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Impact of monovision on dynamic accommodation of early presbyopes

Meznah S Almutairi[1,2], Basal H Altoaimi[1] and Arthur Bradley[2]

[1]Department of Optometry, College of Applied Medical Sciences, King Saud University, Riyadh, Saudi Arabia, and [2]School of Optometry, Indiana University, Bloomington, USA

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Correspondence: Meznah S Almutairi
E-mail address: mzalmutairi@ksu.edu.sa

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Abstract

Purpose: To examine the impact of monovision on dynamic changes in accommodation, pupil responses, spherical aberration and resultant image quality in early presbyopes.

Methods: Refractive state, pupil size and spherical aberration levels were monitored in nine early presbyopes who exhibited some accommodation (40–50 years, mean = 42 ± 2.37 years) using a Shack-Hartmann aberrometer as a binocularly viewed stimulus stepped closer (from 2 m to 40 cm), or farther (from 40 cm to 2 m). Comparison data from two fully presbyopic (i.e. non-accommodating) subjects (ages 46 and 61 years) and two young adults (ages 26 and 29 years) were also collected. Each subject was fit with four different refractive strategies: (1) both eyes corrected for 2 m, (2) both eyes corrected for 40 cm, (3) monovision with the measured right eye corrected for 2 m and, (4) monovision with the right eye corrected for 40 cm. Monochromatic image quality was quantified using the AreaMTF metric.

Results: When fit with monovision, the largest number of early presbyopes produce an accommodative response dominated by the right eye correction (distance or near) as the stimulus is abruptly changed from the retinal conjugate plane of one eye to that of the other eye. However, the accommodative responses in some early presbyopes were always dominated by the distance corrected eye, the near corrected eye, or by convergence. When the stimulus approached, the near corrected eye experienced high image quality only if there was no accommodative response. However, reduced image quality was observed if an accommodative response was initiated. Neither accommodation nor pupil response latencies were longer with monovision corrections compared with bilateral distance corrections ($p > 0.05$). In the early presbyopes, spherical aberration was reduced during near viewing, but primarily due to pupil miosis and not lens shape changes.

Conclusion: As the stimulus was abruptly changed from the retinal conjugate plane of the distance corrected eye to that of the near corrected eye, most early presbyopes fit with monovision accommodated, which resulted in a decline, not an increase in image quality in the near corrected eye. These results reveal a non-optimal accommodative strategy in early presbyopes fit with monovision.

Introduction

Adjusting the optical power of the eye to focus stimuli at closer distances, accommodation, is achieved by ciliary muscle contraction and increase in the lens curvature, and the converse is true for disaccommodation as the eye adjusts power to focus on farther distances.[1] The accommodative responses of human eyes exhibit latencies between 300–500 ms,[2,3] and completion of the accommodation response can take up to about 1 s (routinely in the range 500 and 1000 ms) with mean velocities between 1 and 2 D s^{-1}.[2–4] Studies of accommodation dynamics in older eyes have reported normal[1,5,6] or increased latencies,[7] and some studies observed slower accommodation or disaccommodation rates.[1,5,6,8–10]

Presbyopia is caused by the age-related loss of accommodation resulting in zero accommodation in the population over 50 years of age,[1,11] and a common clinical strategy to treat presbyopia induces anisometropia (corrects one eye for distance and the other eye for near) with contact lenses, corneal refractive surgery, or intra ocular lenses[12,13] with the goal of generating clear vision at both distance and near without any accommodation.[14] This 'monovision' has been reported to be the most widely used and accepted contact lens treatment for presbyopia[15–18] with a reported success rate between 70% and 80%.[19] Clinical reports show that monovision is recommended most and works better for early presbyopes with low adds.[15,18,20–22] Pre-presbyopic patients fit with monovision corrections employ their accommodation to focus stimuli beyond the near point of their distance corrected eye, even though a focused image in the near corrected eye could be achieved with less or zero accommodation,[23–25] suggesting that their accommodative effort is dominated by binocular convergence and proximal cues[26,27] not a minimum effort to optimise image quality or achieve a focused retinal image.[28,29]

The influence of convergence on accommodation is most easily seen when the defocus signal is made 'open-loop' with small pupils,[26,30,31] laser speckle,[27] or already blurred stimuli.[32–35] Monovision can also partially open the defocus loop of accommodation. For example, if optical vergence of a binocularly viewed target focused by the distance corrected eye is abruptly changed by an amount equal to the add power in the monovision prescription, the focused image will switch from one eye to the other, analogous to adding a purely convergence cue.[26] Such a distance change will generate very obvious changes in each monocular image, but potentially no change in the binocular percept, which will remain dominated by the focused image in one of the eyes.[13,14,36,37] Thus, binocular image quality would be the same if the patient accommodated perfectly or if they refrained from accommodating (as is the case when defocus is made open loop). Therefore, during an accommodative response to an object at the far point of the near corrected eye, image quality would decline until the accommodation response was completed, and if significant accommodative lag exists (as is common in early presbyopic eyes),[38,39] an accommodation response in this situation would actually lead to a reduction in image quality. The aim of this study was to explore the accommodation and disaccommodation behaviour of monovision corrected early presbyopes presented with such a step change in stimulus distance between the far point of the distance and near corrected eyes. Do they take advantage of the near add and refrain from accommodation as the stimulus is abruptly changed from the retinal conjugate plane of one eye to that of the other eye, or do they initiate an accommodative response that leads to reduced image quality?

Methods

Subjects

Dynamic accommodative responses of nine presbyopic subjects aged between 40 and 50 years who exhibited some accommodation (41 (four subjects), 42 (two subjects), 46 (two subjects), and 47 years (one subject)),[40] and for comparison, two fully presbyopic (i.e. non-accommodating) subjects age 46 and 61) and two younger subjects (ages 27 and 29 years) were also tested. Accommodation gain and amplitude of the nine early presbyopes has been reported previously.[38] Our age sampling was motivated by the known ages at which patients begin to rely on presbyopic corrections (early estimates around 40 years, and later into the fifth decade for monovision.[41–44] All had best-corrected visual acuity of 6/6 (20/20) or better in both eyes, <1.00 dioptre (D) of anisometropia, and an absence of ocular disease or a history of ocular surgery. The mean spherical equivalent was -1.00 ± 2.06 D for the right eye and -1.00 ± 1.82 D for the left eye, and all testing was made while binocularly viewing through their subjectively determined distance spectacle plane corrections (SL *Figure* 1) modified to make either the distant 2 m target or the near 40 cm target conjugate with the retina without any accommodative response (distance Rx + 0.50 D and distance Rx + 2.50 D, respectively). Sighting dominance was measured with a hole in the card test (seven subjects were right eye dominant while six were left eye dominant), although its relevance to monovision is uncertain.[45] The experiment followed the tenets of the Declaration of Helsinki and was approved by the institutional research board at Indiana University. All subjects were recruited from the Indiana University population and informed consent was obtained from all subjects after verbal and written explanation of the study procedures.

Experimental set-up

Wavefront aberrations and pupil size were recorded (5.6 Hz sampling rate) using a Shack-Hartmann Complete Ophthalmic Analysis System (COAS) aberrometer (www.wfsci.com) as stimuli were alternately presented on one of two binocularly viewed identical micro-displays (www.emagin.com) positioned at 2 m and 40 cm from the observers' spectacle plane (target vergences of -0.50 D and

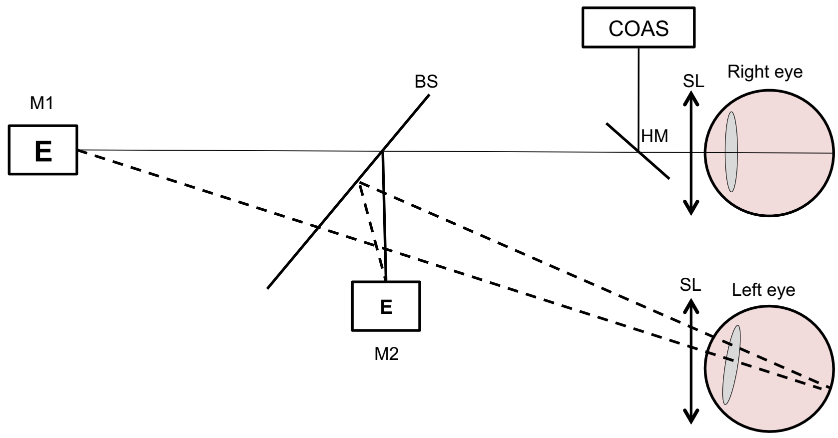

Figure 1. Schematic of the experimental setup. SL: spectacle lenses place at the measurement spectacle plane; HM: near infrared reflecting and visible light transmitting hot mirror; BS: 50/50 beam splitter; M1 and M2: micro displays placed at 2 m and 40 cm, respectively.

−2.50 D) in an otherwise dark room. A dark room avoided accommodation responses to other objects in the lab, and produced generally large pupils which helped reveal the near viewing pupil miosis and provided more comprehensive aberration measurements. Both displays were located along the primary gaze angle for the right eye, and the near display was viewed via reflection from a 50/50 beam splitter (www.edmundoptics.com) as shown in *Figure* 1. Stimuli were abruptly (between frames) switched between monitors. Individual aberrometry samples were time-stamped as was each change of the stimulus between distance and near displays using the Indiana University online time-stamp, which is accurate to 0.1 s.

Both micro displays had 852 × 600 pixels (13 × 9 mm display with 15 microns pixel width), which displayed 4 cd m^{-2} high-contrast black single 20/40 characters at both test distances on a white 400 cd m^{-2} background (luminance values measured through the beam splitter). No rotation was required for the measured right eye to maintain fixation, but the left eye had to rotate and thus subjects converged or diverged to maintain single vision as the target switched from far to near or vice versa. During the asymmetric convergence, which includes a conjugate versional movement of half the angle and then a symmetric vergence, the measured right eye must abduct with a short duration saccade[46] of approximately 4.3 degrees as target distance was changed from 2 m to 40 cm. Studies examining the isoplanatic extent of the human eye surrounding the fovea reveal that 4 degree eye rotations will introduce between approximately 0.1 and 0.2 D change in spherical refractive state.[47,48] We confirmed that asymmetric convergence or eye movement artefacts have no measurable effect on changing the eye's refractive state by testing a full presbyope with zero accommodation. We found no change in refractive state of the presbyope who maintained binocular fixation as the target abruptly changed from 2 m to 40 cm.

Experimental procedures

Refractive state was measured with four different optical corrections: (1) both eyes corrected for 2 m, (2) both eyes corrected for 40 cm, (3) monovision with the measured right eye (RE) corrected for 2 m and the unmeasured left eye (LE) corrected for 40 cm, (4) monovision with the RE corrected for 40 cm and the unmeasured LE is corrected for 2 m. Subjects were instructed to fixate the 20/40 character centred on the micro displays. At any time, only one of the two micro-displays were illuminated. The initial stimulus (at either 2 m or 40 cm) was viewed for 10 s after which an audible beep initiated each trial during which the subject was instructed to fixate and avoid blinking. After 3 s of aberrometry data collection, stimuli were switched to the other micro display for 3 s. During each trial, therefore, the accommodative demand of the visible stimulus abruptly changed by 2.00 D from 2 m to 40 cm or vice versa, which with monovision corrections changed between the retinal conjugate planes of the unaccommodated distance corrected eye to that of the unaccommodated near corrected eye, and vice versa.

Aberrometry and accommodation measures

Wavefront slope data for the full measured pupils (which varied in diameter during the experiment) were fitted with first differentials of the Zernike circular polynomials, from which two different commonly used measures of refractive state (RS) were calculated. Paraxial refractive error is the correcting lens that flattens the wavefront at the centre of the pupil and Minimum RMS (minRMS) refraction, often referred to as Zernike refraction, describes the sphere lens that corrects the average curvature of the wavefront across the entire pupil and thus minimises the total wavefront RMS. Both are calculated directly from Zernike coefficients

C_n^m in microns (μm) for a pupil radius R in millimetres (mm):[49,50]

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

$$\text{MinRMS RS} = \frac{(-C_2^0 4\sqrt{3})}{R^2}$$

Both measures of refractive state were employed because estimates of accommodative response amplitude depend on the pupil weight used to determine refractive state.[51] Measured refractive state at the spectacle plane was converted to the eye's entrance pupil plane using standard paraxial transfer equations and normalised to the refractive state required to focus the distant 2 m stimulus.[38] Image quality was quantified using the AreaMTF metric, which unlike Strehl ratio based metrics, provides meaningful estimates of image quality in the presence of up to 2.00 D of defocus.[50] Response latency was defined as the time at which changes in refractive state and pupil diameter reached two standard deviations above the mean of the pre-step responses.

Results

Figure 2 plots sample refractive state (top), pupil diameter (middle) and spherical aberration (bottom) responses to either a 2.00 D stimulus step closer (left panels), or 2.00 D step farther (right panels) for a 41-year-old subject (S3) viewing through either a bilaterally matched distance (blue symbols) or near (red symbols) correction. Black dashed lines represent the accommodative stimulus in dioptres. Measured refractive states have been normalised to that required to focus the 2 m distant target (measured RS + 0.50 D). Accommodative responses are indicated when the refractive state is more myopic than required to focus the 2 m stimulus in the distance corrected eyes, or more myopic than required to focus the 40 cm stimulus for the near corrected eyes.

As the stimulus changed from 2 m to 40 cm, this 41-year-old subject responded with a −1.25 D change in paraxial refractive state (*Figure* 2a) when viewing through the distance correction (+0.50 D), exhibiting a 0.75 D accommodative lag when viewing the 40 cm target. A large pupil miosis (pupil diameter decreased from 6.1 to 4.5 mm, *Figure* 2c), and a significant reduction in positive spherical aberration (*Figure* 2e) accompanied the accommodative response. The + 0.11 μm of primary spherical aberration (bottom row) present prior to the accommodative response generated a 0.40 D apparent accommodative lead in the minRMS measure of refractive state (*Figure* 2a, blue triangles), but due to changes in lens structure and pupil miosis, the measured spherical aberration approached zero (−0.003 μm) following the change in viewing distance, removing any differences between the paraxial and minRMS measures of refractive state. When viewing through the bilateral near correction (+2.50 D), normalised refractive state before the −2.00 D stimulus step was slightly more and slightly less than −2.00 D when measured with the minRMS and paraxial measures, respectively (red symbols, *Figure* 2a). In spite of the approximately zero accommodative response (normalised refractive states remained at about −2.00 D reflecting the added + 2.00 D spectacle lens), a large pupil miosis (from 6.4 to 3.8 mm, *Figure* 2c), and the accompanying reduction in positive spherical aberration (*Figure* 2e) removed most of the differences between paraxial and minRMS refractive states (*Figure* 2a).

When viewing the stimulus that stepped from 40 cm to 2 m (right panels in *Figure* 2), normalised refractive state changed from about −1.50 D to −0.25 D (*Figure* 2b), pupil diameter increased from 3.5 to 4.9 mm (*Figure* 2d), and spherical aberration increased from −0.016 to 0.043 μm (*Figure* 2f). Because the pupil did not dilate to the same diameter as that seen in the left panels when viewing the distance stimulus, measured spherical aberration levels were also smaller, as were the final differences in paraxial and minRMS refractive states.

To minimise this pupil size and spherical aberration dependency of the measure of refractive state,[52] the impact of monovision corrections on dynamic accommodative responses reported in *Figures* 3–6 describe paraxial refractive states. The mean (±1 standard error of the mean) accommodative, pupillary and spherical aberration responses are plotted for the nine early presbyopes in our sample as the stimulus was stepped from 2 m to 40 cm (*Figure* 3, left panels) and from 40 cm to 2 m (*Figure* 3, right panels). In each panel, data for the four refractive conditions are shown: bilateral distance correction for 2 m (filled blue circles), bilateral near correction for 40 cm (filled red triangles), monovision with distance correction over the measured right eye (open blue circles), and monovision with near correction over the measured right eye (open red triangles).

With the step from 2 m to 40 cm, the accommodative responses were largest when fit with bilateral distance correction (mean = 0.82 D), and smallest (mean = 0.21 D) when fit with bilateral near. With monovision, the mean accommodative responses were 0.56 D and 0.29 D when the right and left eyes, respectively, viewed through the distance correction (*Figure* 3a). Pupil diameter and spherical aberration changes were almost identical for all four conditions (*Figure* 3c & d), changing on average from 5.86 mm and 0.12 μm before the step to 4.35 mm and 0.02 μm at 1.5 s after the stimulus step. These results

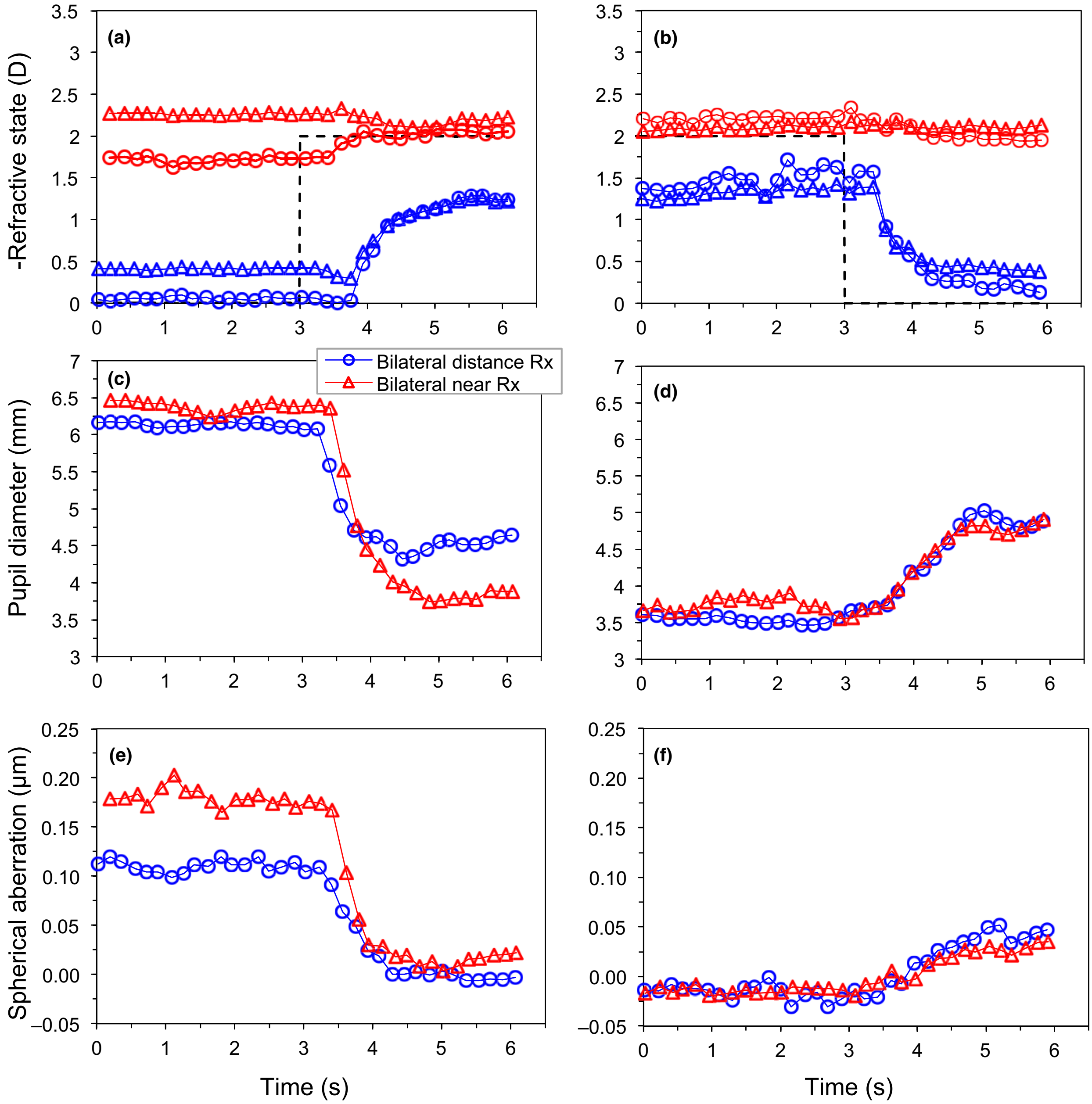

Figure 2. Measured refractive state as stimulus was switched from 2 m to 40 cm (a) and from 40 cm to 2 m (b), and the accompanying changes in pupil (c, d) and spherical aberration (e, f) are plotted as a function of time for a 41-year-old subject (S3) fit with a bilateral distance correction (blue symbols), and bilateral near correction (red symbols). Refractive changes are plotted using both paraxial (circles) and minimum RMS (minRMS) criteria (triangles). Dashed line represents the 2.00 D stimulus change.

confirm that pupil miosis associated with near vision occurs with and without an associated accommodative change, because miosis with bilateral distance and bilateral near were almost identical (actually slightly larger mean miosis with bilateral near correction, 1.65 mm vs 1.39 mm). Likewise, because the approximately equal changes in spherical aberration with bilateral distance and bilateral near correction (mean reduction of 0.07 µm), the primary spherical aberration reduction in early presbyopes as they view near targets is dominated by pupil miosis rather that accommodation. The pupil and spherical aberration changes that accompanied the stimulus were also observed in the two younger subjects (ages 26 and 29 years), and the two non-accommodating presbyopes

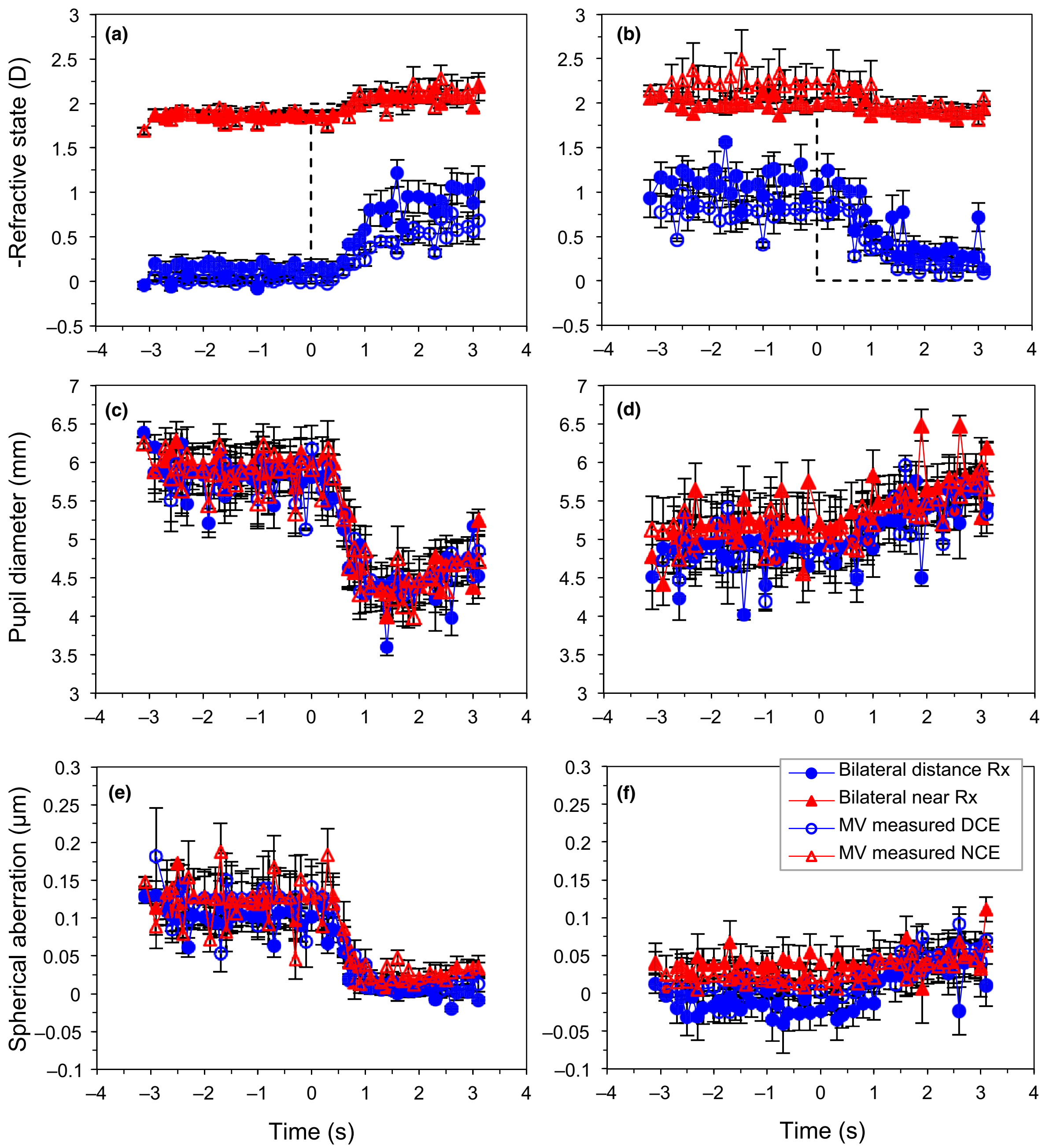

Figure 3. Mean paraxial refractive state (a, b), pupil diameter (c, d)) and spherical aberration (e, f) plotted as a function of time for early presbyopes (N = 9, 40 to 50 years) as the stimulus was stepped from 2 m to 40 cm (left panels) or from 40 cm to 2 m (right panels) at time = 0.0 s. In each subplot, data for the four refractive conditions are shown: bilateral distance correction (filled blue circles); bilateral near correction (filled red triangles); monovision (MV) with distance correction in measured right eye (DCE, open blue circles); and MV with near correction in measured right eye (NCE, open red triangles). Dashed line represents the 2D stimulus change. Error bars represent ±1 standard error of the mean (SEM).

(ages 46 and 61 years), emphasising that near pupil miosis and reductions in spherical aberrations occur almost independent of the accommodation responses.

When the stimulus stepped from 40 cm to 2 m (*Figure* 3, right panels), the pre-step refractive state mirrored the post-step data when changing from distance to near. As the stimulus was stepped to 2 m, refractive state in the distance corrected right eye dropped to −0.30 D and −0.20 D with the bilateral and monocular distance corrections, respectively. With a near corrected right eye, normalized

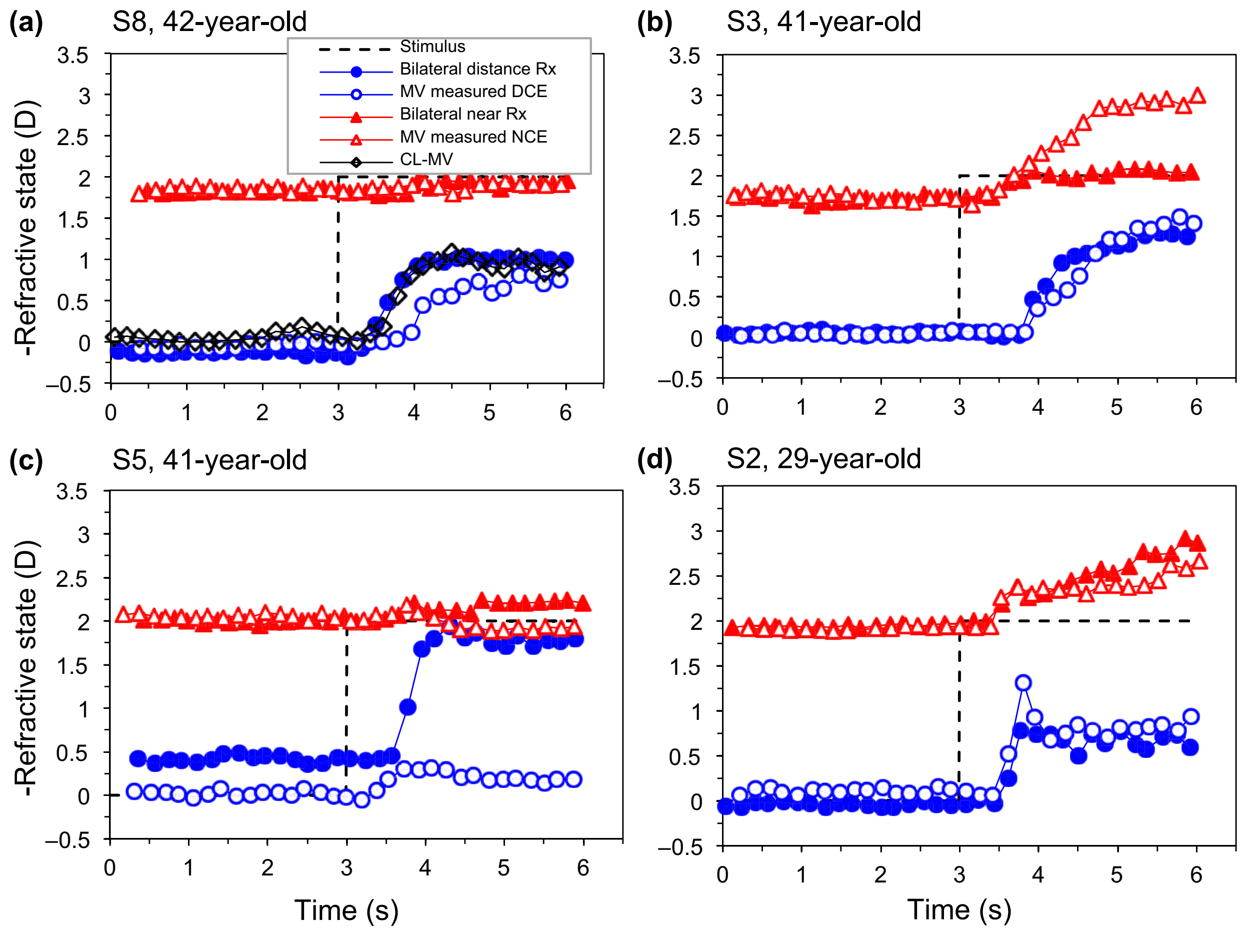

Figure 4. Paraxial refractive state (far-to-near) against time as the stimulus was stepped from 2 m to 40 cm. The colour code in each subplot is the same as in Figure 3. (a) S8, a 42-year-old subject (black diamonds show data collected with this subject's habitual monovision correction), (b) S3, a 41-year-old subject, (c) S5, a 41-year-old subject, and (d) S2, a 29-year-old subject.

refractive states were almost stable at ~-2.00 D with bilateral near correction and dropped from −2.20 D to −1.90 D with monovision (*Figure* 3b). The accommodative data in *Figure* 3 reveals that, on average, early presbyopes fit with monovision produce an accommodative response dominated by the right eye correction (distance or near). However, when the right eye is corrected for distance, monovision produces generally lower responses than for bilateral distance correction (0.56 D vs 0.82 D for accommodation and 0.63 D vs 0.75 D for disaccommodation) and conversely, when the right eye is corrected for near it produces slightly larger responses compared to bilateral near correction (0.29 D vs 0.21 D for accommodation and 0.28 D vs 0.10 D for disaccommodation).

The between subject standard deviations in refractive state (average S.D. across all conditions = 0.3 D) were 3× larger than the within subject SDs observed from repeat measures (S.D. = 0.1 D). Also, the between subject accommodative response SDs with bilateral distance correction increased from 0.24 D before the response to 0.48 D after the 2.00 D far-to-near response. This increase is primarily due to between subject differences in accommodative response amplitudes (ranging from 0.40 D to 1.90 D, as anticipated in this age group.[38]

In addition to between subject differences in accommodative gain, pupil size, and spherical aberration levels observed with bilaterally matched corrections, not every subject responded the same way to the monovision corrections. As shown in *Figure* 3, the mean response for the early presbyopes viewing with monovision correction revealed a significant right eye dominance, but this was not observed in every subject. Examples of four unique accommodative behaviours observed with monovision are plotted for the far to near step (*Figure* 4) and the near to far step (*Figure* 5). For example, when stepping from far to near, the behaviour of subject S8 reveals a right eye dominance behaviour, with monovision accommodation mirroring that exhibited with bilateral distance and bilateral near

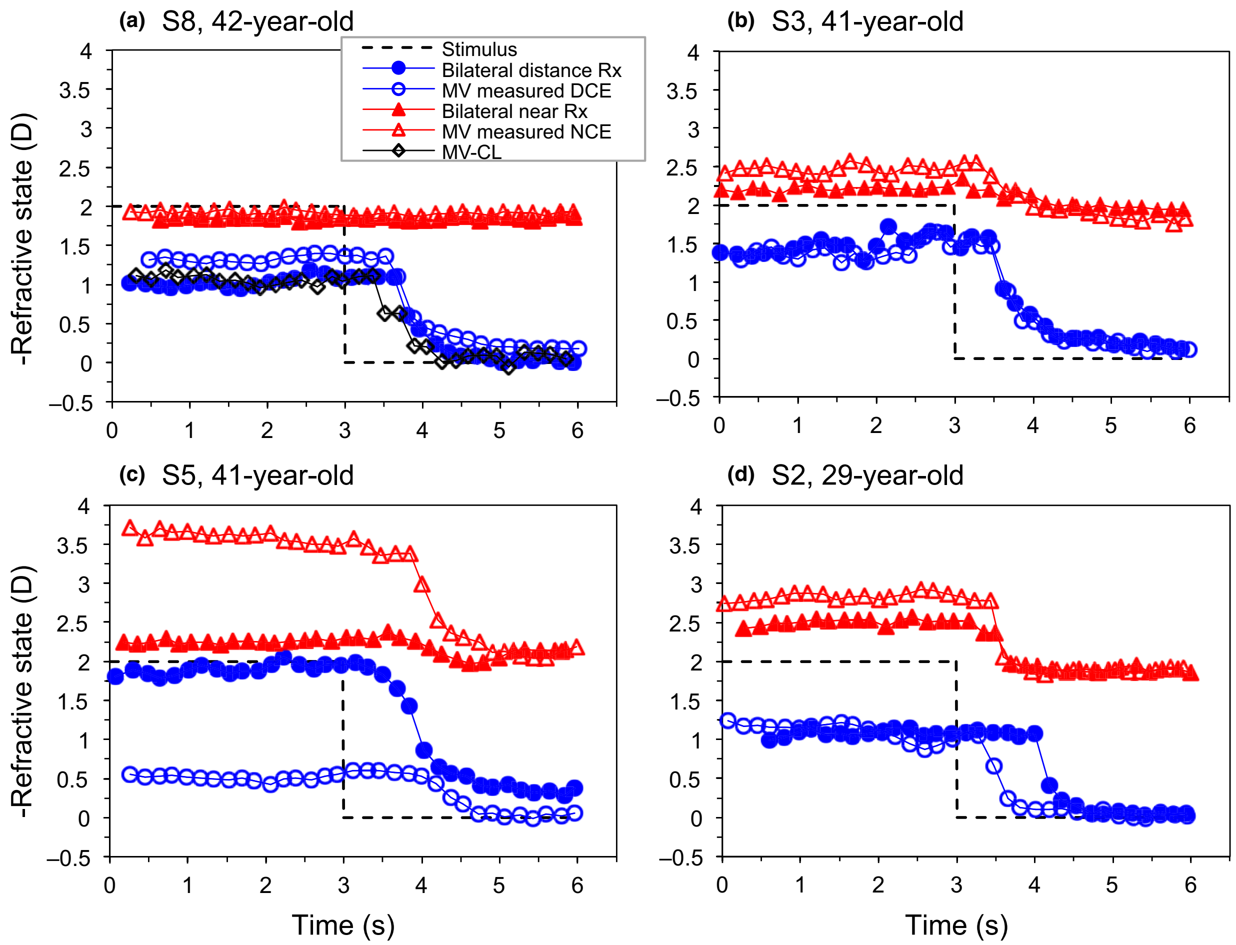

Figure 5. Paraxial refractive state (near-to-far) against time as the stimulus was stepped from 40 cm to 2 m for: (a) S8, a 42-year-old subject (black diamonds show data collected with this subject's habitual monovision correction); (b) S3, a 41-year-old subject; (c) S5, a 41-year-old subject; and (d) S2, a 29-year-old subject. The colour code in each subplot is the same as that in Figure 3.

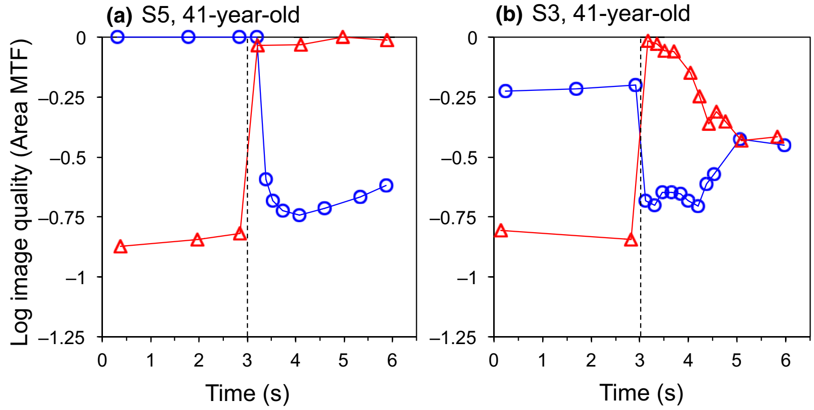

Figure 6. Examples of image quality in the distance (blue circles) and near (red triangles) corrected eyes of two monovision corrected subjects as the stimulus was stepped (dashed black line) from the distance corrected eye far point (2 m) to the near corrected eye far point (40 cm). S5 did not initiate an accommodative response (a) and S3 initiated a low gain accommodative response (b). Accommodation curves for these subjects are plotted in Figure 4.

corrections when the right eye had the distance or near monovision correction, respectively (*Figure* 4a). Subject S3, however, always accommodated (1.25 D) if either or both eyes had a distance correction (*Figure* 4b), but mostly refrained from accommodating with bilateral near corrections (response ~ 0.25 D). Subject S5 (*Figure* 4c), refrained from accommodating when either the right, left or both eyes contained a + 2.00 D near correction, only accommodating when both eyes had a distance correction. Therefore, when fit with a monovision correction, one subject accommodated in an attempt to focus the right eye (S8), one the distance corrected eye (S3), and one the near corrected eye (S5). A fourth pattern reveals that S2 accommodated similar amounts irrespective of the optical correction (*Figure* 4d), suggesting that either convergence or proximal cues, which were common to all four optical conditions, were dominating the accommodative behaviour of this subject. In summary, of the nine early presbyopes, four subjects exhibited the right eye dominance, two subjects exhibited the distance corrected eye dominance, one the near corrected eye dominance, and two the convergence dominated behaviours. In addition, of the two young adults, one subject exhibited distance corrected eye dominance and the other exhibited convergence dominance (ages 26 and 29, respectively).

When stepping from 40 cm to 2 m (*Figure* 5), we also observed evidence of right eye dominance (e.g. S3 and S8), distance corrected eye dominated responses (S5) and matching accommodation responses for all four optical conditions (S2), with eight early presbyopes, two subjects; a young and an early presbyope, and one young subject showing these respective behaviours. When S8 was tested with their clinically prescribed habitual monovision contact lens correction (distance correction in right eye, +1.25 D near add in the left eye) the responses revealed the same right eye dominance seen with our + 2.00 D spectacle lens induced monovision (*Figures* 4a & 5a, black diamonds).

The intended function of monovision is to expand the depth of field by providing one in-focus image (right or left eye) when viewing either near or distance targets. This goal will be met by mature presbyopes, who lack any accommodation, but as the data in *Figures* 2–5 show, early presbyopes fit with monovision sometimes accommodate as targets are moved closer or farther between the retinal conjugate planes of the unaccommodated eyes. The different types and magnitudes of these accommodative responses will determine the defocus and thus the achieved image quality in each eye at both distances. *Figure* 6 shows examples of how image quality (log AreaMTF) varies during the far to near stimulus trials for two sample subjects exhibiting different accommodative behaviour with monovision: one refraining from accommodation (*Figure* 6a), and one accommodating when either eye had a near correction (*Figure* 6b). These plots show data from the measured right eyes, but because of the consensual nature of accommodative and pupil responses[53–55] these accommodative behaviours can also be used to infer the refractive, pupil, and image consequences for the unmeasured left eye.

Subject S5, who had high accommodative gain (*Figure* 4c) to the −2.00 D distance to near step (average response = 1.8 D), always refrained from accommodating to the 2.00 D step if either eye had a near correction. Therefore, this subject achieved approximately focused images in one eye both before and after the step from far to near, and thus the distance corrected eye had high image quality when the stimulus was at 2 m and the near corrected eye at 40 cm (*Figure* 6a). S3 whose monovision responses mirrored the 1.25 D accommodative responses observed with bilateral distance correction when either the right or left eye had the distance correction (*Figure* 4b), resulted in improved image quality in the distance corrected eye (*Figure* 6b, blue circles), but the converse was true in the near corrected eye (*Figure* 6b, red triangles) where image quality declined such that after about 2 s image quality was reduced in both distance and near corrected eyes.

Latency analysis reveals that, with bilateral distance corrections, statistically significant refractive state changes (mean post-step response> 2 S.D. above the mean of the pre-step responses) occurred on average about 0.5 s after the far-near step and about 0.7 s after the near-far step (mean(S.D.) = 0.534(0.217) and 0.71(0.248), respectively). With monovision, this significant refractive change occurred on average about 0.4 s after the far-near step and about 0.5 s after the near-far step (mean(S.D.) = 0.477 (0.233) and 0.576(0.271), respectively). Pupil latencies were generally shorter and less variable (mean(S.D.) = 0.29 (0.118) with bilateral distance correction, and slightly longer (0.4(0.14) s) with monovision). In summary, monovision corrections did not introduce significant delays in accommodation or pupil responses to the distance steps ($p > 0.05$).

Discussion

In this study, the impact of monovision on dynamic accommodation and disaccommodation patterns was explored among a group of early presbyopes who make up the patient group that has most successfully employed monovision (only one subject used monovision as their habitual correction). When subjects were presented with a step change in stimulus distance from the unaccommodated retinal conjugate plane of one eye to that of the other eye, some always initiated an accommodative response controlled by the distance corrected eye that led to reduced image quality in both eyes (e.g. subject S3, *Figure* 4 & *Figure* 6). However, others demonstrated a form of right eye dominance that also led to reduced image quality only if the right eye was corrected for distance (e.g. subject S8, *Figure* 4 & *Figure* 6). This accommodative eye dominance did not correlate with the measured sighting dominance. Other subjects employed an optimal accommodative response utilising the near add provided by monovision to focus the near target, which resulted in focused images and high image quality both before and after the stimulus step (e.g. Subject S5, *Figure* 4 & *Figure* 6). An earlier study by Schor and Erickson[25] contains many parallels with the current study design and data. When measuring range of distances enabling clear vision while viewing through a + 1.50 D monovision correction, early presbyopes exhibited different types of visual behaviours: some only saw clearly at distance with a distance corrected right eye, while some were able to see clearly at distance and near via some sensory 'switch' from the distance to the near corrected eye. The implications of these two behaviours are summarised in the Schor paper[25]: as the target was moved proximally approaching the far point of the near corrected eye 'the binocular image became blurred despite the fact that the movable target was within the clear zone of the left (near corrected) eye. This suggests an inability to switch ocular dominance from one eye to the other to maintain clarity'. In our study, some subjects exhibited the ability to switch accommodation control between the eyes, while others did not.

The bias in the accommodative behaviour data (dominated or controlled by the right eye) could be influenced by our experimental set-up in which the left eye had to rotate to maintain fixation after the step stimulus whereas the right eye did not. Therefore, as the stimulus was stepped, its retinal image location in the right eye did not change and thus the image quality change signal remained in the same retinal location, but in the left eye, the post-step stimulus was now located in a different retinal location (approximately a 2.3 mm shift in retinal location). However, in an experimental set-up that retained targets along the primary gaze axis for both eyes, similar right eye dominance was also observed.[25]

The less than optimal accommodative behaviour seen in the majority of the early presbyopes poses the question of whether successful monovision patients are able to modify their accommodative responses to changing target distances, effectively requiring negative relative accommodation[56] to achieve a focused image in one eye as the target distance is reduced. Our study did not employ a selection of successful monovision patients, but perhaps success with monovision requires adaptation to the modified accommodation/convergence relationship. Those subjects who always accommodated to the stimulus step with the monovision correction retain the normal convergence relationship to accommodation, but end up with reduced binocular image quality due to low accommodative gain. Do early presbyopes who are successful with monovision re-calibrate the relationship between accommodation and convergence via some neural adaptation?[57] The relationship between convergence and accommodation in patients with monovision correction is complicated by observations that monocular defocus produces reduced fusional ranges[58] and in some cases can induce strabismus.[59] Because many early presbyopes fit with monovision will exhibit some accommodation, design modifications of the simple monovision that include bifocal or multifocal optics in combination with monovision[13,60] should also include residual accommodation in their design because accommodation and multifocality can both be effective at reducing image blur at intermediate distances.

A previous study including young and early presbyopes tested monocularly,[61] found that accommodative latency was shorter than that for the pupil, but the current study observed generally shorter latencies for the pupil response ($p = 0.024$). We also observed that pupil responses were present in the absence of accommodation, and perhaps linked to the (unmeasured) convergence response, which may have shorter latencies (e.g. <200 ms,[46]), triggering earlier pupil responses than those observed with monocular testing. In addition, we found no age related trend in accommodative latency, but the disaccommodative latencies lengthened slightly as age increased (66.75 ms year^{-1}), in agreement with previous studies using monocular viewing conditions.[1,4] The mean pupil miosis with bilateral distance correction was 1.78 mm, which is approximately the same ($p > 0.05$) as the 1.84 mm mean miosis with bilateral near correction. Because the former condition initiated accommodation and convergence while the latter produced almost zero accommodation but the same convergence, we conclude that convergence and not accommodation is driving the pupil miosis in presbyopic subjects.

With accommodation and pupil miosis (when viewing with bilateral distance corrections), the mean positive spherical aberration in the unaccommodated eyes (0.1 ± 0.05 μm) reduced to almost zero after accommodation (0.005 ± 0.02 μm). However, when early presbyopes converge without accommodating (when viewing with bilateral near corrections), the positive spherical aberration was also reduced (due to smaller pupils), but remained positive (0.022 ± 0.02 μm). With monovision corrections, spherical aberration was reduced on average to 0.01 μm as the target stepped from far to near, a change dominated by the accompanying pupil miosis (diameters decreased on average from 5.8 to 4.2 mm). The difference between these two results emphasise the small impact of actual accommodation and the accompanying lens shape changes, while emphasising the dominant contribution of pupil miosis in reducing spherical aberration during near vision in early presbyopia.

The main observation of this study emphasises that pre-conceptions about the impact of monovision on distance and near vision quality should not assume that the 40 to 50-year-old patient group would not accommodate as targets approach and recede. This age group has remaining accommodation,[38–40] and when activated as stimuli approach the far point of the near corrected eye, low gain accommodation can lead to reductions in binocular image quality (neither eye has a focused image, *Figure* 6b). The heterogeneity in the accommodative response patterns reported in our subjects and by a previous study[25] may therefore play a significant role in the success of this type of presbyopic correction. Optimal behaviour would include activating any residual accommodation as viewing distance decreased until target distances approach the far point of the near corrected eye where image quality would be increased by fully relaxing accommodation, which is an accommodative analogue of the heterogeneous sensory switching behaviour described by Schor and Erickson.[25] Data from this study indicates that some early presbyopes do not exhibit this optimal behaviour when first fit with a monovision correction. When considered with the heterogeneity of sensory switching in monovision reported by Schor and Erickson,[25] our accommodation results challenge our understanding of how the brain processes large image quality differences between the two eyes, and how this processing might enable or prevent the clinical success of monovision.

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Conflict of interest

The authors report no conflicts of interest and have no proprietary interest in any of the materials mentioned in this article.

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