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Blur limits for defocus, astigmatism and trefoil

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ABSTRACT

We investigated the limits at which blur due to defocus, crossed-cylinder astigmatism, and trefoil became noticeable, troublesome or objectionable. Black letter targets (0.1, 0.35 and 0.6 logMAR) were presented on white backgrounds. Subjects were cyclopleged and had effectively 5 mm pupils. Blur was induced with a deformable, adaptive-optics mirror operating under open-loop conditions. Mean defocus blur limits of six subjects with uncorrected intrinsic higher-order ocular aberrations ranged from 0.18 ± 0.08 D (noticeable blur criterion, 0.1 logMAR) to 1.01 ± 0.27 D (objectionable blur criterion, 0.6 logMAR). Crossed-cylinder astigmatic blur limits were approximately 90% of those for defocus, but with considerable meridional influences. In two of the subjects, the intrinsic aberrations of the eye were subsequently corrected before the defocus and astigmatic blur were added. This resulted in only minor reductions in their blur limits. When assessed with trefoil blur and corrected intrinsic ocular aberrations, the ratio of objectionable to noticeable blur limits in these two subjects was much higher for trefoil (3.5) than for defocus (2.5) and astigmatism (2.2).

1. Introduction

The question of the extent to which the retinal image may be degraded by defocus or aberration before it starts to appear to be noticeably blurred is of great importance for our understanding of the basic processes of vision, for the design of visual instruments, corrective lenses and other visual aids, and for the outcomes of refractive surgery.

There have been many reports of subjective depth-of-focus for spherical blur (Atchison, Charman, & Woods, 1997; Atchison, Fisher, Pedersen, & Ridall, 2005; Atchison, Guo, & Fisher, 2009; Campbell, 1957; Campbell & Westheimer, 1958; Charman & Whitefoot, 1977; Ciuffreda et al., 2006; Jacobs, Smith, & Chan, 1989; Ogle & Schwartz, 1959; Plakitsi & Charman, 1993; Tucker & Charman, 1986; Walsh & Charman, 1988; Wang & Ciuffreda, 2005; Wang & Ciuffreda 2006; Wang, Ciuffreda, & Irish, 2006), but few of subjective limits for astigmatism or for other monochromatic aberrations.

In two pioneering studies, Burton and Haig (1984) and Haig and Burton (1987) asked subjects to compare quasi-monochromatic computerised images on a video-monitor, one image being aberrated by different amounts of Seidel aberrations, the other being affected only by diffraction. They determined the aberrations corresponding to just noticeable differences in image quality when subjects viewed the targets through 2 mm pupils, where the eye's monochromatic aberrations had negligible effect and only diffraction degraded the retinal image of the targets. To compensate for this further stage of diffraction, inverse filtering was applied to the computer images to ensure that the retinal images were those required, i.e. those experienced by an aberration-free eye with a 2 mm pupil and those with the additional aberration. Across subjects and in their two studies, the authors determined 75% thresholds of about 0.11, 0.11, 0.15 and 0.23 μm for the Seidel coefficients for defocus, spherical aberration, astigmatism and coma, respectively. Converted to longitudinal values, the limits for astigmatism as cylinders were about 1.4 times greater than those for defocus blur (0.32 DC compared with 0.23 D). Using a broadly similar method, Legras, Chateau, and Charman (2004) found that, in dioptric terms, the cross-cylinder blur limit was about 1.25 times the limit for defocus.

Clinical data on the relative effects of spherical and cylindrical errors on visual acuity can also be used to predict the likely effects of astigmatism on blur limits, although this must be done with caution, since such visual acuity data are not directly concerned with just-detectable decrements in the clarity of images. A further complication is that the effects of cylinder on acuity measured with letter targets are known to vary with the axis of the cylinder and the form of the particular letter (Rabbetts, 2007).

Sloan (1951) determined the relationship between visual acuity and ametropia, based on clinical studies (Crawford, Shagass, & Pashby, 1945; Kempf, Collins, & Jarman, 1928) and found that cylindrical

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errors reduce visual acuity at 0.8 the rate for spherical errors. Using Pincus' (1946) data of visual acuity versus refraction for military recruits, but omitting hypermetropic and compound hypermetropic astigmatism, Raasch (1995) found that pure cylindrical errors C reduce visual acuity at about 0.7 the rate for spherical errors, slightly lower than the factor given by Sloan (Sloan, 1951). If these results could be transferred to blur limits, then the limits for cylindrical errors should be about 1.3 times greater than those for spherical errors of the same magnitude.

Note here that corrections are often considered in terms of mean sphere M and crossed-cylinder astigmatic components J_{180} and J_{45} (Thibos, Wheeler, & Horner, 1997) where

$$M = S + C/2, \quad J_{180} = -[C\cos(2\theta)]/2, \quad J_{45} = -[C\sin(2\theta)]/2$$

In these equations, S and C are again sphere and cylinder errors, and θ is the cylinder axis. In the geometrical optics approximation, the sizes of the blur circle produced by 1 D of M, J_{180}, or J_{45} are the same, and hence they are likely to have similar effect on visual acuity. However, if the effects of diffraction are allowed for, both the point-spread function and the modulation transfer functions for astigmatism vary with orientation, whereas those for spherical defocus do not (Charman & Voisin, 1993).

There has been some recent work on the effect of individual and combined aberrations on visual acuity and contrast sensitivity. Applegate, Ballentine, Gross, Sarver, and Sarver (2003) and Applegate, Marsack, Ramos, and Sarver (2003) had three well-corrected subjects with small pupils determine visual acuity using letter charts which were pre-distorted as if they were viewed by aberrated eyes. Different Zernike aberrations with coefficients of the same magnitude had different effects on the visual acuity simulation, with aberrations of small or no orientation dependence having greater effects than those of higher orientation dependence. In dioptric terms, ratios of visual acuity loss with astigmatism compared to defocus were 1.1 and 0.8 for high- and low-contrast letters, respectively (Applegate, Ballentine, et al., 2003), and 0.8 for high-contrast letters (Applegate, Marsack, et al., 2003). Furthermore, depending upon sign and type, different aberrations could combine to improve visual acuity beyond that achievable with single aberrations having the same root-mean-square (rms) wavefront error as the combination. Rocha, Vabre, Harms, Chateau, and Krueger (2007) also investigated the influence of different aberrations on vision. These were simulated with an adaptive optics system that initially compensated for the aberrations of the subjects' eyes. For 5 mm pupils, individual second, third and fourth-order Zernike rms aberrations of 0.3 μm all reduced Landolt C visual acuity by about 0.15 logMAR relative to the fully corrected state, but for aberrations of 0.9 μm, spherical aberration and defocus produced greater losses (0.6 logMAR) than did oblique astigmatism (0.39 logMAR), oblique coma (0.34 logMAR) and oblique trefoil (0.23 logMAR).

Several other studies (Piers, Fernandez, Manzanera, Norrby, & Artal, 2004; Piers, Manzanera, Prieto, Gorceix, & Artal, 2007; Guo, Atchison, & Birt, 2008; Atchison et al., 2009) have explored the effect on through-focus visual performance of eliminating one or more of the eye's normal aberrations and have found greater rates of loss of visual acuity and contrast sensitivity away from best focus and small decreases in the corresponding blur limits.

Although information on the relationship between aberration levels and through-focus visual acuity is useful, what is more important for many practical purposes such as spectacle lens tolerances is the level of additional aberration at which an individual with normal inherent levels of higher-order ocular aberration becomes aware of the blur due to the extra aberration. This report describes an investigation, using adaptive optics, into the subjective blur limits of a small group of subjects when the aberrational blur was produced by crossed-cylinder astigmatism. In contrast to earlier laboratory studies, which were confined to cylinders or cross-cylinders with either vertical or horizontal axes, the effect of changing axis orientation was also explored. Since blur limits depend upon the criterion used to assess the blur, the study used three different criteria as employed in earlier work (Atchison et al., 2005, 2009). The blur limits for astigmatism were also compared with those for defocus. Extensions to the present investigation included determining the effect of correcting the inherent higher-order aberrations of the eye on the blur limits for defocus and astigmatism, with orientation varied for astigmatism. Blur limits were also measured for third-order trefoil after correction of all other intrinsic ocular aberrations.

2. Methods

2.1. 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 six subjects in good ocular and general health, five of whom were used in a previous study of defocus blur limits (Atchison et al., 2005). Data from the previous study are not presented here. Age range was 24–70 years (mean 31 ± 10 years). Only right eyes were used. One subject was myopic (refraction −2.25 D) and the other subjects were emmetropic (subjective refractions −0.25 D to +0.75 D). Subjects had ⩽0.25 D cylinder by subjective refraction and corrected visual acuities of at least 6/6. Subjects were cyclopleged with 1% cyclopentolate, applied every hour. Pupils were dilated to at least 6 mm; for one subject, this required an additional drop of 2.5% phenylephrine at the start of each session. All six subjects took part in an experiment measuring defocus and astigmatic limits without any correction for the higher-order aberrations of their eyes. Two of the subjects, DAA and WNC, underwent further experiments measuring defocus, astigmatism and trefoil blur limits when their intrinsic higher-order ocular aberrations were corrected. All sessions were conducted with 5.0 mm pupils.

2.2. Apparatus

The apparatus was the same as that described in detail by Atchison et al. (2009) (Fig. 1). A 543 nm He–Ne laser was used for calibration purposes. Radiation was provided by a superluminescent

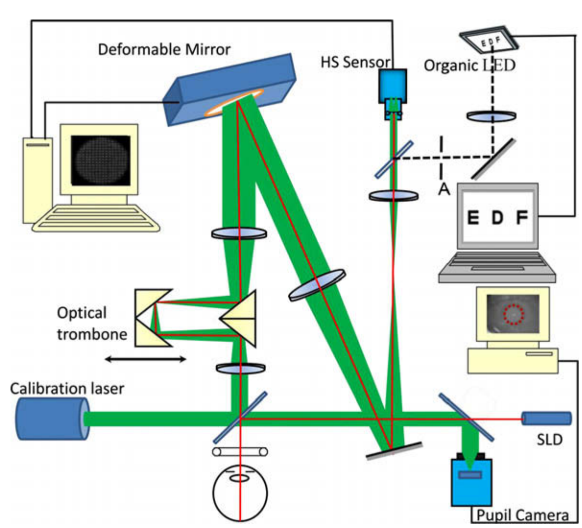

Fig. 1. Experimental system. See text for details.

diode (Hamamatsu Photonics, 830 nm, FWHM 25 nm) with 14 μW irradiance at the cornea, 50 times lower than the Australian/New Zealand laser safety standard limits (Standards Australia, 2004). The pupil position was monitored and realigned as necessary using infrared illumination and images from a Pixelink Pl-A741 firewire camera displayed on a computer monitor. The eye pupil was also imaged onto the surface of an ImagineEyes Mirao52 deformable mirror and onto the microlens array of a HASO 32 Hartmann–Shack sensor. An optical trombone arrangement, consisting of a set of fixed right-angle mirrors and a set of movable right-angle mirrors, between the pupil and the mirror varied defocus independent of the mirror (precision 0.1 mm/0.0088 D). The radiation reflected from the subject's fundus was imaged onto the camera of the Hartmann–Shack sensor.

Polychromatic (black on white) stimuli were provided by a white OLED microdisplay (eMagin Corporation) with a background luminance of approximately 60 cd/m^2. This was seen by subjects through a Badal lens and a 2.5 mm stop *A* that was conjugate with the eye pupil and provided the effective 5.0 mm pupil size. Stimuli consisted of three 99% Weber-contrast black letters selected from the 10 letters (D, E, F, H, N, P, R, U, V, Z; non-serif, 5 × 4 matrix, letter spacing equal to letter width) found on Bailey–Lovie charts (Bailey & Lovie, 1976). Three target sizes were used, with detail of 0.1, 0.35 and 0.6 logMAR (approximately 6/7.5, 6/13 and 6/24 Snellen, respectively). Five presentations were made at each letter size, with a random selection of three letters for any presentation.

2.3. Procedures and instructions

Three different blur criteria were used in the study. Subjects determined "clear", "noticeable" blur, "troublesome" blur and "objectionable" blur positions by rotating a knob on a control box to alter the shape of the deformable mirror in open-loop mode. The use of the method of adjustment with manual knob has some shortcomings, but we have argued previously that the approach is valid and reasonable for this type of experiment, particularly for exploring a number of parameters in a short time (Atchison et al., 2005).

As previously described (Atchison et al., 2005, 2009) 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.*"

Limits for defocus blur were measured for comparison with the astigmatism blur-limit data. For defocus, *M*, the control knob was rotated in both the clockwise and the anticlockwise directions to induce hypermetropic and myopic blur respectively.When establishing the blur limits for crossed-cylinder astigmatism, *J*, 8 semi-meridians encompassing 180° were used. Different procedures were adopted depending on the meridians. For oblique and regular astigmatism (Zernike terms Z_2^{-2} and Z_2^2) the knob could be rotated in both clockwise and anticlockwise directions. For regular astigmatism, clockwise rotation produced astigmatism in which the aberration was maximally negative along the horizontal meridian and maximally positive along the vertical meridian, and anticlockwise rotation produced astigmatism in which the signs of the aberrations were reversed from this. To be consistent with the ANSI/ISO standards on wavefront convention in ophthalmic optics (American National Standards Institute, 2004; International Standards Organisation, 2008), we used absolute values for the astigmatism coefficient C_2^2 and assigned the 0° meridian for the anticlockwise rotation and the 90° meridian for clockwise rotation. A similar effect occurred for oblique astigmatism, except that here the 45° meridian coincided with the anticlockwise rotation and the 135° meridian coincided with clockwise rotation. For any other meridian, there was a combination of the two Zernike aberrations, and it was possible to rotate in only the clockwise direction. We produced angles of 22.5°, 67.5°, 112.5° and 157.5°. The order of meridians was 0° and 90°, 45° and 135°, 22.5°, 67.5°, 157.5° and 112.5°.

For two of the subjects, blur limits were also measured for astigmatism and defocus after correction of all other intrinsic ocular aberrations. Additionally, blur limits were measured for third-order trefoil after correction of all other intrinsic ocular aberrations. Blur limits for this aberration were assessed in broadly the same way as those for astigmatism, but now the angles were, in order, 0° and 60°, 30° and 90°, 15°, 45°, 105° and 75° (i.e. a 120° range, as trefoil repeats every 120°).

The step size for the three aberration types at 5.7 mm pupil diameter was 0.1 μm specified in the "fringe" system, in which normalisation terms are not included in Zernike polynomials. To put this into the ANSI/ISO system, the coefficient must be divided by the relevant normalisation term (Atchison, 2004). Each step corresponded to a 15° turn of the knob. For the 5.0 mm pupil used for viewing the targets, the step size in the ANSI/ISO system was approximately 0.044 μm (equivalent to 0.049 D) for defocus, 0.031 μm for astigmatism (0.025 D) and 0.024 μm for trefoil.

At the start of each session, the mirror was turned on. Using the calibration laser with the feedback of the Hartmann–Shack sensor, the operator drove the mirror to minimise the system's aberrations (rms < 0.026 μm for 5 mm pupil size). After at least 20 min and checking with a hand optometer that the subject had minimal residual accommodation, he/she was aligned carefully in the apparatus with the help of a bitebar. The operator moved the optical trombone until the Zernike defocus coefficient C_2^0 was within ±0.05 μm. The subject's wavefront aberrations were measured. The operator adjusted the mirror to reduce the Zernike second-order astigmatism coefficients to within ±0.05 μm and generally to within ±0.03 μm (5 mm pupil). Residual aberrations were determined. Next, the subject determined a "best-focus" position by moving the optical trombone backwards and forwards for six settings. The mean of these was taken as the position at which the trombone was set for the session. The subject altered blur by rotating the knob in one direction to determine "noticeable", "troublesome" and "objectionable" blur positions. The operator reset the mirror defocus to the "best-focus" position and the subject made determinations in the opposite direction. The operator would always remind the subject of the overall direction he/she should rotate the knob and the blur criterion to be used. The orders of initial direction and letter size were randomised. Each letter size was presented five times and limits for the blur criteria were recorded.

After measurements were taken, the operator checked the residual aberrations after resetting the mirror to the "best-focus" position.

The procedure for astigmatism and trefoil was almost the same as for defocus, except that, as described above, for some meridians measurements could only be made with a clockwise rotation of the knob. For two subjects, defocus and astigmatism blur limits were also determined following minimisation of higher-order aberrations. For this situation, and also during the determination of the trefoil blur limits for these two subjects, rather than the operator manually adjusting the mirror to reduce astigmatism coefficients, all aberrations other than defocus were minimised at 830 nm.

2.4. Calibration

At the end of each subject's session, calibrations of the mirror were made to convert mirror settings to wave and longitudinal aberrations. The subject was removed from the apparatus, the superluminescent diode was turned off, and the calibration laser was turned on. For the aberration of interest (and meridian for astigmatism and trefoil), the mirror was varied in 0.3–1.0 μm Zernike fringe steps to cover the range of subject settings. For each mirror setting, all aberrations were measured with the wavefront sensor according to the ANSI/ISO aberration standards (American National Standards Institute, 2004; International Standards Organisation, 2008). A quadratic fit was then made for the aberration of interest. In all cases, the second-order term was small compared to the linear term. The calibration was different for each subject and aberration, since the mirror initially has to correct either the subject's astigmatism alone or their astigmatism combined with all higher-order aberrations. The nature of these individual aberrations affects the ability of the mirror to faithfully change its shape to alter a particular aberration without accompanying change in other aberrations.

2.5. Analysis

The Zernike aberration coefficients for astigmatism and trefoil were converted to magnitude and axis format (American National Standards Institute, 2004; International Standards Organisation, 2008) using

$$C_{nm} = \sqrt{(C_n^{-m})^2 + (C_n^m)^2}, \quad \alpha_{nm} = \arctan(C_n^{-m}/C_n^m)/|m|$$

where for astigmatism $n = 2$ and $m = 2$, and for trefoil $n = 3$ and $m = 3$.

When analysing the data, the measurements of second-order Zernike aberration coefficients were converted to dioptres for defocus M and astigmatism J by multiplying by 1.11 and 0.78 according to the formulae

$$M = \frac{4\sqrt{3}C_2^0}{R^2}, \quad J = \frac{2\sqrt{6\left[\left(C_2^{-2}\right)^2 + \left(C_2^2\right)^2\right]}}{R^2} = \frac{2\sqrt{6}C_{22}}{R^2}$$

where C_2^0 is the defocus Zernike coefficient (μm), C_2^{-2} and C_2^2 are the astigmatism Zernike coefficients (μm) and R is the pupil semi-diameter in mm (2.5 mm). To help in interpretation of later plots involving astigmatism, we note that a conventional crossed-cylinder astigmatic blur of $y/-2y \times \alpha_{22}$ in magnitude and axis format is $A = y$, α_{22}, e.g. $+1.0/-2.0 \times 180$ gives 1.00, 180 and $+1.0/-2.0 \times 90$ gives 1.00, 90.

For each subject, direction of blur (for defocus) or meridian, blur limit criterion, and letter size, the five measurements were averaged. For defocus, the dioptric equivalents were shifted so that the midpoints of the noticeable limits in the two directions were zero.

For defocus, an analysis of variance was conducted on blur limits with subjects as repeated measures, and with blur direction, blur criterion, and letter size as within-subject factors. For astigmatism, an analysis of variance was conducted on blur limits with subjects as repeated measures, and meridian, blur criterion, and letter size as within-subject factors. For both analyses, a Greenhouse–Geisser correction was used where Mauchly's test of sphericity was significant for the within-subjects factors.

3. Results

3.1. Residual aberrations

Table 1 shows subjects' residual wavefront aberrations for 5 mm pupils. The root-mean-square (rms) values are the values obtained when astigmatism was reduced to near zero with the adaptive-optics mirror, and defocus ignored (i.e. they include only higher-order aberrations and any residual uncorrected second-order astigmatism). Where individual aberrations had rms values >0.1 μm, the coefficients are given. Aberration levels appear to be typical of those for normal subjects with the pupil sizes and ages involved, e.g. Applegate, Donnelly, Marsack, Koenig, and Pesudovs (2007). For the two subjects for whom full adaptive-optics corrections were used, residual aberrations at the start of sessions were reduced to 0.05–0.06 μm (DAA) and 0.06–0.08 μm (WNC). Residual aberrations by the end of sessions had increased to 0.06–0.07 μm and 0.10–0.12 μm for these two subjects, the increases of 20–100%, reflecting real changes in aberrations over the session and minor changes in head/eye position.

3.2. Calibrations

Fig. 2 shows calibration curves for subject DAA when (a) astigmatism and (b) trefoil were manipulated along particular meridians. Fits in each case are quadratic. The astigmatism plot (left panel) shows that the astigmatism introduced effectively changed in a linear way with the mirror setting. The plot also shows that the astigmatism changes were accompanied by very small changes in defocus: the latter varied by only 0.03 μm across the range of astigmatism settings. Changing the astigmatism setting introduced negligible amounts of other aberrations (<0.1 μm variation, not shown). The fit for this figure is representative of the astigmatism for all subjects, both without and with adaptive-optics correction. The trefoil plot (right panel, Fig. 2) shows that although the trefoil mirror setting introduced linear changes in the trefoil there was also some accompanying variation in astigmatism for this subject, with the change in astigmatism being 15% of the change in trefoil. Although undesirable, we considered this to be small enough to allow evaluation of the trefoil blur limits. The other subject for whom trefoil was measured showed a change in astigmatism <1% of the change in trefoil. Changing the trefoil setting introduced negligible amounts of other aberrations for both subjects (not shown).

3.3. Defocus versus astigmatism

Fig. 3 shows the group mean blur limits at each letter size for defocus (solid symbols) and astigmatism (open symbols) as a function of astigmatic meridian. Each individual panel shows the limits for 0.6 (top), 0.35 (middle) and 0.1 (bottom) logMAR letter sizes. The three panels show noticeable blur limits (top), troublesome blur limits (middle) and objectionable blur limits (bottom). Note the different vertical scales used in the panels. The defocus is the average of positive and negative values.

Mean blur limits and their 95% confidence limits for defocus for the group ranged from 0.18 ± 0.08 D (just noticeable, 0.1 logMAR) to 1.01 ± 0.27 D (objectionable, 0.6 logMAR). Across the range of subjects and meridians, the ratio of astigmatism blur limits to defocus blur limits varied between 0.83 and 0.95 for various combinations of letter sizes and blur limits, with a mean and its 95% confidence limits of 0.90 ± 0.04. Disregarding meridional variation, this indicates that astigmatism has slightly more subjective blurring effect than does defocus of the same magnitude.

Table 1
Total residual root-mean-square (rms) wave aberrations and major individual aberrations (microns) for each subject for 5 mm pupils (only aberrations >0.1 μm are listed). For each eye, astigmatism has been corrected and defocus has been set to zero.

Subject	Rms aberrations (μm)	Major individual aberrations and their coefficients (μm)
DAA	0.16	Spherical aberration +0.12
CO	0.27	Horizontal coma +0.17, vertical coma −0.13, spherical aberration +0.14
EM	0.25	Trefoil −0.11, oblique trefoil −0.18
PG	0.18	Spherical aberration +0.13
AM	0.22	Trefoil −0.18
WNC	0.23	Horizontal coma +0.16, vertical coma −0.11

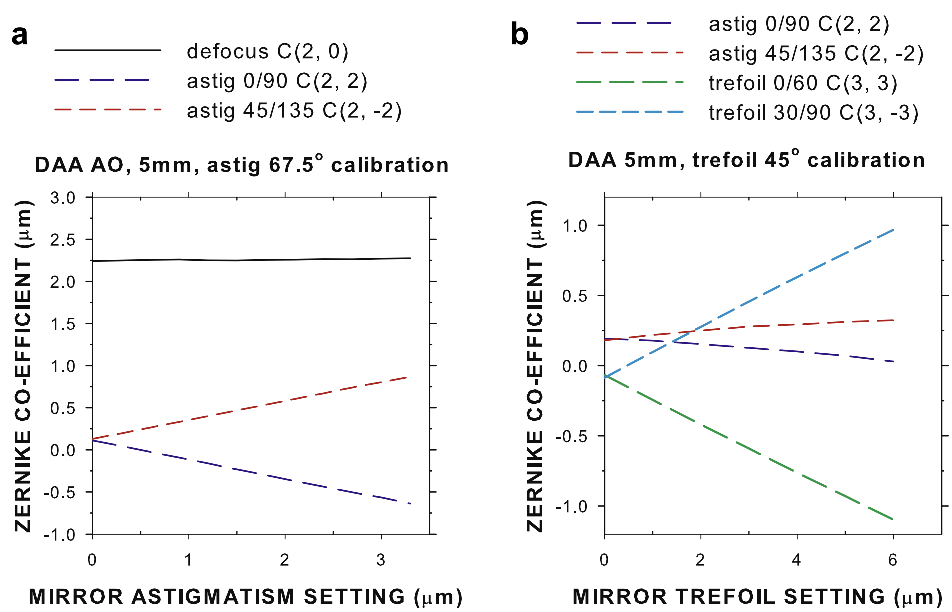

Fig. 2. Main changes in aberration coefficients with change in mirror setting for subject DAA for (a) astigmatism with instrument meridian 67.5°, and (b) trefoil with instrument meridian 45°. Note that coefficients are not zero at the zero mirror setting; this is because of adjustments of the system to correct the subject's aberrations, either with the optical trombone (defocus) or with the mirror (astigmatism, trefoil).

3.4. Effect of meridian on astigmatism blur limits

Meridian had a significant effect on the subject group blur limits ($F_{2.8,14.0} = 4.4$, $p = 0.024$). Within-subjects contrast testing showed that the limits for 90° were significantly less than those for 67.5°, 22.5°, 157.5° and 0°, the limits for 112.5° were significantly smaller than those for 157.5° and 0° and the limits for 45° and 135° were significantly smaller than those for 0°. Relative to the results for the 90° meridian, these effects amount to considerable mean increases, averaged across all letter sizes and criteria, of 76–80%, or 0.20–0.21 D, for 157.5° and 0° (Fig. 3).

3.5. Effect of blur-limit criterion on defocus and astigmatism blur limits

For defocus, blur-limit criterion had a highly-significant effect on blur limits ($F_{1.1,5.5}$=37.3, $p = 0.001$). There were significant interactions of blur criterion with letter size ($F_{1.3,6.6} = 23.4$, $p = 0.002$). Across all letter sizes, the ratio of troublesome to noticeable blur limits was 1.7 times and the ratio of objectionable to noticeable blur limits was 2.6 times. The ratio of troublesome to noticeable blur increased from 1.5 times for 0.1 logMAR letters to 1.8 times for 0.6 logMAR letters, and the ratio of objectionable to noticeable blur increased from 2.4 times for 0.1 logMAR letters to 2.8 times for 0.6 logMAR letters. These results are similar to those of the previous studies (Atchison et al., 2005, 2009).

For astigmatism, the blur-limit criterion again had a highly-significant effect on blur limits ($F_{2.8,14.0} = 4.4$, $p = 0.024$). There were significant interactions of blur criterion with letter size ($F_{1.25,6.3} = 24.5$, $p = 0.002$) but not with meridian. Across all letter sizes, the ratio of troublesome to noticeable blur limits was 1.7 times and the ratio of objectionable to noticeable blur limits was 2.6 times. The ratio of troublesome to noticeable blur increased from 1.6 times for 0.1 logMAR letters to 1.8 times for 0.6 logMAR letters, and the ratio of objectionable to noticeable blur changed little with letter size.

The influence of blur criterion on blur limits was thus similar for defocus and astigmatism.

3.6. Effect of letter size on defocus and astigmatism blur limits

For defocus, letter size had a highly-significant effect on blur limits ($F_{2,10} = 55.6$, $p < 0.001$). Across both blur directions and the blur criteria, increasing letter size from 0.1 logMAR to 0.6 logMAR increased blur limits by 2.3 times. Again, these results are similar to those of the previous study (Atchison et al., 2009).

For astigmatism, letter size again had a highly-significant effect on blur limits ($F_{1.0,5.0} = 18.9$, $p = 0.007$). As noted in this section, there were significant interactions of letter size with blur criterion, but there were none between letter size and meridian. Across all orientations and blur criteria, increasing letter size from 0.1 logMAR to 0.6 logMAR increased blur limits by 2.2 times.

The influence of letter size on blur limits was thus similar for defocus and astigmatism.

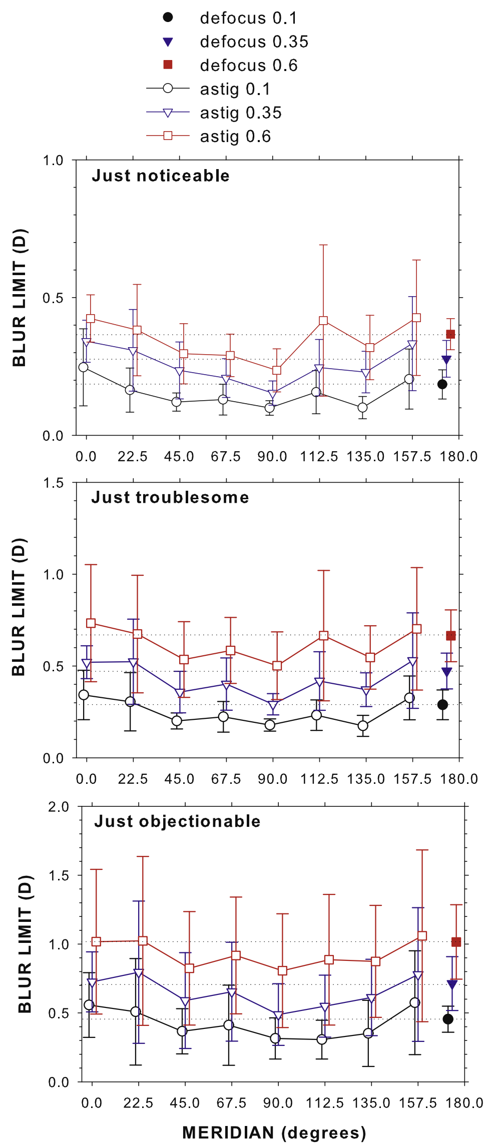

Fig. 3. Mean defocus (solid symbols) and astigmatism blur limits (open symbols) as a function of astigmatism axis for the subject group ($n = 6$). Pupil size 5 mm. Limits are shown for noticeable blur (top row), troublesome blur (middle row), and objectionable blur (bottom row): in each case results are shown for letter sizes 0.1, 0.35 and 0.6 logMAR. Note that the vertical scales differ in the three rows. Blur is expressed in dioptres (see text). Error bars represent ±95% confidence intervals. For clarity, data for different blur criteria are off-set slightly relative to each other and horizontal dotted lines are drawn through defocus symbols.

3.7. Effect of adaptive optics condition on defocus and astigmatism blur limits

Fig. 4 shows subject DAA's defocus and astigmatism blur limits, with the left and right columns showing results without and with adaptive-optics correction of higher-order aberration, respectively. Fig. 5 is similar, but for subject WNC. The left-hand columns of Figs. 4 and 5 show that, when higher-order aberrations are uncorrected, blur limits for individuals vary with the meridian of the astigmatism. For subject DAA, this variation is significant but generally small (Fig. 4). For subject WNC, the effects are significant and considerable with much larger blur limits for 0° and 157.5° than within the range 22.5–112.5° (Fig. 5).

For defocus, adaptive-optics correction reduced DAA's blur limits for the different criterion-letter size combinations to about 52–88% of the values obtained with no correction, with a mean of 70%. The corresponding values for WNC were 66–110% with a mean of 83%. These reductions are statistically significant ($p < 0.01$).

For astigmatism, adaptive-optics correction reduced DAA's blur limits for the different criterion-letter size combinations to 82–93% of their original values, with a mean of 88%. The corresponding values for WNC were 76–115%, mean 98%. Thus, for these subjects and across all meridians, the reductions in blur limits with adaptive-optics correction were proportionately smaller for astigmatism than for defocus. Adaptive-optics correction reduced the meridional variation in blur limits for WNC.

It is probable that the results of correction of monochromatic aberrations will vary with the aberrations of the individual eye but it seems reasonable to suggest that any associated reductions in defocus and astigmatic blur limits will be always modest, at least for 5 mm pupils and during observation of white-light targets, when uncorrected chromatic aberrations will still play an important role in degrading the retinal image and will thus tend to mask the improvement in image quality given by correction of the monochromatic aberrations.

3.8. Between-subject effects for defocus and astigmatism blur limits

For defocus, there was a significant between-subjects effect ($F_{1,5} = 176.0$, $p < 0.001$) 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 blur criteria and letter sizes) were 1.0–1.7. In general, subjects showed proportionate effects with variation in blur criterion and letter size. In the previous study the ratios were 1.0–3.1; the least-sensitive subject of the other study was not used this time.

For astigmatism, there was a significant between-subjects effect ($F_{1,5} = 38.9$, $p = 0.002$) on blur limits. The ratios of blur limits, averaged across all meridians, blur criteria and letter sizes were 1.0–2.1. As evidenced by comparing the left-hand columns of Figs. 4 and 5, between-subject effects were not proportionate with change in meridian.

In general, between-subject variation was similar for defocus and astigmatism.

3.9. Blur limits for trefoil for subjects DAA and WNC

Fig. 6 shows trefoil blur limits with 5 mm pupils for subjects DAA and WNC with adaptive-optics correction for intrinsic ocular aberrations. The corresponding defocus blur limits are shown for comparison. Unlike the previous figures, the side scale is in micrometres rather than dioptres. Microns are used here because trefoil cannot usefully be expressed in dioptric terms. For direct comparison purposes, previous dioptric results with adaptive-optics correction (Figs. 4 and 5) can be expressed in microns by multiplying them by factors of 0.902 (defocus) and 1.276 (astigmatism). When expressed in microns, the blur limits were a mean 50% and 18% greater for trefoil than for defocus and astigmatism, respectively.

The calibration results showed intrusion of variable astigmatism for subject DAA as trefoil was varied (Fig. 2). As the change in astigmatism was only 15% of the change of trefoil for this subject, and less than 1% for subject WNC, this was not considered important.

Overall, WNC had slightly greater trefoil blur limits than DAA (mean difference about 12%). Both subjects showed meridional effects but, as was found in the case of astigmatism, this was more marked for WNC than for DAA.

Across all letter sizes, the ratio of troublesome to noticeable blur limits for the two subjects was 2.2 times and the ratio of objectionable to noticeable blur limits was 3.5 times (for defocus

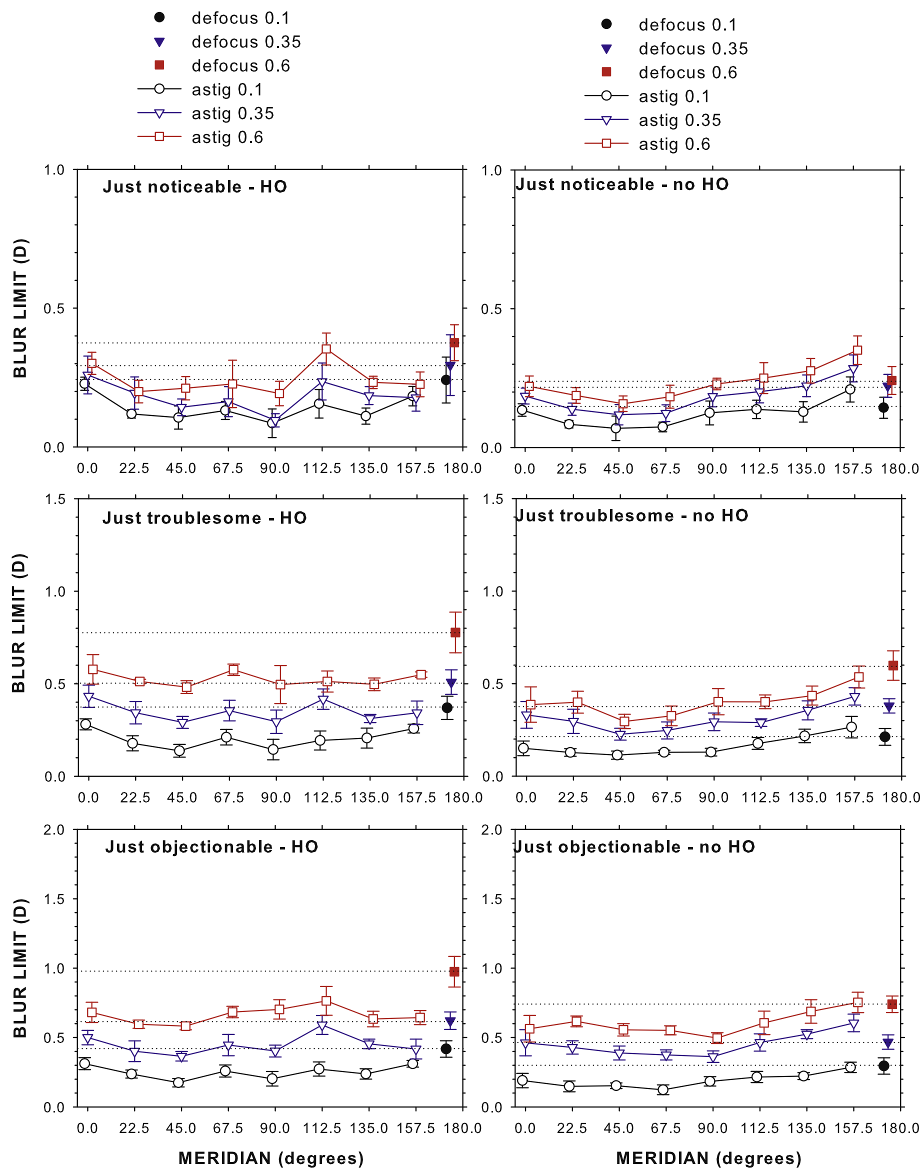

Fig. 4. Mean defocus (solid symbols) and astigmatism blur limits (open symbols) of subject DAA as a function of astigmatism axis. Pupil size 5 mm. Limits are shown for noticeable blur (top row), troublesome blur (middle row) and objectionable blur (bottom row): in each case results are shown for letter sizes 0.1, 0.35 and 0.6 logMAR. Note that the vertical scales differ in the three rows. Results are without correction of higher-order aberrations ("HO", left column) and with correction of higher-order aberrations ("no HO", right column). Pupil size 5 mm. Error bars represent standard deviations of five measurements. For clarity, data for different blur criteria are off-set slightly relative to each other and horizontal dotted lines are drawn through defocus symbols.

with adaptive optics for these two subjects the values were 1.7 and 2.5 times; corresponding values for astigmatism were 1.6 and 2.2). The ratio of troublesome to noticeable blur increased from 1.6 times for 0.1 logMAR letters to 2.7 times for 0.6 logMAR letters (defocus 1.6–2.1 times, astigmatism 1.5–1.9 times), and the ratio of objectionable to noticeable blur increased from 2.3 times for 0.1 logMAR letters to 4.4 times for 0.6 logMAR letters (defocus 2.3–2.9 times, astigmatism 1.9–2.9 times) (Fig. 7). This shows that, at the largest letter size, the relationships between the three blur criterion limits are considerably different for trefoil than for defocus and astigmatism.

4. Discussion

As might be expected, the present study showed that astigmatic blur limits were affected by a variety of factors.

We note first that there were meridional influences on astigmatic blur limits: such influences were not explored in earlier studies. The 90° meridian gave the smallest blur limits for this group of subjects, with meridians nearly at right angles to this having substantially increased limits. For the subject group and averaged across all letter sizes and blur criteria, at 157.5° and 0° these effects amounted to mean increases of 76–80%, or 0.20–0.21 D, with respect to the values for the 90° meridian (Fig. 3). These effects are analogous to clinical observations of the impact of cylindrical errors on visual acuity (Rabbetts, 2007).

The meridional dependence of astigmatic blur limits is expected to be at least in part due to the interaction of the added astigmatism with other existing aberrations of the eye, including influence of the choice of best-focus position. Simulations showed little effect of astigmatic meridian on the image quality of letters in the absence of other aberrations. However, in eyes with normal levels of higher-order aberration, the situation is more complex. There appears to be little interaction of astigmatic meridian with some aberrations (e.g. coma, trefoil, see, e.g. top row of Fig. 8), but there

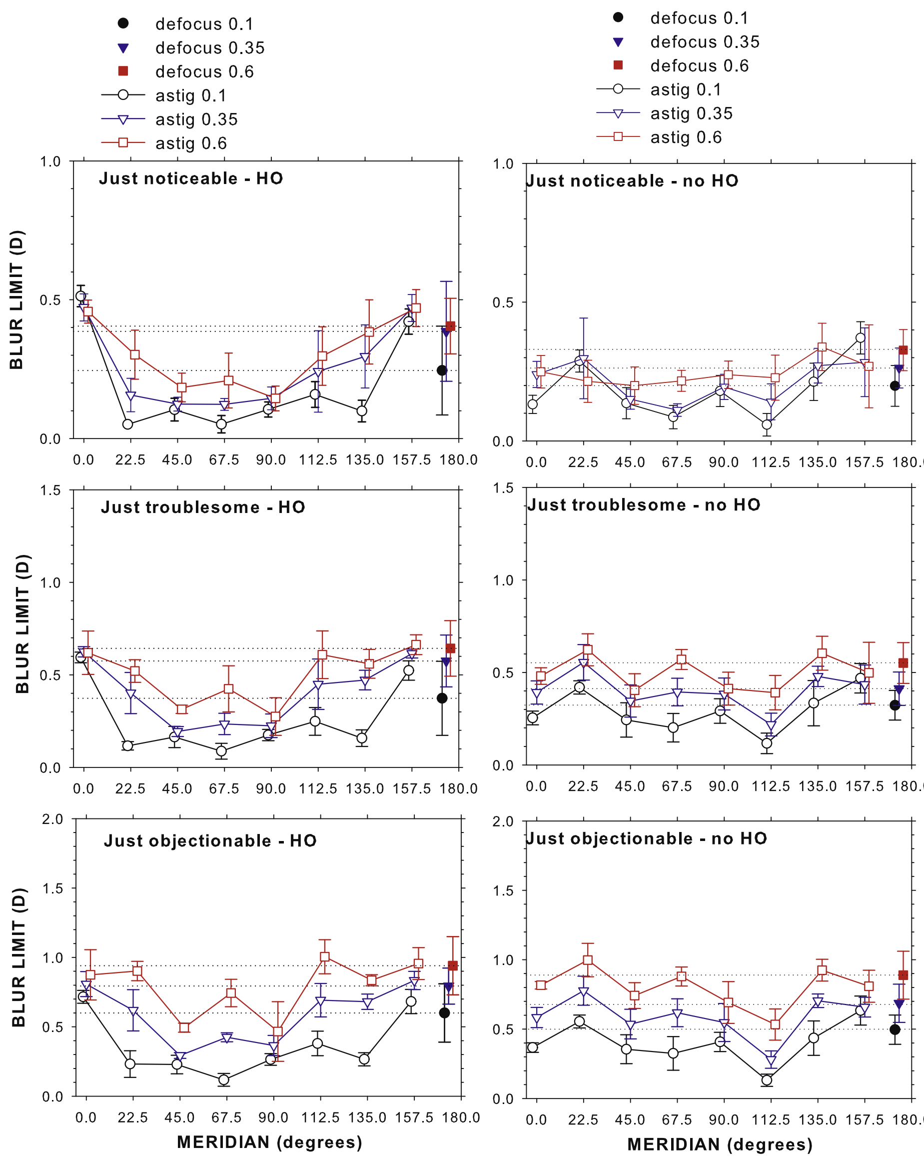

Fig. 5. Mean defocus and astigmatism blur limits of subject WNC. Other details are as for Fig. 4.

are considerable interactions with other aberrations such as secondary astigmatism (bottom row, Fig. 8).

There was also considerable intra-subject variability for astigmatic blur limits. As well as interactions of astigmatism with other aberrations, the random letters selected were a factor. In general, closed letters such as P and R appeared to blur before open letters, and particular letters were possibly affected more by some astigmatic meridians that were others.

Overall, mean blur limits for defocus and 5 mm pupils (Fig. 3) ranged from 0.18 ± 0.08 D (just noticeable, 0.1 logMAR) to 1.01 ± 0.27 D (objectionable, 0.6 logMAR). Disregarding meridional variations, crossed-cylinder astigmatism had only a slightly more deleterious subjective effect than defocus on vision: without adaptive correction of higher-order aberrations, and across all subjects, meridians and blur criteria, blur limits for crossed-cylinder astigmatism were about 90% of the corresponding defocus blur limits. This value is compatible with the results of previous work., which also suggested that the degrading effects of defocus blur were broadly similar to those of crossed-cylinder astigmatism, with visual acuity deteriorating for astigmatism by 0.8–1.1 times (Applegate, Ballentine, et al., 2003, Applegate, Marsack, et al., 2003) and 0.7–1.0 times (Rocha et al., 2007) the values found for defocus, and with the just-detectable blur limit for cross-cylinder astigmatism being about 1.25 times that for defocus (Legras et al., 2004). We note that Legras et al. were comparing their simulated aberrated images with those for a standard eye which itself suffered from aberrations which included significant astigmatism (−0.38 DC axis 180°), whereas in the present study any existing astigmatism in the subjects' eyes was first corrected. Other conditions also differed. Thus, it is not unreasonable that slightly different results were obtained. As noted earlier, the geometric prediction is that the blurring effects should be the same (Thibos et al., 1997). For most practical purposes, given the variations across subjects, meridians, letter sizes and other factors, it seems reasonable to assume as a working approximation that the blurring effects of defocus and crossed-cylinder astigmatism are indeed similar (cf. Raasch, 1995) and that tolerances in visual instrumentation and ocular corrections should be set accordingly.

For the two subjects tested with full adaptive correction, reducing the higher-order aberrations had mild to moderate effects on blur limits for the white-light targets used: the limits were reduced to about 76% (defocus) and 93% (astigmatism) of their original val-

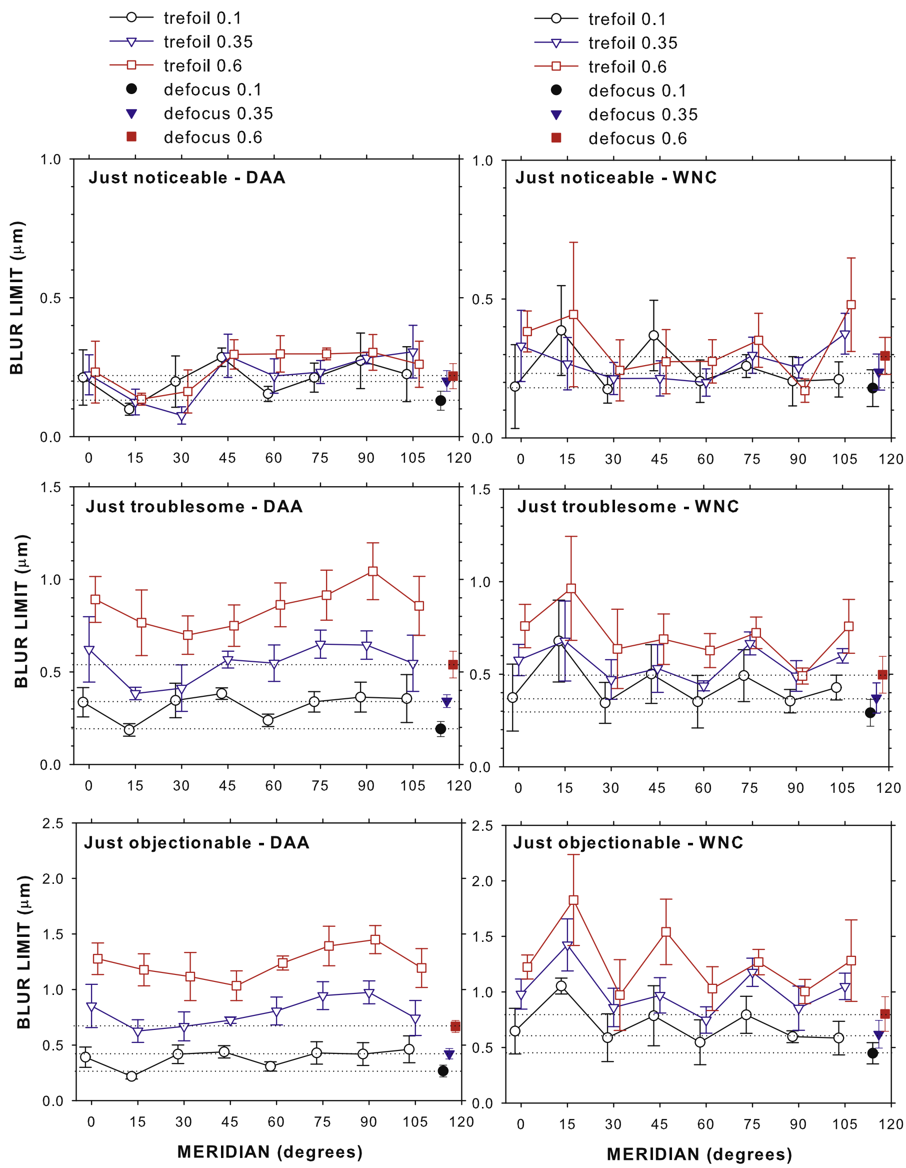

Fig. 6. Mean trefoil (open symbols) and defocus blur limits (solid symbols) for subjects DAA (left column) and WNC (right column) as a function of trefoil axis for noticeable blur (top row), troublesome blur (middle row) and objectionable blur (bottom row): in each case results are shown for letter sizes 0.1, 0.35 and 0.6 logMAR. Intrinsic ocular higher-order aberrations have been corrected. Note that the vertical scales differ in the three rows. Pupil size 5 mm. Error bars represent standard deviations of five measurements. For clarity, data for different blur criteria are off-set slightly relative to each other and horizontal dotted lines are drawn through defocus symbols.

ues. It seems reasonable to attribute the lack of a more marked effect to the fact that chromatic aberration remained uncorrected. It is well-known that the potential visual benefits of aberration are only fully realised when both monochromatic and chromatic aberrations are eliminated (see LeGras & Rouge, 2008; Yoon & Williams, 2002) and the same must apply to reductions in aberration tolerances. It may be, too, that neural adaptation to the eye's intrinsic aberrations plays a role (Artal et al., 2004; Chen, Artal, Gutierrez, & Williams, 2007) and that correction of aberration produces less effect on sensitivity to blur than might be expected on purely optical grounds.

For the two subjects tested, there was a considerably different relationship between the different blur limits for trefoil as compared with those for defocus and astigmatism. For trefoil, the ratio of objectionable to noticeable blur limits was much higher for the 0.6 logMAR letters (4.4) than for 0.1 logMAR letters (2.3) (Fig. 7). While a trend of increasing ratios with larger letters also occurred with defocus and astigmatism, this was much less marked (e.g. 2.9 and 1.9 for 0.6 and 0.1 logMAR letters, respectively, for astigmatism). For trefoil, both subjects noted that, with objectionable blur and large letters, the letters appeared to lose contrast rather than become blurred as was the case with astigmatism, and this necessitated a change in criterion about what was objectionable. This loss of contrast was supported by simulations (Fig. 9). Relevant here is the finding by Rocha et al. (2007) that substantial amounts of oblique trefoil (0.9 µm for a 5 mm pupil) produced much smaller decrements in acuity (+0.22 logMAR) than the same rms level of defocus (+0.62 logMAR) and oblique astigmatism (+0.39 logMAR), even though the effects for the different aberrations were similar at lower rms levels (0.1 and 0.3 µm). This may imply that as the amount of trefoil is increased from zero, noticeable blur occurs at similar rms levels as in the case of other aberrations. However, with further increase in the trefoil, enough high-frequency information still remains for recognition of letters to be possible and acuity to suffer little loss, whereas with increasing defocus and astigmatism this high-frequency information is lost at a lower

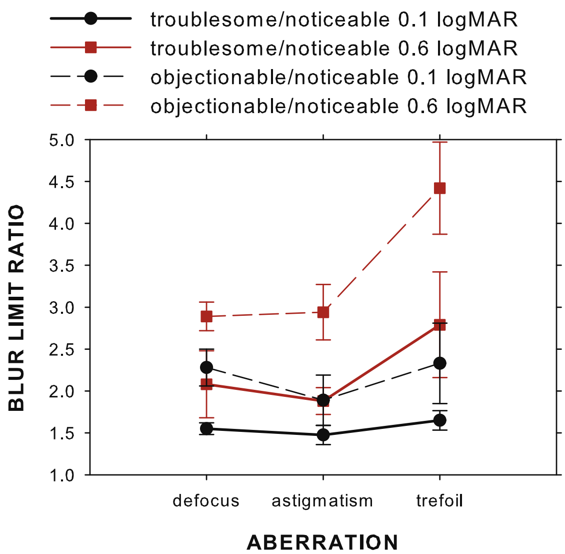

Fig. 7. Some ratios of blur limits for defocus, astigmatism and trefoil for subjects DAA and WNC. The lines join the means for the two subjects and the extremes of each vertical bar indicate the values for the individual subjects.

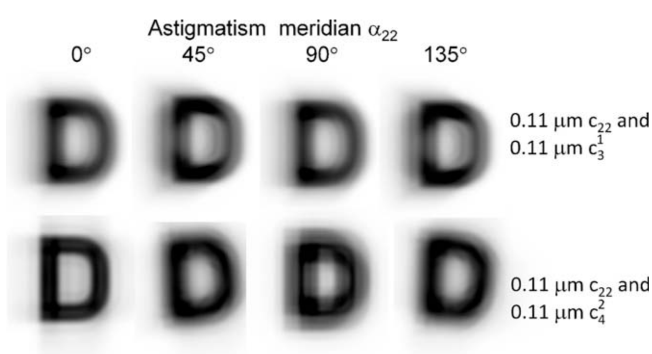

Fig. 8. Simulations of combinations of astigmatism and other aberrations on image quality of a 0.1 logMAR letter D. The effect of meridian of astigmatism is more marked in the presence of secondary astigmatism (bottom row) than in the presence of coma (top row). Pupil size 5 mm.

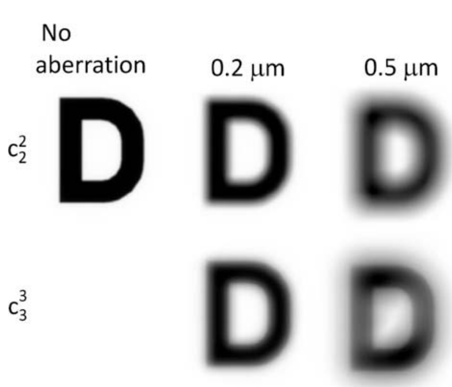

Fig. 9. Simulations of effects astigmatism (top row) and trefoil (bottom row) on image quality of a 0.6 logMAR letter D. Pupil size 5 mm. For the two aberrations, 0.2 μm coefficient produces similar effects on quality, slightly blurring the letter. For a 0.5 μm coefficient, astigmatism produces a very blurred letter, while trefoil results mainly in reduced contrast.

rms aberration level (see Fig. 9 for examples), resulting in a correspondingly higher loss in acuity. The ratios of the limits of troublesome and objectionable blur to noticeable blur for trefoil would, then, be expected relatively greater than those for defocus and astigmatism, as observed in the present study. We note too that the recent study (Fernández-Sánchez et al., 2008) in which trefoil (orientation not specified) was introduced by custom-made contact lenses showed that low levels of trefoil (0.07 and 0.17 μm) had no effect on visual acuity or contrast sensitivity with a 5 mm pupil but that 0.96 μm caused significant losses. This is broadly compatible with our data (Fig. 6) which show that, for the smallest, 0.1 logMAR, letter size used, just noticeable limits for trefoil were about 0.2 μm (higher than the low levels used by Fernández-Sánchez et al.) and objectionable blur limits, at which the letters were beginning to be difficult to recognise, were about 0.5 μm, so that levels of 0.96 μm would be expected to cause acuity loss.

As only two subjects were examined with full adaptive correction to investigate the influence of astigmatism, defocus and trefoil on blur limits, the results for these conditions must be treated with some caution. The finding of a different dependence of trefoil blur limits on letter size than occurred for defocus and astigmatism blur limits is supported by simulations (Fig. 9) and a previous visual acuity study, as described in the previous paragraph.

The Mirao 52 mirror performed very well in open-loop mode with astigmatism blur (and defocus as shown in the previous study), at least for the range of aberrations of our subjects. Calibrations showed that the measured aberrations were linear functions of induced aberration with little other aberration introduced. For trefoil, astigmatism was induced that changed at 15% and 1% of the rate of the trefoil for two subjects. This was considered acceptable. The intrusion of other aberrations could be controlled by monitoring aberrations using a laser that bypasses the eye and provides feedback to the mirror during experiments.

In the experiments, a 5.7 mm pupil was used to control aberrations, while aberrations were measured at a 5.0 mm pupil. Because of the nature of Zernike polynomials, a given higher-order Zernike polynomial for a given pupil size will, when truncated by a smaller pupil, give additional lower-order terms. For trefoil, other terms produced were small and inconsequential. This would not be the case for some other aberrations such as spherical aberration, for which a reduction from a 5.7 mm to a 5.0 mm pupil would introduce a defocus coefficient that is −68% of the amount of the spherical aberration coefficient at the larger pupil. It is reasonable to correct across a larger pupil size than is required for measurement because of concerns about the accuracy of the wavefront at the edge of the pupil, and a way of providing accurate aberrations such as spherical aberration would be to have a more sophisticated waveform at the controlling pupil size to guarantee the correct aberrations at the smaller, measuring pupil size.

5. Conclusions

Under the conditions of the study, in eyes with their normal levels of higher-order aberration crossed-cylinder astigmatic blur had a slightly more adverse effect on vision than spherical blur. The astigmatic blur limit across the subjects, criteria, letter sizes and pupil diameters tested was, on average, about 90% of the corresponding defocus limit. Although astigmatic meridian had a significant effect on the blur limits, it was not large. As a working approximation, then, the values of tolerances for defocus blur can also be used for crossed-cylinder astigmatic blur. With the black letter targets on a white background used and no correction for ocular chromatic aberration, correction of higher-order aberrations slightly reduced the limits of defocus blur but had less effect on the astigmatic limits. Subjective limits of trefoil blur were higher than those for defocus and astigmatism, particularly when the objectionable blur criterion was used. This was because increases in trefoil appeared to primarily affect the contrast of the letter images rather than the sharpness of their contours. The results are particularly relevant to spectacle lens design, notably that of progressive addition lenses in which aberrations cannot be eliminated from visually-sensitive regions: the data can help designers to understand how much aberration can be tolerated.

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