Available online at www.sciencedirect.com

ScienceDirect

Vision Research 47 (2007) 2531–2542

Vision Research

www.elsevier.com/locate/visres

The response of the amblyopic visual system to noise

Dennis M. Levi *, Stanley A. Klein, Inning Chen

University of California, Berkeley, School of Optometry and The Helen Wills Neuroscience Institute, Berkeley, CA 94720-2020, USA

Received 11 December 2006; received in revised form 2 May 2007

Abstract

Visual perception is limited by both the strength of the neural signals, and by the noise in the visual nervous system. Here we use one-dimensional white noise as input, to study the response of amblyopic visual system. We measured the thresholds for detection and discrimination of noise contrast. Using an *N*-pass reverse correlation technique, we derived classification images and estimated response consistency.

Our results provide the first report of the sensitivity of the amblyopic visual system to white noise. We show that amblyopes have markedly reduced sensitivity for detecting noise, particularly at high spatial frequencies, and much less loss for discriminating suprathreshold noise contrast. Compensating for the detection loss almost (but not quite) equates performance of the amblyopic and normal visual system.

The classification images suggest that the amblyopic visual system contains adjustable channels for noise, similar to those found in normal vision, but "tuned" to slightly lower spatial frequencies than in normal observers. Our *N*-pass results show that the predominant factor limiting performance in our task in both normal and amblyopic vision is internal random multiplicative noise. For the detection of white noise the raised thresholds of the amblyopic visual system can be attributed primarily to extra additive noise. However, for the discrimination of suprathreshold white noise contrast, there is surprisingly little additional deficit, after accounting for the visibility of the noise.

Keywords: White noise; Psychophysics; Amblyopia; Classification images; Reverse correlation; Double-pass; Internal noise

1. Introduction

Visual perception is limited by both the strength of the neural signals, and by the noise in the visual nervous system (Barlow, 1957; Dosher & Lu, 1999; Eckstein, Ahumada, & Watson, 1997; Levi, Klein, & Chen, 2005; Pelli, 1990; Pelli & Farell, 1999). Indeed, internal noise is explicitly or implicitly incorporated into all extant models of spatial vision, and has been extensively quantified and modeled by measuring performance on a background of white noise [i.e., random fluctuations in luminance over space, time, or both] (Dosher & Lu, 1999; Eckstein et al., 1997; Pelli, 1990; Pelli & Farell, 1999).

Humans with naturally occurring amblyopia have marked abnormalities in spatial vision (see Kiorpes, 2006; Levi, 2006 for recent reviews). These abnormalities include reduced visual acuity, contrast sensitivity, position acuity and extensive crowding (Ciuffreda, Levi, & Selenow, 1991; McKee, Levi, & Movshon, 2003). Importantly, a number of recent studies have used stimuli either added to (e.g., Huang, Tao, Zhou, & Lu, 2007; Kiorpes, Tang, & Movshon, 1999; Levi & Klein, 2003; Levi, Waugh, & Beard, 1994; Pelli, Levi, & Chung, 2004; Xu, Lu, Qiu, & Zhou, 2006) or multiplied by (Mansouri, Allen, & Hess, 2005; Simmers, Ledgeway, Hess, & McGraw, 2003; Wong, Levi, & McGraw, 2001, 2005) background of white noise in order to try to estimate the factors limiting amblyopic vision. However, to date, almost nothing is known about what aspects of the input noise the amblyopic visual system

---

* Corresponding author. Fax: +1 510 642 7806.
E-mail address: dlevi@berkeley.edu (D.M. Levi).

0042-6989/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.visres.2007.06.014

is sensitive to, i.e., what is the signal in noise delivered through the amblyopic eye?

Knowing about the sensitivity of the amblyopic visual system to white noise is important because white noise is broadband, containing a broad range of spatial frequencies with equal amplitude. An important study by Kersten (1987) suggests that humans with normal vision are quite efficient at detecting noise over a wide range of stimulus spatial frequencies (from 1 to 6 octaves in bandwidth—see also Levi et al., 2005; Taylor, Bennett, & Sekuler, 2003, 2004). Kersten's study is important because it raised questions about the now well-accepted multiple-channel model of visual detection. The multiple-channel model asserts that there are a number of narrow (1–2 octaves) bandwidth channels, each sensitive to a different range of spatial frequencies, and there is considerable evidence to support the existence of such channels for detection of simple patterns on a uniform background (see Graham, 1989 for a review). For detection of combinations of a few sinusoids the channels are combined inefficiently (Graham, 1989). However, Kersten's results seem to imply that visual noise is detected by an "adjustable" visual channel (i.e., a channel whose spatial frequency tuning is determined by the noise), just as auditory noise is detected by an adjustable auditory channel (Green, 1960). This notion has been confirmed using classification image methods to directly measure the observers' sensitivity to the components of the noise (Levi et al., 2005; Taylor et al., 2003, Taylor, Bennett, & Sekuler, 2004—discussed below). Thus the response of the visual system to white noise cannot be simply predicted on the basis of an observer's contrast sensitivity function (Jamar & Koenderink, 1985; Kersten, 1987). The classification images suggest that sensitivity to spatial noise in the normal visual system is not simply determined via passive filtering (i.e., it is not simply the input noise convolved with the observer's contrast sensitivity function). Rather, these results suggest that there must be active neural interactions. Are these interactions compromised by amblyopia? On a practical level it is also important to know which spatial frequencies within the white noise band the amblyopic visual system responds to in order to interpret the effect of the noise on the visibility of signals.

Finally understanding the amblyopic visual system's response to white noise is important because studies using white noise added to a stimulus have reached different conclusions. For example several studies have concluded that compared with normal observers, amblyopes have little or no elevation in internal noise (e.g., Pelli et al., 2004; Kiorpes' others), while others have suggested that amblyopes have increased internal noise (Levi & Klein, 2003; Xu et al., 2006). Typically these studies use a fixed (physical) noise contrast for both amblyopic and normal eyes, and it is not clear that the amblyopic visual system responds in the same way to the noise since the noise (or some components of the noise) may be less visible through the amblyopic eye. Thus it is important to understand the response function of the amblyopic visual system over a range of noise contrast levels.

In order to investigate these questions we asked amblyopic observers to discriminate differences in the strength of one-dimensional white noise. We measured their response consistency and classification images and compared the results with those of normal observers.

Our recent results and modeling show that in the normal visual system, detection and discrimination of noise is limited by three factors: a non-optimal template (i.e., the weighted combination of energy in each stimulus component) plus systematic noise (to be henceforth called consistent noise) in the form of higher order nonlinearities (like probability summation) among different spatial frequency channels, and by sources of random internal noise (Levi et al., 2005). Here we show that the amblyopic visual system has reduced sensitivity to noise, and we apply the *N*-pass response classification method to tracking down the factors that limit amblyopic performance.

2. Methods

Our methods are identical to those of Levi et al. (2005) and will only be described briefly.

2.1. Observers

Fifteen observers participated in these experiments; 10 amblyopic (4 anisometropic, 3 strabismic and 3 with both strabismus and anisometropia) and five normal control observers (from Levi et al., 2005) participated in this study. Details of the 10 amblyopic observers are provided in Table 1, and their results are color-coded according to their classification (anisometropic—green; strabismic—red; both—blue) in all of the figures. Viewing was monocular, with appropriate optical correction. All experiments were performed in compliance with the relevant laws and institutional guidelines.

2.2. Stimuli

Each noise stimulus was presented for 0.75 s, with a mean luminance of 42 cd/m^2 and a dark surround. The noise is a one-dimensional grating consisting of 11 harmonics (either 0.5–5.5, 1–11 or 2–22 c/deg) with phases and amplitudes randomized. The stimuli can be seen in the inset of Fig. 1. We varied the range of harmonics by varying the viewing distance. For the lowest range (0.5–5.5 c/deg) with $f = 0.5$ c/deg, the noise appeared in a 2.2 degree square field. Slightly more than one cycle of the fundamental was displayed. At the higher ranges, (1–11 or 2–22 c/deg), the field size was proportionally smaller.

2.3. Psychophysical methods

We used a rating-scale signal detection method of constant stimuli to measure the observers' performance.

The stimulus pattern, $P_k(x)$, for the kth trial is given by

$$P_k(x) = N_k \sum_m n_{k,m} \cos(2\pi m f x + \phi_{k,m}) \tag{1}$$

where m is summed from 1 to 11, f is 0.5, 1, or 2 c/deg, $\phi_{k,m}$ is a random number with a uniform distribution from 0 to π and $n_{k,m}$ is a random number centered at zero with a Gaussian distribution and unity standard deviation. The overall component contrast is set by N_k, the "intended" rms stimulus contrast that takes on one of three levels for discrimination and four levels for detection. Note that the actual component contrast differs from N_k because of the Gaussian noise $n_{k,m}$. For a fixed value of N_k