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Limits of spherical blur determined with an adaptive optics mirror

David A. Atchison\textsuperscript{a}\textsuperscript{*}, Huanqing Guo\textsuperscript{a}, Scott W. Fisher\textsuperscript{b}

\textsuperscript{a}School of Optometry and Institute of Health & Biomedical Innovation, Queensland University of Technology, 60 Musk Avenue, Kelvin Grove, Qld 4059, Australia

\textsuperscript{b}Carl Zeiss Vision, 19 Cooroora Crescent, Lonsdale, SA 5159, Australia

\textsuperscript{*}Corresponding author. Tel +61-7-3138-6512; fax: +61-7-3138-6030.

E-mail address; d.atchison@qut.edu.au (D.A. Atchison)
Abstract

We extended an earlier study (Atchison et al., 2005) in which we investigated limits at which induced blur of letter targets becomes noticeable, troublesome and objectionable. Here we used a deformable adaptive optics mirror to vary spherical defocus for conditions of a white background with correction of astigmatism, a white background with reduction of all aberrations other than defocus, and a monochromatic background with reduction of all aberrations other than defocus. We used 7 cyclopleged subjects, lines of three high-contrast letters as targets, 3 to 6mm artificial pupils, and 0.1 to 0.6 logMAR letter sizes. Subjects used a method of adjustment to control the defocus component of the mirror to set the ‘just noticeable’, ‘just troublesome’ and ‘just objectionable’ defocus levels. For the white-no adaptive optics condition combined with 0.1 logMAR letter size, mean “noticeable” blur limits were ±0.30 D, ±0.24 D and ±0.23 D at 3mm, 4mm and 6mm pupils, respectively. White-adaptive optics and monochromatic-adaptive optics conditions reduced blur limits by 8% and 20%, respectively. Increasing pupil size from 3mm to 6mm decreased blur limits by 29%, and increasing letter size increased blur limits by 79%. Ratios of troublesome to noticeable and of objectionable to noticeable blur limits were 1.9 and 2.7 times, respectively. The study shows that the deformable mirror can be used to vary defocus in vision experiments. Overall, the results of noticeable, troublesome and objectionable blur agreed well with those of the previous study. Attempting to reduce higher order aberrations or chromatic aberrations reduced blur limits to only a small extent.

Keywords: adaptive optics, blur limits, defocus, deformable mirror, letter size, pupil size
**Introduction**

Depth-of-focus of the human eye has been of interest to the vision community for a long time. From a perceptual viewpoint, it is usually considered to be the focus range over which a target’s clarity, contrast and form do not appear affected relative to the in-focus situation. This focus range is affected by target factors such as detail size, luminance, colour and contrast, and by other factors such as retinal eccentricity, observer experience, and pre-adaptation to defocused targets (Wang et al., 2006). Wang & Ciuffreda (2006) provided a comprehensive review of these factors. In addition to depth-of-focus being considered in terms of “just noticeable” blur limits, some investigators have considered other blur limits such as “adequate” vision (Plakitsi and Charman, 1993), “clear and comfortable” vision (Fisher, 1997), “bothersome” and “non-resolvable” blur (Ciuffreda et al., 2006), and “just troublesome” and “just objectionable” blur (Atchison et al., 2005), while Wang and Ciuffreda (Wang and Ciuffreda, 2005) measured four successive blur discrimination limits. Such investigations are of particular relevance to the design of progressive addition lenses, for which compromises in vision are necessary and for which the designer needs an understanding of the blur that wearers will tolerate.

In a previous study, we used cyclopeged subjects, a Badal optometer with lines of three high contrast letters on a 100 cd/m$^2$ white background as targets, 3 to 6mm artificial pupils, and 0.0 to 0.7 logMAR sizes of the letters. Mean “noticeable” blur limits for 0.0 logMAR letters were ±0.33 D, ±0.30 D and ±0.28 D at 3mm, 4mm and 6mm pupils, respectively. Magnitudes of troublesome and objectionable limits were 1.6 to 1.8 times and 2.1 to 2.5 times greater than “noticeable” limits, respectively. Blur limits increased by 1.6 to 2.1 times as letter size increased from 0.0 to 0.7 logMAR, and limits reduced by about 17% as pupil size increased from 3mm to 6mm.

A practical way of introducing defocus in blur limit studies is moving target or lens assemblies. With the advent of deformable mirrors used in adaptive optics, an alternative is to induce defocus with
the mirror. This can be extended further by determining how defocus interacts with various levels of other aberrations, induced or corrected, to determine blur limits. Deformable mirrors have been used to achieve unprecedented retinal imagery (Liang et al., 1997), and this has lead to studies of photoreceptor type distributions in normals, congenital colour defective eyes and diseased eyes (Choi et al., 2006, Duncan et al., 2007, Hofer et al., 2005a, McMahon et al., 2008, Roorda and Williams, 1999, Wolfing et al., 2006, Baraas et al., 2007, Carroll et al., 2004), apparent colour of lights for small stimuli (Hofer et al., 2005b) and “micro”perimetry (Makous et al., 2006). They have also been used to determine the effect of correcting higher order aberrations on visual acuity, contrast sensitivity and accommodation (Chen et al., 2006, Liang et al., 1997, Yoon and Williams, 2002), determine subject acceptability of rotated versions of subjects’ aberrations (Artal et al., 2004, Chen et al., 2007), investigate interactions of defocus and aberrations upon visual acuity and contrast sensitivity (Guo et al., 2008, Piers et al., 2004, Piers et al., 2007), and determine the influence on simulated amounts of aberrations on vision (Rocha et al., 2007).

To extend the use of a deformable mirror in blur limit studies beyond varying defocus, it can correct or induce other monochromatic aberrations. Correcting higher-order aberrations improves in-focus acuity by 0.1 to 0.15 logMAR (Guo et al., 2008, Yoon and Williams, 2002), followed by a more rapid loss of visual acuity with defocus, particularly at small levels of defocus (Guo et al., 2008). If a person adapts to improved in-focus vision, the more rapid loss of visual acuity may reduce at least the “noticeable” blur limits. It may be expected that correcting aberrations will interact with variables such as pupil size and letter. For example, the advantages and disadvantages of removing aberrations may be more obvious for large rather than smaller pupil sizes. Compensating for chromatic aberrations by the use of monochromatic targets should accentuate any such interactions.

In this report, we investigate the feasibility of using a deformable mirror in blur limit studies and we investigate the influence of correcting monochromatic and chromatic aberrations on blur limits. Results will be compared with those of our previous study (Atchison et al., 2005).
Methods

Subjects

This study followed the tenets of the Declaration of Helsinki and received ethical clearance from the Queensland University of Technology’s Human Research Ethics Committee.

There were 7 subjects in good ocular and general health, selected from staff and students at QUT (15 subjects were used in the previous study). The age range was 24 to 53 years (mean 31±10 years, median age 27 years). All subjects were screened for possible susceptibility to cyclopentolate. Right eyes only were used. One subject was myopic (refraction –2.25 D) and the other subjects were essentially emmetropic (subjective refractions -0.25 D to +0.75 D). All subjects had ≤ 0.25 D cylinder by subjective refraction and all subjects had visual acuity of at least 6/6. Subjects were cyclopleged with 1% cyclopentolate, applied every hour of each session. All pupils were dilated to at least 6mm. For two subjects, this required an additional drop of 2.5% phenylephrine at the start of each session.

Apparatus

The apparatus setup was similar to that used by Guo et al. (2008) except for changes in deformable mirror, sensor and magnification. The system consisted of five channels: laser calibration, radiation source, pupil position monitoring, wavefront operations and visual stimulus (Fig. 1). The laser calibration channel consisted of a 543 nm He-Ne laser, a microscope objective, a 10 µm pinhole filter and a collimating lens, with the collimated beam joined to the radiation source and wavefront operation channels at uncoated pellicle beamsplitter BS₁. The radiation source channel consisted of an infrared superluminescent diode (Hamamatsu Photonics, 830 nm, FWHM 25 nm), 1mm aperture A₂,
mirror $M_4$, beamsplitter $BS_2$, and beamsplitter $BS_1$ which reflected the radiation into the eye. Irradiance at the cornea was 14 µW, 50 times lower than the Australian/New Zealand laser safety standard limits (Standards Australia/Standards New Zealand, 2004). The pupil position monitoring channel consisted of beamsplitters $BS_1$ and $BS_2$, mirror $M_3$ and a Pixelink Pl-A741 firewire camera with 35mm focal length lens, together with an infrared LED illumination ring. The subject’s pupil image was displayed on a computer monitor and used to keep the eye aligned by adjusting the position of the bitebar upon which the subjects’ head was mounted.

Light reflected from the retina passed along the wavefront operations channel. $L_1$ and $L_2$ imaged the eye pupil onto the surface of the deformable mirror, and $L_3$ and $L_4$ imaged the eye pupil onto the microlens array of a Hartmann-Shack sensor. Magnifications were -2 between the pupil and the deformable mirror and 0.5 between the pupil and the HS sensor. An optical trombone between lenses $L_1$ and $L_2$ varied defocus independent of the mirror (precision 0.1 mm or 0.0088 D). When the system was set up, a good quality plane mirror was used in place of the deformable mirror. The collimation of the green laser beam was checked with a shear interferometer at different locations within the system (between $L_2$ and the mirror and between $L_4$ and the sensor).

The deformable mirror was an Mirao52 (ImagineEyes, Paris, France). It has 52 actuators under a protected silver coating deformable membrane. Each actuator has a miniature magnet and a miniature coil attached to the deformable membrane. The current flowing through the coil makes the magnet and coil attract or repel each other by magnetic force. Different currents provide different magnetic forces that can drive the membrane to deform accordingly. The surface diameter is 15mm and inter actuator spacing is 2.5 mm. Fernández et al. (2006) provided a comprehensive description of the mirror’s performance. Before the experiments were started, the mirror’s interaction matrix, which is the transitional matrix between actuator response and wavefront slope, was determined by sequentially sending each actuator ±0.2 Volt to push and pull the membrane. The command matrix, which converts the desired wavefront slope to actuator responses, was calculated by determining the pseudo-inverse
matrix of the interaction matrix. To overcome the mirror’s small hysteresis and non-linearity, during closed loop operation the adaptive optics continuously altered the incoming wavefront slopes targeting certain slopes (e.g., a zero slope across the pupil).

The Hartmann-Shack sensor was a HASO 32 system consisting of a lenslet array, camera and associated software. The lenslet array has 40×32 microlenses with 0.114 mm pitch and 2.2 mm focal length. Modal reconstruction with 65 Zernike polynomials was used to fit wavefronts from slope measurements.

We checked the aberrations of real eyes and model eyes with the system and found similar values of spherical aberration coefficient $C_4^0$ as for a COAS-HD aberrometer (Wavefront Sciences). Incorporating defocus by moving the optical trombone gave expected values.

The visual stimulus channel was split from the wavefront operations channel at cold mirror BS$_3$. The channel consisted of Stop A$_3$, a 150 mm Badal lens and an OLED display. The stop, conjugated with the eye’s entrance pupil, was the limiting aperture for the optical system and was magnified onto eye a factor of 2 times. The OLED display was provided by an eMagin Corporation Monocular Design Reference Kit (EMA-200002) combined with either a white or green microdisplay (EMA-100301 and EMA-100303, respectively). The green display was rendered nearly monochromatic with an interference filter (550 nm, FWHM 10 nm). Because of light losses in the optical system, luminance of the displays was determined by a comparison technique using an auxiliary source placed to the side of the optical system. The brightness controls for the displays were set so that the luminances of the white and monochromatic displays were approximately 60 cd/m$^2$ as seen by subjects.

Target consisted of three 99% Weber contrast black letters selected randomly from the set of 10 letters (D, E, F, H, N, P, R, U, V, Z; non-serif, 5 × 4 matrix, spacing equal to letter width) used on Bailey-Lovie charts (Bailey and Lovie, 1976). Three targets sizes were used with detail of 0.1, 0.35 and 0.6 logMAR (approximately equivalent to 6/7.5, 6/13 and 6/24 letters). The equation relating height of letters to logMAR values was
letter size (mm) = 0.436332*10^{\log_{10} \text{MAR}}

Stop sizes were 1.5, 2 and 3 mm, with corresponding pupil sizes of 3, 4, and 6 mm.

**Procedures and instructions**

The subjects determined positions of “clear”, “noticeable” blur, “troublesome blur” and “objectionable” blur. This was done by rotating a knob on a control box in clockwise and anticlockwise directions to alter mirror shape under open loop control. Rotation in the clockwise direction was equivalent to adding positive lenses in front of an emmetropic eye, and was considered to be positive defocus (and equivalent to moving an auxiliary lens away from the observer as in the previous study). The step size of 0.1 µm defocus co-efficient for the reference pupil size of 6.8 mm was equivalent to 0.060 to 0.073 D (see *Methods – calibrations*, *Results - calibrations*). Each step corresponded to 15° turn of the knob.

Separate sessions were done for each adaptive optics condition: white-no adaptive optics, white-adaptive optics, and monochromatic-adaptive optics. Each session lasted between 90 and 120 minutes. The order in which these were conducted was different for each subject. Within each session, three pupil sizes were used, with the order in which these were conducted being different for each session.

Similarly to previously (Atchison et al., 2005) subjects were given an explanation of the nature of the task to be performed regarding the different blur criteria:

“In this experiment we want you to turn the knob to find the following three levels of blur…

**First Noticeable/Just Noticeable blur:** This is the knob position where you first notice a change in the crispness and sharpness of the letters, but the letters should still be clear enough to read.

**Just troublesome blur:** This is the knob position at which you first start to be troubled by the lack of clarity of the target. You should still be able to read the letters.
**Just objectionable blur:** *This is the level of blur at which you would refuse to tolerate on a full time basis. The blur has just reached a point at which it is unacceptable; you may or may not be able to read the chart."

While generally moving in the one direction, subjects were told that they could rotate the knob backwards and forwards to help find each blur limit. They were advised to turn the knob slowly. At the start of each session, the subject had some practice until confident in making judgements.

The procedure for each session was as follows. The mirror was turned on. Using the laser calibration channel and with the feedback of the Hartmann-Shack sensor the operator drove the mirror to minimise the system’s aberrations \( \text{RMS} < 0.036 \, \mu\text{m} \) for 6 mm pupil. After allowing 20 minutes at least for dilation and cycloplegia, the subject was aligned carefully in the apparatus. The operator moved the optical trombone so that Zernike defocus co-efficient \( C_2^0 \) was within \( \pm 0.05 \, \mu\text{m} \). The subject’s wavefront aberrations were measured. For the white-no adaptive optics condition, the operator adjusted the mirror so that the Zernike second order astigmatism co-efficients were reduced to within \( \pm 0.05 \, \mu\text{m} \), but for the other two conditions all aberrations at 830 nm were minimized. The residual aberrations were determined. Next, the subject determined a “best focus” position by moving the optical trombone backwards and forwards for 6 settings with the 3 mm pupil. The mean of these was taken as the position at which the trombone was set for the session. The subject then altered defocus by rotating the knob in one direction to determine “noticeable” blur. The subject proceeded to obtain the “troublesome” and “objectionable” blur positions in the same direction. These positions were recorded by the operator. The operator reset the mirror defocus to the zero position and the subject made determinations in the opposite direction. This was the basic set of measurements. The operator would always remind the subject of the overall direction he/she should rotate the knob and the type of determination that was being made. The order of initial direction was randomised, as was the order in which letter sizes were presented. Each letter size was presented five times.
After measurements were taken for a pupil size, the operator checked the residual aberrations after resetting the mirror to the “best focus” position. Short breaks were taken between determinations with each pupil size.

**Calibration**

At the end of each aberration condition, a calibration of the mirror was done to convert the mirror settings to actual wave and longitudinal defocus. The subject was removed from the apparatus, the SLD was turned off, and the green laser was turned on. The mirror was set to the most negative end of its range used in the session and defocus varied in 0.2 µm steps until the positive end of the range used in the session was reached. The mirror was then stepped back in the opposite direction until the negative limit was reached again. For each mirror setting, all wave aberration co-efficients were measured with the wavefront sensor according to ophthalmic wave aberration standards (American National Standards Institute, 2004; International Standards Organisation, 2008). A quadratic fit was made for defocus (in most cases the second order term was small compared to the linear term). The Zernike defocus of the measurement was converted to dioptres by multiplying by 0.77 according to

\[ M = \frac{4\sqrt{3}C^n_{2,2}}{R^2} \]

where \( C^n_{2,2} \) is the Zernike coefficient in µm and \( R \) is the pupil semi-diameter in mm (3 mm).

**Analysis**
For each subject, adaptive optics condition, pupil size, letter size, direction of blur and blur limit criterion, the dioptric equivalents of the 5 measurements were averaged. These dioptric equivalents were shifted so that the midpoints of the noticeable limits in the two directions were taken as zero.

An analysis of variance was conducted on blur limits with subjects as repeated measures and adaptive optics condition, pupil size, letter size, direction of blur and blur criterion as within-subject factors. We used unsigned blur limits to properly estimate the effect of direction. Where Mauchly’s test of sphericity for within-subjects factors was significant, the Greenhouse-Geisser correction was used. As applicable, subsets of these analyses were conducted.

The midpoints of just noticeable limits were referenced to the midpoints for the 3 mm pupil, 0.1 logMAR letter size combination. A similar analysis of variance to the above was conducted on midpoints with subjects as repeated measures and adaptive optics condition, pupil size and letter size as within-subject factors.
Results

Aberrations and residual aberrations

Table 1 shows the residual aberrations shown by subjects in the white-no adaptive optics condition (6 mm pupil). These are for when astigmatism of the eye is corrected by the mirror and do not include defocus. The major aberrations for each subject and their magnitudes are also shown.

Table 2 shows the ranges for each subject’s residual aberrations upon adaptive optics correction of aberrations and at the end of subsessions, a subsession being one adaptive optics condition combined with one pupil size. The first and second ranges in each cell are the root-mean-square aberrations before and after measurements, respectively. Aberrations are greater at the end of the sessions by a factor of up to 2 times, reflecting real changes in aberrations over the session and minor changes in head/eye position.

Calibrations

Fig. 2 shows the Zernike defocus co-efficient versus deformable mirror defocus setting for one subject for the white-no adaptive optics condition. Changes in defocus were highly linear with the changes in the mirror defocus setting for all subjects and adaptive optics conditions ($R^2 > 0.994$). Fig. 3 shows aberrations (6 mm pupil) measured at the same time as the calibrations were made for the same subject as in Fig. 2. The astigmatism values indicate the mirror position to correct the eye’s astigmatism. The largest variations across the range of defocus settings are astigmatism 0.11 µm and spherical aberration 0.07 µm. This is the worst case, with the next largest variation being 0.08 µm for this subject.
**Midpoints of “noticeable” blur range**

Fig. 4 shows the midpoints as a function of letter size for each of the three pupil sizes, with a) showing results for the white-no adaptive optics condition, b) showing results for white-adaptive optics condition, and c) showing results for the monochromatic-adaptive optics condition.

When all parameters were considered together, letter size had a significant effect on mid-point ($F_{2,12} = 4.4$, $p = 0.04$), while adaptive optics condition and pupil size had no significant effects.

Considering the white-no adaptive optics condition only, pupil size had a significant effect ($F_{2,12} = 4.2$, $p = 0.04$) while letter size failed marginally to have a significant effect ($F_{2,12} = 3.4$, $p = 0.07$). Increasing pupil size from 3 mm to 6 mm and increasing letter size from 0.1 logMAR to 0.6 logMAR moved the mean midpoints -0.07 D and -0.05 D, respectively (Fig. 4a).

For the white-adaptive optics condition, neither pupil size nor letter size affected the midpoint significantly (Fig. 4b). For the monochromatic-adaptive optics condition (Fig. 4c), the letter size only has a small (-0.02 D), but significant effect ($F_{2,12} = 4.6$, $p = 0.03$).

**Effect of adaptive optics condition on blur limits**

Fig. 5 shows the blur limits as a function of letter size for each of the three pupil sizes, with a-c (top row) showing noticeable blur limits, d-f (middle row) showing troublesome blur limits, and g-i (bottom row) showing objectionable blur limits. The left column shows results for white-no adaptive optics, the middle columns show results for white-adaptive optics and the right column shows results for monochromatic-adaptive optics.

Adaptive optics condition had a significant effect on blur limits ($F_{2,12} = 9.0$, $p = 0.004$). Across all pupil sizes, letter sizes, directions and blur criteria, the white-adaptive optics and monochromatic-adaptive optics conditions had blur limits that were smaller than those for the white-no adaptive optics.
condition by 8% and 20%, respectively (Fig. 5). According to within-subjects contrasts, both the white-no adaptive optics and the white-adaptive optics conditions were significantly different from the monochromatic-adaptive optics condition (p = 0.004 and 0.038, respectively), but not from each other (p = 0.18).

Effect of pupil size on blur limits

Pupil size had a highly significant effect on blur limits (F_{2,12} = 28.3, p < 0.001). Blur limits decreased as pupil size increased, but this was more marked between 3 mm and 4 mm pupils than between 4 mm and 6 mm. Across all conditions, letter sizes, directions and blur criteria, increasing pupil size from 3 mm to 4 mm decreased blur limits by 18% and increasing pupil size from 3 mm to 6 mm decreased blur limits by 29% (Fig. 5). Within-subjects contrasts show a marginal significant difference between blur limits for 4 mm and 6 mm pupils (p = 0.05).

Effect of letter size on blur limits

Letter size had a highly significant effect on blur limits (F_{1.04,6.2} = 61.3, p < 0.001). Blur limits increased in a linear manner with log letter size (Fig. 5). Across all conditions, pupil sizes, directions and blur criteria, increasing letter size from 0.1 logMAR to 0.6 logMAR increased blur limits by 79%.
Effect of direction of blur on blur limits

Surprisingly, direction had a significant effect on blur limits ($F_{1,6} = 14.6$, $p = 0.01$). Across all conditions, pupil sizes, letter sizes and troublesome and objectionable blur criteria, the negative blur limits were 95±6% of the positive blur limits (the noticeable limits were ignored here as by definition they were equal in positive and negative directions).

Effect of blur limit criterion on blur limits

Across adaptive optics conditions, pupil sizes, letter sizes, and directions, the ratio of troublesome to noticeable blur limits was 1.9 times and the ratio of objectionable to noticeable blur limits was 2.7 times. There were similar ratios for the different adaptive optics conditions. There were significant interactions of blur criterion with letter size ($F_{1.15,6.69} = 38.8$, $p < 0.001$) and with pupil size ($F_{1.66,9.97} = 23.0$, $p < 0.001$). The ratio of troublesome to noticeable blur increased from 1.8 times for 0.1 logMAR letters to 2.0 times for 0.6 logMAR letters, and the ratio of objectionable to noticeable blur increased from 2.6 times for 0.1 logMAR letters to 2.9 times for 0.6 logMAR letters.

Between-subject effects

There was a significant between-subjects effect ($F_{1,6} = 56.1$, $p < 0.001$) on blur limits. There was a considerable range of sensitivity between subjects. Ratios of blur limits of the subjects (blur limit of subject divided by limit for the most sensitive subject, averaged across all adaptive optics conditions, pupil sizes and blur limits) were 1.0, 1.3, 1.3, 1.9, 2.1, 2.1 and 3.1. Fig. 6 contrasts the results for the second most sensitive subject and the least sensitive subject.
Subjects showed similar proportionate effects with variation in adaptive optics condition, pupil size, letter size, and blur criterion.

Comparison with previous investigation

Fig. 7 compares results from this study with the previous study for 4 mm pupils (Atchison et al., 2005). For the present study we used limits for only the white-no adaptive optics condition, and for the previous study we used limits for only 0.0, 0.3 and 0.6 logMAR letters. Overall, the present study gave slightly smaller limits. Across all pupil sizes, letter sizes, and directions, the present study had noticeable, troublesome and objectionable blur limits that were 0.84, 0.94 and 0.98 times the respective limits for the previous study. The mean troublesome/noticeable and objectionable/noticeable ratios in this study were 1.9 and 2.7 times compared with 1.7 and 2.3 times in the previous study.

Letter size had a similar effect on blur limits in both studies. Interpolating to account for the differences in letter size steps between the two studies, the effects of increasing letter size across all pupil sizes, directions and blur criterion were 75% and 79 % for the previous and present studies, respectively.

Discussion

Summary

For the white-no adaptive optics condition combined with 0.1 logMAR letter size, mean “noticeable” blur limits were ±0.30 D, ±0.24 D and ±0.23 D at 3mm, 4mm and 6mm, respectively.
Compensating for the optical defects of the eye by reducing monochromatic aberrations (white light adaptive optics condition) and by reducing monochromatic aberrations and eliminating chromatic aberrations (monochromatic-adaptive optics condition) reduced blur limits by 8% and 20%, respectively, although the first of these was not significant. Increasing pupil size from 3mm to 6mm decreased blur limits by 28%, and increasing letter size from 0.1 logMAR to 0.6 logMAR increased blur limits by 79%. The ratios of troublesome to noticeable blur limits and of objectionable to noticeable blur limits were 1.9 and 2.7 times, respectively. There was a considerable range of sensitivity of 3 times between subjects. The results of noticeable, troublesome and objectionable blur without adaptive optics correction agreed well with those of a previous study (Atchison et al., 2005).

The study shows that the deformable mirror can be used successfully to vary defocus in vision experiments using an open-loop mode. In the rest of this section we discuss further the important findings of the study, point out shortcomings in our work and indicate further analyses and other investigations that might be done.

**Using the mirror**

The ImagineEyes MIRAO52 mirror can be used to vary defocus in vision experiments as change in other aberrations was small as defocus was varied. In an additional experiment to confirm the ability of the mirror to change defocus with negligible changes in other aberrations, we compared the influence of adaptive optics on blur limits for one subject when we altered the defocus of the system with the deformable mirror and also by having the subject move the trombone. This was done under white light conditions and 5 mm pupils. This subject, who has considerable spherical aberration of +0.24 µm, showed substantial reduction in blur limits under both conditions of approximately 29% (he had a 26% effect in the main experiment for 6 mm pupil).
Nevertheless there are some issues to consider regarding the mirror. One issue is movement of the head and eye during visual experiments. Although we controlled alignment manually, we could not ensure that subjects’ aberrations did not change while they were making measurements. The larger a person’s aberrations and the larger the consequent adaptive optics correction, the less successful is the correction if the eye moves in the apparatus, as investigated in the context of movement and rotation of ideal correcting devices by Guirao et al. (2001). It would be good to take continuous, closed loop measurements during experiments. The problems with this are the “strain” that lengthy measurement time might place on the mirror and the visibility of the near infrared source interfering with the visual task. We note a psychophysical investigation by Dalimier et al. (2008) into the effects of aberrations on contrast acuity, in which they used updates of aberration correction between measurements. This was not feasible to use at low luminances where the source would interfere with adaptation, in which case they measured the aberrations at the end of runs (length of runs not given) and disregarded runs where rms was higher than 0.2 µm (6 mm pupil). Their first procedure is probably not feasible in an investigation such as ours where updating aberration correction might have some small effects on the important variable of defocus. The second procedure has merit, although finding an RMS below a certain level at the end of a run does not ensure that it was always below this level for the complete run. In our procedure we measured the aberrations at the end of subsessions (Table 2), but these were with best alignment.

Improvement in monitoring equipment so that compensations are made for eye movements is something that will probably be included in future equipment.

Effect of attempting to correct higher order aberrations on the blur limits

Minimizing the higher order aberrations with the deformable mirror reduced the blur limits by a mean of 8%, but this was not significant (Fig. 5). Eliminating chromatic aberration as well reduced
blur limits by a further 12%. It is possible that a better procedure for maintaining low levels of aberrations during sessions would have resulted in some further reduction in blur limits in the adaptive optics corrections (see Discussion – using the mirror). Speculation can be given to the degree to which subjects adapted to the improved in-focus vision given by corrections of monochromatic and chromatic aberrations eg to what extent did subjects lower the threshold judgement as to what constitutes blur, and were they influenced by a neural template based on their usual aberrations that would counteract this effect (Artal et al., 2004, Chen et al., 2007)?

We note that the white-no adaptive optics condition already included a careful correction of astigmatism with the deformable mirror beyond the correction of clinically measured levels of astigmatism (nearest 0.25 D or possibly 0.12 D) as done in some other adaptive optics studies. 0.12D of astigmatism is equivalent to 0.22 µm for a 6 mm pupil size, and not correcting astigmatism as carefully as we did may have increased the blur limit difference between the no-adaptive optics and the adaptive optics conditions.

Comparison with the previous study

We have compared our experimental conditions with those of the previous study (Atchison et al., 2005) in Results – comparison with previous investigation. Broadly the results of the two studies agree well, but the blur limits in this study were slightly smaller eg 16% for the noticeable blur limits. This may be due partly to the careful correction of astigmatism in this study with the deformable mirror. In this study we found slightly bigger troublesome and objectionable blur limits relative to noticeable blur limits than in the previous study. Also, we found a small but significant effect of blur direction that was not apparent in the previous experiment. It is possible that the method of altering defocus may have a role. Five subjects held the control box in the left hand and turned the knob with the right hand, one did the opposite and another subject swapped the use of the hands.
In the previous study without adaptive optics (Atchison et al., 2005), we found a movement of the midpoint of noticeable blur limits in the negative direction as pupil size increased and letter size increased, although the effect of pupil size was not significant. A small shift was found also in this study (Fig. 4) and was significantly affected by pupil size and just failed to be significantly affected by letter size. This shift is consistent with positive spherical aberration which moves the contrast sensitivity peak in the negative direction as pupil size increases and spatial frequencies reduce. Three of our subjects had considerable amounts of spherical aberration of +0.19, +0.24 and +0.37 µm (Table 1), while the other four subjects had small amounts of -0.09 to -0.02 µm. The two subjects with the largest spherical aberrations showed the greatest midpoint shifts.

There were only 7 subjects in this study compared to 15 subjects in the previous study and this could have biased the results in some way. The subjects in this study had a range of experiences in visual psychophysics experiment, but this is also true of the previous study.

In the previous study, we used Non-linear Mixed Effects Modelling with orthogonal polynomials to determine the significance of various parameters on blur limits. We found that blur limits were linearly related to a constant and to pupil size, quadratically related to log letter size detail, and linearly related to the interaction of pupil size and letter size (for linear pupil size and quadratic component of log letter size detail). Equations for each blur criterion were then determined in the form

\[ L_{\text{directionBlur criterion}} = a + b \times \text{logMAR} + c \times \text{pupil size} + d \times \text{logMAR} \times \text{pupil size}. \]

No such analysis was done on this occasion because of the small number of subjects.

**Acknowledgements**

We thank Carl Zeiss Vision for loaning the ImagineEyes deformable mirror, the HASO wavefront sensor and associated software.
### Tables

<table>
<thead>
<tr>
<th>Subject number</th>
<th>Root-mean-square aberrations (µm)</th>
<th>Major aberrations and magnitudes of co-efficients (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.34</td>
<td>Vertical coma -0.19, Spherical aberration +0.24</td>
</tr>
<tr>
<td>2</td>
<td>0.29</td>
<td>Vertical coma -0.12, Oblique trefoil -0.12, Spherical aberration +0.19</td>
</tr>
<tr>
<td>3</td>
<td>0.22</td>
<td>Oblique trefoil +0.18</td>
</tr>
<tr>
<td>4</td>
<td>0.25</td>
<td>Trefoil -0.12, Oblique trefoil -0.14</td>
</tr>
<tr>
<td>5</td>
<td>0.51</td>
<td>Vertical coma +0.24, Oblique trefoil -0.16, Spherical aberration +0.37</td>
</tr>
<tr>
<td>6</td>
<td>0.18</td>
<td>Trefoil +0.13</td>
</tr>
<tr>
<td>7</td>
<td>0.26</td>
<td>Oblique trefoil -0.17</td>
</tr>
</tbody>
</table>

Table 1. Root-mean square aberrations and major aberrations for each subject (6 mm pupil). This is after astigmatism correction and disregarding defocus.

<table>
<thead>
<tr>
<th>Subject number</th>
<th>White-adaptive optics (µm)</th>
<th>Monochromatic-adaptive optics (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.07-0.08, 0.13-0.15</td>
<td>0.07-0.08, 0.13-0.15</td>
</tr>
<tr>
<td>2</td>
<td>0.07-0.08, 0.09-0.12</td>
<td>0.07-0.08, 0.11-0.13</td>
</tr>
<tr>
<td>3</td>
<td>0.05-0.06, 0.09-0.12</td>
<td>0.05-0.06, 0.10-0.13</td>
</tr>
<tr>
<td>4</td>
<td>0.07-0.08, 0.13-0.15</td>
<td>0.07-0.08, 0.12-0.15</td>
</tr>
<tr>
<td>5</td>
<td>0.06-0.07, 0.12-0.14</td>
<td>0.06-0.07, 0.13-0.15</td>
</tr>
<tr>
<td>6</td>
<td>0.07-0.08, 0.13-0.15</td>
<td>0.07-0.08, 0.13-0.15</td>
</tr>
<tr>
<td>7</td>
<td>0.06-0.07, 0.06-0.07</td>
<td>0.06-0.07, 0.06-0.07</td>
</tr>
</tbody>
</table>

Table 2. Residual root-mean square aberrations before commencement and after subsessions involving adaptive optics correction (6 mm pupil, disregarding defocus).
Fig. 1
White-no AO subject 4

**Fig. 2**

- astigmatism C(2, -2)
- astigmatism C(2, 2)
- oblique trefoil C(3, -3)
- vertical coma C(3, -1)
- horizontal coma C(3, 1)
- trefoil C(3, 3)
- spherical aberration C(4, 0)

**Fig. 3**
Fig. 4
Fig. 5

White-no AO, 4mm pupil

LETTER SIZE (logMAR)

BLUR (D)

subject 1 noticeable
subject 1 troublesome
subject 1 objectionable
subject 6 noticeable
subject 6 troublesome
subject 6 objectionable

Fig. 6
White-no AO, 4mm pupil

- present noticeable
- present troublesome
- present objectionable
- previous noticeable
- previous troublesome
- previous objectionable

Fig. 7
Figure Captions

Fig. 1. Experimental system.

Fig. 2. A defocus calibration curve for subject 4 (defocus co-efficient is for 6 mm pupil).

Fig. 3. Changes in aberration co-efficients (6 mm pupil) with change in mirror defocus setting for subject 4 for white-no adaptive optics condition.

Fig. 4. Location of midpoints of noticeable blur limits for different letter sizes and pupil sizes for a) white-no adaptive optics, b) white-adaptive optics and c) monochromatic-adaptive optics. The midpoints for each subject were referenced to his/her midpoints for the 3 mm pupil, 0.1 logMAR letter size combination. Error bars represent ±95% confidence intervals. For clarity, the data for the different pupil sizes are off-set slightly relative to each other.

Fig. 5. Mean blur limits as a function of letter size for noticeable blur (top row), troublesome blur (middle row), and objectionable blur (bottom row). Left column is for white-no adaptive optics, the middle column is for white-adaptive optics, and the right column is for monochromatic-adaptive optics. Error bars represent ±95% confidence intervals. For clarity, the data for the different pupil sizes are off-set slightly relative to each other.

Fig. 6. Noticeable, troublesome and objectionable blur limits for the white-no adaptive optics and 4mm pupils for a) subject 1, and b) subject 6. The positive values are for clockwise (positive) blur and the negative values are for anticlockwise (negative) blur.
Fig. 7. Comparison of present and previous study (Atchison et al., 2005). The positive values are for clockwise (positive) blur and the negative values are for anticlockwise (negative) blur.
References


