



## Local motion processing limits fine direction discrimination in the periphery

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### ABSTRACT

Visual sensitivity is reduced in the periphery for many discrimination tasks. Previously it has been reported that motion coherence thresholds are higher for dot stimuli presented in the periphery, a finding that could arise either from (a) impaired motion integration or (b) from motion integrators inheriting more noisy local directional signals. We sought to disentangle these factors using an equivalent noise paradigm. We report a deterioration in discrimination thresholds in the periphery that does not result from reduced visibility and is fully accounted for by an increase in local directional uncertainty with no change in sampling efficiency. Changes in motion coherence thresholds with stimulus eccentricity, measured using similar stimuli, exhibit a high degree of inter-subject variability.

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### 1. Introduction

For static images, visual acuity decreases with eccentricity (Kelly, 1984; Rovamo, Virsu, & Nasanen, 1978) and even when stimuli are increased in size and/or contrast to compensate for reduced acuity (*M-scaling*), performance decreases with eccentricity for tasks of widely differing complexity, such as phase discrimination (Bennett & Banks, 1987; Bennett & Banks, 1991; Rentschler & Treutwein, 1985; Stephenson, Knapp, & Braddick, 1991), line-orientation sensitivity (Levi, Klein, & Aitsebaomo, 1984), discrimination of isolated (Strasburger, Harvey, & Rentschler, 1991) or crowded (Toet & Levi, 1992) alphanumeric characters, image classification (Juttner & Rentschler, 1996), reading (Chung, Mansfield, & Legge, 1998; Fine, Peli, & Pisano, 1993; Latham & Whitaker, 1996) and face identification (Melmoth, Kukkonen, Makela, & Rovamo, 2000). For appropriately *M*-scaled dynamic images, motion detection (McKee & Nakayama, 1984; Smith, Hess, & Baker 1994; Solomon & Sperling, 1995; van de Grind, van Doorn, & Koenderink, 1983; Whitaker, Makela, Rovamo, & Latham, 1992; Wright & Johnston, 1983), discrimination (McKee & Nakayama, 1984; Waugh & Hess, 1994; Wright & Johnston, 1983), and velocity discrimination (McKee & Nakayama, 1984) are approximately invariant across the retina. Furthermore, peripheral vision can be more sensitive to motion (Wright, 1987) and flicker (Kelly, 1971a; Kelly, 1971b) at high temporal frequencies, although apparent speed can appear reduced (Johnson & Wright, 1986).

Using a motion coherence paradigm (the minimum number of dots required to move coherently within a field of randomly moving dots in order to sustain a criterion threshold level), direction discrimination thresholds have been found to be higher in the periphery than in the fovea for normally sighted subjects (Raymond, 1994) and glaucoma patients (Joffe, Raymond, & Chrichton, 1997). When direction discrimination was assessed using drifting gratings, Levi et al. (1984) reported that thresholds deteriorated in the periphery in both normal and amblyopic eyes. It remains unclear, however, what limits observers' performance in these tasks. Wright (1987) reports that when drifting gratings were equalized by a scaling factor to take into account the change in spatial scale in the periphery, peak sensitivity to motion was constant across the visual field. van de Grind, Koenderink, and van Doorn (1987) examined signal:noise thresholds for motion detection in the fovea and periphery of scaled dot stimuli as a function of velocity and contrast. They found that the determining factor in the signal:noise ratios was the contrast of the dots, specifically, thresholds deteriorated more slowly in the fovea than in the periphery when the contrast was lowered. This is consistent with McKee and Nakayama (1984) who found that velocity discrimination of moving gratings was poorer in the periphery as a result of lower spatial resolution but was contrast invariant down to roughly 10% contrast. Although it appears that motion thresholds can be equated across the visual field in some tasks when the stimuli are appropriately scaled in either size or contrast, it has yet to be determined what actually limits performance in the periphery. In principle changes in performance could be accounted for entirely or partially by changes in the size or bandwidth of motion sensor receptive fields, changes in their spacing and numbers, or increases in their levels of internal noise.

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Here, we use an equivalent noise (EN) paradigm to examine changes in direction discrimination across the visual field and to disentangle the relative influence of the factors listed above. This methodology has previously been used successfully to examine the integration of oriented and drifting elements (e.g., Dakin, 2001; Dakin, Mareschal, & Bex, 2005a; Dakin, Mareschal, & Bex, 2005b; Heeley, Buchanan-Smith, Cromwell, & Wright, 1997; Lu & Doshier, 1999; Watamaniuk & Heinen, 1999), and relies on the assumption that a psychophysically measured threshold results from the sum of both internal and external sources of noise. Given that observers' thresholds are estimates of response variance, by expressing external noise imposed onto the stimulus in terms of variance, thresholds ( $\sigma_{obs}$ ) can be decomposed into internal noise ( $\sigma_{int}$  which represents the precision of a stimulus sample), sampling efficiency ( $n_{samp}$  which represents the number of samples being recruited for the task), and external noise ( $\sigma_{ext}$ ) using a variance summation model. These different components are illustrated schematically in Fig. 1 for the motion integration task used here. Fig. 1a illustrates how internal noise limits the precision with which the direction of each moving element is coded by the local motion detectors. Fig. 1b illustrates how the number of samples averaged by global motion integrators limits the precision with which the overall direction of the stimulus can be represented. In our experiment, the stimuli consist of a set of moving Gaussian dots each of whose direction was drawn from a wrapped normal distribution. Increasing the standard deviation of the direction distribution increases external directional noise (Fig. 1c). The EN fit to direction discrimination thresholds as a function of external noise is illustrated on the graph in Fig. 1c where the symbols represent direction thresholds, the solid line the EN fit, and the parameters in the caption represent the derived estimates of internal noise and sampling efficiency. The dashed line shows how sampling efficiency modulates thresholds at all levels of external noise

(i.e., a vertical shift in the function) and the dotted line shows how internal noise mostly modulates thresholds at low levels of external noise. In the present manuscript, we use the EN paradigm to determine whether the higher direction thresholds measured in the peripheral visual field result from elevated internal noise, from reduced sampling efficiency or a combination of both sources of error.

2. Methods

2.1. Stimuli

Stimuli were fields of 32 moving Gaussian elements ( $\sigma_{x,y} = 3$  arcmin), presented within a circular window of radius  $2^\circ$ . All elements were of "infinite-life-time" and were wrapped to the diametrically opposite point as they moved out of the window. Movies were 500 ms long and updated at 37.5 Hz. Elements had a velocity of approximately  $5.6^\circ/s$  and moved with directions drawn from a wrapped normal (WN) distribution, defined on the range  $\theta \in [0, 2\pi)$  by the probability density function:

$$f(\theta) = \frac{1}{\sigma\sqrt{2\pi}} \sum_{k=-\infty}^{\infty} \exp\left[-\frac{(\theta - \mu - 2\pi k)^2}{2\sigma^2}\right] \quad (1)$$

2.2. Procedure

Details of the experimental procedure and fitting techniques can be found in Dakin et al. (2005a). Briefly, subjects were presented with a field of 32 moving, Gaussian elements and were required to make a judgment of their overall direction: either clockwise or counter-clockwise of vertical (upwards). The center of the stimuli was presented at the fovea, and at eccentricities of  $4^\circ$ ,  $8^\circ$ , and  $16^\circ$  in separate runs. The direction of the referent motion was indicated by crosshairs present on the screen at the same time as the stimulus. Subjects signaled their response by pressing one of two keys on a computer keypad. Feedback, in the form of an audible beep, was given for incorrect responses.

The direction of motion of each element was randomly drawn from WN distributions (Eq. (1)) with eight different standard deviations ( $\sigma$ ):  $0.5^\circ$ ,  $1.0^\circ$ ,  $2.0^\circ$ ,  $4.0^\circ$ ,  $8.0^\circ$ ,  $16.0^\circ$ ,  $23.0^\circ$ ,  $32.0^\circ$ ,  $45.0^\circ$ , or  $64.0^\circ$ . A method of constant stimuli was used to

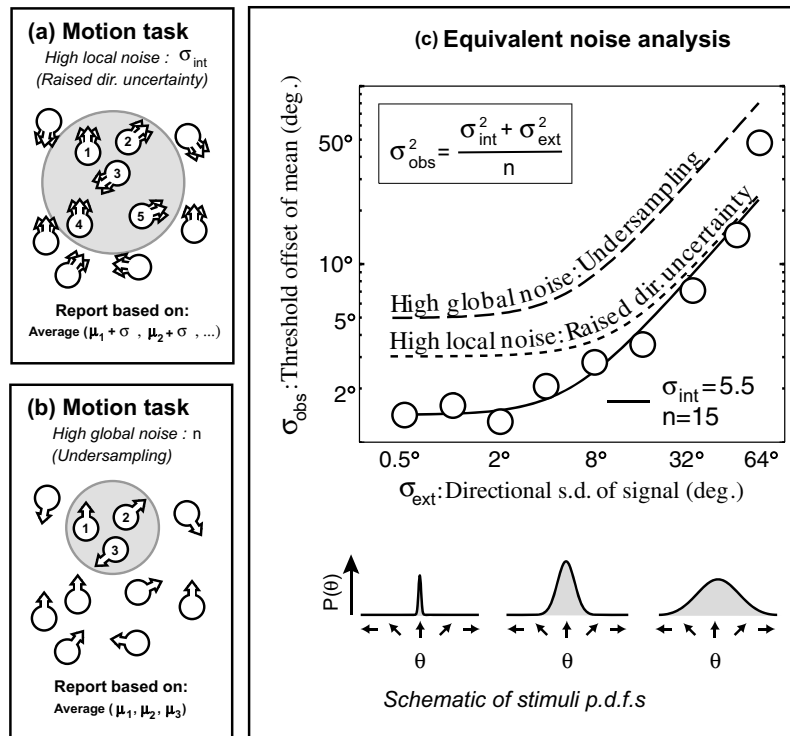


Fig. 1. (a) Direction discrimination of a set of moving elements is limited both by (a) local factors (the precision of each direction-estimate—illustrated here schematically by the range of multiple arrow-heads) and (b) global factors (the number of directions combined—illustrated by the area of the shaded region). (c) Thresholds are plotted as a function of the range of directions present in the stimulus ( $\sigma_{ext}$ ), observers' performance (open circles) is good when external directional noise ( $\sigma_{ext}$ ) is low and deteriorates as it increases. Equivalent noise exploits additivity of variance to model the data (boxed equation) in terms of external noise ( $\sigma_{ext}$ ), internal local noise ( $\sigma_{int}$ ) and global sampling limits on integration ( $n$ ). In the example shown, the observer pooled approximately 15 local direction-estimates, each with a precision of  $5.5^\circ$ .

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