



Lens induced aniso-accommodation

Lynn Marran, Clifton M. Schor *

Vision Science Group and School of Optometry, University of California, Berkeley, CA 94720, USA

Received 19 August 1996; received in revised form 25 March 1997; accepted 30 January 1998

Abstract

Despite the evidence for consensual accommodation in response to consensual accommodative stimuli, only a few studies have investigated the binocular accommodative response to unequal (aniso) accommodative stimuli. Past studies investigating an unequal binocular accommodative response (aniso-accommodation) to aniso-accommodative stimuli have been limited by viewing conditions and measurement technique making the results, which were equivocal, difficult to interpret. This investigation addressed these limitations by the following design parameters: (1) monocular dichoptic blur cues were provided in the binocular stimulus target to provide subjects feedback on their aniso-accommodative response and to alert the investigator of a monocular blur suppression response; (2) a training period was provided; (3) in the subjective method, each eye's stigma was positioned near the dichoptic letter viewed by the other eye. By this method, a true aniso-accommodative response could be differentiated from successive consensual responses; (4) a large range of aniso-accommodative stimuli was used, 0.50–3.0 D, presented in incremental steps of 0.5 D, allowing measurement of an average 0.75 D aniso-accommodative response for the highest (3.0 D) aniso-accommodative stimulus; (5) aniso-accommodation was measured as a function of viewing distance. For four of seven subjects, the gain of the aniso-accommodative response was significantly greater at near than at far viewing distances; (6) aniso-accommodation was confirmed objectively with measures of the response to steady state and step aniso-accommodative stimuli, using a binocular SRI Dual Purkinje Eye Tracker Optometer System. The aniso-accommodative response to step stimuli showed a very long latency period (about 11 s) and a response time of 4.5 s. A potential benefit of aniso-accommodation would be to overcome small amounts of uncorrected anisometropic refractive error. This would preserve fine stereo acuity which is impaired by unequal intraocular image contrast. Aniso-accommodation also may provide an appropriate efferent feedback signal for each eye's unique refractive error which could be used to guide developmental isometropization (attainment of equal refractive error in the two eyes.) © 1998 Elsevier Science Ltd. All rights reserved.

Keywords: Accommodation; Anisometropia; Binocular; Stereopsis; Development

1. Introduction

Binocular accommodation may be described as a yoked consensual response in which both eyes change their accommodative state equally to a change in an accommodative stimulus. This consensuality suggests that the neural input to accommodation is bilaterally symmetrical and several components of accommodative control appear consensual: (1) the small accommodative fluctuations which occur during steady state accommodation are correlated in phase and amplitude between the two eyes [1]; (2) in the absence of an accommodative stimulus, the accommodative resting

states of the two eyes are closely matched [2,3]; (3) the accommodative response amplitude of the covered eye closely matches that of the viewing eye under monocular viewing conditions [4,5]. These results strongly support the existence of a common control center responsible for equal neural innervation of the ciliary apparatus of each eye.

On the other hand, such evidence does not preclude the possibility of coexisting innervation for the independent accommodative control of the two eyes. Such independent control would allow for accurate yet unequal binocular accommodation, when there are unequal or conflicting accommodative stimuli to the two eyes. Unequal accommodative stimuli can arise in uncorrected anisometropia (where the two eyes are unequal in optical power) or when the eyes view a near

* Corresponding author. Tel.: +1 510 5240161; fax: +1 510 6435109; e-mail: lmarran@Spectacle.berkeley.edu.

object located away from the midline (in asymmetrical gaze). In these conditions, unequal binocular accommodation (aniso-accommodation) could be used to preserve fine stereoacuity. Aniso-accommodation might also serve an important developmental role by providing feedback from the accommodative response of each eye to guide refractive error development from neonatal anisometropia to early infancy isometropia (attainment of equal refractive error in the two eyes).

Despite the potential importance of aniso-accommodation, only a few studies have directly investigated the binocular accommodative response to unequal accommodative stimuli. The results have been equivocal with the majority of studies suggesting that aniso-accommodation does not occur. Unfortunately, however, none of these studies utilized optimal viewing conditions or measurement techniques, rendering it difficult to draw firm conclusions with regard to whether the ocular-motor system is capable of making aniso-accommodative responses. Potential confounds exist in previous studies due to a variety of reasons including: (1) asymmetrical viewing conditions which provided insignificant (less than 0.33 D) aniso-accommodative stimuli [6,7]; (2) the potential for participants to make successive monocular accommodative responses [7,8]; (3) the absence of monocular feedback cues [9]; and (4) the use of potentially rivalrous dichoptic patterns [4]. The present study sought to re-address the issue of aniso-accommodation using a paradigm that avoided the confounds outlined above.

2. General methods

2.1. Subjects

Seven subjects (two females and five males; aged between 16 and 22 years) participated in the study according to their availability. Experiments were undertaken with the understanding and written consent of each subject. This investigation was limited to those subjects who demonstrated aniso-accommodation; and subjects who frequently engaged in near work tasks were solicited because pilot work suggested that these subjects were most likely to demonstrate an ability for aniso-accommodation. Subjects were required to demonstrate a total binocular accommodative amplitude of at least 10.0 D; corrected visual acuity of 20/20 and stereo acuity of 20 arc s (Randot™ Stereo Optical, Chicago, IL). Additionally, subjects were required to pass a series of binocular functional tests which included accommodative responses to step stimuli ($\pm 1.5^{\Delta}$) at 0.25 Hz, vergence responses to disparity step stimuli ($\pm 6^{\Delta}$) at 0.50 Hz and normal horizontal vergence amplitudes [10] at viewing distances of 40 cm and 6 m. Approximately four additional subjects met these

criteria but did not demonstrate a robust aniso-accommodative response after several training sessions and therefore did not participate in the experimental sessions.

3. Stigmascope experiments

3.1. Reference condition

Pilot data suggested that despite identical visual conditions, the gain of individual subjects' responses could vary between sessions, particularly if more than a week passed between sessions. Fatigue, motivation, and recent experience with the aniso-accommodation task seemed to influence the response. To minimize the influence of these factors, each Experimental condition was compared to a Reference condition that was run on the same day.

The Reference condition served as a bench mark for the gain of the aniso-accommodative response for that individual subject for that given day. The methods and stimulus conditions of this Reference condition were the same as Experiment I, as described below. If it was not possible to schedule a Reference condition on the same day as the Experimental condition, the Experimental condition was compared to a Reference condition nearest in date, usually within three days. The longest time elapsed between an Experimental condition and its Reference condition was 1.5 weeks (for subject CG).

The absolute disparity, accommodative demand, and target stimulus of the Experimental condition and the Reference condition were matched, unless the effects of these parameters were being investigated (as in Experiment II and IVa for accommodation, Experiment IIIb for accommodation and vergence, and Experiment IIIa for target configuration).

3.2. Apparatus

3.2.1. Standard target for stigmascope

The standard target used to measure accommodation with the stigmascope and to train subjects to aniso-accommodate was a binocular fusion target that contained dichoptic letters (Fig. 1A). The rectangular outline surrounding the letters served as a binocular stimulus for sensory and motor fusion. The grid provided a rich background of fusional and perspective cues. The dichoptically viewed letters, the 'R' and the 'L', provided subjects blur feedback on the accuracy of their monocular accommodative response while also serving as a binocular suppression check. The overall subtense of each letter was 0.50° , while the width of the pen stroke, or line detail in the letter subtended 0.15° . Subjects either crossed-fused or uncrossed-fused the

target in a manner similar to the free fusion technique of an autostereogram. The fusion technique was used to

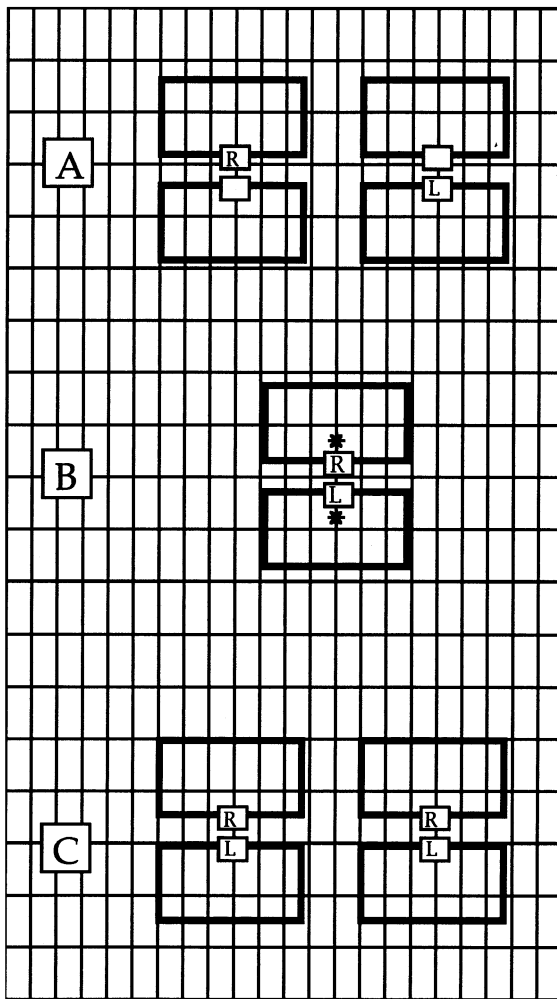


Fig. 1. (A) The standard target used during the stigmascopes experiments and in training subjects. The dichoptically viewed letters, the 'R' and the 'L', provided subjects monocular blur feedback on the accuracy of right eye's and left eye's accommodative responses, respectively, while also serving as a binocular suppression check. The rectangular boxes served as a binocular stimulus for sensory and motor fusion and the grid provided a rich background of fusional and perspective cues. (B) The appearance of the target when fused by the subject. The small stars depict the right- and left-eye stigmas that the subject used to monitor the accommodative response. Subjects were instructed to enter their settings only when both stigmas were simultaneously clear. As a check that these instructions were followed, the stigmas were positioned on the binocular stimulus target in a crossed-paired position so that each eye's stigma was positioned near the dichoptic letter viewed by the other eye. The right-eye stigma appeared below the 'L' and the left-eye stigma appeared above the 'R'. This percept of the fused target (without the stars depicting the stigmas) was used in Experiment IIIb. Filters with polarization planes 90° orthogonal to each other covered the 'R' and 'L' letters. Subjects wore Polaroid glasses so that the right eye viewed the 'R' and the left eye the 'L'. (C) The target that subjects free-fused in Experiment IIIa which presented identical stimuli to the two eyes. Because each eye viewed both letters, the dichoptic monocular blur feedback of the original target was eliminated.

present dichoptic stimuli, rather than a Polaroid filter technique, in order to maximize the contrast and luminance of the accommodative stimuli. However, the Polaroid filter technique was tested as one of the control experiments. The dichoptic letters were spaced apart vertically 0.3 cm or 0.85°, center to center. The horizontal separation of the dichoptic letters was adjusted according to the requirements of the Experimental condition and the size of the target. The retinal image size of the target was matched across conditions.

With the exception of Experiment II, the target was viewed at 20 cm which presented an absolute disparity stimulus of 30^Δ combined with 16.5^Δ produced by the horizontal letter separation of 3.3 cm. This separation added 16.5^Δ of either convergence or divergence for subjects who crossed-fused or uncrossed-fused the target, respectively. Thus, the total absolute disparity stimulus was 46.5^Δ for crossed-fusers and 15.5^Δ for uncrossed-fusers. (This is calculated using a standard 6-cm inter-pupillary distance).

3.2.2. Stigmascopes

A pair of stigmascope built into a Wheatstone mirror haploscope were used to measure the accommodative response subjectively (Fig. 2). A haploscopic presentation of the stigmascope allowed dichoptic viewing of two point light sources (1 mm), or stigmas. Each stigma was imaged on the binocularly viewed target described above (Fig. 1B) by beam splitters before each eye. The beam splitters were adjusted to allow the reflected images of the stigma to be optically superimposed onto the accommodative target, close enough to the dichoptically viewed letters, so that both dichoptic letters and both stigmas could be viewed while the subject binocularly fused the target. A crossed-paired position of the stigmas was used so that each eye's stigma was positioned near the dichoptic letter viewed by the other eye. This was done to avoid the possibility of inadvertently measuring successive monocular accommodative responses. If subjects used a 'cheating' strategy in which they rapidly switched their accommodative state as they looked back and forth between the letter-stigma pair, each eye's accommodative response would be directionally opposite to its stimulus, e.g. appropriate to the accommodative stimulus of the other eye. By this crossed-paired design, a true aniso-accommodative response could be differentiated from successive consensual responses to right and left eye stimuli.

Each stigma illuminated a cross-hair placed in the 1-mm pinhole at point S in Fig. 2. The cross-hairs were seen as focused when they were optically conjugate to the retina. The cross-hair was added to the stigma to increase the accuracy of the accommodative measurement. The depth of focus (DOF) for this cross-hair was 0.12 D. The DOF sets the sensitivity limit of the

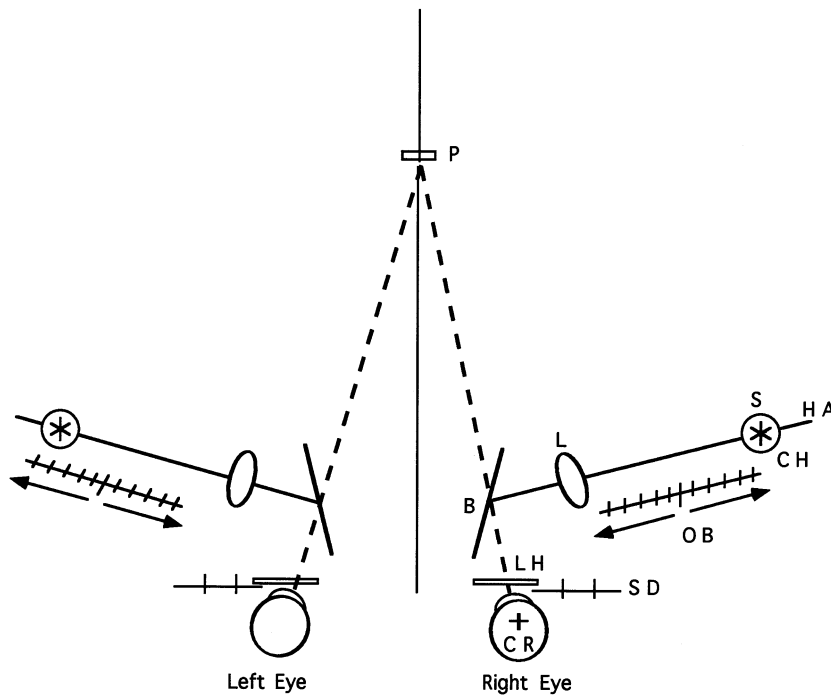


Fig. 2. A pair of stigmascopes built into a Wheatstone mirror haploscope for subjective assessment of the aniso-accommodative response. The target (Fig. 1A) that subjects viewed was mounted on a platform (P) which could be moved fore and aft for placement at any range of viewing distances from 15 to 100 cm from the spectacle plane of the observer. Two point-light sources, or stigmas (S) were viewed dichoptically and were imaged on the binocularly viewed target by beamsplitters (B) before each eye. The arms of the haploscope (HA) allow horizontal positioning of the stigmas on the target. The pivot points of the arms of the haploscope were coincident with the eyes' centers of rotation (CR). The separations of the pivot points were adjusted to match each subject's distant interpupillary distance. The subject, using the method of bracketing, adjusted the focus of each stigma by moving it along an optical bench (OB) toward a 10-D lens (L). Each stigma illuminated a cross-hair (CH), which was seen as focused by the subject when it was optically conjugate to the retina. Subjects were positioned at the beginning of each experimental session, so that both eyes were equally distant from the target. This was achieved by adjusting the head position of the subject while on a bite bar so that the corneal apex of each eye was aligned with a sighting device (SD) built into the apparatus. This positioned the secondary focal points of the 10-D lens to be coincident with the anterior nodal points of each eye, and the eye's center of rotation (CR) to be coincident with the pivot points of the two arms of the haploscope. Subjects remained on the bite bar for all measurement sessions. In Experiment IVa and in a control experiment in Experiment II, lenses were placed before one or both eyes in the lens holder (LH), which was at the subject's spectacle plane. For the remaining experiments, aniso-accommodation was stimulated with lenses placed in lens clips over subjects' glasses or over standard lenless frames if the subject did not wear glasses.

instrument in monitoring accommodation. Thus variability in the recordings greater than 0.12 D reflected variability in the accommodative response of the subject rather than limitations set by the instrument. The subject, using the method of bracketing, adjusted the focus of the cross-hairs by turning a knob which moved the stigma along an optical bench toward a 10.0 D lens. (The stigma/illuminated cross-hair will herein be referred to as the stigma.) A potentiometer transformed stigma position on the optical bench to a voltage analog that was digitized by a PC computer. Stigma positions relative to the 10.0 D lens (in centimeter units) were stored on this computer. These values were then retrieved and transformed to dioptric units relative to the anterior nodal point and then corrected to reference the accommodative response to the spectacle plane by a calibration function. Since the stigma was viewed through lenses in the spectacle plane (1.5 cm from the cornea), referencing the response to the spectacle plane

allowed us to circumvent the necessity for a non-linear calibration function for the effect of lenses on the stigma position. For each lens or stimulus condition, eight settings were obtained and averaged.

Subjects were positioned, at the beginning of each experimental session, so that both eyes were equally distant from the target. This was achieved by adjusting the head position while the subject was on a bite bar until the corneal apex of each eye was aligned with a sighting device built into the apparatus. This positioned the secondary focal points of the 10.0 D lens to be coincident with the anterior nodal points of each eye and the eyes' centers of rotation to be coincident with the pivot points for the two arms of the haploscope. The separation of these pivot points was adjusted to match the distant interpupillary distance of each subject. After the subject was aligned, the stigmas were horizontally positioned on the target by rotating the arms of the haploscope about these pivot points. This

design allowed rotation of the haploscope arms without translation artifacts. Adjustment of the vertical positions of the stigmas was controlled by tilting the beam splitters along their horizontal axis. Subjects remained on the bite bar for all measurement sessions. The target was mounted on a platform (P) (Fig. 2) which could be moved fore and aft, allowing target placement at any viewing distance ranging from 15 to 100 cm.

3.2.3. Subjects' instructions

Subjects were trained to adjust their eyes' focus until both dichoptic letters in the fused target were simultaneously clear. They were allowed unlimited time to accomplish this during training. During measurement sessions, they were allowed 3 min to accomplish this. Typically after training, 30 s or less was required to clear both letters. Subjects then focused the stigma superimposed on the target by hand, using the method of bracketing. When both pairs of letters and stigmas were simultaneously clear, voltage analogs of their settings were entered into the computer by pressing a response key. If at any time the subject could no longer keep both letters simultaneously clear after the 3 min allowed, they reported this to the examiner and were instructed to continue to set each stigma so that both stigmas were simultaneously clear. If the subject could not keep the target binocularly fused, or if one of the dichoptic letters disappeared, the session was terminated.

3.2.4. General analysis techniques

3.2.4.1. Uncorrected refractive error. With the exception of the cycloplegia experiment (Experiment IVa), subjects wore their normal correction during the experiments plus any cylinder correction that was discovered by a standard refractive-error-assessment technique. This cylinder correction was found to be necessary for reliable and consistent haploscopic settings. Any uncorrected sphere was accounted for in the data analysis (See Results). All uncorrected spheres were small enough to fall within the range of accommodative stimuli.

In addition, because the sensitivity of the stigmascope measurement (0.12 D) was greater than any subjective refraction technique and to allow for any fluctuations in refractive error (or tonic accommodation) over the course of the experiment, a second correction for anisometropia was made in the data analysis. This was done by subtracting the subject's response to the iso-accommodative stimuli of the binocularly worn lenses in the lens series from their response to the aniso-accommodative stimuli of the monocularly worn lens of the same power.

3.2.4.2. Comparison of the aniso-accommodative response between the Experimental and Reference conditions. Each Experimental condition was compared to a Reference condition (See General methods). Aniso-accommodative responses were plotted as a function of aniso-accommodative stimuli. Slopes and r^2 values were fitted to the results of each of these conditions and appear in the upper left-hand corner of each graph. To test for significant differences in these slopes, the responses of the Experimental condition were subtracted from the responses of the Reference condition to matched aniso-accommodative stimuli of the lens series and a 'difference slope' was created. Regression analysis was then used to determine if this 'difference slope' was significantly different from zero. P -values less than 0.05 and 0.01 are represented by * and **, respectively, and appear next to subjects' initials in the graphs.

4. Specific experiments

4.1. Experiment I. Lens induced aniso-accommodation

4.1.1. Methods

This experiment was conducted to test the main hypothesis, that aniso-accommodation exists and increases in magnitude as the aniso-accommodative stimuli increases. A series of plus (convex) lenses was introduced in 0.5 Δ steps while the subjects binocularly fused the standard target (Fig. 1A) presented at 20 cm and attempted to keep both dichoptic letters simultaneously clear. For each new lens power, lenses were introduced monocularly before each eye in an alternating sequence to present aniso-accommodative stimuli and then binocularly to present iso-accommodative stimuli. All lenses were introduced in the spectacle plane. Subjects were given 3 min to respond to the aniso-accommodative stimulus and measurements began when they subjectively reported simultaneous clarity of both dichoptic letters. The lens series began with +0.50 Δ and continued in the plus direction up to +3.0 Δ , unless the subject experienced suppression of one of the dichoptic letters or could no longer fuse the target, at which point the session was terminated. Many subjects reported suppression of one of the dichoptic letters at aniso-accommodative stimuli greater than 3.0 D; the highest amount demonstrated by a highly trained subject was 3.75 D. For this reason, the investigation was limited to this range. Plus lenses rather than minus lenses were used to stimulate aniso-accommodation to insure that the highest accommodative stimulus level did not exceed half of any subject's accommodative amplitude.

Repetitions of this experiment served as the Reference conditions (which was conducted on or near the same day as the Experimental condition) against which experiments II-V were compared.

4.1.2. Results

Fig. 3 illustrates the mean slopes of individual subjects' aniso-accommodative responses as a function of aniso-accommodative lens stimuli. The number of sessions making up this mean is noted in the upper right-hand corner of each graph and represents the number of Reference conditions each subject participated in. For all subjects but JA, this represents at least two separate sessions. (Time limitations prevented subject JA from participating in more than one run of this condition). The standard error bars represent the variation in the accommodative response that occur over time for an individual subject. The mean slopes of the aniso-accommodative response across subjects ranged from 0.19 to 0.38 ($\bar{x} = 0.27$). All subjects' aniso-accommodative responses were significantly greater than zero ($P < 0.05$).

5. Target distance

5.1. Experiment II. The effect of target distance on lens induced aniso-accommodation

5.1.1. Methods

To examine the influence of target distance and the level of accommodation on the aniso-accommodative response, aniso-accommodation was measured for a target at 1 meter (Experimental condition). This was compared to the response at 20 cm (Reference condition). Target size for the 1-m viewing condition was increased to match the visual angular subtense of the 20-cm viewing condition. The same procedures as in Experiment I were used in both the Experimental and Reference conditions; however, minus lenses rather than plus lenses were used to create the iso and aniso-accommodative stimuli in the Experimental condition. This allowed us to match the range of aniso-accommodative stimuli of Experiment I, while keeping the stimulus within the far point of the eye for the Experimental condition. Separation of the dichoptically viewed letters in the targets of both the Experimental and the Reference condition for this experiment were adjusted to present an absolute disparity of 30^Δ . This 30^Δ disparity stimulus was used to keep the vergence stimulus within the subject's motor fusion range while viewing the 1-m target. The disparity stimulus of the 20-cm target was adjusted to 30^Δ so that the absolute disparity was matched in both conditions. All subjects used the crossed-fusion technique in this experiment.

5.1.2. Results

Fig. 4 illustrates individual subjects' aniso-accommodation responses as a function of anisometric

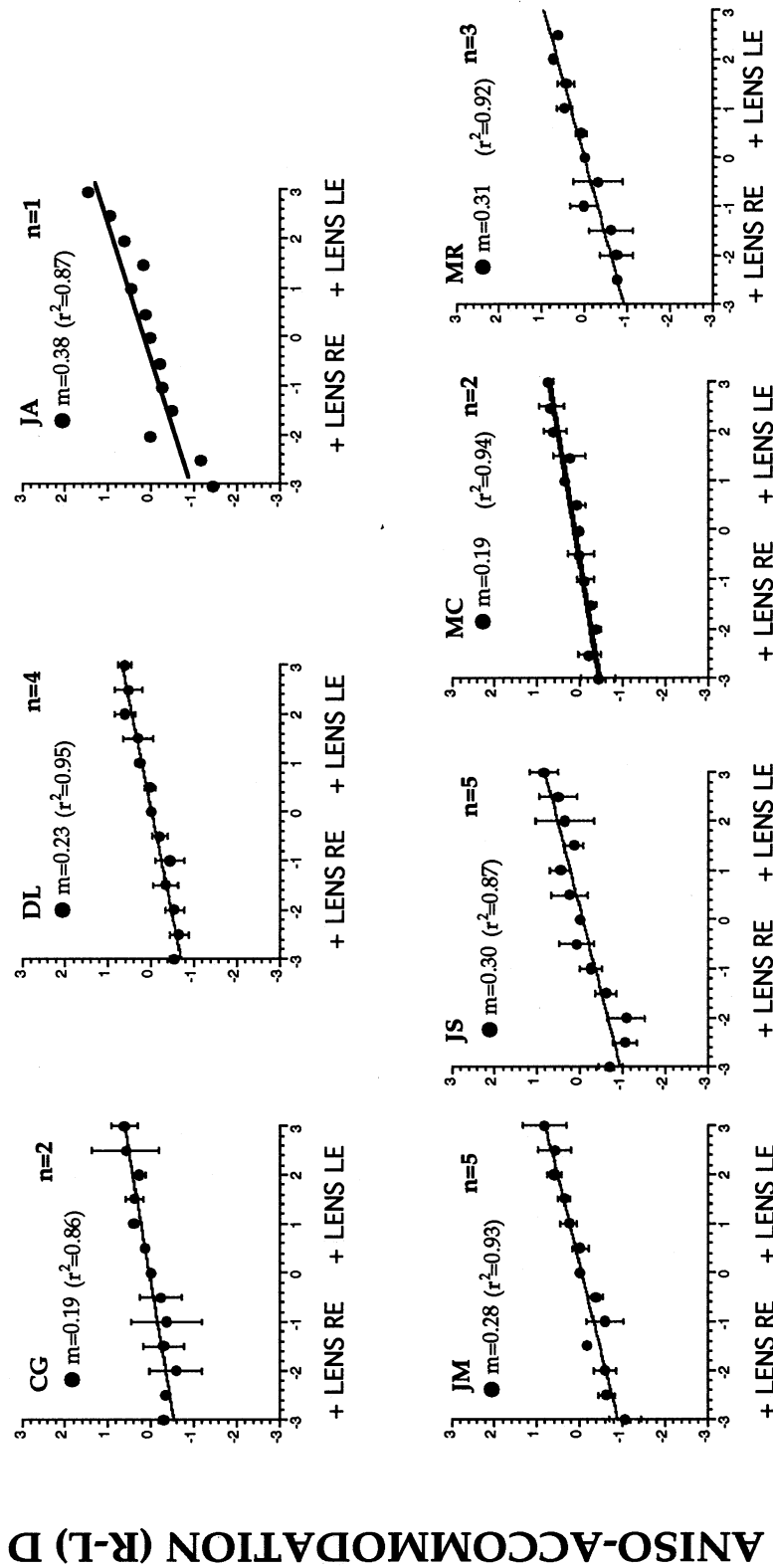
lens power to a near target, 20-cm, (\circ) compared to the more distant target, 1-m (\blacktriangle). The slopes ranged from 0.12 to 0.38 ($\bar{x} = 0.26$) for the 20-cm target (Reference condition) and 0.03 to 0.27 ($75 \bar{x} = 0.14$) for the 1-m target (Experimental condition). The gain of the aniso-accommodative response in four subjects (DL, JA, MC and MR) was significantly reduced in the Experimental condition compared to the Reference condition ($P < 0.01$). For the remaining three subjects, there was no significant difference in the Reference and Experimental conditions. When the two conditions are compared across subjects using a paired t-test, the gain of the aniso-accommodative response was significantly reduced in the Experimental (1-m) condition ($t = 2.41$, $df = 6$, $P = 0.03$).

5.2. Control experiment

5.2.1. Lenses

For all the experiments, except Experiment IVa, the lenses used to introduce aniso- and iso-accommodative stimuli were worn in lens clips over subjects' glasses or if the subject did not wear glasses, lenses were worn in clips over standard lensless frames with the clips attached at the top and bottom of the frame. Decentration and/or tilt of a lens can introduce unwanted cylindrical and spherical power [11]. This effect occurs at lower decentration or tilt angles in a convex (positive) lens than a concave (negative) lens of equal power [12]. The effect increases with the power of the lens worn. Two control experiments were conducted to test whether the use of these two different types of lenses (positive vs. negative) could explain the differences in the gain of the aniso-accommodative response as a function of viewing distance, demonstrated by some subjects in Experiment II.

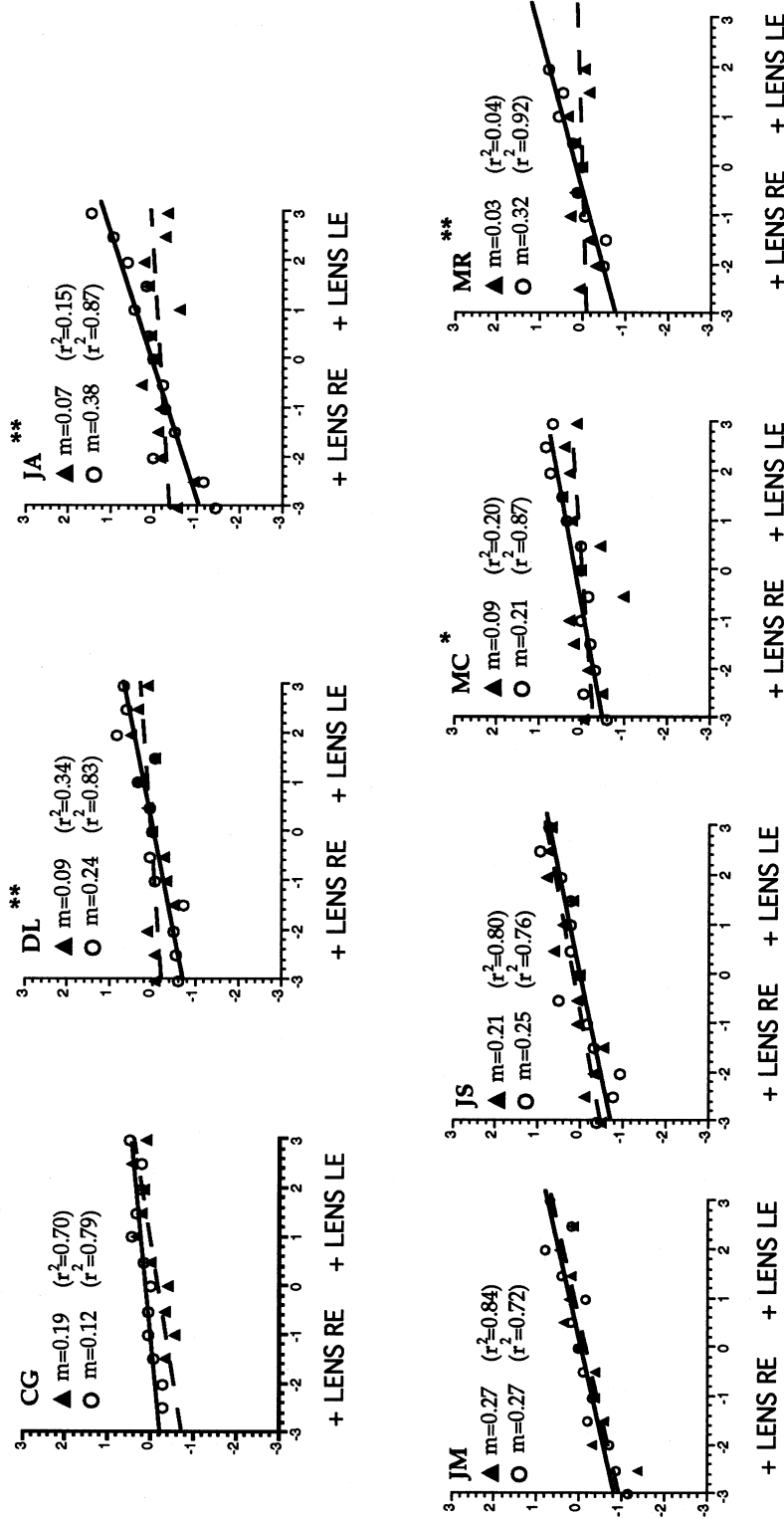
The experimental procedure of Experiment I was used for both control experiments. In the first control experiment, two subjects were run using the lens clips described above. Immediately afterward, this condition was repeated with the same lenses worn in special lens holders (Fig. 2) which allowed the experimenter to center carefully the lens and insure that there was no lens tilt with respect to the visual axis of the eye. The slopes of the aniso-accommodative response in the two conditions were virtually identical for each subject, 0.24 vs. 0.29 (DL) and 0.17 vs. 0.10 (MC), lens clips vs. lens holders, respectively. In the second control condition, again using the experimental procedure of Experiment I, two subjects were run, first with plus lenses and then with minus lenses. (Lenses were worn in the lens clips.) Again the slopes were virtually the same, 0.25 vs. 0.23 (DL) and 0.11 vs. 0.14 (MC) plus vs. minus lenses, respectively.



ANISO-ACCOMMODATION STIMULUS (L-R) D

Fig. 3. Each graph in this figure represents the aniso-accommodative responses of an individual subject to the incremental aniso-accommodative lens series of Experiment I. Repetitions of this experiment served as the Reference conditions (which were conducted on or near the same day as the Experimental condition) against which Experiments II–V were compared. Each data point represents the mean of the subject's settings to each lens of the lens series for all the Reference conditions for that subject and the error bars are the standard error of this mean. The 'n' value in the upper right-hand corner of each graph represents the number of Reference conditions for each subject. The x-axis represents the aniso-accommodative stimulus. The y-axis represents the aniso-accommodative response. The sign convention for the aniso-accommodative stimulus is L-R lens power, so that positive values indicate that the plus lens was worn on the left eye and negative values indicate the plus lens was worn on the right eye. The sign convention for the aniso-accommodative response is R-L, where plus indicates a greater relative accommodative response for the right eye and minus indicates a greater relative accommodation response by the left eye. Slope and r^2 values from regression analysis of the aniso-accommodative response for this experiment appear in the upper left-hand corner of the graph. All slopes are significantly different than zero ($P < 0.01$).

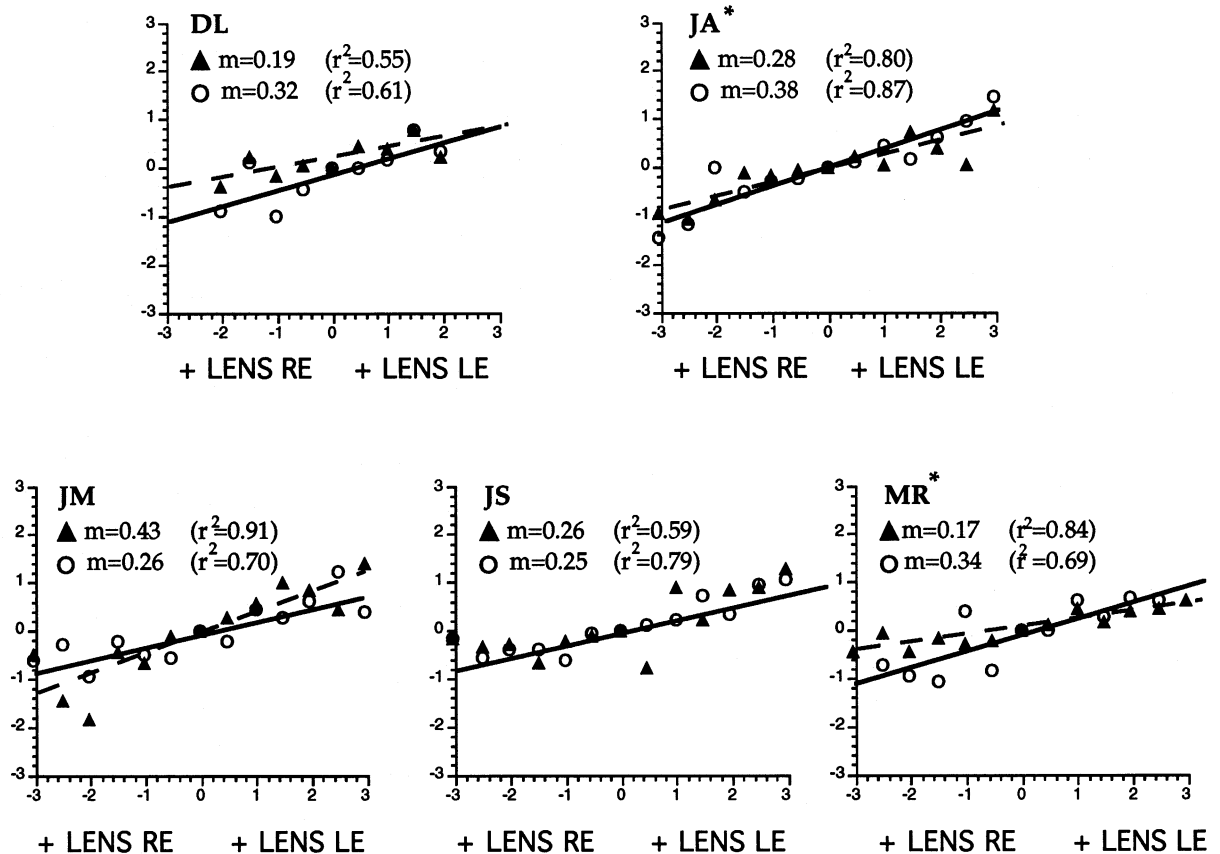
ANISO-ACCOMMODATION (R-L) D



ANISO-ACCOMMODATION STIMULUS (L-R) D

Fig. 4. Each graph in this figure represents the results of Experiment II, the aniso-accommodative responses of an individual subject viewing the far target (1-m) of the Experimental condition compared to viewing the near (20-cm) target of the Reference condition. The x-axis and y-axes and sign conventions are the same as in Fig. 3. The filled triangles and dashed line represent the responses and regression slope of the Experimental condition and the open circles and solid line represent the responses and regression slope of the Reference condition. Each data point represents the mean of 8 haploscopic settings. The standard error of these eight settings fell within 0.10 D unless otherwise indicated in the text (See Results). If the slopes are significantly different, significance levels of $P < 0.05$ and $P < 0.01$ are represented by single or double asterisks, respectively, next to the subject's initials.

ANISO-ACCOMMODATION (R-L) D



ANISO-ACCOMMODATION STIMULUS (L-R) D

Fig. 5. Each graph in this figure represents the results of Experiment IIIa, which was a comparison of the aniso-accommodative responses of an individual subject viewing the Nondichoptic (Binocular) target of the Experimental condition (\blacktriangle) compared to the responses while viewing the Standard dichoptic target of the Reference condition (\circ). Sign conventions and notations are the same as in Fig. 3.

6. Visual stimulus

6.1. Experiment IIIa. The effect of viewing a nondichoptic (binocular) target on the aniso-accommodation response

6.1.1. Methods

To test the hypothesis that dichoptic monocular blur feedback was required for aniso-accommodation to occur, aniso-accommodation was measured while subjects fused a Nondichoptic (Binocular) target (Fig. 1C.) Because each eye viewed both letters, the dichoptic monocular blur feedback of the original target was eliminated. This was compared to subjects' aniso-accommodative responses in the Reference condition which used the Standard target (Fig. 1A). The target distance and methods were the same as described in

Experiment I for both Experimental and Reference conditions.

6.1.2. Results

Fig. 5 illustrates individual subjects' aniso-accommodation responses to the Standard dichoptic target of the Reference condition (\circ) compared to their response to the Nondichoptic (Binocular) target of the Experimental Condition (\blacktriangle). The slopes ranged from 0.25 to 0.38 ($\bar{x} = 0.31$) for the Reference condition and 0.17 to 0.43 ($\bar{x} = 0.27$) for the Experimental condition. The gain of the response for the Experimental condition was significantly lower than the Reference condition for subjects JA and MR, ($P < 0.05$) The higher gain of JM for the Experimental condition was not significant ($P > 0.05$). In a paired *t*-test comparison across subjects, there was no significant difference in the gains of the two conditions ($P = 0.51$).

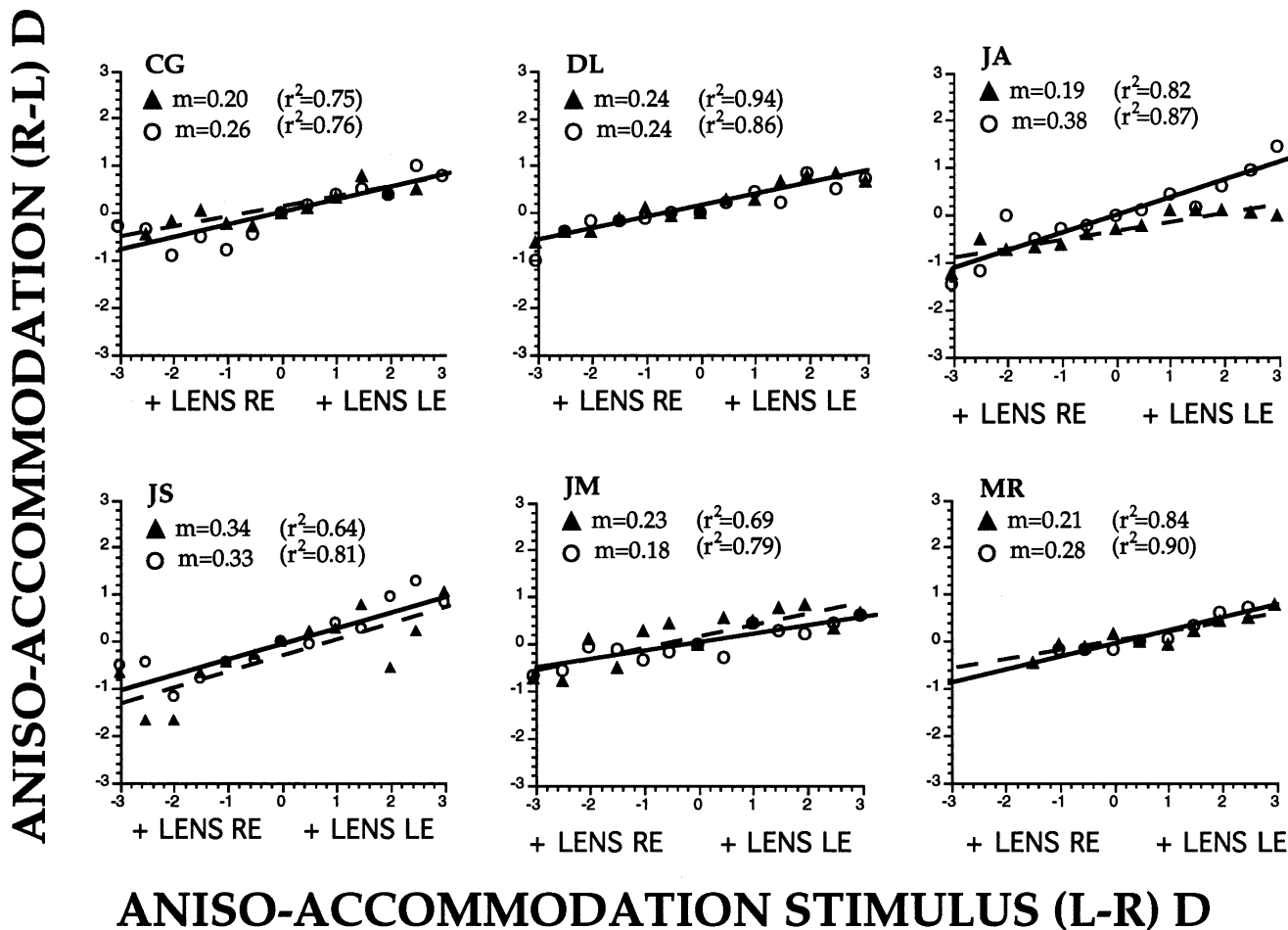


Fig. 6. Each graph in this figure represents the results of Experiment IIIb, which was a comparison of the aniso-accommodative responses of an individual subject viewing the Polaroid target of the Experimental condition, where accommodation and vergence stimuli were matched, 5.0 D and 5.0 MA (▲); to the responses while viewing the standard dichoptic target of the Reference condition (○). Sign conventions and notations are the same as in Fig. 3.

6.2. Experiment IIIb. The effect of viewing a target with matched accommodation and vergence stimuli (Polaroid target) on the aniso-accommodation response

6.2.1. Methods

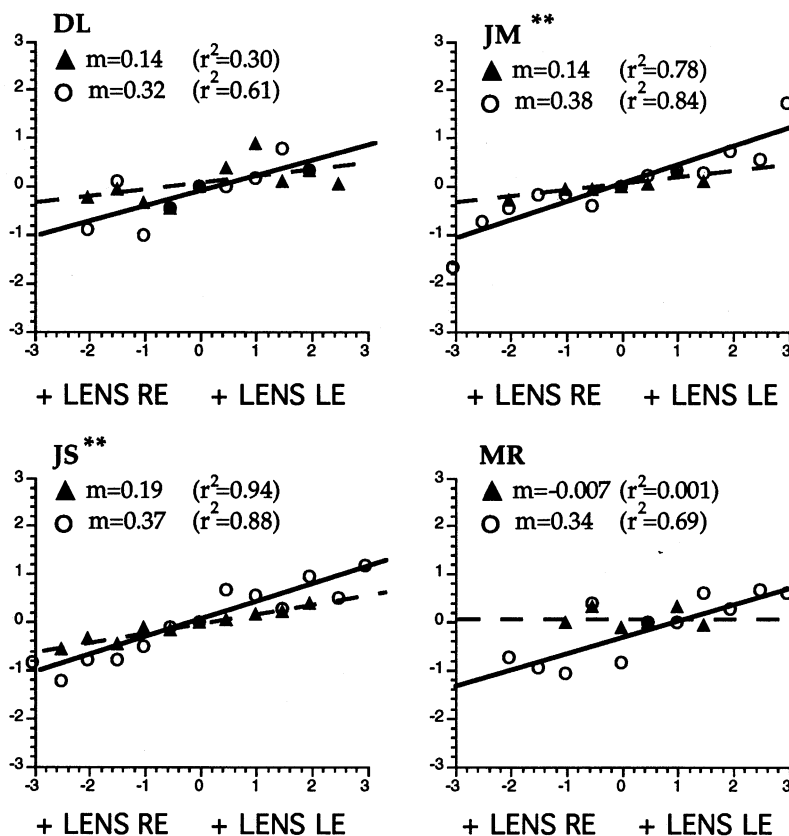
To rule out the possibility that aniso-accommodation was dependent on disassociating (mismatching) the accommodative stimulus from the vergence stimulus as occurs in the free fusion technique using the Standard target, aniso-accommodation was measured while subjects viewed a Polaroid Target in which accommodation and vergence were matched (5.0 D and 5.0 meter angles (MA), respectively). (Meter angles, a unit of convergence, like diopters, a unit of accommodation, is the reciprocal of the viewing distance expressed in meters.) The illustration of the fused target shown in Fig. 1B was used as the stimulus in this Experimental condition. Filters with polarization planes 90° orthogonal to each other covered the 'R' and 'L' letters. Subjects wore Polaroid glasses so that the right eye viewed the 'R' and the left eye viewed the 'L'. The combined Polaroid over the eye and target

was equivalent to a 0.5 neutral density filter, reducing the target illuminance half a log unit or to 31.6% of its original value. Subjects' aniso-accommodation responses to this target were compared to their aniso-accommodative responses to the standard target (the Reference condition). The target distance and methods were the same as described in Experiment I for both Experimental and Reference conditions.

6.2.2. Results

Fig. 6 illustrates individual subjects' aniso-accommodative responses to the Standard dichoptic target of the Reference condition (○) compared to the Polaroid target of the Experimental condition (▲). The slopes ranged from 0.18 to 0.38 ($\bar{x} = 0.28$) for the Reference condition and 0.19 to 0.34 ($\bar{x} = 0.24$) for the Experimental condition. The gains of the response for the two conditions were not significantly different for any subject ($P > 0.05$). Subjects did report greater difficulty in making their settings for the Experimental condition because of the reduced contrast of the Polaroid target.

ANISO-ACCOMMODATION (R-L) D



ANISO-ACCOMMODATION STIMULUS (L-R) D

Fig. 7. Each graph in this figure represents the results of Experiment IVa, which was a comparison of the aniso-accommodative responses of an individual subject while partially cyclopleged (▲) compared to same-subject responses without cycloplegia (○). Sign conventions and notations are the same as in Fig. 3.

7. Accommodative and pupillary state of the eye

7.1. Experiment IVa. Lens induced aniso-accommodation under cycloplegia

7.1.1. Methods

To test the hypothesis that the demonstrated aniso-accommodation was a result of an undiscovered artifact of the subjective recording technique, aniso-accommodation was measured after administration of 1% cyclopentolate. Cyclopentolate is an anticholinergic agent that blocks the response of the ciliary muscle and iris sphincter muscle to cholinergic stimulation, producing paralysis of accommodation and mydriasis. If consensual accommodation could be completely inactivated by the use of cycloplegia, it would be expected that aniso-accommodation also would be eliminated. If cycloplegia was incomplete, effecting only partial paralysis and a partial diminution in accommodation, a similar reduction in the aniso-accommodative response could be

expected. If the consensual response was diminished but the aniso-accommodative response was unchanged, this would suggest that the presumed aniso-accommodative response was a measurement artifact, the source of which would require further investigation.

Because the target was viewed at 20 cm with cyclopleged eyes, subjects began the aniso-accommodative lens series by wearing a +5.0 D collimating lens over both eyes. Lenses were worn in lens holders mounted in the haploscope and were carefully centered along the visual axis of each eye. In addition, the subject wore their full refractive error correction, as assessed by standard clinical refraction techniques. In an alternating sequence, one eye wore the +5.0 D lens while the plus power was reduced in 0.5 D steps for the other eye until +2.0 D was reached, or the subject experienced suppression. As in Experiment I, for each lens power used, iso-accommodation was also measured. In this experiment, the response to the iso-accommodative lenses was used to plot an accommodative response

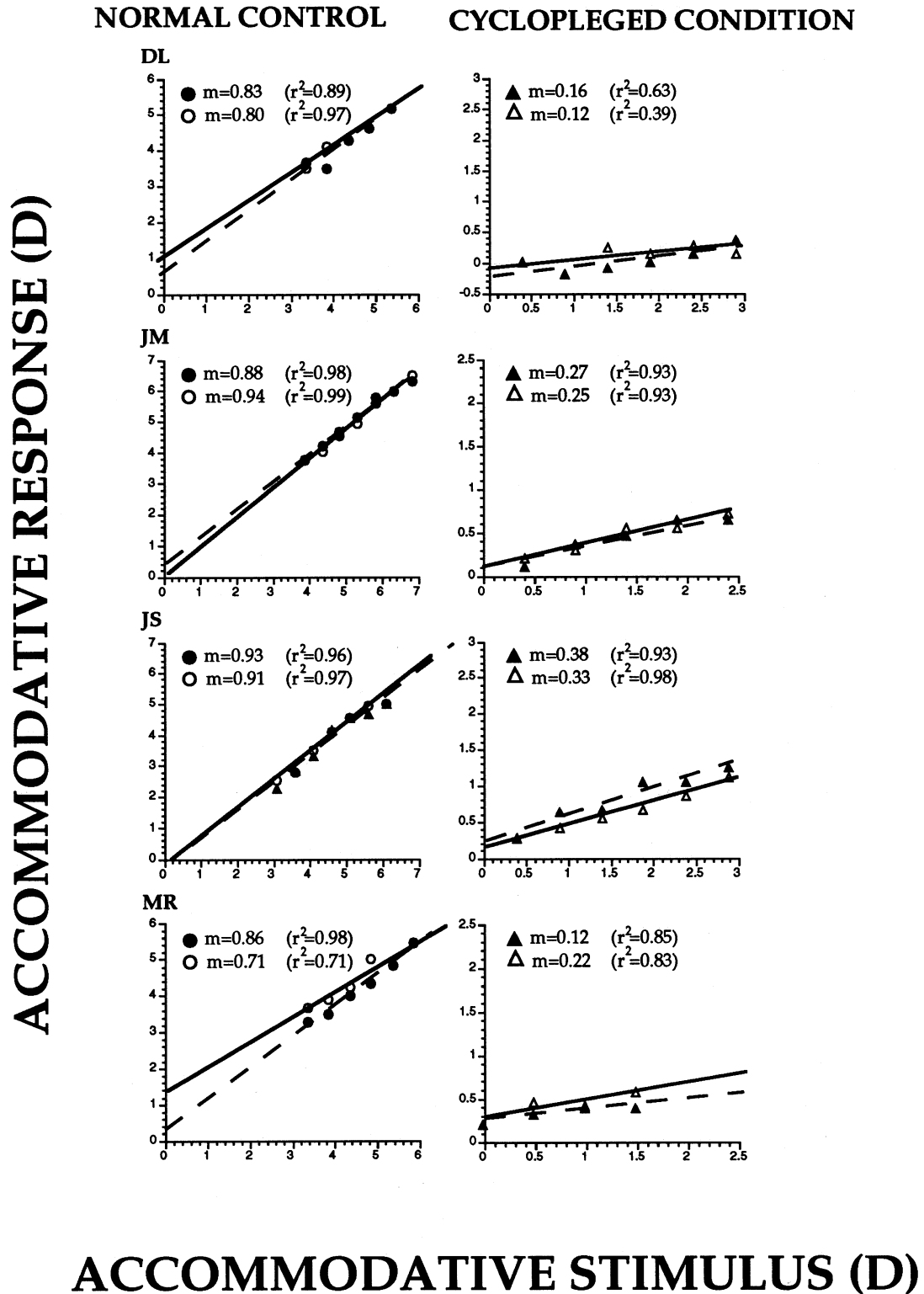
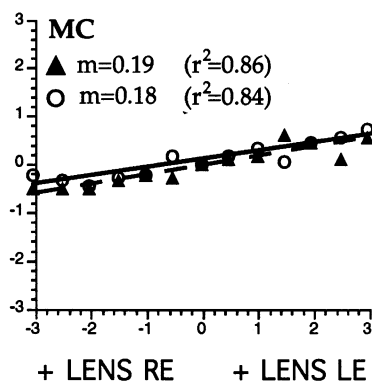
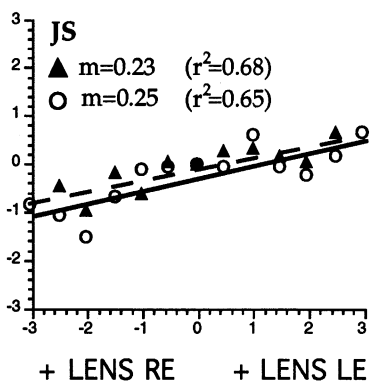
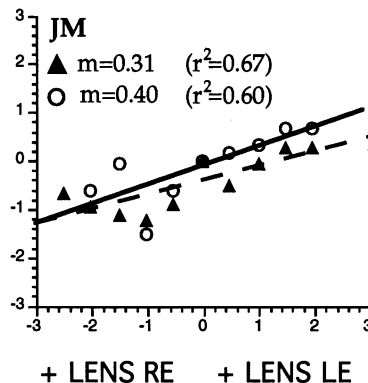
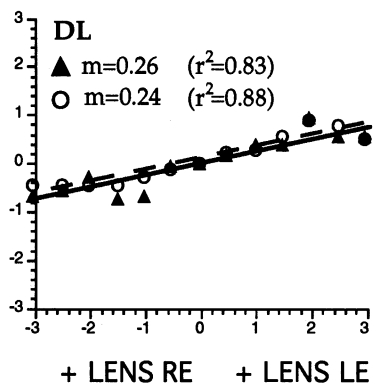


Fig. 8. This figure demonstrates the degree of cycloplegia induced in each subject in Experiment IVa. The x -axis represents the iso-accommodative stimuli. The y -axis represents the accommodative responses. The left-column graphs and circle symbols represent individual subjects' accommodative response function in the normal non-cyclopleged state of the Reference condition. The right-column graphs and triangle symbols represent individual subjects' accommodative response function in the cyclopleged state of the Experimental condition. The filled symbols represent the right eye's response and the open symbols represent the left eye's response. The dashed lines and the solid lines represent the regressions for the right eye and left eyes, respectively. Slope and r^2 values for each eye appear in the upper left-hand corner of the graphs.

ANISO-ACCOMMODATION (R-L) D



ANISO-ACCOMMODATION STIMULUS (L-R) D

Fig. 9. Each graph in this figure represents the results of Experiment IVb, which measured the aniso-accommodative responses of an individual subject while under the mydriasis state of the Experimental condition (▲) compared to same-subject responses without mydriasis (○). Sign conventions and notations are the same as in Fig. 3.

function of each eye, and thus quantify the level of cycloplegia induced and its effect on the consensual accommodative response. The reduction in this iso-accommodative response was then compared to the reduction in the aniso-accommodative response. In addition, the aniso-accommodative response under cycloplegia was compared to the aniso-accommodative response of the Reference condition that was conducted with the same target and methods of Experiment I.

7.1.2. Results

Fig. 7 illustrates individual subjects' aniso-accommodation responses in the normal accommodative state of the Reference condition (○) and after administration of 1% cyclopentolate (▲). The slopes ranged from 0.32 to 0.38 ($\bar{x}=0.35$) for the Reference condition and -0.007 to 0.19 ($\bar{x}=0.12$) for the Experimental cyclopleged condition. The gain of the response was significantly reduced in two subjects (JS and JM) for the cyclopleged condition ($P < 0.01$). Another subject's

(MR) gain was reduced to nearly zero but failed to be significant because of the limited range over which the slopes could be compared. This limited slope occurred in the cyclopleged condition, because suppression of one letter occurred at lower levels of anisometric stimuli, 1.50 D for this subject. Other subjects reported suppression of one of the letters at an average of 2.0 D anisometric stimulus for the cyclopleged condition, in contrast to most subjects who completed the full lens series (up to 3.0 D anisometric stimuli) for the non-cyclopleged condition. In addition, subjects reported that it was more difficult to make both letters simultaneously clear at lower anisometric lens values in the cyclopleged condition, on average at 1.0 D compared to 1.50 D without cycloplegia. They did not report this difficulty during the mydriasis experiment (Experiment IVb). This indicates that this subjective perception of anisometric blur with lower levels of aniso-accommodation was not the result of the smaller depth of focus due to the secondary mydriatic effect of the cycloplegia.

Comparison across subjects of the cyclopleged Experimental condition to the Reference condition revealed that the slopes were significantly reduced in the cycloplegic condition ($t = 6.01$, $df = 3$, $P < 0.01$).

Further analysis demonstrated that only partial cycloplegia was achieved in all subjects (Fig. 8). Using the accommodative responses to the lenses placed binocularly before the eyes in the lens series (the iso-accommodative stimuli), an accommodative response function was plotted for the Experimental cyclopleged condition (right column) and the Reference condition (left column). On average, the accommodative response function in the cyclopleged condition was reduced 73% compared to the non-cyclopleged condition. Thus, only partial cycloplegia was effected, leaving 27% of the accommodation response intact. A similar analysis was conducted on the aniso-accommodative response. It was found to be reduced 67% in the cyclopleged condition, leaving 33% of the aniso-response intact.

7.2. Experiment IVb. Lens induced aniso-accommodation under mydriasis

7.2.1. Methods

The bracketing technique and the crossed-paired position of the stigmas that subjects used should have eliminated the possibility that aniso-accommodation occurred as a result of unequal pupillary constriction and the corresponding unequal depth of focus of the two eyes. However, to isolate the effect of mydriasis (pupil dilation) from that of cycloplegia in Experiment IVa, and to test the possible effects of pupil size variations and interactions with spherical aberration on the aniso-accommodative response, aniso-accommodation was measured after pupil dilation. Furthermore, since pupil dilation would be required for an accurate objective measurement of aniso-accommodation (because the SRI optometers make use of the Scheiner principle to measure the eye's accommodative response), it was important to determine if aniso-accommodation could occur under complete mydriasis. Mydriasis was accomplished by administration of 2.5% phenylephrine hydrochloride, a sympathomimetic agent with little or no cycloplegic action [13]. With the exception of inducing mydriasis for the Experimental condition, the methods and target used for the Experimental condition and Reference condition were the same as in Experiment I.

7.2.2. Results

Fig. 9 illustrates individual subjects' aniso-accommodative responses both with and without mydriasis (filled triangles and open circles, respectively). The

slopes ranged from 0.18 to 0.40 ($\bar{x} = 0.27$) for the Reference condition and 0.19 to 0.31 ($\bar{x} = 0.25$) for the mydriatic condition. The gain of the response was not significantly different for any of the subjects for these two conditions ($P > 0.05$).

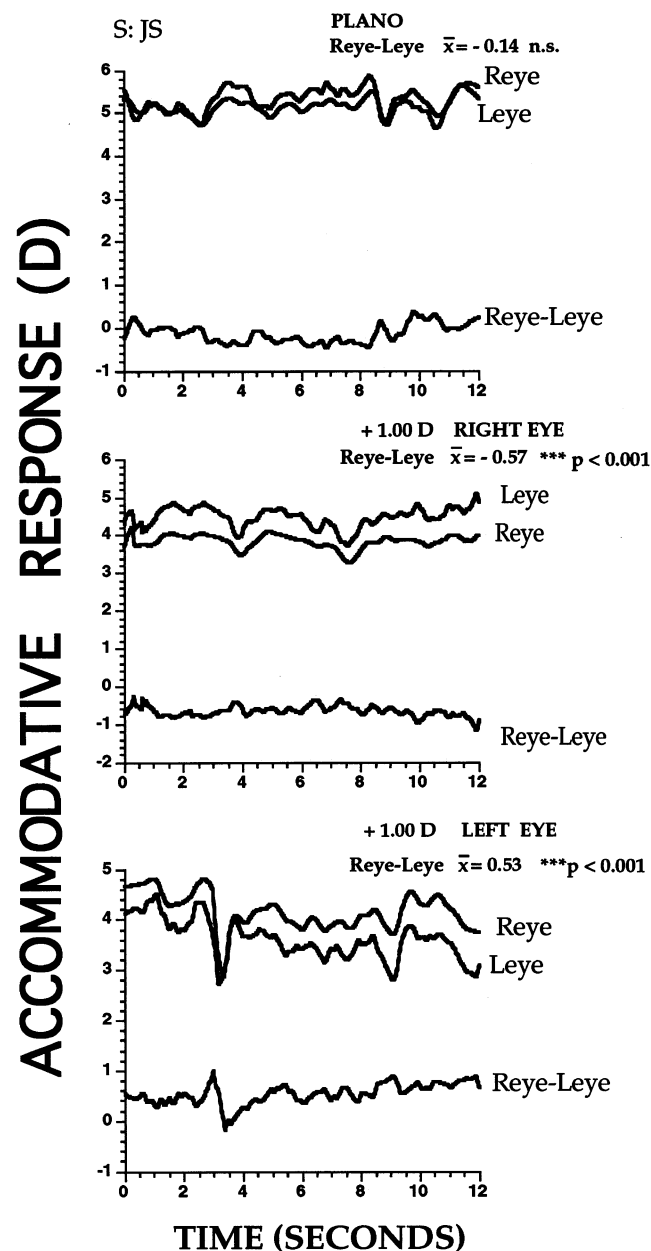


Fig. 10. Representative traces of binocular optometer recordings of the accommodative response to three steady-state lens conditions: Plano on both eyes, +1.0 D on the right eye, and +1.0 D on the left eye (top, middle and bottom traces respectively). The x-axis is time in seconds. The y-axis is the accommodative response in diopters. The accommodative responses of the right and left eye are labeled in the figure. The line trace near the x-axis represents the aniso-accommodative response (Right eye minus Left eye). In the upper right-hand corner, the amount of aniso-accommodation (Right eye minus Left eye) for the trace is shown as well as the significance level.

7.3. Experiment V. Objective verification of closed-loop lens induced aniso-accommodation

7.3.1. Methods

Objective verification of lens-induced aniso-accommodation to steady-state and step aniso-accommodative stimuli was achieved using an SRI dual Purkinje binocular eye tracking system, as described below. Two trained subjects who demonstrated an ability to aniso-accommodate on the haploscope were used in these experiments.

7.3.2. Apparatus

7.3.2.1. Dual-Purkinje-Image Eyetracker and Infra-red Optometer. For objective verification of lens-induced aniso-accommodation, a Stanford Research Institute (SRI) binocular eye tracking system composed of a fifth generation, two dimensional Dual-Purkinje-Image Eyetracker and two high resolution dynamic Infrared-Optometers, were used to track continuously both binocular horizontal eye position and binocular accommodation [14]. The instrument has a resolution and noise level of approximately 1 min of arc for eye position and 0.10 D for accommodation [15]; [14]. The optometers measure accommodation simultaneously in both eyes. They electronically sense retinally reflected infrared beams using the Scheiner principle. Voltage analogs of accommodation and eye position were digitized at a rate of 40 Hz and stored for off-line analysis. To allow accurate recording of the accommodative response, subjects' pupils were dilated with 2.5% phenylephrine hydrochloride. Lenses were placed before the optical path of the subject's eyes at a point that was conjugate to the entrance pupil.

7.3.2.2. Eyetracker/optometer target. The same target as shown in Fig. 1A was used during the objective recording of aniso-accommodation but, in order to stabilize eye position, the letters were replaced by Nonius lines to provide precise feedback to the subject on vergence eye position. The length of each Nonius line subtended 0.85° . Subjects were instructed to maintain their fixation at a point between the two Nonius lines while keeping the lines aligned and clear. The target was presented 20 cm from a point conjugate to the subject's entrance pupil and was viewed haploscopically from front surface mirrors in the visual stimulators of the SRI apparatus. Subjects adjusted the mirrors to provide the level of convergence they needed to keep the target single and clear.

To exclude eye movement artifact on the accommodation measurement, the subject viewed the target and made left and right horizontal eye movements every 3 s in an alternating sequence at the beginning or end of the experimental session. Three 12-s periods were

recorded for eye movements of 1.5° , 2.5° and 3.5° from the center of the target. Using the same technique, one 12-s period was recorded for vertical eye movements of 0.85° , the vertical separation of the two Nonius lines. Accommodation was measured simultaneously. This allowed quantification of the effects of eye movements on the measurement of accommodation. Trials in which eye-movement artifacts occurred were discarded.

7.4. Experiment Va. steady state response to aniso-accommodative stimuli

7.4.1. Methods

There were five steady-state accommodative conditions, three conditions which presented iso-accommodative stimuli for calibration purposes (Plano, +1.0 D, and +2.0 D) and two steady-state conditions which presented equal but oppositely signed aniso-accommodative stimuli (± 1.00 D). The conditions were presented in a random order but the subject was informed of the accommodative stimulus being presented. For each accommodative condition, three 12-s trials were recorded. A 12-s trial began when the subject indicated by a hand signal that the Nonius lines of the target were simultaneously clear and aligned. Subjects remained on the bite bar for the entire recording session, which included the five lens conditions and the four eye-movement calibration trials described above.

7.4.2. Results

Representative traces of three 12-s runs for the iso-accommodative and oppositely signed aniso-accommodative conditions are illustrated in Fig. 10. The amount of aniso-accommodation (Right eye minus Left eye) for the trace is shown as well as the confidence level. Positive values represent greater relative accommodation in the right eye. Averaging across the three trials of each lens condition, the aniso-accommodative responses for the three conditions for this subject (JS) were 0.29, -0.6 and 0.90 D to the Plano, +1.00 in front of the right eye and +1.00 in front of the left eye, conditions, respectively. The steady-state aniso-accommodative responses were significantly different from the iso-accommodative condition (paired *t*-test, $P < 0.001$).

7.5. Experiment Vb. step response to aniso-accommodative stimuli

7.5.1. Methods

After conducting the same calibration procedures as described above, binocular accommodation was measured to step aniso-accommodative stimuli. Three step sizes were used, +1.00, +1.50 and +2.00 D (convex lenses placed over the right eye) and three 50-s trials at 40 Hz recorded for each step size, for a total of nine trials. The trial began with iso-accommodative stimuli.

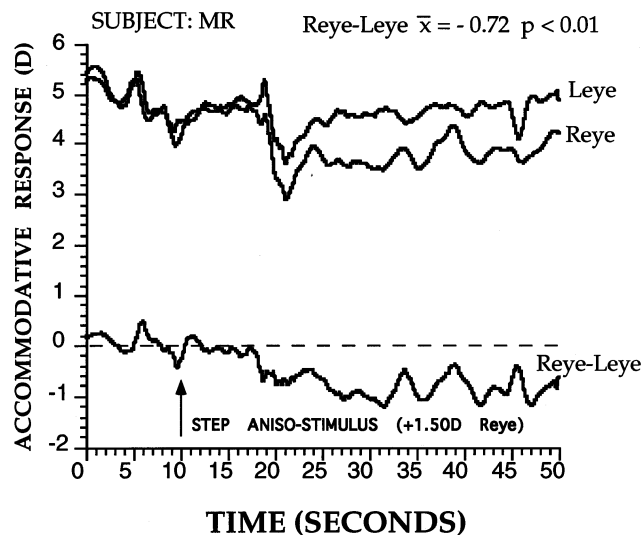


Fig. 11. Representative traces of binocular optometer recordings of the accommodative response to a 1.50 D step size. The x- and y-axes are the same as in Fig. 10. The arrow represents the time that the aniso-step stimuli was introduced, about 10 s. In the upper right-hand corner, the amount of aniso-accommodation (Right eye minus Left eye) which occurs after the aniso-accommodative stimulus was introduced is shown, as well as the significance level.

At 10 s into the trial, the monocular lens was introduced. The subject was instructed to maintain fixation at a point between the two Nonius lines in the target while keeping them aligned and attempting to make the lines clear.

7.5.2. Results

The difference in the means of the aniso-accommodation (Right Eye minus Left Eye) before the step response and after the completed step response (these two points were determined by eye) was calculated for each trial. The average of these means for the three trials of each step size were +0.10 D for the 1.00 D step, -0.65 D for the 1.50 D step and -0.33 D for the 2.00 D step. Fig. 11 illustrates the response to a 1.50 D step introduced monocularly before the right eye at 10 s. The aniso-accommodative response in this trace is -0.72 D. Using a paired *t*-test analysis this change in accommodation to the step stimulus was determined to be significant ($P < 0.001$). This response represents a gain of about 0.35. Analysis of trials where a clear step response occurred for the step stimulus (six of the nine trials), showed that aniso-accommodative response latency (time of response onset from onset of stimulus) was about 11 s. Once begun, it took between 3.5 and 5.0 s for attainment of the final response level.

8. Discussion

These experiments demonstrate (using both subjective and objective measurements) that physiologically significant (> 0.50 D) aniso-accommodation is possible. Partial cycloplegia was shown to reduce the aniso-accommodative response by an amount proportionally equivalent to the loss of consensual accommodation, and mydriasis did not affect the aniso-accommodation. These controls eliminate the possibility that the aniso-accommodative response is a perceptual artifact or the result of pupillary constriction.

8.1. Characteristics of the aniso-accommodative response

The shape of the accommodation stimulus response function (accommodative response regressed against accommodative stimulus) for monocular accommodation is generally sigmoid in shape with the linear portion typically characterized by a slope ranging from 0.80 to 1.0 [16]. This investigation found that the aniso-accommodative response function can best be described as linear with a slope of 0.24. The suppression response for aniso-accommodative stimuli greater than 3.0 D may have prevented the measurement of an asymptotic portion of the response.

Although the objective data are limited to two observers, the differences between the reaction time and total response time of the consensual accommodative response vs. the aniso-accommodative response is noteworthy; latencies of 0.40 vs. 11.0 s and completion times of 1.25 vs. 4.5 s, for iso- and aniso-accommodation, respectively. Subjective reports of clarity to aniso-accommodative stimuli approximately coincide with these objectively measured response times. The longer latency and completion time for aniso-accommodation suggest a system designed to respond to steady-state, rather than dynamically changing, visual conditions. The long response time may explain the absence of an aniso-accommodative response to dynamically presented stimuli [17].

8.2. Previous investigations

The equivocal reports of previous investigations [6–8], which reported a wide range of aniso-accommodative responses (from 0.14 to 2.91 D) may be explained by the possibility that only successive monocular accommodative responses were measured. In this investigation, the crossed-paired placement of the stigmas eliminated this potential artifact. Additionally, the target that subjects viewed provided monocular blur suppression cues that alerted the investigator to a monocular suppression response and provided subjects with feedback about their aniso-accommoda-

tive responses. When the target lacked these monocular blur feedback cues, (Experiment IIIa), two of the five subjects had significantly reduced aniso-accommodative responses. A more dramatic reduction in the response might have occurred if naive observers had been used. (Subjects in this experiment already had substantial training with the dichoptic target that contained suppression cues.)

8.3. Target distance

In Experiment II, four of the seven subjects showed a significantly smaller aniso-accommodative response when the stimuli was at 1 m compared to their response when the stimuli was at 20 cm. Several hypotheses were tested to explain these inter-subject differences including differences in: (1) accommodative level (uncorrected refractive error, accommodative lag or lead); (2) tonic accommodation; (3) ACA ratios and fusional vergence ranges.

8.3.1. Accommodative level

If a coupling of the aniso-accommodative response to the overall level of accommodation occurred, this may explain the distance-dependent effect and would suggest that aniso-accommodation occurs by independent monocular gain adjustment at the final pathway. For instance, a constant proportional reduction in one eye, say 20%, would result in a greater net change for higher levels of overall accommodation than for lower levels. Comparative analysis across subjects revealed no systematic differences between subjects in either the overall accommodative response levels at 1 m, corrected for refractive error, nor in individuals' ratio of accommodative level in the 1-m condition over the 20-cm condition, to explain inter-subject differences in the distance dependent effect.

Furthermore, although the group average comparison of the effect of cycloplegia on the iso-accommodative response and aniso-accommodative response (Experiment IVa) at first suggests a proportional reduction, this linear relationship only holds approximately true for only two of the four subjects (JM and JS). In comparison, of the remaining two subjects, DL showed relatively less reduction in the aniso-accommodative gain than would be expected from his iso-accommodative gain loss and MR showed relatively more reduction in the aniso-accommodative gain than would be expected from her iso-accommodative gain loss. Despite these opposite outcomes on the effect of cycloplegia on the aniso-accommodative response, both DL and MR showed the same distance dependent effect in Experiment II. These observations support the conclusion that a simple coupling of the aniso-accommodative response to the overall level of accommodation does not explain inter-subject or intra-subject differences in the gain of

the aniso-accommodative response as a function of target distance.

8.4. Tonic accommodation

Tonic accommodation exhibits considerable variation between individuals [18] but is stable for a given individual over time [19]. The gain of aniso-accommodation could be proportional to the amount of blur-driven accommodative effort, which is inversely related to adaptable tonic accommodation ([20]). The median dark focus or resting state of accommodation for young observers is about 1.0 D, ($\bar{x} = 1.5 \text{ D}$; S.D. = 0.77 D). Individual values can range from 0.0 to 4.0 D ([18]). The typically reduced aniso-accommodative response observed for the 1-m target may have been because this target distance was close to the dark focus value of most observers. By this reasoning, predicted dark focus values of distance-invariant subjects would straddle the 20-cm and 1-m target distances.

An objective infrared Canon R-1 Autorefractor was used to measure both refractive error and tonic accommodation of five of the seven subjects who participated in Experiment II, on an occasion separate from the measurement sessions. Methodology was used to avoid pre-measurement session adaptation effects [21] and proximal accommodative effects [22]. No correlation was found between subjects' tonic accommodation and their dependence on target distance for the aniso-accommodative response.

8.4.1. AC/A and fusional vergence ranges

Since the absolute disparity stimulus of the target in the 20-cm and 1-m conditions was held constant, changes of absolute vergence would not be associated with the difference in the aniso-accommodative gain for the two conditions. However, the vergence stimulus relative to the accommodative stimulus could have been a confounding variable, since the disparity demand matched the accommodative demand in the 20-cm condition but exceeded the accommodative demand in the 1-m condition. To keep the target fused and clear in the 1-m condition, subjects had to exert fusional convergence in excess of the vergence associated with this viewing distance or have high accommodative/convergence (AC/A) ratios.

Gradient AC/A ratios using the Von Graefe technique [23] and Fusional Vergence ranges were measured for all subjects. There were no systematic differences between the distance-invariant and distance-dependent groups in these measurements.

In addition, in a separate control experiment, two subjects who showed a distance-dependent effect were tested with aniso-accommodative stimuli to both the 20-cm and 1-m targets using the polaroid technique for both conditions. This eliminated the mismatch of the accommodative and vergence stimuli of the 1-m view-

ing condition that was present with the Standard Target. Both subjects' aniso-accommodative responses remained significantly lower ($P < 0.01$) in the 1-m condition ($\bar{x} = 0.02$) compared to the 20-cm target condition ($\bar{x} = 0.13$) using this Polaroid technique.

We cannot explain the inter-subject variability in the gain of the aniso-accommodative response with changes in target distance at this time and are investigating it further. However, we tentatively suggest that the high gain of the aniso-accommodative response at near for all subjects may be explained as the natural response of a system seeking to maximize stereoacuity. An aniso-accommodative response to anisometropic stimuli could be used to preserve fine stereoacuity which is impaired by small differences in intraocular image contrast that occur with monocular blur. One and two diopters of anisometropic blur has been shown to cause a 2- and 4-fold increase in stereo threshold, respectively [24,25]. Fine stereo acuity is of paramount importance in near viewing as hand-eye coordination relies on precise distance perception. In contrast, distant viewing conditions provide many cues for depth such as occlusion, size relationships and optic flow which override the need for depth judgments based on stereopsis.

8.5. Isometropization

It is worthwhile considering why the oculomotor system possesses the potential to make aniso-accommodative changes. In addition to the process of emmetropization, isometropization (attainment of equal interocular refractive error) also occurs over the first six years of life. In studies where anisometropia is defined as a 1.0 D difference in the spherical or corresponding meridian refractive power of the two eyes, investigators report the prevalence of anisometropia to be 17.3% in newborns [26], 6.5%, in 1-year-olds [27] and 3.4% in 5–12-year-olds [28]. Isometropization to monocularly worn concave and convex lenses also has been demonstrated in monkeys [29]. Evidence in kittens suggests that isometropization occurs only if accommodation is intact [30].

Accommodation has been hypothesized to provide a feedback loop for emmetropization of the developing eye [31,32]. In a similar manner, aniso-accommodation may play a role in isometropization of the developing eye by providing independent accommodative feedback to the two eyes. The low gain of the aniso-accommodative response function found by this investigation suggests that a complete aniso-accommodative response would not occur, but any appropriate aniso-accommodative response may provide the needed directional signal for isometropic eye growth.

In the experimental induction of anisometropia in monkeys [29], monocularly worn lenses of low power (3.0Δ) produce compensating ocular growth whereas

the higher lens powers 6.0Δ produce inconsistent and/or insignificant changes. This result seems to be specific to the magnitude of the *anisometropic* refractive error rather than the iso-accommodative error of each eye, since the neonatal monkey often has isometropic errors of 6.0 D and greater, from which they emmetropize [33]. Limitations in the amount of emmetropization from anisometropic refractive errors is also seen in human infants [34]. In these high anisometropic refractive conditions, large errors could exceed the operating range of the low-gain aniso-accommodative response.

8.5.1. Hypothesized motor pathways

These demonstrations of aniso-accommodation suggest that the accommodative control mechanism has some independent control over the two eyes. Unilateral accommodation has been observed after stimulation of the third nerve roots at a location proximal to the ciliary ganglion [35]. In addition, unilateral accommodation has been elicited by stimulating various portions of the anteromedian nucleus, AMN (or rostral part of the Edinger-Westphal nucleus [36]).

These findings indicate that aniso-accommodation could be accomplished in at least two ways. While it is generally assumed that most afference to the AMN project to both sides (left and right) of the midline to achieve consensual accommodation, it is possible that some afferent signals project primarily to one side of the midline. Aniso-accommodation could result from recruitment of these unilateral projections. Some of these unilateral projections could be dominated by either the right or left eye to provide monocular error signals for aniso-accommodation. As a second mechanism, there also could be independent gain adjustment of the ipsilateral outputs of the AMN by inhibition mediated by the cerebellum. Limited amplitudes of aniso-accommodation could result from a smaller population of unilateral than bilateral projections or by limited inhibition by the cerebellum.

Acknowledgements

This project was supported by NEI grant EYO 3532.

References

- [1] Campbell FW. Correlation of accommodation between the two eyes. *J Opt Soc Am* 1960;50(7):738.
- [2] Hung G, Semmlow J. Static behavior of accommodation and vergence: Computer simulation of an interactive dual-feedback system. *IEE Trans Biomed Eng* 1980;27:439–47.
- [3] Fisher SK, Ciuffreda KJ, Hammer S. Interocular equality of tonic accommodation and consensuality of accommodative hysteresis. *Ophthal Physiol Optics* 1987;7:17–20.

- [4] Ball E, A study in consensual accommodation, *Am J Optometry Arch Am Acad Optom* 1952;561–574.
- [5] Hokoda S, Ciuffreda K. Measurement of accommodative amplitude in amblyopia. *Ophthalmol Physiol Optics* 1982;2:205–12.
- [6] Ogle KN, Relative sizes of ocular images of the two eyes in asymmetric convergence. *Arch Ophthalmol* 1937;1046–1061.
- [7] Spencer RW, Wilson WK. Accommodative response in asymmetric convergence, *Am J Optom Arch Am Acad Optom* 1954;498–503.
- [8] Rosenberg R, Flax N, Brodsky B, Abelman L. Accommodative levels under conditions of asymmetric convergence. *Am J Optom Arch Am Acad Optom* 1953;244–254
- [9] Stoddard KB, Morgan MW. Monocular accommodation. *Am J Optom Arch Am Acad Optom* 1942;460–465.
- [10] Morgan MW. Analysis of clinical data. *Am J Optom Arch Am Acad Optom* 1944;21:477–91.
- [11] Bennet AG, Edgar DF. Spectacle lens design and performance. Optician, 1979.
- [12] Smith G, Bailey IL. Aspheric spectacle lenses: Introduction. *Optician* 1981;181:21–6.
- [13] Garner LF. Mechanism of accommodation and refractive error. *Ophthalmol Physiol Optics* 1983;3(3):287–293.
- [14] Crane H, Steele C. Accurate three dimensional Eyetracker. *Applied Optics* 1978;17:691–705.
- [15] Cornsweet T, Crane H. Servo-controlled infrared optometer. *J Optic Soc Am* 1970;60:548–54.
- [16] McBrien N, Millodot M. The effect of refractive error on the accommodative response gradient. *Ophthalmol Physiol Optics* 1986;6:145–9.
- [17] Flitcroft D, Judge S, Morley J. Binocular interactions in accommodation control: effects of anisometric stimuli. *J Neurosci* 1992;12:188–203.
- [18] Liebowitz HW, Owens DA. New evidence for the intermediate position of relaxed accommodation. *Doc Ophthalmol* 1978;46(1):133–147.
- [19] Miller RJ. Temporal stability of the dark focus of accommodation. *Am J Optom Physiol Optics* 1978;55(7):447–50.
- [20] Schor C, Tsuetaki T. Fatigue of accommodation and vergence changes their cross-link interactions. *Inv Ophthalmol Visual Sci* 1987;28(103).
- [21] Rosenfield, Ciuffreda, Hung, Gilmartin Tonic accommodation: a review I. Basic aspects. *Ophthalmol Physiol Optics* 1993;13:266–284.
- [22] Rosenfield M, Ciuffreda K. Effect of surround proximity on the open-loop accommodative response. *Inv Ophthalmol Visual Sci* 1991;32(1):142–7.
- [23] Borish IM. *Clinical Refraction* 3rd ed. Chicago: Professional Press, 1970:910.
- [24] Levy NS, Glick EB. Stereoscopic perception and Snellen visual acuity. *Am J Ophthalmol* 1974;78:722–4.
- [25] Westheimer G, McKee SP. Stereoscopic acuity with defocused and spatially filtered retinal images. *J Optic Soc Am* 1980;70:772–8.
- [26] Zonis S, Miller B. Refractions in the Israeli newborn. *J Pediatr Ophthalmol* 1974;11(2):77–81.
- [27] Ingram R, Walker C. Refraction as a means of predicting squint or amblyopia in preschool siblings of children known to have these defects. *Br J Ophthalmol* 1979;63:238–42.
- [28] Flom M, Bedell H. Identifying amblyopia using associated conditions, acuity and non-acuity features. *Am J Optom Physiol Optics* 1985;62:153–60.
- [29] Hung L, Crawford M, Smith E. Spectacle lenses alter eye growth and the refractive status of young monkeys. *Nat Med* 1995;1(8):761–5.
- [30] Hendrickson P, Rosenblum W. Accommodation demand and deprivation in kitten ocular development. *Inv Ophthalmol Visual Sci* 1985;26:343–9.
- [31] VanAlphen GMWH. Choroidal stress and emmetropization. *Vision Res* 1986;26(5):723–34.
- [32] Schaeffel F, Howland HC. Mathematical model of emmetropization in the chicken. *J Optic Soc Am* 1988;5:2080–6.
- [33] Kiely P, Crewther S, Nathan J, Brennan N, Efron N, Madigan M. A comparison of ocular development of the cynomolgus monkey and man. *Clin Vis Sci* 1987;1:269–80.
- [34] Tanlami T, Goss D. Prevalence of monocular amblyopia among anisometropia. *Am J Optom Physiol Optics* 1979;56:704–15.
- [35] Westheimer G, Blair S. The parasympathetic pathways to internal eye muscles. *Invest Ophthalmol* 1973;12:193–7.
- [36] Jampel R, Mindel J. The nucleus for accommodation in the midbrain of the macaque. *Invest Ophthalmol Vis Sci* 1967;6:40–50.