The Relationship Between Fusion, Suppression, and Diplopia in Normal and Amblyopic Vision

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PURPOSE. Single vision occurs through a combination of fusion and suppression. When neither mechanism takes place, we experience diplopia. Under normal viewing conditions, the perceptual state depends on the spatial scale and interocular disparity. The purpose of this study was to examine the three perceptual states in human participants with normal and amblyopic vision.

METHODS. Participants viewed two dichoptically separated horizontal blurred edges with an opposite tilt (2.35°) and indicated their binocular percept: “one flat edge,” “one tilted edge,” or “two edges.” The edges varied with scale (fine 4 min arc and coarse 32 min arc), disparity, and interocular contrast. We investigated how the binocular interactions vary in amblyopic (visual acuity [VA] > 0.2 logMAR, n = 4) and normal vision (VA ≤ 0.2 logMAR, n = 4) under interocular variations in stimulus contrast and luminance.

RESULTS. In amblyopia, despite the established sensory dominance of the fellow eye, fusion prevails at the coarse scale and small disparities (75%). We also show that increasing the relative contrast to the amblyopic eye enhances the probability of fusion at the fine scale (from 18% to 38%), and leads to a reversal of the sensory dominance at coarse scale. In normal vision we found that interocular luminance imbalances disturbed binocular combination only at the fine scale in a way similar to that seen in amblyopia.

CONCLUSIONS. Our results build upon the growing evidence that the amblyopic visual system is binocular and further show that the suppressive mechanisms rendering the amblyopic system functionally monocular are scale dependent.

Keywords: image scale, binocular vision, binocular disparity, amblyopia, neutral density filter, contrast

Information from the two eyes is first combined in the early stages of the visual cortex. There are associated excitatory and inhibitory circuits1 operating within a multiscale parallel processing scheme.2 Three different perceptual states are possible under binocular viewing: fusion of the input from the two eyes into a single combined percept, a diplopic percept where the separate inputs from both eyes are both visible, and suppression of the input from one eye resulting in a single monocular percept. Here we investigated how manipulation of the spatial scale and disparity (misalignment of the monocular images) of the input images can change the probability of receiving each of these percepts. We used this to characterize binocular interactions at the level before horizontal disparity information (stereo) is derived.3

Georgeson and Wallis5 introduced a task in which a blurred horizontal edge was presented to each eye (dichoptic presentation). The disparity between these edges could then be manipulated, with observers responding as to whether they saw a single central edge (fusion), an offset edge (suppression), or a pair of edges (diplopia). The authors explained their results using a model with separate fusion and suppression stages. There is some probability of fusion occurring (depending on the stimulus); if fusion fails, then there is a probability that suppression of the input from one eye will occur; and if both fusion and suppression fail, then diplopia will occur. By expressing disparity in units of the width of the blurred edge, the investigators showed that the maximum disparity at which fusion occurred was roughly scale invariant. The deviation from scale invariance occurred for smaller blurred edges (finer spatial scale) where fusion ranges were broader than would be expected under scale invariance. For suppression there was a greater deviation from scale invariance, where the range over which suppression occurred was broader at finer spatial scales and narrower at coarser spatial scales than one would expect if it were scale invariant.

Our interest is to understand how binocular interactions are perturbed in amblyopia. We set out to address four questions. (1) How critical is a balanced input to each eye for fusion, and does this apply equally to contrast and luminance offsets? (2) What is the relationship between fusion, suppression, and diplopia in amblyopia, and how does this vary with disparity and spatial scale? With the advent of binocular approaches to therapy (for review see Ref. 4), it is important to know whether reducing suppression might simply lead to diplopia rather than successful treatment. (3) Does an neutral density (ND) filter on one eye of a normal observer simulate amblyopic binocular interactions5–7? (4) Can the effects of the ND filter in front of one eye be nullified by increased contrast to that eye, as they are in amblyopic observers?
**Materials and Methods**

**Participants**

Four amblyopic participants (mean age 46.8 ± 12.7 SD, two females) were recruited in the study. Four control participants (mean age 30 ± 4.3 SD, one female) with normal or corrected-to-normal visual acuity (better than 0 logMAR) were also recruited. For participant details, see Table 1. Participants performed the experiment with their best optical correction with a near addition if needed. Informed consent was obtained from all participants prior to the first session. All procedures were performed in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki) and were approved by the Research Ethics Board of the McGill University Health Center.

**Stimuli**

Stimuli were dichoptically presented horizontal edges (Fig. 1) calculated as Gaussian integrals with a blur B = 4 or 32 corresponding to the sigma of the Gaussian (we will refer to 4 min arc as fine scale, and 32 min arc as coarse scale) and a tilt of 2.36° in opposite directions. The motivation for using a tilted edge was to distinguish fusion and suppression, both resulting in a percept of a tilted edge. Stimulus disparity (in multiples of the blur scale, that is, 0 to 8 B in steps of 1 × B) was varied across the trials while stimulus contrast (offset of 0 or 12 dB) and stimulus scale (B = 4 or 32) were varied across blocks. For the 0-dB contrast offset, both edges had 30% Michelson contrast. In the case of the 12-dB contrast offset, one eye was presented with a 15% and the other eye was presented with 60% contrast edge (factor of 4 difference between the eyes). The edges were enclosed within a binocular binary noise frame to control vergence, and accompanied by two horizontal reference lines. The stimulus including the noise frame was scaled to 2.1° and 12.3° for the fine and coarse edges, and presented centrally. Polarity of the edges, that is, darker top or bottom, was randomly chosen on each trial. The edges in both eyes always had the same polarity. The tilt directions were randomly chosen on each trial, with the tilts always in opposite direction between the two eyes.

**Procedure**

Participants viewed a gamma-corrected ViewSonic 3D231 3D display (Brea, CA, USA) (refresh rate = 60 Hz) with polarized glasses (worn over their corrective lenses if necessary) from a distance of 72 cm. The display was driven by a Mac (Intel Core i7, 2.8 GHz, 8 GB RAM; Cupertino, CA, USA), and the stimuli (Fig. 1) were created using Psychtoolbox4 for MATLAB (MathWorks, Natick, MA, USA). On each trial, the stimulus was presented for 200 ms, accompanied by a beep. A single-interval, four-alternative choice design was adopted, and the task was to report the binocular percept using a keyboard. The four responses were a “single flat edge” (no tilt), “single right-tilted edge” (i.e., right side higher), “single left-tilted edge” (i.e., left side higher), or “two (tilted) edges.” These responses indicated fusion, suppression of either eye, or diplopia. Each response initiated the next trial after a 300-ms interstimulus interval.

For the amblyopic participants, the whole experiment consisted of three blocks of all four experimental conditions (2 contrast offsets × 2 scales), each containing 144 trials. The control participants completed two blocks of each condition either with or without a 2 ND filter covering their nondominant eye (determined by the Miles test5) with otherwise identical parameters. Before each block, participants aligned the percepts of the two eyes using a nonius cross. Every participant was provided with at least 144 training trials to familiarize with the task prior to data collection. The

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**Table 1. Participants’ Details**

<table>
<thead>
<tr>
<th>ID</th>
<th>Age/Sex</th>
<th>AME/NDE</th>
<th>VA</th>
<th>Stereo, Arc Sec</th>
<th>W4D Supp</th>
<th>Refraction</th>
<th>Strabismus</th>
</tr>
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<tr>
<td>A1</td>
<td>37/F</td>
<td>RE, strab</td>
<td>0.68</td>
<td>None</td>
<td>Yes</td>
<td>−1.0</td>
<td>5° exoT</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LE</td>
<td>1.25</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A2</td>
<td>35/M</td>
<td>RE</td>
<td>0.9</td>
<td>None</td>
<td>Yes</td>
<td>+0.5 − 0.5 × 60</td>
<td>15° exoT</td>
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<tr>
<td></td>
<td></td>
<td>LE, strab</td>
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<td>0.9</td>
<td></td>
<td>+2.0</td>
<td></td>
</tr>
<tr>
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<td>RE, mix</td>
<td>0.5</td>
<td>None</td>
<td>Yes</td>
<td>+4.25 − 1.0 × 80</td>
<td>5° esoT</td>
</tr>
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<td></td>
<td>LE</td>
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<td>0.0</td>
<td></td>
<td>+8.5 − 0.75 × 100</td>
<td></td>
</tr>
<tr>
<td>A4</td>
<td>54/M</td>
<td>RE</td>
<td>0.1</td>
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<td>2.5° esoT</td>
</tr>
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<td></td>
</tr>
<tr>
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<td>RE</td>
<td>0.0</td>
<td>0.0</td>
<td>No</td>
<td>0</td>
<td>None</td>
</tr>
<tr>
<td></td>
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<td>0</td>
<td></td>
</tr>
<tr>
<td>N2</td>
<td>F/24</td>
<td>RE</td>
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<td>0.0</td>
<td>No</td>
<td>4.0</td>
<td>None</td>
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<td></td>
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<td>0.0</td>
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<td></td>
</tr>
<tr>
<td>N3</td>
<td>M/32</td>
<td>RE</td>
<td>0.0</td>
<td>0.0</td>
<td>No</td>
<td>−1.25 − 2.75 × 180</td>
<td>None</td>
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<td></td>
<td></td>
<td>LE</td>
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<td>0.0</td>
<td></td>
<td>−3.75</td>
<td></td>
</tr>
<tr>
<td>N4</td>
<td>M/30</td>
<td>RE</td>
<td>0.0</td>
<td>0.0</td>
<td>No</td>
<td>0</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LE</td>
<td>0.0</td>
<td>0.0</td>
<td></td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

AME, amblyopic eye in amblyopic subjects; NDE, nondominant eye in normal subjects; W4D Supp, Worth Four Dots Test Suppression; exoT, exotropia; esoT, esotropia; RE, right eye; LE, left eye; VA, visual acuity.
The probability of fusion (pFuse) is expressed as a generalized Gaussian function of disparity:

\[
p_{\text{Fuse}} = p_{\text{Fuse}_0} \cdot \exp \left( -\frac{(2) \cdot d^2}{\sigma_f^2} \right) \quad (1)
\]

where \( d \) = disparity in blur units, \( \sigma_f \) = fusional range in blur units, and \( q \) = fusion steepness. In order to reduce the number of free parameters, we fixed the fusion steepness at \( q = 4.3 \)

If the observer does not see a single flat edge, then the next question is if he or she sees only one of the single tilted edges that were shown to each eye (consistent with suppression of the input from the other eye). We assume that the probability of suppression is at its maximum at zero disparity \( (p_{\text{Supp}}) \) and falls with increasing disparity in a similar manner to fusion:

\[
p_{\text{Supp}} = p_{\text{Supp}0} \cdot \exp \left( -\frac{(2) \cdot d^2}{\sigma_s^2} \right) \quad (2)
\]

The probability of diplopia was calculated as

\[
p_{\text{Double}} = 1 - (p_{\text{Fuse}} + p_{\text{Monoc}}) \quad (3)
\]

Finally, the probability of diplopia was calculated as

\[
p_{\text{Monoc}} = p_{\text{Supp}} \cdot (1 - p_{\text{Fuse}}) \quad (4)
\]

The model was fit by varying four free parameters (Table 2; Supplementary Fig. S1): the probability of fusion at zero disparity \( (p_{\text{Fuse}_0}) \), the disparity range for fusion \((\sigma_f)\), the

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**Table 2. Model Estimates of Free Parameters and Estimate Error**

<table>
<thead>
<tr>
<th>Group</th>
<th>Stimuli Contrast Offset, db</th>
<th>Scale</th>
<th>( \sigma_s ), Blur Units</th>
<th>( \sigma_f ), Blur Units</th>
<th>Eye Balance Factor</th>
<th>( p_{\text{Fuse}_0} )</th>
<th>RSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTR</td>
<td>0</td>
<td>Fine</td>
<td>3.54 ± 3.14</td>
<td>2.19 ± 1.99</td>
<td>0.32 ± 0.24</td>
<td>0.67 ± 0.61</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>Coarse</td>
<td></td>
<td>2.37 ± 2.54</td>
<td>1.85 ± 1.98</td>
<td>0.54 ± 0.64</td>
<td>0.72 ± 0.78</td>
<td>0.98</td>
</tr>
<tr>
<td>12 NDE</td>
<td>Fine</td>
<td></td>
<td>10.22 ± 9.78</td>
<td>2.50 ± 1.95</td>
<td>0.01 ± 0.01</td>
<td>0.01 ± 0.02</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Coarse</td>
<td></td>
<td>7.97 ± 8.20</td>
<td>0.18 ± 0.18</td>
<td>0.01 ± 0.02</td>
<td>0.06 ± 0.09</td>
<td>1.00</td>
</tr>
<tr>
<td>12 DE</td>
<td>Fine</td>
<td></td>
<td>9.57 ± 9.15</td>
<td>1.45 ± 3.02</td>
<td>1.00 ± 0.98</td>
<td>0.02 ± 0.02</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>Coarse</td>
<td></td>
<td>7.29 ± 7.56</td>
<td>0.77 ± 1.18</td>
<td>1.00 ± 1.03</td>
<td>0.08 ± 0.13</td>
<td>0.99</td>
</tr>
<tr>
<td>CTR ND</td>
<td>0 dB</td>
<td>Fine</td>
<td>8.76 ± 8.27</td>
<td>2.69 ± 2.08</td>
<td>0.98 ± 0.95</td>
<td>0.17 ± 0.13</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>Coarse</td>
<td></td>
<td>3.99 ± 4.37</td>
<td>2.29 ± 3.02</td>
<td>0.90 ± 0.99</td>
<td>0.33 ± 0.43</td>
<td>0.89</td>
</tr>
<tr>
<td>12 NDE</td>
<td>Fine</td>
<td></td>
<td>4.99 ± 4.62</td>
<td>2.88 ± 2.41</td>
<td>0.52 ± 0.45</td>
<td>0.45 ± 0.38</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td>Coarse</td>
<td></td>
<td>3.52 ± 3.70</td>
<td>1.71 ± 2.00</td>
<td>0.07 ± 0.12</td>
<td>0.32 ± 0.38</td>
<td>0.98</td>
</tr>
<tr>
<td>12 DE</td>
<td>Fine</td>
<td></td>
<td>29.69 ± 24.70</td>
<td>0.87 ± 0.55</td>
<td>1.00 ± 0.99</td>
<td>0.04 ± 0.02</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Coarse</td>
<td></td>
<td>15.92 ± 17.01</td>
<td>1.46 ± 6.23</td>
<td>0.99 ± 1.01</td>
<td>0.01 ± 0.04</td>
<td>1.00</td>
</tr>
<tr>
<td>AMB</td>
<td>0 dB</td>
<td>Fine</td>
<td>48.07 ± 21.62</td>
<td>7.11 ± 6.58</td>
<td>0.98 ± 0.97</td>
<td>0.18 ± 0.17</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Coarse</td>
<td></td>
<td>9.02 ± 9.88</td>
<td>0.96 ± 1.05</td>
<td>0.90 ± 0.95</td>
<td>0.75 ± 0.84</td>
<td>0.95</td>
</tr>
<tr>
<td>12 NDE</td>
<td>Fine</td>
<td></td>
<td>14.69 ± 11.99</td>
<td>6.40 ± 5.77</td>
<td>0.96 ± 0.91</td>
<td>0.38 ± 0.34</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>Coarse</td>
<td></td>
<td>3.97 ± 3.70</td>
<td>1.84 ± 2.22</td>
<td>0.28 ± 0.38</td>
<td>0.53 ± 0.64</td>
<td>0.87</td>
</tr>
<tr>
<td>12 DE</td>
<td>Fine</td>
<td></td>
<td>99.71 ± 203.88</td>
<td>8.69 ± 6.99</td>
<td>0.99 ± 0.98</td>
<td>0.09 ± 0.08</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Coarse</td>
<td></td>
<td>16.90 ± 18.56</td>
<td>0.88 ± 1.00</td>
<td>0.98 ± 1.00</td>
<td>0.20 ± 0.24</td>
<td>1.00</td>
</tr>
</tbody>
</table>

*\( p_{\text{Fuse}_0} \)* probability of fusion at zero disparity; \( \sigma_s \), fusional range; \( \sigma_f \), suppression range. 12-dB NDE, 12-dB relative contrast offset to the nondominant eye; 12-dB DE, 12-dB relative contrast offset to the dominant eye. 0 dB, zero contrast offset; 12-dB NDE, 12-dB relative contrast offset favoring the nondominant (amblyopic) eye; 12-dB DE, 12-dB relative contrast offset favoring the dominant (fellow fixing) eye. AMB, amblyopic group; CTR ND, control group with 2 ND over the nondominant eye; CTR, control group; RSS, residual sum of squares.
disparity range for suppression ($\delta_f$), and finally the EBF. For all fitting we used the nlfit MATLAB routine, and the goodness of fit for each condition was quantified by Equation 6:

$$r^2 = 1 - \frac{\text{RSS}}{\text{TSS}}$$ (7)

where

$$\text{RSS} = \sum (y_i - m_i)^2$$ (8)

and

$$\text{TSS} = \sum (y_i - y_{\text{mean}})^2$$ (9)

where $y_i$ and $y_{\text{mean}}$ refer to the data and $m_i$ refers to the model prediction.

**RESULTS**

Figure 3 shows results in two rows for the 0- and 12-dB contrast offset averaged over four normal observers (for fits of individual of each observer see Supplementary Figs. S2–S13). We plot the probability of “single flat edge,” “single tilted edge,” and “double edge” responses as a function of disparity. Results shown in the two columns are for two levels of stimulus scale (4 and 32 arc min). Our descriptive model provides an excellent account of these data (solid lines). We provide the fitted parameters in Table 2, and make comparisons with those parameters to describe the differences within and between our data. In the top row, where the contrast between the two eyes is balanced, three features are evident in both stimulus scales: “single flat edge” responses dominate at small disparities; “double edge” responses dominate at large disparities, and “single tilted edge” responses (fairly low at all disparities) show a small peak at intermediate disparities, which is approximately balanced between the two eyes. The effects of a contrast offset are seen in the bottom two rows. Introducing a 12-dB contrast difference between the eyes abolishes the fusion response previously seen at small disparities and replaces it with suppression by the eye with higher contrast. It also reduces the degree of diplopia seen at larger disparities, with those responses being replaced by the “one tilted edge” response.

The effect of reducing the mean luminance in one eye using a 2 ND filter (factor of 100) is shown in Figure 4. The top row is a replotted from Figure 3, showing the balanced results...
without an ND filter. The second row shows the effect of putting the filter in front of the nondominant eye. This causes the eye without the ND filter to dominate, particularly at the finer stimulus scale ($\text{EBF} \approx 1$). However, there is still a degree of “single flat edge” response at small disparities indicating persisting fusion (fine-scale $p_{\text{Fuse}} = 0.17$ versus coarse-scale $p_{\text{Fuse}} = 0.33$). We find that the effects of the ND filter are stronger at the finer scale, with the data at the coarse scale showing a smaller effect when the ND filter is introduced.

The remaining two rows show the effect of combining the ND filter with the 12-dB contrast imbalance. At fine scale, increasing the contrast to the eye with ND filter has the effect of reducing the dominance of the other eye ($\text{EBF} = 0.52$ versus $\text{EBF} \approx 1$), increasing fusion at small disparities ($p_{\text{Fuse}} = 0.45$ versus $p_{\text{Fuse}} = 0.17$) and diplopia at large disparities ($\sigma_s = 8.76$ versus $\sigma_s = 4.99$). Increasing the contrast to the eye with the reduced luminance goes some way to balancing out the effects at the fine scale (though fusion is still reduced). At the coarse scale, the 12-dB contrast offset seems to have overcompensated for the effects of the ND filter and introduced an imbalance in the opposite direction. From these results it seems that the effect of the luminance imbalance is scale dependent, and consequently the contrast imbalance necessary to counteract that effect is also scale dependent.

**FIGURE 4.** Results averaged over four control participants (error bars show standard error), showing the effect of using a 2 ND filter to reduce the luminance to one eye. The top row is replotted from Figure 3 for the purpose of comparison. The other three rows show the results with an ND filter in front of the nondominant eye with different interocular contrast offsets: 0 dB (balanced), 12 dB favoring the nondominant eye, and 12 dB favoring the dominant eye.
the bottom row of Figure 4, we show that reducing the contrast of the stimulus seen by the eye with the ND filter results in near-complete suppression of that eye.

Results from amblyopes are presented in Figure 5. There is suppression of the amblyopic eye evident at all disparities (top row). One of the most remarkable results is that at the coarse scale with no contrast offset there is a dominant “single flat edge” response at small disparities, indicating fusion ($p_{\text{Fuse}} = 0.75$). This does not occur at the fine scale ($p_{\text{Fuse}} = 0.18$), consistent with the known scale dependence of the amblyopic deficit, where higher spatial frequencies tend to show poorer sensitivity. There is also evidence of diplopia at large disparities for the coarse scale, indicating a reduced suppression range compared to the fine scale ($\sigma_s = 9.02$ at coarse scale versus $\sigma_s = 48.07$ at fine scale). When the contrast balance is shifted to favor the amblyopic eye by 12 dB, we also see a difference between the two scales. At the fine scale we observe a reduction in suppression and an increase in fusion. At the large scale, the increased contrast to the amblyopic eye results in a reversal of suppression of the fellow fixing eye by the amblyopic eye, similar to what we saw in the ND results (Fig. 4). Apart from this reversed suppression, the relationship between fusion and diplopia at this large scale was similar to that found in normal observers and quite different from the anomalous interactions seen at the fine stimulus scale. When the contrast is reduced in the amblyopic eye (bottom row) there is near-complete suppression of the amblyopic eye.

Results from control subjects with ND filters in front of one eye and from amblyopes can be compared using Figures 4 and 5. There we see a different relationship between suppression and disparity and a reduced degree of diplopia in the amblyopic participants. For the coarse-scale stimulus, suppression at large disparities in the ND filter case is weaker compared to the amblyopic data. Complementary changes are observed for the diplopia. At the coarse stimulus scale, amblyopes show stronger fusion at small disparities and weaker diplopia at larger disparities than exhibited by the ND simulation (amblyopes $p_{\text{Fuse}} = 0.75$ versus controls with ND $p_{\text{Fuse}} = 0.33$). Although, at the fine stimulus scale, the ND filter does a good job in simulating the amblyopic responses in terms of reducing fusional responses at small disparities (amblyopes $p_{\text{Fuse}} = 0.18$ versus controls with ND $p_{\text{Fuse}} = 0.17$), amblyopic participants still show larger suppression at larger disparities (amblyopes $\sigma_s = 48.42$ versus controls with ND $\sigma_s = 8.76$).

**DISCUSSION**

For normal balanced binocular vision (no contrast offset, no luminance offset), our results are essentially a replication of
those of Georgeson and Wallis, and we find broad agreement with their results. Our direct approach of identifying fusional responses by tilting the edges shown to each eye does, however, also show that if the contrast is offset by 12 dB, then fusion is abolished at small disparities. The main effect of contrast offset is a pervasive suppression (though the strength of the effect varies somewhat across spatial scale). One may argue that some of our “single tilted edge” responses may result from perception of a fused edge with the tilt corresponding to a contrast-weighted average of the edges seen by the two eyes. In normals this would make only a small difference, as the 12-dB contrast offset is outside of the range where fusion occurs for stimuli having horizontal tilts. In amblyopes, this would lead only to underestimation of our key finding that fusion responses are dominant at the coarse scale and that imbalancing the interocular contrast in favor of the amblyopic eye can reestablish fusional responses at fine scale.

The effect we found of reducing the luminance of one eye of a normal observer was very similar to that produced by a contrast offset. Our results showed this at the fine spatial scale; however, it is possible that a similar result would be found for the coarse scale with a different contrast offset. In response to our first question concerning the importance of a balanced binocular input for fusion and the role of interocular luminance difference (ND in front of one eye), we conclude that a balanced binocular input in terms of contrast is essential for normal binocular interactions. A balanced interocular luminance input is also important.

Suppression of the amblyopic eye, particularly in the central visual field, is well established. At the coarse scale our amblyopes, even with zero contrast offset, show fusion dominating over suppression at small disparities. Offsetting contrast in favor of the amblyopic eye produces an essentially normal pattern of interactions between suppression and diplopia as a function of disparity with the addition of a reverse suppression. In other words, now the amblyopic eye suppresses the fellow fixing eye rather than the other way around. At the fine scale the situation is different; amblyopes also have a significant, though small, degree of fusion, but it is heavily overshadowed by a more dominant suppression.

The conclusion regarding our second question is that for amblyopes, fusion can dominate for small disparities when the spatial scale is coarse, but suppression dominates for small disparities in the central visual field when the spatial scale is fine. The consequences of offsetting the contrast, such that the amblyopic eye receives higher contrast than that of the fellow fixing eye, is to reduce suppression at small disparities and correspondingly increase fusion at small disparities for stimuli of fine spatial scale. We presume that even amblyopes with a strong suppression would show a similar pattern of results, although fusional responses at the coarse scale may not be as prominent. At finer scale, possibly a higher contrast offset may be required to elicit fusional responses. This is relevant to a recently proposed treatment of amblyopia in which the balance between the two eyes is reestablished (for a review see Ref. 4). This study suggests that the extent to which suppression precludes normal binocular combination depends upon spatial scale. Also we argue, using a paradigm different from that originally reported by Mansouri et al., that interocular balance is an important factor because we show conditions under which the amblyopic eye suppresses the fellow fixing eye.

It has been suggested that the effects of an ND filter can mimic the binocular interactions that characterize amblyopia. We find a distinct difference between these two conditions. For fine-scale stimuli the suppression in amblyopia did not depend on the disparity of the stimuli, whereas in the case of the ND filter suppression reduced at large disparities, revealing diplopia. For stimuli of coarse scale there was also a difference. Unlike the ND filter simulation, in amblyopia, fusion dominates at small disparities; suppression is least at small disparities, and diplopia is not dominant at large disparities. In response to our third question, we reason that the degree to which the 2 ND filter on a normal can simulate amblyopia in our amblyopic sample is only approximate at best.

Finally, we set the fourth question, whether the effects of a contrast offset can null the effects of a luminance offset, thereby restoring the normal pattern of responses. At fine spatial scales, the effects of the contrast offset did broadly counteract the effects of a luminance offset, producing a normal pattern of responses. However, at the coarse scale the level of contrast offset that we used (12 dB) was an overcompensation. We have additional data for an offset of 6 dB that show the restoration of normal responses for the coarse scale (not shown), indicating that the necessary contrast offset is scale dependent.

These results further extend the growing evidence that the amblyopic visual system has binocular architecture, but is rendered monocular through interocular suppression. We show that the extent of how suppression precludes normal binocular combination depends on spatial scale—in particular, that fusion in amblyopes can occur at coarse spatial scales in the presence of more suppression at finer scales. We also show that unbalancing contrast between the two eyes in favor of the amblyopic eyes results in binocular interactions comparable to those of control participants. These two results highlight the fusion abilities of amblyopes and potentially explain why emerging therapeutic interventions that rely on balancing the contributions of the two eyes do not induce diplopia.

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