Adaptive optics system for investigation of the effect of the aberration dynamics of the human eye on steady-state accommodation control

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It is now known that defocus is not the only aberration in the eye that exhibits dynamic behavior during fixation. It is currently unknown what effects, if any, the dynamics of these other aberrations have on steady-state accommodation control. We constructed an adaptive optics system to serve as a tool for future investigations in this area. The system has several design features of interest, including automated precompensation of defocus and astigmatism and a method to bypass a scanner used to reduce speckle. It also has the facility to measure the eye’s aberrations independent of the aberration manipulation device—a 37-actuator membrane deformable mirror. Coherence function analysis was used to assess the deformable mirror performance in terms of coupling between Zernike modes. Modes beyond third radial order showed severe coupling. Pilot data were collected on one subject to demonstrate the utility of this system in steady-state accommodation studies. The value of the system for future work in this area is discussed. © 2006 Optical Society of America

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1. INTRODUCTION

It is well known that during steady-state viewing conditions the accommodation level of the eye exhibits small fluctuations. These so-called microfluctuations are of the order of a few tenths of a diopter and were first observed by Collins more than 60 years ago.1 The power spectrum of these fluctuations consists of two main frequency components. The high-frequency component (HFC), which has a peak of activity around 1–2 Hz, has been shown to be correlated with the arterial pulse.2–5 The low-frequency component (LFC), however, which is in the region <0.6 Hz, is believed to be under neurological control as its magnitude is dependent on the stimulus conditions. Under degraded conditions such as low luminance6 and blur,7 and when the depth of focus is increased with small pupils,8,9 the magnitude of the LFC increases and low-frequency drifts in the accommodation level are evident. As the LFC is too slow to aid dynamic accommodation responses, it has been suggested that it may aid the maintenance of steady-state accommodation. For an out-of-focus eye, one direction of change would improve the image contrast and the other would decrease it, and an initial response could be refined and maintained in this manner.10 Investigators have proposed that an increase in the LFC may represent the accommodation system attempting to maintain sufficient feedback.6 Hence, measurement of the microfluctuations of accommodation, in particular the LFC, has the potential of providing information on the ideal characteristics of a stimulus necessary for optimum steady-state accommodation control.

It has been shown that during steady-state viewing the aberrations of the eye beyond defocus also display dynamic behavior.11–15 Adaptive optics (AO) is an invaluable tool that allows one to manipulate aberrations in real time and so gain an insight into their effect on accommodation. So far, however, all efforts have been concentrated on their effect on the dynamic accommodation response.16–18 It is not known what effect, if any, these aberrations have on the control of steady-state accommodation.

This paper describes an AO system with several interesting features constructed as a tool to investigate the effect of the aberration dynamics of the human eye on steady-state accommodation control. The performance and suitability of the system for this purpose were also assessed. Pilot data were collected on one subject to demonstrate the feasibility of the system for measurements of accommodation fluctuations in response to modulation of the aberrations introduced into the target by the system’s deformable mirror.

2. EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1. All of the optical components are mounted on a 600×1200 mm breadboard. The eye is illuminated by a laser diode operating at
817 nm that enters the system via beam splitter BS_1. The beam enters the system off axis so that reflections from the lenses and cornea can be blocked by aperture A_2.

A. Illumination Arm

1. Defocus and Astigmatism Precompensation
The primary aim of the defocus and astigmatism precompensation system is to free the stroke of the deformable mirror for manipulation of the higher-order aberrations. Correction of sphere is by a Badal focus corrector consisting of two plane mirrors PM_1 and PM_2 on a motorized stage. Cylinder is corrected by two rotating cylinders directly in front of the eye. The correction is fully automated and the details of operation have been described elsewhere. The system can correct to an accuracy of \( \approx 0.1 \) D dependent on the subject.

2. Scanner Bypass
After passage through the Badal optometer the beam passes to a scanner that is conjugated with the eye's pupil by lenses L_4 and L_5. This scans the beam at 200 Hz with a scan angle of around 1° to reduce speckle noise. It is not desirable for the light from the target (stimulus) to pass via the scanner. The scanner is bypassed using two cold mirrors CM_1 and CM_2 as shown in Fig. 2. These reflect visible light and pass infrared light. The light from the target enters the system via cold mirror CM_3.

B. Wavefront Sensing Arm
The aberration manipulation device is a 37-actuator membrane deformable mirror (OKO Technologies) that is in a plane conjugate to the eye's pupil. The maximum stroke of the membrane is 9 \( \mu \)m peak-to-valley. For a 6 mm pupil, 65\% of the total mirror diameter is used.

A Shack–Hartmann sensor is used. The lenslet array of the sensor is conjugated with the deformable mirror via lenses L_8 and L_9 so that, taking into account magnifica-
tion changes through the system, the lenslet array samples the pupil at 0.6 mm intervals. The focal length is 7 mm. The reference beam defines the aberration-free position of the Shack–Hartmann spots. It passes through as few optics as possible in order that, during a full correction, for example, the aberrations of the system as well as those of the eye are corrected.

In order to determine the mirror control voltages required to modulate each Zernike aberration mode at a given amplitude, an artificial eye is used consisting of a lens with a piece of card as the retina. In this instance it is necessary for the wavefront-sensing light to pass via the deformable mirror. When measuring the aberrations of a real eye, however, it is necessary for the light from the target only to pass via the deformable mirror. In this case the deformable mirror is bypassed for the wavefront-sensing light using a flip-in hot mirror HM1 as shown in Fig. 3. This reflects infrared light but passes visible light.

3. SYSTEM PERFORMANCE

The system was designed with the intention of using the deformable mirror to modulate certain Zernike aberration modes at a given amplitude and frequency. Hence when the subject views a target via the deformable mirror he or she will view an image with time-varying aberrations. In experiments in which one may want to attribute a particular accommodation behavior to a particular aberration type, it is important to characterize how well an aberration mode is produced by the mirror in terms of accuracy and independence.

A. Aberration Generation

The Zernike-basis convention recommended by the Optical Society of America/Visual Science and its Applications taskforce was used in the generation of aberrations. The magnitude of a given Zernike aberration mode was modulated by the mirror in a discrete sinusoidal sequence. The amplitude of the aberration mode in question at the $i$th sample is given by

$$Z_{Mag} = Z_{Amp} \sin(2\pi f \Delta t),$$

where $Z_{Mag}$ is the magnitude of the Zernike aberration mode at time $(i \Delta t)$, $\Delta t$ is the time between samples (frames), $f$ is the required frequency, and $Z_{Amp}$ is the amplitude of the Zernike aberration mode in question.

The equation governing the control of the deformable mirror is the common integral controller in which the vector of control signals (or voltages) $c$ at time $t_{j+1}$ is given by

$$c(t_{j+1}) = g(CM(a_{req} - a_{mean}) + c(t_j),$$

where $g$ is the gain, $CM$ is the control matrix, and $a_{req}$ and $a_{mean}$ are the vectors of Zernike coefficients required and measured, respectively. At first sight it may appear that in order to generate a particular Zernike aberration mode with a particular magnitude, one merely need set the gain to one and the corresponding coefficient to the desired value in $a_{req}$ with all other elements zero. This would be possible only if the change in the aberrations were linearly dependent on each actuator control signal. However, this is not true in practice. To obtain the control signals for each $Z_{Mag}$, the system was run in closed loop using Eq. (2) with the gain $g$ set extremely low—to 0.003—and the number of iterations $j$ set to 100. These values were chosen to achieve high accuracy of the final result. Too high a gain leads to initial overshoots which is undesirable. Too few iterations can mean that the desired value is not reached. We found that lowering the gain and/or increasing the number of iterations made no significant difference in the final result.

Note that for this procedure the artificial eye was used. It was necessary for the sensing light to pass onto the deformable mirror so HM1 was flipped out of the beam path. Fourteen system modes in the formation of the control matrix were chosen, which corresponded to a condition factor of $\sim 0.05$.

B. Analysis

For each Zernike aberration mode up to and including fourth radial order, the mirror modulated the magnitude of the chosen mode at a frequency of 0.2 Hz. The ampli-

![Fig. 3. (Color online) Function of the hot mirror HM1. When the mirror control voltages are being determined, HM1 is flipped out of the beam path. When making measurements on a real eye, HM1 is flipped into the beam path so that the deformable mirror (DM) is bypassed for the wavefront sensing light but not for the light from the target.](image-url)
tudes chosen were of an order of magnitude similar to that of the aberrations of the subject's eye, as it was these amplitudes that were used in the pilot experiment. For each case the aberrations from an artificial eye were measured over a pupil diameter of 4.2 mm for 43 s and sampled at 11.61 Hz. Again HM₁ was flipped out of the beam path.

The independence of the modes was tested using the coherence function, which is a measure of the correlation between two signals in frequency space. This is given by

$$\gamma(f) = \frac{|G_{xy}(f)|^2}{G_{xx}(f)G_{yy}(f)}$$

where $G_{xy}$ is the cross-spectral density function (CSD), and $G_{xx}$ and $G_{yy}$ are the power or autospectral density functions (PSDs). A value close to one indicates dependence at that particular frequency. For a signal $x$ (or $y$) sampled at a frequency $F_s$ over a time period $T$, giving $N$ data points, the estimated CSD and PSD are given by

$$G_{xy} = \frac{2}{NF_s}X(f,T)Y(f,T),$$

$$G_{xx} = \frac{2}{NF_s}|X(f,T)|^2,$$

where $X(f,T)$ and $Y(f,T)$ are the discrete Fourier transforms of $x$ and $y$, respectively.

For each Shack–Hartmann measurement the coefficient of each Zernike aberration mode up to and including fifth radial order was calculated. The Welch method was then used to calculate a smooth estimate of the CSDs and PSDs. This consisted of splitting each aberration time-course signal into three sections and extracting each one using a Hanning window to form the averaged CSDs and PSDs. The time-course signals were also detrended to eliminate contributions to the CSDs and PSDs from signals with a period greater than the signal length. Those aberrations that had a coherence function value greater than 0.9 at the frequency of 0.2 Hz were considered to be dependent and so coupled to the mode in question.

C. Results

An example for mode 5 [astigmatism (0°, 90°)] is shown in Fig. 4. The lower three plots are an example of the time

![Fig. 4](https://example.com/fig4)

Fig. 4. (Color online) Time trace of astigmatism (A) and three of the coupled modes: (B) 8, (C) 10, (D) 13.

![Fig. 5](https://example.com/fig5)

Fig. 5. (Color online) Plots representing the coupling that exists between Zernike modes for the mirror.
traces of three coupled modes (8, 10, and 13). As can be seen, the amplitudes of the coupled modes are small in comparison with that of the intended mode. The results are summarized in Fig. 5. Each plot represents the results from driving a particular Zernike aberration mode. Each data point shows the amplitude of the driven mode and coupled modes relative to the intended amplitude of the driven mode. Note the different scales. In general the amplitude of the driven aberration mode is more accurate as radial order decreases. Modes beyond third order show severe coupling. No actuator clipping was observed. Hence the failure to reach the desired amplitude in some cases was not a result of limited mirror stroke, but of the limited number of mirror actuators and modes used in the reconstruction of the control matrix.

4. PILOT EXPERIMENT

One 28-yr-old emmetropic subject was used. The subject was stabilized using a bite bar and was an experienced observer with good fixation stability. The subject’s aberrations were measured at the beginning of the session. The pupil size over which the measurements were made was 4.2 mm. The Zernike aberration modes generated by the deformable mirror and their amplitudes (peak-to-valley/2) are shown in Table 1.

Modes beyond third radial order were not considered due to the severe coupling. The magnitudes chosen were similar to the subject’s normal fluctuations. The frequencies investigated were 0.2 Hz and 0.4 Hz (LFC region) and 1 Hz (HFC region). The stimulus was a high-contrast, black and white, square-wave grating with a spatial frequency of 3 c/deg viewed at optical infinity. Aberrations were modulated at increasing frequencies in the order shown in Table 1. For each aberration modulated at a given frequency the aberrations of the eye were measured twice, each time over a period of 78 s. Between each aberration at a given frequency there was a 10 min break to determine the necessary control voltages for the subsequent trial. HM1 was flipped into the beam path so that the wavefront-sensing light bypassed the deformable mirror and so allowed the aberrations of the subject’s eye to be measured independently of the mirror. During the experiment the subject’s normal fluctuations were left uncorrected.

For each measurement the Zernike coefficients up to and including fifth radial order were calculated. As only the accommodation fluctuations were of interest, the Zernike term representing defocus was the only coefficient of concern. For each measurement the accommodation level A in diopters was calculated using

\[ A = \frac{4 \sqrt{5} d_0^2}{R^2}, \]

where \( d_0 \) is the coefficient of Zernike defocus in \( \mu \text{m} \) and \( R \) is the pupil radius in mm. Each of the two time-course measurements was split into three segments to give a total of six sections. The averaged PSD was calculated. Hence the time length of each section was 26 s and the resolution of the PSDs was 0.038 Hz. The sampling frequency was 16 Hz; therefore data could be acquired for frequencies in the range 0.038–8 Hz. Again the data were detrended and a Hanning window was used.

The 95% confidence intervals of the PSDs were calculated by

\[
\frac{nG_{xx}}{\chi^2_{n, 0.025}} \leq G_{xx} \leq \frac{nG_{xx}}{\chi^2_{n, 0.975}},
\]

where \( \chi^2_{n, 0.025} \) and \( \chi^2_{n, 0.975} \) are the 2.5 and 97.5% points of a \( \chi^2 \) distribution with \( n \) degrees of freedom.\(^\text{22} \) The degrees of freedom are equal to twice the number of records over which the average of \( G_{xx} \) has been formed, and so are 12 in this case. Frequency components up to 2 Hz were considered in the analysis.

Eye blinks cause abrupt changes in the aberration measurements and lead to an increase in power across a range of frequencies.\(^\text{24} \) Hence blinks are effectively a source of noise. The average time span of a blink is 250 ms.\(^\text{25} \) We deleted four data points in the accommodation record each time a blink occurred. This corresponded to a time span of 250 ms because of our sampling frequency of 16 Hz. We then used a cubic spline function to interpolate between the points before and after the blink.

The results are summarized in Fig. 6. Each plot highlights the frequencies at which there were significant changes in the subject’s accommodation PSD when the mirror was modulating each of the Zernike mode aberrations at the frequencies selected. By “significant” we mean that the 95% confidence intervals of the accommodation fluctuations PSD when the mirror was stationary, compared with when the mirror was modulating a particular aberration mode, did not overlap. In the majority of cases there was an increase in the PSD of accommodation fluctuations at certain frequencies when the mirror was modulating an aberration. In no case was a change in the target perceived by the subject.

| Table 1. Zernike Aberration Modes and Their Amplitudes Generated by the Deformable Mirror |
|-----------------|----------------|
| Mode          | Description     | Amplitude (\( \mu \text{m} \)) |
| 4              | Defocus         | 0.017 (0.027 D) |
| 5              | Astigmatism (0°, 90°) | 0.017 |
| 6              | Trefoil         | 0.0067 |
| 7              | Vertical coma   | 0.0067 |

5. DISCUSSION

A first step toward determining if higher-order aberrations play a role in steady-state accommodation control is to determine if the accommodation system is sensitive to them. We have presented an AO system and procedure that will allow one to do this in future investigations.

One issue in AO is the load placed on the aberration manipulation device by the defocus and astigmatism of ametropic subjects. The system presented here has the ability to precompensate for defocus and astigmatism in an automated manner to within 0.10 D, dependent on the subject. This frees the stroke of the deformable mirror for manipulation of the higher-order aberrations and so is beneficial for any AO system for vision science. The mir-
ror can induce or correct only a few tenths of a diopter of sphere or cylinder, whereas the Badal optometer and rotating-cylinders arrangement has a range of ±6 D sphere and 0 to −6 D cylinder. The compensation is continuously variable as opposed to discrete steps that would be the case if trial lenses were used or spectacles worn. Hence a greater accuracy of correction can potentially be achieved at the cost of increased system complexity. The Badal optometer can also be used to change the vergence of the target and hence vary the accommodative demand placed on the subject. This is of interest as the fluctuations of accommodation\(^2^6\) and the aberrations of the eye\(^2^7\) have been shown to be dependent on accommodation level.

A previous difficulty in the application of AO to vision science was the incorporation of a scanner when one wished to view a target via the aberration manipulation device. Here we have demonstrated that this can be overcome easily by using two cold mirrors to allow visible light to bypass the scanner. Typically 20% of the infrared light is lost during each pass through a cold mirror. However, we found that despite this, and the large number of optical elements in the system, there was a more than sufficient amount of light available for wavefront sensing. One issue is the noncommon path of the sensing light and the target light. This is unavoidable, and we believe that the benefit of the scanner outweighs this minor drawback. Again this technique is of use not only in the application of AO in accommodation studies but in psychophysical experiments.

The magnitude of the microfluctuations of accommodation has the potential of providing information on the ideal characteristics of a stimulus required for optimum steady-state accommodation control. In an AO system the wavefront-sensing light normally passes to the sensor via the aberration manipulation device. It was necessary in the system presented here to determine the control voltages of the mirror required to produce a given modulation of each Zernike mode aberration. However, if one wishes to measure directly the accommodation microfluctuations of a subject in response to induced aberrations in the target, it is desirable to bypass the deformable mirror. This was achieved easily by a flip-in hot mirror and so required minimum change to the optical setup when switching between determination of control voltages and measurement of the accommodation microfluctuations. In future experiments one may wish to correct selectively in real time certain aberrations during the steady-state response and investigate the effect on the accommodation fluctuations. This would require closed-loop operation of the system and hence some of the wavefront-sensing light would be required to pass via the deformable mirror. A future suggested enhancement would be to have two permanent parts to the sensing branch, one that bypasses the deformable mirror and one that does not. This may increase system complexity considerably, however.

If one wishes to attribute particular accommodation behavior to a particular aberration it is important to recognize the limitations of the aberration manipulation device. A methodology was employed to test the ability of the deformable mirror to modulate Zernike aberration modes both accurately and independently. As can be seen from Fig. 5, it is virtually impossible to drive any Zernike aberration mode totally independently. However, particularly for modes below coma, the amplitudes of the coupled aberration modes are very low in comparison with the amplitude of the intended aberration mode. In general the amplitude of the driven aberration mode is more accurate as radial order decreases. These results are to be expected as the mirror has a finite number of actuators and a limited number of system modes were used in the construction of the control matrix. Modes 10, 11, and 12

![Fig. 6. (Color online) Significant changes in the PSD of the accommodation microfluctuations of one subject when the mirror was modulating each of the Zernike mode aberrations at 0.2 Hz, 0.4 Hz, and 1 Hz.](image)
(tetrafoil, secondary astigmatism, and spherical aberration) were particularly difficult for the mirror to produce as some of the coupled modes had a larger amplitude than that of the intended mode. We would recommend for future work that a mirror with a larger number of actuators be used. As no clipping was observed, the stroke of the mirror was sufficient for this type of experiment. The methodology used here will be of value to other investigators wishing to rigorously test the performance of their mirror in generating Zernike polynomials accurately and independently.

The pilot data showed that there were significant changes in the accommodation microfluctuations of the subject when the deformable mirror introduced aberration modulations into the target. More data are required, however, to elucidate whether these changes were due to the aberration modulations of the target or merely instability of the accommodation fluctuations over time. What we have shown, however, is that the system presented here is suitable for the measurement of accommodation fluctuations in human subjects in response to the aberration dynamics introduced into a target by use of AO.

6. CONCLUSION

We have demonstrated that AO has utility in the investigation of the potential role of the higher-order aberrations of the human eye in steady-state accommodation control. A system has been presented that has several design features that are well suited for future work in this area. Assessment of the mirror performance suggests that it is not suitable for generating Zernike modes beyond third order; hence more actuators are needed. The design features discussed may be of use to workers involved in the construction of AO systems in other areas of vision science.

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