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The influences of visibility and anomalous integration processes on the perception of global spatial form versus motion in human amblyopia

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Abstract

Do amblyopes demonstrate general irregularities in processes of global image integration? Or are these anomalies stimulus specific? To address these questions we employed directly analogous global-orientation and global-motion stimuli using a method that allows us to factor out any influence of the low-level visibility loss [Simmers, A. J., Ledgeway, T., Hess, R. F., & McGraw, P. V. (2003). Deficits to global motion processing in human amblyopia. *Vision Research* 43, pp. 729–738]. The combination of orientation and motion coherence thresholds reported here provides comparable psychophysical measures of global processing by spatial-sensitive and motion-sensitive mechanisms in the amblyopic visual system. The results show deficits in both global-orientation and global-motion processing in amblyopia, which appear independent of any low-level visibility loss, but with the most severe deficit affecting the extraction of global motion. This provides evidence for the existence of a dominant temporal processing deficit in amblyopia.

Keywords: Amblyopia; Contrast; Global; Spatial; Extrastriate

1. Introduction

Amblyopia is characterized by distorted representations of spatial form and over the past 40 years, the site of the perceptual deficit in human amblyopia has been the subject of considerable speculation. Although it is known that the site of the processing deficit is cortical, rather than retinal, in both humans and animals (for a current review see Moseley & Fielder, 2002), little is known about its extent within the cortex.

Amblyopia is thought to reflect alterations in the neuronal properties of V1, including reduced spatial resolution, reduced contrast sensitivity and a reduced number of binocular cells (Chino, Shansky, Jankowski, & Banser, 1983; Crewther & Crewther, 1990; Eggers & Blakemore, 1978; Kiorpes, Kiper, O'Keefe, Cavanaugh, & Movshon, 1998). Animal models, however suggest that while the known single cell deficit to the striate cortex may be sufficient to characterize the loss in resolution and contrast sensitivity, it is insufficient to explain many of the perceptual anomalies reported in amblyopia (Barrett, Pacey, Bradley, Thibos, & Morrill, 2003; Kiorpes et al., 1998; Kiorpes & McKee, 1999). This

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has led to the suggestion that additional deficits may exist beyond the striate cortex. Modest evidence from both primate (Movshon et al., 1987) and cat studies (Schroder, Fries, Roelfsema, Singer, & Engel, 2002) support a disruption in the binocular organization of extrastriate cortical areas in amblyopia. It is also clear from neuroimaging studies that additional cortical deficits are associated with visual processing stages (areas) beyond striate cortex in human amblyopia (Barnes, Hess, Dumoulin, Achtman, & Pike, 2001; Imamura et al., 1997; Sireteanu, Tonhausen, Muckili, Zanella, & Singer, 1998).

It follows then that in recent years it has become increasingly apparent that the extent of the deficit in amblyopia can depend on the visual function measured. The key question is whether higher integrative levels of visual processing "inherit" abnormalities from lower levels, or whether additional developmental abnormalities arise in direct consequence of impoverished visual input.

In visual space it is often necessary to integrate (i.e. compare, combine or pool) information over an extended area to derive a reliable and accurate global percept. This means that information about image structure over extended areas of visual space must be based on the combined responses of a number of independent, local inputs. Studies of the integration of motion and orientation are thought to reflect the integrative properties of neurons in primate extrastriate cortex and in normal observers such global estimates of mean direction (Kiorpes, 2003; Newsome & Pare, 1988; Verghese, Watamaniuk, McKee, & Grzywacz, 1999) and orientation (Dakin, 2001; Dakin & Watt, 1997) can be combined with great accuracy in the absence of spatial structure. These results are consistent with both psychophysical (Burr, Morrone, & Vaina, 1998) and neurophysiological evidence (Felleman & Van Essen, 1987; Gattass, Gross, & Sandell, 1981) showing increases in receptive field size at higher stages of visual processing.

Current work has revealed abnormalities in such global processing in amblyopia. Form integration paradigms have shown deficits in contour integration (Chandna, Pennefather, Kovacs, & Norcia, 2001; Hess, McIlhagga, & Field, 1997; Kovacs, Polat, Pennefather, Chandna, & Norcia, 2000; Kozma & Kiorpes, 2003), judgments of circularity (Hess, Wang, Demanins, Wilkinson, & Wilson, 1999; Jeffrey, Wang, & Birch, 2004), global orientation discrimination (Simmers & Bex, 2004) and the detection of structure in Glass patterns (Kiorpes, 2003; Lewis et al., 2002). Motion integration deficits have also been revealed after early visual deprivation in humans (Ellemberg, Lewis, Maurer, Brar, & Brent, 2002; Simmers, Ledgeway, Hess, & McGraw, 2003) and monkeys (Kiorpes, 2003; Tang et al., 1998). These results certainly imply a far more complex perceptual change in amblyopia than would be predicted by the well established losses in resolution and contrast sensitivity. Furthermore higher-level capabilites such as the individuation of elements or "counting" (Sharma, Levi, & Klein, 2000) the perception of visual illusions (Popple & Levi, 2000) and more recently, mirror symmetry (Levi & Saarinen, 2004) have also been reported abnormal in amblyopia.

Recently, we have reported global-motion processing deficits in human amblyopia that are unrelated to (independent of) the contrast sensitivity deficit, and that these may be more extensive for contrast-defined than for luminance-defined stimuli (Simmers et al., 2003). In that study we employed random-dot-kinematograms (RDKs) of the type originally developed by Newsome and Pare (1988). Normal and amblyopic observers were required to identify the global (overall) direction of image motion carried by a small proportion of dots that were displaced in a consistent direction ("signal" displacements) amongst spatially interspersed dots whose displacement directions were stochastic ("noise" displacements). As this task necessarily requires the ability to integrate local motion information across space and time, we speculated that the site of these deficits must include the extrastriate cortex, in particular the dorsal stream. Several visual areas within the dorsal stream, such as MT/V5 and MST (and their human homologues), appear well suited to mediate global-motion processing as they contain cells whose receptive fields extend over very large regions of space. However it is currently unknown whether amblyopes demonstrate more general irregularities in the processing of global image structure (e.g. motion, orientation, etc.) or exhibit anomalies that are specific to encoding global motion direction.

Therefore, as there is now firm evidence that global-motion processing is anomalous in amblyopia and because of the importance of extrastriate processing for such a task, the present investigation employs a directly analogous global-orientation task to assess the relative involvement of form-sensitive mechanisms in the extraction of the overall image spatial structure in amblyopia. It is likely that sensitivity to global form and global motion are mediated by distinct functional processing mechanisms in the visual system although these do not necessarily correspond to the gross anatomical separation of dorsal and ventral streams (Braddick, O'Brien, Wattam-Bell, Atkinson, & Turner, 2000). Indeed there is accumulating evidence of not only convergence of the magno- and parvocellular inputs (Devalois, Cottaris, Mahon, Elfar, & Wilson, 2000; DeYoe & Van Essen, 1988; Sawatari & Callawat, 1996; Takeuchi, De Valois, & Hardy, 2003) but functional interactions between the neural mechanisms involved in the processing of shape and motion information about objects (Kourtzi, Bulthoff, Erb, & Grodd, 2001). Therefore this dichotomy may not be as marked as originally thought.

It has also been suggested that the course of development for dorsal stream mechanisms (motion coherence tasks) may be more protracted than those underlying ventral stream mechanisms (form coherence tasks) (Braddick, Atkinson, & Wattam-Bell, 2003; Gunn et al., 2002). It is therefore possible that the relative efficacy of each may be differentially affected during visual development. However if the impoverished ability of amblyopes (compared with normals) to extract global-motion direction is indicative of a more general and nonspecific deficit influencing the fidelity of processes which serve to integrate local visual cues, regardless of how they are defined, performance on a global-orientation task might well be expected to be compromised to a similar degree.

Comparing findings across previous studies that have investigated global perceptual processing in amblyopia is difficult because of (1) the variety of paradigms employed and the likelihood that different mechanisms underlie sensitivity (i.e. Glass patterns versus contour integration) (2) the different types of amblyopia (i.e. stimulus deprivation versus strabismus or anisometropia). Therefore, in the present investigation and as a continuation of our global-motion paradigm we have undertaken an analysis that distinguishes between contrast-dependent (i.e. visibility-based) as opposed to signal:noise-dependent deficits in strabismic and anisometropic amblyopia, in an attempt to ascertain whether any global-orientation processing deficits observed are striate or extrastriate in origin. Importantly this task is directly analogous to the global-motion task therefore allowing a comparison between form and motion sensitive mechanisms in amblyopia as well as assessing performance for both first-order and second-order stimulus types. Observers were required to make judgments of the global statistics (in this case the overall or net orientation) of a stimulus composed of a large number of randomly positioned dots (elements) as a function of the dot modulation or contrast (visibility) of the dots (see Fig. 1 for illustrations). Coherence thresholds were quantified through the gradual introduction of incoherently orientated pairs of neighbouring dots until the global organization could no longer be detected reliably. Although a local mechanism can encode the orientation of any single pair or cluster of elements in the stimulus, performance is ultimately limited by a global mechanism that integrates local estimates over the entire visual field.

2. Methods

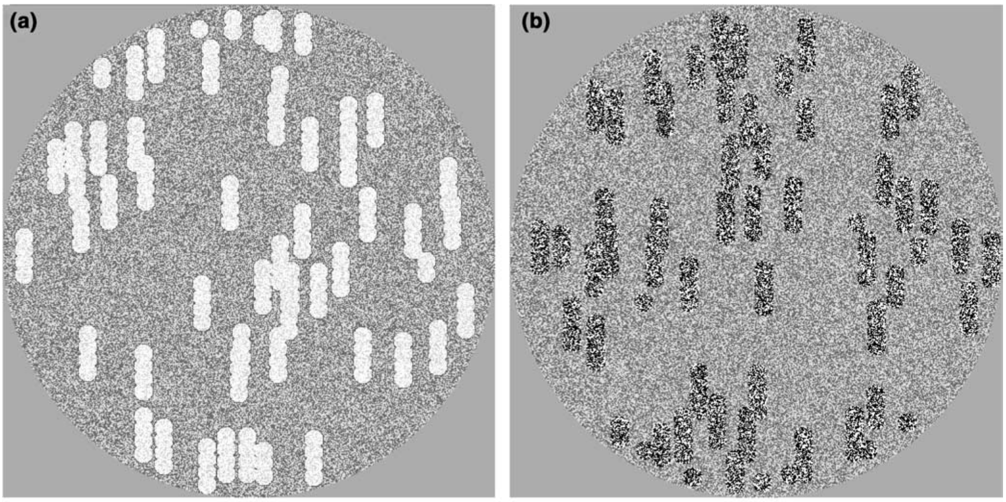
2.1. Observers

Three strabismic, four anisometropic and three strabismic/anisometropic amblyopes (29.9 ± 10.5 years) were recruited for the study (see Table 1 for clinical details). For the purposes of this study amblyopia was defined as a visual acuity of 20/30 or worse in the amblyopic eye and anisometropia was defined as an interocular difference of greater than 1.00 dioptre sphere or 1.0 dioptres of cylinder. A control group of eight observers (mean age 29.4 ± 5.8 years) with normal visual acuity and normal binocular vision were selected. Viewing was monocular in all cases with the appropriate refractive correction. All experimental procedures followed the institutional guidelines, and informed consent was obtained after the nature and possible consequences of the experiment had been explained. All subjects were experienced in psychophysical testing.

2.2. Apparatus and stimuli

Stimuli were computer generated and displayed on an *SONY Multiscan 520 GS* monitor (with a frame rate of 75 Hz), which was gamma-corrected with the aid of internal look-up-tables. As an added precaution psychophysical procedures were used to ensure that any residual luminance non-linearities were minimized (Ledgeway & Smith, 1994; Nishida, Ledgeway, & Edwards, 1997). The stimuli were presented within a circular window at the centre of the display, the diameter of which subtended an angle of 12° at the viewing distance of 0.84 m. The mean luminance of the remainder of the display (which was homogeneous) was approximately 50 cd/m^2.

In order to illustrate the analogous relationship between the global-orientation stimuli used in the present experiment and the global-motion stimuli we have used previously (Simmers et al., 2003), it is informative to consider the construction of the latter stimuli first. In a global-motion stimulus (RDK) a random spatial array of dots is presented on the first frame of a motion sequence and on subsequent frames the dots are displaced in order to create the impression of motion. The global-motion coherence level of the stimulus is manipulated by requiring only a percentage of the dot displacements on each image update to be in the same direction ("signal" displacements) and the remainder to be in random directions ("noise" displacements). In our previous work, for example, the direction of the "signal" displacements was chosen to be either upwards or downwards on each trial with equal probability. It is evident that over the total time course of the display the individual dots will trace out trajectories in space that, in principle, can be considered as "motion streaks" in space–time. The overall orientation of these streaks in space–time indicates the direction of global motion and their spatial extent depends on the motion coherence level (percentage of "signal" displacements present on each image update).



First-order (luminance-defined) dots

Second-order (contrast-defined) dots

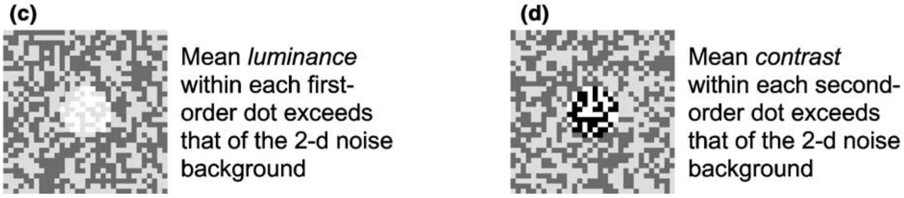


Fig. 1. Illustration of the (a) first-order (luminance-defined) and (b) second-order (contrast-defined) global-orientation dot stimuli used in the present study. The orientation coherence of the stimuli is ~100% and "orientation streaks" (in this case vertical), formed by local clusters of spatially proximal dots, are readily discernible in each image. A magnified view of a single first-order dot (c) and a single second-order dot (d) are shown for clarity (see text for details).

The motion streaks become readily apparent if the individual frames of a RDK motion sequence are simply spatially superimposed to create a single static image. This effectively converts the motion information carried by the dots into spatial orientation information (i.e. the motion streaks appear as "orientation streaks" in the resulting space–space representation). Perceptually these tasks are identical to the observer, integrating frames *sequentially* produces continuous apparent motion (motion streaks in space–time) and *simultaneously* produces spatial structure i.e. orientation (orientation streaks in space–space), thereby allowing us to directly compare integration over both time and space.

In the present experiment we used this technique (see below) to construct global-orientation stimuli (Fig. 1) that are directly comparable to the global-motion stimuli we have used previously to study amblyopia.

Each global-orientation stimulus was generated anew immediately prior to its presentation (on any one trial) and was composed of a single image containing a spatial array of circular dots. This was achieved in practice by computing a nominal RDK global-motion sequence composed of four successive frames (each containing 50 non-overlapping dots of diameter 0.47°). In the first frame the dot positions were determined randomly and on subsequent frames were displaced by 0.3°. The individual frames were then spatially superimposed to create a single static image that was then presented for a total stimulus duration of 426.7 ms. This enabled us to produce displays in which the consistency of the local orientation signals between matching pairs of neighbouring dots (separated spatially by 0.3°) could be varied (i.e. signal:noise ratio of the local orientations could be varied to measure a global-orientation coherence threshold). Performance, which is quantified in terms of the minimum number of "signal" dots (coherence) required to support orientation discrimination, was measured as a function of the dot modulation or contrast (visibility) of the dots. The stimulus conditions were therefore directly comparable to those used previously to investigate both first-order and second-order global motion perception (Simmers et al., 2003).

Each dot was composed of two-dimensional (2-d), static noise produced by assigning individual screen pixels (1.41×1.41 arc min) within the area of each dot to be "black" or "white" with probability 0.5. The dots were presented on a 2-d, static noise background which filled the entire circular display window (mean luminance of 50 cd/m^2 and Michelson contrast of 0.1), either the mean luminance (in the case of first-order dots as shown in Fig. 1a and c) or the mean contrast (in the case of second-order dots as shown in Fig. 1b and d)

Table 1
Clinical characteristics of the amblyopic subjects

Subject	Visual acuity	Spectacle prescription	Ocular alignment
●[a]	RE 20/15	RE + 3.25DS	L XOT
	LE 20/40	LE + 3.75DS	10Δ
■[a]	RE 20/20	Nil	LSOT
	LE 20/200		14Δ
◆	RE 20/80	Nil	R SOT
	LE 20/20		18Δ
■[a]	RE 20/80	RE + 5.00DS	R SOT
	LE 20/20	LE + 1.75	16Δ
◆[a]	RE 20/20	RE − 2.25/−1.25 × 180	L XOT
	LE 20/50	LE − 3.00/−1.75 × 170	10Δ
●[a]	RE 20/20	RE + 4.00/ − 1.00 × 170°	L XOT
	LE 20/127	LE + 6.00/ − 1.75 × 177°	10Δ
●[a]	RE 20/15	RE piano	Straight
	LE 20/80	LE + 2.50DS	
■[a]	RE 20/15	RE − 0.25DS	Straight
	LE 20/200	LE + 3.50/−0.50 × 90°	
◆[a]	RE 20/25	RE + 1.50DS	Straight
	LE 20/50	LE + 3.00/−0.5 × 150°	
▲	RE 20/20	RE + 0.25/−1.75 × 135°	Straight
	LE 20/30	LE + 0.75/−3.50 × 55°	

Red symbols correspond to individual strabismic, green symbols to strabismic anisometropes and blue symbols to anisometropic amblyopes—superscript "a" indicates amblyopic subjects who participated in both the global-orientation and global-motion experiments. (For interpretation of colour in this table, the reader is referred to the web version of this article.)

of which could be less than that of the noise within the dots.

The luminance modulation (visibility) of the first-order dots was defined as

$$\text{Dot luminance modulation} = (\text{DL}_{\text{mean}} - \text{BL}_{\text{mean}})/(\text{DL}_{\text{mean}} + \text{BL}_{\text{mean}}),$$

where DL_{mean} and BL_{mean} are the mean luminances of the noise within the dots and background, respectively, averaged over pairs of noise elements with opposite luminance polarity. The luminance modulation of the first-order dots could be varied in the range 0–0.3 (separated by ~1/6 octave steps). This gave us a possible 36 modulation amplitudes for the luminance-defined stimuli. [1]

The contrast modulation (visibility) of the second-order dots could be varied in an analogous manner according to the equation:

$$\text{Dot contrast modulation} = (\text{DC}_{\text{mean}} - \text{BC}_{\text{mean}})/(\text{DC}_{\text{mean}} + \text{BC}_{\text{mean}}),$$

where DC_{mean} and BC_{mean} are the mean contrasts of the noise within the dots and background, respectively, computed over pairs of noise elements with opposite luminance polarity. The contrast modulation of the second-order dots could be varied in the range 0–0.8 (separated by ~1/48 octave steps). This gave us a possible 66 modulation amplitudes for the contrast-defined stimuli. [1]

2.3. Procedure

In the present task, neighbouring dots within the display were positioned relative to each other such that they were oriented either consistently (co-linearly) to form an elongated streak ("signal" orientations) or in a random manner ("noise" orientations). The dots defining the "noise" orientations had a random "positional" displacement, but the same separation as the dots comprising the "signal" orientations, and were offset in a random direction (spanning the 360° range) from the previous dot in the orientation streak.

The observer's task was to indicate whether the "signal" orientations were either horizontal or vertical (randomised on each trial). Global-orientation thresholds were measured using an adaptive staircase procedure that varied the proportion of local "signal" orientations (orientation coherence level) present on each trial, according to the observer's recent response history. At the beginning of each run of trials the staircase began with the maximum number of "signal" orientations possible (i.e. with 100% orientation coherence all dots formed extended streaks oriented along the same axis). This was decreased following three correct consecutive responses and increased following each incorrect global-orientation judgement. The staircase tracked the global-orientation coherence level producing 79% correct responding. Eight staircase reversals were collected before the staircase terminated and the threshold was taken as the mean of the last six reversal points. Each threshold reported is based on the mean of at least five such staircases. In those observers with amblyopia, measurements were repeated with both the amblyopic eye and non-amblyopic eye in random order. In normal observers the right or left eye was randomly assigned.

3. Results

Fig. 2a shows the mean normal result (black symbols) in which global-orientation thresholds for first-order dots are plotted against the dot modulation (contrast). Similar to global-motion thresholds (Edwards, Badcock, & Nishida, 1996; Simmers et al., 2003)

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[1] All observers began each trial at the highest modulation amplitude for both stimuli types this was then reduced to a level at which performance reached chance. The range of amplitude modulations chosen in between these two values were tailored for each individual observer. To fit the data reliably, performance was assessed at no fewer than 10 modulation depths for both luminance and contrast-defined stimuli.

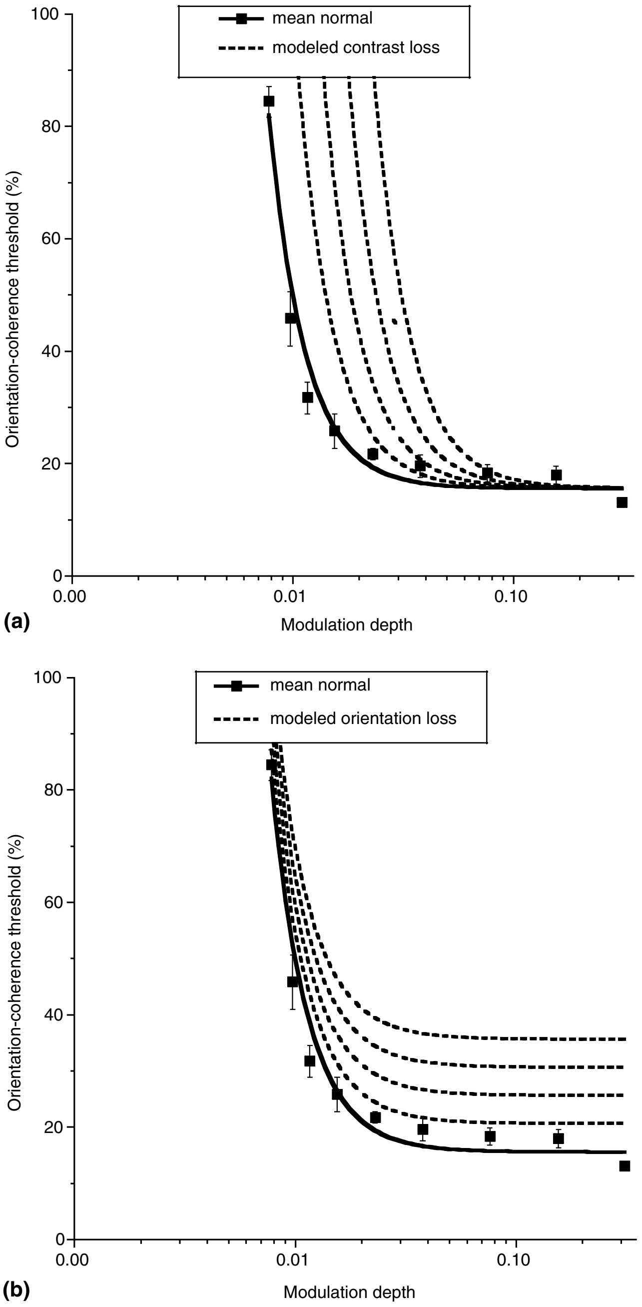

Fig. 2. The mean first-order (luminance-defined) global-orientation coherence thresholds for the eight normal observers are plotted as a function of the dot modulation. The relationship between the global-orientation threshold and the magnitude of the dot modulation is fitted by a power function plus a constant. (a) The dashed curves demonstrate hypothetically how a systematic difference in absolute sensitivity can be predicted by a simple translation of the threshold versus dot modulation function along the dot contrast axis (a contrast-specific deficit). (b) The dashed curves again demonstrate in theory how a systematic difference in the ability to extract global orientation, will manifest as a simple translation of the threshold versus dot modulation function along the threshold axis (a global orientation-specific deficit).

global-orientation thresholds exhibit asymptotic behavior at high levels of dot modulation but increase markedly as the magnitude of the dot modulation decreases. In the case of normal observers, the relationship between the global-orientation threshold and the magnitude of the dot modulation is well described by a power function plus a constant (solid black line). $y = ax^b + c$, where a, b and c are constants. For the normal population the mean corresponding values for the first-order stimuli are $a = 1.75\text{e}{-04}$ (±8.72e−05 s.e.m); $b = -2.65$(±0.1 s.e.m); $c = 15.69$ (±0.31 s.e.m) and for the second-order stimuli are $a = 1.37$ (±0.25 s.e.m); $b = -3.46$ (±0.17 s.e.m); $c = 23.88$ (±0.79 s.e.m).

Similar to our global-motion task, if performance in amblyopia is limited by reduced visibility due to the contrast sensitivity deficit thought to reside in V1, then we would expect the response function (mean global-orientation threshold versus dot modulation (contrast)) for the amblyopic visual system to be well described by a laterally translated (to the right on this co-ordinate system) version of the normal response curve, as modeled by the dashed curves also depicted in Fig. 2a.

However, if performance is solely limited by a deficient global-orientation extraction process, the response function for the amblyopic visual system should shift vertically on these axes, as shown by the model predictions (dashed curves) in Fig. 2b.

The raw data for individual amblyopic subjects is displayed in Fig. 3 for both first-order (Fig. 3a) and second-order (Fig. 3b) stimuli. Whilst most amblyopes displayed reduced performance on this task, the underlying deficit was composed of both a contrast/visibility component (evident by a lateral shift in the response function) and a global orientation-based component (evident by a vertical shift in the response function).

Fig. 3 illustrates well the variability of deficit in the raw data for our group of amblyopic observers; it is difficult to assess by inspection the degree to which each response function is shifted either vertically or laterally. Therefore a summary of the relative contributions of visibility and global-orientation processing to the overall deficit is shown in Fig. 4, where the derived component anomalies for contrast and global-orientation deficits are plotted for individual amblyopes. These component anomalies were best described by independently fitting a two-parameter model, and taking the ratio of the best fitting parameters describing the lateral (contrast or visibility) and vertical (global-orientation sensitivity) shifts to the raw data, to bring them into correspondence with the mean performance exhibited by normal subjects. In all cases the numerator is represented by the mean values for the normal observers (see above) and the denominator is that of each individual amblyope. The dashed line(s) represent a ratio of one indicating no difference in threshold between the normal and amblyopic observers with respect to either the contrast or global-orientation extraction of the stimuli.

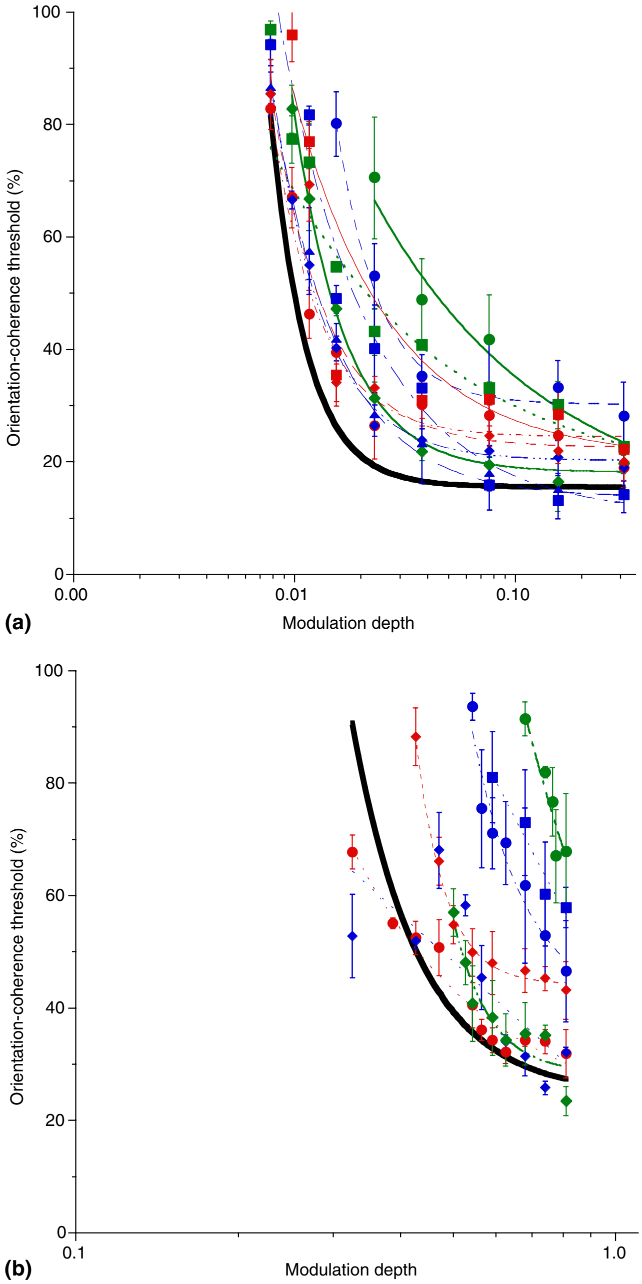

Fig. 3. Individual global-orientation thresholds. The solid black line represents the mean results for eight normal observers: (a) shows the global-orientation threshold of each individual amblyope for the luminance-defined, first-order dots and (b) shows the global-orientation threshold of each individual amblyope for the contrast-defined, second-order dots. Each datum represents the mean of a minimum of five blocks of trials and error bars represent ±1 s.e.m. Curves represent a power function fit to the data.

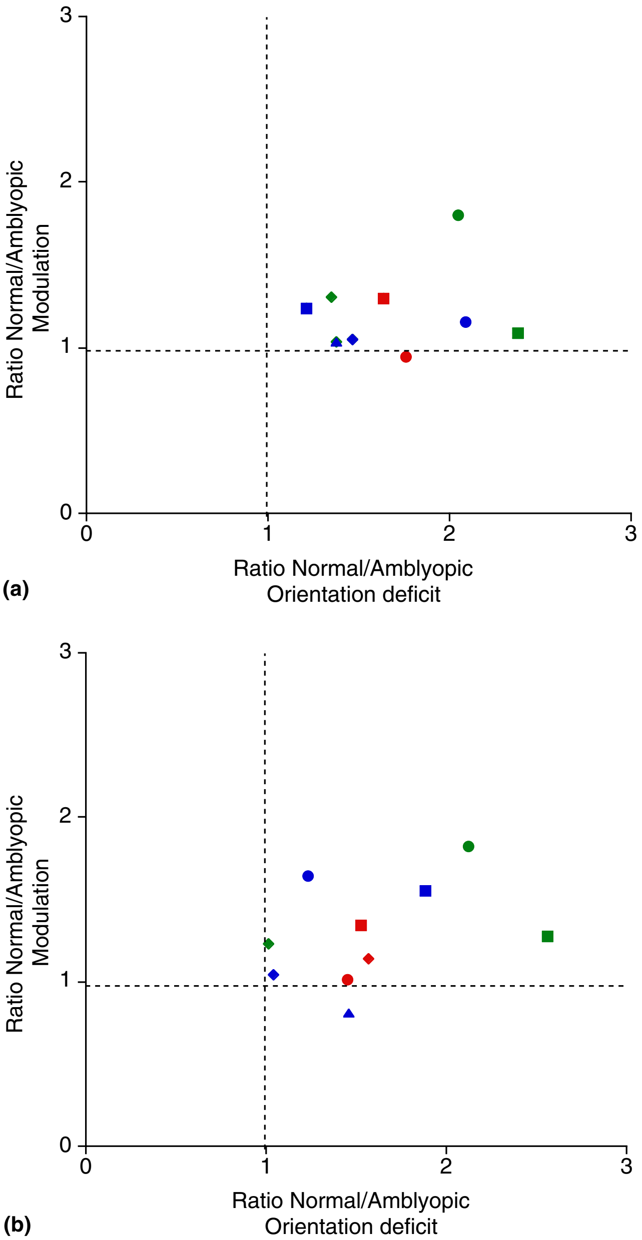

Fig. 4. Ratio of normal to amblyopic eye performance for both first-order (a) and second-order (b) stimuli. The dashed line(s) represent a ratio of one indicating no difference in threshold between the normal and amblyopic observers with respect to either encoding the contrast or extracting the global orientation of the stimuli. Values falling along the horizontal dashed line are consistent with a deficit specific to extracting global orientation; values that fall along the vertical dashed line are consistent with a contrast-specific deficit.

Due to the limited sample size per amblyopic subject group (strabismic versus anisometropic versus anisometropic strabismics) and in order not to violate the assumptions of ANOVA, analyses were carried out for a single generic amblyopic subject group. Therefore to fully explore the pattern of deficits in this subject group, an analysis of variance was carried out for *amblyopic subject group* (all amblyopes) and the factors of *stimulus type* (first-order versus second-order) and *component anomaly* (contrast versus global orientation). ANOVA revealed no significant effect of stimulus type (first-order versus second-order) ($F = 0.001$; $p = 0.98$) and a significant effect of the component anomaly (spatial versus visibility) ($F = 11.369$; $p = 0.002$) with no significant interaction ($F = 0.64$; $p = 0.43$). Therefore, unlike our previous global-motion task amblyopes did not show a greater deficit or indeed a selective loss, as has previously been reported for isolated static stimuli (Wong, Levi, & McGraw, 2001), in the processing of second-order patterns. There was however a significant main effect of component anomaly ($F_{(1,7)} = 9.705$; $p = 0.01$) demonstrating that global-orientation deficits, when collapsed across subject group and stimulus type, were significantly greater than contrast (visibility) deficits. None of the other possible interactions reached significance at the 0.05 probability level. Although the sample size may have been too small for statistical analysis of any group differences, the figures appear to show no difference across patient types (strabismic versus anisometropic versus anisometropic strabismics). These results do however provide clear evidence for a global-orientation processing deficit in amblyopia that cannot be simply explained by reduced visibility resulting from the known contrast sensitivity loss.

Conventional visual acuity measures in the amblyopic eye were also not found to be a reliable indicator of overall performance with no significant correlation between either first-order contrast ($r_{(8)} = -0.22$; NS) or global orientation ($r_{(8)} = -0.06$; NS) and second-order contrast ($r_{(8)} = -0.26$; NS) or global orientation ($r_{(8)} = -0.23$; NS). This is evident in Fig. 4a and b where the poorest (■ 20/200) and best (▲ 20/30) individual visual acuities in the amblyopic subject group do not then consequently dictate the upper and lower limits of either the contrast *or* orientation based deficit.

In a directly analogous task we have previously reported a global-motion deficit in amblyopia that was significantly larger for second-order stimuli than first-order stimuli. However in the present experiment the deficits for global-orientation processing for both types of stimuli were found to be of comparable magnitude in the amblyopic subject group. To determine whether amblyopes are anomalous at integrating visual information in general, we assessed performance with the comparable global-motion task (for details see Simmers et al., 2003) in eight of our amblyopic subjects (see Table 1 for subject selection).

Fig. 5 compares the ratios obtained with the same individual amblyopic subjects for global-motion and global-orientation encoding deficits with both first-order (a) and second-order (b) stimuli. Interestingly there were significant differences between the results obtained in each of the four conditions ($F_{(3,21)} = 8.580$; $p = 0.03$). Pairwise comparisons (*t*-test) revealed that the deficits in global-motion processing were significantly more extensive for the second-order stimuli than the first-order motion stimuli. In addition the second-order, global-motion processing deficit was significantly greater than the global-orientation encoding deficits for both types of stimuli.

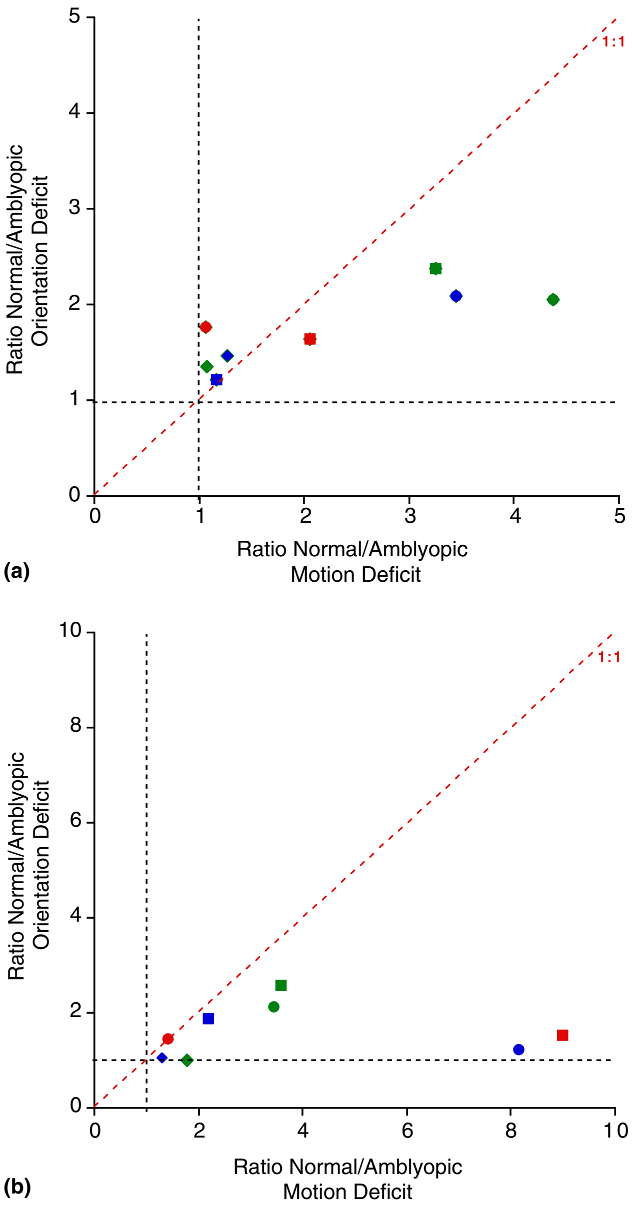

Fig. 5. Comparison of the ratios for global-motion and global-orientation performance for both first-order (a) and second-order (b) stimuli in the same amblyopic observers. The dashed line(s) represent a ratio of one indicating no difference in threshold between global-motion and global-orientation deficits measured using comparable visual stimuli. Values falling along the horizontal dashed line are consistent with a deficit affecting only global-motion processing; values that fall along the vertical dashed line are consistent with a orientation-specific deficit. The red dashed line represents the 1:1 line and the preponderance of values lying beneath this line indicate a greater deficit in global motion extraction, especially for the second-order stimuli. (For interpretation of colour in this figure, the reader is referred to the web version of this article.)

Fig. 6 compares the modulation (contrast) processing deficits in the same individual amblyopic subjects measured using the global-motion and global-orientation tasks with both first-order (a) and second-order (b) stimuli. This figure clearly illustrates the comparable nature

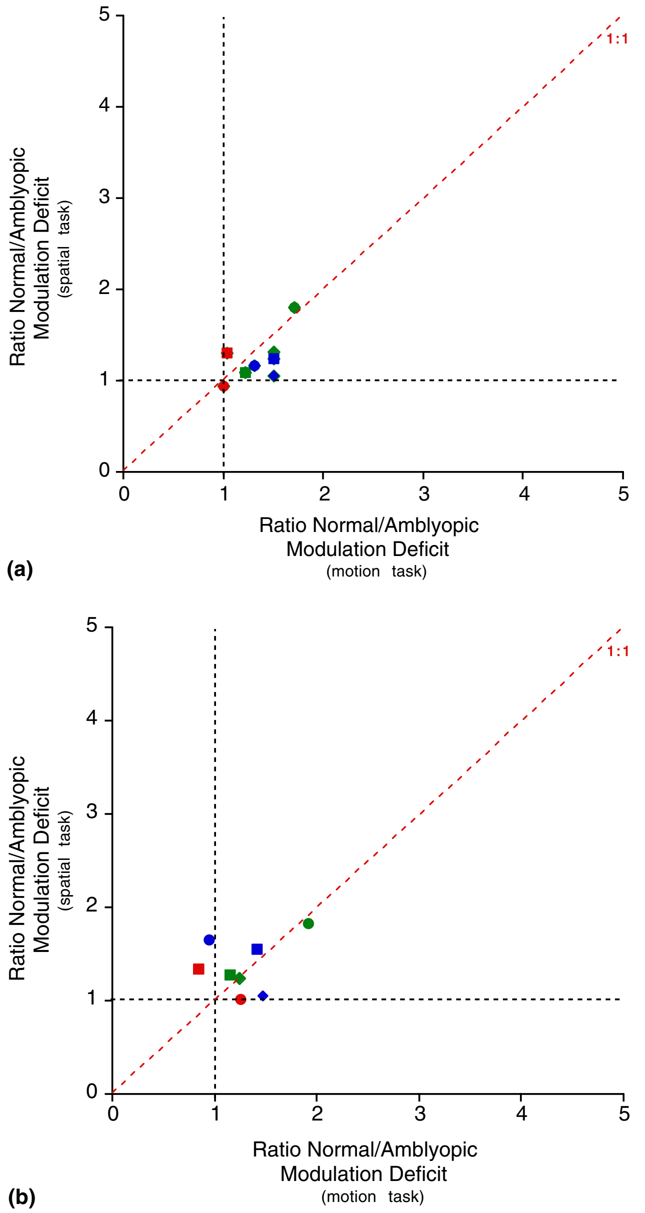

Fig. 6. Comparison of the ratios for the contrast-specific deficits present for both first-order (a) and second-order (b) stimuli. The dashed line(s) represent a ratio of one indicating no difference in the contrast-specific deficit between the global-motion and global-orientation experiment. The red dashed line represents the 1:1 line and the preponderance of values lying on this line indicates that any contrast-specific loss present in individual amblyopic subjects was comparable in terms of magnitude between the global-motion and global-orientation tasks. (For interpretation of colour in this figure, the reader is referred to the web version of this article.)

of any visibility loss with respect to either experimental paradigm, with no significant differences being evident ($F_{(3,21)} = 0.842$; NS).

These results are important in that not only have we shown deficits in global-orientation and global-motion processing in amblyopia, which appear to be independent of any low-level visibility loss, the ability to integrate local second-order motion signals across space and time (to derive a global percept of image motion) appears to show the greatest impairment overall.

This is readily evident in Fig. 7, which summarises the magnitudes of the component anomalies found using the two tasks. This clearly suggests that there is a temporal processing deficit in amblyopia, which is particularly marked for the encoding of second-order, global-motion direction.

4. Discussion

Our study shows convincingly that there is also a global-orientation processing deficit in human amblyopia that consists of both contrast (visibility) and signal:noise dependent components. These deficits are present for both luminance-defined and contrast-defined stimuli, but interestingly the spatial integration based loss is not as extensive as that found for the processing of analogous global-motion stimuli, particularly in the case of contrast-defined patterns (see Fig. 7). This is a strong conclusion because the motion and spatial tasks were identical in every respect except for the fact that the motion stimuli were presented sequentially whereas the spatial stimuli were presented simultaneously. For motion, second-order stimuli were more affected than first-order ones, a result not found for spatial processing. These results suggest independent deficits for spatial and motion coding in amblyopia with global-motion coding being affected more severely, particularly for second-order stimuli.

In a comparison of monocular versus binocular deprivation (congenital cataracts) two separate studies have looked at sensitivity to form (Lewis, Ellemberg, Maurer, Wilkinson, & Wilson, 2002) and motion (Ellemberg et al., 2002) integration. In both studies binocular deprivation consistently resulted in a more profound loss of visual function and as in the present study a greater loss in sensitivity was evident for the perception of global motion. Although obvious comparisons can be made between these and our own study, deprivation amblyopia is in itself a rare and uncommon form of amblyopia typically associated with very poor residual visual function and widely believed to be both qualitatively and quantifiably different from the more common forms of amblyopia (strabismus and anisometropia), therefore this paradigm may not be especially useful in understanding amblyopia generally.

Useful comparisons may however be drawn from a recent behavioral study, which looked at contour integration in amblyopia as a form of global perceptual organization in non-human primates (Kozma & Kiorpes, 2003). In this study contour integration was impaired in both strabismic and anisometropic animals and similar to our study the integration deficits were

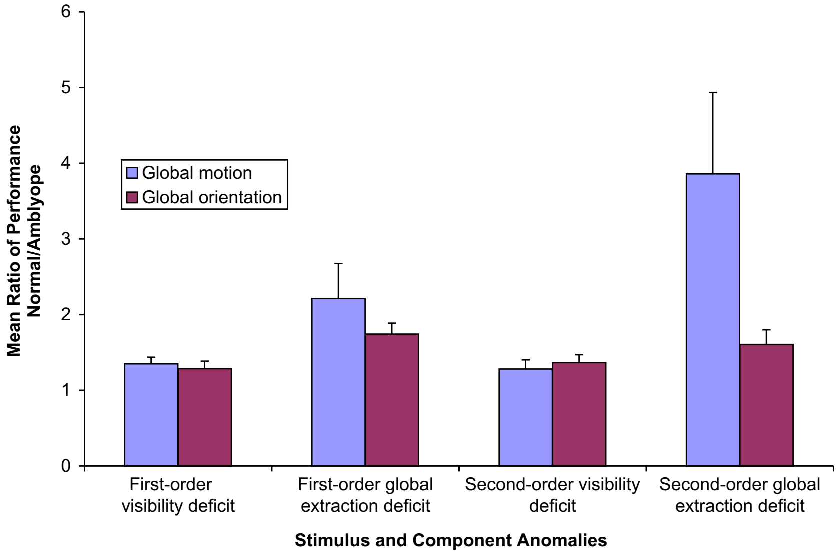

Fig. 7. Summary of the mean deficits (±1 standard deviation) in amblyopic performance consistent with losses specific to encoding stimulus contrast (visibility), global orientation and global motion for both first-order and second-order stimuli.

also clearly unrelated to losses in contrast sensitivity, supporting our findings in the present study that deficits in global processing appear independent of any low-level visibility loss. Coupled with deficits to the fellow eye (Kovacs et al., 2000; Simmers et al., 2003) this would indicate a disruption to processing mechanisms beyond V1. The authors suggest that elevated central noise in the amblyopic visual system could be responsible for losses in sensitivity.

On the basis of the available neurophysiological evidence and the likelihood that more complex visual processing occurs in a roughly hierarchical fashion further along the visual pathway, it seems not unreasonable to locate the contrast-dependent anomaly in striate cortex where it has been shown by numerous studies that cells in the amblyopic visual system have altered spatial responses and lowered contrast sensitivity (Chino et al., 1983; Crewther & Crewther, 1990; Eggers & Blakemore, 1978; Kiorpes et al., 1998; Movshon et al., 1987). The signal:noise deficit (ability to integrate local information across the visual field) is likely to involve extrastriate visual areas where single cell neurophysiology has documented cells with much larger receptive fields composed of multiple subunits capable of such an integrative role (Movshon, Adelson, Gizzi, & Newsome, 1985). This is not meant to imply, however, that a common mechanism would necessarily mediate both the integration of oriented static spatial cues and the integration of moving signals. Based on the little direct physiology that is available, the former could take place within the ventral stream; predominantly concerned with the processing of spatial form and may be associated with the perceptual discrimination of overall image shape and contour orientation and the latter almost certainly within the dorsal processing stream; which is concerned with motion processing with the ultimate role of motor actions (Ungerleider & Mishkin, 1982). Although functional interactions between the two now seem highly likely (Kourtzi et al., 2001). Within the context of this framework, our results for the present spatial task and the previous motion task (Simmers et al., 2003) suggest that there are deficits at the level of both the ventral and dorsal extrastriate cortex, it is interesting to speculate that the dorsal stream may be more disadvantaged in amblyopia, as evidenced by the relatively impaired performance of our observers on the global-motion detection task. The pattern of results reported here appears consistent with previous suggestions of dorsal stream vulnerability in specific developmental disorders and neurological impairment (Atkinson et al., 2001; Braddick et al., 2003; Gunn et al., 2002).

Interestingly, evidence is emerging that higher cortical areas are relatively delayed in their development compared to V1 (Bachevalier, Hagger, & Mishkin, 1991; Distler, Bachevalier, Kennedy, Mishkin, & Ungerleider, 1996; Rodman, 1994), and moreover that the extraction of local features appears to develop relatively early, whereas the integration of these local features may emerge substantially later and at different times for different types of image structure independent to the development of spatial resolution (Ellemberg et al., 2002; Kiorpes & Bassin, 2003; Kovacs et al., 1999; Lewis et al., 2002). These observations raise the intriguing possibility that specific visual deficits may co-vary with the age of onset of amblyopia.

Most perceptual anomalies that have been reported in amblyopia have been explicable in terms of the striate deficit that we know is present in animals made artificially strabismic, anisometropic or form-deprived (Chino et al., 1983; Crewther & Crewther, 1990; Eggers

& Blakemore, 1978; Kiorpes et al., 1998; Movshon et al., 1987). Few tasks requiring global integration of the kind reported in this study have been used on the same human amblyopes with comparable form (orientation) and motion stimuli and when they have the conclusions have not been definitive when it comes to extrastriate function. For example, contour integration tasks of the kind reported by Field, Hayes, and Hess (1993) and Kovacs and Julesz (1993) involve a global integrative process at which amblyopes have demonstrated reduced performance (Hess et al., 1997). However the cortical site of this type of integration is currently unknown, suggestions have been made implicating both striate and extrastriate sites (Altmann, Bulthoff, & Kourtzi, 2003; Kourtzi, Tolias, Altmann, Augath, & Logothetis, 2003; Kozma & Kiorpes, 2003). With respect to the reduced performance found in amblyopia one proposal that has been advanced, is in terms of the known positional deficit amblyopes demonstrate in judging the relative position of a target for well-separated stimuli (Hess & Holliday, 1992). Whether this positional deficit is downstream in V1 or situated in the extrastriate cortex where the integration proper may occur is presently unknown.

In another form of global perceptual processing the ability with which amblyopes can integrate local samples of orientation to judge the mean orientation of a population of differently oriented elements has been questioned. These studies would suggest that amblyopes are able to integrate orientation information across visual space with either no performance difference evident between the amblyopic and fellow eye (Mansouri, Allen, Hess, Dakin, & Ehrt, 2004) or conversely that the neural representation of local image structure appears to show a greater variability compared to normal performance in both the amblyopic and fellow eye (Simmers & Bex, 2004). The latter result being more consistent with the present study and a deficit at global stages of visual processing in amblyopia. Thus, it may well be that not all forms of global integration are equally affected in amblyopia.

Taken together the deficits in global-orientation and global-motion processing reported in the present study, suggest that global perceptual organization is impaired in amblyopia consistent with deficits to extrastriate processing mechanisms. Our finding that the integration of local motion signals is affected to a greater extent than comparable spatial integration would argue that the deficit in amblyopia differentially affects the dorsal extrastriate processing stream.

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