Available online at www.sciencedirect.com
SCIENCE DIRECT®
Vision Research 45 (2005) 1967–1974
Vision Research
www.elsevier.com/locate/visres

Noticeable, troublesome and objectionable limits of blur

David A. Atchison [a,*], Scott W. Fisher [b], Carol A. Pedersen [a], P. Gareth Ridall [c]

[a] *School of Optometry, Queensland University of Technology, Victoria Park Road, Kelvin Grove, QLD 4059, Australia*
[b] *SOLA International Research Centre, Sola International Holdings, 19 Cooroora Crescent, Lonsdale, SA 5159, Australia*
[c] *School of Mathematical Sciences, Queensland University of Technology, GPO Box 2434, Brisbane, QLD 4001, Australia*

Received 25 July 2004; received in revised form 5 December 2004

Abstract

We investigated limits at which induced blur becomes noticeable, troublesome and objectionable. We used 15 cyclopleged subjects, a Badal optometer with lines of three high contrast letters as targets, 3–6 mm artificial pupils, and 0.0–0.7 logMAR letter sizes. For 0.0 logMAR size, mean "noticeable" blur limits were ±0.33D, ±0.30D and ±0.28D at 3 mm, 4 mm and 6 mm, respectively, but increased by about 70% for 0.7 logMAR letters. All limits reduced by about 17% as pupil size increased from 3 mm to 6 mm. Letter size had a significant influence on all blur limits (1.6–2.1 times), but blur direction had no significant effect. Magnitudes of "troublesome" and 'objectionable" limits were 1.6–1.8 times and 2.1–2.5 times relative to "noticeable" limits, respectively. Our results suggest criteria for troublesome and objectionable blur are relatively unaffected by letter size.

Keywords: Blur *limits*; Defocus; Letter size; Pupil size; Visual acuity

---

1. Introduction

Several studies have investigated depth-of-focus of the human eye. A criterion for depth-of-focus relevant to the clinical situation is the defocus for which the visual acuity or contrast sensitivity do not decrease by more than a certain amount or below a certain limit e.g. 6/6 visual acuity (Charman, 1979; Legge, Mullen, Woo, & Campbell, 1987; Ogle & Schwartz, 1959; Tucker & Charman, 1975). A practical criterion for depth-of-focus that is relevant to clinical and everyday situations is the perception of 'blur", and involves finding the defocus limits by which a target's clarity, contrast and/or form start to appear affected relative to the in-focus situation (Atchison, Charman, & Woods, 1997; Campbell, 1957; Jacobs, Smith, & Chan, 1989). In simple terms, with this criterion we are finding how much defocus provides "just noticeable" blurring of a target.

There are several factors that will influence depth-of-focus. These include differences in subjective judgements between people, the nature of the targets, pupil size and target size. Pupil size is important to consider, as this influences the size and shape of retinal images, and it may vary considerably in the environments for which good vision is required. Distance tasks often involve fine detail, and in the case of driving it is advantageous to be able to recognize information at a long distance. Hence target detail as small as 1 min arc detail (0.0 log min arc detail, Snellen equivalent 6/6) may be involved. On the other hand, the most common font sizes for printed material are 10–12 point, with 10 point being particularly common for newspapers. Taking into account both lower and upper case letters the 10–12 point spans a letter height range of approximately 2–4 mm. When viewed at a distance of about 45 cm this range of letter sizes produces a visual angle range of approximately 15–30′ (approx 0.5–0.8 log min arc detail).

Atchison et al. (1997) used 5 subjects, with a Badal optometer apparatus and single letter Es as targets, to

---

[*] Corresponding author. Tel.: +61 7 3864 5711; fax: +61 7 3864 5665.
E-mail address: d.atchison@qut.edu.au (D.A. Atchison).

0042-6989/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.visres.2005.01.022

investigate depth-of-focus using the "just noticeable" criterion for depth-of-focus. Pupil size was an important influence on depth-of-focus between 2 mm and 4 mm pupils, but not between 4 mm and 6 mm pupils. Across a range of letter sizes from −0.2 to 0.87 log min arc detail (Snellen equivalent 6/3.8 to 6/45), the "just noticeable" blur limits for high contrast letters decreased from a mean ±0.43D for a 2 mm pupil, to ±0.29D for a 4 mm pupil, and to ±0.28D for a 6 mm pupil. Low contrast letters (21% Michelson contrast) increased the "just noticeable" blur limits marginally by 0.08D. Letter size was an important influence on "just noticeable" blur limits. For a 4 mm pupil, the "just noticeable" blur limits increased from ±0.22D for the smallest letter to ±0.39D for the largest letter.

Generally people are sensitive to small errors in most single vision lenses: +0.50D defocus is definitely unacceptable and sometimes +0.25D defocus is also unacceptable (Atchison, Schmid, Edwards, Muller, & Robotham, 2001; Miller, Kris, & Griffiths, 1997). However, awareness of blur is not usually the symptom noticed by patients with these small errors.

For some ophthalmic lenses such as single vision aspheric lenses and progressive addition lenses, the desire for clear vision at a particular distance is compromised by cosmetic considerations, the need to reduce aberrations such as distortion, and the need to have different zones of the lens providing different power. Patients may be prepared to cope with blur in certain regions of a progressive lens if in return they have a lens with good cosmetic appearance and little distortion. As an example, Fisher (1997) found that "clear and comfortable" vision was provided within a region of progressive lens out to the +1.0D astigmatic contour, which is more than double the mean limits of "just noticeable" (spherical) blur found by Atchison et al. (1997). Thus, as well as "noticeable" blur limits, for some lens design purposes it is useful to have other limits such as "troublesome" and "objectionable".

In this study, we extend the study of Atchison et al. (1997) to look not only at the "noticeable" blur limits, but also at the limits at which vision becomes "troublesome" and "objectionable". We were interested in the influences of the direction of defocus, pupil size, and letter size and chose ranges of 3–6 mm and 0.0–0.7 log min arc detail for the latter two, respectively.

2. Methods

2.1. Subjects

There were 15 subjects in good ocular and general health, predominantly selected from staff and students at QUT. The age range was 17–49 years (mean 28 years, median 20 years). All subjects were screened for possible susceptibility to cyclopentolate. For ease of use of the apparatus, only right eyes were used. Refractive errors ranged from −2D to +1.25D mean sphere with ⩽0.50D cylinder, and all subjects had visual acuity of at least 6/6. Subjects were cyclopleged with 1% cyclopentolate applied every hour. All pupils were dilated to at least 6 mm.

2.2. Apparatus and instructions

A Cambridge Research Systems Ltd (Rochester, Kent, UK) VSG2/5 card (http://www.crsltd.com/catalog/vsg25/) was used with a program to present single lines of three alphabetical characters of a logMAR visual acuity chart on a Sony Triniton monitor. The three letters were randomly selected from the 10 letters used on Bailey–Lovie charts (D, E, F, H, N, P, R, U, V, Z; non-serif, 5 × 4 matrix, spacing equal to letter width (Bailey & Lovie, 1976)). Black letters were used on a white background of luminance 100 cd/m^2 without any optics in place (Weber contrast 99%). Low lighting in the room this produced wall illuminance levels of approximately 20–40 lux.

Letters were viewed through a modified Badal Optometer mounted on an optical bench (Atchison et al., 1997; Fig. 1). The letters were 8.6 m from the eye. Because of restrictions of space, they needed to be viewed through a mirror, which required them to be inverted about the vertical axis. A movable auxiliary −6D lens produced a minified image of the letters. This image acted as the target for a Badal optometer system equipped with a fixed +5.00D lens. Movement of the −6D lens was by rack and pinion controlled by the subject.

An artificial pupil of variable size was placed 10 mm in front of the subject's eye, which was placed at the focal point of the Badal lens. As necessary, extra lenses were placed next to the artificial pupil (20 mm from the eye) to adjust the range of settings of the −6D lens so that it did not touch the +5D lens. These extra lenses incorporated the subject's sphero-cylindrical correction.

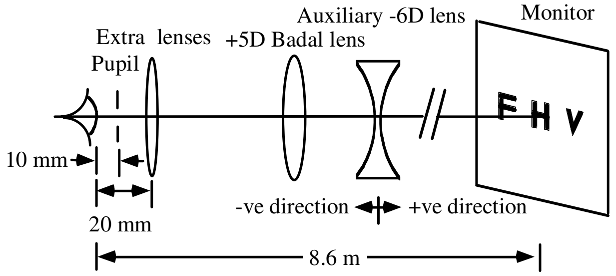

Fig. 1. Experimental setup, not to scale. The letters are actually inverted about the vertical axis to compensate for reflection in the mirror (not shown) between the auxiliary lens and monitor.

Three pupil diameters were used: 3 mm, 4 mm and 6 mm. Their order was randomised. Most subjects had preliminary checks and measurements with one pupil size in one session, and measurements with the other pupil sizes on another day. Due to time constraints, some subjects had measurements with all pupil sizes at the one session, with appropriate breaks and maintenance of cycloplegia.

Five letter sizes were used, with the log of the size of target detail (logMAR) being 0.0, 0.30, 0.47, 0.60 and 0.70. The actual sizes on the monitor were determined by the viewing distance and the magnification of the system (-0.833 times), with adjustment because of the extra lenses placed near the eye (the maximum compensation was 8% for a -4D extra lens used with the myope requiring a refractive correction of -2D). Raytracing was used to determine the vergence of light at the cornea of the eye, with 4 cm of movement corresponding to approximately 1 dioptre change in vergence.

The subjects determined positions of "clear", "noticeable" blur, "troublesome blur" and "objectionable" blur. This was done in both negative and positive directions, corresponding to the auxiliary lens moving towards and away from the eye, respectively (moving towards the eye is equivalent to increasing the power of negative lenses placed immediately in front of the eye or inducing hypermetropic defocus). Subjects knew which way the lens was moving from tactile feedback.

The measurement procedure was as follows. The subject determined a "clear" position by moving the -6D lens back and forth. This position was recorded by the experimenter as a scale reading, to the nearest 0.5 mm. The subject then moved in one direction to determine "noticeable" blur. The initial direction of movement was randomised. This position was again recorded by the experimenter. The subject then obtained the "troublesome" and "objectionable" blur positions, which were also recorded. The subject found a "clear" position again and then proceeded similarly in the opposite direction. This was the basic set of measurements. This was determined for each letter size (presented in random order). Five sets of such determinations were made.

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 use the knob to set the lens to the following four levels of blur…*

> ***Best clear position***: *This is the lens position at which the target is as clear and sharp as you can make it.*
> ***First Noticeable/Just Noticeable blur***: *This is the lens 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 lens 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.*"

At each stage the experimenter reminded the subject the direction they should move, and the type of determination they were making.

2.3. Analysis

Scale readings were converted to vergences at the eye. The midpoints of the positive and negative foci for just noticeable blur for each letter and at each pupil size were determined. Relative to these reference points, the blur limits were calculated for each of the three blur criteria in each direction of movement.

The change in location of the midpoints with pupil size and letter size was also investigated, by choosing each subject's reference midpoint to be that of 0 logMAR with a 3 mm pupil. A repeated measures ANOVA was performed to determine the contribution of letter size and pupil size to the midpoint.

A Non-linear Mixed Effects Model was used to analyse relationships between blur limits (in diopters), pupil size (in millimetres), and letter size (in logMAR), while removing the effects of individual subject variability (Pinheiro & Bates, 1995).

3. Results

3.1. Location of midpoint of "noticeable" blur range

The variations in mean midpoint for the different pupil sizes and the different letter sizes are shown in Fig. 2. Increasing pupil size from 3 mm to 6 mm moves mean midpoints about (–)0.02D towards subjects and increasing letter size from 0.0 logMAR to 0.7 logMAR moves mean midpoints about (–)0.04D towards subjects as letter size increases, although different subjects show different patterns. The effect of pupil size is not significant (F 0.53, df 2.28, $p = 0.60$). The effect of letter size, while small, is significant (F 20.763, df 1.95, 27.2, $p < 0.001$).

3.2. Effect of direction of movement on blur limits

There were no significant differences between the limits for "towards" (negative) and "away" (positive) directions of movement. The effects of pupil size and letter size on blur limits were similar for both negative and positive blur (Fig. 3a–c).

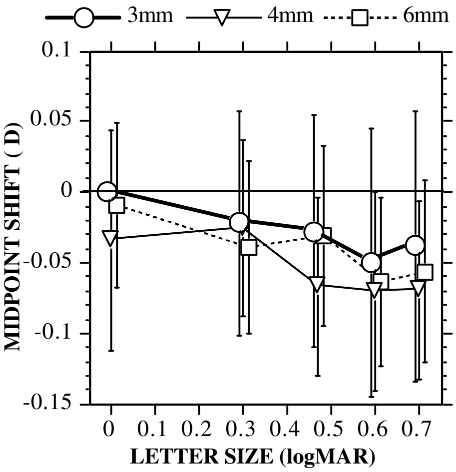

Fig. 2. Location of midpoint for different letter sizes and pupil sizes. A constant has been added to the results for each subject so that the mean for 0 logMAR letters and 3 mm pupil size is zero for each subject. Error bars represent ±95% confidence intervals. For clarity, the data for the different pupil sizes are off-set slightly relative to each other.

3.3. Effect of blur limit criterion on blur limits

Fig. 3a–c shows the effect of changing letter size and pupil size and blur limits, for each blur criterion. The proportionate changes are 1.6–1.8 times from noticeable to troublesome blur criteria and 2.1–2.5 times from noticeable to objectionable blur criteria.

3.4. Effect of pupil size on blur limits

As pupil size increased, blur limits decreased (Fig. 3). For each 1 mm of pupil diameter increase, blur limit changed by 0.014D–0.019D in the modelling. This is very small, and is statistically significant only for noticeable blur limits ($p < 0.001$), and for the troublesome limit in the “towards subject” (negative blur) direction only ($p = 0.012$). The influence of pupil size is greatly affected by its interaction with letter size.

The difference between the results found with the smallest and largest pupil sizes is from 0.04D (for noticeable blur, 0.0 logMAR) to 0.26D (for away-objectionable blur, 0.7 logMAR). Another way to look at the results is that blur limits were reduced by 1.10–1.25 times from 3 mm to 6 mm pupils for the various letter size and blur criteria combinations.

3.5. Effect of letter size on blur limits

Fig. 3 shows the importance of the letter size on blur limits, with blur limits increasing by 1.6–2.1 times from 0.0 to 0.7 log min arc target detail for the various pupil size and blur criteria combinations.

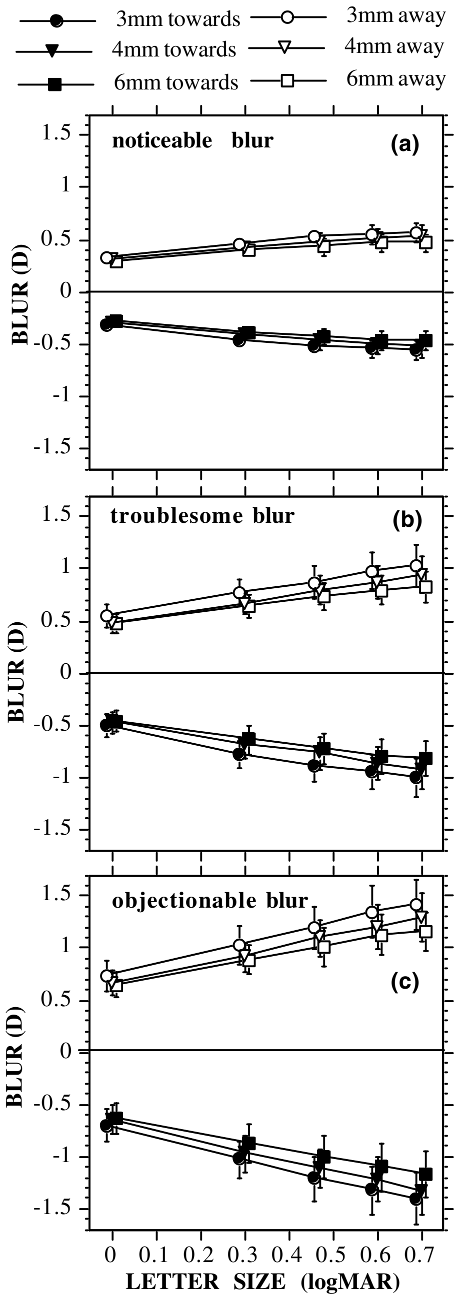

Fig. 3. Mean blur limits as a function of letter size for (a) noticeable blur, (b) troublesome blur, and (c) objectionable blur. Error bars represent ±95% confidence intervals. For clarity, the data for the different pupil sizes are off-set slightly relative to each other.

Statistical analysis of the effect of letter size on blur limit supports a linear relationship between letter size and blur limit for the troublesome and objectionable blurs, and a quadratic relationship between letter size and blur limit for the noticeable blur limits and the towards Troublesome blur limit (see Section 3.7). For these blur criteria, the effect of the second-order component is opposite to that of the linear component, that is, as letter size increases blur limit increases less quickly

(Fig. 3). There is also a significant interaction between the effects of letter size and pupil size on blur limits for each blur criterion.

3.6. Cumulative frequency histograms

Fig. 4a and b show cumulative frequency histograms for all blur criteria for the smallest and largest letter sizes. Only the results for the 4 mm pupil are shown here. Cumulative frequency histograms for 3 mm and 6 mm pupil sizes are similar, but over larger and smaller ranges of blur limits, respectively. Comparing the two parts of Fig. 4 shows the increased range of blur limits with increase in letter size, and both parts show the increased spread of results as the criterion changes from Noticeable to Troublesome and then to Objectionable. The blur limits in both towards-subject and away-from-subject blur criteria are similar, demonstrating the lack of significance between directions that was mentioned previously.

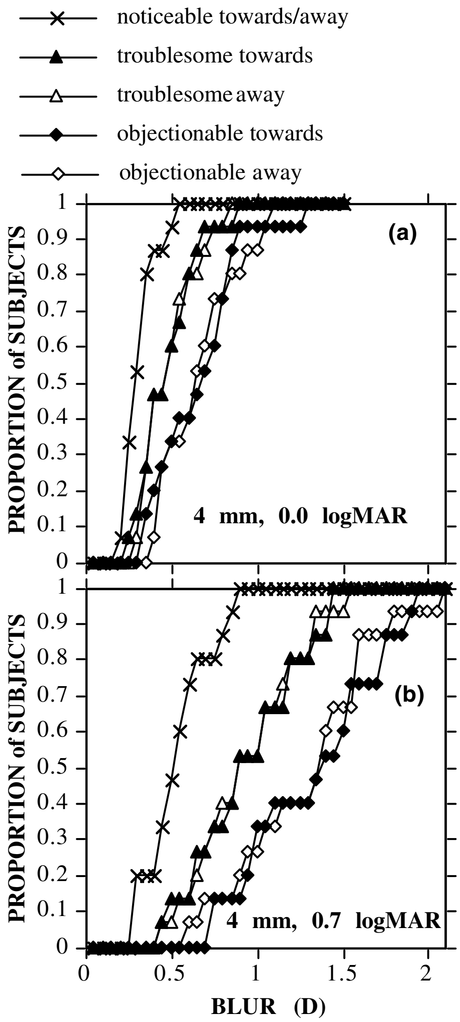

Fig. 4. Cumulative frequency histograms for 4 mm pupil size and the different blur criteria for (a) 0.0 logMAR letters, and (b) 0.7 logMAR letters.

3.7. Modelling

As part of the Non-linear Mixed Effects Modelling, we used 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 (Fig. 5a) and quadratic component of log letter size detail (Fig. 5b) these were not significant for all blur criteria). Based on these significances, equations for each blur criterion were then determined and are shown below in the form

$L_{\text{directionBlur criterion}} = a + b * \text{logMAR} + c * \text{logMAR}^2 + d * \text{pupilsize} + e * \text{logMAR} * \text{pupilsize}$. The number of degrees of freedom is 1106 in each case. Standard errors are given in brackets. Non-significant coefficients are bolded:

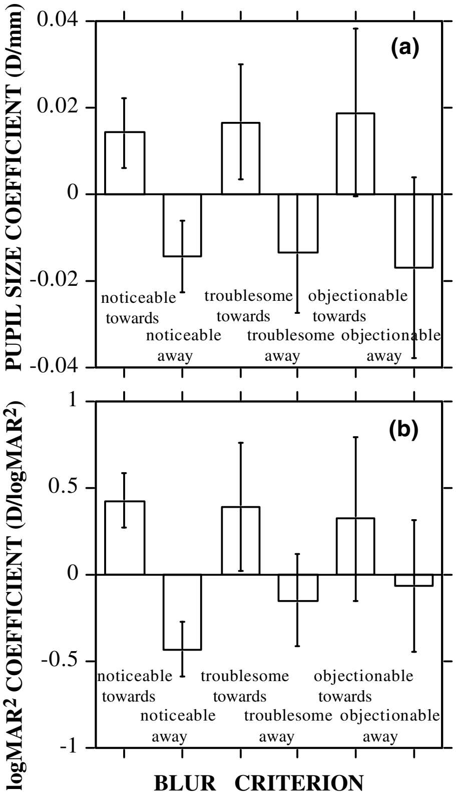

Fig. 5. Model coefficients as a function of blur criterion for (a) pupil size and (b) letter size detail squared (logMAR^2). Error bars represent the ±95% confidence intervals—coefficients are significantly different from zero where the error bars do not cross the axis.

$$\begin{aligned} L_{\text{toNoticeable}} = {} & -0.367(\pm 0.032) - 0.591(\pm 0.048)\text{logMAR} \\ & + 0.250(\pm 0.048)\text{logMAR}^2 \\ & + 0.0143(\pm 0.0041)\text{pupilsize} \\ & + 0.0233(\pm 0.0071)\text{logMAR} \cdot \text{pupilsize} \end{aligned}$$

$$\begin{aligned} L_{\text{toTroublesome}} = {} & -0.550(\pm 0.052) \\ & - 1.031(\pm 0.098)\text{logMAR} \\ & + 0.23(\pm 0.11)\text{logMAR}^2 \\ & + 0.0168(\pm 0.0067)\text{pupilsize} \\ & + 0.0592(\pm 0.0116)\text{logMAR} \cdot \text{pupilsize} \end{aligned}$$

$$\begin{aligned} L_{\text{toObjectionable}} = {} & -0.741(\pm 0.075) - 1.40(\pm 0.11)\text{logMAR} \\ & + \mathbf{0.198}(\pm 0.140)\text{logMAR}^2 \\ & + \mathbf{0.0189}(\pm 0.0099)\text{pupilsize} \\ & + 0.0861(\pm 0.0127)\text{logMAR} \cdot \text{pupilsize} \end{aligned}$$

$$\begin{aligned} L_{\text{fromNoticeable}} = {} & 0.367(\pm 0.032) + 0.591(\pm 0.048)\text{logMAR} \\ & - 0.250(\pm 0.048)\text{logMAR}^2 \\ & - 0.0143(\pm 0.0041)\text{pupilsize} \\ & - 0.0233(\pm 0.0071)\text{logMAR} \cdot \text{pupilsize} \end{aligned}$$

$$\begin{aligned} L_{\text{fromTroublesome}} = {} & 0.540(\pm 0.0061) \\ & + 0.948(\pm 0.065)\text{logMAR} \\ & - \mathbf{0.0857}(\pm 0.079)(\text{logMAR})^2 \\ & - \mathbf{0.0135}(\pm 0.0070)\text{pupilsize} \\ & - 0.0635(0.0099)\text{logMAR} \cdot \text{pupilsize} \end{aligned}$$

$$\begin{aligned} L_{\text{fromObjectionable}} = {} & 0.731(\pm 0.087) \\ & + 1.221(\pm 0.088)\text{logMAR} \\ & - \mathbf{0.036}(\pm 0.113)(\text{logMAR})^2 \\ & - \mathbf{0.0168}(\pm 0.0106)\text{pupilsize} \\ & - 0.0783(\pm 0.0123)\text{logMAR} \cdot \text{pupilsize} \end{aligned}$$

The significances of the parameters have been discussed already, but a few points will be emphasised or added. Because the reference midpoints are halfway between the toNoticeable and fromNoticeable blur criteria, the coefficients for these criteria are the same except for changes in sign. Most coefficients are significantly different from zero for all blur criteria, with the exceptions being the second order logMAR and pupil size coefficients for "to-objectionable", "from-troublesome" and "from-objectionable" blur criteria. Most coefficients increase as the blur criterion changes from noticeable to troublesome and then to objectionable. The exceptions are the pupil size coefficient, which decreases as the blur criterion changes from "to-noticeable" to "to-troublesome" (Fig. 5b), and the second-order logMAR coefficient, which decreases as the blur criterion changes from "noticeable" to "troublesome" and then to "objectionable" (Fig. 5a). All coefficients become more variable (as indicated by the increasing size of the confidence intervals) as the blur criterion changes from "noticeable" to "troublesome" and then to "objectionable".

4. Discussion

This study investigated the limits of defocus that provide "noticeable", "troublesome" and "objectionable" blur, for 15 subjects and targets consisting of lines of three high contrast letters. The mean midpoint of "noticeable" blur limits moved about 0.05D in the near (myopic) direction as the letter size increased from 0.0 logMAR to 0.7 logMAR (Fig. 2). Most likely this shift is due to positive spherical aberration, which causes low frequency detail to have a more myopic focus than high frequency detail (Atchison & Scott, 2002; Charman & Jennings, 1976; Green & Campbell, 1965).

For the smallest letter size of 0.0 logMAR, the mean "noticeable" blur limits were ±0.33D, ±0.30D and ±0.28D at 3 mm, 4 mm and 6 mm, respectively (Fig. 3a). These limits increased to ±0.56, ±0.53D and ±0.47D at the largest letter size of 0.7 logMAR. The small effect of pupil size (about 1.2 times) is consistent with other studies that found small influence above 3 mm to 4 mm (Campbell, 1957; Marcos, Moreno, & Navarro, 1999; Ogle & Schwartz, 1959). An aberration-free system is expected to have smaller depth-of-focus as pupil size increases, but increasing magnitude of aberrations as pupil size increases provides some balance by making deterioration in image quality less noticeable away from the optimal focus. Atchison et al. (1997) attributed the increase in range of "noticeable" blur with increase in letter size (1.7 times in our experiment) to changing subject criteria of what constitutes blur, from change in image form for small letters near resolution, to image contrast at intermediate letters, and to changes in edge sharpness for large letters.

In the previous experiment using similar equipment and procedures, Atchison et al. (1997) found mean limits for "noticeable" blur of ±0.25D and ±0.21D at 0.0 logMAR for 4 mm and 6 mm pupils, respectively, and found mean limits of ±0.35D and 0.34D at 0.6 to 0.87 logMAR for 4 mm and 6 mm pupils, respectively. Thus our results represent a 1.4 times increase relative to the previous study. A within and between repeated ANOVA (4 mm and 6 mm pupils with 0.7 logMAR in this study and averaged over 0.6–0.87 logMAR in previous study) did not find this change to be significant (*F*

3.4, df 1, 18, $p = 0.082$). However there were only five subjects in the previous study which gives a low power to the ANOVA, and there may be a real difference that might occur in part because overall the subjects in this study were less experienced in psychophysical experimentation than the subjects in the previous study.

Magnitudes of negative and positive blur limits for "troublesome" and objectionable" criteria were similar, regardless of pupil size or letter (Fig. 3b and c). Their magnitudes relative to the "noticeable" limits ranged from 1.6 to 1.8 and 2.1 to 2.5 times, respectively. Pupil size had only a small effect on these blur limits (1.2 times), and for modelling the relationship was not significant for the blur criteria of "to-objectionable", "from-objectionable" and "from-troublesome". However, there was a considerable influence of letter size on these blur limits of 1.7–2.1 times.

Our results suggest that the criteria for just troublesome and objectionable blur (the supra threshold criteria) are relatively constant as a function of letter size over the tested range. It appears that subjects may be using the legibility of the letters to base their judgments of 'troublesome' and 'objectionable'. This would explain well the relatively linear relationship between letter sizes and blur thresholds (see Fig. 5). Fig. 6 provides some idea of how letter size and blur interact in that the subjective appearances of letters are similar when both size and blur are doubled.

The spherical defocus used in this study is only one type of blur experienced by spectacle wearers. Astigmatism and higher order aberrations such as coma are common in progressive lenses. Fig. 7 illustrates the effect of astigmatism. Letters contain a large proportion of vertical and horizontal lines, and due to the closer horizontal than vertical spacing of letters in sentences horizontal blur (astigmatism × 90) has a greater impact on legibility than other orientations. Directional effects of astigmatism in daily life were investigated by Miller et al. (1997), who found that 70% of 20 subjects were dissatisfied with +0.50D × 180 astigmatism (vertical blur) added to spectacle corrections, and this percentage increased to 95% with either +0.50D × 90 or +0.50D × 45 astigmatism (horizontal and oblique blur). Research into a general model for subjective blur needs to consider directional blur types and the nature and contrast of targets.

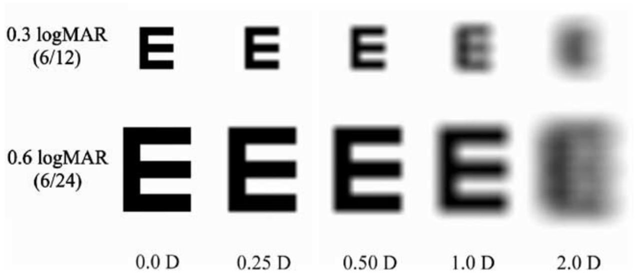

Fig. 6. Simulated appearances of different sized letter Es at different blur (D) levels using a model eye. The added blurs are equivalent to placing positive lenses at the spectacle plane 14 mm in front of a model eye similar to the Liou and Brennan (1997) model eye but with a constant lens refractive index 1.445. Larger Es (0.6 logMAR) are twice the size of small Es (0.3 logMAR). Pupil size 4 mm. The letters will have these logMAR values if viewed at approximately 180 cm. Appearances of larger Es are similar to those of smaller Es at half the blur levels.

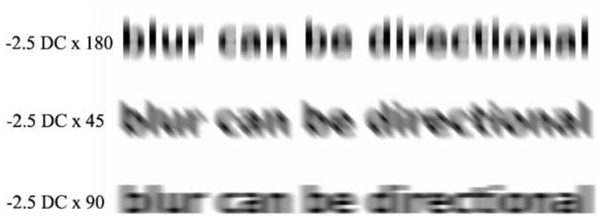

Fig. 7. Effect of orientation of induced astigmatism on text legibility. The added blurs are equivalent to placing negative cylindrical lenses at the spectacle plane 14 mm in front of a model eye similar to the Liou and Brennan (1997) model eye but with a constant lens refractive index 1.445. Pupil size 4 mm. Letter size 20 min arc (bottom to top). The letters will have these logMAR values if viewed at approximately 60 cm. The ×90 and ×45 orientations degrade legibility more than the ×180 orientation.

The Method of Adjustment that was employed has limitations such as anticipation and habituation. There is also lack of independence between the responses of the subjects to the three criteria. However, we believe that we are justified in using this method for two reasons: (a) *Length of time for other psychometrics techniques*. In pilot trials, we tried the Methods of Limits with two subjects and found this to produce comparable results to the Method of Adjustment. However, these measurements were exceedingly tedious and would not have allowed us to use a wide range of parameters on several subjects. (b) *Independence of measurement to criteria is not relevant to many situations*. Exposure to defocus tends to be in situations where there are strong relativistic effects (focusing a camera, projector and for spectacle lenses). In our experience subjects find it difficult to make absolute blur judgments in the absence of base line experiences, and they like to "drive" the level around to get a feel for where they are in the continuum. The task was meant to relate to the blur found in spectacle lenses such as in the periphery of a progressive addition lens. In this case the blur flanking a reading zone is generally encountered in the sequence of less to more blur, the wearer turning their head once the 'troublesome' level is reached. We are not convinced that making the measures more independent would have been particularly useful for the external validity of our findings.

We conclude by noting that there may be neural adaptations affecting the determination of clear vision and sensitivity to blur. Optometrists are familiar with comments from patients that vision seems to improve after a period of time without refractive correction, and recent studies show improvements in visual function during sustained periods of defocus (George & Rosenfield, 2004; Mon-Williams, Tresilian, Strang, Kochhar, & Wann, 1998; Pesudovs & Brennan, 1993). Judgements of focus can be manipulated by adapting to images of scenes to which spatial frequency filtering has been applied (Webster, Georgeson, & Webster, 2002).

Acknowledgments

We thank our subjects and computing-technician John Stephens.

References

Atchison, D. A., Charman, W. N., & Woods, R. L. (1997). Subjective depth-of-focus of the eye. *Optometry and Vision Science, 7*, 511–520.

Atchison, D. A., Schmid, K. L., Edwards, K. P., Muller, S. M., & Robotham, J. (2001). The effect of under and over refractive correction on visual performance and spectacle lens acceptance. *Ophthalmic and Physiological Optics, 21*, 255–261.

Atchison, D. A., & Scott, D. H. (2002). Contrast sensitivity and the Stiles–Crawford effect. *Vision Research, 42*, 1559–1569.

Bailey, I. L., & Lovie, J. E. (1976). New design principles for visual acuity charts. *American Journal of Optometry and Physiological Optics, 53*, 740–745.

Campbell, F. W. (1957). The depth of field of the human eye. *Optica Acta, 4*, 157–164.

Charman, W. N. (1979). Effect of refractive error in visual tests with sinusoidal gratings. *British Journal of Physiological Optics, 33*, 10–20.

Charman, W. N., & Jennings, J. A. M. (1976). The optical quality of the monochromatic retinal image as a function of focus. *British Journal of Physiological Optics, 31*, 119–134.

Fisher, S. W. (1997). Relationship between contour plots and the limits of "clear and comfortable vision" in the near zone of progressive addition lenses. *Optometry and Vision Science, 74*, 527–531.

George, S., & Rosenfield, M. (2004). Blur adaptation and myopia. *Optometry and Vision Science, 81*, 543–547.

Green, D. G., & Campbell, F. W. (1965). Effect of focus on the visual response to a sinusoidally modulated spatial stimulus. *Journal of the Optical Society of America, 55*, 1154–1157.

Jacobs, R. J., Smith, G., & Chan, C. D. C. (1989). Effect of defocus on blur thresholds and on thresholds of perceived change in blur: Comparison of source and observer methods. *American Journal of Physiological Optics, 66*, 545–553.

Legge, G. E., Mullen, K. T., Woo, G. C., & Campbell, F. W. (1987). Tolerance to visual defocus. *Journal of the Optical Society of America A, 4*, 851–863.

Liou, H.-L., & Brennan, N. A. (1997). Anatomically accurate, finite model eye for optical modeling. *Journal of the Optical Society of America A, 14*, 1684–1695.

Marcos, S., Moreno, E., & Navarro, R. (1999). The depth-of-field of the human eye with polychromatic light from objective and subjective measurements. *Vision Research, 39*, 2039–2049.

Miller, A. D., Kris, M. J., & Griffiths, A. C. (1997). Effect of small focal errors on vision. *Optometry and Vision Science, 74*, 521–526.

Mon-Williams, M., Tresilian, J. R., Strang, N. C., Kochhar, P., & Wann, J. P. (1998). Improving vision: neural compensation for optical defocus. *Proceedings of the Royal Society (London) B. Biological Sciences, 265*, 71–77.

Ogle, K. N., & Schwartz, J. T. (1959). Depth of focus of the human eye. *Journal of the Optical Society of America, 49*, 273–280.

Pesudovs, K., & Brennan, N. A. (1993). Decreased uncorrected vision after a period of distance fixation with spectacle wear. *Optometry and Vision Science, 70*, 528–531.

Pinheiro, J. C., & Bates, D. M. (1995). Model building for nonlinear mixed-effects models. Technical Report 91, Department of Biostatistics, University of Wisconsin–Madison, USA.

Tucker, J., & Charman, W. N. (1975). The depth-of-focus of the human eye for Snellen letters. *American Journal of Physiological Optics, 52*, 3–21.

Webster, M. A., Georgeson, M. A., & Webster, S. M. (2002). Neural adjustments to image blur. *Nature Neuroscience, 5*, 839–840.