Investigation of interocular blur suppression using luminance-modulated and contrast-modulated noise stimuli

Akash S. Chima
Anglia Vision Research, Anglia Ruskin University, Cambridge, UK

Monika A. Formankiewicz
Anglia Vision Research, Anglia Ruskin University, Cambridge, UK

Sarah J. Waugh
Anglia Vision Research, Anglia Ruskin University, Cambridge, UK

Presenting two sufficiently dissimilar images, one to each eye, may result in interocular suppression. The present study measured interocular suppression depth and extent in binocularly normal participants when blurring one eye only with varying dioptric lens powers (+0.5, +1, +2, and +4 D). Visual stimuli consisted of eight concentric rings of alternate polarity, divisible into eight sectors, within the central circular 24° visual field. Binocular “ring” stimuli therefore consisted of 64 individually testable dichoptic sectors. Using a two-alternative forced choice paradigm with a staircase procedure, signal strength of each dichoptic sector in the blurred eye was adjusted to perceptually match that of the surrounding ring from the nonblurred eye, determining the point of subjective equality. Rings were defined by differences in luminance (L), luminance-modulated noise (LM), or contrast-modulated noise (CM). Suppression depth was similar irrespective of sector location within the visual field and increased with increasing difference in interocular blur. Adding dynamic noise (LM vs. L stimuli) reduced the effect of blur on measured suppression depth. Significantly deeper suppression was measured for CM than for LM stimuli, both created using dynamic noise, the difference increasing at higher levels of interocular blur. As binocularity is disrupted with interocular blur, this result suggests that CM envelope combination may be processed by later mechanisms receiving binocular input than those required for the processing of LM stimuli. Differences in suppression depth between LM and CM stimuli could not be attributed to differences in spatial summation properties, stimulus visibility, noise modulation, or differential effects on blur discriminability.

Introduction

Different levels of blur presented to the two eyes create images that cannot be fused into a single percept. Diplopia and confusion ensue, and the input of one eye is suppressed (Harrad, Sengpiel, & Blakemore, 1996; Sengpiel & Blakemore, 1996; Sireteanu & Fronius, 1981; Travers, 1938). Interocular blur suppression can also occur pathologically in response to unequal refractive error, i.e., anisometropia (von Noorden, 1985) as well as in response to organic causes of interocular blur differences, such as monocular cataact, leading to form deprivation (Wiesel & Hubel, 1963a).

During visual development, disturbances of binocular vision, such as those mentioned above, may result in amblyopia (Daw, 2006; Hubel & Wiesel, 1965; von Noorden, 1974; Wiesel & Hubel, 1963b), which is characterized by deficits in many aspects of monocular spatial vision as well as binocular motion integration and stereoaucity (McKee, Levi, & Movshon, 2003). However, binocular function is not absent in amblyopia as D. H. Baker, Meese, Mansouri, and Hess (2007) measured normal central binocular summation in amblyopes when contrast strength in threshold units was equated between the eyes.

Monocular blur effects on normal vision have been found to mimic some aspects of spatial perception in anisometric amblyopia (Barbeito, Bedell, Flom, & Simpson, 1987; Formankiewicz & Waugh, 2013; Levi & Klein, 1985, 1990; Song, Levi, & Pelli, 2014). For example, Levi and Klein (1982a, 1982b) found the same relative differences in Vernier and grating acuities in
anisometric amblyopia. Therefore, if normal vision could be “scaled up,” for example, by using optical blur, spatial perception similar to anisometric amblyopes may occur. Additionally, Barbeito et al. (1987) found that reducing luminance levels (with neutral density filters) degraded optotype acuity of anisometric amblyopic eyes and monocularly blurred normal eyes similarly. Formankiewicz and Waugh (2013) recently reported that the ratio of visual acuity to the extent of crowding remains constant in monocularly blurred normals, and this result was confirmed in anisometric amblyopes (Song et al., 2014). Interestingly, a close relationship between this ratio and stereopsis, a binocular measure related to interocular suppression, was also noted. Song et al. (2014) further suggested that blur is a good model for purely anisometric amblyopia, which is mainly size limited, like normal central vision with added blur.

Pianta and Kalloniatis (1998) compared binocular suppression characteristics of monocularly blurred normals and anisometric amblyopes using a reaction time paradigm for the detection of a 0.65° dichoptically flashed test disc across different luminance levels. Similar reaction times were measured for the two groups, indicating similarity of interocular suppression characteristics. Physiological evidence also shows that rearing animals with monocular blur under binocular viewing conditions leads to anisometric amblyopia (Kiorpes, Kiper, O’Keefe, Cavanaugh, & Movshon, 1998; Maguire, Smith, Harwerth, & Crawford, 1982; E. L. Smith et al., 1997; E. L. Smith, Harwerth, & Crawford, 1985).

Clinical and experimental methods of measuring interocular suppression in amblyopia have been employed for more than 150 years (for review, see Joosse, Simonsz, & de Jong, 2000). Clinical techniques are generally insensitive and largely only detect, rather than quantify, foveal suppression. Suppression studies of anisometric amblyopia have shown a central circular loss in the visual field (Gottlob, Charlier, & Reinecke, 1992; Irvine, 1948; Sireteanu & Fronius, 1981; Sireteanu, Fronius, & Singer, 1981), which may also be expected with interocular blur suppression. Ideally, to assess real differences in suppression depth per se across the visual field, stimuli should be scaled to account for the larger spatial summation areas in the periphery. The task could also be made more comparable to real-world vision by employing suprathreshold contrast matching rather than threshold luminance detection during suppression (e.g., Barrett, Panesar, Scally, & Pacey, 2012; Joosse, Simonsz, van Minderhout, Mulder, & de Jong, 1999; Joosse et al., 1997). Finally, stimuli would be binocularly viewed with only a small dichoptic element tested to further simulate natural viewing conditions.

A new method of suppression mapping has satisfied some of these criteria (Babu, Clavagnier, Bobier, Thompson, & Hess, 2013). Suppression depth and extent was quantified using a method of adjustment and a suprathreshold interocular contrast matching task. Strabismic and nonstrabismic amblyopic participants decreased the signal strength in the nonamblyopic eye to match the surrounding ring seen by the amblyopic eye. Deeper suppression was measured centrally compared to peripherally.

All previous suppression studies have used visual targets that can be discriminated from their background by luminance differences. However, linear receptive fields of V1 are not able to detect stimuli without systematic differences in mean luminance (Chubb & Sperling, 1988). One example of a visible stimulus not defined by changes in mean luminance is a contrast-modulated noise (CM) stimulus, constructed by multiplying a square-wave envelope by a dynamic noise carrier rather than adding to it as is the case for a comparable luminance-modulated noise (LM) stimulus. The dynamic noise carrier would be detected by a multitude of early striate, high spatial frequency, linear mechanisms. For the CM stimulus, however, the envelope could not be extracted until after a subsequent nonlinear rectification stage by another lower spatial frequency linear filter (for review, see C. L. Baker, 1999; C. L. Baker & Mareschal, 2001). It is currently unclear where in the cortex the nonlinear rectification step occurs and whether the spatial mechanisms involved receive greater degrees of binocular input than do the simple linear mechanisms of early cortex that process LM stimuli (Allard & Faubert, 2006, 2007).


We aim to measure interocular blur suppression using LM and CM dynamic noise stimuli in order to determine whether clinical mapping of suppression using them might be valuable and to gain additional insight into the nature of CM stimulus processing. If they are more sensitive to interocular blur suppression, they may also hold significance for earlier detection of suppression and more sensitive monitoring of treatment in clinical conditions of degraded binocularity, e.g., amblyopia.

The existence of dynamic visible noise making up LM and CM noise stimuli may in itself affect
suppression measurements as target detectability (e.g., Nordmann, Freeman, & Casanova, 1992; Rovamo & Kukkonen, 1996; Schofield & Georgeson, 1999, 2003) and discriminability (Legge, Kersten, & Burgess, 1987) are reduced. It is also known (at least anecdotally) that clinical suppression depth is “broken down” by the introduction of temporal transients to the stimulus of the suppressed eye (also see Scheiman & Wick, 2008).

In this study, experiments are designed to map interocular blur suppression in participants with normal vision with increasing degrees of interocular blur, using luminance (L), LM, and CM stimuli. Interocular blur may simulate suppression that occurs in anisometropic amblyopia. Additionally, it provides insight into basic mechanisms of blur suppression, also encountered in monovision contact lens wear, with which vision is intentionally unbalanced, encouraging suppression to enable clear viewing across a wide range of viewing distances. First, suppression measurements are compared for L and LM stimuli to experimentally assess the effects that noise per se has on suppression depth. Second, comparisons are made between suppression maps for LM and CM stimuli. Depth and extent of suppression is measured across the central 24° of the binocular visual field. Deeper suppression measured for CM stimuli would provide evidence that these stimuli are processed by mechanisms optimally driven by coordinated binocular input, a potentially valuable finding both theoretically and clinically.

Methods

Participants

Four binocularly normal nonpresbyopic participants (two male and two female) participated; one was an author (ASC), and the others (SE, SP, and CP) were naive to the purpose of the experiments. Each participant wore his or her optimal refractive correction (all spherical equivalent refractive errors ≤ ±1 D). All participants had 6/5 or better corrected visual acuity in each eye and stereoacuity of at least 30 arcsec as measured with the Dutch Organization for Applied Scientific Research (TNO) stereo test (Lameris Ootech, Ede, The Netherlands). All participants were right eye dominant with the sighting dominance test (Fink, 1938). Informed consent was obtained from all participants, and the Anglia Ruskin University Research Ethics Committee approved the conduct of the research project, thus ensuring that the research complied with the tenets of the Declaration of Helsinki.

Equipment

Stimuli were generated with an Apple MacBook Pro (MacBook Pro; Apple Computer, Cupertino, CA) running Matlab (The MathWorks, Natick, MA) with Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). They were then presented on eMagin DualPro head-mounted organic light-emitting diode (OLED) displays (Dual Pro Z800; eMagin Corp., Hopewell Junction, NY) via a Matrox DualHead2Go adapter (Matrox Graphics, Inc., Quebec, Canada). These eMagin displays have been shown to have an 8-bit luminance capability with a linear response profile (Black, Thompson, Maehara, & Hess, 2011). However, luminance profiles obtained for each of our screens after 1 hr “warming up” showed poor linearity. We linearized and equalized the luminances of each screen by recording outputs with a ColorCAL II Colorimeter (Cambridge Research Systems, UK) and gamma-corrected look-up tables. In the worst case, 200 luminance steps were available to use such that each step resulted in a 1% change in luminance modulation of a 100% range. Thus there were at least seven possible luminance steps available within a detection threshold estimate and many more within a suprathreshold contrast matching estimate during the tasks. Cooper, Jiang, Vildavski, Farrell, and Norcia (2013) measured two similar Sony OLED displays and found minimal or no adjacent pixel spatial interactions with wide contrast ratios although this may vary across manufacturers.

One screen for each eye allowed for the dichoptic presentation of stimuli. Each screen had a resolution of 800 × 600 pixels, refresh rate of 60 Hz, and mean luminance 45 cd/m². The effective viewing distance was found to be 80 cm, and thus any blurring lens was added to the power of a lens with this focal length, i.e., +1.25 D, accounting for the amount of accommodation required for the viewing distance.

Stimuli

Schematics of the L, LM, and CM stimuli are provided in Figure 1A through F. L stimuli are similar to, but not the same as, those used in a recent study of amblyopic suppression mapping (Babu et al., 2013). Images presented to the left eye (Figure 1A, left) were fused with those presented to the right eye (Figure 1A, right) to give one fused cyclopean image.

For L (Figure 1A, B) and LM (Figure 1C, D) conditions, stimuli consisted of eight concentric rings. The central ring (a circle) had a radius of 0.75°. Each subsequent ring from the center was doubled in area, resulting in the outermost ring having a radius of 12°. The area of subsequent rings was doubled to account for larger spatial summation areas in the periphery.
relative to the central visual field. Figure 2 shows a schematic depiction of a fused L stimulus, in which sectors are delineated by black lines, showing 64 sectors in total. Sector orientation is defined by the blue dashed lines (not perceived by participants during experiments).

For the CM condition (Figure 1E, F), four rings were created covering the same 24° visual angle, making the sectors double the size of L and LM stimuli to account for larger spatial summation areas found foveally and peripherally for CM relative to LM stimuli (Sukumar & Waugh, 2007). Although different spatial summation areas have not always been found for foveally viewed stimuli, e.g., Schofield and Georgeson (1999), and spatial summation slopes (exponents of power functions fit to the data) are similar for LM and CM spatial stimuli (Wong & Levi, 2005; Sukumar & Waugh, 2007), Sukumar and Waugh (2007) were able to quantify critical summation areas out to 10° eccentricity, finding CM areas to be consistently larger. In the current study, we conduct a control experiment to show that this choice of differently sized sectors for different stimulus types does not affect experimental outcomes. The rate of constant about the mean luminance although the contrast of the high and low CM rings and the adjustable sector change. Thus, the difference between each ring is the modulation of contrast, rather than modulation of luminance. (A, C, and E) Green and red blind-spot markers for left and right eyes, respectively. All horizontal axes show horizontal pixel numbers. Ordinate axes vary as in (E and F).
fall-off with eccentricity in spatial summation is similar for LM and CM stimuli (A. T. Smith & Ledgeway, 1998; Sukumar & Waugh, 2007); thus the same scaling with eccentricity (i.e., sector area doubling) was used for all L, LM, and CM stimuli. Each ring for all stimulus types (L, LM, and CM) was divisible into eight sectors (as shown in Figure 2, black lines) so that any localized suppression scotomata, or orientation effects, could be revealed.

The following equation (Schofield & Georgeson, 1999) describes how L, LM, and CM stimuli were constructed:

\[ I(x, y) = I_0[1 + nN(x, y) + IL(x, y) + mnM(x, y)N(x, y)] \]  

where \( I(x, y) \) is the luminance at position \((x, y)\), and \( I_0 \) is mean luminance; \( n \) is noise contrast (set to 0 for L stimuli). Noise was different for LM \((n = 0.25) \) and CM \((n = 0.50) \) to give the largest adjustable modulation range available to each LM and CM stimuli. The effect of different LM and CM noise amplitudes is assessed in a control experiment (see Results). \( N(x, y) \) is the value of binary noise at position \((x, y)\), either \(-1\) (dark) or \(1\) (bright). The Weber contrast of the rings, \( l \), was set to 0.50 and \(-0.50\) for light and dark rings (Figure 1A, C), respectively, in relation to the mean luminance background. For each adjustable sector, \( l \) changed according to the participant response. The background provides the baseline from which modulation measures are taken. As LM and CM stimuli are varied in LM or CM, respectively, the rings and adjustable sector are quantified in terms of their “modulation,” i.e., \( I \) for L and LM stimuli or \( m \) for CM stimuli. Thus for L stimuli, \( n = 0, m = 0, \) and \( l \) is adjusted; for LM stimuli, \( n = 0.25, m = 0, \) and \( l \) is adjusted; and for CM stimuli, \( n = 0.50, l = 0, \) and \( m \) is adjusted.

For LM and CM stimuli, the noise check size was 4 \times 4 pixels with an angular subtense of 10 arcmin at 80 cm (equivalent viewing distance), clearly resolvable for all of our participants at all eccentricities tested (previous luminance resolution thresholds reported in the literature for a 12° eccentricity range from 2.5 to 6.3 arcmin, e.g., Anderson & Thibos, 1999; Ludvig, 1941; Millodot, Johnson, Lamont, & Leibowitz, 1975; Rovamo, Virsu, & Näätänen, 1978). The smallest sector has a radius of 0.75°. Kukkonen, Rovamo, and Näätänen (1995) found that, for binary noise to be effectively spectrally flat (i.e., white), a minimum of four noise checks per cycle of grating should be present. If one cycle of a grating is considered equivalent to two rings, this criterion is satisfied. Schofield and Georgeson (2003) found that noise type and amplitude had no effect on CM modulation sensitivity functions. For LM modulation functions, sensitivity was reduced when noise spectral energy was strongest. Therefore, spectrally broadband binary noise is sensible to use in the present study. Dioptric blur degrades energy more at high spatial frequencies; however, as the noise is broadband, energy existing at lower frequencies still supports both LM and CM stimuli. The effect of blur on specific stimulus detectability is examined in a control experiment.

Ten different spatial frames of stimuli were drawn after each participant response using randomly generated noise, which was always correlated between the eyes. These spatial frames were presented in a random order every two temporal frames to create dynamic noise. Head-mounted displays (HMDs) were running at 60 Hz with screens that were refreshed simultaneously, so each frame was presented for 33.33 ms. A. T. Smith and Ledgeway (1997) demonstrated the importance of using dynamic noise when investigating contrast-defined motion perception.

**Procedure**

Participants were instructed to look in the center of the binocularly viewed central ring (0.75° radius). Brightly colored blind-spot markers (1° diameter discs) were also presented 15° temporally on each screen along the horizontal midline (see Figure 1). If accurate fixation was not maintained, these markers became highly visible, no response was made, and participants were instructed to refixate before making a valid response. Furthermore, alignment calibration was performed during preliminary experiments to ensure binocular fusion. Two squares of 1° side length with centers vertically displaced by 1° were presented dichoptically (i.e., one square to each eye). If squares were horizontally offset, participants moved the squares using the keyboard until they were perceived as one above the other. Alignment in pixels was recorded, and the main experiment stimuli were moved accordingly. Binocular fusion was achieved in all participants in these experiments without adjustment (as they were binocularly normal).

Before testing began, participants were given a practice session with each type of stimulus until comfortable with the task, i.e., the standard deviation of staircases had stabilized to within 15% of the mean. In brief, a matching task allowed for measurement of the point of subjective equality (PSE) using a one up, one down staircase and a two-alternative forced choice (2AFC) psychophysical paradigm. The participant had to decide whether the stimulus strength of the sector to be judged in the fused stimulus was stronger or weaker than the surrounding ring. The variable sector was always presented to the blurred (nondominant) eye with the surrounding ring presented to the nonblurred (dominant) eye.

In more detail, the target was presented binocularly, excluding the sector to be adjusted (a sector to be adjusted is shown in the outer ring in Figure 1A, C, and
E), which was presented dichoptically. In the left (nondominant) eye, the ring that the sector was a part of was set to mean modulation while the adjustable sector varied in modulation according to the participant response. In the right (dominant) eye, the sector corresponding to that being adjusted was set to mean modulation while the surrounding ring was either a fixed increment (0.50) or decrement (−0.50) modulation. Both of these fixed deviations from the mean modulation are collectively known as the “baseline modulation,” which is 0.50.

One sector at a time was assessed, in L, LM, or CM modulation until the PSE was reached. This occurred when the adjusted sector (presented to the blurred eye) was perceived as having the same characteristics as the surrounding ring (presented to the nonblurred eye). Staircases were initiated randomly from either halfway between a true average and maximum modulation or halfway between a true average and minimum modulation. Preliminary experiments showed that for these suprathreshold contrast-matching stimuli, participants could not discriminate several 1% steps of modulation close to the PSE. To increase efficiency of the PSE estimation, step size was initially 0.10 (of a maximum 1.0 modulation range), reducing to a 0.05 step size after the first two staircase reversals. The PSE for each sector was calculated from the mean of the last four of six reversals. An audio cue signified a modulation change after each participant response. There was no time limit placed on judgments made. Participants were encouraged to take enough time as they felt necessary to make an accurate response. After the PSE was obtained for each sector, a longer audio cue of a lower pitch signified that a new sector was to be adjusted. No feedback was given, and the order of sector presentation was systematic and counterbalanced carefully parceling out the effects of practice, adaptation, and fatigue. Systematic presentation order reduced overall variability of responses and also alerted participants to the location of the patch.

Suppression mapping was performed for five levels of blur (no blur, +0.5 D, +1 D, +2 D, and +4 D) placed before the nondominant (left) eye. The no blur condition was used to provide a baseline measurement of suppression as participants did not all have a perfectly balanced interocular match, possibly due to sensory eye dominance. Some participants reported binocular rivalry for very differently presented luminances to the two eyes during pilot experiments, particularly for the most central sectors. In this case, participants were instructed to continue responding in the direction of adjustment until perception without rivalry was perceived, i.e., the modulation difference between adjustable sector and corresponding mean luminance became more similar. No rivalry was reported close to a perceived interocular match, which is reflected in the small staircase standard deviations. Therefore rivalry served as a cue to grossly bracket the interocular matching task in some (usually no and low blur) conditions, which was followed by adjustments relying on interocular suppression.

**Analysis**

Mean PSEs were obtained from four runs for each of the five levels of blur (including the no blur condition) across the three types of stimuli (L, LM, and CM) except for participant SE, who completed either two or three runs. Each participant therefore completed between 1,600 and 3,200 staircases (800–1,600 for participant SE). PSE modulation values are normalized across stimulus type using the following equation:

$$S_{\text{norm}} = \frac{M_{\text{match}} - M_{\text{baseline}}}{M_{\text{baseline}}}$$

where $S_{\text{norm}}$ is the normalized depth of suppression, $M_{\text{match}}$ is the PSE modulation, and $M_{\text{baseline}}$ is the baseline modulation. Depth of suppression is expressed as −1 to 1, where 1 is the maximum level of suppression (signal strength needed to be doubled for the sector in the blurred eye to match perception of the surrounding ring), 0 is an interocular match (signal strength is perceived as the same in each eye), and −1 is maximum binocular facilitation (signal strength in the blurred eye was reduced to minimum to match perception of the surrounding ring).

Pilot experiments showed that with high levels of blur, suppression was sometimes too deep to measure. Here, the staircase reached the maximum measurable normalized suppression value. If this occurred, $S_{\text{norm}}$ was set to the maximum value for analysis. After practice, in experiments, this occurred for participants CP, using CM stimuli for the +4 D blur condition, and SE, using LM stimuli for the +4 D blur condition. This is reflected by the lack of standard error bars for CP’s and SE’s set of data for those conditions.

**Results**

Mean depth of suppression averaged across all four observers is plotted using color-coded maps of the measured visual field for each monocular blur level in Figure 3. Each sector of the stimulus is represented by a color. Red denotes interocular suppression, i.e., the stimulus strength was increased in the blurred eye to obtain a binocular perceptual match. Green sectors show facilitation, i.e., the stimulus strength was decreased in the blurred eye to obtain a binocular perceptual match. Yellow sectors depict a perceived interocular match that occurred for equal stimulus strengths to each eye. The color bar to the right of
such that any level of blur led to statistically deeper suppression than the no blur condition. Overall, there was no significant effect of sector eccentricity, \( F(7.00, 3.73) = 1.64; p = 0.29 \), or orientation, \( F(1.70, 5.11) = 0.19; p = 0.80 \), and no higher-order interactions.

An a priori hypothesis was that increasing blur might lead to differential eccentricity effects on suppression, hence the overall analysis conducted above. In Figures 4, 5, and 6, data have been collapsed across orientation to visualize depth of suppression across eccentricity for L, LM, and CM stimuli, respectively.

### Suppression of L versus LM stimuli

In order to investigate the effects of noise itself on interocular blur suppression, the results for L and LM stimuli only were statistically compared. The repeated-measures ANOVA was performed with factors of stimulus type (two levels), blur (five levels), sector orientation (four levels), and sector eccentricity (16 levels). There was a significant main effect of blur, \( F(1.37, 4.11) = 15.59; p = 0.014 \), but no main effects of stimulus type, \( F(1.00, 3.00) = 2.09; p = 0.24 \), eccentricity, \( F(1.33, 4.00) = 1.83; p = 0.26 \), or orientation, \( F(1.53, 4.60) = 0.85; p = 0.45 \). There were also no significant higher-order interactions. Thus no localized regions of blur suppression occurred within the central 24°. Suppression values of some LM sectors with +4 D blur were above the measurable range for participant SE, which artificially reduces the variance for this level of blur. When the ANOVA was carried out without the +4 D data, statistical significance outcomes were unchanged.

To obtain relative depth of suppression values, depth of suppression averaged across eccentricity and orientation for each level of blur, for each participant, was subtracted from the respective no blur values. Mean relative depth of suppression data are plotted against level of blur in Figure 7 and fit with linear functions to provide an estimate of rate of increase in depth of suppression with increasing level of blur.

Slope values for each participant and averaged across participants are provided in Table 1. Absolute slope values are different for each participant, but they are always steeper for L than LM stimuli, and this difference in rate is statistically significant, \( F(1, 3) = 50.67; p = 0.006 \). Thus, noise reduces the effect of blur on measured depth of suppression. This difference is, on average, 0.045 ± 0.026 relative depth of suppression units per diopter.

### Suppression of LM versus CM stimuli

To compare interocular blur suppression for different types of spatial stimuli that use the same dynamic
noise, results obtained for LM and CM stimuli were statistically compared. Sectors for LM stimuli were averaged to match sector sizes for CM stimuli to allow for statistical comparison across stimulus type (two levels), blur (five levels), sector orientation (four levels), and eccentricity (eight levels).

There is a significant effect of stimulus type, $F(1,3) = 37.59$, $p = 0.009$, such that CM stimuli are suppressed more deeply than LM stimuli. There is also a significant effect of blur on depth of suppression, $F(1.83, 5.50) = 48.05$, $p < 0.0005$. As with the L versus LM comparison, comparing LM and CM stimuli showed

Figure 4. Average of all orientations (blue dashed lines, Figure 2) was taken for each level of blur for L stimuli, for participants (A) ASC, (B) CP, (C) SE, and (D) SP; error bars represent standard error. The mean across all participants is shown (E); error bars represent standard deviation across participants. Legend in (A) applies to (A through E).
no significant effects of eccentricity, $F(1.29, 3.86) = 1.47, p = 0.31$, or orientation, $F(1.52, 4.57) = 0.056, p = 0.91$, on measured depth of suppression, and there were no significant higher-order interactions. Results averaged across orientation are plotted across eccentricity for different blur levels in Figures 5 and 6 for LM and CM stimuli, respectively. With increasing interocular blur, depth of suppression increases approximately evenly across the visual field for both types of stimuli; however, suppression is deeper for CM stimuli. For participants SE (with LM stimuli) and CP (with CM stimuli), there were several sectors that required maximum modulation to be perceptually near a match for the highest level of blur, artificially reducing the variance of the data. Reanalysis without the +4 D blur data reveals that the significant effects of stimulus type,
$F(1, 3) = 18.98, p = 0.022$, and blur, $F(1.88, 5.64) = 18.00, p < 0.004$, still hold true.

To more clearly view the rate of change of suppression with increasing interocular blur, data are collapsed across all orientations and eccentricities for each participant and normalized by each participant’s no-blur depth of suppression measure to calculate a relative depth of suppression. The averaged data obtained across the four observers for each level of blur is shown in Figure 8. The results of linear fits are provided in Table 2. Again, although absolute slope values are different for each participant, slopes are consistently higher for CM stimuli, $F(1, 3) = 84.69, p = 0.003$. The difference between LM and CM slopes is, on

Figure 6. Average of all orientations (blue dashed lines, Figure 2) was taken for each level of blur for CM stimuli, for participants (A) ASC, (B) CP, (C) SE, and (D) SP; error bars represent standard error. The mean across all participants is shown in (E); error bars represent standard deviation across participants. Legend in (A) applies to (A through E).
average, $0.087 \pm 0.006$ relative depth of suppression units per diopter.

In these experiments, in order to attain equivalent modulation amplitude ranges, different amplitudes of noise were used (see Stimuli section). In addition, to more fairly compare suppression depths measured for LM and CM stimuli, different sector sizes were used to account for previously reported different summation areas for detecting the two types of stimuli (Sukumar & Waugh, 2007). Could these differences have accounted for our measured differences in suppression depth? Was the effect of dioptic blur different on visibility strength of suprathreshold LM and CM stimuli, accounting for increased suppression measured for CM stimuli? Control experiments were performed to determine whether our key result, that CM stimuli are more deeply suppressed with interocular blur than LM stimuli, was due to these other potential confounding factors.

**Control experiment 1: LM versus CM sector size**

Mean results for relative depth of suppression (relative to the no blur condition) for two participants (ASC and SP) for whom the size of LM sectors was doubled to match CM sector size and the size of CM sectors was halved to match LM sector size are shown in Figure 9. Each point represents the average of sectors of two full orientations. For both sizes of LM sectors, slope values were similar: $0.081 \pm 0.008$ for smaller and $0.088 \pm 0.019$ for larger sectors. Thus, the difference in measured suppression depth between LM and CM stimuli in the main experiment was not due to the difference in sector size. When CM sectors were made smaller (to match LM sector sizes in the main experiment), even higher slope values were found ($0.23 \pm 0.026$ vs. $0.18 \pm 0.010$), showing that reducing sector size can have the effect of increasing measured suppression depth.

**Control experiment 2: Visibility of LM versus CM stimuli**

Sensitivity to detecting CM stimuli is much lower than that for detecting LM stimuli (Schofield &

<table>
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<tr>
<th>Participant</th>
<th>Slope ± 1 SE for L stimuli</th>
<th>Slope ± 1 SE for LM stimuli</th>
<th>$L - LM$ slopes (± 1 SE)</th>
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<tr>
<td>ASC</td>
<td>0.16 ± 0.015</td>
<td>0.10 ± 0.012</td>
<td>0.06 ± 0.0096</td>
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<tr>
<td>CP</td>
<td>0.14 ± 0.033</td>
<td>0.099 ± 0.017</td>
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<td>SE</td>
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<tr>
<td>SP</td>
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<td>Mean</td>
<td>0.15 ± 0.042</td>
<td>0.11 ± 0.049</td>
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</table>

Table 1. Values for L and LM slopes and the difference between them for each participant with the mean (±standard error) for each participant and the mean across all participants (±standard deviation) in bold.
Georgeson, 1999). Could differences in strength of stimulus visibility (i.e., difference in modulation between the rings and background) between the LM and CM stimuli have resulted in different depths of suppression? Monocular detection thresholds for individual LM and CM sectors were measured for two participants (ASC and SP) for similar configuration stimuli to Figure 1C and E with same noise contrasts as were used in the main experiment. A three down, one up staircase with a 2AFC procedure was used in which participants monocularly viewed the concentric ring stimuli and, in each trial, indicated whether a near-detection sector was in one of two positions in the central ring. The sector was either to the right of the vertical midline in the superior half of the ring or directly opposite in the inferior half of the ring. An average of four measurements from each participant revealed that stimuli for the main experiments were 4.6× detection threshold for LM stimuli and 3.7× detection threshold for CM stimuli (see Figure 11B). Visibility of the LM stimulus was then reduced to 2× and 3.5× visibility and depth of suppression mapped across two full orientations for a +2 D interocular blur condition. Suppression depth did not change significantly with the reduction in LM stimulus visibility as shown in Figure 10. Thus, it is unlikely that our main result can be explained on the basis of differing stimulus visibility levels.

Control experiment 3: Discriminability of LM versus CM stimuli

Given that the main experimental task was a suprathreshold matching task, it is possible that blur had differential effects on discriminability rather than detectability of LM and CM stimuli, leading to a difference in measured suppression. To test this, two participants performed a contrast-discrimination task for LM and CM stimuli for no blur and +2 D binocular blur conditions. A method of constant stimuli was used to obtain a measure of discriminability from the psychometric function slope:

![Figure 8. Mean taken across each sector in the LM and CM stimuli for each level of blur (diopters). Data averaged across four participants are shown and fit with linear functions. LM is represented by blue and CM by red. Blue within red circles denote overlying points. Error bars show standard deviation.](image-url)
where $x_0$ is the offset of the error function ($\text{erf}$) along the abscissa and represents the stimulus matching point. Slope parameter $\beta$ represents discriminability. A 2AFC task was employed in which participants decided whether a peripheral or central sector was of higher or lower modulation than the surrounding ring.

Without blur, slopes were similar for LM (0.20 ± 0.05) and CM (0.25 ± 0.11) stimuli; with blur similarly for LM (0.19 ± 0.02) and CM (0.22 ± 0.03). Thus differences in measured depth of suppression between LM and CM stimuli found in the main experiment are not likely due to increased difficulty in detecting modulation change for CM versus LM stimuli.

Control experiment 4: The effects of noise amplitude and blur on stimulus visibility

Is the finding of deeper interocular blur suppression for CM stimuli dependent on the amplitude of noise used? In the main experiment, to ensure an equal range of measurable suppression depth, different noise amplitudes were required: 0.5 for CM and 0.25 for LM. A control experiment measured the effect of noise amplitude on relative depth of suppression of LM and CM stimuli with interocular blur. Two full orientations
of stimuli at each noise amplitude were measured and the average taken across all measured sectors (see Figure 11A). For LM stimuli, relative depth of suppression decreased as noise amplitude increased. The converse is true for CM stimuli. When noise amplitude is increased, relative suppression increases.

Stimulus detectability also varied with different noise amplitude (see Figure 11B). Detection thresholds were obtained in the same way as in Control Experiment 2. At low noise amplitudes, LM stimuli were more visible than CM stimuli, approaching similar visibility at 0.5 noise amplitude. As stated above in the main experimental condition (amplitudes of 0.5 for CM and 0.25 for LM), LM stimuli were slightly more visible (4.6 × threshold) than CM stimuli (3.7 × threshold). These visibility levels were quite robust to the effects of increasing levels of blur (see Figure 11C). Thus neither the increased interocular suppression measured with increasing levels of blur nor the significant differential effects of interocular suppression measured for LM and CM stimuli can be explained by differential stimulus visibilities.

Control experiment 5: The effects of interocular blur on stimulus visibility

Although we have shown so far that the effects of blur on overall stimulus visibility cannot explain measured differences in interocular depth of suppression found for LM and CM stimuli, they do not directly simulate experimental conditions in which a blurred stimulus and sector is combined with a nonblurred stimulus. Adding dioptric blur only to one image introduces differential stimulus magnification, which varies depending on what part of the lens the image enters (for a +5.25 D lens by a maximum of 8.7% centrally to 9.1% at 12°). Effective dioptric power also varies slightly across the lens (by 0.15 D at 12° or 2.85%) (Jalie, 2003). Despite these differences, our participants were able to align images successfully and make perceptual matches of the blurred sector to the surrounding ring for both LM and CM stimuli.

An ideal control would be to enable this to occur under monocular viewing conditions so that one could examine visibility and blur effects on the suprathreshold matching task itself for both LM and CM stimuli and compare the results to those performed dichopti-
In the Appendix, we show how we achieved monocular and dichoptic experimental setups, using matching CRT monitors and combinations of optical components. We assessed perceptual matches monocularly and dichoptically, with and without +2 D imposed blur. The results shown in Figure 12 suggest that (a) carefully calibrated CRT monitors arranged dichoptically produce deeper suppression for CM than LM stimuli in a manner similar to that measured with the virtual reality goggles, and (b) when arranged in monocular fashion, with blurred and nonblurred rings combined, a larger increase in modulation was required to perceptually match a blurred LM sector with the surrounding ring than was required to match a blurred CM sector with the surrounding ring, the opposite result to what is found for interocular suppression measurements.

Therefore, deeper interocular suppression of CM compared to LM stimuli cannot be explained by differences in target visibility with blur, noise level chosen, discriminability, or spatial summation properties.

Discussion

In this study, interocular blur suppression of L, LM, and CM stimuli during binocular viewing was measured in binocularly normal participants across the central 24° visual field. For the no blur condition, some participants showed mild suppression or facilitation rather than a perfect interocular match, suggesting that sensory eye dominance is being quantified. Li et al. (2010), using a dichoptic motion coherence paradigm to assess sensory eye dominance in a binocularly normal population, found a large minority (39%) with interocular imbalance.

Our results show no localized interocular blur suppression regions within the central circular 24° of the visual field measured. Simpson (1991), when measuring suppression at fixation, found a greater interocular blur difference (1.75 D) was required to cause suppression of a larger stimulus (triangles subtending 0.57°) than a 0.75 D blur difference required to suppress a smaller one (triangles subtending 0.28°). This result suggests that increasing interocular blur difference leads to increases in the extent of suppression. The present study, however, using sector sizes of 0.75° or larger, found no systematic change in the extent of suppression across the visual field with greater levels of interocular blur although increasing depth of suppression was measured.

Binocular rivalry alternations were reported centrally by some participants in the present study with no and +0.5 D blur. Binocular luster, for which uniform light and dark fields combine to produce a lustrous, metallic appearance (Helmholtz, 1925), may also be, in part, responsible for deeper central suppression measured with L stimuli rather than fusion and binocular brightness averaging (Levelt, 1965). This should only have contributed to responses at the largest modulation differences (Anstis, 2000). As these differences reduced near the PSE, binocular brightness averaging occurred, therefore, having minimal effect on measurement of depth of suppression.

Suppression of LM and CM stimuli

The present study is the first to compare interocular blur suppression across the visual field for LM and CM stimuli. Deeper suppression is measured for CM than for LM stimuli with increasing levels of blur.

It is thought that separate additional processing is required for detecting CM than LM spatial stimuli (Allard & Faubert, 2007; C. L. Baker & Mareschal, 2001; Ellemberg, Allen, & Hess, 2006; Mareschal & Baker, 1998; Schofield & Georgeson, 1999). Larsson, Landy, and Heeger (2006) found striate and extrastriate fMRI responses to be similar in magnitude for L stimuli; however, a larger extrastriate than striate response was evoked by CM stimuli, implying additional extrastriate processing present for CM stimuli. Similarly, monkey V2 cells respond to contours not defined by a change in luminance (Leventhal, Wang, Schmolesky, & Zhou, 1998; Peterhans & von der Heydt, 1989; von der Heydt, Peterhans, & Baumgartner, 1984) and, more recently, specifically with CM stimuli (Li et al., 2014) as found previously in cat (Mareschal & Baker, 1998).

It has also been suggested that CM stimuli engage more binocularly driven units in their processing than do LM stimuli (Hairol & Waugh, 2010; Wong et al., 2005).
The current results showing deeper interocular blur suppression for CM stimuli support this notion. Other differences in our LM and CM stimulus characteristics (sector size, stimulus strength), the effects of blur on stimulus visibility and on stimulus discriminability, were investigated and could not account for measurements of deeper suppression using CM stimuli.

The effect of blur on LM and CM stimuli

The low-pass filtering effect of blur may have affected LM and CM stimuli differently. Control experiments were performed in which a blurred sector was monocularly matched to a nonblurred surrounding ring. Relative modulation matches (differences between blurred sector and nonblurred surrounding ring modulation) were higher for LM than CM stimuli for the monocular task, different from the findings of the main experiment. The dichoptic control again showed deeper suppression for CM compared to LM stimuli, mirroring results of the main experiment. Thus, suppression measures cannot be explained by the effect of blur on the monocular perception of the stimuli and are specific to interocular blur suppression. This agrees with clinical findings in which interocular blur suppression occurs in successful monovision contact lens wear as blurred images at distance or near are not perceived (Collins & Goode, 1994; Kirschen, Hung, & Nakano, 1999; Simpson, 1991; Yang, Blake, & McDonald, 2010); rather suppression acts to negate perception of the blurred image.

Adding blur only marginally reduces the ability to extract second-order contrast-modulation information (the envelope), demonstrated by a small decrease in stimulus visibility. Monocular effects of blur on stimuli, i.e., low-pass filtering and contrast reduction, therefore cannot explain the increase in blurred eye signal required to overcome interocular suppression to obtain an interocular match. The first stage of linear processing in current filter-rectify-filter models (C. L. Baker, 1999; C. L. Baker & Mareschal, 2001; Y. Zhou & Baker, 1993) of second-order stimulus processing is little affected by blurring stimuli in the present study due to the broadband nature of the noise and the energy remaining after the effects of blur. It would be interesting to see how recent models of binocular combination of LM and CM stimuli (Ding & Sperling, 2006; Meese, Georgeson, & Baker, 2006) would deal with our interocular blur suppression and how they relate to findings in amblyopia (D. H. Baker, Meese, & Hess, 2008; Ding, Klein, & Levi, 2013a, 2013b); however, this is beyond the scope of the current paper. Recent literature suggests that because stereopsis (Wilcox & Hess, 1996) and binocular phase combination (J. Zhou, Georgeson, & Hess, 2014; J. Zhou, Liu, Zhou, & Hess, 2014) for CM stimuli are unaffected by interocular carrier correlation, extraction of CM envelope information occurs before binocular combination. More interestingly here, binocular combination for LM and CM stimuli appears to be different. The results of the current study suggest that extraction of the CM envelope occurs by units more sensitive to binocular disruption.

Blur as a model of anisometropic amblyopia

Although previous studies have found optical blur to be a good model for monocular spatial vision in anisometropic amblyopia (Barbeito et al., 1987; Levi & Klein, 1982a, 1982b; Pianta & Kalloniatis, 1998; Song et al., 2014), not all aspects of amblyopic perception are mimicked well by short-term application of blur. For example, Hess, Pointer, Simmers, and Bex (2003) showed that anisometropic amblyopes perceive sharp edges as sharp, as opposed to blurred, with an interocular blur-discrimination task, unlike normal participants blurred monocularly.

Babu et al. (2013), using L-only mapping stimuli, found deeper suppression centrally than peripherally in anisometropic amblyopes within the central 20° diametrical visual field. Our results averaged across four normal observers for interocular blur suppression show no localized suppression. Thus, monocular diplopic blur in binocularly normal adults might not be an accurate model for interocular suppression in anisometropic amblyopia. However, other small differences in target and experimental paradigm also exist between Babu et al.’s study and our own, which might influence the measured outcomes. For example, Babu et al. used a central black fixation dot only to monitor fixation, which may also have influenced central suppression assessment, and a method of adjustment to determine the perceptual matches, which is more prone to effects of visual adaptation. Only by using our stimuli and experimental paradigm on anisometropic amblyopes will it become clearer how well our interocular blur suppression results relate to suppression patterns found in anisometropic amblyopia.

Addition of noise

The addition of noise to L stimuli reduces the effectiveness of interocular blur suppression. Adding noise reduces stimulus visibility (see Figure 11B), which therefore may be expected to be more easily suppressed. Rather, our results show empirically that the presence of dynamic noise breaks suppression down, a finding known anecdotally to clinicians, perhaps through
mechanisms of flash suppression (e.g., Tsuchiya & Koch, 2005; Wolfe, 1986; Yang & Blake, 2012).

**Conclusion**

Interocular blur suppression operates broadly across the central 24° visual field rather than in localized areas. Suppression of CM stimuli is deeper than for LM stimuli and is more affected by increasing differences in interocular blur. This result suggests that CM stimuli may be processed by later, more binocular processing mechanisms than those required for the processing of LM stimuli. Similar to the binocularly normal participants with interocular blur differences in this study, unilateral amblyopes have disrupted binocularity and may show deeper suppression for CM than LM (or L) stimuli. The appropriate use of L, LM, and CM stimuli may therefore prove to be valuable in clinical mapping of interocular suppression in normal and anomalous spatial vision.

*Keywords: blur, interocular suppression, luminance-modulated noise, contrast-modulated noise, suppression mapping, binocular vision*

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Commercial relationships: none.
Corresponding author: Akash S. Chima.
Email: akash.chima@anglia.ac.uk.
Address: Anglia Vision Research, Anglia Ruskin University, Cambridge, UK.

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Appendix

The effect of blur on perception of CM relative to LM stimuli may have caused the different results for LM and CM stimuli. Therefore, a monocular control experiment was devised to see if similar results to the main experiment were obtained. If results are similar, differences in LM and CM results in the main experiment cannot be due to interocular blur suppression as this would not be present in the monocular condition. The task was to monocularly match a dioptically blurred sector to a nonblurred surround whereas the entire left eye stimulus was blurred in the main experiment, including the variable sector, which was matched to a nonblurred surrounding ring. Figure A1 shows the experimental setup.

On one CRT display, only a sector surrounded by mean luminance was presented, which was 25 cd/m² through a 5-cm² beam-splitter, which reduced luminance by 50% and had similar reflectance. Another CRT of the same model displayed the rest of the stimuli (horizontally inverted due to use of beam-splitter) with the corresponding sector as mean luminance. This arrangement was the same for all stimulus types. Stimuli covered the same central 24° of the visual field at 40 cm. Luminance look-up tables (LUTs) were defined in a similar way to the head-mounted displays (HMDs) used in the main experiment, and luminances were selected from linearized LUTs (with luminances equated across both screens) to draw the stimuli. A beam-splitter was used to physically combine the image of each screen (image paths shown by dashed lines in Figure A1) to the left eye only, which was fully corrected with a +2.50 D working distance lens to control accommodation. A +1.75 D lens at 7 cm from the eye blurred (+2 D effective blur) the left screen image only, i.e., a sector on a noiseless mean luminance background. The right screen area corresponding to the sector was also noiseless mean luminance.

Participants (ASC, SW, and SP) matched the sector to the surrounding ring modulation. For LM stimuli, two central and two peripheral sectors were adjusted, and for CM, one central and one peripheral sector were chosen (covering the same area of the visual field as the two central and two peripheral LM sectors, respectively). A similar modulation-matching task was performed with two CRT screens dichoptically (Figure A2) to investigate whether interocular modulation matches would differ from the monocular task (Figure A1) and also to compare with the main experiment.

Figure A1. Control experiment setup. Stimuli from left and right screens are combined to give a similar percept to the main experiments with the exception of blur affecting only the adjustable sector presented on the left screen. The rest of the stimulus is presented on the right screen. Dashed lines show image projection paths where they are physically combined at the beam-splitter. An eye patch covered the right eye.

Figure A2. Experimental setup for dichoptic equivalent of monocular modulation-matching task. Stimuli from each screen (dashed lines) are binocularly fused to give a cyclopean percept with the use of an angled mirror, which also prohibited cross talk. This experiment is analogous to the main experiment with HMDs.
Experimental setup was similar to the monocular task although a mirror was used and not a beam-splitter (Figure A2).

Each of the six conditions (monocular or dichoptic, LM or CM, with or without blur) was repeated four times by ASC and SP and one to two times by SW. Modulation matches between central and peripheral sectors were similar for all conditions, and therefore, the mean of all sectors for each condition was taken to provide a single PSE value of the sector relative to the surrounding ring. The relative modulation match was then calculated as the difference between with and without blur for each condition and data plotted in Figure 12.