Effects of adaptive optics on visual performance

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ABSTRACT

Some results concerning the correction loop of an Adaptive Optics (AO) system for the eye are presented. This is part of a project aiming to study the effects of AO on visual performance, using psychophysical methods. The AO system used in the project is presented. It comprises a Shack-Hartmann sensor, which measures the light deformation after a double-pass in the eye, and two corrective blocks. A Badal optometer coupled with cylindrical lenses is used to remove the main refractive aberrations, while a deformable mirror deals with the remaining aberrations. This system can enable one to carry out psychophysical experiments as a stimulus is viewed by the subject through the same optics. A bimorph mirror has been tested in view of correcting ocular simulations, and recently implemented in the system. The experimental results, consistent with the simulations, yield to a residual root-mean-square wavefront deviation of about 0.06 microns over a 4.8 mm pupil, corresponding to a Strehl ratio of approximately 0.6.

Keywords: Adaptive Optics, ocular aberrations, vision science, deformable mirror

1. INTRODUCTION


Adaptive Optics has only recently been implemented in vision science, following its development for astronomy since the 1970’s - 1980’s. It was not until 1997 that the first results using an AO system to correct the eye higher-order aberrations were obtained, although Smirnov had already mentioned the idea much earlier in 1961.\textsuperscript{1} The motivations for dynamically correcting ocular aberrations are to be found in the limitations reached by the classical ophthalmic correction. Beyond defocus and astigmatism, usually referred as sphero-cylindrical aberrations, the refractive optics of the eye exhibits other higher-order aberrations. Small decenterings, tilts or irregularities of the lens and cornea, result in higher spatial frequency deformations of the light going through the eye. Temporal fluctuations have also been reported up to a frequency of 5 Hz\textsuperscript{2,3} and even higher.\textsuperscript{4,5} Possible factors accounting for this behavior include the fluctuations and microfluctuations in accommodation, the heart beat, or the tear film that builds up over the cornea after blinking. The presence of these aberrations was highlighted by several statistical studies.\textsuperscript{6–8}

Liang \textit{et al.} first reported both high-resolution retinal images and a possible enhancement of vision thanks to AO,\textsuperscript{9} and built an AO system to validate this idea.\textsuperscript{10} Following this successful experiment, several other systems have since been built around the world.\textsuperscript{4,11–14} Some systems were implemented in view of improving the quality of retinal images obtained with a Scanning Laser Ophthalmoscope (SLO) or an Optical Coherence Tomograph (OCT) for bio-medical purposes. Indeed, getting close to the diffraction limit enables one to reveal some physiological structures, or detect abnormalities. But another aspect that can be studied is the effect of adaptive optics on visual performance. Yoon \textit{et al.}\textsuperscript{15} showed that the expected improvement on vision shall be very limited, especially when talking about contrast sensitivity. Vision is not only limited by optical aberrations, but also by diffraction, chromatic aberrations, scattering, and eventually retinal resolution. However, being able to correct ocular aberrations yields to the possibility of separating these various limiting factors, and point out their relative importance according to environmental conditions such as light level.

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1.2. Principles of Adaptive Optics

Adaptive optics systems aim to correct the aberrated wavefront using adjustable optical elements. An extensive coverage of this subject is given by Roddier.\cite{roddier1993} We consider here the main elements: a sensor to measure the wavefront deformation, a correcting device, and a control system to send a command according to the signal detected. As can be seen in Figure 1, a coherent light source produces a plane wavefront which enters the eye and is reflected by the retina. The deformed wavefront is measured by the sensor and automatically corrected with an opposite phase deformation produced by the deformable optical device, both actions being performed in planes conjugated with the pupil of the eye. Meanwhile, a stimulus can be seen through the corrective optics of the system so that aberrations introduced by the AO compensate for the aberrations of the eye.

The effective operation of the AO system is done through computer control using the interaction matrix between the signals and the commands, which is obtained through the calibration of the system

\[ s = Bc \]  

where \( s \) is the M-long vector containing the M measurements performed over the wavefront, and \( c \) is the N-long vector containing the commands sent to the mirror. The minimum norm least-square solution of this problem is the Moore-Penrose pseudo-inverse of this matrix,\cite{moore1920} \( B^+ \), which can easily be obtained by singular value decomposition (SVD) of \( B \)

\[ B = U \times W \times V^T \]
\[ \Rightarrow B^+ = V \times W^{-1} \times U^T \]  

This principal components decomposition defines \( U \) and \( V \) as orthogonal sets of the system modes in the sensor base and the mirror base respectively. \( W \) gives the singular values, or the gain of the system for each mode: the lower the singular value, the less responsive the system and the bigger the command to be sent. The number of modes is limited by the number of sensor signals and commands (degrees of freedom in each base), and can be even further reduced. In a closed-loop, the command sent at the iteration \( i \) is then simply

\[ c_i = c_{i-1} - g \times B^+ s_i \]  

with \( g \) the gain calculated experimentally according to the speed and stability of the system.

2. APPARATUS

The AO system presented in this paper has been previously extensively described by one of the authors.\cite{author1994} We shall here briefly describe the main components and focus on the particularities of the set-up, as shown in Figure 2.
The eye is illuminated by a 817 nm collimated source (1 mm diameter) and the reflected light is sensed by a Shack-Hartmann sensor. Currently Shack-Hartmann sensors are widely used amongst the vision science community working with AO. The physical concept is to sample the aberrated wavefront with a lenslet array placed in a conjugated plane of the pupil where the wavefront deformation is to be measured. The displacement of each spot measured with respect to a reference is proportional to the local slope of the wavefront. In our present configuration, the pupil of measurement corresponds to a 4.8 mm pupil. A more thorough discussion on the deformable mirror will be given in Section 3. Another source, referred to as the “reference” in the layout, is used to calibrate the Shack-Hartmann: since it does not go through many optics, the collimated beam from this 822 nm source is closer to produce a perfectly plane wavefront on the lenslet array. The spots obtained are then used as reference spots. A complementary arm has been added in the system to image the pupil and helps alignment. Finally, another branch helps implementing the imaging system for the stimulus onto the retina (“Psychophysics” branch in Figure 2).

Some special features can be noticed in the system. A scanner has been added in the illumination path, based on an original idea introduced by Hofer et al. It enables us to get rid of the speckle effect on the Shack-Hartmann spots that comes from light scattering on the retina. It is important that the scanner is placed in the pupil plane so that light entering the pupil always goes through the same point, and is descanned on its way back from the eye. Figure 3 gives an illustration of the scanner effect. The scanner is typically operating at a frequency of 300 Hz with a scan angle entering the eye of less than 1°.

One can also note in the layout the presence of a Badal optometer and cylindrical lenses. These optical elements were added in the system in order to correct for sphero-cylindrical refractive errors (or at least for most of it), and take some load off the deformable mirror. A complete description of their use has previously been given by one of the authors. The Badal optometer consists of two mirrors placed on a translation stage and acts as if the closest lens in front of the eye was displaced to compensate for myopia or hyperopia. As for the two cylindrical lenses, they can be independently rotated so that they correct for any amount and angle of...
astigmatism. Both the Badal optometer and the rotating cylinders pair are controlled in the same way as the mirror using the Shack-Hartmann sensor in a closed-loop correction similar to the one described in Section 1. The range of spherical correction is $\pm 6D$ and that of cylindrical correction from 0 to 6D.

3. THE DEFORMABLE MIRROR

3.1. Description of the Mirror

Different compensation devices have been tested for vision science applications. The requirements for this particular use are a compact size, to avoid the expansion of the set-up with required magnification, a relatively low price, and a spatial resolution and stroke matched to the spatial frequencies and amplitude of the ocular aberrations. The devices that can be found in literature include liquid-crystal spatial light modulators (LCSLM), or deformable mirrors (DM) that obey different electric principles (electro-static, piezo-electric or electrostrictive effects) and present different characteristics in terms of diameter, number of actuators, and stroke. A good summary has recently been presented by Horsley et al.

The device presented in this paper is a bimorph membrane mirror manufactured by AOptix (Campbell, CA, USA). Its electrodes are directly attached to the mirror, which consists of two layers of an electrostrictive ceramic lead magnesium niobate (PMN) material as shown in Figure 4. Thanks to the ground electrode placed between

Figure 4. Structure of the AOptix bimorph mirror. The effect on the mirror of a voltage applied to one of the back face electrodes is shown.

the two layers, a potential applied to any electrode will result in a parabolic deformation: a concave curvature for the front face electrode, or a convex curvature for the back face electrodes. Due to its very high capacitance, the front face electrode cannot be driven fast. Hence, it shall be used to produce the static overall wanted defocus of the DM. On the other hand, the 35 back face electrodes can be used as dynamic actuators, although the effective reflective area of the mirror (10.2 mm diameter) covers only 19 of them. These 19 actuators are referred to as curvature actuators, whereas the remaining outer ring of electrodes produce a slope.

The electrostrictive effect produces a surface curvature which is proportional to the voltage applied, hence the deformation recorded should follow a quadratic dependence on the applied voltage. In fact, a recent study showed that the behavior of the mirror is slightly different from this theoretical prediction, and the deformation goes from a quadratic law below 50 V, to a linear dependence before reaching saturation (from 200 V). In this project, we use a modified version of the software provided by AOptix, which corrects for non linearity. Hence, we will assume that the response of the mirror is linear.
The peak-to-peak surface deformation, when the maximum voltage of 250 V is applied to all the electrodes, is 16 µm, while the single deformation produced by one actuator varies from 3 µm (for the first 19 channels) to 7.5 µm.

3.2. Simulation of Aberration Correction

Before implementing the mirror in the system, we statically simulated its performance in view of correcting ocular aberrations. A commercial Twyman-Green interferometer, manufactured by FISBA, was used. Each particular deformation produced by the actuators was recorded as a phase map to form the influence function matrix of the mirror. From this matrix, one can perform calculations to fit particular wavefronts with the shapes that the mirror can produce. Because of the large calculations involved (each phase map contained over one hundred thousand values), IDL was used as the programming language. We used the SVD procedure to obtain the modes of the mirror.

\[ IFM_I = U_M W_M V_M^T \]  

This procedure has already been described for the AO systems in Section 1.2. As the number of actuators is much smaller than the number of measurements, the orthogonal set of phase maps associated with a set of commands to the mirror is not a complete set. The SVD used in this work gives a reduced matrix \( U_M \), which contains only the modes \( U_{M,i} \) associated with a singular value. Hence any phase map \( \Phi \) can be decomposed as a sum of weighted modes of the mirror with a residual

\[ \Phi = \sum_{i=0}^{N} \alpha_i U_{M,i} + \Phi_R \]  

where \( U_{M,i} \) is a column vector of \( U_M \) and \( N \) is the number of non-zeros singular values. The sum of weighted modes represent the projection of \( \Phi \) on the measurement space. The command to apply to the mirror to produce this phase is then simply

\[ C = \sum_{i=0}^{N} \frac{1}{\lambda(i)} \alpha_i V_{M,i} \]  

where \( V_{M,i} \) is a column vector of \( V_M \) and \( \lambda(i) \) is the \( i \)th singular value of \( W_M \).

We used as initial phase maps those generated by a MATLAB code written by L. Thibos. This program was based on a statistical model of the aberration structure of normal, well-corrected eyes. Following an extensive study over 200 eyes, Thibos et al. decomposed the measured wavefronts in Zernike polynomials and calculated the mean, variance and covariances for all the Zernikes. Hence, the code generates simulated eye wavefronts, represented by a vector of 36 Zernike coefficients according to the OSA/VSIA Taskforce convention. It is worth noticing that the piston, tip and tilt terms were removed before the calculations. Indeed, these terms do not affect the quality of the image, therefore they will not be corrected by our AO system.

The initial wavefronts generated by the MATLAB code were projected onto the set \( U_M \) of mirror modes

\[ \Phi_M = U_M U_M^T \Phi \]  

and the difference between \( \Phi_M \) and \( \Phi \) was calculated in terms of rms over a pupil of 6 mm. This pupil size, although larger than the actual measurement pupil size on the Shack-Hartmann, was chosen in view of an ulterior enlargement of our measurement pupil size. The results for 100 generated eyes are presented in Figure 5. It is important to note that when doing this wavefront projection, it is crucial to check that the commands needed to produce the desired mirror deformation are not out of range. These commands can be calculated with the pseudo-inverse of the influence matrix from Eq. 7.

The mean residual rms found is 0.064 µm. For comparison, when simulating a similar correction with a 37-actuator micromachined electro-static mirror from OKO technologies (Delft, The Netherlands), the residual rms was about 0.2 µm, with some actuators often saturating. In fact, for the bimorph mirror, there was a saturation of one actuator or more for only 5 out of 100 eyes to be corrected. In case of a saturation, the correction to be applied could be improved by changing the other commands, but we did not investigate further this problem.
When relating the results to the visible range ($\lambda = 550$ nm), the residual rms corresponds to $\lambda/9$, or a Strehl ratio of 0.59. This is very close to the diffraction limit according to the Maréchal criterion, i.e. a Strehl ratio of 0.8.

Although the simulated correction is an open-loop calculation that could be optimized when some actuators are saturating, it remains a theoretical and idealized analysis of the performance of the system. Indeed, it was already pointed out that the non-linear behavior of the mirror had been compensated for in the software provided; however this was not exactly validated by the experiments. Moreover, it shall be noted that the wavefront measurements here were obtained with a high resolution interferometer. For a real use of the mirror in the system, noise and other limiting factors should affect the sensibility of the measurements, hence the least-square fitting of the wavefront. Finally, the dynamics of the ocular aberrations is another factor to account for in a closed-loop effective correction.

4. SYSTEM PERFORMANCE

Three different subjects were tested with the AO system under normal viewing conditions (no pupil dilatation). They had their head fixed with a bite-bar, which enabled easy and reliable alignment. Short series of correction (50 frames) were applied. The displacements of the Shack-Hartmann spots were recorded during the correction so that the wavefront could be reconstructed and the rms wavefront error could be plotted. The rms was calculated from the Zernike fit up to the 5th order of the wavefront. The 5th order is commonly accepted as the limit of significant aberrations in the eye. Hence, in practice, the correction with adaptive optics is performed up to the 5th order.\(^{20}\) The Zernike terms can be easily calculated as their derivatives are proportional to the spots displacements on the Shack-Hartmann sensor.\(^{19}\)

4.1. Sphero-Cylindrical Correction

The associated Badal optometer and cylindrical lenses pre-correction were used for one of the subjects (see Figure 6. The gain $g$ was set to 0.9 and 5 iterations were necessary to reach the correction. This pre-correction confirmed previous results obtained,\(^{18,21}\) with a remaining defocus term of a few hundredths of a micron, and the combined astigmatism terms of a few tenths of a micron. Again, these terms are given according to the Zernike basis as described in the OSA/VSIA Taskforce conventions.\(^{24}\) For the 4.8 mm pupil size we were using, the Zernike terms obtained after correction of subject JB corresponded to a sphero-cylindrical prescription of 0.23D sphere and -0.39D cylinder. These figures appear to be acceptable, since they are close to the typical ophthalmic prescription precision (0.25D).
The utility of the sphero-cylindrical correction in terms of pre-correction achievement can be outlined from Figure 7. The final residual rms is comparable in both cases, owing to the sufficient stroke of the bimorph mirror to match the amount of sphero-cylindrical aberration of subject JB. However, it shall be noticed that a pre-correction of the subject results in a faster DM closed-loop correction. Hence it makes it preferable to use the Badal optometer and the cylindrical lenses.

4.2. Bimorph Mirror Correction

The bimorph mirror was implemented in the system and the closed-loop relation (Eq. 3) was used with a gain set to 0.5 and a number of modes to 15. These parameters were experimentally found as to give optimized correction and speed, while still preserving the stability of the loop.

As can be seen on Figures 7 and 8, the results obtained for the three different subjects all yield about the same results: a residual wavefront rms of about 0.05-0.07 µm for a 4.8 mm pupil. On the right graph in Figure 8, we represented the variations of the rms wavefront error before correction to show the aberration dynamics that exists, mainly due to accommodation variation in this case. It shall be noted that this variation is very inter-subject dependent. Hence it helps understanding the difference in apparent stability of the correction between subjects JB, EL and RM. As for the speed of the system, we had a frame rate of about 10 Hz when closing the loop for dynamic aberrations. Looking at the time needed to get the correction on the different graphs obtained, we can evaluate the closed-loop bandwidth to the order of 2 Hz.

5. DISCUSSION AND CONCLUSION

The performance of the system tested on these three subjects is quite in agreement with the simulations performed. Although the pupil size taken for the measurements is smaller than the one taken for the calculations, an
experimental degradation with respect to the predictions was to be expected for reasons given above (Sect. 3.2). In this project, we are aiming to extend the measurement pupil size to 6 mm, and expecting to obtain similarly low results. Our results are comparable to those obtained by other research groups using a closed-loop AO system to correct ocular aberrations: Hofer et al. found a 0.1 µm residual rms wave-front error for a 4.8 mm pupil corrected with a micromachined electro-static mirror as well as with another electrostrictive effect driven mirror.12 Fernández et al. found about 0.1 µm residual rms error for a 5.5 mm pupil with an electro-static mirror.25

As was outlined in Section 1, the expected improvement in visual performance given by adaptive optics is limited. In fact, only minor improvements of high contrast acuity shall be expected for normal eyes,26 although more significant gains in contrast sensitivity could be theoretically measured.27 Guirao et al. reported a calculated visual benefit of about 2.5 for a 5.7 mm pupil at 16 c/deg, which is a quite low spatial frequency considering the limit given by diffraction for a 6 mm pupil at 160 c/deg. If our present results are confirmed with a larger pupil size, then we can aim to effectively measure some effects on vision.

In conclusion, this paper demonstrates the successful implementation of a new correcting device in a AO system used to correct ocular aberrations. An efficient method to simulate the performance of the mirror to match typical ocular aberrations was presented and tested. The bimorph mirror experimentally proved to achieve comparable correction to that obtained with similar systems. The promising results encourage further use of the system in particular with psychophysical experiments.

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REFERENCES


