restricted conditions for accommodation do not match the free-space, binocular viewing conditions of real life, where numerous accommodation cues are available, it was hoped that they would optimize the chances of revealing any systematic deficits of the accommodative abilities of myopes as compared to emmetropes.

**Methods**

The study followed the tenets of the Declaration of Helsinki and written informed consent was obtained from all participants after the nature and possible consequences of the study had been explained. The project protocol was approved by the Senate Committee on the Ethics of Research on Human Beings of the University of Manchester. Twenty adult subjects (14 female, 6 male) between the ages of 18 and 37 were recruited from among the staff and students at the University of Manchester, UK. All subjects were free from oculcar disease and myopic...
retinal degeneration. They had a visual acuity of 6/6 or better in the tested eye and no known accommodative anomalies or significant ocular history. Only one subject was an experienced observer for accommodation and psychophysical studies. Subjects with astigmatism of over 1.25 D were excluded from the study, and the right eye was used for all measurements. Ten of the subjects were emmetropic (overall mean sphere +0.19 D, range −0.37 D to +1.37 D), and 10 were myopic (overall mean sphere −2.89 D, range −1.13 D to −6.63 D). The mean age was 25.1 years (range 19 to 37) for the emmetropes and 26.4 years (range 20 to 36) for the myopes. The myopic group included 7 early-onset myopes (myopia onset at age 14 years or before) and 3 late-onset myopes (myopia onset at 15 years of age or older). In the early-onset myopes, 3 were progressing myopes (defined as an increase of 0.5 D or more in the previous 2 years as reported by the subject) and 4 were stable. In the late-onset myopes 1 was progressing, while 2 were stable. All subjects underwent a full subjective refraction on the right eye (based on least-negative prescription with maximum achievable visual acuity). Myopic refractive error was corrected for distance viewing with thin disposable soft contact lenses to within ±0.25 D (best sphere), which was confirmed with over-refraction and visual acuity measurements. Any residual refractive error was then corrected with trial lenses. Contact lenses were worn by 8 of the 10 myopes, who were all habitual contact lens wearers. The other 2 myopes had refractive errors −1.00/−0.25 × 5, and −1.00/−0.25 × 175, and did not wear contact lenses for the experiment. Instead a −1.00 D lens was added in the trial frame in addition to the lenses used to alter target vergence.

The grating targets, which were placed at a distance of 1 m from the eye, consisted of vertical, sine-wave Gabor targets (Gabor, 1946). Gabor targets were used rather than true gratings to minimize any edge effects which might affect the subjects’ accommodation. The target luminance was described by a function of the form:

\[ L = L_{\text{mean}}(1 + C \sin \left\{ 2\pi Fx \right\} \cdot \exp\left\{ -\left( x^2 + y^2 \right)/2\sigma^2 \right\} \], 

where \( L_{\text{mean}} \) was the mean luminance (45 cd/m²), \( x \) and \( y \) were angular Cartesian coordinates on the screen, measured from the peak of the Gaussian envelope, \( C \) was the grating contrast (0.8 or 80%), \( F \) the target’s dominant spatial frequency and \( \sigma \) the standard deviation of the Gaussian envelope (constant at 1.2 degrees). All targets subtended a total of 6 deg of visual angle. There were 4 grating targets (spatial frequencies, \( F = 1, 4, 8, \) and 16 cycles/degree) and one 80% contrast optotype “E” target. Note that, because the Gaussian envelope was the same for all the Gabor targets, their relative bandwidth decreased with the nominal center frequency \( F \). The octave bandwidths were 0.453 (1 c/deg), 0.112 (4 c/deg), 0.056 (8 c/deg) and 0.028 (16 c/deg): there was negligible content at higher harmonics of the fundamental frequencies.

The optotype was a letter “E”. This subtended a visual angle of 25 minutes of arc (equating to a 6/30 letter), with the horizontal bars crudely approximating to a 6 c/deg square-wave grating. The letter was sufficiently large to be recognizable with large errors of focus, so that any subject who habitually minimized their accommodative effort could recognize the letter in the presence of substantial accommodative lag. In contrast, to produce accurate retinal focus subjects ideally needed to accommodate to produce maximal edge sharpness rather than to simply ensure letter recognition.

All the targets were included in a PowerPoint presentation, alternately interleaved with blank screens, and presented on a CRT monitor having a green phosphor (chromaticity coordinates \( x = 0.290, y = 0.611 \), peak wavelength 547 nm with a bandwidth of about 30 nm, Mitsubishi Diamond Pro 2070SB, Cambridge Research systems, UK).

Stimulus–response functions were measured by altering the target vergence with lenses. The subjects viewed the targets presented on the monitor at a fixed 1 m distance (vergence −1.00 D) with a natural pupil through an open-view Shin-Nippon SRW-5000 auto-refractor (Ajinomoto Trading Inc, Tokyo, Japan, see Mallen, Wolffsohn, Gilmartin, & Tsujimura, 2001). The auto-refractor incorporated a circular aperture that allowed a 6 deg field at 1 m: this served to black out the surround and remove other possible accommodative stimuli. As the aperture was positioned at 19 cm (vergence −5.26 D) from the eye, it represented a much higher and more peripheral stimulus than the main targets and was not expected to have any effect on the responses. The left eye was occluded and the targets were observed monocularly through the aperture using the right eye, with the room lights off. The subjects wore a trial frame, at a vertex distance of 12 mm, into which lenses (+1.00, −0.50, −2.00, −3.50, −5.00 D) were placed to alter the vergence of the targets and create accommodative stimuli covering the range 0–6 D in 1.5 D steps (nominally +0 D, 1.5 D, 3 D, 4.5 D and 6 D). The size and spatial frequency of each set of targets was adjusted to compensate for magnification produced by the different trial lenses used and target vergences were corrected for the vertex distance of the trial lenses. Note that both the target and the field aperture were seen through the lenses, so that the vergence of the latter always remained about −5 D greater than that of the target. The grating targets were presented in random order to each subject, followed by the optotype.

Subjects were told to view the targets “keeping them as clear as possible at all times.” Although the subjects were familiarized with the requirements of their task, no attempt was made to systematically train them through practice or feedback to produce maximal responses, since it was hoped that they would produce “natural” responses which reflected their accommodative performance in
normal life. When the subject reported that each stimulus was clear, 3 readings were taken with the auto-refractor. Each target was interleaved with a blank screen and the target was presented for the minimum duration (i.e. just long enough for the subject to be able to report the target to be clear and to take the readings), to avoid grating adaptation effects. Accommodation responses, expressed in vector form (Thibos, Wheeler, & Horner, 1997), were calculated from the means of each triplet of auto-refractor readings, with appropriate allowance for the power and vertex distance of the trial lenses worn. An increase in power of the eye, corresponding to a more negative refraction, was taken as a positive accommodation response. Estimated responses for the vertical grating targets were based on measurements of refraction in the horizontal meridian of the eye: those for the optotype were based on best-sphere refractions.

Data analysis

Two single-figure indices were used to characterize each response/stimulus curve: its slope and the accommodative error index. The error index was used because slope values alone do not demonstrate whether the responses succeed in yielding precisely focused retinal images. A curve with a slope of unity does not necessarily coincide with the “ideal” 1:1 or Donders’ response/stimulus line and substantial lags or leads may still be present. The accommodative error index (Chauhan & Charman, 1995) takes account of both the extent to which responses deviate from Donder’s line over the chosen stimulus interval and the goodness of fit of the data points to the regression line. The index essentially involves determining the mean magnitude of the response error between the ideal line and the regression line over the stimulus interval and dividing it by the value of \( r^2 \) for the regression line (\( r \) is the product moment correlation coefficient). If the regression line fit is

\[
y = mx + c,
\]

where \( y \) is the response, \( x \) the stimulus, \( m \) the slope and \( c \) the intercept, and the regression line does not cross the Donder’s line, the accommodative error index, \( I \), is given by:

\[
I = |(1 - m)[(x_2 + x_1)/2] - c|/r^2,
\]

where \( x_1 \) and \( x_2 \) are the stimulus levels defining the range over which the regression fit applies. If the two lines intersect within the chosen stimulus interval, a slightly more elaborate expression must be used (Chauhan & Charman, 1995).

Results

Stimulus–response functions for each target type were plotted for each subject. The accommodative response curves generally showed the usual form of an initial non-linear region followed by a quasi-linear region (Ciuffreda, 1991, 1998). There were, however, considerable inter-subject variations in the form of the curves for different targets. Figure 1 shows some typical data. Note that emmetrope 3 (\(-0.25/-0.25 \times 175\)) has reasonably consistent responses but emmetrope 4 (\(+0.25/-0.25 \times 135\)), who has generally more scattered responses, has difficulty in accommodating to the gratings at zero vergence. Myope 4 (\(-1.00/-0.25 \times 5\)) has reasonably accurate responses which vary little with the target except for the highest stimuli, whereas myope 9 (\(-6.50/-0.25 \times 20\)) produces erratic and inaccurate responses to almost all the stimuli.

As a further indication of the differences between individual subjects, Figure 2 shows the full set of response/stimulus curves for the optotype target. Note that one emmetrope found it difficult to relax accommodation to view the optically more-distant stimuli, and that one of the myopes completely failed to accommodate systematically to the target.

In an initial attempt to quantify possible differences between the various response/stimulus curves, the accommodative response slope was calculated for the quasi-linear part of the accommodative response curve by determining the regression line fit for data obtained with 1.5 D stimulus onward. The results for individual subjects in the two refractive groups are shown in (Figures 3A and 3B). The emmetropic group (Figure 3A) appears to be divided into two equal sub-subgroups, showing for the gratings targets different patterns of change in slope with spatial frequency. In the first sub-group, slopes tend to increase with the spatial frequency of the target. In the second, slopes are maximal at around 4 c/deg and decrease at higher spatial frequencies. There appears to be no correlation between the pattern of behavior and the age of the subjects. With the exception of one 21 year-old, who has an unusually low slope, slopes for optotypes are generally similar to the maximal slopes for the grating targets.

Mixed performance for the grating targets is also observed among the myopic group, but it is more difficult to classify the differences involved (Figure 3B). There is no obvious relation between the pattern of slope change and the magnitude, onset or progression of the myopia. It is of interest that some myopes (\(-1.37 \text{ D}, -2.25 \text{ D}\)) had very poor response gradients for the optotype, while the \(-2.00 \text{ myope (stable)} \) essentially failed to accommodate to all but the lowest frequency of grating and the optotype. In general a greater spread of accommodative behavior is observed in the myopic group than in the emmetropic group.
The mean slopes of the subjects within the two groups are given in Table 1. Note that the standard deviations are larger for the myopic group. There are, however, no significant differences between the mean slopes of the two refractive groups (non-parametric Kruskal–Wallis ANOVA by ranks: \( p = 0.95 \)) and the spatial frequency of the individual targets has no significant effect on the slope of the accommodative response curve (Kruskal–Wallis ANOVA by ranks: \( p = 0.21 \)). It is evident from Table 1 (see also Figure 2) that the variability found in the accommodative response functions was greater in the myopic group for all targets.

While the slope values show how the response is changing with the stimulus, they give no indication of the magnitudes of the actual errors (lags or leads) of focus, which may be very high even though the slope is close to unity. Unfortunately, evaluation of such errors with infrared auto-refractors is not straightforward, since the results of all auto-refractors include corrections for the position of the reflecting layer within the retina and for longitudinal chromatic aberration between the infra-red and visible wavelengths. In addition, they include a further correction to bring their results into line with those of clinical subjective procedures. The latter are typically carried out at a testing distance of 6 m (vergence \( -0.17 \) D) and involve a “least negative, most positive correction.” They thus leave the “emmetropic” eye slightly myopic, relying on depth-of-focus to give clear vision of the test chart. Overall, then, it is likely that an auto-refractor measurement of perfect “emmetropia”
implies an eye that, from the strictly optical point of view is, slightly myopic. As far as we are aware, no one has established the difference between the true and outputted values of refractive error for the Shin-Nippon instrument. For the present purposes, we have assumed that our Shin-Nippon estimates of responses are 0.25 D too low. We have therefore amended the intercept values in our regression line fits by this amount when the fits are used to derive the error indices.

The accommodative error index values for the different subjects and targets for the nominal stimulus range 1.5 to 6.0 D are shown in Figure 4. Apart from one poorly

Figure 2. Response/stimulus curves for the high-contrast 6/30 optotype as measured with the auto-refractor for (A) emmetropes and (B) myopes.

Figure 3. Slopes of regression-line fits to the response/stimulus data over the stimulus interval 1.5 to 6.0 D inclusive for individual subjects as a function of stimulus spatial frequency and for the optotype target. For clarity, results for each subject are successively displaced upward by one unit (A) emmetropic subjects arranged in order of ascending age (B) myopic subjects, arranged in order of increasing mean sphere error. E and L indicate early- or late-onset myopia and * indicates that the myopia is progressing.
accommodating myopic subject, who also had unusually low slope values, and particular combinations of individual subjects and targets, error indices are generally of the order of 1 D or less.

The mean values of the error index are given in Table 2. Note that in general the indices are quite high. Since $r^2$ values for the response/stimulus plots generally exceeded 0.9, this implies that mean errors of accommodation were quite large (typically between 0.5 and 1.0 D). However, in a few cases when slopes were very low $r^2$ values were also very low, giving unrealistically high values of error index: in these cases the index was assigned a value of 3, giving the ceiling effect observable in Figure 4B.

Kruskal-Wallis analysis of variance by ranks shows no significant difference in the mean accommodative error indices between myopes and emmetropes ($p = 0.53$) and between different spatial frequencies of the targets used in the study, including the optotypes ($p = 0.25$).

As noted earlier, several subjects had difficulty in accommodating to stimuli at zero vergence (i.e. at optical infinity). Table 3 shows the mean ($\pm 1 SD$) accommodative errors (generally leads) with these stimuli for the individual subjects within each refractive group. The values presented like those of Figure 1 are directly based on the auto-refractor readings, with no further correction for possible zero error. The problems experienced by some subjects, who include both myopes and emmetropes, are obvious.

### Discussion

The present study fails to demonstrate any systematic differences between the response/stimulus curves of emmetropic and myopic refractive groups and, in particular, fails to demonstrate that changing the spatial frequency of a grating target produces significantly different variations in the accommodation responses of the two groups. Thus we cannot confirm the hypothesis that myopes normally make less use of high spatial frequency information to guide their accommodation response.

However, under the conditions used, where only a limited subset of the components of accommodation may be active, the striking aspect of the results is that they are heavily dependent on the individuals involved. The

<table>
<thead>
<tr>
<th>Target</th>
<th>Emmetropes ($N = 10$)</th>
<th>Myopes ($N = 10$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 c/deg</td>
<td>0.62 ± 0.15</td>
<td>0.74 ± 0.20</td>
</tr>
<tr>
<td>4 c/deg</td>
<td>0.83 ± 0.13</td>
<td>0.78 ± 0.30</td>
</tr>
<tr>
<td>8 c/deg</td>
<td>0.76 ± 0.12</td>
<td>0.70 ± 0.32</td>
</tr>
<tr>
<td>16 c/deg</td>
<td>0.78 ± 0.20</td>
<td>0.68 ± 0.31</td>
</tr>
<tr>
<td>Optotype</td>
<td>0.81 ± 0.15</td>
<td>0.66 ± 0.32</td>
</tr>
</tbody>
</table>

Table 1. Mean slopes and standard deviations of the accommodation response/stimulus curves, over the stimulus interval 1.5 to 6.0 D inclusive, for the different targets for the emmetropic and myopic refractive groups.

<table>
<thead>
<tr>
<th>Target</th>
<th>Mean AEI, emmetropes (D)</th>
<th>Mean AEI, myopes (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 c/deg</td>
<td>0.84 ± 0.30</td>
<td>0.67 ± 0.34</td>
</tr>
<tr>
<td>4 c/deg</td>
<td>0.57 ± 0.29</td>
<td>0.77 ± 0.82</td>
</tr>
<tr>
<td>8 c/deg</td>
<td>0.85 ± 0.35</td>
<td>0.82 ± 0.78</td>
</tr>
<tr>
<td>16 c/deg</td>
<td>0.59 ± 0.22</td>
<td>1.04 ± 0.85</td>
</tr>
<tr>
<td>Optotype</td>
<td>0.87 ± 0.31</td>
<td>0.96 ± 0.76</td>
</tr>
</tbody>
</table>

Table 2. Mean accommodative error indices, in dioptries, and their standard deviations for the different targets for the emmetropic and myopic refractive groups.

Figure 4. Changes in the error index, I, as a function of the spatial frequency of the grating target and for the optotype (A) emmetropes (B) myopes. Ages (years) are given for the emmetropes and refractive errors (D) for the myopes.
frequencies whereas Bour (1981), Owens (1980), and tend to be maintained or increase at higher spatial contrast at low spatial frequencies. Charman and Tucker of focus are required to substantially change image tends to produce low response gradients, since large errors low spatial frequency sinusoidal gratings (1 c/deg or less) expected, finding in all studies is that accommodation to any, of the subject’s refractive error. A common, and have systematically studied the effect on the results, if none of them appears to show that the effect of target grating frequency is statistically significant. Thus the mean slope data fail to show that the effect of target grating frequency is markedly different in emmetropes and myopes. The same null result was found for the error indices. Although the present study did not show a statistically significant difference in the accommodative response functions between the two refractive groups, the variability of the accommodative response functions was found to be larger in the myopic group.

Considering first the results obtained with relatively narrow-band grating targets, it is well known that image modulation falls away more rapidly with defocus as the spatial frequency of the target increases (Charman & Tucker, 1977, 1978). Thus if accommodation always acted to produce near-maximal image modulation, tolerances to focus error would be smaller at higher spatial frequencies. The effect is complicated by the presence of accommodation-dependent spherical aberration, which results in a spatial-frequency dependence in the optimal focus, that for low spatial frequencies being closer to the marginal focus and that for higher spatial frequencies closer to the paraxial focus (Charman, 1979; Charman, Jennings, & Whitefoot, 1978; Green & Campbell, 1965; Koomen, Skolnik, & Tousey, 1951). Further complication arises from accommodative miosis and the change in spherical aberration with accommodation (Plainis, Ginis, & Pallikaris, 2005). It would be expected that response and stimulus would be equal at a value approximating to the individual’s tonic level of accommodation (typically around 1 D, Leibowitz & Owens, 1978; McBrien & Millodot, 1987), with leads at the lowest stimulus levels and lags at levels above the tonic value.

Many earlier authors have explored the accommodation response/stimulus curve for sinusoidal grating targets (e.g. Bour, 1981; Charman & Tucker, 1977, 1978; Owens, 1980; Phillips, 1974), although none of them appears to have systematically studied the effect on the results, if any, of the subject’s refractive error. A common, and expected, finding in all studies is that accommodation to low spatial frequency sinusoidal gratings (1 c/deg or less) tends to produce low response gradients, since large errors of focus are required to substantially change image contrast at low spatial frequencies. Charman and Tucker (1977, 1978) found that the response/stimulus gradient tended to be maintained or increase at higher spatial frequencies whereas Bour (1981), Owens (1980), and Phillips (1974), found that response accuracy was optimal at spatial frequencies of 3–5 c/deg, around the peak of the photopic contrast sensitivity function, and that gradients decreased at higher and lower spatial frequencies. Some of these differences can reasonably be explained in terms of the different instructions given to the subjects, which in Charman and Tucker’s case encouraged the maximal use of voluntary accommodation, whereas Owens’ subjects were told to “view naturally, without straining the eye,” thereby encouraging subjects to rely mainly on reflex accommodation (Ciuffreda & Hokoda, 1985; Francis, Jiang, Owens, & Tyrrell, 2003; Owens, 1980; Stark & Atchison, 1994). Further work using dynamic stimuli (Mathews, 1998; Mathews & Kruger, 1994; Stone, Mathews, & Kruger, 1993) supports the view that higher spatial frequencies play little role in reflex accommodation.

All of our subjects were given the instruction to “keep the targets clear.” Examination of Figure 3 suggests that in practice half of the emmetropes had gradients that increased with spatial frequency while in the other half they peaked at around 4 c/deg or showed ambiguous changes. Thus the emmetropic group displayed mixed behavior similar to that found by Ciuffreda and Hokoda (1985). The myopes’ behavior was broadly similar, with the exception that one subject showed little response to any grating except 1 c/deg. While there were minor differences in the mean slopes for each grating (Table 1) the differences between the refractive groups do not reach statistical significance. Thus the mean slope data fail to show that the effect of target grating frequency is markedly different in emmetropes and myopes. The same null result was found for the error indices. Although the present study did not show a statistically significant difference in the accommodative response functions between the two refractive groups, the variability of the accommodative response functions was found to be larger in the myopic group.

When the individual subjects are considered, however, substantial inter-subject differences in both slopes and error indices are found. We attribute these to variations in the reliance that individuals place on the different components of accommodation, allied to the nature of the defocus changes in the images of sinusoidal gratings. For larger errors of focus, the grating images are subject to the phenomenon of spurious resolution (Smith, 1982). It is therefore possible that some subjects may accommodate to bring one of the secondary, supra-threshold spuriously resolved images onto the retina, rather than attempting to accommodate to the primary image (Charman & Tucker, 1977). The result is substantial accommodative error, usually a lag, since there is a tendency to minimize the accommodation exercised when the target vergence is high.

In the present case, accommodation to a spuriously resolved image is most likely to occur for the 16 c/deg grating, which has the narrowest relative spatial bandwidth. The exact effects depend on the pupil size and
aberrations of the individual subject, Stiles-Crawford
apodization, the frequency spectrum of the object, and
the spectral composition of the illumination but, to
qualitatively illustrate their nature, Figure 5 shows the
through-focus changes in retinal image modulation for an
80% modulated 16 c/deg grating target (as used in the
study) which might be expected for a diffraction-limited
eye with a 4 mm pupil working at a wavelength of
550 nm. The retinal contrast threshold for this spatial
frequency is less than 0.01, (Campbell & Green, 1965;
Sekiguchi, Williams, & Brainard, 1993). Note that the
modulation in the peaks of spurious resolution is substi-
tially higher than this, so that the grating may be detected,
necessarily in the correct phase, at several positions of
focus. Evidently, then, a subject may report that the image
is “clear” when viewing a spuriously resolved image with
a substantial accommodative lag.

The probability of an individual choosing to accom-
modate to a spuriously resolved image presumably
depends upon the reliance placed on each of the
components of accommodation. For accurate accommo-
dation to the higher spatial frequency gratings, the subject
must exercise enough accommodation to successfully
locale the primary image of the grating, rather than one
of the spuriously resolved images. Since, in the stimulus
conditions used, convergence and proximity cues are
lacking and blur cues may be ambiguous, if the target is
not at a vergence corresponding to the tonic accommoda-
tion level of the individual, subjects may have to rely on
voluntary accommodation to bring the grating target into
approximately correct focus. Hence those subjects who
habitually rely primarily on proximity and binocular cues
are likely to accommodate poorly to the higher-frequency
gratings. It appears that both the emmetropic and myopic
groups contained such subjects, leading to a reduction in
slope and an increase in error index (Figures 3 and 4). The
precise nature of their accommodative errors will depend
upon the position of their tonic levels in relation to the
stimulus values.

The 6/30 letter “E” target represents a slightly different
challenge to the accommodation system. It is a broad-
band-frequency target which can be resolved with rela-
tively large errors of focus (around 1.5 D, e.g. Rabbetts,
1998). More precise accommodation simply improves
dge sharpness, as higher spatial frequency components
come into better focus, and in principle it ought to be
much easier to achieve an accurate focus than with
sinusoidal grating targets (Ciuffreda, Dul, & Fisher,
1987; Heath, 1956b; Tucker & Charman, 1987). However,
it is of interest that, although most subjects accommodated
reasonably well to the optotype, except perhaps at the
highest (5.72 D) stimulus level, their errors of focus and
error indices (Figure 4) were quite substantial, suggesting
that they were using a criterion which depended more on a
tolerance to defocus based on a “troublesome” or “bother-
some blur” criterion rather than on “just noticeable blur”
(Atchison, Fisher, Pedersen, & Ridall, 2005; Ciuffreda
et al., 2006). One of the myopes completely failed to
accommodate systematically as the stimulus vergence
varied, giving a gradient of effectively zero (Figure 2):
others have also found that young, clinically normal, adult
subjects may fail to accommodate when presented with
static or dynamic stimuli (e.g. Chen, Kruger, Hofer,
Singer, & Williams, 2006; Heron, Charman, & Grey,
1999). In general, for the optotype, variations between the
response curves of subjects were larger within the myopic
group. Another possible reason for the low accommodative
responses found in some of the subjects could be the lack
of chromatic cues in the targets used in the present study
(Fincham, 1951; Kruger, Mathews, Katz, Aggarwala, &
Nowbotsing, 1997). Since all the targets were presented
using the green phosphor of the CRT monitor, the
accommodative response of at least some of the subjects
is likely to be lower than the response found under more
natural polychromatic conditions.

It could be argued that responses of at least some
subjects would have been both more accurate and more
consistent had they been trained to the task. Our reasons
for not doing this have been mentioned earlier: we felt that
subjects should be asked to accommodate in a way that
felt natural to them and which reflected their normal
judgments of the clarity of the stimuli under the
conditions of the study. Under conditions where some
cues to accommodation have been removed it is usually
found that subjects learn to make use of alternative cues to
guide their responses. For example, Fincham (1951) found
that 60% of subjects who accommodated normally in
white light were initially unable to accommodate in
monochromatic light but most soon learned to do so.

To determine whether the responses could be influenced
by further encouragement and instruction, the measurements

Figure 5. Changes in the modulation in the retinal image of a 16 c/deg
grating for an aberration-free eye with a 4 mm pupil and light of
wavelength 550 nm.

Modulation of retinal image for 16 c/deg grating, 4
mm pupil, 550 nm

<table>
<thead>
<tr>
<th>Defocus (D)</th>
<th>Retinal image modulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.8</td>
</tr>
<tr>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>1</td>
<td>0.6</td>
</tr>
<tr>
<td>1.5</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>0.4</td>
</tr>
<tr>
<td>2.5</td>
<td>0.3</td>
</tr>
<tr>
<td>3</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Downloaded from jov.arvojournals.org on 05/13/2019
for the optotype target were repeated for the two myopic subjects with the lowest gradients. Before the repeat session, it was emphasized to subjects that they should concentrate on achieving maximal perceived contrast and sharpness when accommodating. Figure 6 compares the initial and repeated data for the subjects. The accommodative response gradients for the optotype targets improved from 0.27 to 0.76 for myope 2 and from 0.23 to 0.74 for myope 5. The new values are comparable to the group mean for the emmetropes.

It is evident from Figure 6 that the original low gradient for myope 2 was caused by the subject’s failure to accommodate adequately to the 5.72 D stimulus: all the other repeated measurements were very close to the original measurements. The repeated results for myope 5 showed far more typical responses in comparison to the irregular responses obtained for this subject originally. This emphasizes the problem of carrying out studies of this type. To what extent are we assessing voluntary aspects of accommodation rather than the limits of performance of the system?

All subjects had originally claimed that the target was “clear,” even though for some it must have been markedly out of focus. Those subjects with reasonably accurate initial responses showed similar responses upon repetition. With training and encouragement, the initially under-accommodating subjects achieved more accurate responses, as shown above. However, while this result shows that these subjects have the potential to accommodate reasonably well, it appears that with monocular stimuli they initially do not normally bother to do so. As noted earlier, it may be that under normal binocular conditions, they habitually place a strong reliance on vergence accommodation to help the response to rise to an appropriate level and that monocular studies give little indication of their real-life accommodation abilities. As a result, under monocular conditions they must learn to use voluntary accommodation as a replacement for the missing convergence accommodation. As noted earlier, an alternative, or additional, factor that may pose initial problems for some individuals who place strong reliance on chromatic cues is the relatively narrow spectral bandwidth of the targets (Fincham, 1951; Kruger et al., 1997).

For all targets, it is of interest that many of the subjects experienced considerable difficulty in relaxing their accommodation to view the targets at zero vergence (optical infinity, see Table 3). In this case, subjects are required to reduce their accommodation below its tonic level in the face of significant opposing proximal cues, a task that proved particularly difficult for several subjects when the target was a 16 c/deg grating.

One further factor that deserves consideration when comparing the responses of individual subjects is the possible effect of their pupil size and aberrations on depth-of-focus and hence, possibly, on the accuracy of their responses. We did not measure individual depths-of-focus. Pupil diameters in the experiment were generally in the range of 4–6 mm, in which depth-of-focus varies only weakly with pupil diameter (e.g. Atchison & Smith, 2000). In related studies (Charman & Radhakrishnan, 2009) we found no systematic differences in the pupil diameters or accommodative miosis (mm/dioptre of accommodation response) between emmetropes and myopes. Some previous studies have shown that monochromatic aberrations can play an important role in

![Figure 6](https://example.com/figure6.png)

Figure 6. Response/stimulus curves for the optotype target for myopic subjects 2 and 5 in the original and repeat measurements.
driving accommodation (Chen et al., 2006; Fernández & Artal, 2005; Wilson, Decker, & Roorda, 2002). Monochromatic aberrations show a large degree of variability between individuals (Castejón-Mochón, López-Gil, Benito, & Artal, 2002; Paquin, Hamam, & Simonet, 2002; Porter, Guirao, Cox, & Williams, 2001) and also change as a function of accommodation (Cheng et al., 2004; Radhakrishnan & Charman, 2007). With this in mind, it is possible that differences in monochromatic aberrations between individuals may account for some of the variability observed in the present study.

Finally we note that a mixture of early, late, stationary and progressing myopes was included in our subject groups and it remains possible that significant differences from emmetropes might have been found had the myopic group been more homogeneous. However, examination of the data for individual subjects as shown in Figures 3B and 4B gives no obvious indication that this is likely to be the case.

Conclusion

The present study fails to establish the existence of any systematic difference in the responses of emmetropes and myopes to sinusoidal grating targets. The dominant feature of the data in both refractive groups is inter-subject variation, which we attribute to variations in the reliance that different individuals place on particular accommodative components.

Acknowledgments

This research was supported by a doctoral training grant from the University of Manchester.

Commercial relationships: none.
Corresponding author: John Taylor.
Email: John.Taylor@postgrad.manchester.ac.uk.
Address: Faculty of Life Sciences, Moffat Building, University of Manchester, Sackville Street, PO Box 88, Manchester, M60 1QD, UK.

References


