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The effect of modulating ocular depth of focus upon accommodation microfluctuations in myopic and emmetropic subjects

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ABSTRACT

The magnitude of accommodation microfluctuations increases in emmetropic subjects viewing low luminance targets or viewing a target through small artificial pupils. Larger microfluctuations reported in myopia may result from an abnormally large depth of focus (DoF). The effect of modulating the size of the DoF has not been investigated in myopic subjects and may help to explain the cause of the increased DoF. Accommodation microfluctuations were recorded under two experimental conditions. Firstly, 12 emmetropes (EMMs), and 24 myopes (MYOs) viewed a Maltese Cross target with luminance levels of 0.002, 0.2, 6 and 600 cd/m^2 and in darkness, and second, 14 EMMs and 16 MYOs viewed a Maltese Cross target through pupil diameters of 0.5, 1, 2, 3, 4 and 5 mm presented in Maxwellian view. The magnitude of the accommodation microfluctuations increased significantly with a target luminance of 0.002 cd/m^2 ($p < .03$) and pinhole diameters of <2 mm ($p < .05$). For all other luminance levels and pupil diameters the magnitude was constant. For both conditions, MYOs had significantly larger microfluctuations than EMMs ($p < .01$). Considerable inter-subject variability was observed in the degree to which the magnitude of the microfluctuations increased, for both the 0.002 cd/m^2 luminance and 0.5 mm pupils, however, this was not correlated with refractive error. The increase in the magnitude of the microfluctuations while viewing a low luminance target (0.002 cd/m^2) may be due to a shallower contrast gradient in the cortical image, with a consequent increase in DoF. The microfluctuations also increase when viewing through small pupils (<2 mm), which increases the DoF without altering the contrast gradient. The larger microfluctuations found in the MYOs consolidates the theory that MYOs have a larger DoF than EMMs and therefore have a higher threshold for retinal image blur.

1. Introduction

1.1. Accommodation microfluctuations

When viewing a stationary stimulus, the accommodation system continuously changes its refractive power (Campbell, Robson, & Westheimer, 1959; Charman & Heron, 1988; Collins, 1937; Collins, Davis, & Wood, 1995; Denieul, 1982; Kotulak & Schor, 1986a; Seidel, Gray, & Heron, 2003; Winn, Pugh, Gilmartin, & Owens, 1990). The magnitude of the accommodation microfluctuations has been found to alter systematically with the target characteristics and this has led to the suggestion that the microfluctuations have a role in accommodation response control: variations in pupil size (Campbell et al., 1959; Gray, Winn, & Gilmartin, 1993a; Stark & Atchison, 1997), target luminance (Gray, Winn, & Gilmartin, 1993b) and the spatial frequency content of the stimulus (Niwa & Tokoro, 1998) have been shown to affect the magnitude and temporal frequency composition of the microfluctuation waveform. Increasing stimulus vergence demand also increases the magnitude of the microfluctuations (Day, Strang, Seidel, Gray, & Mallen, 2006; Denieul, 1982; Heron & Schor, 1995; Kotulak & Schor, 1986b; Miege & Denieul, 1988; Stark & Atchison, 1997). This systematic relationship between the accommodation microfluctuations and these stimulus characteristics suggests that the accommodation system may monitor information about the edge profile of the target and use this information during feedback.

It is well established that the accommodation error detector monitors the level of cortical image blur within a closed-loop negative feedback system and responds to changes in the level of cortical image blur, in order to maintain image clarity. It is suggested that the accommodation error detector obtains information regarding blur by monitoring changes in the contrast of this image (Charman & Tucker, 1978; Gray et al., 1993b; Hung, Semmlow, & Ciuffreda, 1982; Kotulak & Schor, 1986a; Mathews & Kruger, 1994). Specifically, the accommodation controller may monitor the gradient of the cortical image. The contrast gradient is the difference in luminance between two points in the image divided by the space between these two points. It is likely that the accommodation controller monitors the maximum gradient contained with-

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in the image. As this is altered by different stimulus conditions, the microfluctuations may change in magnitude to provide consistent feedback to the accommodation controller.

1.2. Accommodation microfluctuations and target luminance

Reducing the luminance of a target has been shown to increase the size of microfluctuations (Gray et al., 1993b). Gray et al. (1993b) found that microfluctuations are constant in magnitude (~0.21 D) when the target luminance is altered within the range 11.63 and 0.01 cd/m^2, with increases occurring at 0.004 (~0.46 D) and 0.002 cd/m^2 (~0.57 D) (Gray et al., 1993b). Although reducing target luminance does not alter the contrast gradient of the target itself, there will be a loss of perception of the high spatial frequency components within the target. The maximum spatial frequency which can be detected for a given target luminance can be calculated using data from van Nes, Koenderink, Nas et al. (1967), who measured detection thresholds for sine wave gratings of several spatial frequencies and mean luminance levels. The calculated data in Fig. 1 shows the highest spatial frequency detectable at 50% modulation for a given luminance through a 2 mm pupil. Our calculations show that a reduction in target luminance causes the high spatial frequency information to become undetectable.

High spatial frequency information within the target, which is above threshold at high luminance levels, ensures a cortical image with a sharp edge and a steep contrast gradient. Reducing target luminance produces a reduction in the maximum spatial frequency available to the accommodation error detector, causing a shallower contrast gradient in the cortical image. The maximum contrast gradient of the cortical image as a function of luminance, calculated using the data from Fig. 1, is illustrated in Fig. 2. This shows that the maximum contrast gradient within the cortical image is constant at high target luminance and reduces progressively when target luminance falls below ~0.02 cd/m^2.

One consequence of this reduction in contrast gradient is an increase in the ocular depth of focus (DoF). DoF is the amount of blur that is undetectable by the accommodation error detector and which fails to stimulate an accommodation response. By combining the data from Figs. 2 and 3 with previous calculations of the amount of defocus present when the modulation transfer was 50% (Walsh & Charman, 1989), we obtain Fig. 4. This is a theoretical estimation of the size of the DoF for a target containing a broad spectrum of spatial frequencies as a function of target luminance. An exponential function has been fitted ($y = 1.7115\,e^{-0.1547x}$, $R^2 = .94$) and the fit extrapolated up to a spatial frequency of 50 cpd. It can be seen that as target luminance decreases, the DoF remains small and relatively constant until increases in the DoF are observed when the luminance reaches ~0.002 cd/m^2. As target luminance decreases further, a progressive reduction in DoF is observed.

It is apparent that the level of luminance that produces increases in the magnitude of the microfluctuations (Gray et al., 1993b) corresponds to the luminance at which a reduction in contrast gradient of the cortical image and a consequent increase in DoF. Therefore, it seems likely that the increases in the microfluctuations results from the loss of high spatial frequency information available to the accommodation error detector.

1.3. Accommodation microfluctuations and pupil size

Reductions in pupil size are known to increase the DoF by reducing the size of the blur circle on the retina, making the eye

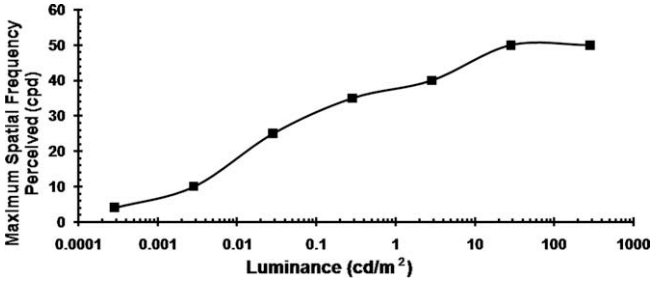

Fig. 1. Theoretical values of the maximum detectable spatial frequency at a given target luminance calculated using data from van Nes et al. (1967). Each data point is the highest spatial frequency visible at 50% modulation through a 2 mm pupil at a given luminance level.

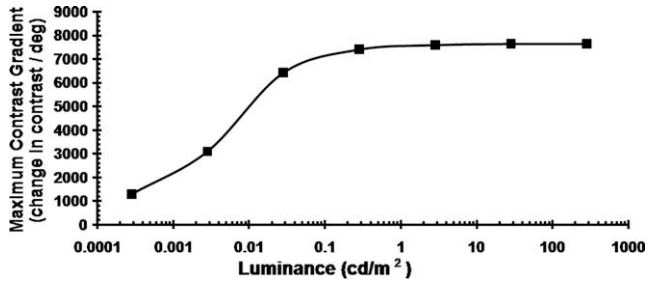

Fig. 2. The maximum contrast gradient of the cortical image of a target containing a broad spectrum of spatial frequencies as a function of target luminance. This was calculated using the MTFs in Fig. 1 in combination with the maximum spatial frequency that can be perceived at that given luminance (from the data of van Nes et al., 1967; Fig. 1).

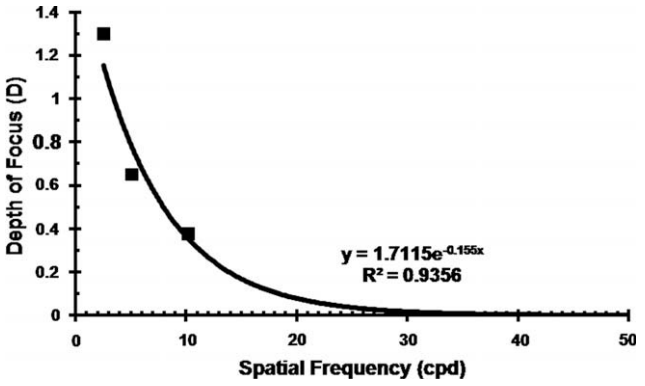

Fig. 3. Theoretical values of the size of the depth of focus as a function of spatial frequency, taken as the amount of defocus that reduces the modulation transfer of each spatial frequency to 50% from Walsh and Charman (1989). An exponential function has been fitted ($R^2 = .94$, $y = 1.7115e^{-0.1547x}$) and the graph extended up to a spatial frequency of 50 cpd.

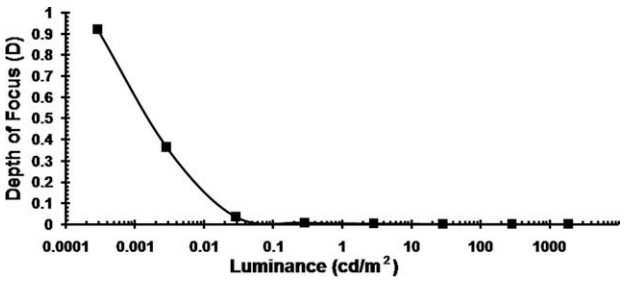

Fig. 4. Theoretical values of the depth of focus (DoF) of a target containing multiple spatial frequencies at a given target luminance. For a given luminance, the highest spatial frequency available is taken from Fig. 1 and the DoF at this spatial frequency from Fig. 3 is plotted in this graph.

less able to detect any blur created by the target. Increases in the magnitude of the microfluctuations have been reported when viewing targets through small artificial pupils (Atchison, Charman, & Woods, 1997; Campbell, 1957; Charman & Whitefoot, 1977; Ogle & Schwartz, 1959; Stark & Atchison, 1997). Campbell et al. (1959) found that the microfluctuations are larger through a 1 mm pupil compared to a 7 mm pupil. Gray et al. (1993a) measured the accommodation microfluctuations while viewing a Maltese cross target through pupil diameters of 0.5, 1, 2, 3, 4 and 5 mm. Large pupil diameters produced small microfluctuations (~0.20 D) and increases in the magnitude of the microfluctuations are observed when the pupil diameter is reduced to ⩽2 mm (~0.31 D) (Gray et al., 1993a). As this corresponds with the pupil diameter at which increases in DoF are found (Atchison et al., 1997; Campbell, 1957; Charman & Whitefoot, 1977; Ogle & Schwartz, 1959), it is likely that the microfluctuations increase in magnitude to attempt to provide the error detector with consistent feedback information. When the DoF is small, the accommodation controller can detect changes in blur with small microfluctuations. It is likely that when the DoF is larger, the microfluctuations have to increase in magnitude before the system can detect the same change in blur.

There is a reduction in retinal illuminance caused by using small artificial pupils and so this also has the potential to increase the magnitude of the microfluctuations as discussed previously. Stark and Atchison (1997) addressed this problem by using Maxwellian viewing conditions rather than real artificial pupils and showed a significant negative correlation between the magnitude of the accommodation microfluctuations and pupil diameter (1, 2, 4 and 6 mm). The use of Maxwellian system to image the pupils at the nodal point of the eye maintains a relatively consistent level of retinal illuminance, and their data confirms that the increases in the magnitude of microfluctuations found with small artificial pupils are not a result of reductions in retinal illuminance.

These findings are supported by calculating the retinal illuminance likely to be present when small artificial pupils are used. As retinal illuminance is proportional to pupil area, then the retinal illuminance will be reduced by 400× when viewing through a 0.5 mm diameter pupil compared to a 5 mm diameter pupil. When a target of luminance 100 cd/m^2 (used by Gray et al., 1993a) is viewed through a 0.5 mm pupil, the effective luminance is likely to be around 0.25 cd/m^2, which is well above the luminance shown to produce significant increases in the magnitude of the microfluctuations (0.002 cd/m^2; Gray et al., 1993b). It is possible that the value may not be as low as this because the Stiles–Crawford Effect is likely to produce a (small) increase in apparent brightness for the smaller pupils. Fig. 2 shows that there is no change in the contrast gradient of the cortical image for different pinhole diameters as a result of the reduction in luminance. The effect of viewing through small pupils will produce a narrowing of the point spread function (Campbell & Gubisch, 1966), which would theoretically steepen the contrast gradient of the cortical image.

In summary, there is no significant change in the contrast gradient of the cortical image when pupil diameter is altered using Maxwellian viewing conditions. Whilst a steep contrast gradient is maintained, small pupils (<2 mm) increase the DoF by restricting light to paraxial rays, and therefore any changes in the contrast gradient created by blur go undetected by the accommodation controller.

1.4. Microfluctuations, depth of focus and refractive error

Studies measuring the magnitude of the accommodation microfluctuations in different refractive groups have reported that late onset myopes have larger microfluctuations than both emmetropes (EMMs) and early onset myopes (EOMs) (Seidel et al., 2003), and LOMs demonstrate a different pattern of response with increasing target vergence (Day et al., 2006). Day et al. (2006) found that while EMMs and EOMs show systematic increases in the rms value of the microfluctuations with increasing target vergence, LOMs show no change in the magnitude of the microfluctuations at target vergences between 0 and 3 D and they increased in size at 4 D (Day et al., 2006). Both sets of authors suggested that the differences found in the LOMs could be caused by the larger DoF previously reported in myopic subjects (Collins, Buehren, & Iskander, 2006; Rosenfield & Abraham-Cohen, 1999; Vasudevan, Ciuffreda, & Wang, 2006). A recent study reporting reduced contrast sensitivity at spatial frequencies ⩾8 cpd in MYOs (Radhakrishnan, Pardhan, Calver, & O'Leary, 2004). If MYOs are less able to detect these high spatial frequencies, the contrast gradient of the cortical image would be flatter, and this could possibly account for the larger DoF observed in MYOs.

Although it has been suggested that larger microfluctuations in MYOs are due to increased DoF, the effect of modulating the size of the DoF in myopic subjects on the microfluctuations is unknown. Changing the target luminance modulates the spatial frequency content of the cortical image used by the accommodation error detector, altering both the contrast gradient of the image and the DoF. Conversely, using small pupils in a Maxwellian viewing system modulates DoF without significantly changing the spatial frequency content or contrast gradient of the cortical image. The aim of this study is to investigate the effect of altering the DoF in myopic and emmetropic subjects using changes in target luminance and pupil diameter.

2. Methods

2.1. Subjects

Healthy, young adult volunteers participated in both experiments. All subjects had ⩽0.50 D of astigmatism, no ocular or systemic disease and 0.1 logMAR visual acuity or better. All subjects gave informed consent, the study was approved by the Glasgow Caledonian University, School of Life Sciences Ethics Committee and was conducted in accordance with the Declaration of Helsinki.

The subjects completed a questionnaire regarding their refractive history before taking part in the experiment. The subjects were then sub-divided, depending upon the refractive error of their right eye. Emmetropia (EMM) was classified as a mean spherical equivalent refractive error (MSE; sphere +0.5*cyl) between −0.25 and +0.75 D and all myopic subjects had a MSE Rx ⩽ −0.75 D.

Table 1 provides the mean age and MSE of each subject group in Experiments 1 and 2. There was no significant difference in age between the EMMs and the MYOs in either experiment (Experiment 1: t-test, $t_{36} = -0.623$, $p = .539$; Experiment 2: t-test $t_{30} = 0.539$, $p = .539$), but there was a significant difference in MSE between the EMMs and MYOs in both experiments (Experiment 1: t-test $t_{36} = 5.445$, $p < .001$; Experiment 2: t-test $t_{30} = 6.083$, $p < .001$).

Table 1
Subject groups of Experiment 1 and 2. Age and refractive error rows show mean ± SD. Refractive errors are calculated as the MSE of the right eye (sphere + 0.5*cyl).

Experiment	1		2	
Group classification	EMMs	MYOs	EMMs	MYOs
No. subjects	12	24	14	16
Age (yrs)	22.5 ± 5.1	22.5 ± 4.0	19.6 ± 2.0	20.2 ± 2.3
Age of myopia onset (yrs)	N/A	14.3 ± 5.6	N/A	11.6 ± 3.9
MSE (D)	−0.06 ± 0.55	−2.76 ± 1.67	−0.09 ± 0.47	−3.23 ± 2.11
Range (D)	−0.50 to +0.63	−6.50 to −0.50	−0.50 to +0.75	−7.75 to −1.00

2.2. Stimulus

In both experiments, a Maltese cross target (angular subtense: 1.5°) was viewed monocularly using the right eye through a +5 D Badal lens (Badal, 1876). This target was chosen because it has a wide spatial frequency spectrum independent of orientation, and the target has been used previously in many accommodation experiments (Day et al., 2006; Diether & Wildsoet, 2005; Gray et al., 1993a, 1993b; McLin & Schor, 1988; McLin, Schor, & Kruger, 1988; Okada et al., 2006; Seidel et al., 2003; Strang, Winn, & Gilmartin, 1994).

The accommodation response falls to a resting, tonic accommodation (TA) level in darkness or when viewing a target through a small artificial pupils (Gray, Strang, Winfield, Gilmartin, & Winn, 1998; Schor, Kotulak, & Tsuetaki, 1986; Strang, Gilmartin, Gray, Winfield, & Winn, 2000). Previous work has shown that the magnitude of accommodation microfluctuations increases with increasing accommodation response level (Day et al., 2006; Denieul, 1982; Heron & Schor, 1995; Kotulak & Schor, 1986b; Miege & Denieul, 1988; Stark & Atchison, 1997). To minimise the effect of alterations in the accommodation response level during both experiments, the target was placed at the stimulus position that produced an accommodation response equal to the TA level. Measurements of the TA level were obtained at the start of the each experiment by taking an average of 10 static readings with the optometer. As the measured value of the TA level varies according to which method is used (Gray et al., 1998), the TA was measured using different methods for the experiments. In Experiment 1, the TA was measured after 3 min in darkness, and during Experiment 2 the measurement was taken while subjects viewed a distant target through a 0.5 mm diameter pinhole in the Maxwellian viewing system.

In both experiments all conditions (luminance levels or small pupils) were conducted in a random order and there was a break of at least 3 min between conditions so that adaptation effects were minimised. During this break, subjects were in a room with a mesopic luminance level (0.6 cd/m^2).

2.2.1. Experiment 1

Target luminance was altered using neutral density filters placed in front of the target, producing luminance levels of 0.002, 0.2, 6 and 600 cd/m^2.

2.2.2. Experiment 2

The target (80% contrast, 600 cd/m^2 luminance) was imaged through a +5 D Badal lens system (Badal, 1876), and presented within a Maxwellian viewing system, which was used to present the artificial pupils (see Fig. 5). The Maxwellian viewing system was used to reduce proximity effects and to maintain a high, relatively consistent retinal illuminance in comparison with real artificial pupils (see earlier calculation). The light source was placed directly behind the real pinhole, producing a point source of light. The pinhole was positioned at the focal point of the +5 D auxiliary lens, which produced a real image of the pinhole at infinity. This image acted as an object for the second +5 D (Badal) lens which created a virtual image of the pinhole at the nodal point of the eye. Pupil sizes of 0.5, 1, 2, 3, 4 and 5 mm were presented at the nodal point of the eye in a random order.

Precise alignment was carried out on each subject to ensure accurate artificial pupil sizes and viewing of the stimulus. Initially, accommodation responses were measured for a range of target positions while the subject viewed through the 0.5 mm pupil, to confirm that the accommodation system was open-loop (Ward & Charman, 1987).

2.3. Accommodation measurement and analysis

Throughout the experiment, all myopic subjects were fully corrected with mid-water content (58%) thin soft contact lenses (Acuvue, Johnson & Johnson, UK) which they adapted to for at least 30 min before any measurements were taken. Contact lenses have recently been shown not to affect the measurement of the accommodation microfluctuations (Day, Strang, Seidel, & Gray, 2007).

Accommodation responses of the right eye were recorded using a specially modified, open field, infrared autorefractor (Shin-Nippon SRW-5000, Shin-Nippon, Japan). This instrument has been found to be repeatable and accurate in both children (Chat & Edwards, 2001) and adults (Mallen, Wolffsohn, Gilmartin, & Tsujimura, 2001), and the operation of the Shin-Nippon in both static and continuous modes has been previously described (Mallen et al., 2001; Wolffsohn, Gilmartin, Mallen, & Tsujimura, 2001).

For each condition, 10 static measurements of the accommodation level were taken, and an average of these gave the mean level of the accommodation response. The autorefractor was then used in dynamic mode (Wolffsohn, Gilmartin, Mallen, & Tsujimura, 2001) to record 2 min of continuous accommodation responses at a sampling rate of 52 Hz. During recording in the dark focus condition, the subject was instructed to look straight ahead and relax their eyes, and during all other conditions the task was to look at the centre of the Maltese cross and to keep it clear. In dynamic mode, the instrument was calibrated for each individual subject while they were viewing a 0.0 log MAR letter at a distance of 6 m. Ten repeatable measures of the dimensions of the measurement ring in pixels were made and the average of these was used as the calibration value (Wolffsohn et al., 2001).

For each condition, the first 100 s of data that contained not more than 2 blinks every 20 s were used for data analysis. Blinks were removed from the data automatically using Microsoft Excel

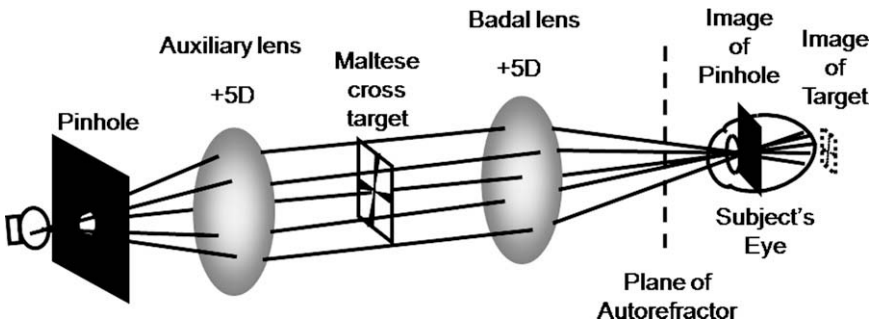

Fig. 5. Stimulus set up of Experiment 2. The pinhole is placed in a Maxwellian viewing system and the Maltese cross behind a Badal lens. The pinhole is set in front of a light source and at the focal point of a +5 D lens. A second +5 D lens then focuses an image of the pinhole at its focal point, which is coincidental with the nodal point of the subject's eye. The Maltese cross target is placed in front of the +5 D Badal lens, and is imaged on the subject's retina.

macro capabilities as described previously (Day et al., 2006). Each 100 s recording was divided into 10 segments each of 10 s duration and the average root mean square (rms) value of these recordings was calculated.

3. Results

3.1. Accommodation responses

Figs. 6 and 7 show group mean accommodation response levels for the EMMs and MYOs for each condition during Experiments 1 and 2, respectively. There was no significant variation in the accommodation response level in either refractive group across the different luminance levels (EMMs: ANOVA, $F_{4,60} = 0.961$, $p = .418$, MYOs: ANOVA, $F_{4,115} = 0.876$, $p = .544$) or artificial pupil diameters (EMMs: $F_{5,84} = 0.955$, $p = .453$; MYOs: $F_{5,96} = 0.510$, $p = .767$).

3.2. Accommodation microfluctuations

3.2.1. Experiment 1

3.2.1.1. All subjects. In all subjects, the rms of the accommodation microfluctuations varied significantly with target luminance (ANOVA: $F_{4,180} = 19.170$, $p < .001$). The rms of the microfluctuations was at a constant level as target luminance was reduced and then increased significantly when the luminance reached 0.002 cd/m^2. The rms at 0.002 cd/m^2 was significantly greater than that found for all higher luminance levels (Scheffe post hoc: $p < .03$ for all comparisons). The rms during the dark focus condition was not significantly different from that recorded for the 0.002 cd/m^2 target luminance (Scheffe post hoc, $p = .93$), but it was significantly larger than all other target luminance levels (Scheffe post hoc: $p < .001$ for all comparisons).

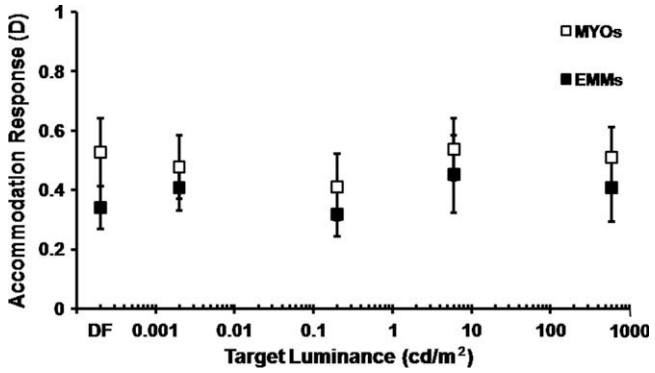

Fig. 6. Accommodation responses of EMMs and MYOs for all target luminance levels. Error bars are standard errors of the mean.

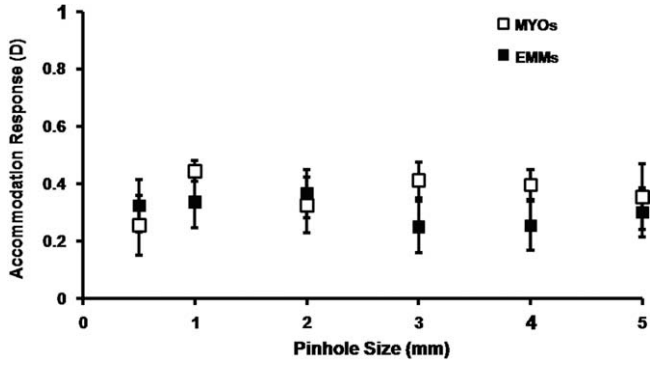

Fig. 7. Accommodation responses for each pinhole size in EMMs and MYOs. Error bars are standard errors of the mean.

3.2.1.2. Refractive group differences. The subjects were classified into EMMs and MYOs and the mean rms of the microfluctuations as a function of luminance, for these refractive groups is shown in Fig. 8. Comparing the rms of the microfluctuations across all luminance conditions, the MYOs demonstrated significantly larger microfluctuations than the EMMs (ANOVA, $F_{1,180} = 7.899$, $p < .001$). Additionally, both groups demonstrated significant increases in the rms with reductions in target luminance (EMMs: ANOVA, $F_{4,60} = 4.427$, $p < .05$; MYOs: ANOVA, $F_{4,120} = 15.271$, $p < .001$). In the EMMs, the rms when viewing the 0.002 cd/m^2 target was significantly larger than that found when viewing the 600 cd/m^2 target (Scheffe post hoc: $p < .05$) and the rms during the dark focus condition was significantly larger compared with target luminance levels of 0.2 and 600 cd/m^2 (Scheffe post hoc: $p < .035$ for both comparisons). The MYOs had significantly larger microfluctuations during the dark focus condition and the 0.002 cd/m^2 target luminance in comparison to all other target luminances (Scheffe post hoc: $p < .04$ for all comparisons).

3.2.1.3. Individual variability. Inspection of individual subject data revealed considerable individual variability in the magnitude of the accommodation microfluctuations. The increase in the rms of the microfluctuations when viewing the 0.002 cd/m^2 target compared with the size of the microfluctuations while viewing the 600 cd/m^2 target was calculated for each subject. The average change in the accommodation microfluctuations between these two luminance levels was 0.12 ± 0.10 D and ranged between −0.06 and +0.36 D. The increases in the magnitude of the microfluctuations were not correlated with either refractive state (Pearson correlation$_{36} = -0.151$, $p = .379$), or the magnitude of the microfluctuations when viewing the 600 cd/m^2 target (Pearson correlation$_{30} = -0.177$, $p = .303$).

3.2.2. Experiment 2

3.2.2.1. All subjects. The rms of the microfluctuations increased significantly with reductions in the diameter of the artificial pupils (ANOVA, $F_{5,180} = 18.522$, $p < .001$). The rms was significantly larger when viewing through the 0.5 mm artificial pupil compared with all other pupil sizes (Scheffe post hoc, $p < .04$ for all comparisons). Additionally, when viewing through the 1mm diameter pupil, the microfluctuations were significantly larger than those found with the 3, 4 and 5 mm pinholes (Scheffe post hoc, $p < .05$ for all comparisons).

3.2.2.2. Refractive group differences. Fig. 9 shows the rms of the microfluctuations for each artificial pupil diameter in EMMs and

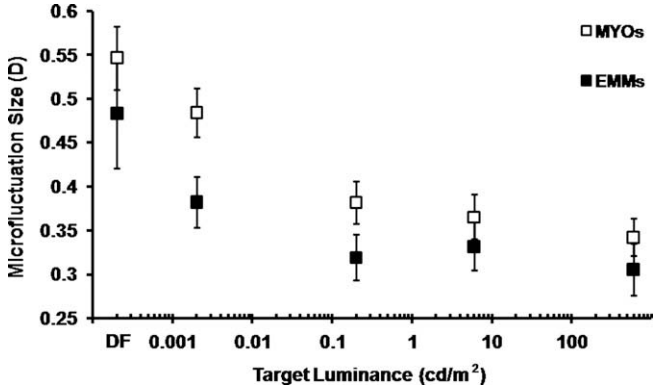

Fig. 8. RMS values of the accommodation microfluctuations of the EMMs and MYOs for all target luminance levels. Error bars are standard errors of the mean.

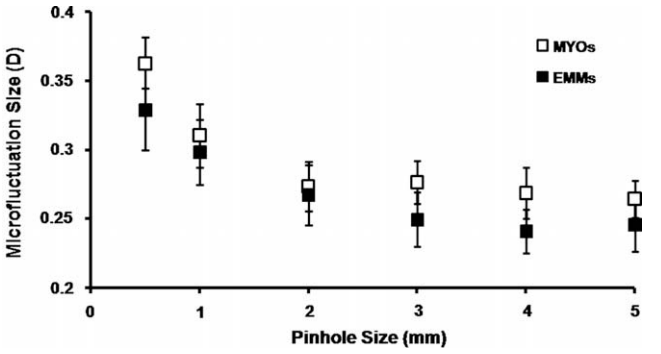

Fig. 9. RMS values of the accommodation microfluctuations of the EMMs and MYOs for all pupil sizes. Error bars are standard errors of the mean.

MYOs. The MYOs showed significantly larger rms values than the EMMs for all artificial pupil diameters (ANOVA, $F_{5,180} = 7.012$, $p < .01$). A similar variation in the rms with changing pupil diameter was observed in both refractive groups, with increases in the rms for the smallest pupil diameters (EMMs: ANOVA, $F_{5,84} = 7.559$, $p < .001$, Scheffe post hoc showed the RMS for the 0.5 mm pupil was significantly larger than 3, 4 and 5 mm pinholes, $p < .01$ for all comparisons; MYOs: ANOVA $F_{5,96} = 9.982$, $p < .001$, Scheffe post hoc showed the RMS for the 0.5 mm pupil was significantly larger than 2, 3, 4 and 5 mm pinholes, $p < .001$ for all comparisons).

3.2.2.3. Individual variability. Substantial variability between subjects was observed in the amount by which the rms of the microfluctuations increased while viewing through the smallest artificial pupils. Therefore, the difference was calculated between the RMS of the accommodation microfluctuations when viewing through the 0.5 mm pupil and the average RMS of the microfluctuations when viewing through the larger (2, 3, 4 and 5 mm) pupils. These differences ranged from −0.02 to +0.25 D with a mean ± SD of +0.09 ± 0.07 D. There was no significant correlation observed between the calculated differences and refractive error (Pearson correlation$_{30} = -0.008$, $p = .967$), or the rms of the accommodation microfluctuations when viewing through the larger pupils (Pearson correlation$_{30} = -0.116$, $p = .541$).

4. Discussion

4.1. Microfluctuations and luminance

These studies show that accommodation microfluctuations maintain a constant magnitude over a range of target luminance from 600 to 0.2 cd/m^2 but increase in magnitude when the target luminance is reduced to 0.002 cd/m^2 or in complete darkness. These results are consistent with a previous study (Gray et al., 1993b) that showed increases in the magnitude of microfluctuations for target luminances of 0.004 and 0.002 cd/m^2. The rms values obtained in the current study compare well with those found previously (Gray et al., 1993b).

The magnitude of the microfluctuations has been found to increase with increases in the accommodation response level (Day et al., 2006; Denieul, 1982; Heron & Schor, 1995; Kotulak & Schor, 1986b; Miege & Denieul, 1988; Stark & Atchison, 1997), although this cannot account for the present results as the mean static accommodation response was constant throughout the experiment. Small pupils would not influence the magnitude of the microfluctuations since pupil diameters were maintained at >2.9 mm throughout the experiment.

Under high luminance conditions the high spatial frequency information contained within the target is above threshold and this produces a cortical image with a sharp edge and a steep contrast gradient. This is ideal for the accommodation error detector because small changes in focus produce a relatively large change in the contrast gradient, there is a small DoF. Therefore, small microfluctuations are sufficient to provide the feedback information used by the accommodation controller. Reducing target luminance to $\leqslant$0.002 cd/m^2 produces a reduction in the maximum spatial frequency available to the accommodation error detector, and a shallower contrast gradient. This is less ideal for the error detector, since large changes in focus are required to produce an equivalent alteration in the contrast gradient, there is a large DoF. The microfluctuations need to increase in magnitude in order to provide the feedback information for the accommodation controller.

4.2. Microfluctuations and pupil diameter

The use of a Maxwellian view system in Experiment 2 allows DoF to be altered without significant changes in the contrast gradient of the cortical image. Using this optical system in myopic and emmetropic subjects, the results replicate and extend upon previous reports of the variation in accommodation microfluctuations with pupil diameter (Campbell et al., 1959; Gray et al., 1993a; Stark & Atchison, 1997). The magnitude of the accommodation microfluctuations remains constant as pupil size reduced from 5 to 2 mm and then increases in size while subjects view the target through the 1 and 0.5 mm pupils. The rms values of the microfluctuations compare very well with those found previously (Gray et al., 1993a).

Under large pinhole conditions, the contrast gradient of the cortical image is steep and the DoF small. Therefore, small changes in focus produce a relatively large change in the contrast gradient, which is ideal for the accommodation error detector because small microfluctuations are sufficient to provide the feedback information needed. When small pinholes (<2 mm) are presented in Maxwellian viewing conditions, there is no significant change in the contrast gradient of the cortical image. Whilst a steep contrast gradient is maintained, the small pupils increase the DoF by restricting light to paraxial rays, and therefore any changes in the contrast gradient created by blur go undetected by the accommodation controller. This is less ideal for the error detector since large changes in focus are required to produce an equivalent alteration in the contrast gradient, so the microfluctuations need to increase in magnitude in order to provide the feedback information for the accommodation controller.

4.3. Refractive group differences

In both experiments, the MYOs had significantly larger microfluctuations than the EMMs across all conditions. In Experiment 1, the myopic subjects were divided into EOMs and LOMs, and both groups had significantly larger microfluctuations than the emmetropic subjects. If the MYOs have a larger DoF (Collins et al., 2006; Rosenfield & Abraham-Cohen, 1999; Vasudevan et al., 2006), the microfluctuations would need to be of a larger magnitude to provide consistent feedback to the accommodation controller. This reduced sensitivity to blur has previously been proposed as the cause of larger accommodation microfluctuations in myopic subjects (Day et al., 2006; Seidel, Gray, & Heron, 2005; Seidel et al., 2003). The potential cause of a larger DoF in MYOs is a recently reported reduction in sensitivity to spatial frequencies $\geqslant$8 cpd (Radhakrishnan et al., 2004) which would produce a shallower contrast gradient of the cortical image.

Although the microfluctuations were found to be larger in myopic subjects, there was no difference in the way that the magnitude

of the microfluctuations altered with changing DoF in either refractive group, irrespective of whether the DoF was altered by reductions in target luminance or small pupil diameters. This suggests that while MYOs may have an inherently larger DoF, the accommodation control system responds in a similar manner to the EMMs when alterations in the size of the DoF occur.

4.4. Inter-subject variability

The data from both experiments show a large degree of inter-subject variability. There were large differences between subjects in the magnitude of the increase in the microfluctuations in the lowest compared to highest luminance condition and in the smallest compared to largest pupil conditions. This increase in the magnitude of the microfluctuations is not correlated with refractive state or the magnitude of the microfluctuations when viewing under optimal stimulus conditions (the 600 cd/m^2 target in Experiment 1 or the 2–5 mm pupil diameters in Experiment 2). Therefore, the inter-subject variability is unlikely to be related to the size of the DoF and may instead be due to differences in either innervational or anatomical factors between individuals.

Inter-subject variations affecting the anatomy close to the ciliary body could result in differences in the physical limit of the maximum size of the accommodation microfluctuations. As there is a correlation between eye size and refractive error (Atchison et al., 2004; Strang, Schmid, & Carney, 1998), there may be a relationship between the anatomy near the ciliary body and refractive error and therefore it may be expected that the maximum magnitude of microfluctuations should be related to refractive error, but this did not occur. Eye shape has been found to vary between individuals and within MYOs (Atchison et al., 2004; Singh, Logan, & Gilmartin, 2006) and investigations into the biometrics have not found any convincing refractive group trends (Bullimore, Gilmartin, & Royston, 1992; Carney, Mainstone, & Henderson, 1997; Garner & Yap, 1997; Grosvenor & Scott, 1991; Saw et al., 2005; Sorsby, Benjamin, Sheridan, Stone, & Leary, 1961), but have reported differences between individuals.

Alternatively, the inter-subject differences could be attributed to variations in neural innervational accommodation control between subjects. Between subject differences have previously been found in the sympathetic (Gilmartin, Mallen, & Wolffsohn, 2002; Mallen, Gilmartin, & Wolffsohn, 2005) and parasympathetic (Davies, Wolffsohn, & Gilmartin, 2005) innervation control of accommodation. During the experiments, the accommodation system may increase the magnitude of the microfluctuations until it recognises that no additional feedback information is being gained, and some subjects may have a larger neural threshold than others. Another possibility is that there may be a variation in the extent to which subjects use the DoF information during accommodation control. There are other cues to the accommodation system, such as aberrations, proximity and cognition, that some subjects could use instead, or to varying degrees. Individual variations in the ocular aberrations have been reported (Artal, Benito, & Tabernero, 2006; Cheng et al., 2004) and the direction of the change in astigmatism and coma with accommodation is variable between subjects (Cheng et al., 2004). The sensitivity to chromatic aberration is described as 'widespread' (Kruger, Mathews, Aggarwala, & Sanchez, 1993), the ability for subjects to accommodate with elimination of chromatic aberration being evident in 60% of subjects (Fincham, 1951).

The inter-subject variability in the utilisation of cues to the accommodation system could account for the individual differences reported in accommodation lags (Plainis, Ginis, & Pallikaris, 2005) and dynamic steps (Kasthurirangan, Vilupuru, & Glasser, 2003) as well as accommodation responses, errors and microfluctuations at all levels of accommodative reading demand between subjects (Harb, Thorn, & Troilo, 2006). Further, the individual differences could account for the discrepancies found between studies investigating the accommodation response of different refractive groups. Under experimental conditions, where not all cues are available to the accommodation system, myopes have reduced accommodation accuracy through negative lenses but not when positive lenses or real targets are used (Abbott, Schmid, & Strang, 1998; Gwiazda, Thorn, Bauer, & Held, 1993). Some studies find less accurate responses in MYOs (McBrien & Millodot, 1986), while others do not (Abbott et al., 1998; Nakatsuka, Hasebe, Nonaka, & Ohtsuki, 2003; Ramsdale, 1985), and some report differences when sub-categorising myopic subjects according to myopia progression but not age of onset (Abbott et al., 1998). If subjects only have access to a portion of the usual cues available to the accommodation system during everyday viewing, and inter-subject variability exists as to which cues are used, this could cause some subjects to be less accurate than others under certain experimental conditions.

5. Conclusions

The increase in the magnitude of the microfluctuations while viewing a low luminance target (0.002 cd/m^2) may be due to a shallower contrast gradient in the cortical image, with a consequent increase in DoF. The microfluctuations also increase when viewing through small pupils (<2 mm), which increases the DoF without altering the contrast gradient. The larger microfluctuations found in the MYOs consolidates the theory that MYOs have a larger DoF than EMMs and therefore have a higher threshold for retinal image blur.

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