Effect of temporal location of correction of monochromatic aberrations on the dynamic accommodation response

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Abstract: Dynamic correction of monochromatic aberrations of the eye is known to affect the accommodation response to a step change in stimulus vergence. We used an adaptive optics system to determine how the temporal location of the correction affects the response. The system consists of a Shack-Hartmann sensor sampling at 20 Hz and a 37-actuator piezoelectric deformable mirror. An extra sensing channel allows for an independent measure of the accommodation level of the eye. The accommodation response of four subjects was measured during a +/− 0.5 D step change in stimulus vergence whilst aberrations were corrected at various time locations. We found that continued correction of aberrations after the step change decreased the gain for disaccommodation, but increased the gain for accommodation. These results could be explained based on the initial lag of accommodation to the stimulus and changes in the level of aberrations before and after the stimulus step change. Future considerations for investigations of the effect of monochromatic aberrations on the dynamic accommodation response are discussed.

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The accommodation system of the human eye is responsible for bringing an object of interest into focus on the retina. The visual environment is rich with cues that enable the system to respond in the correct direction i.e. for a far-to-near target the power of the lens increases (accommodation), and decreases for a near-to-far target (disaccommodation). These cues include chromatic aberration and binocular disparity. See for example [1]. When these cues are removed such as viewing monocularity in monochromatic light, some individuals can still accommodate in the correct direction. Hence another potential cue recognized by researchers is blur due to monochromatic aberrations [1,2]. Even-order aberrations, such as spherical aberration, give an odd-error, i.e. directional cue, as they result in the point spread function (PSF) being different depending on whether an image is focused in front of or behind the retina. Wilson and colleagues have demonstrated that subjects can perceive these differences [3]. It has been shown that accommodation can be stimulated by inducing monochromatic aberrations [4], and static correction of these aberrations has been shown to improve the steady-state accommodative level when fixating on a stationary target [5].

The monochromatic aberrations are not static but fluctuate many times per second [6]. They also change with accommodation, see for example [7]. Adaptive optics (AO) allows the opportunity to manipulate these aberrations in real-time and measure their effect on the
dynamic accommodation response (AR). For a review of AO for the eye see [8]. Two studies have demonstrated that real-time correction of monochromatic aberrations adversely affects the AR to a step change in stimulus vergence for some subjects [9,10]. In one study only accommodation was considered [9], while in the other, results for accommodation and disaccommodation were pooled together [10]. There is evidence however that accommodation and disaccommodation may have different control strategies [11]. Hence one issue when determining the effect of aberration correction on the AR is that the results may depend on whether the eye is accommodating or disaccommodating. Chin et al. found that inverting aberrations following a step change in stimulus vergence adversely affected disaccommodation only [12]. In the aforementioned studies, aberrations were either corrected throughout the experimental run, i.e. before and after the step [9,10], or only after the step [12]. Hence another issue to consider when determining the impact of aberrations on accommodation control is how the time location of the correction impacts the accommodation system. Koshroyani and Hung, for example, have suggested that the initial part of the response to a step change in vergence is determined from information gathered prior to the response [13]. Hence manipulation of aberrations during the latency period may have the largest impact on the response.

The aim of this study was to investigate the impact of the temporal location of correction of monochromatic aberrations on the dynamic AR. The responses to both a positive (near-to-far) and negative (far-to-near) step change in stimulus vergence were compared to elucidate any differences in how aberrations impact the control strategy processes of disaccommodation and accommodation.

2. Method

Four subjects participated in the study. The AR of their right eye to a step change in vergence was measured whilst aberrations were corrected at varying time locations. Their left eye was occluded. Each subject was free from ocular pathology and had no history of ocular surgery. The ages ranged from 24 to 34 years and the refractive error of the right eye ranged from −6 D to + 5 D sphere and −2 D to 0 D cylinder. The three subjects who were not emmetropic wore their spectacles during the experiment. Each subject gave informed consent to take part in the study.

2.1 Instrumentation

To measure and correct the aberrations of the eye, a closed-loop AO system was used. A simplified schematic of the system is shown in Fig. 1. The aberrations are measured at 20 Hz using a Shack-Hartmann sensor which samples the pupil at 0.5 mm intervals. Aberrations are corrected using a 37-actuator piezoelectric deformable mirror (DM), (Flexible Optical BV, The Netherlands). Aside from measuring the aberrations of the eye via the DM, a direct measurement of the eye’s aberrations is also obtained. Full details of the system can be found at [14].

2.2 Experimental procedure

Each subject was asked to fixate on a green (550 nm) Maltese cross stimulus. The cross subtended 1° at the eye and had a luminance of 6.7 cd/m^2 as measured in the pupil plane. The stimulus was placed at an accommodative demand of 2 D using a Badal optometer arrangement. Each experimental run lasted 4 s during which either a + 0.5 D or −0.5 D step change in stimulus vergence occurred at 2 s. This change in vergence was achieved by stepping the Zernike defocus term with the DM by an amount given by

\[
Def_{\text{Dop}} = \frac{4\sqrt{3} \cdot C_4^2}{R^2},
\]

(1)
where $C_n^0$ is Zernike coefficient for defocus in micrometers and $R$ is the pupil radius in mm. During each measurement run the aberrations of the subject either remained uncorrected or were corrected at various time locations. There were five correction conditions:

1. Aberrations left uncorrected, i.e. step only (SO).
2. Correction after the stimulus step change (CAS).
3. Correction before the stimulus step change (CBS).
4. Correction throughout the experimental run (CT).
5. Correction during the AR latency period (CDL).

These conditions are illustrated in Fig. 2. The aberrations were measured and corrected over the central 5 mm pupil of the subject’s eye. 5 mm was chosen as this was the largest pupil size for each subject that resulted in a full circular set of spots on our Shack-Hartmann sensor. An aperture in the stimulus branch limited the diameter of the beam from the stimulus to 5 mm in the pupil plane. Subjects were stabilized using a bite bar. When a correction was applied, second order aberrations (excluding defocus) up to and including the sixth radial order were corrected. The Zernike convention used is that as specified by the Optical Society of America [15]. When a correction was applied during the latency period the aberrations were corrected for the first 7 frames (i.e. 350 ms) once the step was applied. The reason for choosing 350 ms in which to apply the correction was two-fold. Firstly, this closely corresponds to the latency value reported in the literature [16], and secondly, we wanted a conservative value so that there was no correction after the latency period. Ten repeated trials were obtained for each experimental condition for both the + 0.5 D and −0.5 D steps. Each condition was presented in a randomized order to minimize prediction effects.

Before the data collection session, training was provided for the step only (SO) condition for both step directions so that the participant was familiar with the nature of the experiment. In between each trial, the participant was removed from the bite bar and the DM was set to the ‘flat position’ which corrected for the aberrations of the system. The participant then re-adjusted to the initial accommodative level of 2 D. To avoid the effect of hysteresis on the DM and ensure a constant accommodative starting point for each run, an artificial eye was used to flatten the mirror by running a closed-loop correction for several seconds. Data were collected over a number of sessions to avoid visual fatigue.
Fig. 2. Summary of the experimental conditions. Either the subjects aberrations were left uncorrected (SO), or a correction was applied after the step (CAS), before the step (CBS), throughout the experimental run (CT), or during the latency period (CDL). Only the positive step in vergence is shown for clarity.

2.3 Data analysis

For each measurement run the time course of the accommodation level in diopters was calculated using

\[ Ac(t_i) = \frac{4\sqrt{3} \cdot C_2^0(t_i) - 12\sqrt{5} \cdot C_4^0(t_i)}{R^2}, \]  

where \( t_i \) is the time at which measurement \( i \) was taken, \( C_2^0 \) and \( C_4^0 \) are the Zernike coefficients for defocus and spherical aberration respectively, and \( R \) is the pupil radius [17]. The Zernike coefficients are those as measured in the eye-only channel. On visual inspection of the resulting ARs for each subject, overshoots were encountered in a number of cases. Because of this, a more flexible data analysis approach that could be applied to responses both with and without overshoots was needed. Two different functions were fitted to the ARs to determine the response characteristics. The parameters calculated were the latency (reaction time), starting accommodative level, gain, overshoot magnitude and maximum velocity.

Function 1- Boltzmann sigmoidal function

To determine the latency, each AR was fitted to a Boltzmann sigmoidal function given by

\[ AR_{\text{sig}}(t_i) = y_1 + \frac{y_2 - y_1}{1 + \exp((y_3 - t_i) / y_4)}, \]  

where \( y_1 \) is the initial accommodation level, \( y_2 \) is the final accommodation level, \( y_3 \) is the time location when the curve is half way between \( y_1 \) and \( y_2 \), and \( y_4 \) is inversely proportional to the slope of the curve. For this part of the analysis, the magnitude of the overshoot, or the maximum absolute value after the step, was determined to be the final accommodation level. All subsequent values in the response were set to this value. To fit the curve a custom written Matlab program was used to estimate the initial value of \( y_1 \) to \( y_4 \). Then the \textit{lsqcurvefit} routine was used to adjust the variables to optimize the fit. The latency was defined as the time difference between the onset of the stimulus step and where the fitted curve changed by two percent of the final level [9]. Figure 3(a) illustrates the procedure for a typical response of subject EM to a + 0.5 D change in vergence. The Boltzmann sigmoidal function was used to calculate the latency only. To calculate the starting accommodation level \( AR_{\text{start}} \), the average of the five data points (250 ms) before the onset of the step change in stimulus vergence was used. Hence further references to the starting level represent the results from this calculation, not \( y_1 \) in Eq. (3). The maximum velocity was the maximum value of the absolute gradient of the AR following the latency period.
Fig. 3. Data analysis procedure of a typical response of subject EM to a +0.5 D step change in vergence. (a) For starting level and latency. The starting level is the average of the accommodation level 250 ms before the step. The latency is obtained from a Boltzmann sigmoidal fit. (b) For overshoot and gain. The response is fitted to a damped sinusoid. The overshoot is the difference between the final level and the peak of the primary overshoot. The gain is the difference between the starting level and final level divided by the step size. Dashed lines represent the fitted curves.

Function 2 - Damped sinusoidal function

In order to find the AR gain and overshoot, the responses after the latency period were fitted to a damped sinusoid given by

\[ AR_{ds}(t_i) = z_1 + [z_2 \cdot \exp(-rt_i) \cdot \cos(\omega t_i - \varphi)], \tag{4} \]

where \( z_1 \) is the accommodation level at the end of the response, \( z_2 \) is the magnitude of the cosinusoidal function, \( r \) is the inverse of the decay time constant for the exponential function, \( \omega \) is the frequency of the cosinusoidal function and \( \varphi \) is the phase \[11\]. Again, Matlab was used to determine the variables to optimize the fit. Figure 3(b) shows the damped sinusoidal fit to the AR in Fig. 3(a). From this fit the response gain was calculated as

\[ G = \frac{AR_{start} - z_1}{A_{step}}, \tag{5} \]

where \( AR_{start} \) is the starting accommodation level and \( A_{step} \) is the step change in stimulus vergence. The overshoot magnitude was calculated as the difference between the peak of the primary overshoot and the final steady-state level \( z_1 \). In cases where there was no overshoot, the primary overshoot peak and \( z_1 \) are equal. Figure 4 shows an example of the fitting of both the Boltzmann sigmoidal and damped sinusoidal function to a typical response of subject YP to a + 0.5 D change in vergence. In this case there is no overshoot in the AR. Figures 3 and 4 illustrate the flexibility of the aforementioned analysis of ARs of different shape.

To determine whether the temporal location of the correction had a significant effect on the AR, the data were analyzed using a planned comparisons procedure with a Bonferroni correction. For each parameter i.e. latency, starting level, gain, overshoot and maximum velocity, and each step change, i.e. + 0.5 D and −0.5 D, each correction condition was compared to the step only (SO) condition using a paired t-test. This resulted in four comparisons for each parameter and step direction. Hence a result was determined to be significant if \( p < 0.05/4 \), i.e. if \( p < 0.0125 \). For each parameter, the results for each vergence step were also compared using a paired t-test to determine any differences between disaccommodation and accommodation. A result was determined significant if \( p < 0.50 \).
Fig. 4. Data analysis procedure of a typical response of subject YP to a + 0.5 D step change. The latency is found using a Boltzmann sigmoidal fit. The gain is found using a damped sinusoidal fit. In this case there is no overshoot in the response. Dashed lines represent the fitted curves.

3. Results

Figure 5 shows the average rms wavefront error for each subject with and without correction of aberrations as measured in the DM channel. The average across subjects is also shown. Tip, tilt and defocus have not been included. The values with the correction are the average of those determined just before the step and at the end of the experimental run for the CT condition for both step directions. The rms wavefront error is on average reduced from $0.17 \pm 0.03 \mu m$ to $0.10 \pm 0.02 \mu m$ (41% reduction).

In the measurement records of all subjects a lag (residual negative response) of accommodation to the 2 D stimulus was observed. The mean lag of accommodation taken as the average accommodation level of the first measurement of each measurement run across all subjects was $0.34 \pm 0.15$ D (mean ± 1 SD).

3.1 Effect of location of correction

Figure 6 shows the AR averaged across subjects for each condition for each vergence step. Latency, starting level, and maximum velocity were not affected by any timed correction of aberrations for either step direction ($p > 0.0125$). We also found no statistically significant
Fig. 6. The AR for each condition and each step change in vergence averaged across subjects. (a) The responses to the +0.5 D step, i.e. disaccommodation. (b) The responses to the −0.5 D step, i.e. accommodation. The responses have been shifted so they all start at approximately the same level for comparison of the gains. Also shown is the ‘ideal’ response.

Fig. 7. The average gain for each condition for each vergence change. (a) Gain for responses to the +0.5 D step, i.e. disaccommodation. (b) Gain for responses to the −0.5 D step, i.e. accommodation. * indicates significant differences (p < 0.0125).

When considering each subject individually, all subjects had a lower gain value for the CAS condition in comparison to the SO condition for disaccommodation. The difference only reached statistical significance for subject MC. For accommodation, all subjects had a larger gain value for the CAS condition in comparison to the SO condition. The results did not reach statistical significance however. The lack of statistical significance is likely to result from within-subject variability.

The overshoot magnitude of the CDL condition was larger than that of the SO condition for accommodation only (p = 0.011). The magnitudes were 0.18 ± 0.22 D for the SO condition, versus 0.29 ± 0.25 D for the CDL condition. Three of the four subjects demonstrated a higher gain for the CDL condition in comparison to the SO condition for accommodation. The differences did not reach statistical significance.
3.2 Effect of stimulus step direction

Figure 8(a) shows the average AR across all conditions and subjects for disaccommodation (response to +0.5 D step), and accommodation (response to −0.5 D step). Figure 8(b) shows the average AR across conditions for each subject for disaccommodation and accommodation. The AR parameters for disaccommodation and accommodation were compared across all conditions and between conditions.

Latency

Averaging across all conditions and subjects, the latency of disaccommodation was statistically significantly greater than that of accommodation; 434 ± 184 ms, versus 373 ± 155 ms \((p = 0.001)\). As the average latency for both accommodation and disaccommodation was greater than the 350 ms we used for applying a correction during the latency period, the correction was primarily within the bounds of the latency period. All subjects showed a statistically significant difference between the average latency for disaccommodation and accommodation. Three subjects had a greater latency for disaccommodation.

Comparison of the latency across all subjects for each condition revealed a statistically significant difference between accommodation and disaccommodation for the CAS and CDL conditions only; \(p = 0.04\) and \(p = 0.02\) respectively. For the CAS condition the latency was 414 ± 162 ms for disaccommodation versus 336 ± 120 ms for accommodation. For the CDL condition the latency was 479 ± 216 ms for disaccommodation versus 374 ± 138 ms for accommodation. Three subjects had a larger latency for the CAS and CDL conditions for disaccommodation, while one subject showed the opposite. Only the CAS condition for subject EM, and the CDL condition for YP, reached statistical significance.

Gain

The average gain for disaccommodation and accommodation across all conditions and subjects was 1.06 ± 0.65 and 0.96 ± 0.42 respectively. The difference in gain was not statistically significantly different \((p = 0.11)\). EM and YP showed no significant difference between the gain for disaccommodation and accommodation. For KH the gain was significantly higher for disaccommodation while the reverse was true for MC.

For the SO and CBS conditions across all subjects the gain for disaccommodation was greater than that of accommodation; 1.18 ± 0.51 versus 0.86 ± 0.35 for the SO condition \((p = 0.002)\), and 1.20 ± 0.62 versus 0.86 ± 0.37 for the CBS condition \((p = 0.007)\). This trend was seen for all subjects individually for the SO case and in three subjects for the CBS case. The differences reached statistical significance for KH only. For the CAS condition across all subjects, the gain for disaccommodation was less than that of accommodation; 0.80 ± 0.52 versus 1.11 ± 0.40 \((p = 0.007)\). Three subjects showed this trend, and for two of these subjects the differences were statistically significant.
Overshoot magnitude

The overshoot magnitude averaged across all subjects and conditions was significantly greater for disaccommodation than for accommodation; 0.25 ± 0.24 D versus 0.20 ± 0.19 D (p = 0.015). Three subjects showed this trend. The difference was statistically significant for KH only. For subject YP, the overshoot magnitude was significantly greater for accommodation.

Considering each condition, the overshoot for the CAS and CT conditions was significantly greater for disaccommodation. Other conditions showed no statistically significant difference. For the CAS condition the overshoot magnitude was 0.27 ± 0.24 D, versus 0.17 ± 0.13 D (p = 0.02), for disaccommodation and accommodation respectively. For the CT condition the magnitudes were 0.29 ± 0.26 D, versus 0.18 ± 0.13 D (p = 0.010). Three subjects had a larger overshoot for disaccommodation in the CAS and CT conditions, two of which reached statistical significance. Subject YP had a lower overshoot for disaccommodation in both conditions. This was only significant for the CAS condition.

Maximum velocity

There were no significant differences between the maximum velocity of disaccommodation and accommodation averaged across conditions and subjects (p = 0.56). The maximum velocity was 3.49 ± 1.58 D/s and 3.42 ± 1.37 D/s for disaccommodation and accommodation respectively. Three subjects had a larger maximum velocity for disaccommodation but the differences reached statistical significance for KH only. YP showed a statistically significant larger velocity for accommodation. Considering each condition separately, there was no statistically significant difference in the maximum velocity between accommodation and disaccommodation for any condition. For EM the maximum velocity for disaccommodation was larger than that of accommodation for the CBS condition (p = 0.049). For KH, the same was true for the CT condition (p = 0.03). For YP, the maximum velocity for disaccommodation was significantly smaller than accommodation for the CAS, CBS and CDL conditions. Comparison of each parameter between disaccommodation and accommodation averaged across all conditions and subjects, is presented in Table 1.

| Table 1. Comparison of properties of disaccommodation and accommodation. |
|-------------------------|-------------------------|-----------------------|
|                         | Disaccommodation        | Accommodation         | p-value   |
| Latency (ms)            | 434 ± 184               | 373 ± 155             | 0.001*    |
| Gain                    | 1.06 ± 0.65             | 0.96 ± 0.42           | 0.11      |
| Overshoot (D)           | 0.25 ± 0.24             | 0.20 ± 0.19           | 0.015*    |
| Max. Velocity (D/s)     | 3.49 ± 1.58             | 3.42 ± 1.37           | 0.56      |

Values shown are mean ± SD. * indicates significant differences at the p = 0.05 level.

4. Discussion

In this study we investigated how the time location of the dynamic correction of monochromatic aberrations affects the AR to a + 0.5 D and −0.5 D step change in vergence. We also compared the response characteristics of disaccommodation, i.e. the response to the + 0.5 D step, and accommodation, i.e. the response to the −0.5 D step. The correction of aberrations were either carried out after the step, CAS, before the step, CBS, throughout the entire 4 s measurement run, CT, or during the first 350 ms of the latency period, CDL.

4.1 Latency

When considering each vergence change separately, we found that correction of aberrations had no statistically significant effect on the latency period for either disaccommodation or accommodation. This is consistent with previous studies which have corrected aberrations either throughout the experimental run [9,10], or after the step [12]. Further, this study has shown that correction before the step and correction for a limited time during the latency period also has no effect on the latency period. Schor and Bharadwaj have developed and
validated a model of the AR response to a step change in stimulus vergence [18]. In this model they use a common latency period for accommodation and disaccommodation, suggesting that latency is independent of blur. Hence it is not surprising that we found the latency to be unaffected by correction of the monochromatic aberrations.

Studies have shown that it is possible to alter the latency period of some subjects under certain experimental conditions. Bharadwaj and colleagues compared the accommodation response to a 2 D step change in stimulus vergence before and after a 1.5 hrs adaptation period in which changes in neuromuscular demand were repetitively induced [19]. During the adaptation period, a 2 D step change in blur was followed by either a further 2 D increase or 1.75 D decrease, 350 ms later. They found that for some of their subjects, latency was reduced. In our experiment the subjects were familiarized with the experiment by using the step only condition. The correction conditions and step changes in vergence were then presented in random order. Hence it is unlikely that the accommodation system adapted to any of the correction conditions. Future experiments might include exposing the subject to a particular condition over a period of time and then testing whether changes in the latency occur for other conditions. The latency of the AR response within subjects is also reduced with predictability of the stimulus [20]. However, in our experiment the subject was not aware of the exact time the trial started. Also Chin et al. found that correcting aberrations while viewing a sinusoidally moving target produced no significant effects in terms of the latency [21].

On average, the latency for accommodation was significantly less than that for disaccommodation; 373 ms versus 434 ms. This was true for three of the four subjects. These values are in the range typically reported in other studies using AO to manipulate monochromatic aberrations [9,12]. In these studies however, the latency of accommodation and disaccommodation were not compared. In the literature some authors report accommodation to have the shortest latency, e.g [16], some report disaccommodation to have the shortest latency, e.g [22], and others report that there is no difference, e.g [23]. Hence there is no consensus on whether the latency of accommodation and disaccommodation differ, or how they may differ. It has been suggested that inconsistencies in the literature may be because of different experimental and analytical methodologies [22], or it is subject dependant.

Comparing the latency between disaccommodation and accommodation for each condition we found that the latency for disaccommodation was greater than that of accommodation for all conditions. The differences reached statistical significance for the CAS and CDL conditions only. The lack of statistically significant differences between disaccommodation and accommodation for the other conditions may be due to slightly larger variance for these other conditions.

4.2 Starting level

All subjects showed a lag of accommodation to the 2 D stimulus. The average lag was 0.34 ± 0.15 D. This value is similar to the values for the subject in the study by Fernández and Artal who accommodated to a 2 D stimulus (Fig. 9) [9]. The starting level reflects the steady-state component of the accommodation system and is likely to be influenced by the level of blur present. Reduction of blur via aberration correction decreases depth of focus and increases the symmetry in the through focus modulation transfer function [6,24,25]. Gambra and colleagues report a reduction in the AR lag or lead for four of their five subjects when correcting aberrations [5]. We found no statistically significant differences in the starting level of accommodation for any correction conditions. For conditions in which aberrations were corrected before the step, i.e. CBS and CT, the starting levels were on average less negative, but they failed to reach statistical significance, possibly due to variability. In the experiments by Gambra et al. the stimulus was viewed in 1 D steps from 0 to 6 D. Whether a significant difference occurred in response to the 2 D demand is unclear. From Fig. 9(F) in their study there appears to be little or no difference at 2 D.
4.3 Gain

Several investigators support the idea that the AR to a change in stimulus vergence is controlled using both an open-loop and closed-loop mechanism; see for example [13,18]. The initial part of the response is believed to be due to a fast preprogrammed open-loop movement, i.e. there is no visual feedback during this part of the response. Mucke and colleagues have found evidence that for accommodation (response to a far-to-near target), contrast sensitivity of high spatial frequencies is suppressed during the fast phase of the AR [26]. The response is refined and held by a slower closed-loop mechanism involving visual feedback. The gain in this experiment was determined from the difference between the starting level immediately before the step change in stimulus vergence and the final resting level of the AR. Hence the resulting gain is determined using visual feedback and so will depend upon the blur level before and after the step change in stimulus vergence. Consequently one would expect to see changes in the gain for conditions in which the level of blur owing to the aberrations (excluding defocus), is different before the step in comparison to after the initial AR such as in the CAS condition. Although changes in the starting level and final steady-state level of the AR response did not reach statistical significance for any condition or vergence step, we did find that the gain for the CAS condition was statistically significantly different from the SO condition for both disaccommodation and accommodation.

For disaccommodation the gain was significantly lower in the CAS condition as compared to the SO condition; 0.80 versus 1.18. For accommodation the gain was significantly higher in CAS condition as compared to the SO condition; 1.11 versus 0.86. This can be explained using Fig. 9. Figure 9(a) is a schematic of the defocus as measured in the DM channel for the + 0.5 D step, which results in disaccommodation. As there was a lag in the accommodation response, the starting level is below that of the 2 D stimulus level. Once the DM has introduced the + 0.5 D step, the eye will disaccommodate to ‘undo’ the defocus that is introduced. As the DM starts to continually correct the rms wavefront error after the step, the depth of focus of the eye will be reduced. As the defocus level of the eye needs to be such that the target is within the depth of focus for it not to appear blurred, the eye will then come to rest at a level that is higher than where it originally started before the step change was introduced. This will result in the gain for the CAS condition for disaccommodation being reduced. Figure 9(b) illustrates the case for accommodation. Owing to the initial lag, the gain for the CAS condition will increase in comparison to the SO condition.

We observed no statistically significant change in the gain for the CBS, CT and CDL conditions in comparison to the SO case. Following the same argument as above for the CT condition, the reduction in the depth of focus both before and after the step would result in no change in the gain. In the case of the CDL condition, correction is limited to a 350 ms period. With this system we find that it takes 5 iterations (250 ms) to reduce the wavefront error to the 0.1 µm limit of the system [27]. Hence the 350 ms correction period is sufficient to correct the average static level of the aberrations present before the eye responds. Figure 10 shows the changes in the rms wavefront error for disaccommodation and accommodation averaged across subjects and conditions. For disaccommodation the rms wavefront error increases as the eye disaccommodates. As this magnitude is similar to the amount of correction provided by the DM, the correction effect of the DM is undone. Consequently, the gain for the CDL condition would not be statistically different from the SO condition. For accommodation, the rms wavefront error decreases as the eye responds, making the CDL condition similar to the CAS condition (p = 0.98, paired t-test). The reason why the CDL condition in this case was not statistically significantly different from the SO condition is likely to be because of the slight increase in variance for this condition as compared to the CAS condition. In the case of the CBS condition, the reduction in the rms with accommodation will make the CBS and CT conditions similar (p = 0.96), resulting in no significant difference in the gain. We do not know why for disaccommodation the CBS condition was not statistically significantly different from the SO condition as we might expect (p = 0.82). We do note however that from Fig. 7, the gain results for disaccommodation tend to be more variable than for...
accommodation. This may be a result of an inherent instability in disaccommodation control [18].

Fig. 9. Illustration explaining the changes observed in the gain for the CAS condition. (a) Represents the defocus level in the DM channel for the disaccommodation case. The DM introduces a + 0.5 D step and then the eye disaccommodates to reduce the blur. Owing to changes in the depth of focus due to correction of aberrations by the DM, the resting level of the eye is closer to the stimulus level than initially. This results in a reduced gain. (b) For accommodation the gain increases owing to the initial lag of the accommodation system.

Fig. 10. Change in the rms wavefront error for disaccommodation and accommodation averaged across subjects and conditions. Aberration terms up to and including sixth radial order, excluding tip, tilt and defocus have been used.

The difference between the gain for disaccommodation and accommodation averaged across all conditions was not statistically significant. When comparing between the ARs for each condition we found that for the SO and CBS conditions, the gain for disaccommodation was statistically significantly higher than that of accommodation. In the CAS condition however, the gain for accommodation was significantly higher. Differences in the gains for the SO conditions are likely to result from differences in the slope of the stimulus-response curve in the stimulus region of −1.5 to −2 D and −2 D to −2.5 D. The gain for disaccommodation is closer to unity than that of accommodation, suggesting that in our experiment there is more lag when the eye is focusing a far-to-near target. Correction of aberrations would tend to reduce the effects of lag. This might explain why there was no significant difference in the CT case. The response would become similar to the stimulus demand for both disaccommodation and accommodation and so the gains would become more equal. One would expect the CBS condition to have a similar result to the SO condition, i.e. disaccommodation to have the largest gain as accommodation is affected more by lag. In the CAS condition, one would expect the impact of the correction after the step to have the opposite impact on disaccommodation and accommodation explaining why accommodation would have the larger gain. In the CDL case, we would expect the result to be similar to the CAS case. We found that the gain for the accommodation for this condition to be higher than that of accommodation, but the difference failed to reach statistical significance.
At first sight our gains may appear large. For example Chen and colleagues found a value of 0.61 averaged across 4 subjects when using a +/-0.5 D step without aberration correction, and 0.51 with correction. However, the difference may be because their baseline stimulus level was at 0.75 D compared to 2 D used here. An accommodative demand of 0.75 D has a much shallower slope on the stimulus response curve compared to the slope at 2 D where the response and stimulus are more equal [28]. Another possible reason for the high gains is that the subjects were given training in the SO condition before data were collected.

4.4 Overshoots

Overshoots were seen in the majority of ARs for all subjects for both the positive and negative steps. The mean overshoot for disaccommodation across all conditions was 0.25 ± 0.24 D. Overshoots in disaccommodation have been observed in other studies such as [11]. Our value for the overshoot of disaccommodation is similar to the value Bharadwaj and Schor obtained for a 2 D starting level and 0.5 D response, (see Fig. 3 in [11]). Overshoots in disaccommodation are thought to result from the disaccommodation response setting off towards the far-point and then switching mid flight to approach the correct destination [11]. Hence they are more prominent for small steps from proximal locations. Accommodation is believed to be initiated directly towards the estimated target level and it is thought to not have overshoots [11]. However we also observed overshoots for accommodation but the average magnitude across all conditions was significantly less than that of disaccommodation. In the raw data shown by Chen et al., overshoots are evident for both the accommodation and disaccommodation responses for some subjects; see Fig. 6 [10]. From Figs. 6 and 8 in our study it can be seen that the overshoot for disaccommodation is more prominent whereas in the case for accommodation the response tends to reach a certain value and then to drift back to a lower level. Schor and Bharadwaj do suggest however that the control of both disaccommodation and accommodation displays some plasticity [18]. As the subjects were given training on the SO condition, they may have adjusted one or both control strategies resulting in them becoming similar. The typical control strategy of disaccommodation results in faster responses than accommodation but at the cost of overshooting the required steady-state level. From Fig. 8 it can be seen that it is accommodation which reaches the required response value quicker than disaccommodation. Hence both control strategies may have been adjusted to balance a trade-off between speed and overshoot.

When comparing the overshoots for disaccommodation and accommodation for each condition we found that the CAS and CT conditions were the only ones in which a difference in overshoot magnitude reached statistical significance. Both of these conditions showed a larger overshoot for disaccommodation. Although the overshoot magnitude is likely to reflect the open-loop part of the response, the resulting magnitude also depends upon the gain as this is influenced by the final resting level of the AR relative to the starting level. We recalculated the overshoot magnitude as a percentage of the change in accommodation level. All significant differences that were previously found for the overshoot magnitude became no longer statistically significant when considering the magnitude in this way. We found no significant difference in the percentage overshoot for disaccommodation and accommodation for each condition. When comparing the percentage overshoot averaged across all conditions we also found that the difference between disaccommodation and accommodation was no longer significant. This suggests that the overshoots are an inherent property of the stability of the accommodative system.

Overshoots are likely to result primarily from the preprogrammed open-loop part of the response. As we found no difference in the percentage overshoot for any correction condition, it may be that correction of aberrations did not affect the preprogrammed part of the response. One possible explanation is that the correction capabilities of our DM were not sufficient to make changes in blur that were noticeable to the accommodative system. A fundamental question is how exactly the eye makes use of blur to calculate the initial part of the response. Kotulak and Schor have proposed that the eye can determine the magnitude and direction of the response by monitoring how blur changes with fluctuations in lens power [29]. This
suggests that the eye may have an ‘online’ calibration mechanism during the latency period. In our experiment we left fluctuations in focus uncorrected. Hence whether or not other aberrations are corrected, and how well they are corrected, might not matter to the eye. This may explain why we found no statistically significant effect of correction of aberrations on the percentage overshoot magnitude.

4.5 Maximum velocity

The maximum velocity of the AR was not affected by correction of the aberrations, and there was no significant difference between the two step directions in vergence. For disaccommodation and accommodation the average values of 3.49 D/s and 3.42 D/s respectively are in line with 0.5 D step responses from a 2 D starting level; see Fig. 7 in the study by Schor and Bharadwaj [18]. For accommodation, peak velocity has been shown to depend on the response magnitude, whereas for disaccommodation it depends upon starting level [18]. As there was no significant difference in the starting level for any correction condition, this might explain why peak velocity was not affected by aberration correction for disaccommodation. As we also found no statistically significant difference in the final resting level for any conditions, this might explain why there were no significant differences for accommodation.

Fernández and Artal found a reduction in the peak velocity in response to far-to-near targets (accommodation) when aberrations were corrected [9]. However, in their experiment they stepped the target from the far point to 1.5 D and 2 D for each subject respectively, whereas we used a 0.5 D step either side of 2 D. In this experiment, one reason behind the small step size was that we wanted to restrict our study to investigating reflex accommodation, i.e. the component of the AR that is automatic and is not influenced by conscious control. Reflex accommodation is restricted to step sizes of less than 1.5-2 D [1,28]. Although we cannot rule out that the final resting level in our experiment involved no conscious effort, it is likely, owing to the larger step size, that the results from Fernández and Artal are not purely reflexive and so cannot be directly compared to our results here. In the case where aberrations were being corrected as the subject responds it may be that the subjects were more tentative. The traces for subject PA in their study (Fig. 8) seem to suggest this. The rms wavefront error for subject SM in their study is slightly higher than those of our subjects; hence aberrations may have played a more important role for this subject. Yamada and Ukai propose that when the defocus signal is large the control system does not use blur to determine the magnitude of the error signal [30]. The eye initiates the fast phase of the response which stops and switches to the slower closed-loop mechanism when the blur is below a certain level. When considering the raw traces for subject SM in the Fernández and Artal study it appears that this may be the case.

4.6 Implications for future work

In future investigations there are several factors that need to be considered in the experimental design if one wishes to determine the impact of monochromatic aberrations on accommodation control and also compare results between studies. These include:

1) Direction of the step change. This will elucidate differences in the control strategies of disaccommodation and accommodation.

2) Magnitude of the step. This will impact the contribution from voluntary versus involuntary input to the ARs. Also, larger steps will result in larger changes in the aberrations and so the impact of correction of aberrations will be affected.

3) Starting level. Whether there is a lag or lead will bias the gain.

4) Training. As the accommodative system of the eye demonstrates plasticity it is important to randomize trials for different experimental conditions.
There is yet to be developed a model for the control of accommodation which specifically incorporates monochromatic aberrations. The effect of monochromatic aberrations on the accommodation system has implications for procedures in which the shape of the cornea is altered either surgically or using orthokeratology, with the aim to reduce the low-order aberrations of defocus and astigmatism. These procedures also induce changes in the higher-order aberrations such as coma and spherical aberration, often increasing their magnitudes; see for example [31]. There is evidence that the eye adapts to its own aberrations [32]. Artal and colleagues found that rotating the aberration profile of subjects caused a decrease in visual acuity. However it is likely that with training, the eye will adapt to a different aberration profile [33]. Other factors such as chromatic aberration and binocular viewing will also need to be incorporated. Monochromatic aberrations affect the level of blur due to chromatic aberration [34]. When viewing with both eyes, differences in aberrations between the eyes may adversely affect vision [35].

5. Conclusion

In this study we used AO to determine the effect of the time location of the correction of monochromatic aberrations on the dynamic accommodation and disaccommodation responses to a step change in vergence. Gain was the only response parameter that was significantly affected by aberration correction. This was true for the case in which the correction was continually carried out after the step change in the stimulus vergence occurred. We found that these changes could be explained based on differences in the level of aberrations before and after the step change in stimulus vergence. The open-loop part of the response was not affected by aberration correction which may imply that the eye has an online calibration system.

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