Accommodation in Early Presbyopes Fit with Bilateral or Unilateral Near Add

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SIGNIFICANCE: When fit with monovision, most early presbyopes (aged 40 to 50 years) accommodated to near objects by focusing the distance corrected eye, leaving the near corrected eye myopically defocused with reduced image quality. A few were able to switch focus to the near corrected eye retaining a consistently focused image in one eye over a wider range of distances.

PURPOSE: The aim of this study was to examine accommodation behavior, pupil responses, and resultant image quality of early presbyopes fit with either bilateral or unilateral (monovision) near adds.

METHODS: Accommodative response and pupil size of 19 subjects (27 to 60 years), including 13 early presbyopes (40 to 50 years), were measured using an aberrometer as a binocularly viewed 20/40 letter E was moved from 2 m to 20 cm. Each subject was fit with different refractive strategies: bilateral distance correction, bilateral +2 diopters (D) near add, and unilateral +2 D near add placed over the measured right eye or unmeasured left eye. Monochromatic image quality was quantified using the Visual Strehl ratio metric.

RESULTS: With bilateral +2 D near add, all early presbyopes mostly refrained from accommodating (gain = 0.22 D/D) until the target approached closer than the 50-cm far point, and they then accommodated accurately until their maximum accommodative amplitude was reached. With monovision, most (10 of 13 early presbyopes) accommodated to focus the distance corrected eye, leaving the near corrected eye myopically defocused with reduced image quality. As stimulus distance became closer than their distance corrected eye's near point, they continued to exert maximum accommodation. Only two early presbyopes relaxed their accommodation to "switch" focus to the near corrected eye as target distance was reduced, and these two did not experience bilateral drop in image quality as stimulus distance became closer than the near point of the distance corrected eye.

CONCLUSIONS: Our data suggest that many early presbyopes will not initially adopt an accommodation strategy that optimizes image quality with monovision, but consistently accommodate to focus the distance corrected eye.

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Optom Vis Sci 2018;95:43–52. doi:10.1097/OPX.0000000000001155

Presbyopia is the result of a slow, naturally occurring, irreversible reduction in accommodative amplitude with increasing age.[1,2] This age-related refractive condition manifests when the accommodative ability of the eye is no longer sufficient for near vision, typically at around 40 years of age.[3] Global estimates indicated 1.04 billion people had presbyopia in 2005, of whom 517 million (49.7%) did not have corrective spectacles.[4] Currently, the loss of accommodation cannot be restored, and it is typically corrected with multifocal spectacles, multifocal contact lenses, or monovision.[5]

Monovision is a widely used method for correcting presbyopia,[6] in which one eye is corrected for distance vision, whereas the other is corrected for near vision, commonly implemented with contact or intraocular lenses or corneal refractive surgery.[7] The goal is to give presbyopes clear vision both at near and distance without the need for spectacle correction.[6] It is generally assumed that the eye refracted for distance will have a focused image when viewing a distant target, whereas the eye refracted for near will have a focused image when viewing a near target. This has to be true for a complete presbyope (zero accommodation, aged ≥50 years).[8] However, this may not be true for younger accommodating eyes as reported by one study, where young patients fit with monovision as a myopia control strategy habitually focused on near targets with their distance corrected eye, leaving the near corrected eye chronically myopically defocused.[9]

The above result is relevant because early presbyopes have higher success rates with monovision than do older presbyopes,[10–12] and early presbyopes have residual accommodation.[13–16] For example, if an early presbyope converges to a target at his/her near point, will he/she accommodate to retain approximate focus in the distance corrected eye, or will he/she refrain from accommodating even though he/she is converging and uses the near corrected eye to focus the near target? When represented with inconsistent binocular convergence and dioptric vergence cues, younger observers can relax their accommodation when attempting to focus a target with zero dioptric vergence even when binocularly converged.[17,18]

The aim of this study was to carefully examine accommodation behavior and pupil responses of early presbyopes fit with either bilateral or unilateral (monovision) near adds under normal clinically relevant binocular viewing conditions with targets that provide image blur, convergence, and proximal cues for accommodation. We were especially interested in how accommodative behavior, aberrations, and pupil size affected image quality in the distance and near corrected eyes of early presbyopes viewing through a monovision correction.

METHODS

Subjects

We tested 19 subjects (9 men and 10 women) between the ages of 27 and 60 years (mean age = 42 ± 7.18 years), including 13 subjects between 40 and 50 years of age with best-corrected visual acuity of 20/20 or better in both eyes, less than 1 diopter (D) of anisometropia, and absence of any ocular disease or a history of ocular surgery. The mean spherical equivalent was −1 ± 1.8 D for the right eye and −1 ± 1.6 D for the left eye. Sighting dominance was measured with a hole in the card test (11 subjects were right-eye dominant, whereas eight subjects were left-eye dominant), although its relevance to monovision is uncertain.[19] The experiment followed the tenets of the Declaration of Helsinki and was approved by the institutional review board at Indiana University. Informed consent was obtained from all subjects after verbal and written explanation of the study procedures.

Apparatus

Because of the impact of spherical aberration on measured refractive state,[20] and thus on measures of accommodation,[21] we monitored refractive state using a Shack-Hartmann aberrometer (Complete Ophthalmic Analysis System; Wavefront Sciences, Inc., Albuquerque, NM), which provides refractive state data across the entire pupil. Also, the size of the exiting wavefront provides a convenient measure of pupil size.[15,22] The Shack-Hartmann aberrometer sampled the exiting wavefront with 0.21-mm diameter lenslets. Aberrations of right eyes were measured with 840-nm radiation reflected into the eye by a hot mirror through which the subject's right eye viewed the test stimulus. Refractive state measurements were adjusted for longitudinal chromatic aberration to 555 nm (a −0.71-D shift in refractive state). All wavefront measurements were obtained at the spectacle plane as this instrument's internal telescope relay lenses made the wavefront sensor optically conjugate to the spectacle plane in the apparatus. The distance Rx was corrected in the spectacle plane. To compute the target vergence and refractive state at the eye's pupil plane, the power of lenses in the spectacle plane as well as the distance of the spectacle plane from the eye must be considered. All target vergences (TV) and refractive state measurements (RS) were measured at the spectacle plane (SP) and transferred to the eye's pupil plane (pp) using paraxial transfer equations[23]:

$$\mathrm{TV_{pp}} = \left[\frac{1}{\left[\left(\frac{1}{\mathrm{TV_{sp}}+\text{distance Rx}}\right)-d\right]}\right] \tag{1}$$

TV_{pp} is the target vergence at the pupil plane, TV_{sp} is the target vergence at the spectacle plane, and d is the trial lens to pupil plane vertex distance.

$$\mathrm{RS_{pp}} = \left[\frac{1}{\left[\left(\frac{1}{\mathrm{RS_{sp}}+\text{distance Rx}}\right)-d\right]}\right] \tag{2}$$

RS_{pp} is the refractive state of eye at the pupil plane, and RS_{sp} is the refractive state of the distance corrected eye measured at the spectacle plane.

The commercial aberrometer has been modified to provide a binocular open-field view of a 4 cd/m^2 microdisplay (LitEye, by eMagin, Inc.) with 852 × 600 pixels (13 × 9-mm display with 15-μm pixel width). All measurements were taken with room lights off to maintain larger pupil diameters. A single high-contrast black-on-white 20/40 letter E was centered on the microdisplay, which was positioned at various selected distances ranging from 2 m to 20 cm (from the spectacle plane to stimulus) stepped along an optical rail aligned with primary line of sight of the measured (right) eye. Thus, no rotation was required for the measured right eye to maintain fixation as the target screen approached, but the left eye rotated to maintain fixation and thus single vision. Retaining the character size at 20/40 maintained the high spatial frequency content of the stimulus and the need for accurate accommodation,[24] while the approaching fixed physical size microdisplay provided a clearly visible proximal and convergence stimulus.

Pupil diameter was measured as the beam diameter at the spectacle plane. To convert the measured diameter at the spectacle plane to the eye's entrance pupil plane, we used the following equation:

$$P_{\mathrm{pp}} = P_{\mathrm{sp}} \times \frac{\left(1/_{(\mathrm{RS_m}+\mathrm{DistanceRx})}\right)-d}{\left(1/_{(\mathrm{RS_m}+\mathrm{DistanceRx})}\right)} \tag{3}$$

P_{pp} is the calculated entrance pupil diameter, P_{sp} is the measured pupil diameter at the spectacle plane, and RS_m is the refractive state of the marginal rays measured at the spectacle plane. Note that we used the marginal pupil refraction in this calculation because it determines the rays that form the exiting beam size and thus the effective pupil size at the measurement plane.

To avoid having pupil miosis caused by increased total amount of light in the retinal image as the display approaches, we kept the illuminance at the corneal plane constant by matching the luminance of the microdisplay to a 4-cd/m^2 white board background located 3 m from the spectacle plane, which was illuminated by a projector. This board covered the full field of view of the microdisplay placed at 20 cm, and thus, when the target distance was changed, the illuminance at the eye's pupil plane remained constant at about 10 lux.

Experimental Procedure

Following a training trial in which each subject was given standardized instructions to focus the letter E at all the times, they were repeatedly encouraged to direct their attention to the target and maintain the best focus possible throughout the experiment. All measurements were performed while subjects viewed targets binocularly with natural pupils, and their head and eye position stabilized with a dental impression. Each subject was fit with four different refractive strategies: (1) bilateral distance correction, (2) bilateral +2 D near add, (3) unilateral +2 D near add (monovision) placed over the measured right eye, or (4) unilateral +2 D near add (monovision) placed over the unmeasured left eye. Trial lenses placed at the spectacle plane were used to introduce the +2 D add. For each testing condition, all subjects were distance corrected and sat in the experimental room with lights off for a 5-minute dark adaptation period before measurements began. Stimulus vergence was increased sequentially from −0.5 to −5 D in steps of 0.25 D. At each target vergence, five wavefront measurements were averaged.

Data Analysis

The wavefront error maps were fitted with Zernike polynomials, from which two different commonly used measures of refractive state were calculated:

(1) minimum RMS (minRMS), often referred to as Zernike refraction describing the sphere lens that corrects the average curvature of the wavefront across the entire pupil and thus minimizes the total wavefront RMS[25]; and
(2) paraxial, the correcting lens that flattens the wavefront at the center of the pupil.[20]

Paraxial and minRMS measures of refractive state in diopters are calculated directly from Zernike coefficients C_n^m in microns for a pupil radius R in mm using the following equations[26]:

$$\text{MinRMS RS} = \left(-C_2^0 4\sqrt{3}\right)/R^2 \tag{4}$$

$$\text{Paraxial RS} = \left(-C_2^0 4\sqrt{3} + C_4^0 12\sqrt{5}\right)/R^2 \tag{5}$$

Accommodative response is defined as the change in refractive state in response to a near target, and accommodative stimulus is defined as the target vergence closer than the eye's far point, as defined below:

$$\text{Accommodative response } (D) = \text{distance } Rx_{pp} - \text{refractive state } (RS_{pp}) \tag{6}$$

$$\text{Accommodative stimulus } (D) = \text{distance } Rx_{pp} - \text{target vergence } (TV_{pp}) \tag{7}$$

Therefore, increases in ocular power in response to a stimulus closer than the far point produces the standard positive accommodative stimulus and response. We incorporate a far-point check in the apparatus for each subject to avoid apparent accommodation lead at distance produced by undercorrected or uncorrected refractive errors (for more details, see Almutairi et al.[16]). Monochromatic image quality at 550 nm was computed with the VSOTF metric (Visual Strehl ratio calculated from the optical transfer function[27]) using measured defocus, higher-order aberrations (up to the eighth order), and measured pupil sizes.

RESULTS

Impact of Spherical Aberration

As previously reported, quantifying accommodation responses in human eyes is complicated by the negative change in spherical aberration that occurs during accommodation,[28,29] which also happens during accommodation of early presbyopic eyes.[16] Consistent with these spherical aberration changes,[21] we found that accommodative gains defined by the minRMS refractive state were on average 24% lower (mean for distance and monovision corrections) than changes observed in the paraxial refractive state (Fig. 1). Because minRMS refractive state varies with pupil size,[30] and because pupil size is varying as the subjects accommodated in the experiment, we chose to plot paraxial refractive state data because it is independent of pupil size,[21] but tends to slightly overestimate the accommodative response of presbyopic eyes.[16,25] Accommodative gain was quantified by the slope of the accommodation stimulus/response curves (Figs. 2 to 4). The minRMS accommodative gain varies from zero to 1.0 in this age group, but in some cases, the paraxial accommodative gain is slightly greater than 1.0. This apparent greater accommodative gain than required was observed in those eyes with the largest negative changes in spherical aberration during accommodation (–0.07 μm/D) and the maximum levels of negative spherical aberration at near

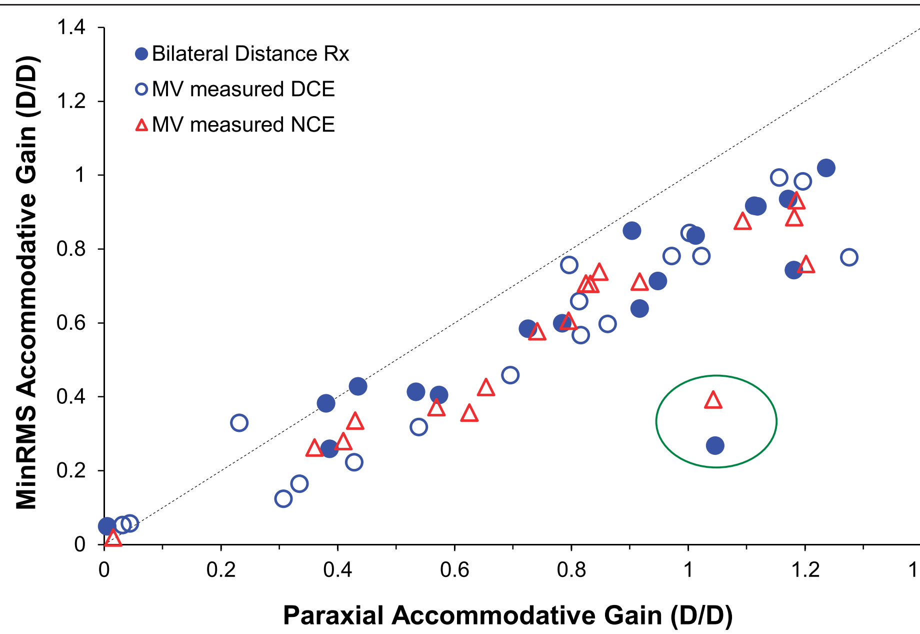

FIGURE 1. Comparison of accommodative gain (diopters of accommodative response/diopters of accommodative stimulus) observed using minRMS and paraxial criteria for each subject fit with their bilateral distance correction (filled circles) and with monovision when the distance corrected eye (DCE) is measured (open circles), or the near corrected eye (NCE) is measured (open triangles). The dashed line represents $y = x$. Outliers indicated as two data points within a green circle.

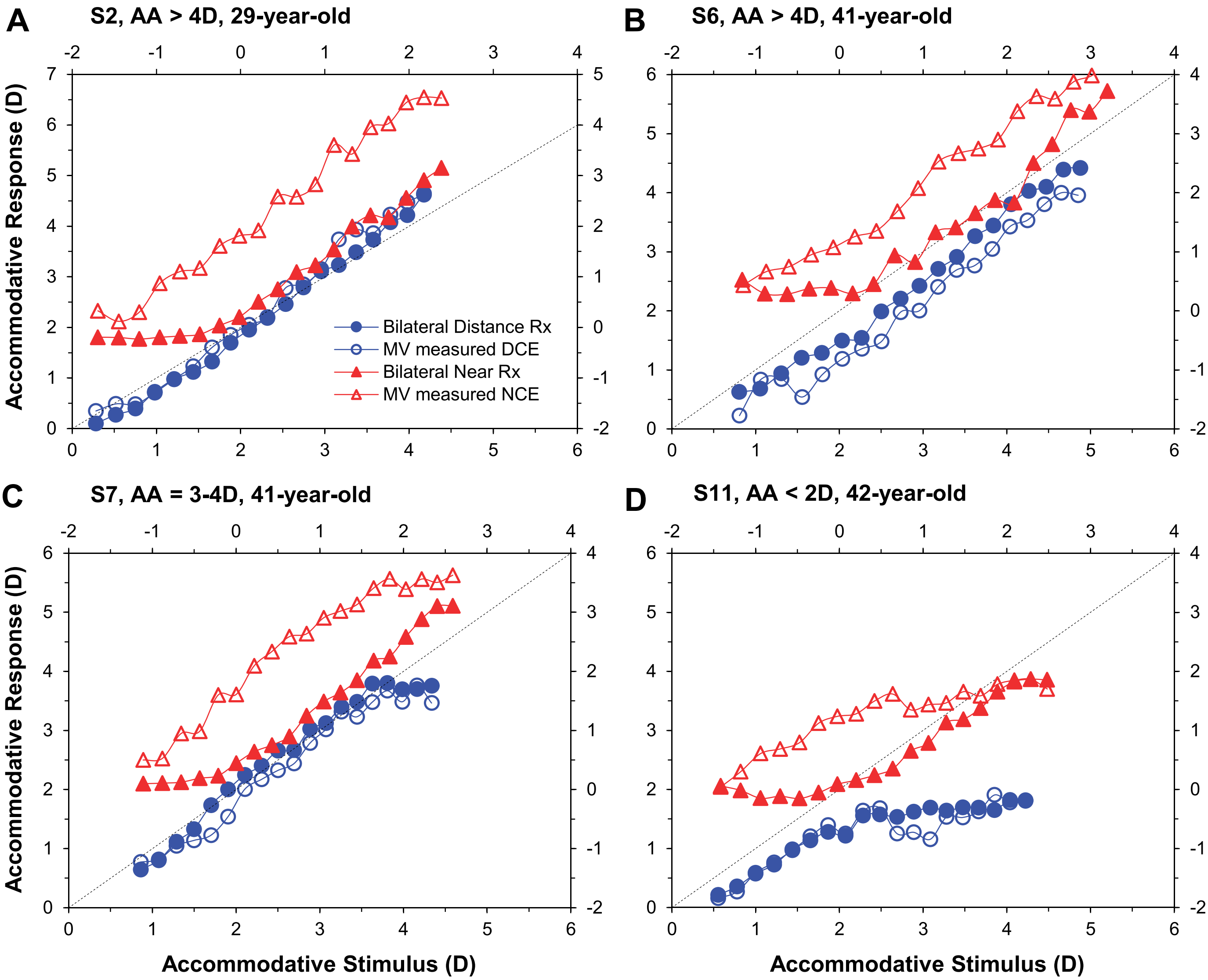

FIGURE 2. Examples of paraxial accommodative responses as a function of accommodative stimulus for four subjects with varying amplitudes of accommodation (AA): (A) S2: AA > 4 D, (B) S6: AA > 4 D, (C) S7: AA = 3–4 D, and (D) S11: AA < 2 D. Each subject viewed the stimuli binocularly with their bilateral distance correction (filled circles), bilateral near +2 D add (filled triangles), and monovision with the measured right eye having a distance correction (DCE, open circles) or the right eye near corrected (NCE, open triangles). Each data point represents the mean of five measurements. The dashed line in each plot represents $y = x$. The double *x*- and *y*-axes scales represent the accommodative stimulus and response for DCE (bottom and left scales) and for the NCE (top and right scales).

(−0.18 μm). In one outlier (two data points within a green circle in Fig. 1), we observed a large difference between minRMS and paraxial accommodative gain, which was due to the dramatic spherical aberration change during accommodation in this eye (see similar large discrepancies in modeling data).[21]

Accommodation Behavior

Paraxial accommodation behavior for different subjects with varying amplitudes of accommodation (0 to >4 D) viewing through bilateral distance correction (filled circles), bilateral near +2 D add (filled triangles), or with monovision in which a unilateral near +2 D add was placed over the measured right (open triangles) or over the nonmeasured left (open circles) eyes is plotted in Figs. 2 to 4. We include double *x*- and *y*-axes scales: the primary scales (bottom and left) represent the accommodative stimulus and response for the distance corrected eyes, and the secondary scales (top and right) represent the accommodative stimulus and response for the near corrected eyes. The bottom and left axes, therefore, represent the physical distances of the stimuli and the physical retinal conjugate planes.

Although the target distance changed from 2 m to 20 cm in every experiment, the actual target vergence range can be slightly different (e.g., see Fig. 2) because the residual uncorrected refractive errors observed during the far-point check can shift the vergence range by a constant, and the generally minus distance corrections included in the spectacle plane cause the familiar reduction of accommodative ocular demand for near stimuli, which is attenuated or reversed by adding the +2 D near add into the trial frame.[23]

A general trend can be seen with bilateral distance corrections (filled circles): accommodation responses are initiated as the target

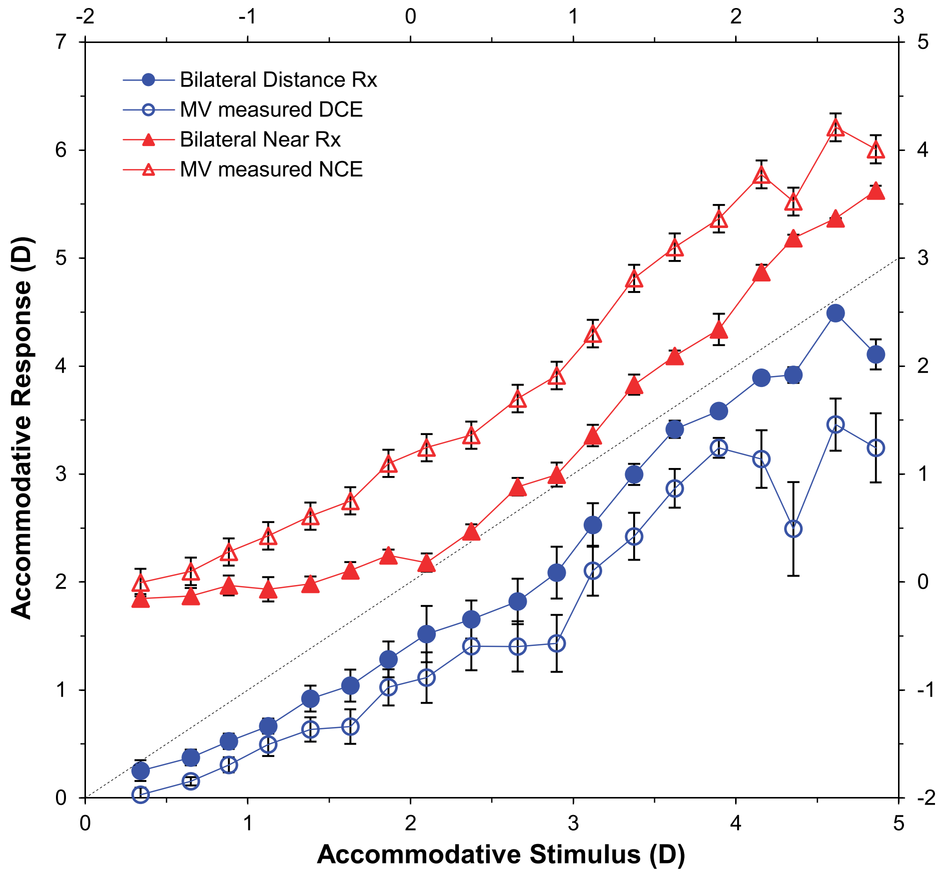

FIGURE 3. Average accommodative stimulus/response curves for early presbyopic subjects (n = 10 of 13 subjects between 40 and 50 years old) who exhibited the typical accommodative responses (accommodation with monovision was similar to that observed with bilateral distance correction). Responses were averaged for all accommodative stimuli beyond each subject's near point. The color code and axes scales are the same as those used in Fig. 2. Error bars represent ± SEM. The dashed line represents $y = x$.

distances were decreased from 2 m, and some subjects show no sign of reaching their maximum response (e.g., see Figs. 2A, B), whereas others reach their maximum accommodative response at less than 4 D (e.g., see Figs. 2C, D). At distances farther than these near points, most subjects accommodate with high gain (e.g., see Figs. 2C, D), which for the paraxial accommodative response measures are approximately 1 (mean = 1.0 ± 0.11 D/D). The minRMS gains for the same eyes (not plotted) were generally less than 1 (mean = 0.76 ± 0.14 D/D). With bilateral near +2 D adds (filled triangles), the measured refractive states generally remained stable at about –2 D until the target approached closer than the 50-cm far point of these eyes. Once the target approached closer than this 50-cm far point, the refractive state tracks the stimulus, with a slight accommodative lead in some cases (e.g., see Fig. 2A, C).

With monovision, we observed two general trends of accommodation behavior. Most subjects (Figs. 2 and 3) responded with monovision as they did with bilateral distance corrections, accommodating to focus the distance corrected eye (12 of 17 accommodating subjects and 10 of the 13 early presbyopes exhibited this behavior). Consistent with these subjects accommodating to focus the distance corrected eye, we observed approximately 2 D of excessive power in the near corrected eye (open triangles) over the full range of accommodation. As stimulus distance became closer than their distance corrected eye's near point, they continued to exert maximum accommodation. Fig. 3 shows the mean accommodative responses (for stimuli beyond each subject's near point) for the ten 40- to 50-year-old early presbyopic subjects who used this typical behavior. Because of the varying accommodative amplitudes in this population, data for accommodative stimuli of less than 1.75 D represent all 10 subjects, but only two subjects continued to accommodate beyond target vergences of –4 D. With monovision corrections, the near corrected eye was always significantly overpowered, focusing on average 1.5 D closer than the stimulus. Accommodative gain with bilateral near adds refrained from accommodating for stimuli beyond the 50-cm far point (mean gain = 0.22 D/D). For targets closer than 50-cm far point, accommodative gain is similar to that observed with their bilateral distance Rx ($P > .05$), but the accommodative gains were generally lower with monovision (mean 11% lower).

When fit with a monovision correction, two subjects with an accommodative amplitude of 4 D accommodated to retain focus in the distance corrected eye, but only up to an accommodative stimulus of 2.5 and 3.0 D (Figs. 4A, B). As the stimulus approached closer, they relaxed their accommodation, producing a large accommodative lag in the distance corrected eye, but approximate focus in the near corrected eye. This eye-switching behavior occurred when the unilateral add was on the right or left eye of S5 (Fig. 4A), but appeared only when the +2 D add was placed in front of the left of S8 (Fig. 4B). After switching focus from the distance to the near corrected eye, both subjects tracked the stimulus with the near corrected eye. Another atypical behavior from an early presbyope

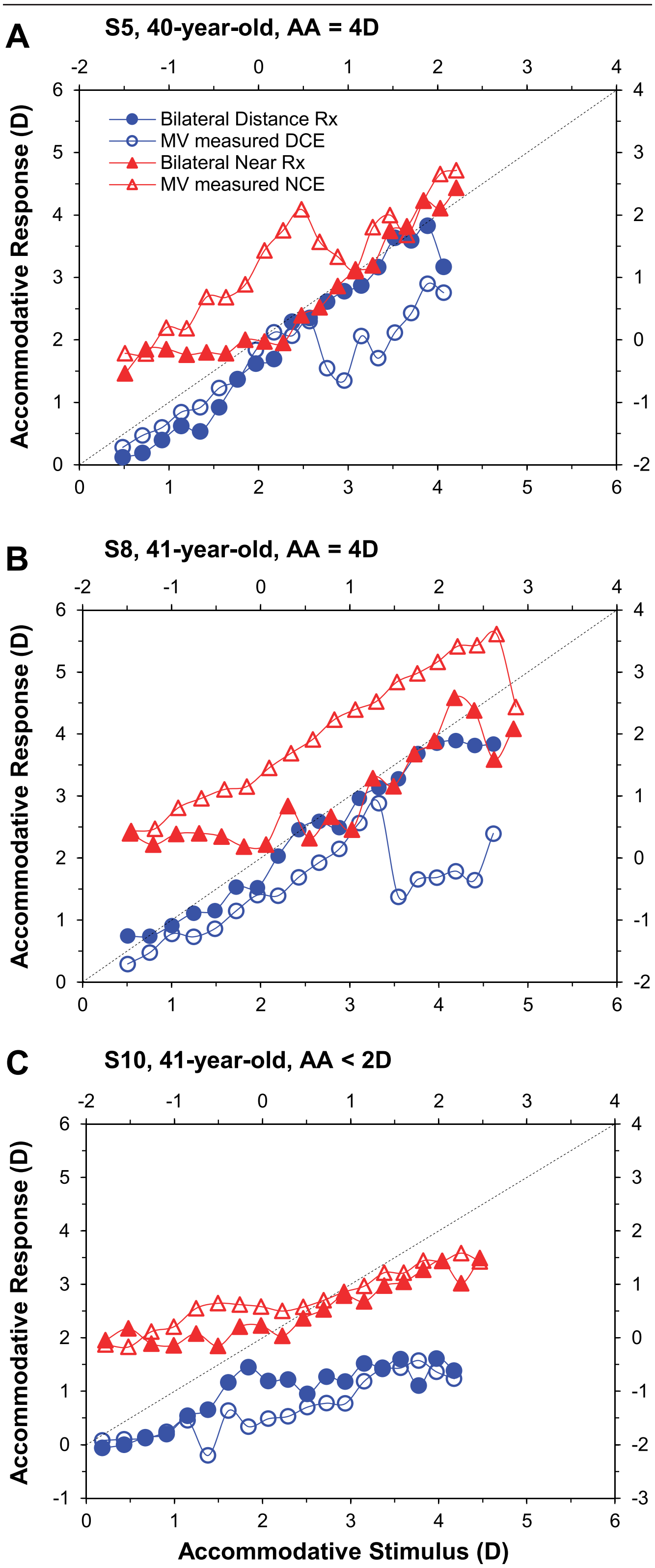

FIGURE 4. Examples of paraxial accommodative response as a function of accommodative stimulus for three early presbyopes who exhibited atypical responses: (A) S5: AA = 4 D, (B) S8: AA = 4 D, and (C) S10: AA < 2 D (same symbols, color code, and axes scales as in Fig. 2). Each data point represents the mean of five measurements. The dashed line in each plot represents *y* = *x*.

(S10) with less than 2 D of accommodation fit with monovision (Fig. 4C) shows accommodation with monovision that is similar to that observed with the bilateral near correction. Most of the accommodative response occurs after the target has approached closer than the 50-cm far point of the near corrected eye.

Defocus and Image Quality

The individual subjects' data in Figs. 2 and 4 reveal that defocus due to accommodative leads or lags varied between eyes and subjects. For example, with monovision, the distance corrected eye of subjects S6 and S7 had average lags of 0.75 and 0.25 D, but their near corrected eyes experienced +1.2 and +1.75 D of defocus, respectively. S11 kept the distance corrected eye in approximate focus beyond the eye's near point, but as the target approached closer, this eye became increasingly defocused, but the near corrected eye achieved a focused image when the target vergence equaled the accommodative amplitude plus the 2 D add, a target vergence of about −3.5 D. The distance corrected eye of S5 who "switched" was well focused up to 2.5 D of accommodative stimulus, but then accommodation was relaxed, allowing the near corrected eye to become approximately focused for vergences of less than −2.5 D.

Image quality is heavily influenced by defocus, but also dependent on pupil size and aberration levels, both of which change during accommodation[2,15,28,29,31] and during near viewing in presbyopic eyes.[2,16,31–34] Near pupil miosis for each of the four refractive conditions (Fig. 5) was not significantly different ($P > .05$, one-way repeated-measures analysis of variance) and did not vary with age. The same previously observed nonlinearity in the near pupil miosis behavior of younger adults[35] was also observed in our early presbyopic subjects. For the restricted target distance range of 2 m to 50 cm, near miosis was typically quite low (mean = −0.08 and −0.03 mm/D) for bilateral distance and bilateral near corrections, increasing to −0.28 and −0.36 mm/D for distances between 50 cm and 20 cm.

With bilateral distance correction, we observed a mean rate of change of spherical aberration of −0.045 ± 0.04 μm/D (microns of C_4^0 per diopter of accommodative stimulus),[16] which was almost identical to that observed with monovision (−0.049 ± 0.05 μm/D). This shift toward negative spherical aberration is due to changes in lens shape,[28] which has also been affected by the accompanying pupil miosis.[21,28,36] Without any near pupil miosis, the change in spherical aberration would have been −0.062 ± 0.06 μm/D. Although there was a negative shift in spherical aberration during accommodation, peak possible image quality (image quality at the retinal conjugate plane) varied little as the target approached the eye (peak VSOTF image quality dropped from a mean of 0.25 to 0.19 as the target vergence changed from −0.5 to −5 D). Changes in the actual achieved image quality were, however, dominated by the amount of defocus caused by accommodative lags, which in our binocular viewing test environment remained small for most subjects who could accommodate more than 2 D (mean lag was −0.46 ± 0.45 D for distances beyond their near point and ≤0.25 D in half of these subjects).

The combined impact of accommodative errors, aberrations, and pupil size on image quality is characterized by the ratio of the achieved/peak VSOTF as target vergence changed (Fig. 6). With bilateral distance correction, image quality for S2, who accommodated over the full stimulus range for this experiment (Fig. 2A), remains within 0.5 log units of peak (mean = −0.24 ± 0.17) over the full stimulus range (Fig. 6A). With bilateral near correction,

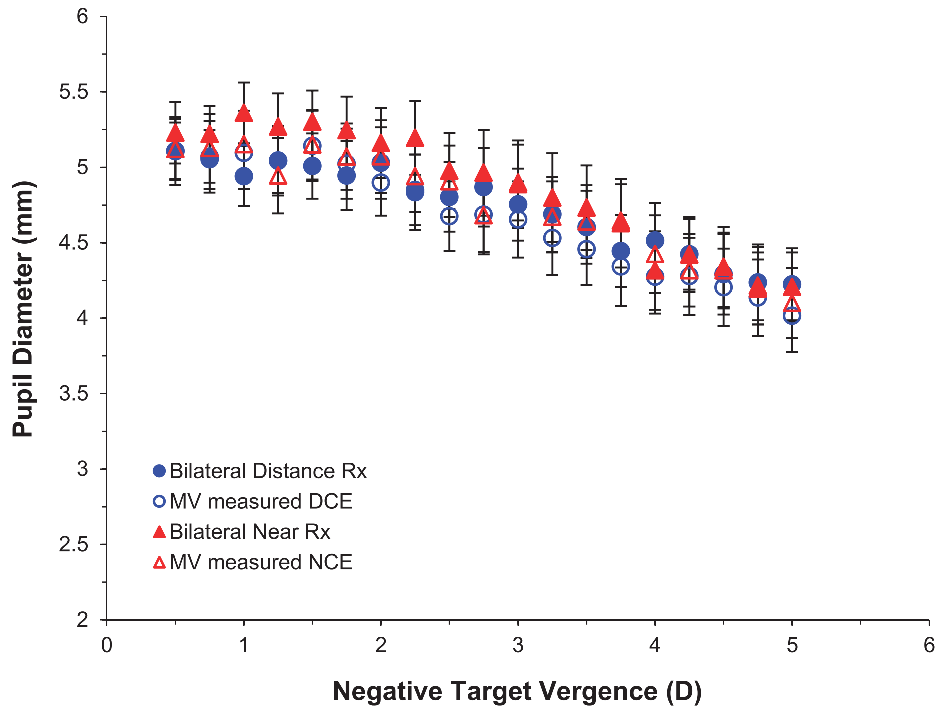

FIGURE 5. Average pupil diameter (mm) as a function of negative target vergence (D) observed with bilateral distance correction (filled circles), bilateral near +2 D add (filled triangles), and monovision when the right distance corrected eye (DCE) is measured (open circles) or when the right near corrected eye (NCE) is measured (open triangles). Error bars represent ± SEM.

image quality at 2 m is about 1% of optimum, but this increased and approached the optimum once the target became closer than the 50-cm far point. With monovision, image quality for the distance corrected eye was very similar to that observed with bilateral distance correction, but remained less than 1% of optimum for the near corrected eye for all target distances.

A similar pattern is seen for S7 and S11 with reduced accommodative amplitude (Figs. 6B, C), but only for distances beyond this subject's near point. With monovision, image quality in the distance corrected eye progressively declined for targets closer than the near point, but conversely increased over this stimulus range for the near corrected eye. As targets approached closer than the near point of the distance corrected eyes (e.g., at −3.5 D for S7 and −2 D for S11), image quality was low in both eyes because of an excess of power (+defocus) in the near corrected eye and insufficient power (−defocus) in the distance corrected eye. The full presbyope S19 (Fig. 6D) exhibits declining image quality with decreasing distance in the distance corrected eye, but an image quality peak at −2 D target vergence in the near corrected eye. Thus, S19 has high image quality in the distance and near corrected eyes only at their respective far points (zero accommodative stimulus), and both eyes have reduced image quality at intermediate distances.

Image quality data for subjects S5 and S8, who relaxed their accommodation to switch their focus to the near corrected eyes, showed abrupt changes in image quality at accommodative stimuli of 2.5 and 3.5 D, respectively (Figs. 6E, F). Image quality in the distance corrected eye dropped to between 2% and 0.3% of optimum, respectively, whereas the image quality in the near corrected eye increases to near optimum. Significantly, this switching behavior avoids the situation reported above, where both eyes have a reduced image quality, because the switch is made by relaxing accommodation from focusing the distance corrected eye to focusing the near corrected eye, and therefore at all distances one eye remains focused.

DISCUSSION

At typical reading distances,[37] most early presbyopes fit with monovision ignored the unilateral near add provided through monovision and accommodated to focus with the distance corrected eye, leaving the near corrected eye myopically defocused and with reduced image quality (Figs. 2, 3, and 6). Only two of our subjects relaxed their accommodation to focus with the near corrected eye as target distance was reduced (Figs. 4A, B). Therefore, monovision corrections in patients with remaining accommodation greater than the add power generally extended the total range of clear vision but did not reduce the accommodative responses for targets farther than their distance corrected eyes' near points. They also retained maximum accommodative responses for distances closer than their distance corrected eye's near point. This behavior comes with the cost of bilateral defocus and a bilateral drop in image quality as target distances become closer than the distance corrected eye's near point (Figs. 6B, C). At these distances, stimuli remain farther than the retinal conjugate plane of the near corrected (and accommodated) eye, producing the classic bilateral dip in image quality observed at intermediate distances when complete presbyopes are fit with monovision.[38,39]

The two subjects who actively switched from focusing the distance corrected to the near corrected eye did not suffer from this

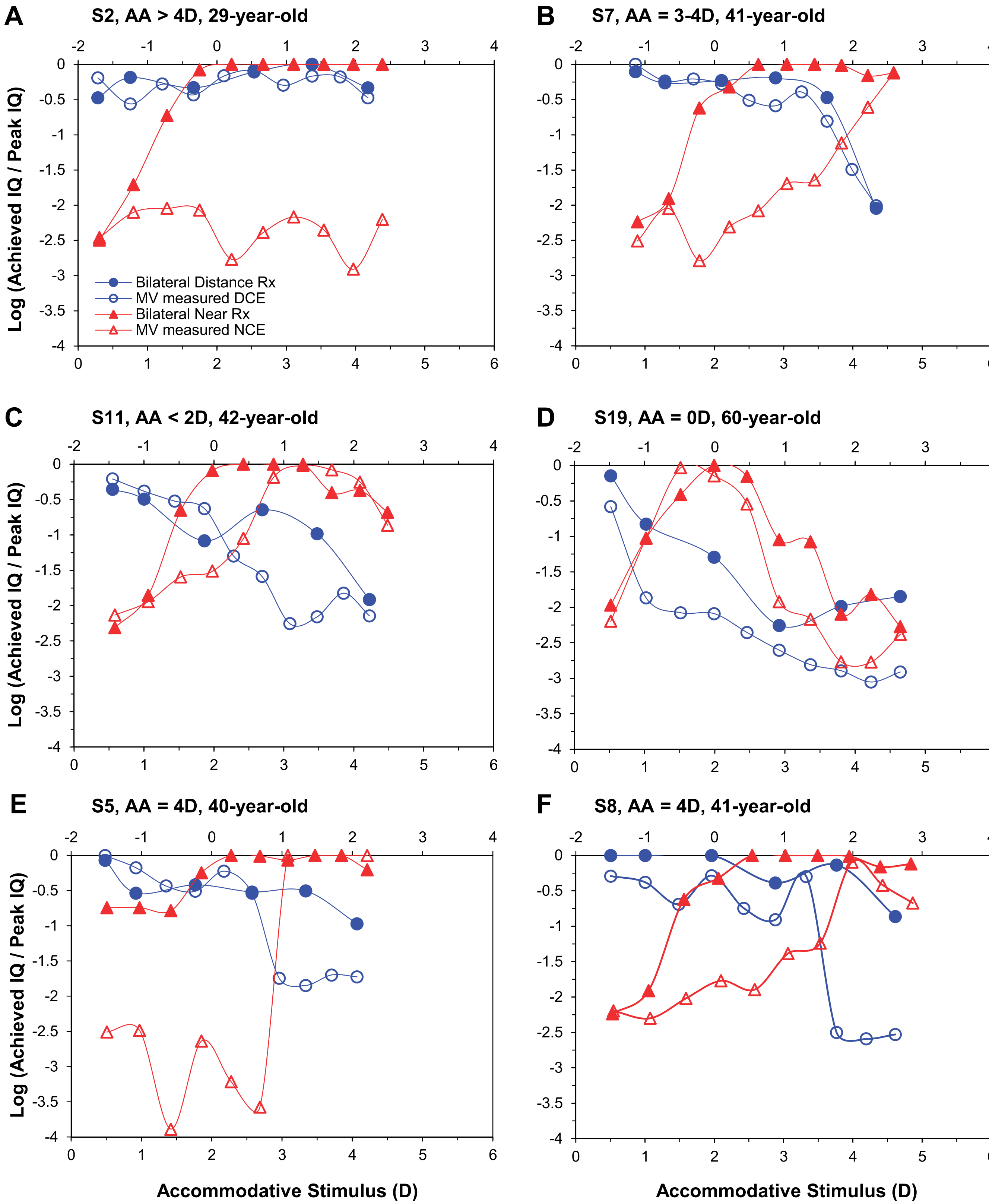

FIGURE 6. Observed drop in VSOTF image quality (log VSOTF normalized to the maximum possible if accommodation was perfect) is plotted as a function of accommodative stimulus for six different subjects with varying amplitudes of accommodation (AA): (A) S2: AA > 4 D, (B) S7: AA = 3-4 D, (C) S11: AA < 2 D, (D) S19: AA = 0 D, (E) S5: AA = 4 D, and (F) S8: AA = 4 D (same *x*-axis scale as in Fig. 2). The drop in image quality is quantified for each subject fit with bilateral distance correction (filled circles), bilateral near +2 D add (filled triangles), and monovision with right eye distance corrected (open circles) or near corrected (open triangles). The accommodative stimulus/response curves for these subjects are plotted in Figs. 2 and 4.

bilateral defocus (Figs. 6E, F), and thus their behavior was better able to take advantage of the monovision correction retaining a consistently focused image in one eye over a wider range of target distances. As long as visual performance and perceived visual quality are dominated by the better focused eye,[38–40] these subjects will retain high-quality vision over an extended dioptric range. This switching behavior is possibly learned by successful monovision patients with remaining accommodation, but was absent in most of our early presbyopes lacking clinical experience with monovision.

The current data highlight a paradox. If early presbyopes fit with monovision do indeed accommodate to focus the distance corrected eye, they will experience no visual gain beyond their near point. In fact, they will experience reduced binocular summation[41] and degraded stereopsis[42,43] because of the habitual monocular defocus in the near corrected eye and benefit from the monovision correction only when targets are closer than their near point. Could this be one reason why some early presbyopes fail to accept a monovision correction?[10,44]

The suboptimal strategy of always accommodating to focus with the distance corrected eye when fit with monovision has been observed in children[9] and in young adults.[14] These subjects did not alter their accommodation response to refocus the near corrected eye, indicating that binocular convergence dominated accommodation responses when fit with monovision,[45,46] avoiding the need to recalibrate the accommodation and convergence interactions. The resulting habitual defocus and image degradation in the near corrected eye would create a risk of developing amblyopia or anomalous eye growth in children,[9,47] but it is unlikely that amblyopia will develop in presbyopes fit with monovision,[7] because the sensitive period for human visual development is completed in late childhood.[48] However, monovision can precipitate strabismus in some binocularly vulnerable patients fit with monovision, perhaps because of the chronic monocular image degradation.[49,50]

The two eyes of normal individuals accommodate equally, that is, consensual accommodation, which is generally found even in the presence of anisometropia/monovision.[51,52] We did not measure the refractive state of both eyes in the current study, but the approximately 2-D difference (1.92 ± 0.25 D) observed when the measured right eye was fit with a distance or near correction as part of monovision emphasizes that irrespective of the eye being fit with the near add the refractive state of the near corrected eye remained about 2 D more myopic than that of the distance corrected eye. This difference would presumably be considerably less than 2 D if significant levels of aniso-accommodation occurred.[53]

When viewing through bilateral near corrections, all but three of our subjects were able to prevent accommodation despite the binocular convergence and proximal cues signaling an approaching target. Binocular convergence has been shown to be a powerful stimulus to accommodation in young adults when the image quality feedback loop is opened, but it can be partially suppressed when image quality is closed loop.[17,45] The closed-loop convergence-driven accommodative gain reported by Ramsdale and Charman[17,46] (see their table 2) was about 0.02 D of accommodation per prism diopter of convergence, predicting 0.2 D of accommodation as the binocularly viewed stimulus approached 50 cm from 2 m, similar to the mean of 0.27 D that we observed. It seems that monovision partially opens this feedback loop, resulting in accommodative behavior that is dominated by the convergence stimulus, even though it can result in lowered image quality.

ARTICLE INFORMATION

Submitted: November 28, 2016

Accepted: September 11, 2017

Funding/Support: None of the authors have reported funding/support.

Conflict of Interest Disclosure: None of the authors have reported a conflict of interest.

Author Contributions and Acknowledgments: Conceptualization: MSA, AB; Data Curation: MSA; Formal Analysis: MSA, BHA, AB; Methodology: MSA, BHA, AB; Project Administration: MSA; Writing – Original Draft: MSA, AB; Writing – Review & Editing: MSA, AB. Some of the data were presented at two meetings: the American Academy of Optometry Annual Meeting, October 2015, New Orleans, Louisiana, and at the Association for Research in Vision and Ophthalmology Meeting, May 2016, Seattle, Washington.

REFERENCES

1. Duane A. Studies in Monocular and Binocular Accommodation, with Their Clinical Application. Trans Am Ophthalmol Soc 1922;20:132–57.

2. Lopez-Gil N, Fernandez-Sanchez V, Legras R, et al. Accommodation-related Changes in Monochromatic Aberrations of the Human Eye as a Function of Age. Invest Ophthalmol Vis Sci 2008;49:1736–43.

3. Ostrin LA, Glasser A. Accommodation Measurements in a Prepresbyopic and Presbyopic Population. J Cataract Refract Surg 2004;30:1435–44.

4. Holden BA, Fricke TR, Ho SM, et al. Global Vision Impairment Due to Uncorrected Presbyopia. Arch Ophthalmol 2008;126:1731–9.

5. Charman WN. Developments in the Correction of Presbyopia I: Spectacle and Contact Lenses. Ophthalmic Physiol Opt 2014;34:8–29.

6. Gupta N, Naroo SA, Wolffsohn JS. Visual Comparison of Multifocal Contact Lens to Monovision. Optom Vis Sci 2009;86:E98–105.

7. Fawcett SL, Herman WK, Alfieri CD, et al. Stereoacuity and Foveal Fusion in Adults with Longstanding Surgical Monovision. J AAPOS 2001;5:342–7.

8. Anderson HA, Hentz G, Glasser A, et al. Minus-lens-stimulated Accommodative Amplitude Decreases Sigmoidally with Age: A Study of Objectively Measured Accommodative Amplitudes from Age 3. Invest Ophthalmol Vis Sci 2008;49:2919–26.

9. Phillips JR. Monovision Slows Juvenile Myopia Progression Unilaterally. Br J Ophthalmol 2005;89:1196–200.

10. Back A. Factors Influencing Success and Failure in Monovision. Int Contact Lens Clin 1995;22(7–8):165–72.

11. Hom MM. Monovision and LASIK. J Am Optom Assoc 1999;70:117–22.

12. Bennett ES. Contact Lens Correction of Presbyopia. Clin Exp Optom 2008;91:265–78.

13. Bullimore MA, Jacobs RJ. Subjective and Objective Assessment of Soft Bifocal Contact Lens Performance. Optom Vis Sci 1993;70:469–75.

14. Schor C, Erickson P. Patterns of Binocular Suppression and Accommodation in Monovision. Am J Optom Physiol Opt 1988;65:853–61.

15. Radhakrishnan H, Charman WN. Age-related Changes in Static Accommodation and Accommodative Miosis. Ophthalmic Physiol Opt 2007;27:342–52.

16. Almutairi MS, Altoaimi BH, Bradley A. Accommodation and Pupil Behaviour of Binocularly Viewing Early Presbyopes. Ophthalmic Physiol Opt 2017;37:128–40.

17. Ramsdale C, Charman WN. A Longitudinal Study of the Changes in the Static Accommodation Response. Ophthalmic Physiol Opt 1989;9:255–63.

18. Bharadwaj SR, Candy TR. Accommodative and Vergence Responses to Conflicting Blur and Disparity Stimuli during Development. J Vis 2009;9:4.1–18.

19. Seijas O, Gomez de Liano P, Gomez de Liano R, et al. Ocular Dominance Diagnosis and Its Influence in Monovision. Am J Ophthalmol 2007;144:209–16.

20. Xu R, Bradley A, Thibos LN. Impact of Primary Spherical Aberration, Spatial Frequency and Stiles Crawford Apodization on Wavefront Determined Refractive Error: A Computational Study. Ophthalmic Physiol Opt 2013;33:444–55.

21. Thibos LN, Bradley A, Lopez-Gil N. Modelling the Impact of Spherical Aberration on Accommodation. Ophthalmic Physiol Opt 2013;33:482–96.

22. Schmitz S, Krummenauer F, Henn S, et al. Comparison of Three Different Technologies for Pupil Diameter Measurement. Graefes Arch Clin Exp Ophthalmol 2003;241:472–7.

23. Rabbetts R. Bennett and Rabbett's Clinical Visual Optics, 4th ed. London: Elsevier Health Sciences; 2007.

24. Heath GG. The Influence of Visual Acuity on Accommodative Responses of the Eye. Am J Optom Arch Am Acad Optom 1956;33:513–24.

25. Lopez-Gil N, Fernandez-Sanchez V, Thibos LN, et al. Objective Amplitude of Accommodation Computed from Optical Quality Metrics Applied to Wavefront Outcomes. J Optom 2009;2:223–34.

26. Campbell CE. Determining Spherocylindrical Correction Using Four Different Wavefront Error Analysis Methods: Comparison to Manifest Refraction. J Refract Surg 2010;26:881–90.

27. Thibos LN, Hong X, Bradley A, et al. Accuracy and Precision of Objective Refraction from Wavefront Aberrations. J Vis 2004;4:329–51.

28. Lopez-Gil N, Fernandez-Sanchez V. The Change of Spherical Aberration during Accommodation and Its Effect on the Accommodation Response. J Vis 2010; 10:12.

29. Plainis S, Ginis HS, Pallikaris A. The Effect of Ocular Aberrations on Steady-state Errors of Accommodative Response. J Vis 2005;5:466–77.

30. Bradley A, Xu R, Thibos L, et al. Influence of Spherical Aberration, Stimulus Spatial Frequency, and Pupil Apodisation on Subjective Refractions. Ophthalmic Physiol Opt 2014;34:309–20.

31. Aldaba M, Vilaseca M, Arjona M, et al. Age-related Changes in Accommodation Measured with a Double-pass System. Ophthalmic Physiol Opt 2013;33:508–15.

32. Chateau N, De Brabander J, Bouchard F, et al. Infrared Pupillometry in Presbyopes Fitted with Soft Contact Lenses. Optom Vis Sci 1996;73:733–41.

33. Radhakrishnan H, Charman WN. Age-related Changes in Ocular Aberrations with Accommodation. J Vis 2007;7:11 1–21.

34. Schafer WD, Weale RA. The Influence of Age and Retinal Illumination on the Pupillary Near Reflex. Vision Res 1970;10:179–91.

35. Charman WN, Radhakrishnan H. Accommodation, Pupil Diameter and Myopia. Ophthalmic Physiol Opt 2009;29:72–9.

36. Gambra E, Sawides L, Dorronsoro C, et al. Accommodative Lag and Fluctuations when Optical Aberrations Are Manipulated. J Vis 2009;9:4 1–15.

37. Dexl AK, Seyeddain O, Riha W, et al. Reading Performance After Implantation of a Modified Corneal Inlay Design for the Surgical Correction of Presbyopia: 1-Year Follow-up. Am J Ophthalmol 2012;153: 994e2–1001e2.

38. Ravikumar S, Bradley A, Bharadwaj S, et al. Expanding Binocular Depth of Focus by Combining Monovision with Diffractive Bifocal Intraocular Lenses. J Cataract Refract Surg 2016;42:1288–96.

39. Vandermeer G, Rio D, Gicquel JJ, et al. Subjective through-focus Quality of Vision with Various Versions of Modified Monovision. Br J Ophthalmol 2015;99: 997–1003.

40. Legras R, Hornain V, Monot A, et al. Effect of Induced Anisometropia on Binocular through-focus Contrast Sensitivity. Optom Vis Sci 2001; 78:503–9.

41. Loshin DL. Binocular Summation with Monovision Contact Lens Correction for Presbyopia. Int Contact Lens Clin 1982;9(3):162–5.

42. Lit A. Presentation of Experimental Data. J Am Optom Assoc 1968;39:1098–9.

43. McGill E, Erickson P. Stereopsis in Presbyopes Wearing Monovision and Simultaneous Vision Bifocal Contact Lenses. Am J Optom Physiol Opt 1988;65: 619–26.

44. Erickson P, McGill EC. Role of Visual Acuity, Stereoacuity, and Ocular Dominance in Monovision Patient Success. Optom Vis Sci 1992; 69:761–4.

45. Fincham EF, Walton J. The Reciprocal Actions of Accommodation and Convergence. J Physiol 1957; 137:488–508.

46. Ramsdale C, Charman WN. Accommodation and Convergence: Effects of Lenses and Prisms in ‘Closed-loop’ Conditions. Ophthalmic Physiol Opt 1988;8:43–52.

47. Barrett BT, Bradley A, Candy TR. The Relationship between Anisometropia and Amblyopia. Prog Retin Eye Res 2013;36:120–58.

48. Vaegan , Taylor D. Critical Period for Deprivation Amblyopia in Children. Trans Ophthalmol Soc U K 1979;99: 432–9.

49. Ito M, Shimizu K, Iida Y, et al. Five-year Clinical Study of Patients with Pseudophakic Monovision. J Cataract Refract Surg 2012;38:1440–5.

50. Pollard ZF, Greenberg MF, Bordenca M, et al. Strabismus Precipitated by Monovision. Am J Ophthalmol 2011;152:479–82 e1.

51. Bharadwaj SR, Candy TR. The Effect of Lens-Induced Anisometropia on Accommodation and Vergence during Human Visual Development. Invest Ophthalmol Vis Sci 2011;52:3595–603.

52. Koh LH, Charman WN. Accommodative Responses to Anisoaccommodative Targets. Ophthalmic Physiol Opt 1998;18:254–62.

53. Marran L, Schor CM. Lens Induced Aniso-accommodation. Vision Res 1998;38:3601–19.