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Identify mechanisms of amblyopia in Gabor orientation identification with external noise

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Abstract

In this study, we applied the external noise method and the PTM model to identify mechanisms underlying performance deficits in amblyopia. Amblyopic and normal observers performed a Gabor orientation identification task in fovea. White external noise was added to the Gabor stimuli. Threshold versus external noise contrast (TvC) functions were measured at two performance criterion levels. For a subset of observers, we also manipulated the center spatial frequency of the Gabor. We found that two independent factors contributed to amblyopic deficits: (1) increased additive internal noise, and (2) deficient perceptual templates. Whereas increased additive noise underlay performance deficits in all spatial frequencies, the degree of perceptual template deterioration increased with the center spatial frequency of the Gabor.

Keywords: Amblyopia; Mechanisms; Internal noise; Perceptual template; Spatial frequency; Perceptual template model; Contrast sensitivity function

1. Introduction

Amblyopia is a developmental visual disorder characterized by reduced vision in the absence of any detectable structural or pathological abnormalities that does not improve with refractive correction (Ciuffreda, Levi, & Selenow, 1991; McKee, Levi, & Movshon, 2003). As a result of the presence of certain sensory impediments during early visual development, such as strabismus (ocular misalignment) or anisometropia (unequal refractive error), amblyopia has been identified as a cortical rather than a peripheral, pre-cortical impairment. Research based on animal models of amblyopia found that V1 neurons responding to high spatial frequency patterns in the amplyopic eye exhibited abnormal contrast sensitivity and spatial properties (Crewther & Crewther, 1990; Eggers & Blakemore, 1978; Kiorpes, Kiper, O'Keefe, Cavanaugh, & Movshon, 1998; Movshon et al., 1987). However, the neuronal deficits in the case of strabismic and anisometropic amblyopia do not sufficiently account for the behavioral deficits measured with the same stimuli, suggesting that neural deficits in amblyopia are not limited to a subset of neurons in V1 (Kiorpes et al., 1998). Consistent with this view, disruption in the binocular organization of extra-striate cortical areas has been documented in primate (Movshon et al., 1987) and cat amblyopes (Schroder, Fries, Roelfsema, Singer, & Engel, 2002). Abnormal activities in extra-striate cortical areas have also been reported in PET (Imamura et al., 1997) and fMRI studies on human amblyopes (Barnes, Hess, Dumoulin, Achtman, & Pike, 2001; Sireteanu et al., 1998). However, a complete neural account of

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amblyopia is still unavailable (Barnes et al., 2001; Daw, 1998; Kiorpes & McKee, 1999).

In this study, we attempted to characterize mechanisms of amblyopia at the overall observer level using the external noise approach (Lu & Dosher, 1998). Traditionally, spatial vision is characterized through measures of contrast sensitivity functions and various visual acuities, such as Snellen acuity, grating acuity, and Vernier acuity (McKee et al., 2003). More recently, a more elaborated method, the external noise approach (Barlow, 1956; Rose, 1948; Tanner & Birdsall, 1958), has become increasingly prevalent in vision research (Ahumada, 1987; Ahumada & Watson, 1985; Burgess, Wagner, Jennings, & Barlow, 1981; D'Zmura & Knoblauch, 1998; Gegenfurtner & Kiper, 1992; Geisler, 1989; Hay & Chesters, 1972; Legge, Kersten, & Burgess, 1987; Lu & Dosher, 1999, 2001; Nagaraja, 1964; Pelli, 1981, 1990; Pelli & Farell, 1999; Tjan, Braje, Legge, & Kersten, 1995; Van Meeteren & Barlow, 1981). The method adds systematically increasing amounts of external noise to the signal stimuli and measures how much signal contrast is required to maintain one or several constant threshold performance levels in detecting or identifying the signal (the "Threshold versus Contrast" or "TvC" function). Contrast sensitivity is then described in terms of intrinsic limitations of the perceptual system: internal additive noise, contrast-gain control or multiplicative noise, nonlinear transducer, and statistical uncertainty (Burgess & Colborne, 1988; Eckstein, Ahumada, & Watson, 1997; Lu & Dosher, 1999; Pelli, 1985; Pelli & Farell, 1999). Initially used to characterize and compare human observers in different perceptual tasks (Burgess, Shaw, & Lubin, 1999), the external noise approach has recently been extended to assay alterations of the intrinsic characteristics of the observer when the state of the observer changes, including attention (Dosher & Lu, 2000a, 2000b; Lu & Dosher, 1998), perceptual learning (Chung, Levi, & Tjan, 2005; Dosher & Lu, 1998; Gold, Bennett, & Sekuler, 1999), and adaptation (Dao, Lu, & Dosher, 2006).

The external noise method was first applied to identify mechanisms of visual dysfunctions in clinical populations by Kersten, Hess, and Plant (1988). The authors measured TvC functions in a grating detection task for patients with cataract, macular degeneration, and amblyopia, and compared the pattern of results with those of the normal subjects. A linear amplifier model (LAM) of the human observer (Pelli, 1981) was used to fit the TvC functions. In the LAM, contrast threshold is described as a function of external noise by the following equation:

$$c_\tau = \sqrt{\frac{N_{ext}^2 + N_{eq}^2}{E_\tau}}, \quad (1)$$

where c_τ is the contrast threshold at performance criterion τ (e.g., 75% correct), E_τ is the sampling efficiency associated with the performance criterion, N_{ext}^2 is the variance of the (experimenter-controlled) external noise, and N_{eq}^2 is the variance of the equivalent intrinsic noise. Three amplyopic patients (one anisometropia, two strabismus) were studied by Kersten et al. (1988). They found that two of them had normal or near normal sampling efficiency but increased equivalent internal noise, and one had lower sampling efficiency but near normal equivalent internal noise.

The external noise method has since been used by others to study amblyopia (Levi & Klein, 2003; Nordmann, Freeman, & Casanova, 1992; Pelli, Levi, & Chung, 2004; Wang, Levi, & Klein, 1998):

- Nordmann et al. (1992) measured grating contrast sensitivity functions on normal and amblyopic subjects with and without a superimposed random noise pattern. They found that the impact of external noise was virtually identical for amblyopes and subjects with normal binocular vision. Their results are consistent with reduced sampling efficiency in amblyopia, based on the LAM model.
- Wang et al. (1998) used a spatial perturbation paradigm to study spatial uncertainty and sampling efficiency in spatial position judgments. They found that spatial uncertainty in both anisometropic and strabismic amblyopes was about tenfold higher than normal subjects. But only strabismus amblyopes showed deficits in spatial integration.
- Levi and Klein (2003) evaluated the perceptual templates and internal noise of amblyopic and normal subjects in detecting and discriminating the positions of fuzzy bars by combining the external noise approach with the classification image technique (Eckstein & Ahumada, 2002) and the double-pass method (Burgess & Colborne, 1988). They concluded that performance decrements in amblyopes are attributable in part to a poorly matched template, but to a greater degree, to higher internal stimulus-dependent noise. In relation to the LAM, a poorly matched template corresponds to lower sampling efficiency. Because the internal noise in LAM is additive and independent of the stimulus, the LAM model cannot accommodate the stimulus-dependent noise in the Levi and Klein result.
- Pelli et al. (2004) used the external noise approach to characterize amblyopic letter identification. Based on the LAM, they concluded that loss of sampling efficiency was the predominant cause of amblyopic visual deficit. In low spatial frequencies (e.g., 2.3 c/d), the equivalent internal noise of the amblyopes was roughly the same as the normal subjects. But paradoxically, the equivalent internal noise of the mild amblyopes was *lower* than the normal subjects in higher spatial frequencies (e.g., 7.8 c/d).

To summarize, these external noise studies based on the LAM have greatly advanced our understanding of the underlying mechanisms of amblyopia. However, the results in the literature are not completely consistent. Some studies attributed amblyopic deficits to reduced sampling efficiency; others attributed them to increased additive