



City Research Online

City St George's, University of London

Citation: Jarkum, T., Devi, P., Solomon, J., Tyler, C. W. & Bharadwaj, S. (2025). The impact of induced optical blur on monocular and binocular depth-related visuomotor task performance. *Investigative Ophthalmology and Visual Science*, 66(15), doi: 10.1167/iovs.66.15.8

This is the accepted version of the paper.

This version of the publication may differ from the final published version. To cite this item please consult the publisher's version.

Permanent repository link: <https://city-ref-test.eprints-hosting.org/id/eprint/36174/>

Link to published version: <https://doi.org/10.1167/iovs.66.15.8>

Copyright and Reuse: Copyright and Moral Rights remain with the author(s) and/or copyright holders. Copies of full items can be used for personal research or study, educational, or not-for-profit purposes without prior permission or charge, unless otherwise indicated, provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way. For full details of reuse please refer to [City Research Online policy](#).

The impact of induced optical blur on monocular and binocular depth-related visuomotor task performance

Tai Jarkum,^{1,2} Preetirupa Devi,¹⁻³ Joshua A. Solomon,³ Christopher W. Tyler³ and Shrikant R. Bharadwaj^{1,2}

Author affiliations:

¹ Brien Holden Institute of Optometry and Vision Sciences, L V Prasad Eye Institute, Road no. 2, Banjara Hills, Hyderabad – 500034, Telangana, INDIA.

² Prof. Brien Holden Eye Research Centre, Hyderabad Eye Research Foundation, L V Prasad Eye Institute, Road no. 2, Banjara Hills, Hyderabad – 500034, Telangana, INDIA.

³ Centre for Applied Vision Research, City St George's, University of London, Northampton Square, London – EC1V 0HB, UNITED KINGDOM.

Corresponding author: Shrikant R. Bharadwaj

Brien Holden Institute of Optometry and Vision Sciences, L V Prasad Eye Institute, Road no. 2, Banjara Hills, Hyderabad – 500034 Telangana, INDIA.

bharadwaj@lvpei.org

Runing title: Optical blur and depth-related visuomotor performance

Number of words in the abstract: 247

Number of words in the revised abstract: 247

Number of words in the manuscript: 7280

Number of words in the revised manuscript: 4702

Number of figures in manuscript: 6

Number of tables in manuscript: 4

Date of submission: 11th August 2025

Date of R1 submission: 3rd November 2025

Abstract

Purpose: To determine the impact of induced optical blur on a 3D task that probes complex visuomotor performance capabilities of humans.

Methods: 15 visually normal, cyclopleged adults (mean $\pm$ 1SD: 23 $\pm$ 2.6 years) guided a metal loop along a wire convoluted in depth without making contact, while being video recorded for analysis. The task was performed binocularly and monocularly, without blur, and with two magnitudes of induced spherical and astigmatic blur of equal strengths (2.25D and 6.25D). Blur patterns were induced before both eyes (isometropia) or before only one eye (anisometropia). For isometropic astigmatism, blur was also induced with parallel and orthogonal axes in both eyes. The buzz-wire patterns, viewing condition and induced blur were all randomized across participants.

Results: Binocular error rate (number of loop-to-wire contacts per second) and error duration (percentage of time spent making errors) increased at high blur strength ($p < 0.001$), more so for astigmatism than spherical power ($p < 0.001$) and more so for isometropic than anisometropic viewing ($p = 0.02$). Low astigmatism with orthogonal axes bilaterally produced higher error rate and error duration than astigmatism with parallel axes bilaterally ($p < 0.001$). Only error duration increased with high blur for monocular viewing ($p \leq 0.004$). Task speed remained invariant across test conditions. Multiple repetitions did not impact task performance.

Conclusions: The deterioration of depth-related visuomotor task performance with optical blur depends on its magnitude, radial symmetry and the similarity between the two eyes. Performance drop is largely from spending more time making/correcting errors, while the overall speed remained undiminished.

Keywords: Anisometropia; Astigmatism; Blur; Defocus; Stereopsis; Visuomotor

1. Introduction

Day-to-day activities like inserting a key into a keyhole or pouring water from a jug into a container are essential visuomotor tasks that require accurate estimates of 3D depth. The hand actions associated with these tasks may be guided by binocular retinal disparity plus monocular depth cues (e.g., motion parallax, texture), with the weight assigned to the former cue being larger than the latter ones.^{1,2} Two studies from Devi et al. support this notion using a visuomotor task that requires participants to move a loop around a wire convoluted in depth without contact.^{3,4} Error rates in this task increase with the loss of binocularity,³ and the associated binocular advantages (i.e., the extent to which binocular error rates are lower than monocular values) decline when binocularity is compromised due to blurred vision from distorted optics.^{3,4} Task speed also decreases with absent/degraded binocularity, albeit with a smaller effect size than that of error rates.^{3,4} Systematically investigating the impact of blurred vision on depth-related task performance is the primary goal of the present study.

Retinal image blur may impact depth-related visuomotor task performance for two reasons. First, optical blur limits visual resolution by degrading contrast and inducing phase shifts in the retinal image.⁵⁻⁷ Both factors impair the ability to resolve the critical details required to perform the task (e.g., estimating the diastereoptic gap between the loop and wire in the buzz-wire task) (Figure 1). Second, dissimilar blur in the two eyes impacts binocular processing by impairing correspondence matching in the monocular retinal images^{8,9}, reducing the overall quality of the disparity signal⁸ and suppressing the worse eye¹⁰⁻¹³. Finally, the gains of vergence-related eye movements and ocular accommodation also decrease with blur, thus impairing the experience of clear and single binocular vision.^{14,15} All these factors may ultimately limit the stereoscopic depth and diastereopsis calculations required by visuomotor tasks (Figure 1). In the context of the Devi et al. (2025) study described above⁴, the exaggerated wavefront aberrations arising from distorted optics of the eye translate into significant, radially asymmetric retinal blur profiles.^{16,17} The blur profiles may also be dissimilar in the two eyes due to asymmetric disease severity.^{16,17} All of these factors could have influenced the buzz-wire task performance in that study.⁴ That there may be complex interactions between these blur dimensions to determine visuomotor task performance is also suggested by differences in the results obtained between eyes with distorted optics (keratoconus) and with regular refractive errors (uncorrected myopia) in their study.⁴ The myopic cohort, characterized primarily by isometric, spherical blur profiles, continued to show a binocular advantage in error rates while the keratoconic cohort, characterized by complex blur profiles as described above, lost the binocular advantage.⁴

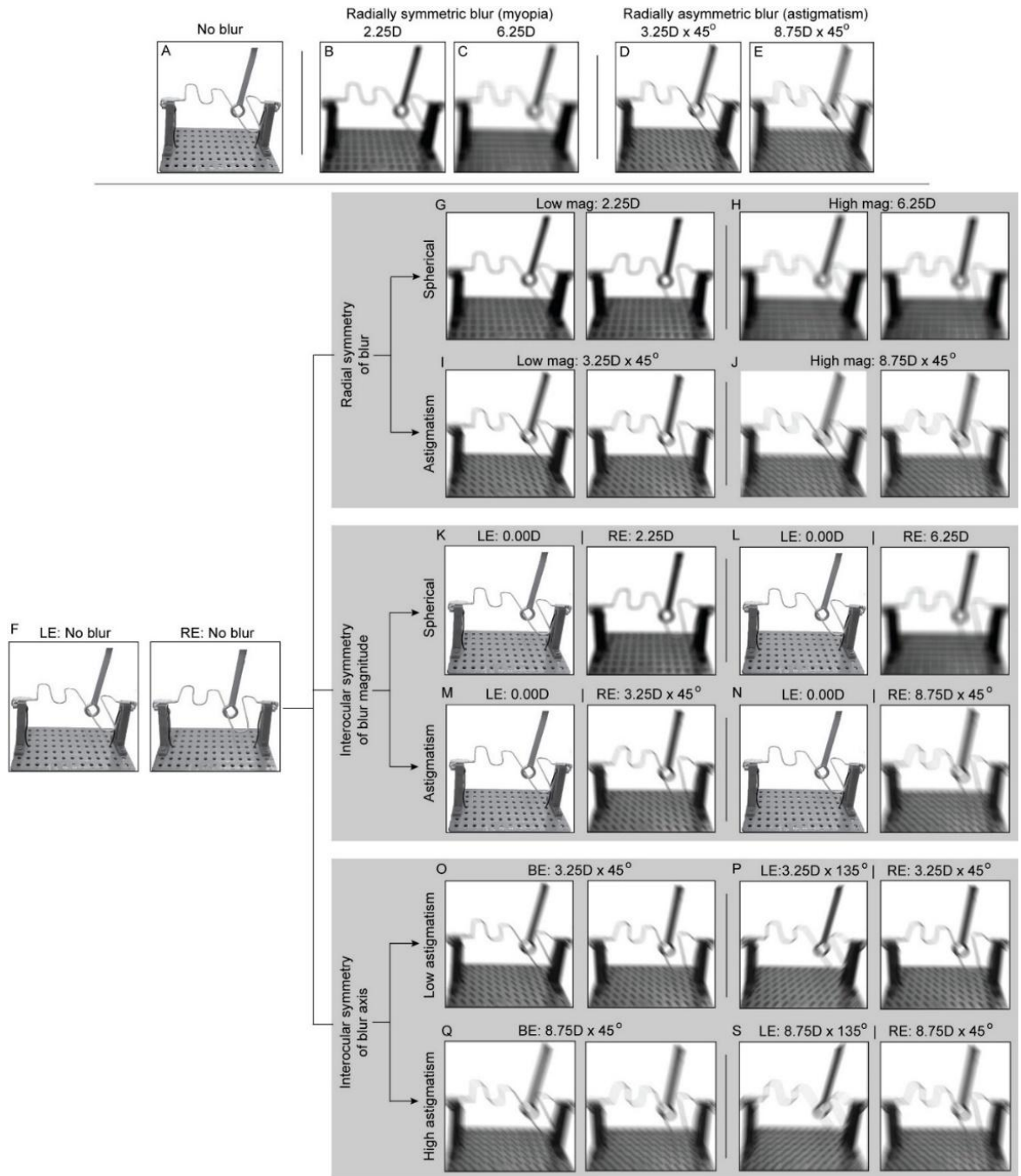


Figure 1: Point-of-view simulations of the buzz-wire apparatus with clear vision (panel A) and with different patterns of monocular optical blur (panels B – E). Panel F – S shows simulated cross-fusible stereo image pairs of the different binocular viewing conditions in this study. All optical simulations were generated for 555 nm light and 5 mm pupil diameter, using standard Fourier optics techniques.¹⁸ The simulations were created by convolving the point-of-view images of buzz-wire with the point spread function obtained by inducing a specific blur along with the population-averaged higher-order Zernike wavefront aberrations reported by Cheng et al. (2004).¹⁹

A systematic study is required to tease out the individual and combined contributions of these blur factors on the buzz-wire task performance. *Few studies in the literature have investigated how vision loss from induced optical^{20,21} and non-optical (Bangerter filter)²² blur affects depth-related visuomotor*

tasks like bead threading, water pouring, peg placement and sports-related interceptive actions. In general, these studies show worsening of task performance with increasing magnitudes of blur. Some tasks like bead threading appear to be more vulnerable to optical blur compared to others like the water pouring task.²¹ While, in principle, these results demonstrate the negative impact of induced blur on visuomotor tasks, the relative impacts of different blur dimensions described above on such tasks remains unknown. This knowledge gap was addressed in the present study by systematically investigated the impact of two different magnitudes of spherical and astigmatic blur presented isometropically or anisometropically on the monocular and binocular buzz-wire task performance (Figure 1). The following hypotheses were tested here.

1. Monocular and binocular buzz-wire task performances will worsen with induced blur, relative to the no blur condition (Figure 1F vs. B – E and Figure 1F vs. G – N). This will be so for the aforesaid reasons of loss in visual resolution and binocularity.
2. Astigmatism will produce greater loss of task performance than comparable strengths of spherical blur (Figures 1B and C vs. D and E, respectively). This will be so because meridional blur in astigmatism may cause greater difficulty in diastereoptic judgments relative to the uniform image-quality loss with spherical blur (Figures 1B and C vs. D and E, respectively). Astigmatism also tends to produce a larger subjective blurring effect than spherical blur.^{23,24}
3. Anisometropia will produce greater loss of binocular task performance than comparable magnitudes of isometropia (Figure 1G and H vs. K and L, respectively, and Figures 1I and J vs. M and N, respectively). This will be so for the aforesaid reasons of binocularity loss with unequal magnitudes of blur in the two eyes.⁸⁻¹³
4. Astigmatism with orthogonal axes in the two eyes will result in greater loss of task performance than those with parallel axes in the two eyes (Figure 1O and Q vs. P and S). This will be so for the reason of binocular correspondence matching.
5. The binocular advantage of task performance will deteriorate in the presence of all forms of blur profiles owing to the underlying loss of binocularity, relative to the no blur condition.

2. Methods

2.1. Participants

The study adhered to the tenets of the Declaration of Helsinki, and it was approved by the Institutional Review Board of L V Prasad Eye Institute (LVPEI), Hyderabad, India. The experiment was initiated after all participants signed the written consent form. Fifteen participants (Mean $\pm$ 1SD age: 23 $\pm$ 2.6 years),

based on convenient sampling, were recruited for the study whose uncorrected, monocular distance visual acuity was better than or equal to 20/25 in both eyes, spherical equivalent refractive error was $\leq \pm 0.50\text{D}$ in both eyes, stereoacuity better than or equal to 40 arc sec and they were free of any ocular or binocular vision anomalies.

2.2. The apparatus, task and outcome measures

The buzz-wire task involves passing a metallic loop around the wire pattern convoluted in depth, without contact (Figure 2A). Physical contact between the loop and the wire results in an auditory “buzz,” signalling an error in the task. A total of 24 unique buzz-wire patterns with five to six depth modulations of 6.5 cm, 4.0 cm and 1.0 cm from the base position across the entire wire length (40.8 cm) were created to avoid practice effects (Figure 2B). This ensured that a given pattern was used no more than twice across the entire experiment. The participant’s head was stabilized using a chin and forehead rest at the beginning of the experiment, ensuring that the distance between the participants and the buzz-wire setup was approximately 33 cm. Stabilizing the head also ensured that the pattern of astigmatic blur experienced did not vary during the task. *The task was performed 45 – 60 mins after instillation of 1% Cyclopentolate HCl eye drops to ensure that the induced blur profiles did not vary with the participant’s accommodative behavior.^{26,27} The effect of cycloplegia was confirmed by near acuity worsening to >N8 on the standard near vision chart at 40 cm viewing distance. Additional eye drops were used, if necessary, to ensure that this criterion was met throughout the experiment. A near-correction of +3D was placed before the participant’s eyes to account for the 33 cm viewing distance at which the buzz-wire task was performed.*

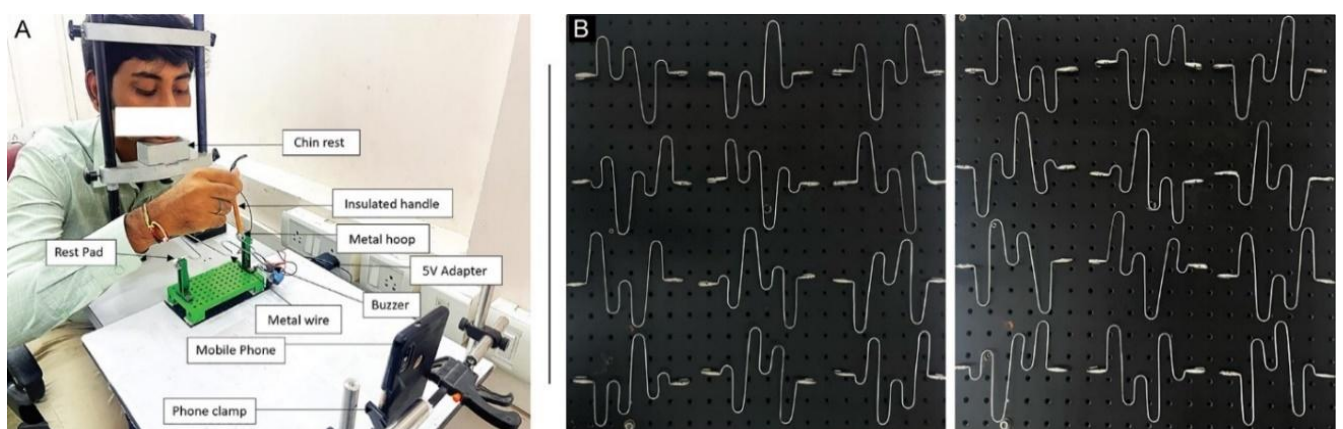


Figure 2: Panel A) The experimental set-up with the key elements highlighted. Panel B) The profiles of the 24 different buzz-wire patterns used in the experiment.

Task instructions and the process of data cleaning and analysis is described in Devi et al. (2024, 2025).^{3,4} Task performance was quantified using three outcome variables. *Error rate* was calculated as the number of error buzzes over the total task duration (in errors/second). *Error duration* was calculated as the total time spent in error divided by the total task duration (in percentage). *Speed* was calculated as the length of the wire divided by the error-free time (in cm/second).

2.3. The induced blur conditions

The blur profiles included the two magnitudes of radially symmetric (spherical blur; Figures 1B and C) or asymmetric (astigmatic blur; Figures 1D and E) blur and with the blur being equal in the two eyes (isometropia; Figures 1G – J) or unequal in the two eyes (anisometropia; Figures 1K – N). Two variants of isometric astigmatic blur were also tested — a profile with similar magnitude and axes of astigmatism in the two eyes (45°) and a profile with similar magnitude but orthogonal axes of astigmatism in the two eyes (45° in the right eye and 135° in the left eye) (Figures 1O – S). The impact of blur magnitude and radial symmetry on the buzz-wire task performance was investigated under binocular and monocular conditions. The impact of interocular symmetry was investigated only under binocular conditions. Monocular testing was always performed on the right eye while the left eye was occluded. For binocular viewing, the blur profiles were introduced either before both eyes (isometric viewing) or only before the right eye (anisometric viewing) while the left eye viewing remained unhindered. All blur profiles were induced using full-aperture trial lenses mounted on a trial frame at a 14 mm vertex distance. Each participant repeated the buzz-wire task thrice with each blur profile, resulting in a total of 48 repetitions per participant ([monocular baseline + 2 monocular spherical blur + 2 monocular astigmatic blur + binocular baseline + 2 isometric spherical blur + 2 isometric astigmatic blur with parallel axes in the two eyes + 2 isometric astigmatic blur with orthogonal axes in the two eyes + 2 anisometric spherical blur + 2 anisometric astigmatic blur] x 3 repetitions of each condition = 48 trials). The first trial was always the binocular baseline condition while the order of remaining trials was randomized within and across participants to minimize any practice effect (see *Supplement II for control experiment investigating the impact of practice on the buzz-wire task performance*). Data was collected across two days on each participant, averaging 2.5 hours per participant per day. Short breaks were provided between trials or whenever required to reduce fatigue.

The two levels of optical blur were purposely chosen in this study to induce significant loss of visual resolution and binocularity. (See Supplement I for an investigation of the relationship between different

blur magnitudes and buzz-wire task performance.) Like Piano and O'Connor (2013)¹³, the lower magnitude of spherical blur (2.25D) used here resulted in a 8-line loss of visual acuity from baseline (Mean $\pm$ 1 SD visual acuity across 8 participants: 0.82 ± 0.16 logMAR) while the higher magnitude (6.25D) resulted in a 14-line loss of visual acuity from baseline (1.42 ± 0.18 logMAR units).³ Comparable strengths (2.30D and 6.19D) of astigmatic blur were induced using cylindrical lenses at 45 degree axes. Note that the total blur strength of a spherocylindrical lens is

$$B = \sqrt{\left(S + \frac{C}{2}\right)^2 + \left(-\frac{C}{2}\cos 2\beta\right)^2 + \left(-\frac{C}{2}\sin 2\beta\right)^2},$$

where S is the power of the spherical component, C is the power of the (positive) cylindrical component, and β is the cylindrical axis.²⁸ The cylindrical powers of our low-powered and high-powered lenses were 3.25 D and 8.75 D, respectively.³⁹ Use of these lenses resulted in 7-line and 12-line acuity losses, relative to baseline, in the same 8 participants (logMAR values were of 0.76 ± 0.15 and 1.25 ± 0.15 , respectively).

In addition to the buzz-wire task, stereo perception thresholds were also measured under cycloplegia (but corrected for the test viewing distance), at a 50-cm viewing distance, using the technique described by Devi et al. (2025).⁴⁰ Stereo thresholds worsened to ≥ 500 arcsec across all induced blur conditions. Since the stereo thresholds were found to have limited correlation with the buzz-wire task performance in the Devi et al. (2025)⁴ study, no further analyses of these thresholds are performed here. Instead,

³ All visual acuities were measured under photopic conditions using a computerized logMAR optotype presentation system (COMPlog Vision Measurement, London, UK).²⁵ Herein, five Sloan optotypes were randomly displayed on an LCD screen and their angular subtense decreased using a staircase algorithm until 3 out of 5 optotypes were incorrectly identified. LogMAR acuity was recorded as the number of optotypes correctly identified at termination, with 0.02 logMAR units allotted per optotypes.

³⁹ These cylindrical powers were selected as the closest available strengths matching the two spherical powers of 2.25 D and 6.25 D according to the equivalence formula described above by Thibos et al. (1997).²⁸ The specific values of matched blur strengths were 2.30 D and 6.19 D at axis 45°.

⁴⁰ Random-dot stimuli were presented on a LCD monitor and controlled using the Psychtoolbox-3 interface of MATLAB (R2024a; The MathWorks, Natick, USA). These dichoptic stimuli were fused using a handheld stereo viewer with built-in periscopic mirrors to adjust for the participant's horizontal phoria and interpupillary distance (Screen-Vu Stereoscope, Portland, OR, USA). The cyclopean image was a vertically-oriented rectangular bar tilted either to the left or to the right in uncrossed horizontal retinal disparity. Participants indicated the direction of the bar tilt while the retinal disparity varied in a two-down and one-up adaptive staircase with each presentation for 11 reversals. While all participants had clinical stereo thresholds better than 40 arc sec (measured using Wirt circles), the average (± 1 SEM) psychophysical stereo threshold (measured with random-dot stimuli) for the baseline condition was 102 ± 19 arc sec. This difference may be attributed to the nature of the stereo stimuli as well as cycloplegia in the laboratory.²⁹

these data simply serve as evidence for deteriorated sensory binocularity across all the induced blur conditions in the present study.

2.4. Statistical analyses

Matlab® and SPSS® (Version 27, IBM, SPSS Inc, Armonk, USA) were used for data analyses. The Shapiro-Wilk test revealed no significant departure from normality in the three outcome variables and hence the data trends were described using parametric statistics. Several statistical analyses were performed to gain a comprehensive understanding of the impact of different combinations blur and viewing conditions on the outcome variables of the buzz-wire task. These details are shown in Table 1, categorized by the underlying study hypotheses. Hypothesis testing also involved an analysis of the binocular advantage in task performance for all three outcome measures (Table 1). *The binocular advantages in error rate and error duration were calculated as ratios of monocular performance to binocular performance. The binocular advantage in speed was calculated as the ratio of binocular speed to monocular speed. These calculations ensured that a ratio greater than unity indicated superior performance under binocular than monocular viewing. For the isometric blur condition, the monocular performance with the corresponding value of blur was used to compute the binocular advantage. For the anisometric blur condition, the monocular performance without any induced blur was used to compute the binocular advantage.* This was done under the assumption that the eye with

Table 1: Description of the different statistical analyses performed to test the study hypotheses.

	Statistics	Independent factors	Dependent variables	Text reference
Hypotheses 1 and 5: Impact of induced blur on task performance vs. baseline				
Mono viewing	1-factor RM-MANOVA	Baseline & all monocular induced blur conditions	Error rate, Error duration & Speed	Table 2, Section 2
Bino viewing		Baseline & all binocular induced blur conditions		Table 2, Section 3
Bino advantage		induced blur conditions		Table 2, Section 4
Hypotheses 2 and 3: Impact of radial and interocular symmetry of blur on task performance				
Mono viewing	2-factor RM-MANOVA	Blur magnitude & Radial symmetry of blur	Error rate, Error duration & Speed	Table 3, Section 1
Bino viewing	3-factor RM-MANOVA	Blur magnitude, radial symmetry & interocular symmetry of blur		Table 3, Section 2
Bino advantage	3-factor RM-MANOVA			Table 3, Section 3
Hypothesis 4: Impact of parallel versus orthogonal astigmatic axis on task performance				
Bino viewing	2-factor RM-MANOVA	Blur magnitude & astigmatic axis orientation	Error rate, Error duration & Speed	Table 4, Section 1
Bino advantage	2-factor RM-MANOVA			Table 4, Section 2

RM-MANOVA: Repeated Measures Multiple Analysis of Variance. The column "Text reference" indicates the location in the tables where the results of a particular statistical analysis appear in the text.

the clear vision is used for viewing while the fellow eye with blurred vision may be suppressed in anisometropia.^{30,31} For the parallel versus orthogonal axes of astigmatism, the monocular performance with corresponding value of blur at 45° and 135° axis was used to compute the binocular advantage.

3. Results

Figures 3 and 4 show the binocular and monocular outcome variables and the respective binocular advantages for the different conditions tested in this study. The data points for the baseline (no blur) and low blur conditions were below the line of equality for error rates and error durations, indicating superior performance under binocular viewing (Figure 3). The distribution of data points in the baseline and low blur condition overlapped, indicating no evidence for difference in task performance between these two conditions (Figure 3). On the other hand, the data distribution for the high induced blur condition shifted upward to the right in isometropia and simply upward in anisometropia, indicating increased error rates and error durations, relative to the other conditions (Figure 3, left and middle column). Accordingly, the baseline viewing showed a robust binocular advantage for the two outcome variables in Figures 4A – D. This advantage was present but lower than the baseline condition for the low blur conditions, irrespective of radial or interocular symmetry (Figures 4A – D). There was no evidence for a binocular advantage in the high blur conditions (Figures 4A – D). Speed as an outcome parameter did not indicate any specific trend, regardless of blur conditions.

3.1. Impact of induced blur on buzz-wire task performance, relative to baseline viewing

The 1-factor RM-MANOVA showed a significant main effect of induced blur on the monocular and binocular task performance ($p < 0.001$) and on the binocular advantage of task performance ($p < 0.001$). For monocular viewing, Bonferroni-corrected pairwise comparison revealed significant worsening of task performance from the baseline condition only for error duration with high spherical and astigmatic blur (Table 2, Section 2). For binocular viewing, the error rates and error durations were significantly higher than baseline condition for high spherical and astigmatic blur under isometric and anisometric viewing conditions (Table 2, Section 3). Similarly, the binocular advantage for error rate and error duration was also significantly lower than the baseline condition for only the high spherical and astigmatic blur under isometric and anisometric viewing conditions (Table 2, Section 4).

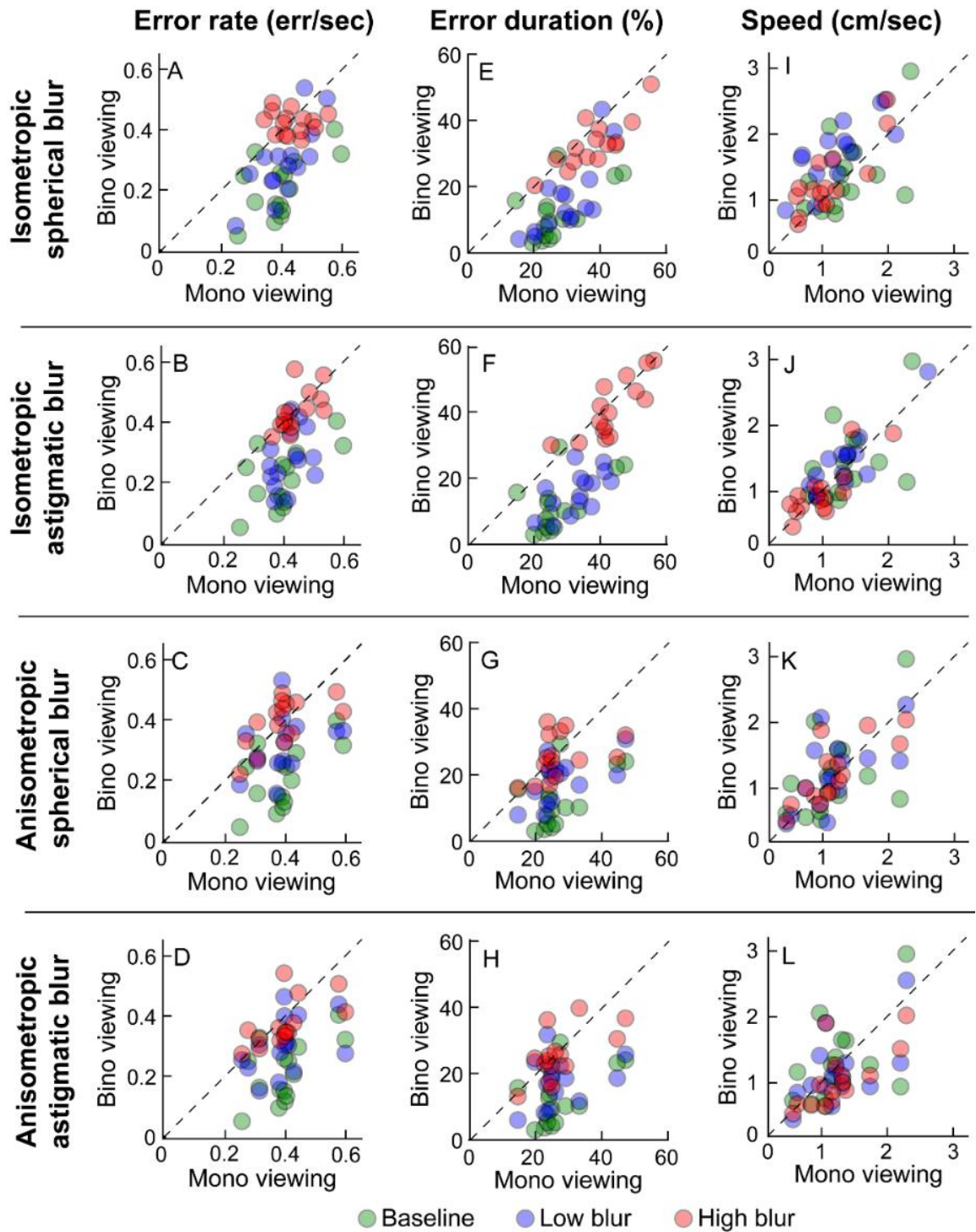


Figure 3: Scatter diagrams of binocular and monocular error rate (panels A – D), error duration (panels E – H) and speed (panels I – L) under baseline no-blur condition (green circles), low blur (blue circles) and high blur (red circles) viewing conditions. The top two rows show data for isometric blur and the bottom two rows show equivalent data for anisometric blur. The same baseline data is plotted in each panel for ease of comparison. The dashed diagonal line in each panel represents equal binocular and monocular performance.

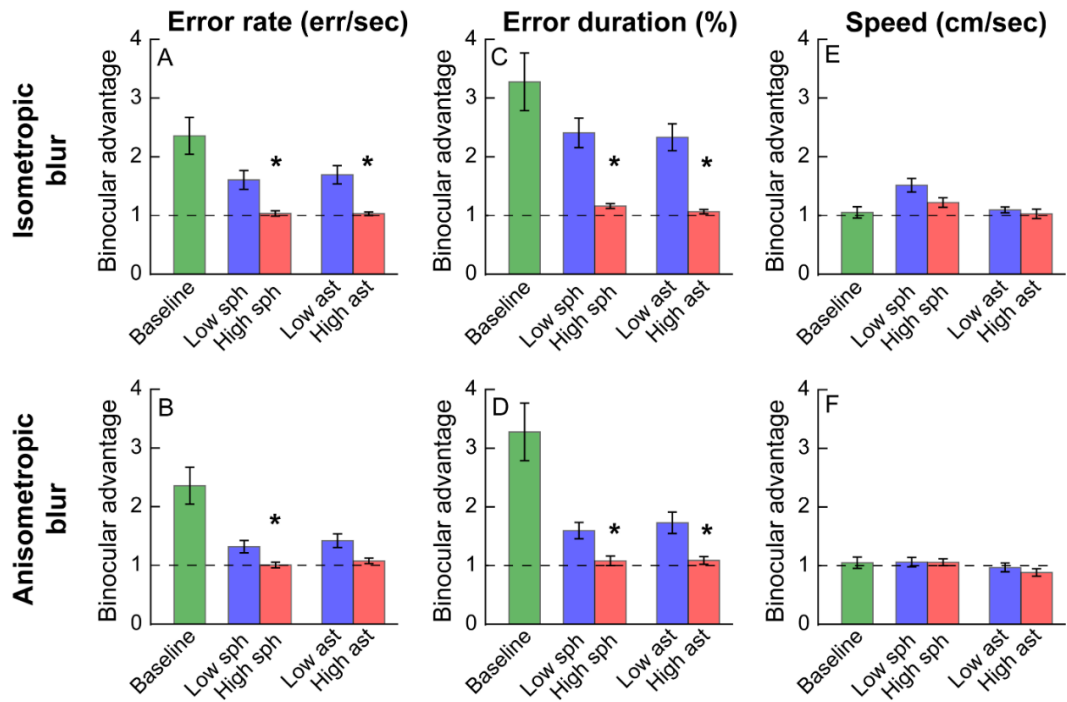


Figure 4: Mean $\pm$ 1 SEM binocular advantage in error rate (panels A and B), error duration (panels C and D), and speed (panels E and F), under baseline no-blur condition (green bars), low blur (blue bars) and high blur (red bars) viewing conditions. The dashed horizontal line in each panel indicates the level of no binocular advantage. The baseline data are the same between isometric and anisometric blur conditions. The asterisk denotes the blur conditions that were significantly different ($p < 0.05$) from baseline.

Table 2: Baseline parameters of error rate, error duration and speed under binocular and monocular viewing condition (Section 1). Results of the post-hoc Bonferroni test conducted as part of the 1-factor RM-MANOVA analysis to compare the error rate, error duration and speed under baseline and the different induced blur conditions (Section 2-4).

Section 1: Baseline Parameters						
	Error rate (err/sec)		Error duration (%)		Speed (cm/sec)	
	Mean $\pm$ SEM	p value	Mean $\pm$ SEM	p value	Mean $\pm$ SEM	p value
Monocular	0.39 $\pm$ 0.02		26.97 $\pm$ 2.22		1.37 $\pm$ 0.11	
Binocular	0.20 $\pm$ 0.02	<0.001	11.81 $\pm$ 2.10	<0.001	1.38 $\pm$ 0.14	0.47
Section 2: Monocular viewing						
	Error rate (err/sec)		Error duration (%)		Speed (cm/sec)	
	Mean diff $\pm$ SEM	p value	Mean diff $\pm$ SEM	p value	Mean diff $\pm$ SEM	p value
Low sph	-0.01 $\pm$ 0.02	>0.99	-2.89 $\pm$ 1.99	>0.99	0.14 $\pm$ 0.10	>0.99
High sph	-0.04 $\pm$ 0.27	>0.99	-10.82 $\pm$ 2.36	0.004	0.28 $\pm$ 0.10	0.18
Low astig	-0.02 $\pm$ 0.02	>0.99	-5.63 $\pm$ 1.82	0.79	0.12 $\pm$ 0.08	>0.99
High astig	-0.04 $\pm$ 0.02	0.92	-16.03 $\pm$ 1.62	<0.001	0.42 $\pm$ 0.12	0.04
Section 3: Binocular viewing						
	Error rate (err/sec)		Error duration (%)		Speed (cm/sec)	
	Mean diff $\pm$ SEM	p value	Mean diff $\pm$ SEM	p value	Mean diff $\pm$ SEM	p value
Low sph iso	-0.08 $\pm$ 0.03	>0.99	-4.20 $\pm$ 2.80	>0.99	-0.34 $\pm$ 0.17	>0.99
High sph iso	-0.21 $\pm$ 0.02	<0.001	-20.91 $\pm$ 1.90	<0.001	0.10 $\pm$ 0.16	>0.99
Low astig iso	-0.06 $\pm$ 0.03	>0.99	-4.11 $\pm$ 1.87	>0.99	0.04 $\pm$ 0.10	>0.99
High astig iso	-0.22 $\pm$ 0.03	<0.001	-29.06 $\pm$ 2.08	<0.001	0.46 $\pm$ 0.16	0.43
Low sph aniso	-0.11 $\pm$ 0.03	0.03	-6.52 $\pm$ 2.15	0.32	-0.03 $\pm$ 0.13	>0.99
High sph aniso	-0.18 $\pm$ 0.03	<0.001	-13.91 $\pm$ 2.30	<0.001	-0.03 $\pm$ 0.15	>0.99
Low astig aniso	-0.09 $\pm$ 0.03	0.46	-5.97 $\pm$ 2.62	>0.99	0.10 $\pm$ 0.12	>0.99
High astig aniso	-0.16 $\pm$ 0.03	<0.001	-13.72 $\pm$ 2.67	0.01	0.21 $\pm$ 0.14	>0.99

Section 4: Binocular advantage						
	Error rate (err/sec)		Error duration (%)		Speed (cm/sec)	
	Mean diff ± SEM	p value	Mean diff ± SEM	p value	Mean diff ± SEM	p value
Low sph iso	0.75 ± 0.30	0.91	0.87 ± 0.48	>0.99	-0.46 ± 0.16	0.44
High sph iso	1.32 ± 0.31	0.02	2.12 ± 0.49	0.02	-0.17 ± 0.12	>0.99
Low astig iso	0.66 ± 0.31	1.00	0.95 ± 0.48	>0.99	-0.04 ± 0.10	>0.99
High astig iso	1.32 ± 0.32	0.03	2.21 ± 0.49	0.02	0.02 ± 0.14	>0.99
Low sph aniso	1.03 ± 0.29	0.09	1.68 ± 0.48	0.12	-0.01 ± 0.10	>0.99
High sph aniso	1.35 ± 0.32	0.03	2.19 ± 0.50	0.02	-0.01 ± 0.11	>0.99
Low astig aniso	0.93 ± 0.35	0.61	1.55 ± 0.56	0.53	0.08 ± 0.10	>0.99
High astig aniso	1.28 ± 0.32	0.05	2.19 ± 0.53	0.03	0.17 ± 0.11	>0.99

Negative values of the mean difference indicate increased error rate, error duration and speed with induced blur, relative to baseline viewing. Sections 1 and 2 of this table show the results for monocular and binocular viewing, respectively. Section 3 shows the results for binocular advantage. Comparisons that reached significance at $p \leq 0.05$ are indicated in bold.

3.2. Impact of radial and bilateral symmetry of blur on buzz-wire performance

The 2-factor RM-MANOVA for monocular viewing revealed significant main effects of blur magnitude and radial symmetry across all three outcome variables (Table 3, Section 1a). Univariate analyses revealed significant effects of blur magnitude and radial symmetry only for the error duration (Table 3, Section 1b) and a significant effect of blur magnitude on the speed (Table 3, Section 1b). The 3-factor RM-MANOVA revealed significant main effect of all the three factors (blur magnitude, radial symmetry of blur and interocular symmetry of blur) on binocular task performance (Table 3, Section 2a). Significant interactions were also noted between the factors, indicating that the impact of these factors on the binocular buzz-wire task performance is not independent of each other (Table 3, Section 2a). The univariate analyses indicated significant main effects and interactions for the error duration variable (Table 3, Section 2b). Only sporadic factors were significant for error rates and speed, as highlighted in Table 3, Section 2b.

The three-factor RM-MANOVA also revealed significant main effects of all three factors on binocular advantage along with a significant interaction between blur magnitude and interocular symmetry (Table 3, Section 3a). Univariate analyses showed a significant loss of binocular advantage in error rate only with blur magnitude (Table 3, Section 3b). The binocular advantage in error duration significantly deteriorated for both blur magnitude and interocular symmetry of blur, with significant interaction between the two factors (Table 3, Section 3b). The binocular advantage in speed also showed a significant loss with all these main factors (Table 3, Section 3b).

304 **Table 3:** Results of 2-factor and 3-factor RM-MANOVAs performed to determine the effect of different patterns
305 of induced blur on the monocular and binocular task performance, respectively.

Section 1: 2-factor RM-MANOVA for monocular performance										
1a. Multivariate tests										
				F		p value		Partial η^2		
Blur magnitude				13.56		<0.001		0.77		
Radial symmetry				4.81		0.02		0.54		
Blur magnitude x Radial symmetry				1.34		0.30		0.25		
1b. Univariate tests										
		Error Rate			Error Duration			Speed		
		Mean $\pm$ SEM	p value	Partial η^2	Mean $\pm$ SEM	p value	Partial η^2	Mean $\pm$ SEM	p value	Partial η^2
Blur magnitude	Low	0.41 $\pm$ 0.01	0.1	0.17	31.23 $\pm$ 1.78	<0.001	0.74	1.24 $\pm$ 0.11	0.001	0.53
	High	0.43 $\pm$ 0.01			40.39 $\pm$ 2.02			1.02 $\pm$ 0.10		
Radial symmetry	Spherical	0.42 $\pm$ 0.01	0.54	0.02	33.82 $\pm$ 1.96	0.006	0.42	1.16 $\pm$ 0.11	0.37	0.05
	Astigmatic	0.42 $\pm$ 0.01			37.80 $\pm$ 1.77			1.10 $\pm$ 0.10		
Blur magnitude x Radial symmetry		-	0.93	0.0001	-	0.27	0.08	-	0.09	0.19

Section 2: 3-factor RM-MANOVA for binocular performance										
2a. Multivariate tests										
				F		p value		Partial η^2		
Blur magnitude				75.81		<0.001		0.95		
Radial symmetry				13.46		<0.001		0.77		
Interocular symmetry				4.78		0.02		0.54		
Blur magnitude x Radial symmetry				4.13		0.03		0.5		
Radial symmetry x Interocular symmetry				5.78		0.01		0.6		
Blur magnitude x Interocular symmetry				47.3		<0.001		0.92		
All interactions				1.2		0.35		0.23		
2b. Univariate tests										
		Error Rate			Error Duration			Speed		
		Mean $\pm$ SEM	p value	Partial η^2	Mean $\pm$ SEM	p value	Partial η^2	Mean $\pm$ SEM	p value	Partial η^2
Blur magnitude	Low	0.30 $\pm$ 0.02	<0.001	0.81	17.02 $\pm$ 1.64	<0.001	0.94	1.45 $\pm$ 0.11	<0.001	0.62
High	0.41 $\pm$ 0.01	31.22 $\pm$ 1.63	1.21 $\pm$ 0.10							
Radial symmetry	Spherical	0.36 $\pm$ 0.02	0.15	1.42	23.2 $\pm$ 1.68	0.03	0.29	1.46 $\pm$ 0.11	0.001	0.56
Astigmatic	0.34 $\pm$ 0.02	25.03 $\pm$ 1.56	1.19 $\pm$ 0.11							
Interocular symmetry	Isometropia	0.36 $\pm$ 0.02	0.47	0.04	26.39 $\pm$ 1.91	0.004	0.45	1.33 $\pm$ 0.11	0.96	0.0001
Anisometropia	0.35 $\pm$ 0.02	21.85 $\pm$ 1.48	1.39 $\pm$ 0.11							
Blur magnitude x Radial symmetry		-	0.70	0.01	-	0.03	0.28	-	0.64	0.01
Blur magnitude x Interocular symmetry		-	0.01	0.37	-	<0.001	0.87	-	<0.001	0.62
Radial symmetry x Interocular symmetry		-	0.17	0.13	-	0.04	0.27	-	0.004	0.47
All interactions		-	0.43	0.04	-	0.06	0.22	-	0.36	0.05
Section 3: 3-factor RM-MANOVA for binocular advantage										
3a. Multivariate tests										
				F		p value		Partial η^2		
Blur magnitude				12.72		<0.001		0.76		
Radial symmetry				4.73		0.02		0.54		
Interocular symmetry				6.75		0.006		0.63		
Blur magnitude x Radial symmetry				0.35		0.79		0.08		

Radial symmetry x Interocular symmetry	1.14	0.37	0.22
Blur magnitude x Interocular symmetry	5.24	0.02	0.56
All interactions	0.88	0.48	0.18

3b. Univariate tests

		Error Rate			Error Duration			Speed		
		Mean $\pm$ SEM	p value	Partial η^2	Mean $\pm$ SEM	p value	Partial η^2	Mean $\pm$ SEM	p value	Partial η^2
Blur magnitude	Low High	1.51 $\pm$ 0.08 1.04 $\pm$ 0.02	<0.001	0.73	2.02 $\pm$ 0.14 1.10 $\pm$ 0.04	<0.001	0.74	1.16 $\pm$ 0.04 1.05 $\pm$ 0.04	0.03	0.28
Radial symmetry	Spherical Astigmatic	1.24 $\pm$ 0.05 1.30 $\pm$ 0.06	0.29	0.08	1.56 $\pm$ 0.08 1.55 $\pm$ 0.09	0.92	0.001	1.21 $\pm$ 0.04 0.99 $\pm$ 0.05	0.002	0.51
Interocular symmetry	Isometropia Anisometropia	1.34 $\pm$ 0.06 1.21 $\pm$ 0.07	0.15	0.14	1.74 $\pm$ 0.10 1.37 $\pm$ 0.09	0.007	0.41	1.21 $\pm$ 0.04 0.99 $\pm$ 0.06	0.02	0.33
Blur magnitude x Radial symmetry		-	0.60	0.02	-	0.69	0.01	-	0.32	0.07
Blur magnitude x Interocular symmetry		-	0.05	0.25	-	0.001	0.53	-	0.16	0.14
Radial symmetry x Interocular symmetry		-	0.68	0.01	-	0.33	0.07	-	0.08	0.20
All interactions		-	0.84	0.003	-	0.77	0.006	-	0.13	0.16

Sections 1 and 2 of this table show the results for monocular and binocular viewing, respectively. Section 3 of this table show the results for binocular advantage. Comparisons that reached statistical significance at $p \leq 0.05$ are indicated in bold.

To better understand the nature of interactions between the different dimensions of blur, the error duration variable is plotted in Figure 5 for the different interaction elements shown in Table 3, Section 2b. Figure 5A plots the interaction between blur magnitude and its radial symmetry across the combined isometropic and anisometropic viewing conditions. The error durations were not statistically different for low spherical and astigmatic blur ($t = 1.99$, $p = 0.06$) but they were significantly higher for astigmatic than spherical blur at the high blur magnitude ($t = 9.77$, $p < 0.001$) (Figure 5A). Figure 5B plots the interaction between blur magnitude and its interocular symmetry across the combined spherical and astigmatic viewing conditions. The error durations were not statistically different for low magnitudes of isometropic and anisometropic blur ($t = -1.47$, $p = 0.15$) but they were significantly higher for isometropic viewing than anisometropic viewing for the high magnitude of blur ($t = 6.94$, $p < 0.001$) (Figure 5B). The mean (± 1 SEM) error duration in the high anisometropic condition ($25.63 \pm 1.58\%$) also matched the mean error duration observed under the monocular baseline no blur viewing condition ($26.97 \pm 2.22\%$) (see horizontal arrow location in Figure 5B). The results indicate worse task performance with the high magnitude of isometropic than with a comparable level of anisometropic blur. Figure 5C plots the interaction between the radial and interocular symmetry of blur across the combined low and high blur magnitudes. Isometropic blur resulted in overall higher error durations than anisometropic blur, but this difference was greater for astigmatic than for spherical blur ($t = 9.77$, $p < 0.001$) (Figure 5C).

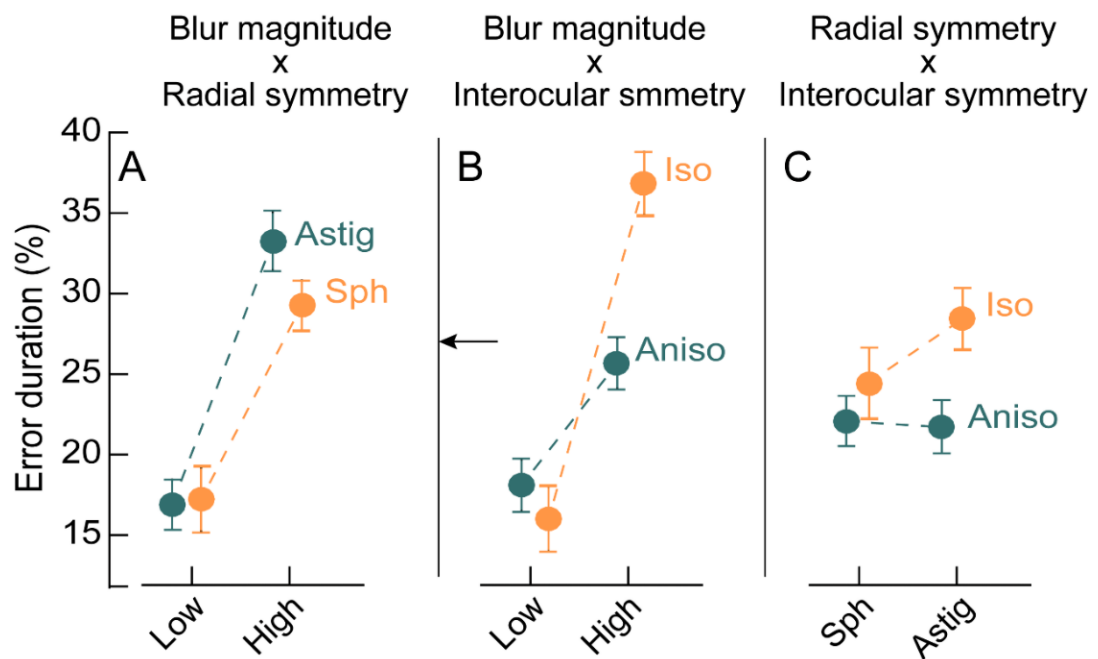


Figure 5: Impact of interactions between blur magnitude, radial symmetry and interocular symmetry of blur on the mean ± 1 -SEM error duration in the binocular buzz-wire task. Panel A shows the interaction of blur magnitude and radial symmetry of blur for the combined isometric and anisometric blur conditions. Panel B shows the interaction of blur magnitude and interocular symmetry of blur for the combined spherical and astigmatic blur conditions. The horizontal arrow indicates the mean baseline (no blur) error duration for monocular viewing. Panel C shows the interaction of radial and interocular symmetry of blur for the combined low and high magnitudes of blur. The data points in each panel are connected only to highlight the interaction between the factors.

3.3. Impact of the bilateral symmetry of astigmatic axis on buzz-wire performance

Error rates (panel A) and error durations (panel B) were worse for the low blur condition with orthogonal axes orientation, relative to the parallel axes orientation (Figure 6). This effect was absent for the high blur condition, with both sets of data falling along the line of equality (Figures 6A and B). Speed decreased with blur magnitude for both parallel and orthogonal axes orientations (Figure 6C). The 2-factor RM-MANOVA revealed a significant main effect of blur magnitude and interocular astigmatic axis orientation and a significant interaction between the factors on the combined outcome variables (Table 4, Section 1a). Univariate tests revealed blur magnitude to have a significant effect on all three outcome variables while the axis orientation had an effect only on the error rate and error duration (Table 4, Section 1b). The binocular advantage for error rate (Figure 6D) and error duration (Figure 6E) decreased with astigmatic blur (see also Table 4, Section 2). It was completely lost when the magnitude of astigmatism was high, irrespective of its axis orientation (Figures 6D and E and Table 4, Section 2). Speed did not show any such trend in the binocular advantage (Figure 6F and Table 4, Section 2).

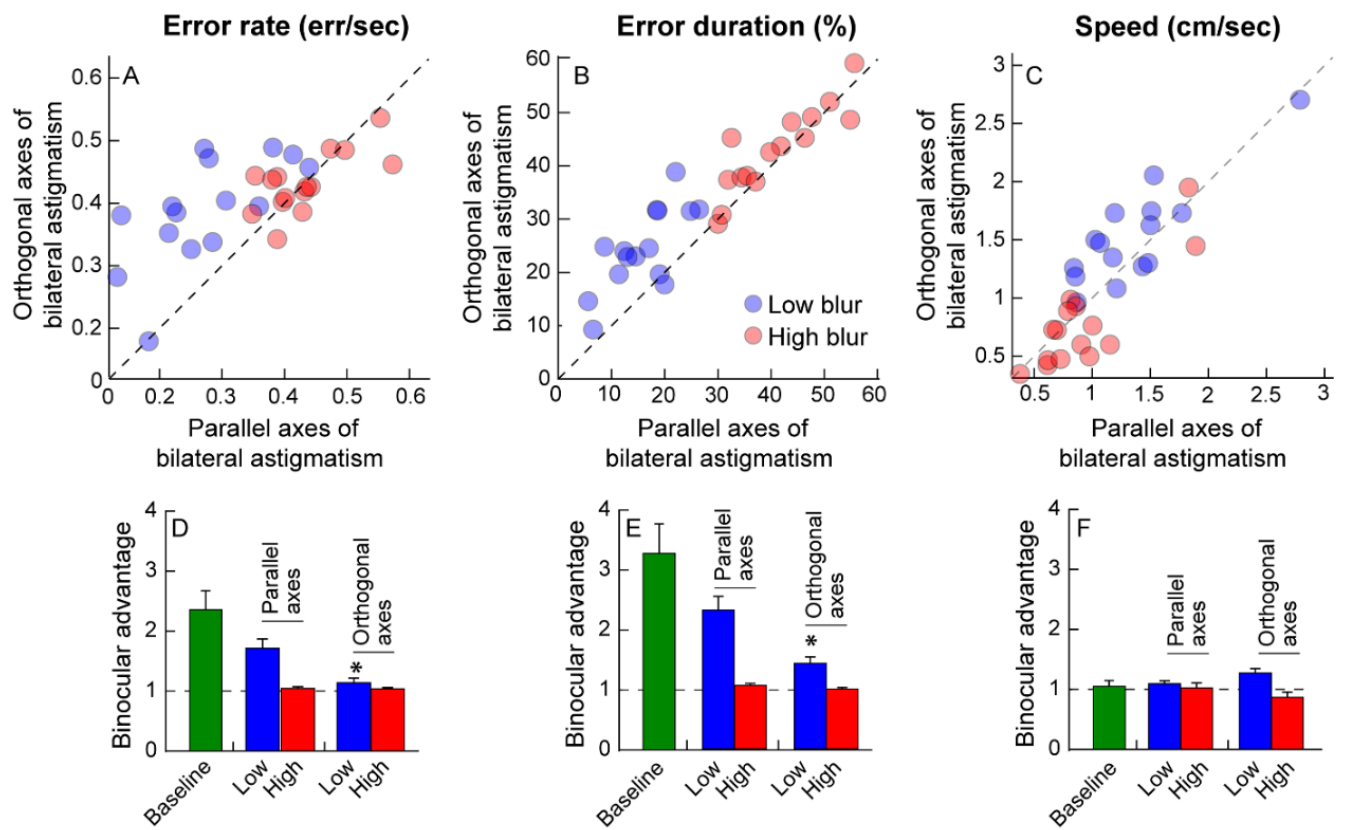


Figure 6: Outcome variables (as scatter diagrams in panels A–C) and binocular advantages (as bar graphs in panels D–F) with parallel and orthogonal axes of astigmatism in the two eyes under low and high blur viewing conditions. The asterisk symbols in panels D and E indicate significant differences between parallel and orthogonal axes.

Table 4: Results of 2-factor RM-MANOVA performed to determine the impact of astigmatic axis orientation on binocular buzz-wire task performance.

Section 1: 2-factor RM-MANOVA for binocular performance

1a. Multivariate tests

	F	p value	Partial η^2
Blur magnitude	14.13	<0.001	0.95
Bilateral axes	87.85	<0.001	0.77
Blur magnitude x Bilateral axes	11.55	0.001	0.74

1b. Univariate tests

		Error Rate			Error Duration			Speed		
		Mean $\pm$ SEM	p value	Partial η^2	Mean $\pm$ SEM	p value	Partial η^2	Mean $\pm$ SEM	p value	Partial η^2
Blur magnitude	Low	0.33 $\pm$ 0.02	<0.001	0.61	20.15 $\pm$ 1.68	<0.001	0.95	1.44 $\pm$ 0.11	<0.001	0.75
	High	0.43 $\pm$ 0.01			41.92 $\pm$ 2.10			0.86 $\pm$ 0.10		
Axis orientation	Parallel	0.35 $\pm$ 0.02	<0.001	0.69	28.40 $\pm$ 1.83	<0.001	0.68	1.14 $\pm$ 0.10	0.62	0.01
	Orthogonal	0.41 $\pm$ 0.01			33.67 $\pm$ 1.87			1.16 $\pm$ 0.10		
Blur magnitude x Axis orientation	–		<0.001	0.61	–	0.001	0.54	–	0.005	0.43

Section 2: 2-factor RM-MANOVA for binocular advantage

2a. Multivariate tests

	F	p value	Partial η^2
Blur magnitude	11.43	0.001	0.74
Bilateral axes	7.45	0.004	0.65

Blur magnitude x Bilateral axes	10.94	0.001	0.73
---------------------------------	-------	-------	------

2b. Univariate tests

		Error Rate			Error Duration			Speed		
		Mean ± SEM	p value	Partial η²	Mean ± SEM	p value	Partial η²	Mean ± SEM	p value	Partial η²
Blur magnitude	Low	1.41 ± 0.10	0.001	0.55	1.88 ±0.15	<0.001	0.68	1.18 ± 0.95	0.02	0.31
	High	1.03 ± 0.02			1.03 ±0.03			0.947 ±0.08		
Axis orientation	Parallel	1.36 ± 0.09	0.002	0.52	1.70 ± 0.12	<0.001	0.60	1.06 ± 0.05	0.82	0.004
	Orthogonal	1.07 ± 0.04			1.22 ±0.06			1.07 ± 0.05		
Blur magnitude x Axis orientation	-		0.001	0.53	-	0.001	0.56	-	0.003	0.49

359

360 4. Discussion

361 4.1. Summary of results

362 *Depth-related visuomotor task performance deteriorates in the presence of induced optical blur under*
363 *binocular and monocular viewing conditions.* The specific study results may be summarized as follows:

- 364 1) Error rates and error duration increased with induced optical blur under monocular and binocular
365 viewing conditions, vis-à-vis, no blur viewing. While this deterioration progressively increased with
366 the magnitude of optical blur (see Supplement I), it reached statistical significance only with the
367 high magnitudes of blur.
- 368 2) A high magnitude of astigmatic blur resulted in higher error rates and error durations in the buzz-
369 wire task, relative to a comparable magnitude of radially symmetric spherical blur. Low astigmatic
370 blur with orthogonal axes in the two eyes produced higher error rates and error durations than
371 comparable blur patterns with parallel axes in the two eyes. This effect is absent with high
372 magnitudes of astigmatic blur.
- 373 3) While similarly low levels of isometric and anisometric blur had similar effects on visuomotor
374 performance, similarly high levels of isometric and anisometric blur did not. In particular, error
375 durations were much greater with high levels of isometric blur than with anisometric blur.
- 376 4) The worsening of the error rate and error duration with optical blur was greater for binocular than
377 monocular viewing conditions. This reflected as an attenuation of the binocular advantage of task
378 performance with low blur viewing and a complete loss of binocular advantage with high blur
379 viewing, all relative to baseline no blur viewing.
- 380 5) The deterioration in buzz-wire task performance manifested differently across outcome variables in
381 this study. The error duration (i.e., the percentage of total task time spent in error) was most
382 sensitive to the presence of optical blur while the speed was least sensitive.

383

Overall, these results support all but the third study hypothesis (*see Section 4.2 for details*). The results also agree with the previous literature that demonstrated losses in visuomotor task performance and prehensile movements with degraded binocularity arising from induced anisometropia^{13,20}, induced visibility loss through Bangerter foils²², and in pathologies like keratoconus⁴ or amblyopia.^{33,34} The present study also extends these findings to other dimensions of blur (radial and interocular symmetry) that are hitherto absent in the literature to the best of the authors' knowledge.

4.2. Buzz-wire task performance with isometropia and anisometropia

Interocular differences in blur magnitude (and/or axes) result in different retinal image qualities and/or aniseikonia, either of which may severely disrupt binocularity.^{10,35} This disruption of binocularity may have been responsible for our participants' relatively poor performances in the buzz-wire task, when compared with what they were able to achieve with similarly blur magnitudes (and/or identical axes) in the two eyes. (See Figures 1O and 1P to qualitatively experience this effect). Low magnitudes of spherical and astigmatic anisometropia also led to higher error duration relative to isometropia, even while this result did not reach statistical significance. Counterintuitively, isometropia led to greater task deterioration than anisometropia for high magnitudes of blur. This finding may be explained by the suppression of the blurred input in anisometropia, thus biasing the buzz-wire task towards the monocular performance of the eye with clear vision. This is suggested from the error duration with high anisometropia becoming similar to the baseline monocular viewing in Figure 5B of this study. This effect may also be observed qualitatively in Figure 1, wherein free-fusion of the simulated anisometropic image pair results in a clear cyclopean percept (Figures 1L and N) while free-fusion of simulated isometropic image pair results in a blurred cyclopean percept (Figures H and J). Indeed, this magnitude of anisometropia was found to induce suppression in the Piano and O'Connor study¹³ from which the blur values were chosen for the present study. Thus, even while the disparity signals may have become effectively useless, the monocular depth cues from the eye with clear vision could be reliably used to perform the buzz-wire task. In contrast, the visual system experiences a double whammy with high magnitude of isometropia – there is a loss of binocularity that negatively impacts stereopsis calculation and there is also a loss in spatial resolution that may preclude effective usage of the monocular depth cues. This monocular advantage may not be available in anisometropes with different magnitudes of blur in the two eyes (e.g., high blur in one eye and low blur in the fellow eye). This condition was, however, not tested here given the already exhaustive list being investigated.

4.3. Speed-accuracy trade-off

Speed-accuracy trade-offs in motor tasks are usually assessed with a change in payoff matrix.³² If behaviour changes with the payoff matrix, it may be due to a change in strategy, although one cannot rule out additional changes in perception. In the present study, changes in error rate (inverse of task accuracy) and speed with task difficulty may not necessarily reflect changes in response strategy, as the perception of the task itself changed with the different blurring lenses used in the study. In this context, a harder task can be expected to decrease response speed and/or increase the error rate. Only in 2 of our 15 participants, speed was positively correlated with error rate across the various blur conditions ($p < 0.05$). Consciously or unconsciously, these participants may have sacrificed accuracy to maintain speed across various blur conditions. Others did not show this correlation, indicating that sacrifices in speed or accuracy to optimize the complementary parameter is not a commonly observed phenomenon in the buzz-wire task.

4.4. Clinical and practical implications of this study

The present study was motivated by the previous observation of poorer buzz-wire task performance in individuals with keratoconus, relative to those with uncorrected myopia.⁴ The present results indicate that the combination of radial and interocular asymmetry of blur in keratoconus may have resulted in the greater loss of buzz-wire performance in this cohort, compared to their myopic counterparts. This observation, however, must be treated with caution, for the keratoconic cohort in the previous study were all corrected for their sphero-cylindrical refractive error. The retinal image quality of these participants may have thus be dominated by the radially asymmetric higher-order aberration terms (e.g., coma and trefoil^{16,17}) and by any residual defocus and astigmatism that remained uncorrected. The present study did not induce blur from higher-order aberrations and thus its direct impact on the buzz-wire task performance remains unknown. Introduction of such patterns of blur before the eye is non-trivial, for it requires the use of advanced phase plates^{36,37} or adaptive optics devices,³⁸ over a defined pupil size. Integration of such technology with visuomotor tasks is futuristic, at best.

The study has some practical implications for activities of daily living with blurred vision. Humans may perform visuomotor tasks with compromised vision that arises from their eye ailment (e.g., uncorrected refractive errors, cataract, retinal pathology) or due to poor compliance in wearing their refractive correction. Whether or not visuomotor performance is impaired depends both on the task requirements and on the extent of vision loss. For instance, tasks that require only a gross judgment of

depth may remain unimpaired in the presence of mild to moderate optical blur, while those that require finer depth judgments may be negatively impacted for comparable levels of blur. This is in line with the observations of Mann et al.²¹ wherein the degree of blur affected the interceptive tasks between a bat and a ball traveling at a certain speed in their study. Piano and O'Connor¹³ also observed that a water-pouring task requiring gross binocularity remained unimpaired with induced spherical anisometropic blur, while a bead-threading task (especially with smaller beads) requiring finer levels of binocularity was significantly impaired by comparable levels of blur. Clinicians are thus urged to consider the task requirements of their patients while planning the blur correction strategy (e.g., contact lens versus spectacle correction for certain sports activity) or counselling patients about their engagements in certain activities of daily living.³⁹ As a corollary to this point, the study also recommends inclusion of a battery of functional vision tests that mimic routine activities of daily living with varying spatial and depth vision requirements. This may reduce the discordance often observed between the patient's clinical assessment that are largely based on measures of "sensory perception" (e.g., visual acuity, contrast sensitivity, stereoacuity) and their ability to perform complex daily vision tasks. The latter tasks tend to challenge patients more than what may be expected from clinical vision testing.^{40,41}

5. Acknowledgements

The authors thank all study participants and Mr. Mohammed Abdul Subhan for creating the buzz-wire patterns used in this study. The study was supported through intramural grants from the Hyderabad Eye Research Foundation, L V Prasad Eye Institute to SRB.

6. References

1. Knill DC. Reaching for visual cues to depth: the brain combines depth cues differently for motor control and perception. *J Vis.* Feb 16 2005;5(2):103-115. doi:10.1167/5.2.2
2. Watt SJ, Bradshaw MF. The visual control of reaching and grasping: binocular disparity and motion parallax. *J Exp Psychol Hum Percept Perform.* Apr 2003;29(2):404-415. doi:10.1037/0096-1523.29.2.404
3. Devi P, Solomon JA, Tyler CW, Dave TV, Kaliki S, Bharadwaj SR. Comparison of Depth-Related Visuomotor Task Performance in Uniocular Individuals and in Binocular Controls With and Without Temporary Monocular Occlusion. *Invest Ophthalmol Vis Sci.* Jul 1 2024;65(8):32. doi:10.1167/iovs.65.8.32
4. Devi P, Bhengra CM, Kumar D, et al. Depth-Related Visuomotor Performance in Keratoconus and Its Relationship to Stereopsis. *Invest Ophthalmol Vis Sci.* Apr 1 2025;66(4):31. doi:10.1167/iovs.66.4.31
5. Ravikumar S, Bradley A, Thibos L. Phase changes induced by optical aberrations degrade letter and face acuity. *J Vis.* Dec 16 2010;10(14):18. doi:10.1167/10.14.18
6. Lakshmi Marella B, Conway ML, Vaddavalli PK, Suttle CM, Bharadwaj SR. Optical phase nullification partially restores visual and stereo acuity lost to simulated blur from higher-order wavefront aberrations of keratoconic eyes. *Vision Res.* Nov 2024;224:108486. doi:10.1016/j.visres.2024.108486

7. Akutsu H, Bedell HE, Patel SS. Recognition thresholds for letters with simulated dioptric blur. *Optom Vis Sci.* Oct 2000;77(10):524-530. doi:10.1097/00006324-200010000-00006
8. Metlapally S, Bharadwaj SR, Roorda A, Nilagiri VK, Yu TT, Schor CM. Binocular cross-correlation analyses of the effects of high-order aberrations on the stereoacuity of eyes with keratoconus. *J Vis.* Jun 3 2019;19(6):12. doi:10.1167/19.6.12
9. Banks MS, Gepshtein S, Landy MS. Why is spatial stereoresolution so low? *J Neurosci.* Mar 3 2004;24(9):2077-2089. doi:10.1523/JNEUROSCI.3852-02.2004
10. Lovasik JV, Szymkiw M. Effects of aniseikonia, anisometropia, accommodation, retinal illuminance, and pupil size on stereopsis. *Invest Ophthalmol Vis Sci.* May 1985;26(5):741-750.
11. Marella BL, Conway ML, Suttle C, Bharadwaj SR. Contrast Rivalry Paradigm Reveals Suppression of Monocular Input in Keratoconus. *Invest Ophthalmol Vis Sci.* Feb 1 2021;62(2):15. doi:10.1167/iovs.62.2.12
12. Marella BL, Vaddavalli PK, Reddy JC, Conway ML, Suttle CM, Bharadwaj SR. Interocular Contrast Balancing Partially Improves Stereoacuity in Keratoconus. *Optom Vis Sci.* Apr 1 2023;100(4):239-247. doi:10.1097/OPX.0000000000002001
13. Piano ME, O'Connor AR. The effect of degrading binocular single vision on fine visuomotor skill task performance. *Invest Ophthalmol Vis Sci.* Dec 17 2013;54(13):8204-8213. doi:10.1167/iovs.12-10934
14. Bharadwaj SR, Candy TR. The effect of lens-induced anisometropia on accommodation and vergence during human visual development. *Invest Ophthalmol Vis Sci.* Jun 1 2011;52(6):3595-3603. doi:10.1167/iovs.10-6214
15. Georgeson MA, Wallis SA. Binocular fusion, suppression and diplopia for blurred edges. *Ophthalmic Physiol Opt.* Mar 2014;34(2):163-185. doi:10.1111/opo.12108
16. Nilagiri VK, Metlapally S, Schor CM, Bharadwaj SR. A computational analysis of retinal image quality in eyes with keratoconus. *Sci Rep.* Jan 28 2020;10(1):1321. doi:10.1038/s41598-020-57993-w
17. Pantanelli S, MacRae S, Jeong TM, Yoon G. Characterizing the wave aberration in eyes with keratoconus or penetrating keratoplasty using a high-dynamic range wavefront sensor. *Ophthalmology.* Nov 2007;114(11):2013-2021. doi:10.1016/j.ophtha.2007.01.008
18. Thibos LN. Calculation of the geometrical point-spread function from wavefront aberrations. *Ophthalmic Physiol Opt.* Jul 2019;39(4):232-244. doi:10.1111/opo.12619
19. Cheng H, Barnett JK, Vilupuru AS, et al. A population study on changes in wave aberrations with accommodation. *J Vis.* Apr 16 2004;4(4):272-280. doi:10.1167/4.4.3
20. Niechwiej-Szwedo E, Kennedy SA, Colpa L, Chandrakumar M, Goltz HC, Wong AM. Effects of induced monocular blur versus anisometropic amblyopia on saccades, reaching, and eye-hand coordination. *Invest Ophthalmol Vis Sci.* Jul 1 2012;53(8):4354-4362. doi:10.1167/iovs.12-9855
21. Mann DL, Abernethy B, Farrow D. The resilience of natural interceptive actions to refractive blur. *Hum Mov Sci.* Jun 2010;29(3):386-400. doi:10.1016/j.humov.2010.02.007
22. Sheppard WEA, Dickerson P, Baraas RC, et al. Exploring the effects of degraded vision on sensorimotor performance. *PLoS One.* 2021;16(11):e0258678. doi:10.1371/journal.pone.0258678
23. Atchison DA, Guo H, Charman WN, Fisher SW. Blur limits for defocus, astigmatism and trefoil. *Vision Res.* Sep 2009;49(19):2393-2403. doi:10.1016/j.visres.2009.07.009
24. Vincent M, Marin G, Legras R. Effect of Simulated and Real Spherical and Astigmatism Defocus on Visual Acuity and Image Quality Score. *Optom Vis Sci.* Jan 2020;97(1):36-44. doi:10.1097/OPX.0000000000001463
25. Laidlaw DA, Tailor V, Shah N, Atamian S, Harcourt C. Validation of a computerised logMAR visual acuity measurement system (COMPlog): comparison with ETDRS and the electronic ETDRS testing algorithm in adults and amblyopic children. *Br J Ophthalmol.* Feb 2008;92(2):241-244. doi:10.1136/bjo.2007.121715
26. Charman WN, Whitefoot H. Astigmatism, accommodation, and visual instrumentation. *Appl Opt.* Dec 15 1978;17(24):3903-3910. doi:10.1364/AO.17.003903
27. Freeman RD. Asymmetries in human accommodation and visual experience. *Vision Res.* Apr 1975;15(4):483-492. doi:10.1016/0042-6989(75)90025-5
28. Thibos LN, Wheeler W, Horner D. Power vectors: an application of Fourier analysis to the description and statistical analysis of refractive error. *Optom Vis Sci.* Jun 1997;74(6):367-375. doi:10.1097/00006324-199706000-00019

29. Saladin JJ. Stereopsis from a performance perspective. *Optom Vis Sci.* Mar 2005;82(3):186-205. doi:10.1097/01.opx.0000156320.71949.9d
30. Devi P, Kumar P, Marella BL, Bharadwaj SR. Impact of Degraded Optics on Monocular and Binocular Vision: Lessons from Recent Advances in Highly-Aberrated Eyes. *Semin Ophthalmol.* Oct-Nov 2022;37(7-8):869-886. doi:10.1080/08820538.2022.2094711
31. Simpson T. The suppression effect of simulated anisometropia. *Ophthalmic Physiol Opt.* Oct 1991;11(4):350-358.
32. Wickelgren WA. Speed-accuracy tradeoff and information processing dynamics. *Acta psychologica.* 1977;41(1):67-85.
33. Niechwiej-Szwedo E, Goltz HC, Chandrakumar M, Hirji Z, Wong AM. Effects of anisometropic amblyopia on visuomotor behavior, III: Temporal eye-hand coordination during reaching. *Invest Ophthalmol Vis Sci.* Jul 29 2011;52(8):5853-5861. doi:10.1167/iovs.11-7314
34. O'Connor AR, Birch EE, Anderson S, Draper H. Relationship between binocular vision, visual acuity, and fine motor skills. *Optom Vis Sci.* Dec 2010;87(12):942-947. doi:10.1097/OPX.0b013e3181fd132e
35. Atchison DA, Nguyen T, Schmid KL, Rakshit A, Baldwin AS, Hess RF. The effects of optically and digitally simulated aniseikonia on stereopsis. *Ophthalmic Physiol Opt.* Jul 2022;42(4):921-930. doi:10.1111/opo.12973
36. Khorin PA, Khonina SN. Simulation of the Human Myopic Eye Cornea Compensation Based on the Analysis of Aberrometric Data. *Vision (Basel).* Mar 12 2023;7(1)doi:10.3390/vision7010021
37. Marchese LE, Munger R, Priest D. Wavefront-guided correction of ocular aberrations: are phase plate and refractive surgery solutions equal? *J Opt Soc Am A Opt Image Sci Vis.* Aug 2005;22(8):1471-1481. doi:10.1364/josaa.22.001471
38. Fernandez EJ, Prieto PM, Artal P. Adaptive optics binocular visual simulator to study stereopsis in the presence of aberrations. *J Opt Soc Am A Opt Image Sci Vis.* Nov 1 2010;27(11):A48-55. doi:10.1364/JOSAA.27.000A48
39. Spinell MR. Contact lenses for athletes. *Optom Clin.* 1993;3(1):57-76.
40. Bhorade AM, Perlmutter MS, Wilson B, et al. Differences in vision between clinic and home and the effect of lighting in older adults with and without glaucoma. *JAMA Ophthalmol.* Dec 2013;131(12):1554-1562. doi:10.1001/jamaophthalmol.2013.4995
41. Latham K, Usherwood C. Assessing visual activities of daily living in the visually impaired. *Ophthalmic Physiol Opt.* Jan 2010;30(1):55-65. doi:10.1111/j.1475-1313.2009.00693.x

Supplementary information

Supplement I

Although high blur magnitudes ($6.25D \times 45^\circ$ and $8.75D \times 45^\circ$) produced performance deteriorations in the main experiment, low blur magnitudes ($2.25D \times 45^\circ$ and $3.25D \times 45^\circ$) did not show any evidence for being different. The first control experiment was conducted to put an upper bound on the magnitude of induced blur necessary for the buzz-wire task performance to significantly depart from the baseline no-blur viewing condition. Towards this end, 6 participants repeated the buzz-wire task (three of whom were already part of the main experiment) with the following magnitudes of isometropic spherical blur introduced before their eyes in randomized order: 1.25 D, 2.25 D, 3.25 D, 4.25 D, 5.25 D and 6.25 D. All other details were the same as the main experiment.

The averaged data of the 6 participants (Figure S1, top row) and the individual data of each participant (Figure 7, 2nd to 7th rows) shows a trend of increasing error rates (Figure S1, left column) and error duration (Figure S1, middle column) with increasing magnitudes of induced spherical blur in the binocular buzz-wire task. Speed did not appear to be altered with increase in the spherical blur (Figure S1, right column). One-factor RM-MANOVA showed a significant main effect of blur magnitude on the combined outcome variables ($p < 0.001$). Univariate analyses confirmed that this effect was due to the worsening of the error rate ($p = 0.003$) and error duration ($p < 0.001$). Post-hoc Bonferroni analyses revealed significant difference in performance between baseline viewing and with 6.25D of induced blur (error rate: $p = 0.04$; error duration: $p = 0.003$). No other pairwise comparisons reached statistical significance.

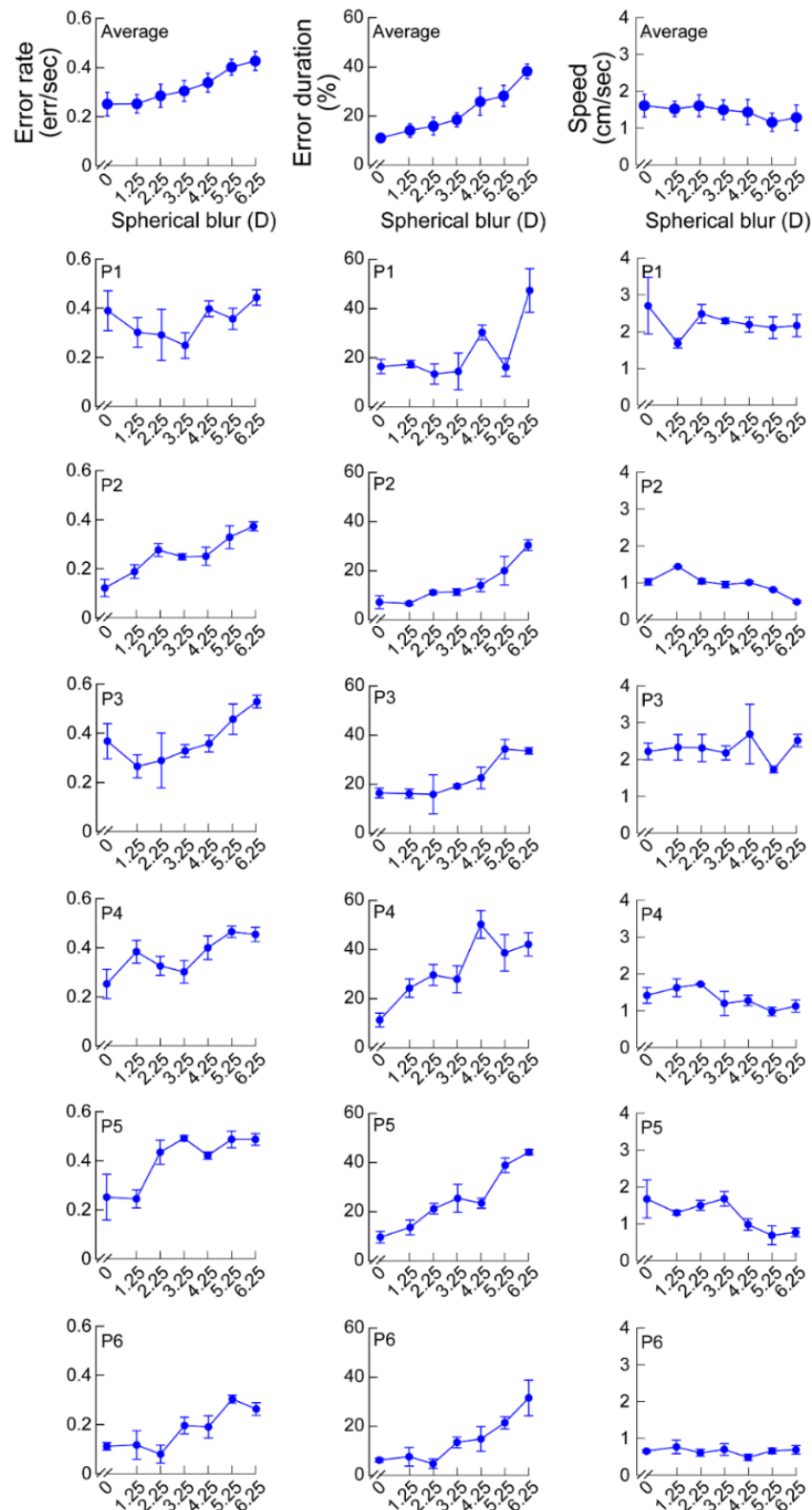


Figure S1: Error rate (panel A), error duration (panel B) and speed (panel C) plotted as a function of the induced isometric spherical blur in the first control experiment of this study. The top row shows average data across all participants, and the remaining rows show data from the individual participants. The lines connecting the dots are included only to help readers easily follow the data trends across different trials. The error bars in the top row represent the ± 1 SEM across the mean data of all participants, while they represent the ± 1 SEM across the three repeated trials in the individual participants.

Supplement II

In the main experiment, each participant repeated the buzz-wire task 48 times, even while the order of the experimental conditions was randomized within and across participants. To address the potential impact of practice on the outcome measures, the second control experiment was performed wherein 6 new participants repeated the task 24 times each under binocular and monocular viewing conditions using the same buzz-wire pattern. This task was performed with no additional blurring lenses. Participants P1, P2 and P3 performed the task binocularly first while participants P4, P5 and P6 performed the task monocularly first. The binocular and monocular versions of the task was performed on two separate days to avoid fatigue. All other details were the same as the main experiment.

Figure S2 plots the average (panel A) and individual (panels B – G) data of error rate (left column), error duration (middle column) and speed (right column) as a function of the trial number under binocular and monocular viewing conditions. The binocular data qualitatively showed a small improvement in error rate and error durations with increasing trials in the initial (Figure S2), but the 2-factor RM-MANOVA did not show any statistical significance in these trends. Inspection of the individual data reveals that this trend of improvement in task performance was present only in 3 subjects (P1, P2 and P3) and that too only under binocular viewing conditions of the initial trials. Binocular and monocular speed did not show any trend with increasing trial numbers (Figure S2). As expected, the univariate analysis showed statistically significant impact of viewing condition on all three outcome variables ($p \leq 0.007$, for all variables).

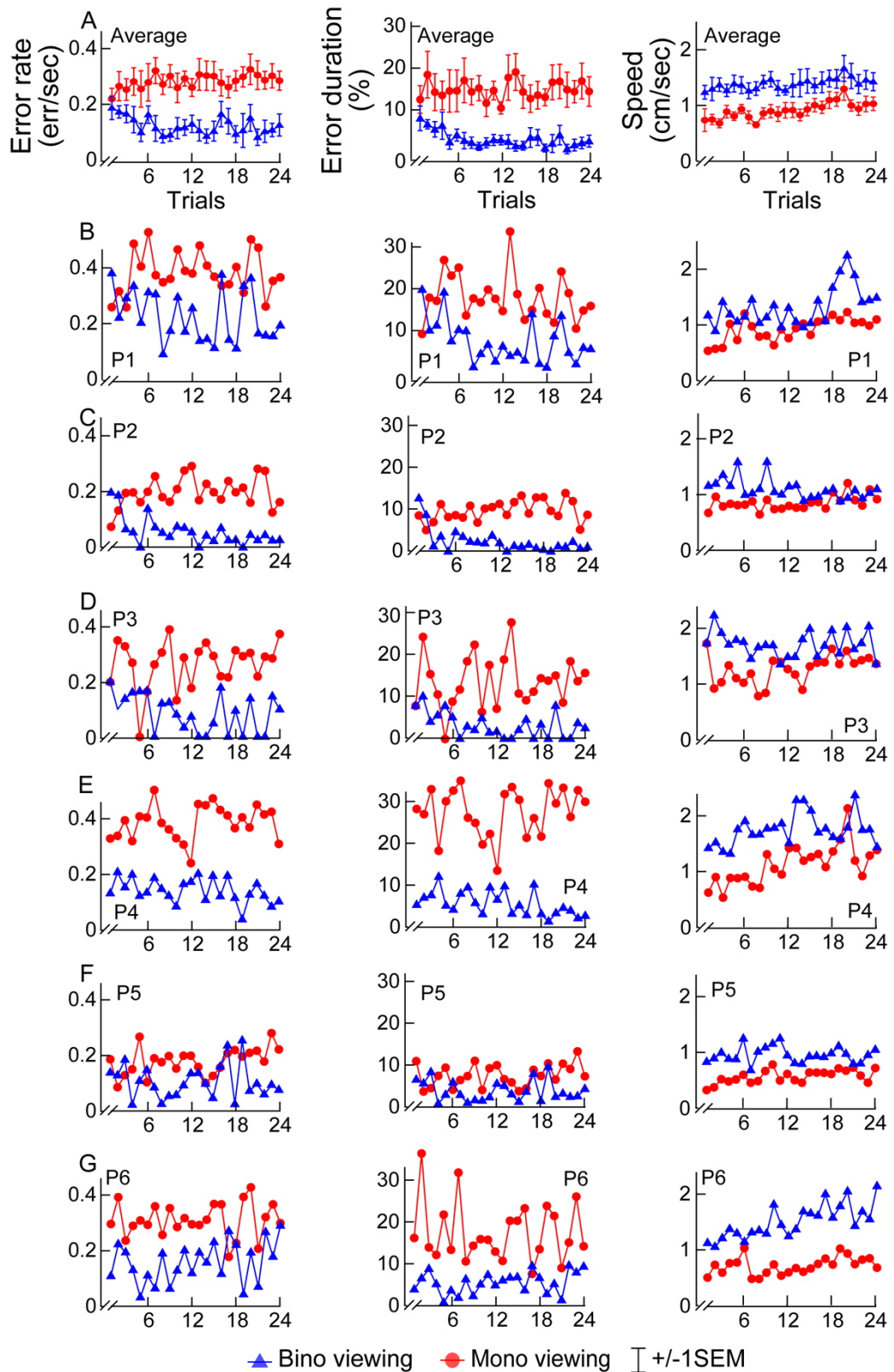


Figure S2: Binocular and monocular error rate (left column), error duration (middle column) and speed (right column) plotted as a function of the repeated trials in the second control experiment of this study. The top row shows average data across all participants and the remaining rows show data from the individual participants. The error bars in the top row represents the ± 1 SEM across the mean data of all participants across each trial.