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Detection, discrimination and integration of second-order orientation information in strabismic and anisometropic amblyopia

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Abstract

To better understand the nature of the cortical deficit in amblyopia we undertook a systematic investigation of second-order processing in 8 amblyopic and 8 normal observers. We investigated local detection, discrimination and global integration. Our local stimulus consisted of a Gaussian patch of fractal noise multiplied by a 1-d sinusoidal modulator. Our global stimulus consisted of an array of such elements.

We revealed second-order detection deficits for stimuli with equi-visible carriers. Orientation discrimination for an isolated second-order patch was comparable in normal and amblyopic eyes. We showed that pure integration of second-order patterns can be normal in amblyopia.

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1. Introduction

Amblyopia involves more than just a deficit to the detection of high spatial frequencies (Gstalder, 1971; Hess & Howell, 1977; Lawwill & Burian, 1966; Levi & Harwerth, 1977). It involves deficits to the processing of supra-threshold stimuli as well (Bedell & Flom, 1981; Bradley & Skottun, 1984; Caelli, Brettel, Rentschler, & Hilz, 1983; Demanins, Hess, Williams, & Keeble, 1999; Fronius & Sireteanu, 1989; Hess, Burr, & Campbell, 1980; Hess & Holliday, 1992; Lawden, Hess, & Campbell, 1982; Pass & Levi, 1982; Treutwein, Rentschler, Zetzsche, Scheidler, & Boergen, 1996; Vandenbussche, Vogels, & Orban, 1986). A large number of such deficits have been highlighted, involving the processing of orientation, spatial frequency, phase, position and contrast

and this has modified the once held view that the neural substrate of amblyopia could be found in the properties of single cortical neurons in V1 (Crewther & Crewther, 1990; Eggers & Blakemore, 1978; Movshon et al., 1987). It is now accepted that there are not only anomalous interactions between cells, that is network abnormalities (Schmidt, Galuske, & Singer, 1999) but also processing beyond area V1 is likely to be affected (Kiorpes, Kiper, O'Keefe, Cavanaugh, & Movshon, 1998; Schroder, Fries, Roelfsema, Singer, & Engel, 2002).

Two important additions to this emerging picture have occurred recently. First, it has been shown that global processing of both motion and form are disturbed in amblyopia and that the basis for this is unlikely to be in V1 (Simmers, Ledgeway, Hess, & McGraw, 2003). Second, this deficit to global processing involves both luminance-modulated stimuli (first-order) and contrast-modulated stimuli (second-order) processing mechanisms, although the latter is more severely affected (Simmers

et al., 2003) also see (Wong, Levi, & McGraw, 2001). Most visual patterns are defined by a change in luminance over space. Second-order stimuli, on the other hand, are defined by a modulation in some other feature, for example contrast. It is likely that the mechanism that processes second-order texture or motion is at a higher level than the mechanism that processes luminance-defined patterns (Dumoulin, Baker, Hess, & Evans, 2003). The global processing deficit in amblyopia for both first- and second-order stimuli does not appear to be a consequence of the V1 loss; it is not due to a loss in visibility of the individual elements, the accuracy with which their positions are encoded or to anomalies at a more local level of processing (i.e. directional or orientational bandwidths). Since the main anomaly involves the stage of global processing (in particular second-order) and this type of processing is thought to occur in specific regions of extra-striate cortex (Dumoulin et al., 2003; Smith, Greenlee, Singh, Kraemer, & Hennig, 1998), it has been suggested that the extra-striate cortex may be primarily affected in amblyopia. This suggestion receives support from brain imaging studies using both PET (Imamura et al., 1997) and fMRI (Barnes, Hess, Dumoulin, Achtman, & Pike, 2001; Sireteanu et al., 1998). Since both motion and form global processing have been shown to be disrupted in amblyopia (Simmers et al., 2003, Simmers, Ledgeway, & Hess, 2005) it is assumed that both dorsal and ventral streams are affected. These psychophysical conclusions are consistent with animal neurophysiology where it has been recognized for some time now that the local processing deficits in V1 are not sufficient to explain the full extent of the behavioural loss (Chino, Shansky, Jankowski, & Banser, 1983; Crewther & Crewther, 1990; Kiorpes et al., 1998).

The two tasks that have been used to identify the deficit to global processing in amblyopia have both involved signals embedded in noise. In such a task, it is optimal for the visual system to integrate as much signal as possible but as little noise as possible: involving both integration and segregation. Our hypothesis is that it is the segregation aspect of these global tasks, rather than signal integration per se, that is particularly deficient in amblyopia. We have two reasons for thinking this. There is a large literature on the role of areas MT and MST in the primate in motion processing and in particular global motion processing (Baker, Hess, & Zihl, 1991; Britten, Shadlen, Newsome, & Movshon, 1992; Movshon, Adelson, Gizzi, & Newsome, 1985; Newsome & Pare, 1988; Rizzo, Nawrot, & Zihl, 1995; Salzman, Murasugi, Britten, & Newsome, 1992; Vaina, Lemay, Bienfang, Choi, & Nakayama, 1990; Zihl, von Cramon, & Mai, 1983). It is known that lesions to this region of the dorsal stream result in specific deficits for global motion processing in both monkeys (Newsome & Pare, 1988) and human (Rizzo et al., 1995; Vaina et al., 1990; Zihl et al., 1983). Furthermore, a study on a "motion-blind" patient (Baker et al., 1991) showed that the patient exhibited a severe deficit for motion perception, only being able to perform well for very high values of coherence. The reason for this is probably deficient segregation processes rather than deficient signal integration per se because less than 10% of the total elements, if stationary, were sufficient to disrupt performance. Such stationary elements are easily segregated by the normal visual system.

The second piece of evidence is that in a recent study Mansouri and co-workers (Mansouri, Allen, Hess, Dakin, & Ehrt, 2004) found that amblyopes performed normally on a global orientation task that relied solely on integration (i.e. devoid of any noise). This task involved estimation of the mean orientation of an array of 1-D Gabor patches, each of which was a sample of a distribution whose mean orientation was to be judged. In such a task, ideally one should integrate all the local orientation information, as all elements are signal and all contain relevant information for the task (Dakin, 2001). No performance deficits were found at low and medium spatial frequencies and only modest ones were found at high spatial frequencies. The finding that global integration was normal for low to mid spatial frequencies is surprising in view of the large deficits reported for a similar task involving global orientation integration using moderate-sized elements (e.g. 0.47° diameter elements) (Simmers et al., 2005). The main difference between the task used by Simmers and co-workers which revealed global motion and orientation deficits in amblyopia and the task used by Mansouri and co-workers which did not, involves the role of noise. The former involved signal as well as noise and therefore integration as well as segregation. The latter, on the other hand, involved only signal and hence purely integration.

The fact that tasks involving solely integration do not reveal a deficit in amblyopia whereas tasks that require both integration and segregation, do, suggests that the problem lies with the segregation side of the task. So far this distinction in the results between tasks requiring integration as well as segregation and those requiring integration alone has been shown only for luminance-defined (i.e. first-order) stimuli (Mansouri et al., 2004) for which the global deficit for integration/segregation tasks is known to be modest (less than a factor of 2); (Simmers et al., 2005, 2003). Global processing for contrast-defined (i.e. second-order) stimuli has been shown to be much more affected (factor of 3.5) than its first-order counterpart in both motion and equivalent form tasks in amblyopia (Simmers et al., 2005) but see (Wong et al., 2001). Therefore, a stronger test of the hypothesis that pure signal integration does not lie at the heart of the reported deficit on tasks involving signal and noise would be to investigate the ability of amblyopes to integrate second-order form information. In this study we