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Crowding between first- and second-order letters in amblyopia

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Abstract

To test whether first- and second-order stimuli are processed independently in amblyopic vision, we measured thresholds for identifying a target letter flanked by two letters for all combinations of first- and second-order targets and flankers. We found that (1) the magnitude of crowding is greater for second- than for first-order letters for target and flankers of the same order type; (2) substantial but asymmetric cross-over crowding occurs such that stronger crowding is found for a second-order letter flanked by first-order letters than for the converse; (3) the spatial extent of crowding is independent of the order type of the letters. Our findings are consistent with the hypothesis that crowding results from an abnormal integration of target and flankers beyond the stage of feature detection, which takes place over a large distance in amblyopic vision.

Keywords: Amblyopia; Crowding; First order; Second order; Letter identification

1. Introduction

Objects in everyday life are rarely seen in complete isolation. When objects are in close proximity with one another, details of the target of interest may be difficult to discern. This effect, known as *crowding*, is ubiquitous in spatial vision, and represents a form of suppressive spatial interaction between visual objects.

Crowding affects task performance such as letter and face identification in people with normal vision (e.g., Bouma, 1970; Chung, Levi, & Legge, 2001; Chung, Li, & Levi, 2007; Martelli, Majaj, & Pelli, 2005; Pelli, Palomares, & Majaj, 2004), but its effect is often more pronounced in individuals with amblyopia (e.g., Flom, Weymouth, & Kahneman, 1963; Hariharan, Levi, & Klein, 2005; Hess, Dakin, Tewfik, & Brown, 2001; Hess & Jacobs, 1979; Levi, Hariharan, & Klein, 2002c; Levi & Klein, 1985; Simmers, Gray, McGraw, & Winn, 1999). Amblyopia is a developmental disorder of spatial vision almost always accompanied by the presence of strabismus, anisometropia or form deprivation early in life (Ciuffreda, Levi, & Selenow, 1991). The signature of amblyopia is the presence of visual deficits in one eye that cannot be attributed to an identifiable ocular pathology. With respect to crowding, previous studies showed that the spatial extent of crowding (defined as the distance between a target and its surrounding objects) is much greater for individuals with amblyopia (especially those with strabismus) than for people with normal vision, even when the poor resolution in the amblyopic eye is taken into account (Hariharan et al., 2005; Hess et al., 2001; Levi et al., 2002c). Three main hypotheses have been suggested to account for the extensive crowding in amblyopia: (1) enlarged cortical receptive fields (Flom et al., 1963); (2) abnormal long-range inhibitory interactions (Bonneh, Sagi, & Polat, 2004; Ellemberg, Hess, & Arsenault, 2002; Levi & Klein, 1985; Wong, Levi, & McGraw, 2005), and (3) abnormal integration of target and flankers beyond the stage of feature detection (Hariharan et al., 2005; Levi et al., 2002c; Pelli et al., 2004).

Given that crowding is a form of spatial interaction between visual objects, it can be utilized as a tool to study how the visual system processes and integrates informa-

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tion from different stimuli. Previously, we used crowding as a tool to examine whether or not first- and second-order visual stimuli are processed independently in normal foveal and peripheral vision. *First-order* targets refer to targets that differ from their background by a change in luminance, hence they are often referred to as luminance-defined targets. In the absence of a change in luminance, targets can still be distinguished from their background by variations in other stimulus attributes such as contrast, texture or motion. These stimuli are often referred to as *second-order* stimuli. There are conflicting reports as to whether or not first- and second-order information is processed via independent visual pathways (for a review, please refer to Chung et al., 2007). Our principal finding that there exists substantial cross-over crowding between first- and second-order letter stimuli in normal foveal and peripheral vision, combined with a survey of the literature, offers a parsimonious explanation for the conflicting results—that first- and second-order processing remains separate at the initial stage of detection and feature extraction, but the signals are combined at a later integration stage (see also Rivest & Cavanagh, 1996).

Much of what we have learned about the visual deficits in individuals with amblyopia is based upon studies that used first-order stimuli. This knowledge is essential as it provides us with a better understanding of the visual deficits that occur primarily in visual cortex V1. Over the past several years, it has become evident that amblyopic deficits are found not only in V1, but also in the extrastriate cortex, as uncovered by several studies that examined second-order processing in amblyopia (Mansouri, Allen, & Hess, 2005; Simmers, Ledgeway, & Hess, 2005; Simmers, Ledgeway, Hess, & McGraw, 2003; Wong & Levi, 2005; Wong, Levi, & McGraw, 2001; Wong et al., 2005). Results from these studies are often interpreted as an amplified amblyopic deficit in the extrastriate cortex that cannot be attributable to the first-order deficit. Indeed, Wong et al. (2005) found that spatial interactions in second-order target detection were abnormal in both eyes of amblyopic observers, and suggested that amblyopia results in predominantly inhibitory interactions between second-order neurons.

Considering that amblyopic deficits are found for both first- and second-order stimuli, it is of interest to examine the interaction between the processing of these two types of stimuli. In this study, we used crowding as a tool to probe into the properties of spatial interaction between first- and second-order signals in amblyopic vision. We were especially interested in the cross-over conditions (first-order target with second-order flankers, and *vice versa*). If abnormal crowding in amblyopia reflects abnormal integration of target and flankers beyond the stage of feature detection, we would expect strong cross-over crowding between first- and second-order stimuli. Hence, the primary question we asked in this study was whether or not there is cross-over crowding in the amblyopic visual system, as occurs in normal fovea and periphery. We shall quantify the effect of crowding by its magnitude (intensity) and its spatial extent. Previously, we proposed a framework to explain how first- and second-order letters interact in normal fovea and periphery, therefore, an auxiliary question of this study was whether or not this framework can be used to explain the combination rules of first- and second-order stimuli in amblyopic vision.

2. Methods

2.1. Observers

Seven observers with amblyopia (five with strabismus, one with anisometropia and one with both strabismus and anisometropia), aged between 21 and 41 years, participated in this study. Table 1 summarizes the visual characteristics of these observers. All observers except JD had previously participated in a perceptual learning study to track the performance for identifying contrast-defined letters with practice (Chung, Li, & Levi, 2006b). JD, however, had participated in an earlier study that involved detection of contrast-modulated static noise patches (Wong & Levi, 2005). Consequently, all observers were familiar with second-order stimuli. They all had best-corrected visual acuity of 20/20 or better in the non-amblyopic eye, and a difference in logMAR acuities between the two eyes that ranged between 0.14 and 0.90 log units. All observers wore

Table 1
Visual characteristics of the amblyopic observers

Observer	Gender	Age (years)	Type	Eye	Visual acuity (logMAR)	Refractive errors	Eye alignment	Stereoacuity (if any)	Letter size used (deg)
AA	F	29	Strab	OD	0.14	−2.00/−2.25 × 180	>30Δ Alt ET		1.17
				OS	−0.04	−3.75/−2.00 × 005	10Δ RHyperT		1.17
AP	F	21	Strab	OD	−0.16	−1.50/−0.50 × 180	3–4Δ LET		0.83
				OS	0.40	−0.75/−0.25 × 180	2Δ LHyperT		1
GK	M	25	Strab	OD	0.04	+0.50/−2.25 × 010	12Δ RET		1.33
				OS	−0.10	+0.50/−2.25 × 170	10Δ RHyperT		0.83
JS	F	21	Strab	OD	−0.10	+1.25	6–8Δ LET		1.3
				OS	0.30	+1.00	4–6Δ LHyperT		1.5
RH	M	41	Strab	OD	−0.10	−1.00/−0.50 × 170	Microtropia 2Δ LET	200″	0.83
				OS	0.50	−1.50/−1.50 × 010			2
SC	M	30	Aniso	OD	−0.14	+0.50		70″	1
				OS	0.32	+3.25/−0.50 × 155			1.67
JD	M	21	Strab + Aniso	OD	−0.10	+2.50	3Δ LET		1
				OS	0.80	+5.00			2