Amblyopic deficits in processing structure-from-motion

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Amblyopic observers exhibit a range of low- and high-level cortical deficits, and there is strong evidence that the extrastriate cortex is selectively affected for signal/noise tasks but not for simple integration tasks. We tested amblyopic and control observers on a structure-from-motion (SFM) task involving signal integration to gauge whether extrastriate processing is compromised at a level where dorsal and ventral information is combined. SFM tasks require integration of local elements to perceive the global structure using motion-defined depth cues. Observers were monocularly presented with a 2-IFC shape discrimination task and asked to indicate whether two consecutive SFM stimuli represented the same or different depth-defined shapes. Amblyopic observers had higher depth thresholds than control observers, even after controlling for low-level differences in contrast thresholds across eyes and observers. Combined with the presence of the deficit in both the amblyopic and fellow-fixing eyes, this suggests a high-level locus for the SFM deficit.

Keywords: amblyopic deficits, structure-from-motion, extrastriate processing


Introduction

Amblyopia is a developmental visual disorder involving a loss of function for one eye’s input that cannot be accounted for by optical factors, often associated either with strabismus, anisometropia, or with early form deprivation (for example, due to an early cataract). While there is some evidence that amblyopic deficits may start as early as the lateral geniculate nucleus (Hess, Thompson, Gole, & Mullen, 2010), the deficits appear to be predominantly cortical in origin (Cleland, Crewther, Crewther, & Mitchell, 1982; Crewther, Crewther, & Cleland, 1985; Hess & Baker, 1984; Hess, Baker, Verhoeve, Keese, & France, 1985; Muckli et al., 2006; for a review, see Kiorpes, 2006). Amblyopic observers exhibit lowered contrast sensitivity, especially at high spatial frequencies (Hess & Howell, 1977; Levi & Harwerth, 1978), as well as spatial uncertainty and spatial distortions for form processing (Hess, Campbell, & Greenhalgh, 1978). The available neurophysiology on animals suggests that the contrast sensitivity loss associated with amblyopia is predominantly striate in origin (Kiorpes, 2006).

Recently, there is accumulating evidence for a high-level (extrastriate) deficit in amblyopia. High-level visual processing is often thought of in terms of motion processing by the dorsal pathway and/or form processing by the ventral pathway. The psychophysical literature suggests that the processing along both of these pathways can be compromised in amblyopia for tasks involving segregation of signal from noise, for example, motion coherence (Aaen-Stockdale & Hess, 2008; Constantinescu, Schmidt, Watson, & Hess, 2005; Ellemberg, Hess, & Arsenault, 2002; Ho et al., 2005; Simmers, Ledgeway, Hess, & McGraw, 2003; Simmers, Ledgeway, Mansouri, Hutchinson, & Hess, 2006) and form coherence (Simmers & Bex, 2004; Simmers, Ledgeway, & Hess, 2005). However, for tasks involving pure signal integration of global stimuli (e.g., orientation or direction averaging), the evidence suggests that both dorsal and ventral functions are normal in amblyopia (Hess, Mansouri, Dakin, & Allen, 2006; Mansouri, Allen, Hess, 2005; Mansouri, Allen, Hess, Dakin, & Ehrt, 2004; Mansouri & Hess, 2006). Here we use a structure-from-motion task that while involving pure signal integration (all dots contain signal and together define a single surface) also involves the integration of motion information derived from dorsal and shape information derived from ventral pathways, at a higher level in the pathway than previously investigated with global motion and form tasks (Peuskens
SFM stimuli are of further interest because, in non-amblyopic observers, they evoke a strong depth percept, even in the absence of disparity cues (e.g., Andersen & Bradley, 1998; Nawrot & Blake, 2001). Amblyopic observers typically lack stereoscopic depth perception (McKee, Levi, & Movshon, 2003), though there is growing evidence that stereopsis can be improved in amblyopic observers by equating the strength of input across eyes (Hess, Mansouri, Thompson, & Gheorghiu, 2009), suggesting that binocular depth mechanisms may not be absent in amblyopic observers as long assumed but rather suppressed by the strength of input to the fellow eye. Thompson and Nawrot (1999) investigated whether the weak or absent stereopsis in amblyopic observers might be compensated for by increased reliance on other depth cues but found that amblyopic observers were severely impaired at judging depth in the context of motion parallax tasks as well, suggesting the possibility of a more generalized depth perception deficit. By testing the availability of SFM depth-from-motion cues to amblyopic observers, this study provides additional insight into the specificity of depth perception deficits in amblyopia.

We tested amblyopic and control observers and found that amblyopic observers exhibit a deficit on a 3D SFM processing task. Amblyopic observers are known to have higher contrast thresholds than control observers. Thus, the lower performance on the task could be accounted for by having more difficulty detecting the elements themselves. In Experiment 2, we modified the stimulus to allow us to rule out contributions of contrast deficits, by first measuring contrast detection thresholds for the stimuli separately for each eye, and then testing SFM perception at a fixed multiple of the contrast threshold for each eye. Again, we found deficits for amblyopic processing relative to control processing, suggesting a high-level locus for these deficits.

### Experiment 1

#### Methods

**Observers**

We tested 12 amblyopic observers (7 females; 5 males; mean age = 35.6, range = 20–62; see Table 1 for clinical details) and 12 control observers (6 females; 6 males; mean age = 31.3, range = 20–59). All control observers

<table>
<thead>
<tr>
<th>Amblyopic Observer</th>
<th>Acuity (RE)</th>
<th>Acuity (LE)</th>
<th>Refraction (RE)</th>
<th>Refraction (LE)</th>
<th>Squint (deg)</th>
<th>Type</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>20/40</td>
<td>20/25</td>
<td>+0.400 - 1.50 x 100</td>
<td>Plano</td>
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<td>RE mixed</td>
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<tr>
<td>2</td>
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<td>20/50</td>
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<td>+2.50 - 1.50 x 75</td>
<td>XT 6</td>
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<tr>
<td>3</td>
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<td>20/80</td>
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<td>LE strab</td>
</tr>
<tr>
<td>4</td>
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<td>20/40</td>
<td>Plano</td>
<td>-0.25 - 0.75 x 70</td>
<td>ET 5</td>
<td>LE strab</td>
</tr>
<tr>
<td>5</td>
<td>20/40</td>
<td>20/25</td>
<td>+1.75 - 0.75 x 180</td>
<td>+1.5 - 0.50 x 180</td>
<td>XT 10</td>
<td>RE strab</td>
</tr>
<tr>
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<td>20/400</td>
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</tr>
<tr>
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<td>20/80</td>
<td>Plano</td>
<td>Plano</td>
<td>ET 1</td>
<td>LE strab</td>
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<tr>
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<td>20/16</td>
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<tr>
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<tr>
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<td>+6.75 - 0.50 x 170</td>
<td>+6.75 - 0.50 x 175</td>
<td>ET 4</td>
<td>LE strab</td>
</tr>
</tbody>
</table>

Table 1. Amblyopic demographics. Squint: ET = esotropia; XT = exotropia. The squint angle is given in degrees, where 1 degree is equal to 1.75 prism diopter. Type: Strab = strabismus; Mixed = strabismus and anisometropia; RE = right eye; LE = left eye.
had normal or corrected-to-normal vision. All observers participated with informed consent in compliance with the Declaration of Helsinki.

Stimuli

Observers performed a 2-interval forced-choice task, discriminating whether the two intervals contained matching or mismatching shape identities. The individual shapes were generated by randomly perturbing the front surface of a half-sphere to create peaks and troughs across the surface (Figure 1). Object exemplars could be individuated on the basis of the particular distribution of perturbations across the surface; however, all objects shared the same average degree of perturbation from a perfect sphere. Note that, unlike the classic SFM stimulus (a rotating transparent cylinder), the SFM stimuli in the current experiment consisted of a front surface only. As a result, there were no opposing motion signals and all dots on the surface only defined one direction of surface rotation. All dots contribute information about the front surface, with their relative velocities providing information about degree of curvature across the surface. Thus, all the dots contain signal—there are no “noise” dots.

Average stimulus depth, along the z dimension, was manipulated across trials to determine the average depth necessary to discriminate the SFM shapes. Because the stimuli were equated in terms of average perturbation from a sphere, fixing the shapes along this dimension required allowing some variability in the distribution of depth across the surface of each individual shape. As a result, the maximum depth range was similar, but not exactly equal, across the individual shapes. For this reason, our unit of depth is the proportion of the maximum (original) stimulus depth: A depth of 1 represents the maximum depth, averaged across the 4 stimuli (corresponding to 12.7 degrees of visual angle; range across stimuli = 10.6–14.9), a depth of 0.5 represents half that maximum depth, and a depth of 0 represents a flat surface.

Three-dimensional SFM stimuli have a number of qualities that may permit an observer to succeed at the task without having perceived a 3D surface per se. These features include (a) 2D contours of the shape against a background of dots, whether stationary or moving, (b) variations in local 2D temporal frequency due to rising and falling surface components in parallel with the line of sight, and (c) in 2AFC matching tasks, local matching of dot motion patterns in lieu of 3D percept. We therefore designed our task and stimuli to avoid these potential confounds.

All stimuli had the exact same 2D contour. Between the two presentation intervals, stimuli were presented at different rotation speeds (chosen randomly from possible stimulus durations of 1.3, 1.5, 1.6, or 1.8 s) and different in-plane orientations (either ±15 degrees from vertical). On every frame, 2D dot density was estimated, and 10% of the dots from the highest density regions were replotted to the lowest density regions. This served to maintain a constant 2D dot density across frames. Note that this is not the same as a limited lifetime presentation where all dots have an equal likelihood of being replotted. All variants on the stimulus (speed, presentation angle, and depth)

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Figure 1. (a) Grayscale image depictions of the shapes represented as SFM stimuli. Observers viewed these grayscale images once at the beginning of the experimental session. During experimental trials, stimuli were presented exclusively as SFM sequences. (b) Sample frames of a single SFM stimulus. Dots were replotted across frames to maintain a constant density and to ensure that the structure was only visible when in motion.
were generated as separate independent movies, such that the specific dot locations differed across trials. Finally, the starting direction of the motion trajectory was also randomized across trials. These modifications ensured that the task could not be successfully performed without the perception of 3D structure: neither 2D contour, local 2D temporal frequency, pattern of motion, nor even the gross sense of 3D orientation would be sufficient to perform the task accurately.

The SFM stimuli were generated in 3D Studio Max and exported to Matlab as object files. Stimulus depth was manipulated by scaling the \( z \)-plane dimension of the object file between a mean depth of 0.08 and 12.7 degrees of visual angle. Custom scripts were used to construct the SFM, in a manner similar to that described previously (Aaen-Stockdale, Farivar, & Hess, 2010). Briefly, stimuli were constructed by first creating a 2D uniformly distributed random dot pattern with 400 dots. This pattern was then projected onto the 3D object, the object rotated, and then the dot positions were projected back to 2D to render the second frame. On each frame, local dot density was calculated and dots falling in regions of top and bottom 5% dot density were distributed so as to ensure that the rule of uniform dot density distribution was maintained. Dots falling on the background of the object, despite never changing in 2D density, were also repositioned at a rate matching the rate of dot replacement on the 3D stimulus. These steps were repeated for every frame to generate an entire series of dot positions in time. The resulting stimuli were each composed of 400 dots uniformly distributed in 2D (each 0.11 deg in diameter), with an overall stimulus diameter of 12.7 deg. Dots were drawn online frame by frame using Matlab’s open GL functionality. The motion trajectory consisted of a half-cycle rotation (either a left-to-right or right-to-left rotation of the stimulus). This half-cycle rotation was presented in repetition to provide two full cycles of rotation of the stimulus (i.e., the same frames were presented in one direction, then reversed, followed by a repetition of both sets of frames; Movie 1).

**Procedure**

Observers were seated 60 cm from the monitor (Compaq P1210, resolution: 1024 × 768, 90 Hz; effective screen size = 39.5 × 29.5 cm) and viewed the stimuli monocularly, with one eye covered by an occluding patch. All observers completed four blocks, two for each eye. Presentation to each eye was alternated across blocks, with the starting eye counterbalanced across observers.

A sequential two-alternative forced-choice (2AFC) task was used, where each trial consisted of two consecutively presented SFM stimuli. Observers indicated whether the two intervals contained either the same or different shapes by key-press response and received auditory feedback in the form of a high- or low-pitched beep for correct and incorrect responses, respectively. Each trial consisted of a 1-s duration fixation point, followed by interval one (1.82 s), an interstimulus interval of 500 ms, and interval two (1.82 s). Observer responses were accepted only after the end of both intervals.

The depth of the SFM stimuli was varied across two interleaved 3-down–1-up staircases to determine the depth thresholds necessary to identify stimulus–identity matches. The presented depth level was always the same for both intervals in each trial, regardless of whether the stimuli were the same or different (i.e., regardless of whether it was a match trial). Because there was some variability in the distribution of depth across the surface of each individual shape, the depth thresholds (which were determined collectively for all trials, pooling across shapes) represent the average depth necessary to perform the task rather than the particular depth required to identify any single isolated shape. Each staircase step was a fixed multiple of the original depth values, ranging from 1 (the original surface depth: corresponding to a mean depth of 12.7 degrees of visual angle) to 0 (a flat surface). The initial value of the staircase was set to 0.5 (equivalent to a mean depth of 6.3 degrees of visual angle). Blocks ended when both interleaved staircases reached 10 staircase reversals or when the block length exceeded 150 trials.

Although there were four stimuli, on any given trial, there was a 50% chance of being presented with a match. The experimental script randomly selected one of the four

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Movie 1. Sample stimulus. This stimulus corresponds to the 4th (bottom) grayscale image depicted in Figure 1a. Stimulus duration has been extended beyond that used in the experimental context to facilitate viewing.
shapes and then either presented that shape twice or in conjunction with a shape randomly selected from the remaining three shapes. The presentation order of the shapes was also randomized.

**Results**

Depth thresholds were obtained separately for each eye and each of the two experimental blocks. Within each block, thresholds were defined as the average of the last six reversals, calculated separately for each of the two interleaved staircases, and then averaged together to produce a single threshold measure for each block.

A 2 group (amblyope vs. control) × 2 block × 2 eye (amblyopic/non-dominant vs. fellow-fixing/dominant) analysis of variance was performed. No significant effect of block was observed, $F(1,22) = 1.992, p = 0.172$, so all threshold data plotted in Figure 1 have been averaged across blocks.

Overall, amblyopic observers had significantly higher thresholds than control observers, $F(1,22) = 7.494, p = 0.012$ (Figure 2a). Considering the individual threshold data for amblyopic (Figure 2c) and control (Figure 2d) observers, it is also apparent that a few of the amblyopic observers were at ceiling performance, suggesting that even with maximal depth information, these observers were unable to reach threshold performance. Thus, the size of the group difference may be underestimated.

There was a general trend for better performance in the stronger eye in both groups (fellow-fixing and dominant eyes, relative to amblyopic and non-dominant eyes; Figure 2b), but this trend did not reach significance ($F(1,22) = 3.885, p = 0.061$), and importantly, there was no indication that this trend differed between the amblyopic and control groups (interaction $F(1,22) = 0.018, p = 0.894$).

Together, these results indicate that amblyopic observers need greater depth cuing to perceive the structure in SFM stimuli and that this processing deficit is not specific to the amblyopic eye.

**Experiment 2**

Experiment 1 established that amblyopic observers exhibited a deficit in the processing of SFM stimuli. However, the results of Experiment 1 do not permit us to rule out contributions of low-level striate deficits such as reduced contrast sensitivity in the amblyopic eye. Although the stimuli in Experiment 1 were presented as high-contrast white dots on a black screen in a dimly lit room, it remains possible that the amblyopic deficit could be at least partially accounted for by reduced stimulus visibility for amblyopic relative to control observers.

Since the contrast sensitivity deficit depends on spatial frequency, it is not ideal to try to correct for it using spatially broadband stimuli such as dots. Experiment 2 presented stimuli at a fixed ratio above contrast threshold for all observers, measured and equated separately for each eye over a narrow spatial frequency band.

To achieve this, we modified the stimulus to replace the broadband local elements used in Experiment 1 with narrowband local elements, to allow for spatial frequency-dependent contrast correction.

**Methods**

**Observers**

All observers who took part in Experiment 1 were invited to return for Experiment 2. Of these, we retained 10 of the original 12 amblyopic observers and 11 of the original 12 control observers.

**Stimulus**

The broadband dots that composed the SFM stimuli in Experiment 1 were replaced with narrowband Gabor patches with a spatial frequency of 4.3 cpd. Because rendering Gabor patches requires more pixels than rendering dots, a few additional stimulus modifications were necessary. The size of the stimulus was enlarged to cover a diameter of 16.1 deg, and the number of elements was reduced from 400 to 200 with each element extending 0.70 deg in diameter.

The full stimulus, therefore, was composed of 200 Gabor micropatterns (each of which were identical copies of a single Gabor micropattern, rendered in advance). The micropatterns were translated across the screen based on the same algorithms that determined the dot translation routines in Experiment 1.

**Procedure**

Observers completed two experimental tasks: a contrast detection task and a shape discrimination task.

The contrast detection task was a 2-interval forced-choice procedure, in which a randomly chosen SFM stimulus was presented in either the first or second interval of each trial. The two intervals were visually cued by presenting a bounding box that contained the stimulus in one of the two intervals. The bounding box was 19.4 deg in diameter, with lines that were 0.04 deg wide. The contrast of the SFM stimulus was varied across two interleaved 3-down–1-up staircases to determine the contrast thresholds necessary to detect the presence of the stimulus. Observers performed one contrast detection block for each eye.
The shape discrimination task was performed using the same procedure outlined in Experiment 1, where observers were required to identify on each trial whether the SFM stimuli presented across the two intervals carried the same or different identities. These stimuli were presented at four times the contrast threshold obtained during the contrast detection task. Observers performed two blocks per eye.

Figure 2. Experiment 1. Depth thresholds for amblyopic and control observers. (a) Observer averages collapsed across blocks and eyes. (b) Observer averages separate for each eye. (c) Individual amblyopic observers. (d) Individual control observers. For (a)–(c), where performance is shown separately for each eye: dark bars indicate the amblyopic eye (non-dominant eye for control observers), and light bars indicate the fellow-fixing eye (dominant eye for control observers). Error bars represent ±1 standard error of the mean.
Results

Consistent with the results of Experiment 1, amblyopic observers required significantly more depth cuing to recognize the SFM stimuli, \( F(1,19) = 9.588, p = 0.006 \) (Figure 3a). This group difference may be underestimated, as about half the amblyopic observers performed at ceiling (Figure 3c), indicating that they were never able to reach threshold performance even with maximum depth cuing. The trend toward better performance in the dominant eye (or fellow-fixing eye for amblyopic observers) observed in Experiment 1 was even weaker in Experiment 2, \( F(1,19) = 3.089, p = 0.095 \), nor was there any indication of a greater effect of eye in the amblyopic group: interaction \( F(1,19) = 1.492, p = 0.237 \).

Unlike Experiment 1, performance also showed an overall improvement across the two test blocks, \( F(1,19) = 5.328, p = 0.032 \). Figure 4 presents the data from Figure 3b replotted separately for each block. The improvement across blocks appears to have been largely carried by a selective improvement in the performance of the fellow-fixing eye of the amblyopic observers (\( t(9) = 2.738, p = 0.023 \)). Neither the amblyopic eye (\( t = -0.199, p = 0.847 \)) nor either eye in the control group (dominant: \( t(10) = 1.429, p = 0.183 \); non-dominant: \( t(10) = 0.967, p = 0.356 \)) improved significantly across sessions.

Because many of the observers overlapped between the two experiments, it was possible to look more closely at performance differences across conditions by restricting the analysis to those observers who performed both experiments and performing a 4-way (group \( \times \) eye \( \times \) run \( \times \) stimulus type) analysis of variance.

As expected, across both experiments, amblyopic observers required more depth information to identify SFM stimuli, \( F(1,19) = 9.616, p = 0.006 \). With the combined data, the dominant eye advantage reached significance, \( F(1,19) = 6.157, p = 0.023 \); however, there was no interaction with group, \( F(1,19) = 1.296, p = 0.269 \), indicating that the dominant eye advantage was not specific to amblyopic observers. There was also an overall improvement in performance across blocks, \( F(1,19) = 6.582, p = 0.019 \), that did not interact significantly with any other condition.

Most importantly, the combined analysis indicated that thresholds were elevated overall in the second experiment relative to the first, \( F(1,19) = 10.455, p = 0.004 \), and that this effect was marginally stronger for amblyopic observers than for control observers, \( F(1,19) = 4.126, p = 0.056 \). This suggested that the Gabor-generated SFM stimuli were, globally, more difficult for observers, requiring greater depth cuing to reliably differentiate between the shape exemplars. As the Gabor stimuli differed in multiple ways from the dot stimuli (size, number of elements, contrast), the reason for the difficulty increase is not readily apparent. Critically, though, control thresholds remained low enough to effectively compare performance between amblyopic and control observers.

Discussion

Amblyopia is known to be associated with a selective deficit for global processing involving segregation of signal from noise in global motion tasks (Aaen-Stockdale & Hess, 2008; Constantinescu et al., 2005; Ellemberg et al., 2002; Ho et al., 2005; Simmers et al., 2003, 2006) and in global orientation tasks (Simmers & Bex, 2004; Simmers et al., 2005). However, the global integration of both motion and form processing, in the absence of noise, is spared in amblyopia (Hess et al., 2006; Mansouri et al., 2005, 2004; Mansouri & Hess, 2006).

This study aimed to determine whether performance deficits are present in an SFM task that involved combining dorsal and ventral information within the context of an integration task, in the absence of noise. Based on the previous findings that integration tasks involving both dorsal (motion) and ventral (orientation) processing are spared in amblyopia, we would not expect a deficit for SFM processing unless there is a deficit at the point of dorsal–ventral integration.

Experiment 1 focused on determining whether amblyopic performance is challenged relative to control performance in this task. Experiment 2 incorporated greater stimulus controls, replicating the results from Experiment 1 in the context of a task where contrast sensitivity differences across eyes were controlled to rule out possible low-level contributions to performance deficits. The results from both Experiments 1 and 2 indicate that amblyopic observers exhibit a deficit in SFM processing. This deficit is present both for low- and high-contrast stimuli, for stimuli that have been equated for contrast visibility across eyes and observers, and for both broadband (dot) and narrowband (Gabor) SFM elements, suggesting that the amblyopic deficit is persistent across a range of experimental parameters.

For both amblyopic and control observers, thresholds were elevated in Experiment 2 relative to Experiment 1. This is not surprising, as the stimuli were presented at much lower contrast in the second experiment and had less scale support. Further, the stimulus modifications necessary to incorporate Gabor patches in place of dots (the reduced number of elements and overall enlarging of the stimulus size) may have negatively impacted performance on the task. For this reason, the critical comparison is how performance compares between amblyopic and control observers rather than across stimulus conditions. Amblyopic and control performance can be more fairly compared in Experiment 2, where stimulus contrast was equated both across eyes and across observers by fixing the contrast at a fixed multiple above threshold. The presence of a large group difference in this context indicates that amblyopic perception of SFM stimuli is compromised for reasons other than known low-level contrast sensitivity deficits. This is consistent with the possibility of higher level deficits in ventral or dorsal visual cortex or at the point where ventral and dorsal information is combined to...
Figure 3. Experiment 2. Depth thresholds for amblyopic and control observers. (a) Observer means collapsed across blocks and eyes. (b) Observer means separate for each eye. (c) Individual amblyopic observers. (d) Individual control observers. For (a)–(c), where performance is shown separately for each eye: dark bars indicate the amblyopic eye (non-dominant eye for control observers), and light bars indicate the fellow-fixing eye (dominant eye for control observers). Error bars represent ±1 standard error of the mean.
solve SFM. Importantly, the results of the current study are unlikely to reflect a feed-forward effect of early contrast-processing deficits in striate cortex, as equating for stimulus visibility did not reduce the size of the amblyopic deficit. If anything, the amblyopic observers had greater difficulty with the stimuli in Experiment 2 despite the careful equating for stimulus visibility across observers. Further, we saw no clear evidence of an advantage for the fellow-fixing eye over the amblyopic eye. Although there was a trend in this direction in Experiment 1, the observed eye difference was equally present in the control group, and the fellow-fixing eye was elevated relative to both control eyes, indicating that there was not a specific impairment to the amblyopic eye. Further, the small (non-significant) dominant eye advantage observed in Experiment 1 was not replicated in Experiment 2, where the absolute levels of performance across eyes can be more fairly compared because stimulus contrast was properly equated to ensure that stimulus visibility was comparable. Together, these results suggest that amblyopia is associated with a general elevation in 3D SFM thresholds, which is not specific to the amblyopic eye and which, therefore, occurs at a level of processing that is at least beyond the point of binocular integration.

Form-from-motion versus structure-from-motion

The current study builds on previous reports of impaired motion processing in amblyopia, including impaired motion parallax (Thompson & Nawrot, 1999), and degraded 2D form-from-motion processing in amblyopia (Giaschi, Regan, Kraft, & Hong, 1992; Ho et al., 2005; Wang, Ho, & Giaschi, 2007). Our results suggest that amblyopic observers not only have difficulty using direction cues to perceive 2-dimensional form from motion but also have difficulty using relative velocity cues to perceive 3-dimensional structure-from-motion. The presence of this additional impairment in structure-from-motion tasks suggests that amblyopia involves cortical deficits beyond that previously identified, as 2D form from motion and 3D structure-from-motion involve different cortical areas (Vaina, 1989; Vaina, Lemay, Beinfang, Choi, & Nakayama, 1990).

Structure-from-motion relative to motion coherence

Previous deficits have been reported in amblyopia for motion coherence (Aaen-Stockdale & Hess, 2008; Constantinescu et al., 2005; Ellemberg et al., 2002; Ho et al., 2005; Simmers et al., 2003, 2006) but not for similar tasks involving pure signal integration (orientation and motion direction averaging; Hess et al., 2006; Mansouri et al., 2005, 2004; Mansouri & Hess, 2006). This suggested that the key feature of the extrastriate deficit in amblyopia for global form (Simmers & Bex, 2004; Simmers et al., 2005) and global motion (Simmers et al., 2003, 2006) was the presence of noise dots that had to be differentiated from signal dots (Mansouri & Hess, 2006).

An important question is: could the presumably lower level extrastriate form and motion coherence deficits present in amblyopia have contributed to the SFM deficit reported here? There are some key differences between motion coherence and SFM tasks that would argue against this.

First, unlike the motion coherence task, the SFM task, as presented here, does not contain any “noise” dots, as all the dots contain signal relevant to solving the task. Although some proportion of dots were replotted across
frames to maintain an even density distribution across space and time, all present dots in all frames contributed signal information. This makes the SFM task more analogous to signal integration tasks (orientation and motion direction averaging), for which amblyopic performance is normal (Mansouri & Hess, 2006).

Second, because the stimulus consists only of a front surface, the stimulus does not include any competing directions, unlike motion coherence stimuli. This also makes our stimuli unlike the classic rotating cylinder SFM stimulus where subjects are required to segregate front and back surfaces. As a result, with our front-surface-only SFM task, not only do all dots contain signal information, but there is also no need to segregate the dots into two separate depth planes, removing any possibility that dots might be erroneously perceived as sources of direction “noise” on the basis of segregation errors. Thus, the task includes no competing motion signals.

The argument that 3D SFM perception might be dependent on the same mechanisms probed by coherent motion tasks might be of greater concern had we actively manipulated the amount of signal presented to the subject across trials (for example, by varying the number of signal dots through thresholding dot lifetime or dot density). Here, however, we manipulated only the depth of the objects to be matched, and therefore, not only were all dots contributing signal information, but the total amount of available signal (i.e., amount of surface information) was also constant across trials and unrelated to subject performance.

Finally, there is at least one previously reported case where substantially elevated coherent motion thresholds did not translate to an impairment in perceiving 3D SFM rotating cylinders, when the SFM stimuli contained 100% signal structure (Vaina, Grzywacz, & LeMay, 1990). Thus, there is no a priori reason to suspect that the known global coherence deficits in amblyopia should predict deficits in 3D structure-from-motion as well.

Cortical processing of 3D SFM

SFM perception is supported by both dorsal and ventral mechanisms. The contribution of the dorsal stream is well established by neurophysiological evidence: In single-cell studies with monkeys, the response strength of MT neurons correlates well with the perceived direction of rotation of SFM cylinders (Bradley et al., 1998; Dodd et al., 2001). Similar correlations have been identified between MST neurons and the tilt angle of SFM planes (Sugihara, Murakami, Shenoy, Andersen, & Komatsu, 2002). This is in contrast with V1 neurons, where only a small proportion of neurons correlate with SFM percepts (Grunewald, Bradley, & Andersen, 2002).

Human MRI imaging studies have identified a wide complex of both dorsal and ventral areas associated with structure-from-motion tasks. These regions include dorsal extrastriate regions like hMT/V5+ (Kriegeskorte et al., 2003; Murray et al., 2003; Paradis et al., 2000, 2008; Peuskens et al., 2004; Vanduffel et al., 2002) and the intraparietal sulcus (IPS; Kriegeskorte et al., 2003; Peuskens et al., 2004), ventral subregions of the object-sensitive lateral occipital complex (LOC; Kriegeskorte et al., 2003; Murray et al., 2003; Paradis et al., 2008; Peuskens et al., 2004), and mid-level regions like V2 and V3 (Paradis et al., 2000; Vanduffel et al., 2002).

For a complex stimulus, like 3D structure-from-motion, where motion, depth, and shape processing all play a role, it is unsurprising that a wide network of visual cortex would be involved in processing the task. Peuskens et al. (2004) isolated the cortical regions associated with different aspects of SFM task performance by having the subject separately judge changes in the shape, motion, or texture while observing the same SFM stimuli. Motion judgments involved only dorsal regions such as hMT/V5+ and anterior IPS, and texture judgments involved only ventral regions, such as the middle and posterior collateral sulci, and the middle lingual gyrus. However, when subjects were asked to judge the shape of the SFM stimuli, both dorsal (MT/V5+ and IPS) and ventral (the lateral occipital sulcus (a subregion of LOC) and the inferior temporal gyrus) regions were involved. These results strongly suggest that SFM shape discrimination tasks, similar to that used in the current experiment, specifically involve high-level integration of information across both ventral and dorsal pathway regions.

Conclusions

The current study identifies a 3D SFM processing deficit in amblyopic observers that is present in both amblyopic and fellow-fixing eyes. This deficit cannot be attributed to known limitations in low-level contrast detection or higher level integration and, therefore, likely reflects deficits endemic to a point in the extrastriate cortex concerned with dorso-ventral integration.

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