Vision Research 50 (2010) 1766–1774

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

Spatial summation of first-order and second-order motion in human vision

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ARTICLE INFO

Article history:
Received 17 November 2009
Received in revised form 24 May 2010

Keywords:
First-order motion
Second-order motion
Spatial summation

ABSTRACT

This study assessed spatial summation of first-order (luminance-defined) and second-order (contrast-defined) motion. Thresholds were measured for identifying the drift direction of 1 c/deg., luminance-modulated and contrast-modulated dynamic noise drifting at temporal frequencies of 0.5, 2 and 8 Hz. Image size varied from 0.125° to 16°. The effects of increasing image size on thresholds for luminance-modulated noise were also compared to those for luminance-defined gratings. In all cases, performance improved as image size increased. The rate at which performance improved with increasing image size was similar for all stimuli employed although the slopes corresponding to the initial improvement were steeper for first-order compared to second-order motion. The image sizes at which performance for first-order motion asymptote were larger than for second-order motion. In addition, findings showed that the minimum image size required to support reliable identification of the direction of moving stimuli is greater for second-order than first-order motion. Thus, although first-order and second-order motion processing have a number of properties in common, the visual system's sensitivity to each type of motion as a function of image size is quite different.

1. Introduction

1.1. First-order and second-order motion

The human visual system is responsive to spatiotemporal information conveyed by a range of image properties. These are generally categorised as first-order (variations in luminance) or second-order (variations in more complex textural properties such as contrast) image statistics. A major unresolved debate in human vision concerns the issue of whether or not first-order motion and second-order motion are encoded by different low-level mechanisms. Although there is an abundance of evidence to suggest that first-order and second-order image properties are encoded separately in the mammalian visual system, at least in the initial processing stages (see Baker (1999), Smith (1994), Lu and Sperling (1995, 2001b) for reviews), a single mechanism could in principle handle both (Johnston, McOwan, & Buxton, 1992). For example in terms of the latter Benton and Johnston (2001) have shown mathematically that the motion of second-order contrast variations is available from conventional image spatiotemporal gradients in the lower contrast regions. Furthermore some phenomena such as the opposite motion induced in a static visual noise carrier, when its contrast is modulated by a moving waveform are difficult to explain if first-order and second-order motion are processed entirely separately in initial processing stages (Johnston, Benton, & McOwan, 1999). Thus the principles governing the perception of second-order image properties are still the subject of much controversy and warrant further study.

1.2. Spatial summation

Spatial summation in vision is a long-established phenomenon and, in short, refers to the fact that performance for detecting the presence of a visual stimulus improves as the size of that stimulus increases (Barlow, 1958; Campbell & Robson, 1968; Howell & Hess, 1978; Legge & Foley, 1980; Robson & Graham, 1981). Spatial summation functions are an important aspect of vision as they provide a behavioural measure of how visual information is integrated across retinal receptive fields (e.g. Anderson & Burr, 1991). A number of studies have investigated the nature of spatial summation for first-order and second-order information in the spatial domain (e.g. Schofield & Georgeson, 1999; Sukumar & Waugh, 2007; Wong & Levi, 2005). However these studies have not provided consistent results, suggesting that spatial summation functions may be heavily dependent on different stimulus parameters (stimulus type, frequency, etc.).

Schofield and Georgeson (1999) measured sensitivity to stationary first-order and second-order signals as a function of Gaussian blob width (defined as 2.5 times the standard deviation of the circularly symmetric Gaussian modulation function) and found similar effects for luminance-modulated and contrast-modulated noise. Sensitivity for detecting both types of stimuli increased as blob size increased and saturated at a similar blob size (~40 arc

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doi:10.1016/j.visres.2010.05.032

min). In addition, the sensitivity curves for luminance-modulated and contrast-modulated noise blobs were virtually parallel. These findings led Schofield and Georgeson (1999) to conclude that the similarity of the detection curves for first-order and second-order stimuli might reflect processing by the same or a functionally similar process. Landy and Oruc (2002) assessed the effects of spatial summation on second-order spatial processing using texture-quilts and found that performance plateaued at approximately 15°. Wong and Levi (2005) have also measured spatial summation areas for second-order stimuli in normal and amblyopic observers using static 1 c/deg. contrast-modulated noise Gabor patterns. They found that detection thresholds decreased at approximately the same rate in normal and amblyopic observers and saturated (flattened) at an image size of 6–8 cycles. In a control experiment, Wong and Levi (2005) compared their findings for second-order Gabors with spatial summation areas for static first-order Gabors in four normal observers. They found that, unlike second-order Gabors for which performance asympoted at an image size of around 6–8 cycles, for first-order Gabors performance failed to asymptote over the range of image sizes employed. Although Wong and Levi (2005) did not pursue this finding further, their results suggest that spatial summation areas are larger for first-order, compared to second-order, patterns.

Most recently, Sukumar and Waugh (2007) investigated spatial summation areas for static first-order and second-order patterns by measuring detection thresholds for luminance-modulated and contrast-modulated Gaussian noise blobs. They found that spatial summation areas were different for detecting luminance-defined and contrast-defined blobs. However they found that modulation thresholds saturated at smaller image sizes for luminance-defined than for contrast-defined stimuli. That is, spatial summation areas were larger for the contrast-defined (second-order) patterns, contrary to that found previously by Wong and Levi (2005).

The effects of spatial summation on the perception of second-order motion has received comparatively little attention. However, Zanker (1993) investigated the disruptive effect of uncorrelated visual noise on the ability to detect both first-order motion (a displaced rectangular region of random dots) and second-order motion (defined by either flicker or relative motion) across a limited range of image sizes. Performance was measured at a fixed image width (0.608°) but image height was varied in the range 0.076–4.864°. He found that when the height of the moving objects increased, sensitivity (percentage of noise superimposed on the image without destroying the perceived motion percept) continued to increase for all types of motion. In each case there was little evidence that a summation limit had been reached and changes in image size were restricted to a single spatial dimension. Thus the spatial integration area for second-order motion perception remains unclear and warrants further study. Therefore the present study investigated the effect of image size on thresholds for discriminating the direction of first-order (luminance-defined) and second-order (contrast-defined) motion.

2. Experiment 1: spatial summation of first-order and second-order motion signals

Experiment 1 investigated the effect of image size on performance for determining the drift direction of first-order (luminance-modulated dynamic noise) and second-order (contrast-modulated dynamic noise) motion.

2.1. Methods

2.1.1. Observers

Four observers (CVH, LS, MA and LA) took part in the study. CVH was an author and LS, MA, and LA were naïve observers. All had normal or corrected-to-normal visual acuity and had no history of any visual disorders.

2.1.2. Apparatus and stimuli

Stimuli were generated using a *Macintosh G5* and presented on a *Dell* monitor (update rate of 75 Hz) using custom software written in the C programming language. For precise control of luminance contrast the number of intensity levels available was increased from 8 to 14 bits using a Bits++ attenuator (*Cambridge Research Systems*). The mean luminance of the display was approximately 68 cd/m^2. Images were viewed binocularly and in darkness at a distance of 69.5 cm. To ensure that the second-order motion stimuli did not contain any luminance artifacts, the monitor was carefully gamma-corrected using a photometer and look-up-tables (LUT). As an additional precaution, the adequacy of the gamma-correction was also checked psychophysically using a sensitive motion-nulling task (Gurnsey, Fleet, & Potechin, 1998; Ledgeway & Smith, 1994; Lu & Sperling, 2001a; Scott-Samuel & Georgeson, 1999).

Stimuli were vertically-oriented, 1 c/deg., luminance-modulated or contrast-modulated dynamic noise patterns, drifting at either 0.5, 2 or 8 Hz. The size of the image varied from 0.125° to 16°, horizontally and vertically. First-order motion was produced by adding a sinusoidal grating to a 1-bit, spatially 2-d, random noise carrier of 0.15 Michelson contrast. The noise carrier was generated by assigning individual (single) screen pixels (1.88 arc min) to be either "white" or "black" with equal probability and there was no spatial variation in luminance within each noise element. A new stochastic noise sample was used for each separate image in the motion sequence. The luminance profile of the first-order motion stimulus as a function of space and time, $L(x, y, t)$, can be described by the equation:

$$L(x,y,t) = L_{\text{mean}}[1 + m\cos\{2\pi(fx - \omega t) + \phi\} + cR(x,y,t)] \qquad (1)$$

where L_{mean} is the mean luminance of the display (68 cd/m^2), f is spatial frequency (c/deg.), ω is temporal drift frequency (Hz), ϕ is the initial spatial phase (randomised at the beginning of each trial), m is the amplitude (modulation depth) and c is the contrast of the noise carrier $R(x, y, t)$ prior to modulation, chosen to be either -1 or +1 with probability 0.5. The modulation depth (m) of the sinusoidal luminance modulation could be varied in the range 0–1 according to the following equation:

$$m = (L_{\max} - L_{\min})/(L_{\max} + L_{\min}) \qquad (2)$$

where $L_{\max}$ and $L_{\min}$ are the maximum and the minimum mean luminances in the image, respectively, averaged over adjacent noise elements with opposite polarity.

Second-order motion was produced by multiplying, rather than adding, a drifting sinusoidal waveform (unsigned for the purposes of multiplication) with a noise field:

$$L(x,y,t) = L_{\text{mean}}[1 + \langle 1 + m\cos\{2\pi(fx - \omega t) + \phi\}\rangle cR(x,y,t)] \qquad (3)$$

where the parameters are identical to those in Eq. (1). The depth (m) of the contrast modulation could be varied in the range 0–1 according to the following equation:

$$m = (C_{\max} - C_{\min})/(C_{\max} + C_{\min}) \qquad (4)$$

where $C_{\max}$ and $C_{\min}$ are the maximum and the minimum local Michelson contrasts in the image, respectively, computed over neighbouring noise elements with opposite polarity. Stimulus examples are shown in Fig. 1.

2.2. Procedure

A single-interval, two-alternative, forced-choice task was employed. On each trial, observers were presented with a fixation cross. Trials were self-paced. Observers initiated each trial by