The effect of ocular aberrations on steady-state errors of accommodative response

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It is well accepted that the accommodation system is characterized by steady-state errors in focus. The purpose of this study was to correlate these errors with changes in ocular wavefront aberration and corresponding image quality when accommodating. A wavefront analyzing system, the Complete Ophthalmic Analysis System (COAS), was used in conjunction with a Badal optometer to allow continuous recording of the aberration structure of the eye for a range of accommodative demands (up to 8 D). Fifty consecutive recordings from seven subjects were taken. Monocular accommodative response was calculated as (i) the equivalent refraction minimizing wavefront error and (ii) the defocus needed to optimize the modulation transfer function at high spatial frequencies. Previously reported changes in ocular aberrations with accommodation (e.g., the shift of spherical aberration to negative values) were confirmed. Increased accommodation errors for near targets (lags) were evident for all subjects, although their magnitude showed a significant intersubject variability. It is concluded that the one-to-one stimulus/response slope in accommodation function should not always be considered as ideal, because higher order aberrations, especially changes of spherical aberration, may influence the actual accommodative demand. Fluctuations may serve to preserve image quality when errors of accommodation are moderate, by temporarily searching for the best focus.

Keywords: accommodation, steady-state errors, spherical aberration, image quality, wavefront

Introduction

When we observe an object in the distance, the retinal image of the target is supposed to be in focus. When we decide to look at a nearby object, the accommodative system generates signals to elicit ciliary muscle contraction and an increase in lens power that is sufficient to maintain a clear retinal image (Campbell & Westheimer, 1960). Defining the stimulus for accommodation has been a prime area of investigation. Among a variety of non-optical cues, such as binocular disparity (Jaschinski, 2001; Tsukamoto et al., 2001), stimulus proximity (Hung, Ciuffreda, & Rosenfield, 1996; Rosenfield, Ciuffreda, & Hung, 1991) and changes in stimulus size (Koh & Charman, 1998; McLin, Schor, & Kruger, 1988) that may dominate depending on the circumstances, defocus blur is considered to be the primary stimulus that controls the accuracy of monocular accommodative response (Toates, 1972).

Moreover, it has been suggested that ocular aberrations other than defocus, which normally degrade the quality of the in-focus retinal image (Charman, 1983), constitute cues that drive the accommodative mechanism. Specifically, it has been shown that accommodation is more accurate to broad-band than to monochromatic targets (Aggarwala, Kruger, Mathews, & Kruger, 1995) and that longitudinal chromatic aberration (LCA) favorably influences accommodative response (Kruger et al., 2004; Stone, Mathews, & Kruger, 1993). In addition, there is evidence that asymmetric monochromatic aberrations, such as astigmatism and coma, provide useful directional cues for accommodation (Campbell & Westheimer, 1959; Charman, 2000; Wilson, Decker, & Roorda, 2002).

It is of interest that, even if objects are at a fixed distance, small changes in focus may be required to optimize image quality (Howland & Buettner, 1989). These steady-state errors form an intrinsic part of the accommodative control system and are of two types. First, the system is characterized by over-accommodation for far targets, known as "lead" of accommodation, and under-accommodation for near targets, known as "lag" of accommodation (Charman, 1995; Morgan, 1944). Clinical refraction techniques accept the lead and leave the eye slightly myopic for true distance vision, relying on ocular depth-of-focus to give adequate retinal image quality. Second, under all conditions, the accommodation response changes rapidly and continuously, showing small fluctuations with typical values of about 0.20 D (Charman & Heron, 1988; Stark & Atchison, 1997; Winn, Charman, Pugh, Heron, & Eadie, 1989). These fluctuations are thought to contribute in the maintenance of the steady-state response to any stimulus by pro-

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ducing temporal changes in retinal image quality (Charman, 2000; Hofer, Artal, Singer, Aragon, & Williams, 2001).

Further evidence regarding optical changes in the retinal image when accommodating is provided by studies that demonstrated changes in higher order aberrations, and especially spherical aberration, which causes significant degradation near the fovea (Atchison, Collins, Wildsoet, Christensen, & Waterworth, 1995; He, Burns, & Marcos, 2000; Lopez-Gil, Iglesias, & Artal, 1998). As has been widely publicized, most eyes suffer from positive spherical aberration when unaccommodated, with a trend toward negative spherical aberration being observed with increasing the accommodation level (Atchison et al., 1995; Cheng et al., 2004; He et al., 2000; Ivanoff, 1956).

Since spherical aberration is coupled to the refraction of the eye, it is expected (especially for large pupils) that accommodation measured with commonly used autorefractometers could be biased (Collins, 2001; Hazel, Cox, & Strang, 2003).

The change of image quality with accommodation has been evaluated in the past using the variance of wavefront error or the root mean square (RMS) of the overall wave aberrations (Atchison et al., 1995; He et al., 2000; Lopez-Gil et al., 1998). The above studies showed a large variability between subjects, with mean RMS increasing at high accommodation levels. There is a trend for retinal image quality to be optimal at the resting point of accommodation (at about 1–2-D vergence), with aberrations increasing for targets both nearer and farther from the eye's resting point (Charman, 1999; He et al., 2000). However, these studies have not taken into account the pupil constriction, which accompanies accommodation and reduces the total effect of higher order aberrations.

Small pupils (< 3 mm) are expected to produce larger errors in accommodation by increasing depth-of-focus and reducing high spatial frequency information from the retinal image due to diffractive effects (Ward & Charman, 1985).

In this study we use a wavefront sensor in conjunction with a purpose-built Badal optometer to allow continuous recordings of the wavefront aberration of the eye for a range of accommodative demands. The defocus needed to optimize image quality at each accommodative level is evaluated using two different image quality metrics. It is shown that the steady-state errors in focus in accommodative response can be partially explained in terms of focusing of the eye to achieve best image quality.

### Methods

#### Subjects

Seven right eyes of seven subjects between the ages of 23 and 33 years were tested (mean age: 28 years). Four were emmetropes and three were low myopes (range: −2.00 to −2.50 D) corrected with spectacles. All subjects had visual acuity better than 6/6 (20/20), normal binocular vision, phoria and near point of convergence, and no ocular pathology. None of the participants had a history of refractive or other ocular surgery. Prior to data collection, subjective accommodative amplitudes were measured to ensure that values were normal for the age group tested. Informed consent was obtained from all participants after they received a written explanation of the nature of the study. The experiment followed the tenets of the Declaration of Helsinki, and conformed to a protocol approved by the Institutional Research Board.

#### Experimental set-up and procedure

The monochromatic wavefront aberration function of the eye was measured using the Complete Ophthalmic Analysis System (COAS, Wavefront Sciences Ltd), which is based on the Shack-Hartmann principle (Thibos, 2000). COAS provides a real-time display of pupil image, which is used to align the patient’s line of sight with the instrument’s axis. COAS uses an 840-nm wavelength superluminescent diode as the light source and utilizes a square lenslet array of 33 x 44 (a total of 1452 lenslets) with each lenslet having a width of 144 µm. According to the manufacturer, the pupil magnification factor is 0.685, which means that the lenslet array samples the exiting wavefront every 210 µm in pupil plane. Based on the number and the distribution of the active Shack Hartmann elements, pupil size can be calculated with a resolution of 0.1 mm.

The software allows continuous recording of Shack-Hartmann images and pupil size about every 130 ms for each frame capture (i.e., a temporal frequency of 7.7 Hz). The data extracted from COAS consist of a set of Zernike coefficients (up to fourth order) in Malacara format that quantify the type and the magnitude of aberrations present.

A purpose-built Badal optometer, depicted in Figure 1, is mounted on top of the COAS sensor. The particular optometer has two target arms that can be illuminated separately. In the present experiment only one target was used. Accommodation was controlled with a target viewed through a beam splitter, allowing for continuous recordings of the wavefront aberration of the tested eye. The Badal focusing block features a two-element Badal lens. Adjusting manually the stimulus back and forth provides changes in target vergences between +1 and −12 D. This is achieved without changing the apparent size of the target, thus inducing a blur-only stimulus for accommodation.

The target was a high-contrast (>80%) single letter E, printed on white paper and illuminated by an incandescent lamp. The letter had an angular subtense of 1.75° (having limbs with widths subtended 21’ arc, equivalent to a 6/126 or 20/420 letter). The center of the letter coincided with the optical axis of the Badal optometer that was also aligned with the optical axis of the COAS. The luminance of the background was 5 cd/m². However, retinal illumi-
inance was not constant for each subject and accommodation level because of differences in pupil sizes.

All measurements were performed with natural pupils without administering any mydriatic or cycloplegic drug. Room lights were dimmed to maintain large pupil diameters. The subject positioned his/her head on the chin rest. The operator manually aligned the subject’s pupil center with the optical axis of the device by means of six dots (that lie on a circle concentric with the pupil) displayed on a video monitor. This ensured that the subject’s line of sight was coaxial with the instrument’s optical axis. For each condition 50 consecutive measurements were taken (with a duration of 6.5 s at 7.7 Hz) for the full pupil without realignment being needed. Right eyes were tested, whereas left eyes were occluded. Subjects were asked to blink prior to all measurements.

Subjects were given a short practice session to familiarize themselves with the procedure. They were also encouraged verbally to direct their attention to the target and maintain best possible focus at all times. Shack-Hartmann images and the resulting wave front aberration data were initially recorded for positive target vergence (i.e., the target was placed behind the subject’s far point at +0.84 D). In subsequent trials, the target was brought progressively closer to the subject to increase the stimulus vergence up to –8.00 D in about 1.00-D steps. A complete measurement session for each subject lasted about 30 min. Target vergence was corrected for effectivity when spectacles were used, using Equation 1:

$$ A = -L(1+2aK) \quad (1) $$

where $A$ is the accommodation demand, $L$ the target vergence, $a$ the vertex distance (13 mm), and $K$ the refractive power of the correcting lens.

### Data analysis

The files containing wavefront information were downloaded on removable media and analyzed off-line (e.g., plotting of wavefront maps) using custom-written scripts in MatLab (V 5.2; The Mathworks Inc., Nantick, MA) mathematical software. The Zernike expansion coefficients derived from the wave inclination data for the full pupil were initially transposed to the OSA format (recommended by the Optical Society of America; Thibos, Applegate, Schwiegerling, & Webb, 2000) and corrected for chromatic aberration (from 840 to 550 nm) (see Appendix A in Ginis, Plainis, & Pallikaris, 2004). Accommodative response for each target vergence was evaluated:

(i) by calculating the equivalent quadratic of a wavefront aberration map (given in Equation 2) using “paraxial curvature matching” (i.e., the second-order paraxial focus [$c_2^0$] and the fourth-order spherical aberration [$c_4^0$] Zernike coefficients). This forms an approximation of spherical equivalent used in common ophthalmic calculations, and was found to be the most accurate method in predicting subjective refraction (Thibos et al., 2004),

$$ M = -\frac{c_2^0 4\sqrt{3} + c_4^0 12\sqrt{5}}{r^2} \quad (2) $$

(ii) by using a computational method that calculates the power of a focusing lens needed to optimize retinal image quality of the accommodating eye. This was calculated using a “weighted” sum of the modulation transfer function (MTF) image metric, the “optimized” MTF with a weighting function (WF) peaking at a spatial frequency of 18 c/deg (see Figure 1b). This was chosen because it has been sug-

![Figure 1b. Presentation of the calculations employed to compute optimized through focus modulation transfer function (MTF) using the Zemax-EE software. The weighting function (black line-circles) forms a weighted sum of the MTF amplitudes at five spatial frequencies, tuned at 18 c/deg. Examples of two MTFs of an eye for two different corrections are shown: minimized wavefront aberration (MTF, green dashed line) and high frequency optimized MTF (w-MTF, red dashed line).](image-url)
gested that while low spatial frequency components of a target provide a "coarse" accommodation guidance, it is the high spatial frequencies or edges of the target that refine in accuracy the final response (Charman & Tucker, 1977).

Other studies (Mathews & Kruger, 1994; Owens, 1980) argued against this hypothesis, suggesting that intermediate spatial frequencies (~5 c/deg) are the most important for accommodation. Even if high spatial frequency content of the target is not the primary feedback feature in monocular accommodation, we feel that, because high spatial frequencies are more sensitive to focus errors, a high frequency tuned MTF is expected to be more effective in detecting small changes in focus. This can be achieved with the WF, which substantially improves high spatial frequencies of the MTF that minimizes RMS wavefront aberration (see Figure 1b).

The effect of Stiles-Crawford apodization under photopic conditions was also included in the calculation of the MTFs. All computational simulations were performed using the ZEMAX-EE (Version 10; Zemax Development Corporation, San Diego, CA). Given that tilt does not influence retinal image quality, first-order terms were not included in any of the analyses performed.

Because accommodation represents an increase in the power of the eye, which counteracts the negative vergence of the accommodation stimulus, positive notation is used in the graphs to describe accommodative response.

Results

Stimulus-response curves

Figure 2 plots mean monocular accommodative responses (as evaluated by the spherical equivalent of the wavefront aberration; see Equation 2) as a function of target vergence for all subjects tested. The intrinsic focusing errors of the accommodation system are confirmed: Observers failed to accommodate "accurately" both at low (over-accommodation) and high (under-accommodation) dioptric stimulus levels. The effects of these errors on retinal image quality are considered in Discussion.

Moreover, it is apparent that, when averaged, the stimulus and response are equal at a vergence in the vicinity of about –1.75 D. This intersection in the response/stimulus curve, which is thought to represent the "resting" or "tonic" level of accommodation (Toates, 1972), varies considerably between subjects tested (range –0.25 to –3.25 D).

The usual accommodation-induced pupillary miosis is clearly shown in Figure 3, where pupil diameter is plotted as a function of accommodative response. It is evident that the higher the accommodative response, the greater the degree of miosis, with the relationship being linear: When averaged across subjects, each diopter of accommodation (A) elicits 0.18 mm of pupil constriction (P) (i.e., the P/A ratio is –0.18 mm/D). However, there is a considerable intersubject variability (P/A ranged between –0.12 and –0.27 mm/D with the correlation coefficient, r, being higher than 0.85 in all cases). Note also that this linear relationship holds up to a degree of accommodative response, and that pupil constriction does not cease when the accommodative response reaches its limit.

![Figure 2](image2.png)

Figure 2. Accommodative response for all subjects as calculated by the $z_2^0$ and $z_4^0$ Zernike coefficients (see Equation 2) of the wavefront aberration. Each data point represents the mean of 50 measurements and errors bars ±1 SD. The dotted line is the ideal 1:1 relationship, and the dashed bold line is the least square regression fit for the linear portion of the curve (for vergences >0). Note that the "resting" points, estimated from the response/stimulus curve intersections, show a significant inter-subject variability.

![Figure 3](image3.png)

Figure 3. Pupil diameter as a function of accommodative response. Data from all subjects are shown. Each data point represents the mean of 50 measurements and errors bars ±1 SD. The dashed lines represent the least square regression fit for each subject.
Changes in higher order aberrations

The overall changes in higher order aberrations with accommodation are qualitatively described in Figure 4, which illustrates wavefront aberration maps for each refractive state from unaccommodated to approximately 8 D of accommodation over the natural pupil diameter. Only higher order terms are included in the calculation of the aberration maps. Data from three subjects are shown. Wavefront error maps were drawn for all subjects and show a considerable variation in the wavefront patterns from individual to individual at each accommodation level. For example, for subject SP it is evident that the higher order wavefront error is minimized at intermediate dioptic stimulus levels (around his resting point of accommodation), whereas for subject AT higher order aberrations increase with accommodation, being maximal at the highest accommodation level (where spherical aberration reaches its maximum magnitude). In contrast, for subject IK the lowest aberrations occurred at the highest accommodation level.

Figure 5 depicts for all individual subjects the changes with accommodation in three higher order aberration modes: primary spherical aberration ($c_{4,0}$), vertical ($c_{3,1}$), and horizontal coma ($c_{3,1}^{-1}$). The most systematic change occurs for the spherical aberration, $c_{4,0}$, which always moves in the negative direction. The magnitude of the change in $c_{4,0}$ is linearly related to the accommodative response for all the subjects (on average 0.048 µm/D, the correlation coefficient, $r$, being higher than 0.93 in all cases). Regarding the coma modes, although there is a tendency (more pronounced for $c_{3,1}^{-1}$) for a change to more positive values with accommodation, there is a significant intersubject variability. Note that, when averaged across all subjects, both mean spherical-like and coma-like aberrations approximate to zero when the response equals -1.5 D, close to the mean.
tonic accommodation level (the intersection in the response/stimulus curves), although this is not the case for all individual subjects. This is further discussed in Conclusions. The other third- and fourth-order wavefront terms underwent small nonsystematic changes. It has to be stressed that the aberration data correspond to different pupil sizes (because of the accommodation-induced pupillary miosis). This analysis was purposely chosen to evaluate retinal image quality under real conditions.

Use of optimized MTF to calculate steady-state errors in focus

Figure 6 plots simulated retinal images of a 6/6 (20/20) letter for a –0.15-D and a –8.05-D vergence target simulated for three different refractive states: the recorded accommodative response (mean of 50 continuous measurements) calculated directly from the wavefront map, the 1:1 "ideal" response (i.e., accommodation fully counteracts target vergence), and the response that maximizes the weighted MTF (see Methods).

As can be seen in Figure 6 (first row), when actual accommodative response is used, the simulated retinal image is significantly degraded, and this is more pronounced for higher target vergences. This is mainly due to the observed steady-state errors in accommodative response (see Figure 2). Furthermore, even if the subjects were achieving a 1:1 accommodative/target response, the simulated image of the letter would not demonstrate optimal sharpness (see middle images in Figure 6). This is mostly achieved when high spatial frequencies are brought to focus.

As a result, the "ideal" accommodative response is not necessarily the 1:1 relationship, but varies depending on the polarity of spherical aberration: Positive $c_4^0$ produces a lead (over-accommodation) for far targets, whereas negative $c_4^0$ results in a lag (under-accommodation) for near targets. For example, for subject AT (see Figure 6), an accommodative lag equal to 1.05 D (compared to the overall 2.65 D) can be attributed to the high negative $c_4^0$ when accommodating, with the resulting optimal image response occurring at 7.00 D and not at 8.05 D, which equals the target vergence. Similarly, for subject TD, an accommodative lead equal to 0.18 D (compared to the overall 0.61 D) can be attributed to the positive $c_4^0$ with the resulting optimal image response occurring at 0.33 D instead of the 0.15-D target vergence.

This is further justified in Figure 7, which presents the characteristic focusing errors derived by the optimized MTF as a function of spherical aberration ($c_4^0$). These errors are calculated for each subject by the difference between the ideal 1:1 response and the optimized MTF. They take a positive value when corresponding to a "lag" and a negative value when resulting in a "lead." The linear trend proves that spherical aberration is the main higher order aberration that contributes to image quality changes during accommodation.

![Figure 6](image-url)  
Figure 6. Plots of simulated retinal images (a 6/6 letter is used) for two target vergences (left, –0.15 D for subject TD; right, –8.05 D for subject AT) as computed by three different estimations of the mean accommodative response: the actual accommodative response (top), the "ideal" 1:1 response (middle), and the dioptric response, which optimizes the MTF (bottom). Note that for the distant target (left), subject TD over-accommodates (0.76-D response corresponds to a –0.15-D target), whereas for a near target (right), subject AT under-accommodates (5.39-D response corresponds to an 8.05-D target).

![Figure 7](image-url)  
Figure 7. Plot of the errors in focus derived from the response needed to optimize MTF as a function of spherical aberration ($c_4^0$). The positive signs in y-axis indicate a "lag" and the negative a "lead." Data from all subjects are shown. Correlation coefficient $r$ is higher than 0.93 in all cases.
Figure 8. Plot of errors in focus while accommodating for a range of target vergences, as calculated by the wavefront error (upper graph) and the optimized MTF (lower graph). Errors bars represent ±1 SD. Positive signs in y-axis indicate a "lag," negative signs a "lead." Data from all subjects are shown.

Figure 8 compares the steady-state errors in focus, as calculated by the wavefront aberration maps and by the optimized MTF, as a function of target vergence. The errors in focus ("lead" for far targets, "lag" for near targets) increase linearly with target vergence for all subjects (see upper graph), although there is a notable between-subject variability (the slope of the regression coefficient ranges from 0.31 D to 0.56 D of focusing error per diopter of target vergence: \( r \) being higher than 0.89 in all cases). It is also evident that predicted focusing errors computed by the optimized MTF response are lower in magnitude, and thus can partly explain the observed accommodative "lag" and "lead."

Fluctuations of accommodation

Figure 9 plots the RMS amplitude of fluctuations (i.e., the standard deviation of the accommodative response) for a range of accommodative demands. It is evident that, although there is a considerable variation in the amplitude of accommodation fluctuations among subjects, the RMS amplitude is minimal for all subjects for a target at infinity. Moreover, there is a strong indication that fluctuations increase in magnitude when near objects are observed. Of particular interest is the observation that the vergence where fluctuation activity is maximal varies among subjects tested (between 2-D and 8-D target vergence).

This effect is better illustrated in Figure 10, which presents dynamic response traces (fluctuations of response) for a wide range of target vergences for two representative subjects. For subject AT fluctuations are more powerful as the stimulus is brought closer to the eye: Mean accommodation effort increases by a factor of 3 over the stimulus vergence

Figure 9. Changes in root mean square (RMS) fluctuations as a function of target vergence. Data from all subjects are shown.

Figure 10. Plots of continuous accommodative response to a stationary target for a range of accommodative demands for subjects AT (left) and SP (right). Total recording period is 6.5 s (50 measurements).
range (from 0.07 D for a −0.15-D target to 0.22 D for a −8.05-D target). However, this is not always the case (i.e., for most of the subjects [see subject SP in Figure 10] fluctuations are higher at intermediate target vergences, decreasing at higher accommodative demands).

The effects of these dynamic changes in accommodative response on retinal image quality are demonstrated in Figure 11, which is a 50-frame (6.5 s) video clip showing microfluctuations of a continuous accommodative response to a 4.11-D target for one subject. The mean response is 3.55 D (SD, 0.17), ranging between 3.23 and 4.02 D. Mean pupil diameter is 5.54 mm.

Discussion

The effect of monochromatic wavefront aberrations on the accuracy of the accommodative response is central in this study. A purpose-built Badal optometer (Figure 1) was used in conjunction with a COAS wavefront sensor to achieve recordings of the accommodating eye. Monocular viewing and the use of a Badal optometer allowed us to eliminate the target proximity cues and vergence-accommodation interactions, producing a blur-only stimulus for accommodation. Moreover, analysis was performed over a natural pupil diameter to simulate real conditions.

The intrinsic steady-state errors of accommodation response (i.e., "lags" at high dioptric stimulus levels and "leads" at low levels; see Figure 2) reported by a number of authors (Charman, 1999; Hazel et al., 2003; He et al., 2000; Kasthurirangan, Vilupuru, & Glasser, 2003; Schaeffel, Wilhelm, & Zrenner, 1993) were confirmed.

Although the increased errors in focus for near targets were evident for all the subjects, the exact value of the accommodative lag, as well as the resting state of accommodation (represented by the intersection in the stimulus/response curves), showed a significant intersubject variability, confirming previous research (e.g., for a review, see Charman, 1995). The magnitude of focusing errors, however, was somewhat higher than reported in early studies. This is not surprising because accommodative lag is expected to increase with monocular viewing (Jaschinski, 2001) and when retinal disparity and convergence, which also drive accommodative response (Fincham & Walton, 1957), are not in play. Moreover, the accuracy of accommodative response is known to depend on stimulus characteristics, such as luminance (Johnson, 1976) contrast (Tucker & Charman, 1987; Ward, 1987), color (Aggarwala et al., 1995), and spatial frequency (Charman & Tucker, 1977), of the target. As a consequence, the fairly large target (1.75° angular size) used in the present study might have produced focusing errors of higher magnitude. Furthermore, early measurements of accommodative response were taken with auto-refractometers, which record spherocylindrical refraction over a small measurement zone, resulting in an underestimation of the focusing errors at higher accommodation levels (Collins, 2001; Hazel et al., 2003).

Another observation is that pupil size decreases linearly with accommodative response until the accommodative system can no longer respond (Figure 3). The lower P/A values found in this study (average was −0.18 mm/D compared to −0.45 mm/D reported by Alpern, Mason, & Jardínico, 1961) are probably due to the restriction of the accommodation stimulus to image blur; it is known that pupil constriction is triggered by other variables, such as image size and accommodative convergence. Moreover, our calculations were based on pupil responses up to 8-D stimulus (compared to a 4-D stimulus by Alpern et al., 1961), and it is known that P/A ratio is exaggerated for low limits of accommodative response (Schaeffel et al., 1993).

It would be expected that pupillary miosis, by increasing depth of focus, would demand less precision from the accommodative system, resulting in an increasing accommodative lag. However, this is true only for pupils below ~3 mm (Tucker & Charman, 1975; Ward & Charman, 1985). Moreover, in this study pupil constriction was found to be less than 1 mm in most cases, which means that changes in depth of focus relax the criterion of accommodative response by less than ±0.05 D (Campbell, 1957).

The present changes of the wavefront aberration pattern when accommodating, as well as the high intersubject variability (Figure 4), have been previously reported by a number of authors (Atchison et al., 1995; Cheng et al., 2004; Vilupuru, Roorda, & Glasser, 2004). Although there is a tendency for coma-like (c_4^{1}, c_4^{2}) aberrations to change to the positive direction, the most prominent transition occurs for symmetric spherical aberration (c_6^0), which consistently moves into the negative direction with increasing accommodation demand (Cheng et al., 2004; He et al., 2000; Vilupuru et al., 2004). These are attributed to
changes in the shape, refractive lens during accommodation (Drexler, Baumgartner, Findl, Hitzenberger, & Fercher, 1997; Roorda & Glasser, 2004).

In spite of the fact that the systematic negative change in $c_4^0$ is evident for all subjects, there are three characteristic patterns: (1) subjects with positive $c_4^0$ in the unaccommodated state, which shifts to negative values with accommodation (most common); (2) those with positive $c_4^0$, which changes to less positive values without crossing through zero; and (3) those with negative $c_4^0$, which changes progressively to more negative values with accommodation.

Since spherical and coma-like aberrations are the predominant aberrations for foveal vision (Atchison et al., 1995; Howland & Howland, 1977; Walsh & Charman, 1985), it is expected that wavefront error and consequently overall retinal image quality would be affected during accommodation. However, due to the different patterns observed between subjects tested, overall image quality is differentially affected: Some subjects show best image quality at far, others at near, and others at intermediate accommodative levels. Finally, because monochromatic aberrations are in play only when pupil diameter is large, it is expected that pupil constriction at near would improve image quality. Considering this intersubject variability, it is not surprising that previous studies have reached confounding conclusions regarding image quality during accommodation (Cheng et al., 2004; He et al., 2000; Vilupuru et al., 2004).

Overall, it appears that optical factors may play an important role in the accommodation response. In any case, optimal monochromatic performance will be achieved only if the eye is precisely focused, with dioptric defocus affecting accuracy of the accommodative response. Considering that spherical aberration is the most significant higher order aberration in defining the equivalent refractive power of the eye (Charman & Walsh, 1989), the shift in its polarity with increasing accommodative response is expected to contribute to the focusing errors of the accommodative response.

To test the effect of higher order aberrations (especially spherical aberration) on the dioptric errors of the eye, the accommodative response needed to optimize image sharpness (optimized MTF) was estimated. It was found (see Figure 6) that if the criterion that drives the accommodative mechanism is image sharpness, the one-to-one matching between the dioptric stimulus level and corresponding accommodative response is not always the ideal: Optimal image quality would result in a "lag" for near targets (when negative $c_4^0$ is present) and a "lead" for far targets (when positive $c_4^0$ is present).

It follows that the steady-state errors in accommodation can partly be explained by optical factors (i.e., the change in spherical aberration that differentially affects image quality) (Figures 7 and 8). The precise estimation of the errors in accommodative response is very important, as increased errors have been reported to contribute to myopia development and progression (Charman, 1999; Flitcroft, 1998; Gwiazda, Thorn, Bauer, & Held, 1993; Seidel, Gray, & Heron 2003).

It has to be noted that the refraction based on computations maximizing optical or visual quality varies substantially between different metrics (Thibos, Hong, Bradley, & Applegate, 2004). This means that the use of another metric (i.e., the minimum RMS spot size) would produce different results. The optimized MTF criterion applied here, with the inclusion of Stiles-Crawford apodisation effect, is expected to improve high spatial frequency content of the target, which is supposed to preferentially drive accommodation response.

One possible limitation is that the wavefront aberration functions and image metrics reported in this study apply for monochromic light of wavelength 550 nm. However, the accommodative target was lit with a source that emits white (broad-band) light. Generalizing these metrics to polychromatic light may yield reasonable image quality over a large range of defocus, because longitudinal chromatic aberration attenuates the degrading effect of monochromatic aberrations on MTF (Charman & Chateau, 2003).

Regarding the stability of accommodative response, the highest is exhibited for targets at infinity (< 0.1 D), with fluctuations increasing (up to 0.3 D) as the target is moved toward a vergence of about –5 D (see Figures 9 and 10). Moreover, in agreement with the literature (e.g., Charman & Heron, 1988; Stark & Atchison, 1997), there is a considerable variation among subjects in both the magnitude of the fluctuations and in their changes with target vergence. Miege and Denieul (1988) postulated that fluctuations show maximal activity near the center of accommodative range, and thus would strongly depend on the full amplitude of accommodation achieved by each subject. Note that microfluctuations in pupil diameter may also contribute to the RMS fluctuations of accommodation: This is expected to be more significant for near targets, as pupil noise was found to be maximal for small diameters, while independent of the mean accommodation response level (Stark & Atchison, 1997; Usui & Stark, 1978).

It has been suggested that although these fluctuations stem from feedback instability (i.e., the elastic and mechanical characteristics of the crystalline lens, and the structure of the ciliary muscle and the zonules; Charman, 1983; Charman & Heron, 1988), they may play a functional role in optimizing image quality by producing temporal changes in the contrast of the retinal image (Alpern, 1958; Charman & Tucker, 1977; Howland & Buettner, 1989; Miege & Denieul, 1988). As a result, fluctuations of higher magnitude are required to maintain the system at higher level of response when moderate errors in accommodation are present (Charman, 2000; Miege & Denieul, 1988). This is validated in Figure 11 (movie), which illustrates that, despite the mean error in focus is about 0.5 D, fluctuations of
increased amplitude in one direction tend to improve the out-of-focus image by guiding the accommodative response, and thus help to maintain an optimal state of focus for the eye. If the above hypothesis is valid, the shape of the stimulus/response curve and the variation of fluctuations with target vergence are expected to be systematically dependent on each other. This issue and the impact of fluctuation on image perception itself are being addressed in a separate study.

Conclusions

To summarize, it should be emphasized that although focusing errors of accommodation response increase when viewing near targets, the change in higher order aberrations may influence the accuracy of the resulting response. Thus, when an image metric that optimizes focus for high spatial frequency information is used as the criterion to estimate accommodative response, focusing errors in accommodation can partially be explained.

It follows that the one-to-one stimulus/response relationship should not necessarily be considered as the ideal: For a spherical aberration shifting from positive to negative values with increasing accommodation, a “lag” for near targets and a “lead” for far targets can be predicted.

Moreover, fluctuations in accommodation seem to play an important role in providing a feedback mechanism in accommodative response. Their increased amplitude, when errors of accommodation are moderate (of ~1-D magnitude), contribute in maintaining the system at high levels of response by temporarily bringing the image to the best focus.

Finally, when changes in aberrations upon accommodation are considered, population-averaged data may lead to erroneous results as a consequence of the significant intersubject variability in the pattern of aberrations and other factors, such as pupil size and full amplitude of accommodation.

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