Visual Psychophysics and Physiological Optics

Binocular Summation Improves Performance to Defocus-Induced Blur

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AQ: 1

PURPOSE. To assess whether there are any advantages of binocular over monocular vision under blur conditions.

METHODS. The effect of defocus, induced by positive lenses, was measured on the pattern reversal visual evoked potential (VEP) and on visual acuity (VA). Monocular (dominant eye) and binocular VEPs were recorded from 13 volunteers (average age, 28 ± 5 years; average spherical equivalent, -0.25 ± 0.73 D) for defocus up to 2.00 D using positive powered lenses. VEPs were elicited using reversing 10 arcmin checks (4 reversals/s). The stimulus subtended a circular field of 7° with 100% contrast and mean luminance 30 cd/m². VA was measured under the same conditions using ETDRS charts. All measurements were performed at 1 m viewing distance with best spectacle sphero-cylindrical correction and natural pupils.

RESULTS. With binocular stimulation, amplitudes and implicit times of the P100 component of the VEPs were greater and shorter, respectively, in all cases than for monocular stimulation. Mean binocular enhancement ratio in the P100 amplitude was 2.1 in focus, increasing linearly with defocus to be 3.1 at +2.00 D defocus. Mean peak latency was 2.9 ms shorter in focus with binocular than for monocular stimulation, with the difference increasing with defocus to 8.8 ms at +2.00 D. As for the VEP amplitude, VA was always better with binocular than with monocular vision, with the difference being greater for higher retinal blur.

CONCLUSIONS. Both subjective and electrophysiological results show that binocular vision ameliorates the effect of defocus. The increased binocular facilitation observed with retinal blur may be due to the activation of a larger population of neurons at close-to-threshold detection under binocular stimulation. (*Invest Ophthalmol Vis Sci.* 2011;52:000–000) DOI:10.1167/iovs.10-6545

Several features of visual perception, such as target detection and resolution[1-3] and motion detection,[4,5] are hampered in the presence of blur. Moreover, although there is a characteristic attenuation in retinal image contrast and the modulation transfer function[6,7] with increasing amount of defocus blur, its effect on spatial visual performance is variable, depending on the spatial characteristics of the target under observation (i.e., spatial frequency content, form, luminance, and color) and the methodology or task used. Visual acuity (VA) is more seriously affected by defocus when using letters than gratings,[8] and the loss in contrast sensitivity with defocus is spatial frequency dependent, being greater for higher spatial frequencies than for low ones.[9-13]

The deterioration in retinal image quality with defocus is dependent on a range of optical factors, such as pupil size,[9,14-16] the Stiles-Crawford effect,[17,18] and the type and amount of coexisting monochromatic and chromatic ocular aberrations.[17-21] Tolerance to defocus is also affected by retinal and neural factors. There is evidence of increased tolerance to defocus at low luminances.[22] Moreover, low-vision patients can tolerate higher levels of blur than normals.[11]

The vast majority of the above studies have investigated blur tolerance under monocular viewing conditions, which cannot incorporate the neuronal integration of information from the two eyes. However, there is strong psychophysical evidence that performance is better under binocular observation. Assuming that the visual system integrates both signal and uncorrelated noise from the two eyes, Campbell and Green[23] proposed a physiological model giving a linear binocular summation ratio (the ratio of binocular to monocular sensitivities) of $\sqrt{2}$, greater than that predicted by probability summation.[24] Succeeding psychophysical studies have shown that binocular overlap enhances contrast sensitivity[25-28] and perceived suprathreshold contrast,[29,30] with the summation ratio for normal observers being approximately 1.4 ($\sqrt{2}$)[25-28] or higher.[29-31] The improvement in VA with binocular viewing at high contrast is less evident, ranging from 5% to 13%.[26,32-34]

The binocular interaction in spatial visual performance has also been studied using pattern reversal visual evoked potentials (VEPs). For example, the amplitude in the binocular VEP P100 component (or the visual evoked response [VER]) is 25%-130% higher than the corresponding amplitude in the better eye or the mean of the two monocular responses.[32,35-42] Binocular facilitation is more pronounced as stimulus contrast increases[40,41] and for small check sizes and midspatial frequencies.[36,43] The effect of binocular stimulation on the P100 latency has been rarely investigated, showing a weaker effect than the P100 amplitude.[36,38]

VEPs have also been measured under conditions of retinal blur. Sokol and Moskowitz[44] and Bobak et al.[45] found a linear correlation between prolonged P100 latencies and the amount of defocus, with the effect being more pronounced the smaller the size of the checks. Similar results have been shown for the P100 amplitude.[46-48]

The aim of this study was to assess whether there are any advantages of binocular over monocular vision under conditions of blur. To do so, we measured the effect of defocus, induced by positive lenses, on the pattern reversal VEP and on high-contrast VA.

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METHODS

Subjects

Thirteen volunteers (4 females, 9 males) with an average age of 28 ± 5 years (range, 20–40 years) participated in the study. Exclusion criteria included spectacle-corrected VA worse than 0.00 logMAR in each eye, hyperopia > 0.50 D, myopia > 2.00 D, astigmatism > 0.50 D, anisometropia > 0.50 D, abnormal phorias, and any history of refractive or other ocular surgery. Average spherical equivalent was -0.25 ± 0.73 D (range: +0.50 to −2.00 D). Verbal consent was obtained from all participants after they had received an oral explanation of the nature of the study. The study was conducted in adherence to the tenets of the Declaration of Helsinki and followed a protocol approved by the University of Crete Research Board.

Procedure

Both VEP and VA measurements were performed at 1.0 m distance, monocularly (dominant eye) and binocularly, with best spectacle sphero-cylindrical correction and natural pupils. Eye dominance was determined by looking through a central hole in an A4 card, held by the participant in both hands away from the body. During the monocular measurements the nondominant eye was covered with an eye patch. Blur was induced using positive spherical powered lenses up to +3.50 D on top of the subjects' correction (corresponding to up to 2.50 D defocus at 1.0 m viewing distance) inserted in a trial frame at 12 mm vertex distance. Power intervals were 0.50 D for lenses up to 1.00 and 0.25 D for lenses between 1.00 and 2.50 D. However, since most subjects showed very noisy monocular VEP responses at 2.50 D defocus, only data up to 2.00 D defocus are presented. The order of viewing testing (monocular versus binocular) and the test method used first (VA versus VEP) were randomized.

VEP Recordings

Recordings of VEPs took place in low photopic lighting conditions (illuminance at cornea was 5 lux) in a sound-attenuated room. Average pupil diameter was 5.7 ± 0.4 and 5.3 ± 0.4 mm under monocular and binocular viewing, respectively. VEPs were elicited using reversing 10 arcmin (3 cpd) checks at a rate of 4 reversals/s (2 Hz) with square wave modulation. Larger check sizes are known to be almost unaffected by defocus.[44,45] The stimulus was displayed on a monitor (Sony GDM F-520 CRT; Sony, ~~CITY, STATE~~) by means of a stimulus generator card (VSG 2/5; Cambridge Research Systems Ltd, Cambridge, UK). The stimulus subtended a circular field of 7° with 100% contrast and a constant mean luminance of 30 cd/m². The circular field was surrounded by a background of the same mean luminance and color (illuminant C; chromatic coordinates, $x = 0.310$, $y = 0.316$). Fixation was achieved using a centrally placed cross.

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VEPs were recorded using silver-silver chloride electrodes. An active electrode was positioned 10% of the distance between the inion and the nasion over the vertex and referenced to an electrode placed at Fz with a ground electrode placed on the forehead. The active and reference electrodes were applied to the head with electrode paste after the area had been thoroughly cleaned. Trigger synchronization was achieved (CED 1401 "micro"; Cambridge Electronic Design, Cambridge, UK). The waveforms were amplified (gain = 10 K) using the CED 1902 (Cambridge Electronic Design). Amplifier bandwidth was set at 0.5–30 Hz (together with a 50 Hz notch filter), and signals were sampled at a rate of 1024 Hz with an analysis time of 0.970 seconds. Data acquisition and averaging were controlled using the commercial software (Signal v. 3.1; Cambridge Electronic Design). Each VEP trace was the average of 64 epochs of 1 second duration each, as suggested by the International Society of Clinical Electrophysiology of Vision (ISCEV).[49] Computerized artifact rejection was performed before signal averaging, according to standard ISCEV guidelines,[50] to discard epochs in which deviations in eye position, blinks, or amplifier blocking occurred.

Scoring of P100 amplitude and latency was calculated on the average waveform. It required manual definition of the lowest negative peak (N75) before P100 peak. Amplitude was scored as the difference between these two points and latency as the time difference between P100 peak and stimulus onset.

Visual Acuity Recordings

VA was assessed with the best-spectacle sphero-cylindrical correction (LogMAR 2000 "new ETDRS" charts; Precision Vision, ~~CITY, STATE~~) at 1.0 m distance with room lights on (chart background luminance was 70 cd/m²; illuminance at cornea was 75 lux). Average pupil diameter (measured using a video camera providing a ×2.8 magnified image of the eye) was 4.7 ± 0.4 and 4.2 ± 0.4 mm under monocular and binocular viewing, respectively. Chart 1 and chart 2 were used for recording VA of the dominant eye and of both eyes, correspondingly. All subjects were asked to identify each letter one by one in each line starting from the upper left-hand letter, and to proceed by row until they could no longer name correctly at least one letter in a line. They were instructed to read slowly and guess the letters when they were unsure. The termination rule for stopping was four or five mistakes on a line. The experimenter scored correct responses on specially designed data forms. VA was derived from the calculation of missed letters up to the last readable line.

RESULTS

Figure 1 shows the effect of positive defocus on mean VA for binocular and monocular vision. There is a strong relationship   **F1**
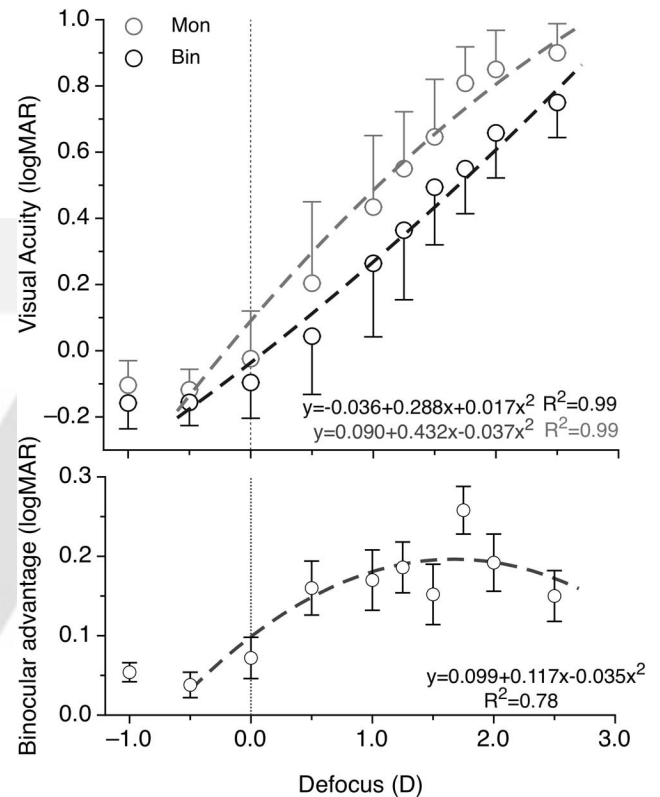
FIGURE 1. *Upper*: mean logMAR acuities at 1.0 m from 13 participants as a function of defocus under binocular (*black circles*) and monocular (*gray circles*) vision; *lower*: difference between binocular and monocular logMAR acuity. Participants wore best spectacle corrections for distance. The bars indicate ± 1 SD (*upper*) and ± 1 SE (*lower*). The equations and the *dashed lines* show second-order regressions. ~~VA of 50 and 10 letters corresponds to 0.0 and 0.8 logMAR, respectively.~~ Note that 0.0 D defocus blur at 1 m viewing distance is achieved using a +1.00 D lens. Moreover, it is possible that subjects may have been able to accommodate to compensate for the negative defocus.

between VA and defocus, with VA decreasing by approximately 0.36 logMAR (18 letters) and 0.24 logMAR (12 letters) per diopter under monocular and binocular viewing, respectively (coefficient of determination R^2 equals 0.99 in both viewing conditions). VA is better with binocular than with monocular observation ($P < 0.01$ at all defocus levels; paired Student's t-test), with the improvement being 0.07 logMAR (13%) at 0.00 D defocus and increasing to 0.26 logMAR (81%) at +1.75 D defocus. The binocular advantage attenuates at a higher level of defocus (0.19 logMAR at +2.00 D and 0.15 logMAR at + 2.50 D). The difference between binocular and monocular logMAR acuity is fitted with a second-order regression ($R^2 = 0.79$) (a linear regression results in a R^2 of 0.54). Note that it is possible that subjects may have been able to accommodate to compensate for the negative defocus when adding lenses between 0.00 and 1.00 D at the 1.0 m testing distance.

Figures 2 and 3 show the effect of defocus on the P100 component of the VEP. P100 amplitude decreases with increasing amounts of defocus (Fig. 2), and P100 latency increases with increasing retinal blur (Fig. 3). The amplitudes and the implicit times of the P100 component of the VEPs are greater ($P < 0.05$ at all defocus levels; paired Student's t-test) and shorter ($P < 0.05$ only at 1.00 to 1.75 D defocus; paired Student's t-test), respectively, with binocular stimulation than

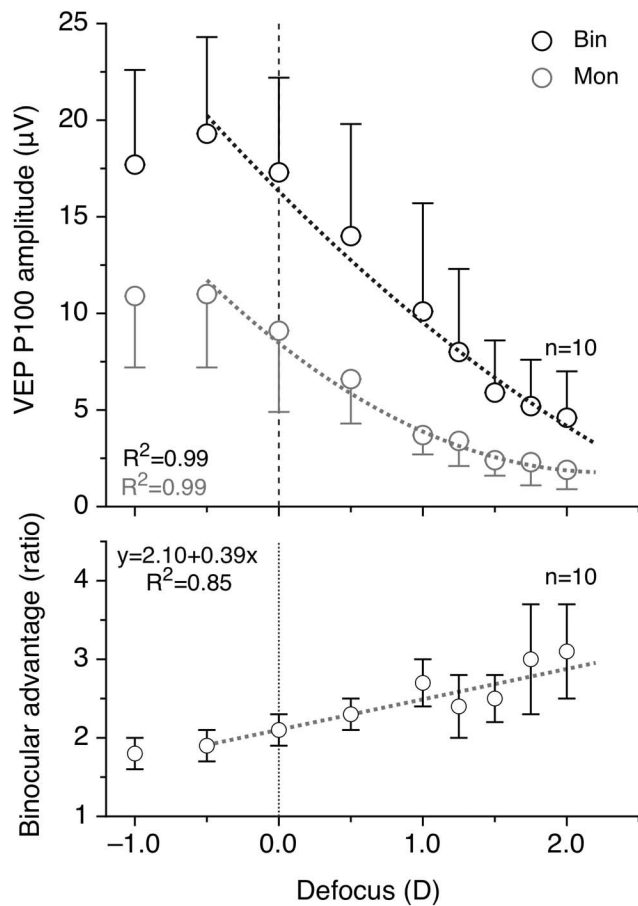**Figure 2.** *Upper:* mean amplitude (in μV) of the VEP P100 component from 13 participants ($n = 10$ for +2.00 D defocus) as a function of defocus under binocular (*black circles*) and monocular (*gray circles*) stimulation; *lower:* mean binocular advantage (ratio) in the VEP P100 amplitude as a function of defocus. The bars indicate ±1 SD (*upper*) and ±1 SE (*lower*). The *dashed lines* form second-order (*upper*) and linear (*lower*) regressions. Note that 0.0 D defocus blur at 1 m viewing distance is achieved using a +1.00 D lens. Moreover, it is possible that subjects may have been able to accommodate to compensate for the negative defocus.
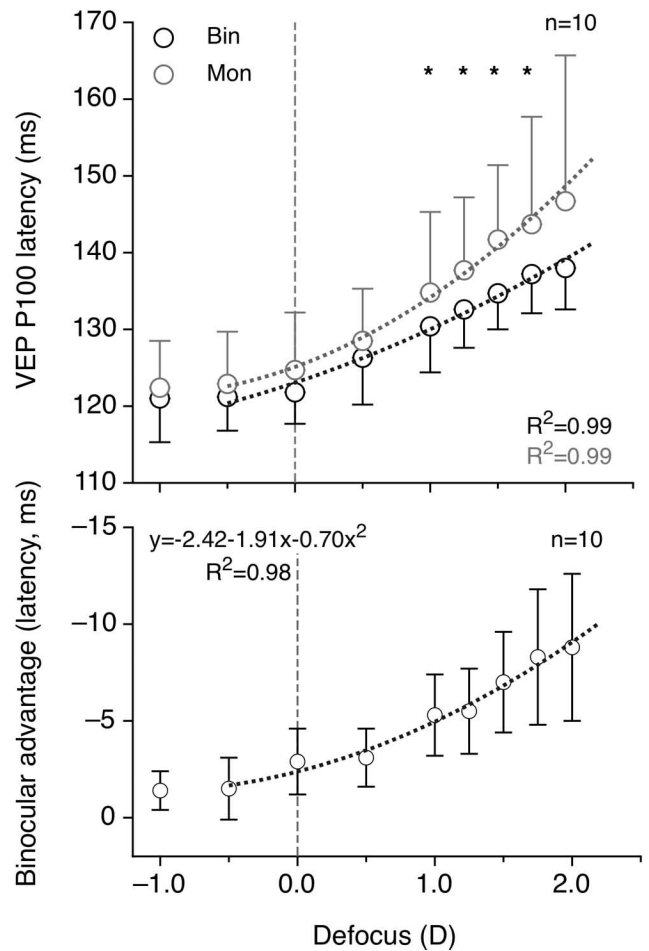
Figure 3. *Upper:* mean latency (in ms) of the VEP P100 component from 13 participants ($n = 10$ for +2.00 D defocus) as a function of defocus under binocular (*black circles*) and monocular (*gray circles*) stimulation; (*lower*) mean binocular advantage (latency) in the VEP P100 amplitude as a function of defocus. The bars indicate ±1 SD (*upper*) and ±1 SE (*lower*). The *dashed lines* form second-order regressions. The *asterisk* indicates significance at the 5% level.

for monocular stimulation, with these effects becoming greater as defocus increases. The mean (± SE) of the binocular enhancement ratio (the ratio of binocular to monocular amplitude) in the P100 amplitude increases linearly from 2.1 (±0.2) in focus to 3.1 (±0.6) at +2.00 D defocus. The mean peak latency is 2.9 ms (±1.7) shorter at 0.00 D defocus with binocular than for monocular stimulation, with the difference increasing to 8.8 ms (± 3.8) at +2.00 D. The binocular-monocular difference in VEP latency versus defocus is best fitted with a second-order polynomial ($R^2 = 0.98$).

Figure 4 compares binocular and monocular VEP amplitudes and latencies of the P100 component for the range of defocus levels tested with corresponding logMAR acuities. VEP amplitude is best correlated with the square of VA ($R^2 = 0.68$ and 0.60 for monocular and binocular stimulation, respectively). On the other hand, VEP latency shows a linear correlation with VA ($R^2 = 0.53$ and 0.71 for monocular and binocular stimulation, respectively).

DISCUSSION

This study shows, for the first time, that binocular vision ameliorates the effects of retinal blur on spatial visual perfor-
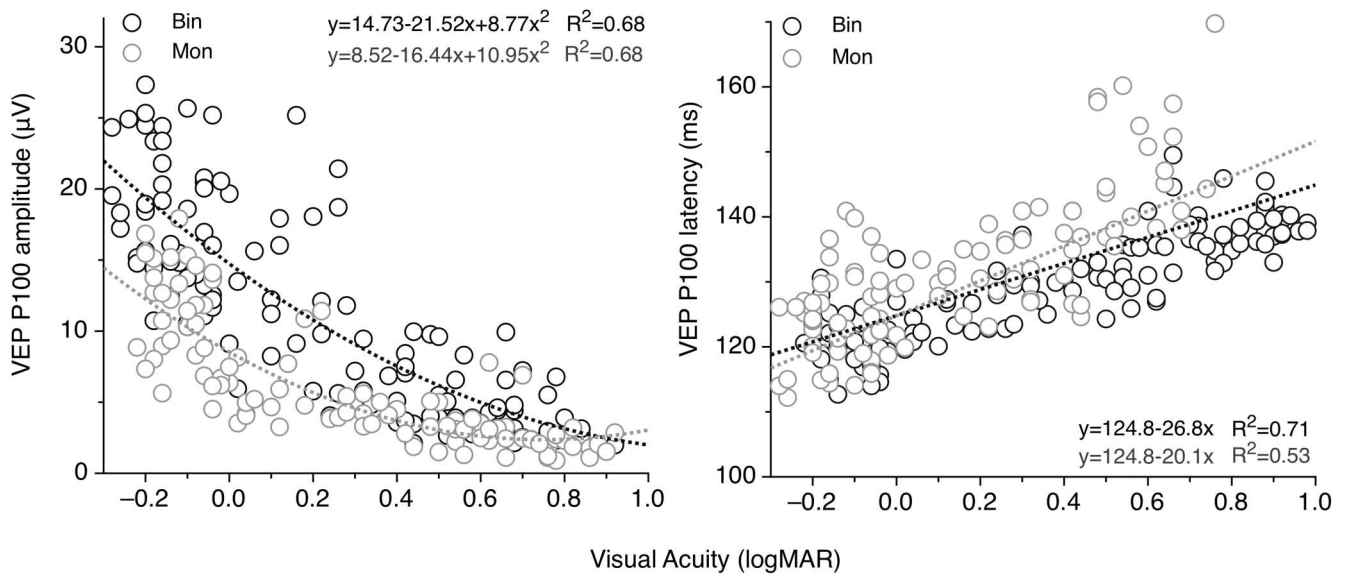
FIGURE 4. Comparison of binocular (*black circles*) and monocular (*gray circles*) VEP P100 amplitudes (*left*) and latencies (*right*) with logMAR acuity for 13 participants for all levels of defocus blur. The *dashed lines* correspond to best-fit second-order polynomials (*left*) and linear regressions (*right*).

mance. This was tested using two different performance measures: suprathreshold responses of the pattern reversal VEP and high-contrast letter acuity.

It is interesting that binocular facilitation increases with the amount of induced defocus. The binocular summation ratio in VEP P100 amplitude was correlated linearly with defocus. Similarly, VEP P100 latency was prolonged under monocular compared to binocular stimulation, with the delay being more pronounced the higher the shift from optimal focus. The binocular superiority in conditions of blur was also observed in the VA task (ranging from 1.18 D in focus to 1.81 at 1.75 D defocus).

An obvious question is: "What are the neural mechanisms underlying the binocular facilitation under conditions of retinal blur?" The diminished VEP responses as a function of monocular defocus can be attributed to optical factors: increased retinal blur leads to attenuation of image contrast and an overall loss in its modulation transfer function.[6,9,11,20] It is notable that binocular facilitation, as evaluated with electrophysiological studies in humans, is more evident as stimulus contrast decreases[40,41] and that the response versus contrast slopes are steeper under binocular than under monocular observation.[41] The binocular superiority for low contrast stimuli has also been shown in Vernier acuity.[51] There is physiological evidence[52] that, under binocular stimulation, cells in the cat's striate cortex show enhanced contrast sensitivity. Moreover, low (close-to-threshold) contrast detection activates more cortical neurons showing facilitatory interactions.[52]

All participants in this work were young people with normal binocular vision. Binocular summation under in-focus conditions decreases with aging, reflecting deterioration in cortical activity, and/or an increasing interocular difference in spatial performance, with the better eye dominating the overall visual performance.[28,31,53] Binocular summation is expected to be hampered in the presence of inhibitory conditions such as amblyopia.[39,54,55]

In the absence of blur, the average binocular enhancement ratio for the amplitude of the VEP P100 component was 2.1. This agrees with ratios reported in previous electrophysiological studies,[32,35–42] which ranged from 1.3 to 2.5, varying with observer, stimulus characteristics, and recording techniques.[36] Facilitatory interaction between the signals from the two eyes

is supported by electromyography[56] and single-cell electrophysiology, demonstrating that binocular interactions exist at the level of single cortical cells[57] and that a larger population of neurons contributes to contrast detection under binocular stimulation.[52] The higher binocular summation ratio found in this and earlier VEP studies, compared to the typical "neural summation" ratio of 1.4 ($\sqrt{2}$) reported in human psychophysical threshold-based work,[23,27] may be a result of the different populations of neurons responsible for threshold and suprathreshold perception.[58–60] Higher summation ratios have also been revealed in masking experiments.[30,61]

In the absence of blur, the improvement in high-contrast VA with binocular observation was significantly lower than that occurring for VEPs, on average being 0.07 logMAR in focus (summation ratio 1.18). Small amounts of binocular interaction for high-contrast targets have also been reported in previous studies.[26,32,33] with binocular superiority improving over that predicted by probability summation as letter contrast decreased.[26]

A limitation of this study is that only positive spherical defocus blur was used and that optical factors, such as pupil size and accommodation, were not controlled. Usually the degradation in spatial visual performance is more rapid in the positive than in the negative direction.[15,62–64] This is attributed to positive spherical aberration, which occurs in most unaccommodated eyes,[65,66] ameliorating the effect of negative defocus on VA. Intersubject variability in spherical aberration may account for some of the intersubject variability observed in the effect of defocus, especially on VEP responses, since recordings were performed for larger pupil sizes compared to VA.

Average pupil diameter was smaller under binocular compared to monocular viewing conditions in VA and VEP recordings by 0.5 and 0.4 mm, respectively, in close agreement with a previous study.[67] It is expected that a smaller pupil with binocular vision would have little effect when in focus, but would result to a better vision for defocus-induced blur. To estimate the effect of the difference in pupil diameter between the two conditions on binocular advantage, we used data from a previous study.[68] We calculated that a 0.5 mm reduction in pupil diameter would explain only 0.02 logMAR of the 0.17

logMAR and 0.19 logMAR superiority of binocular vision at 1.00 and 2.00 D defocus, respectively.

In conclusion, this study has demonstrated that binocular observation, compared with monocular observation, ameliorates the influence of blur on visual performance as measured by VA and the visual evoked potential. The increased binocular facilitation observed with retinal blur may be due to the activation of a larger population of neurons at close-to-threshold detection under binocular stimulation. Further investigation of the relationship between binocular facilitation and blur using other measures of visual performance is needed.

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TABLE OF CONTENTS PRECIS BLURB

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