

Small foveal targets for studies of accommodation and the Stiles–Crawford effect [☆]

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Abstract

The properties of small monochromatic targets as accommodative stimuli are not well understood. We used a dynamic optometer to record accommodation responses to monochromatic disc targets (1.0–27.3 min arc) and to a Maltese cross. Accommodation responded adequately to points as small as 13.6 min arc. The response to these small targets is relevant to the question of whether the Stiles–Crawford (SC) effect could provide a stimulus to accommodation. Previous studies have used pupil apodizing filters to neutralise the natural SC function and so determine how visual performance or accommodation is influenced by the SC effect. However, these filters cannot correct for known inhomogeneities in the SC function across the retina for extended targets. Therefore, we calculated the SC function inhomogeneities across the retinal image of a smaller 13.6-min arc target. Unfortunately, even this small target is too large to permit a homogenous SC function across its extent. Alternatives to the apodizing filter approach are discussed. © 2004 Elsevier Ltd. All rights reserved.

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1. Introduction

The adequacy of small monochromatic targets as stimuli to accommodation is important to our current line of research that investigates whether the Stiles–Crawford effect (of the first kind) can provide a signed stimulus to accommodation. However the properties of small monochromatic targets as accommodative stimuli are not well understood. In addition, studies of the effect of target size on accommodation with polychro-

matic targets have yielded conflicting results. For example, while accommodation becomes poorer as disc diameter increases beyond 30 min arc, the reported rate of this loss with eccentricity differs widely (see Ciuffreda, 1991). Studies with small polychromatic disc targets (4.3 s arc–90 min arc) differ in their conclusions as to the target sizes that provide an adequate accommodative stimulus (Campbell, 1954; Fincham, 1951, 1953; Miller, 1980; Owens & Leibowitz, 1975). In the present study, the response under monochromatic illumination is of interest and only two studies have used this illumination. Fincham (1951) observed qualitatively that participants required a spot size of at least 8 min arc to respond robustly to the interposition of a -0.75 D lens in monochromatic sodium light. In a later study, the minimum target size required for a robust response to the interposition of a -1 D lens in sodium light (15.4 cdm^{-2}) was on average 6.6 min arc for normal trichromatic

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participants (Fincham, 1953). These two studies were limited to some extent by the subjective nature of the accommodation measurements.

An ongoing issue in both accommodation and emmetropization research is whether the defocused retinal image indicates the sign of defocus. While there is evidence for a non-directional stimulus based on defocus blur (Phillips & Stark, 1977; Stark & Takahashi, 1965), other directional stimuli to accommodation such as longitudinal chromatic aberration (LCA; for reviews see Kruger, Mathews, Aggarwala, & Sanchez, 1993; Lee, Stark, Cohen, & Kruger, 1999) and a so-called ‘achromatic stimulus’ (Kruger, Mathews, Katz, Aggarwala, & Nowbotsing, 1997) have been documented. The nature of this ‘achromatic stimulus’ is not yet known, but some possibilities include the monochromatic aberrations of the eye (Campbell, Priest, & Hunter, 2001; Chen, Kruger, & Williams, 2002; Fernandez & Artal, 2002; Wilson, Decker, & Roorda, 2002), ocular astigmatism (Allen, 1955; Campbell & Westheimer, 1959; Walsh & Charman, 1988) and the Stiles–Crawford effect (Fincham, 1951; Kruger, López-Gil, & Stark, 2001; Kruger et al., 1997; Kruger, Stark, & Hu, 2000).

Fincham (1951) proposed a model by which the accommodation system might extract a directional signal from the Stiles–Crawford effect of the first kind (Stiles & Crawford, 1933). However, his model assumes that cone photoreceptors point approximately towards the centre of the globe, while more recent evidence shows that they align approximately to a point off-centre within the entrance pupil (Applegate & Lakshminarayanan, 1993; Dunnewold, 1964; Enoch, 1957; Enoch & Hope, 1972a, 1972b; Enoch & Lakshminarayanan, 1991; Gorrard & Delori, 1995; Laties & Enoch, 1971; Stiles & Crawford, 1933; Westheimer, 1968). Instead, Kruger et al. (2001) hypothesised a more realistic model which uses a decentred SC function to extract a signed input to accommodation. The principles of this method for an on-axis optical system free of aberrations and with all the cone receptors tilted toward the nasal side of the pupil (N, dashed lines) are illustrated schematically in Fig. 1 (after Kruger et al., 2001). Although the defocused spread-functions on the retina are symmetrical (Fig. 1b), after weighting for the nasal decentration of the SC peak, the *effective* blur spread-function is skewed nasally in hyperopic defocus and temporally in myopic defocus (Fig. 1c), and thus might identify the sign of defocus.

One way to test whether the Stiles–Crawford function provides an input to accommodation is to alter the function with a static apodizing filter (Rynders, Thibos, Bradley, & López-Gil, 1997; Scott, Atchison, & Pejski, 2001); as was done for the first time by Kruger et al. (2001). A neutralising apodizing filter alters the transmittance of light at each point in the pupil to provide a uniform SC function (Scott et al., 2001). However, a

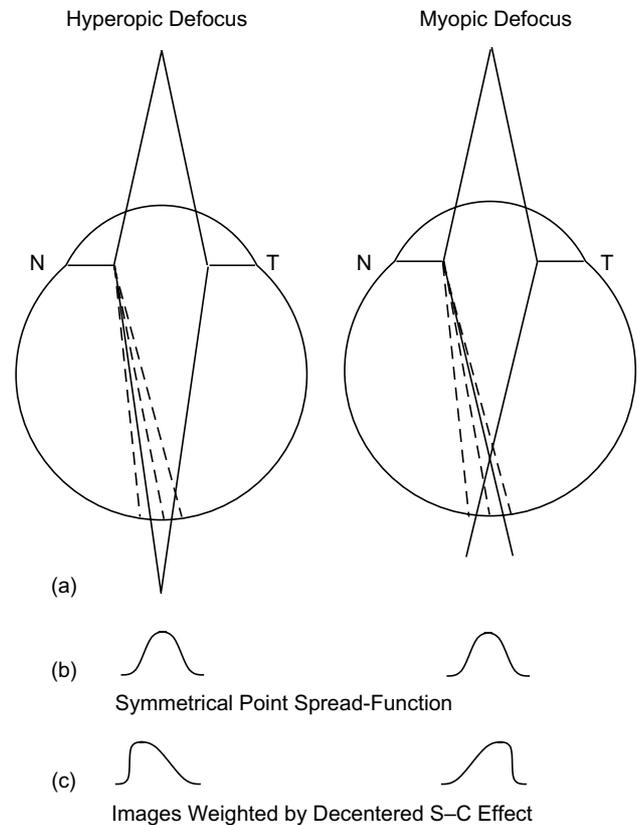


Fig. 1. Method for distinguishing the sign of defocus using a decentred SC effect (after Kruger et al., 2001). See Section 1 for a description of this figure.

single apodizing filter cannot neutralise the SC effect simultaneously at all points across the retinal image because the SC effect is not homogeneous across the retina. For example, directionality (ρ) is reduced at the very centre of the fovea and increases parafoveally (Enoch & Hope, 1973; Westheimer, 1967), reaching an asymptote at 2° with no significant changes out to 10° in the parafovea (Enoch & Hope, 1973). In addition, there are local variations in the position of the SC function peak in a 1° diameter annular region around the foveal centre in some individuals (Williams, 1980). In this region the SC function peak for cones on the nasal and temporal sides of the foveal pit tends towards the nasal and temporal sides of the pupil respectively, and the peak for cones above and below the central fovea tends towards the superior and inferior parts of the pupil respectively. In some myopic eyes there is a progressive increase in the nasal decentration of the SC function peak as measurements are made closer to the optic nerve head (Choi & Garner, 2000; Westheimer, 1968). Finally, there is local disarray in the pointing directions of individual cones over small retinal areas (Roorda & Williams, 2002).

In a previous study (Kruger et al., 2001), we used a sine-wave grating target 11.5° in diameter, and so there

may be concerns that a static apodizing filter could not neutralise known inhomogeneities in the SC function over such an extended area of the central retina. An alternative might be to substitute a point target with a diameter so small that the SC function is effectively homogenous over its extent. Accommodation to this small target would then be measured with either an intact or a neutralised SC function. However, as noted previously, the properties of small monochromatic points as accommodative stimuli are not known. Furthermore, it is not known whether the SC function would indeed be homogenous over the blur-spread functions of these small targets.

Accordingly, two experiments were performed. The aim of the first experiment was to determine the efficacy of small monochromatic point targets as stimuli to accommodation. Objectively measured dynamic accommodation responses to a large standard monochromatic target (a Maltese cross, 6.3° in diameter) were compared with those for centrally fixated monochromatic spot targets of 1.0–27.3 min arc diameter. The eye's SC function was left intact and unaltered. With a pupil size of 3 mm and a retinal illuminance of 141 trolands, accommodation responses were robust to targets as small as 13.6 min arc.

The aims of the second experiment were to estimate the sizes of the retinal blur-spread functions for small point targets, and to estimate the degree of SC function inhomogeneity over such blur-spread functions. It was found that spots sufficiently large to stimulate accommodation adequately have blur-spread functions that are typically too large to allow adequate neutralisation of the SC function with a static apodizing filter.

2. Methods

2.1. Accommodation experiment

2.1.1. Participants

Forty-four individuals volunteered for the study, and 14 were excluded for various reasons. Two participants were excluded for reduced visual acuity, four due to a history of strabismus, one due to amplitudes of accommodation below Duane's (1922) clinical norms in both eyes, and two participants due to over-accommodation in the Badal optical system, one of whom had a history of symptomatic near-work induced transient myopia. One participant was unable to perform the calibration procedure with the stigmatoscope (see Section 2.1.4), one participant was unable to sit comfortably in the apparatus, and three participants withdrew from the study.

The 30 remaining participants took part in preliminary trials to determine whether they could accommodate effectively in monochromatic light (Section 2.1.4).

Some individuals accommodate very poorly in the absence of LCA, and accommodative gain varies widely among individuals (Kruger et al., 1993). Since the aim of the present line of investigation is to understand how the eye responds to light vergence in monochromatic light—and thus in the absence of the chromatic mechanism of accommodation (Kruger, Mathews, Aggarwala, Yager, & Kruger, 1995; Lee et al., 1999)—participants were recruited who appeared to respond well in monochromatic light. Participants were included if, on visual examination of chart recorder traces by the examiner during the preliminary trials (Section 2.1.4), their response in monochromatic light was easily distinguishable from the normal low-frequency fluctuations of accommodation, and if the response to monochromatic targets was present in most of the preliminary trials. Seven participants were found to respond well in monochromatic light according to these criteria with gains ranging between 0.25 and 0.72, corresponding to percentage ranks within the larger group ($n = 30$) in the range 51.7%–100%. Thus, the seven participants were in the upper half of this population with respect to dynamic accommodation in monochromatic light. They were 21–24 years of age. Six were optometry students and one was a member of the public. All were visually normal with no history of amblyopia, strabismus, ocular trauma or disease, cataract, ocular surgery, or head, neck, or back injury. Six participants had no history of binocular vision complaints or vision therapy, and one participant had vision therapy for slight asthenopic complaints one year prior to testing. Visual acuities were normal (logMAR: OD, -0.10 to $+0.04$; OS, -0.10 to $+0.04$), amplitudes of accommodation were within Duane's (1922) clinical norms, and colour vision was normal in both eyes by Nagel Anomaloscope. Dark focus of accommodation varied in the range 0.2–2.9 D (except that dark focus data for two participants were lost). Participants were in good health and were not taking any medication that might have side effects on accommodation. Participants gave informed consent to participation in the study, which was approved by the Institutional Review Board of the College and followed the tenets of the Declaration of Helsinki.

2.1.2. Apparatus

An infrared optometer was used to monitor accommodation continuously along the vertical meridian of the eye (100 Hz, Kruger, 1979) while the participant viewed targets in a Badal stimulus system (Kruger et al., 1993). This stimulus system was modified for the present experiment to allow a non-Maxwellian view of the target. Unlike Maxwellian view, where irregularities in the filament of the light source are imaged in the pupil plane, the present method ensures a uniformly illuminated pupil (Westheimer, 1966). This design feature is essential if, as we hypothesise, the Stiles–Crawford effect

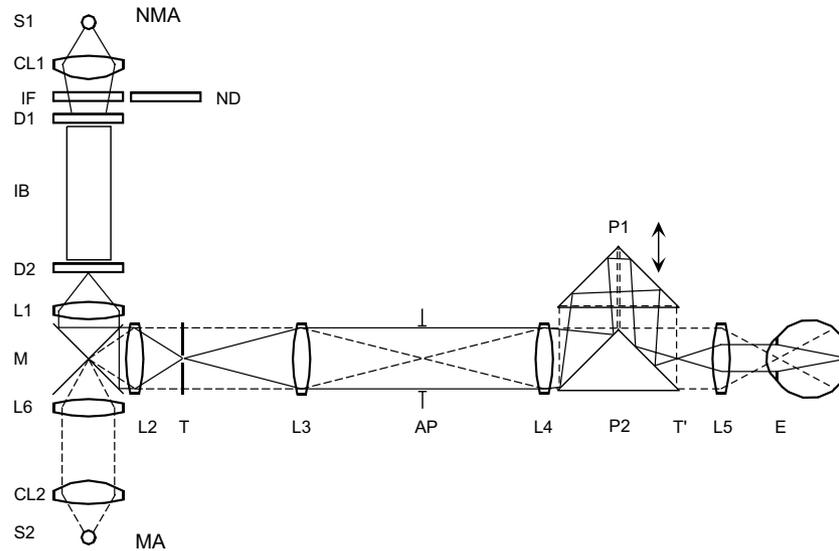


Fig. 2. Badal stimulus system. Key: AP, artificial pupil; CL1, CL2, condensing lenses; D1, D2, opal diffusers; E, eye; IB, integrating bar (Coren, 1970); IF, interference filter (548 nm with 12 nm bandwidth at half-height) mounted in filter wheel; L1–L6, achromatic lenses; M, front-surface mirror; MA, Maxwellian view arm; ND, neutral density filter mounted in filter wheel; NMA, non-Maxwellian view arm; P1, P2, right angle prisms with mirror coating on surfaces other than hypotenuses; S1, S2, tungsten–halogen sources; T, target; T', real image of target. See Section 2.1.2 for further descriptions.

provides a stimulus to accommodation. The primary components of the stimulus system are illustrated in Fig. 2.

Mirror M is placed to use either the Maxwellian (MA) or the non-Maxwellian arm (NMA) of the optical system. In the Maxwellian arm, light from a tungsten–halogen source (S2) was collimated by lens CL2 and brought to a focus at the artificial pupil plane (AP) by lenses L6, L2 and L3. Lenses L4 and L5 and prisms P1 and P2 then imaged the artificial pupil at the natural pupil plane of the eye (E), thus providing a Maxwellian view of source S2 (Westheimer, 1966).

In the non-Maxwellian arm, light from a tungsten–halogen source (S1) was focused by a condensing lens (CL1) and then filtered by either an interference filter (IF) or a neutral density filter (ND) to illuminate an opal diffuser (D1) with pseudo-monochromatic light (548 nm with 12 nm bandwidth at half-height) or white light (2674 K) respectively (Spectrascan PR-704, Photo Research, Chatsworth, California). An integrating bar (IB, Coren, 1970) provided uniform illumination of a second opal diffuser (D2) and an image of this diffuser was formed by lenses L1 and L2 in the plane of the target (T, see also Section 2.1.3).

In both Maxwellian and non-Maxwellian views, light from the target (T) was collimated by lens L3 and focused by lens L4 at the point T' after reflection by the mirrored surfaces of two prisms (P1 and P2). Target image T' was formed close to the focal plane of the Badal lens (L5). Motion of prism P1 (as shown by the arrow) moved the target image T' toward and away from the Badal lens (L5) to alter the vergence of the tar-

get at the eye. The limiting field stop of the optometer (not shown) subtended 6.3° at the eye and was blurred by defocus $+5.2$ D beyond the far point of the eye. An artificial pupil (AP) was imaged close to the entrance pupil of the participant's eye (E) as a 3-mm artificial pupil. To prevent unwanted reflections from the surfaces of the targets (T, Section 2.1.3) that might have been visible to the participant, black cardboard shielding (not shown) was positioned around the optical components, and experimental trials were conducted in a laboratory with a black interior and only minimal essential lighting.

2.1.3. Stimuli

In the preliminary trials, the target was a high-contrast photographic transparency of a Maltese cross on a black background. The target subtended 6.3° at the eye, the central points of each limb subtended approximately 1 min arc at the eye, and each limb of the cross formed an angle of 10° at the centre of the cross. Retinal illuminance was approximately 173 trolands in white light (2674 K) and 141 trolands in pseudomonochromatic green light (548 nm with 12 nm bandwidth at half-height). The Maltese cross was chosen as a standard target because it contains broad spatial frequency content (Mathews & Kruger, 1994), has detail at various orientations, covers a large area of the central field (Ciuffreda, 1991), and provides a good cue to central fixation.

In the main trials there were seven targets including the Maltese cross and six precision pinhole targets in aluminium plate (Melles Griot, Irvine, California) with nominal angular dimensions at the eye of 1.02, 1.70,

3.42, 6.82, 13.6 and 27.3 minarc. Actual angular dimension varied with spectacle magnification (in the range +0.71 to +1.02, mean +0.93) due to trial lenses in place that corrected individual refractive errors (Section 2.1.4). The precision pinholes were checked regularly for unwanted dust or lint particles across the aperture.

2.1.4. Procedures

A preliminary session was used to gather a case history, test colour vision, and measure visual acuity, subjective refraction and accommodative amplitude. The participant was positioned in front of the instrument on a chin and forehead rest while eye position was monitored continuously by one of the investigators with an infra-red camera and video display. Trial lenses were placed in front of the left eye to correct the refractive error of the eye and the right eye was patched. Two of the seven participants wore habitual contact lens corrections during the trials with a contact lens over-refraction in the trial lens holder of the Badal optical system. A staircase psychometric procedure was then used along the horizontal meridian to align the visual achromatic axis (Thibos, Bradley, Still, Zhang, & Howarth, 1990) of the tested eye on the optical axis of the Badal stimulus system (Lee et al., 1999) using the Maxwellian arm of the optical system (Fig. 2). To calibrate the infrared optometer (Kruger, 1979), the participant viewed a Maltese cross target in white light in non-Maxwellian view at several accommodative stimulus levels while simultaneous measurements of optometer output and subjective focus (using bichromatic stigmatoscopy) were made (Lee et al., 1999).

In a preliminary session, the participant viewed a Maltese cross in non-Maxwellian view. The Maltese cross moved sinusoidally between 1 and 3 D at a temporal frequency of 0.195 Hz, and it was viewed in white light with normal LCA intact or in monochromatic light (548 nm with 12 nm bandwidth) to eliminate LCA. We have recently demonstrated that under these stimulus conditions, the response is uncorrelated with voluntary accommodation ability (Stark & Kruger, 2002). Each trial lasted 40.96 s, and there were three trials of each condition presented in random order.

For the main experimental trials, the targets were six monochromatic spot targets and a Maltese cross (Section 2.1.3) presented in non-Maxwellian view. The targets moved sinusoidally between 1 and 3 D at 0.195 Hz during trials lasting 40.96 s, and there were six trials of each condition presented in random order. (Two participants were only available for four trials of each condition, and another participant was only available for two trials of each condition.) The targets were viewed through a 3-mm artificial pupil imaged in the natural pupil plane. Participants were instructed to concentrate their attention at the centre of the target and to keep the target clear (Stark & Atchison, 1994). Participants were

also told that in some cases the target would be small and difficult to see. They were instructed to continue to search actively for the target if it could not be seen. Participants were kept unaware of the experimental conditions. After the final trial, the participant remained in the dark for 3 min to allow accommodative adaptation effects to subside (Rosenfield, Ciuffreda, Hung, & Gilmartin, 1994) and a 30-s recording was made to determine the participant's dark focus.

2.1.5. Analysis

Eye-blinks were edited from the data prior to analysis using standard techniques previously described (Lee et al., 1999). Records with greater than 14.65% interpolated values due to eye-blinks and other causes were not used in the analysis. (This threshold value was obtained by pooling accommodation data from 37 individuals in 1553 trials that were part of three separate accommodation studies conducted in our laboratory over the summer period of 1999. A histogram of percentage-spurious values was formed, and the threshold value was taken as the 95th percentile of the frequency distribution.)

Standard signal processing procedures were used to obtain estimates of gain and phase by fast Fourier transform (Lee et al., 1999). Gain is the amplitude of the response divided by the stimulus amplitude, and phase lag is the distance in degrees from the peak of the stimulus to the peak of the response. The geometrical test (Stark, 2000) was used to make pair-wise comparisons between the responses to the Maltese cross and each spot target. This test is a non-parametric alternative to multivariate analysis of variance, based on randomization theory (Edgington, 1995). A random enumeration procedure was used to calculate the test statistic ($n = 50,000$, Manly, 1991). Dependent variables were (1) accommodation gain and phase expressed in bivariate Cartesian coordinates, (2) scalar gain, and (3) accommodation phase converted to Cartesian coordinates by projection of each accommodation response vector to the unit circle (Batschelet, 1981).

2.2. Stiles–Crawford function inhomogeneities experiment

In the first experiment, targets were specified by their angular dimensions in object space. However, the defocused retinal images of these targets will cover a larger retinal area due to factors such as spherical defocus, diffraction and ocular aberrations. In addition, natural miniature eye movements (that is, tremor, drift and microsaccades) will move the retinal image about on the fovea (Carpenter, 1988), further increasing the potential for SC function inhomogeneity over the extent of the defocused retinal image.

Taking a geometrical–optical approach, the defocused point spread-function may be approximated by

a circular disc (Smith, 1982). To estimate the blur circle diameter as a function of defocus and pupil size, we fit the psychophysical data of Chan, Smith, and Jacobs (1985) with the form $\omega = a + bD + cDE$, where ω is the blur circle diameter (mrad), D is the pupil diameter (m), E is the unsigned magnitude of defocus (D), and where $a = -0.7$ mrad, $b = 800$ mrad m^{-1} , and $c = 860$ mrad ($r^2 = 0.999$). Chan et al.'s (1985) data include the effects of monochromatic aberrations and diffraction, but were collected in white light and so, if anything, may over-estimate the monochromatic blur circle diameters of the present study.

Data from the previous experiment were analysed to obtain estimates of typical levels of accommodative error (defocus) for monochromatic spot targets. Histograms of instantaneous accommodative error were calculated for each trial. For each participant and spot diameter separately, histograms from individual trials were pooled and the 2.5th and 97.5th percentiles of accommodative error were calculated. Then for the group, the average 2.5th and 97.5th percentiles were calculated and these were taken as measures of the typical extent of accommodative error.

The variation in the point of fixation due to miniature eye movements has been described by a bivariate normal distribution. Typical values for the pooled standard deviation (σ) of such a distribution for stabilized head position vary in the range 1.5–4 min arc (Carpenter, 1988). If normality can be assumed, then 95% of the time the fixation point will lie within a diameter of $2 \times 1.96\sigma$, or about 5.9–15.7 min arc. This simple descriptive statistical approach seemed adequate for the present study.

The angular extent of the retina over which SC function inhomogeneities must then be considered is given by the sum of the object diameter, the blur circle diameter, and the diameter of miniature eye movements. Expected changes in the SC function over such retinal extents were then calculated based on published data from several studies. We included the pattern of reduced foveal directionality described by Enoch and Hope (1973), the annular inhomogeneity reported by Williams (1980), and the levels of local cone photoreceptor disarray described by Roorda and Williams (2002).

3. Results

3.1. Accommodation experiment

Accommodation responses to monochromatic spot targets as small as 13.6 min arc were not significantly different from those for the Maltese cross target (Figs. 3–5, Table 1). The responses to spot targets of 6.8 min arc diameter and smaller were significantly poorer than to the cross target (Table 1). Nevertheless, the response

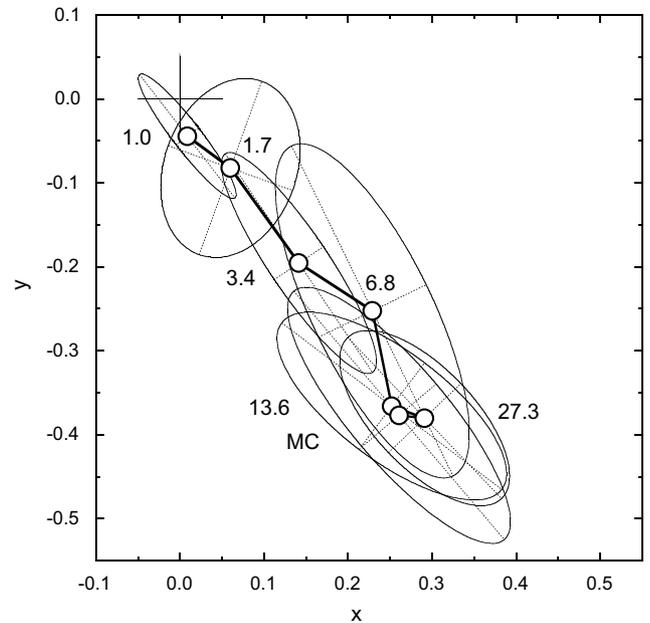


Fig. 3. Gain and phase of accommodation response plotted in Cartesian coordinates (x, y) . Gain is the distance of a point from the origin. Phase is the angle subtended by a point at the origin, using standard trigonometric conventions. Points are labelled by the target spot size (min arc), or by MC for the Maltese cross. A 'perfect response' would have the coordinates (1,0). All group mean data points exhibit a phase lag in the response. Ellipses indicate the bivariate variability in the accommodation data and denote one population standard deviation along the eigenvectors of the sample distributions, assuming bivariate normal distributions (Sokal & Rohlf, 1981).

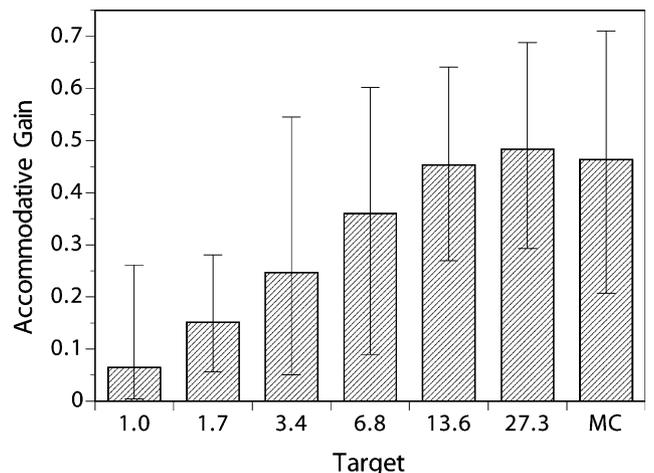


Fig. 4. Mean scalar accommodative gain as a function of target spot size (min arc) and for the Maltese cross (MC). Error bars represent inter-participant variability and denote the range of values obtained ($n = 7$).

to the 6.8-min arc spot target still appears quite robust (Fig. 3) and is significantly better than the response to the smallest spot size of 1.0 min arc (geometrical test, $p = 0.016$). Thus, it appears that targets as small as 6.8 min arc might prove useful as accommodative stimuli.

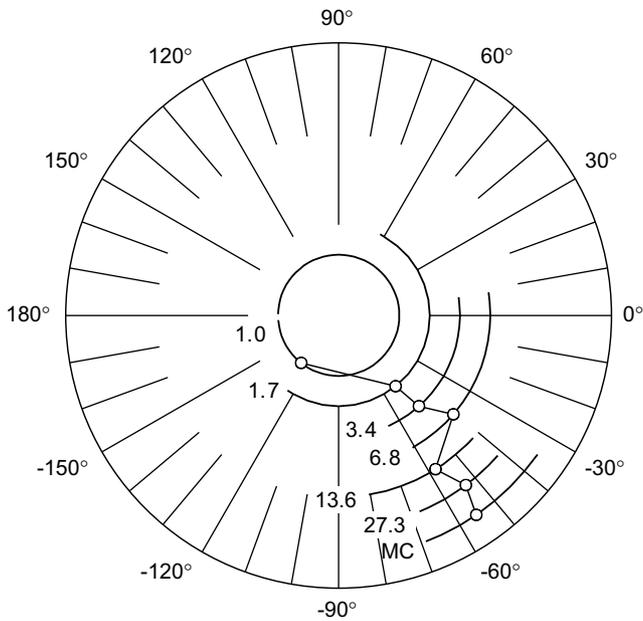


Fig. 5. Vector-averaged phase angle of the accommodation response. Points are labelled by the target spot size (minutes arc), or by MC for the Maltese cross. Arc-shaped error bars represent inter-participant variability and denote the range of polar values obtained ($n = 7$). Distances of points along the radius are arbitrary and have no numerical significance.

Table 1
Probability values for pair-wise comparisons of spot target responses with Maltese cross target responses for given dependent variables

Spot target (min arc)	Gain and phase (bivariate)	Scalar gain	Phase
1.02	0.015*	0.016*	0.047*
1.70	0.015*	0.031*	0.344
3.42	0.031*	0.032*	0.891
6.82	0.031*	0.078	0.077
13.6	0.906	0.797	0.830
27.3	0.828	0.816	0.496

Probability values are for a non-directional alternate hypothesis and were calculated using the geometrical test (Stark, 2000). Values significant at the 5% level are shown with an asterisk.

Table 2
Change in SC function parameters across given retinal extents due to known patterns of SC function inhomogeneity

Inhomogeneity	Physical target diameter (minute arc)			
	6.8		13.6	
	$\Delta\rho$ (mm^{-2})	Δx_{max} (mm)	$\Delta\rho$ (mm^{-2})	Δx_{max} (mm)
Reduced foveal directionality ^a	0.0057	–	0.0065	–
Local receptor disarray ^b	–	0.17	–	0.17
Annular location pattern ^c	–	0.63	–	0.71

A 3-mm pupil is assumed. Values are based on a maximum diameter of the blur-spread function coverage of 44.4 min arc for the 6.8-min arc spot target, and 50.6 min arc for the 13.6-minute arc target (see Section 3.2). The SC function is expressed as $\eta = \eta_{\text{max}} 10^a$, where $a = -\rho(x - x_{\text{max}})^2$, η_{max} is normalised to 1.0, ρ is the directionality constant (mm^{-2}), x is the position in the pupil (mm), and x_{max} is the location of the peak of the SC function.

^a Based on a rate of change of directionality of 0.0154 mm^{-2} per degree eccentricity (that is, radius) within 2° of the fovea ($n = 3$, Enoch & Hope, 1973).

^b Based on an extrapolation of an asymptotic curve ($n = 2$; Fig. 4 of Roorda & Williams, 2002).

^c Based on a rate of change in peak location of 0.0141 mm per min arc of diameter within a 54 min arc diameter centred on the fovea ($n = 3$, Williams, 1980). One of Williams' four participants did not show this effect.

Scalar gains for spot targets of 13.6 and 27.3 min arc were similar to those for the Maltese cross target, but for smaller targets there was a general decline in accommodative gain with decreasing spot size (Fig. 4). The average phase lag of the accommodation response varied little down to 1.7 min arc (Fig. 5), and only the phase lag for the 1.0-min arc target was significantly different from that for the Maltese cross target (Table 1). Inter-individual variability in phase lag became marked for targets of 1.7 min arc and smaller (Fig. 5). The large range in phase lags for the 1.0 min arc target (Fig. 5), combined with low gain values (Fig. 4), suggests that the response at this stage had fallen below the background noise of low-frequency accommodative micro-fluctuations (Charman & Heron, 1988).

3.2. Stiles–Crawford function inhomogeneities experiment

For the 13.6-min arc spot target, 95% of accommodative errors were (on average) in the range -1.18 through $+1.75 \text{ D}$. It was estimated, for a 3-mm pupil, that the defocused retinal image of this target would make excursions over an area of up to 40.8–50.6 min of arc in diameter, depending on the extent of miniature eye movements (Section 2.2). For the 6.8-min arc spot target, 95% of accommodative errors were (on average) in the range -1.31 through $+1.82 \text{ D}$. It was estimated, again for a 3-mm pupil, that the defocused retinal image of this target would make excursions over an area of up to 34.6–44.4 min of arc in diameter.

Taking the estimated retinal extents just cited, we then calculated the expected changes in the SC function for all known and quantitatively documented SC function inhomogeneities (Table 2). The pattern of reduced foveal directionality (Enoch & Hope, 1973) has only small effects on directionality: the errors are only about 11%–13% of the normal foveal ρ value (Applegate & Lakshminarayanan, 1993). Similarly, local disarray in photoreceptor alignment (Roorda & Williams,

2002) is quite small. However, the SC function inhomogeneity described by Williams (1980) appears to be particularly problematic in that large changes in the peak location of the SC function are observed over typically encountered retinal extents of the blur-spread functions.

4. Discussion

For the present target retinal illuminance of 141 trolands and a pupil size of 3 mm, a spot target of at least 13.6 minarc diameter appears to provide an adequate stimulus to accommodation (Table 1, Figs. 3–5). However, SC function inhomogeneities over the extent of the defocused retinal image of this spot target are too large to allow neutralisation of the SC function with a static apodizing filter. In particular, it is the pattern of inhomogeneity described by Williams (1980) that is most problematic. This inhomogeneity, when present, leads to large (≈ 0.8 mm) and rapid changes (≈ 0.8 mm deg⁻¹) in the SC peak location within the central 2° field. As static apodizing filters are inadequate to study the potential stimulus to accommodation provided by the SC function, then alternatives must be sought.

4.1. Methods to investigate the potential SC stimulus

An alternative to neutralising the SC function is to use an apodizing filter to move the peak of the function to the opposite side of the pupil (Kruger et al., 2001). Provided this shift is large, such a ‘reversing’ filter should be disruptive to the accommodative system if the SC function provides a stimulus to accommodation as hypothesised.

A technically challenging approach would be to construct a dynamic apodizing filter. For example, it might be possible to use a small display in the beam path which is then imaged in the eye pupil as an apodizing filter. The transmittance function of this display would be altered in real time to compensate for the location within the visual field of the currently displayed pixel of the target display, and to compensate in real time for changes in eye fixation. The controlling algorithm would need a reasonable model of the way in which the SC function changes systematically over the central field for each participant tested.

Another method that is appropriate when the fixation target does not contain significant high spatial frequency detail (Ward & Charman, 1987) is to use optical modelling software and a schematic eye model to simulate the retinal image in the presence of defocus and the SC function. The simulated retinal image is then presented on a bright display, and viewed through a small pupil (0.5 mm) to open the accommodative system control loop

(Ward & Charman, 1987). This method has been used before and is not challenging (for example, Lee et al., 1999). Because the artificial pupil is so small, the natural SC function of the eye and any inhomogeneities in that function will have only negligible effects on the appearance of the simulated retinal image. In this respect, typical miniature eye movements would not invalidate the experimental paradigm. However, it is also necessary to assume that miniature eye movements are not involved directly in the cue extraction process. Fincham (1951) provided some evidence that voluntary suppression of the miniature eye movements prevented ‘reflexive’ accommodation responses. Whether this suggests a role for these eye movements in cue extraction, or whether the movements are necessary to prevent perceptual fading (Kotulak & Schor, 1986) is not known. Until this issue is resolved, the conclusions drawn from a small-pupil paradigm must be qualified. If no accommodation responses were found to the simulations then this could mean that (1) the SC function does not provide a stimulus to accommodation, or (2) miniature eye movements may be necessary for extraction of a SC function cue. If responses were found to the simulations then this would indicate that miniature eye movements are not necessary for extraction of the SC function cue, although further experimentation would be required to determine if they could aid the response.

It may be noted in passing that the use of electro-mechanical means to open the accommodative system loop (Kruger et al., 1995) would be inappropriate for presentation of simulated retinal images in the present case. This is because with a natural pupil, the SC function of the eye (and the inhomogeneities in the function) would interfere with the intensity distribution in the simulation display.

4.2. Other sources of variability in the SC function

An important consideration for studies of the SC function and accommodation is whether the SC effect is altered by changes in accommodation that occur during an accommodation experiment. Large amounts of accommodation (for example, 9 D) can produce significant nasal shifts (for example, 1 mm) in the location of the SC function peak (Blank & Enoch, 1973; Blank, Provine, & Enoch, 1975; Enoch, 1975; Provine & Enoch, 1975), but the nasal decentration that results from accommodation is small for accommodative responses with moderate amplitudes like those in the present experiment. In an experiment similar to the present study, Kruger et al. (2001) estimated the nasal shift to be 0.07 mm as a result of a sinusoidal accommodative response with an amplitude of 0.8 D. Thus for accommodation experiments that require moderate changes in accommodation, the effects of accommodation on the SC function itself are not critical.

In the present study we have considered a local averaged Stiles–Crawford effect over patches of the retina. However, individual photoreceptors over a small retinal area do not all point to the same position in the entrance pupil (Coble & Rushton, 1971; Enoch, 1967; Heath & Walraven, 1970; MacLeod, 1974; Makous, 1968; O'Brien & Miller, 1953; Ohzu & Enoch, 1972; Roorda & Williams, 2002). This places a limit on the hypotheses that may be tested with apodizing pupils or simulations of point spread functions, because it would be virtually impossible to construct a system to correct for the waveguide properties of individual cones in real-time. Nevertheless, the degree of receptor disarray is quite small. For example, Roorda and Williams (2002) found that the average distance in the entrance pupil between the pointing directions of cones separated by 20 arcmin on the retina was just 0.17 mm. The hypothesis to be tested with apodizing filters or point spread function simulations then is that the SC function averaged over small retinal areas (in the order of 6–13 minarc) may be used to provide a stimulus to accommodation.

4.3. Interactions with monochromatic aberrations

One possible limitation to the use of the Stiles–Crawford effect as a signal to accommodation is that typical ocular aberrations (Porter, Guirao, Cox, & Williams, 2001), such as coma, can also produce skewness in the retinal image, masking to some extent the potential signal provided by the SC function (Fig. 1). It would thus be of interest to determine from a theoretical viewpoint how skewing of the defocused point spread function depends on the interactions between typical ocular aberrations and the SC function. Our recent simulation study indicates that the aberrations of the eye do interact with the SC function in producing skewing of the blur-spread function (Stark, Kruger, & Atchison, 2002). Furthermore, because the aberrations themselves may provide signed cues to accommodation (Wilson et al., 2002), any experimental investigations of the SC function cue would need to separate the effects of the SC function and the monochromatic aberrations.

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