Vision Research 51 (2011) 352–361

Contents lists available at ScienceDirect

Vision Research

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

No interaction of first- and second-order signals in the extraction of global-motion and optic-flow

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ARTICLE INFO

Article history:
Received 13 July 2010
Received in revised form 20 November 2010
Available online 3 December 2010

Keywords:
Global-motion extraction
Motion integration
Second-order motion
Masking

ABSTRACT

Edwards and Badcock (*Vision Research 35*, 2589, 1995) argued for independent first-order (FO) and second-order (SO) motion systems up to and including the global-motion level. That study used luminance (which they called FO) and contrast (SO) modulated dots. They found that SO noise dots did not mask signal extraction with luminance increment dots while luminance increment dots did mask SO signal extraction. However, they argued this asymmetry was not due to a combined FO–SO pathway, but rather due to the fact that the luminance-modulated dots, being also local variations in contrast, are both FO and SO stimuli. We test their claim of FO and SO independence by using a stimulus that can generate pure FO and SO signals, specifically one consisting of multiple Gabors (the global-Gabor stimulus) in which the Gaussian envelopes are static and the carriers drift. The carrier can either be luminance-modulated (FO) or contrast-modulated (SO) and motion signals from the randomly-oriented local Gabors must be combined to detect the global-motion vector. Results show no cross-masking of FO and SO signals, thus supporting the hypothesis of independent FO and SO systems up to and including the level extracting optic-flow.

1. Introduction

Objects in the visual world can be defined by variation in first-order (FO) properties like luminance and color and by second-order (SO) properties such as texture and contrast (Adelson & Bergen, 1985; Cavanagh & Mather, 1989; Schofield, 2000; van Santen & Sperling, 1985; Watson & Ahumada, 1985). Correspondingly, global-motion perception can be driven by luminance-modulated or contrast-modulated signals and compelling percepts of motion result from either type of signal (Badcock & Derrington, 1985; Cavanagh & Mather, 1989; Chubb & Sperling, 1988; Derrington & Badcock, 1985; Smith & Snowden, 1994). The motion of luminance-modulated stimuli can be extracted by locally detecting the orientation of Fourier energy present in the signal (Adelson & Bergen, 1985; van Santen & Sperling, 1985; Watson & Ahumada, 1985). Contrast-modulated stimuli are frequently designed so that their motion cannot be appropriately analyzed by linear filters; motion extraction of the SO spatial patterns requires extra processing including a non-linearity in the processing sequence (Badcock & Derrington, 1985; Chubb & Sperling, 1988; Wilson, Ferrera, & Yo, 1992; Wilson & Kim, 1994).

There has been a large amount of research aimed at characterizing how the human visual system processes these two different types of signals (Badcock & Derrington, 1985; Chubb & Sperling, 1988; Derrington & Badcock, 1985; Edwards & Badcock, 1995; Edwards & Metcalf, 2010; Hutchinson & Ledgeway, 2006; Ledgeway & Smith, 1994; Lu & Sperling, 1995; Smith & Snowden, 1994). However, it still remains a matter of debate whether the visual system processes FO and SO signals using a single pathway with the same neuronal hardware or whether these signals are processed independently (Derrington, Allen, & Delicato, 2004; Johnston & Clifford, 1995) and if it is the latter case, up to what level in the system that independence is maintained.

There is evidence that FO and SO signals are not combined locally to produce a percept of apparent motion (Ledgeway & Smith, 1994; Nishida & Sato, 1995). Ledgeway and Smith showed that interleaved FO and SO stimuli on successive frames could not be integrated to extract a global-motion percept. However, concerns have been raised with this result, with Benton, Johnston, and McOwan (2000) suggesting a model that produced a similar outcome using a single system that processed all temporal and spatial gradients of the luminance field.

Edwards and Badcock (1995) found evidence for independent FO and SO processing at the global-motion level. They used a

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doi:10.1016/j.visres.2010.11.012

random walk global-motion stimulus, which consists of signal dots (a random subset that was selected on each frame transition), that moved in a common direction, and noise dots, that moved in random directions (Newsome & Pare, 1988). The degree to which visual pathways interact at the global-motion level can be established by determining whether noise dots of one type (e.g. SO) affect the extraction of a global-motion signal carried by a subgroup of dots of a different type (e.g. FO). If the two types of dots are processed by independent global-motion systems, then thresholds (the required number of signal dots) would not be affected, whereas if they are processed by a common global-motion system, then thresholds would be elevated. Note that, in using this technique, it is important to ensure that not all of the signal dots are uniquely defined relative to all of the noise dots (Edwards & Badcock, 1994; Snowden & Edmunds, 1999), otherwise performance can be mediated by attentional tracking following pre-attentive segmentation (Croner & Albright, 1997, 1999; Edwards & Badcock, 1996; Murray, Sekuler, & Bennett, 2003; Snowden & Edmunds, 1999).

Edwards and Badcock (1995) found that the threshold for 100 luminance-modulated (which they termed FO) dots was approximately double than that for 50 luminance-modulated dots but adding 50 contrast-modulated (SO) noise dots to 50 luminance-modulated dots did not affect thresholds. They also found that adding 50 luminance-modulated noise dots to 50 SO dots, when the signal was carried by a subset of the SO dots, impaired performance. Thresholds were the same as the condition containing 100 SO dots. They interpreted this set of results as being consistent with independent FO and SO global-motion systems. The asymmetry in the masking effects (SO noise dots not masking the processing of luminance-modulated dots, but luminance-modulated noise dots masking SO processing) was explained by observing that while their contrast-modulated dots were a pure SO stimulus, the luminance-modulated dots, being a local variation in both luminance and contrast, were both a FO and a SO stimulus (this would have been clearer if Edwards and Badcock had used the labels Light-Increment (LI) and Texture-Contrast-Increment (TCI) instead of FO and SO in the original study).

On the basis of this explanation the authors concluded that the FO and SO pathways remained independent up to where translational global-motion is extracted; which was believed to be at cortical area V5/MT (Baker, Hess, & Zihl, 1991; Newsome, Britten, & Movshon, 1989; Newsome & Pare, 1988) but in humans may also occur in areas V3/V3a (Castelo-Branco et al., 2002; Koyama et al., 2005).

The finding of FO–SO independence has been extended to include the level at which radial optic-flow signals are processed (Badcock & Khuu, 2001), which has been linked to cortical area MST (Morrone et al., 2000). While the interpretation of the results by Edwards and Badcock (1995) and Badcock and Khuu (2001) is consistent with independent FO and SO systems, their results could also be interpreted as indicating the existence of two pathways, one sensitive exclusively to FO signals, and a second sensitive to both FO and SO signals. This paper specifically addressed the asymmetry in the masking effect of LI and TCI stimuli by using a different type of stimulus that selectively drove the FO and SO systems. The source of uncertainty in that previous research was that the motion of the envelope of the luminance-defined dots induced a contrast variation that moved with the dots and therefore the luminance-defined dots carried both first- and second-order signals. Consequently, the current study used stimuli that removed this double cue.

In the present study we used modified versions of the global-Gabor stimulus (Amano, Edwards, Badcock, & Nishida, 2009). The global-Gabor stimulus consists of multiple, spatially distributed Gabor elements. The Gaussian envelope of each Gabor remains static with motion being generated by drifting the (FO or SO) carriers. Therefore, in the current study, even with the contrast variation at the boundary of each Gabor due to the profile of the Gaussian envelope in the FO stimulus, such modulation did not move across the visual field. The motion signal was distributed among randomly-oriented Gabors with drifting velocities consistent with the global direction and speed to be extracted. FO carriers were luminance-modulated gratings constructed by adding background pixelation to a sinusoidal variation in luminance. SO carriers were contrast-modulated gratings generated by multiplying a background pixelation, composed of balanced increments and decrements, by a sinusoidal weighting function. Gabors are one-dimensional (1D) stimuli in the sense that the direction of motion is ambiguous for a single Gabor because the aperture problem cannot be solved and local-motion detectors can only indicate a direction of motion that is orthogonal to the orientation of the drifting carrier in each Gabor. It has been shown (Amano et al., 2009) that the visual system can derive a 2D motion vector by pooling this type of local-motion signal across space using an algorithm known as intersection of constraints (IOC) (Adelson & Movshon, 1982; Fennema & Thompson, 1979). This can be contrasted to the situation in which motion signals are carried by dots. With dot stimuli, the aperture problem can be solved locally, resulting in 2D motion signals which are pooled across space using a rule approximating the vector average (Amano et al., 2009; Webb, Ledgeway, & McGraw, 2007).

The current study employs the global-Gabor stimulus to re-examine the independence of the motion processes that extract FO and SO motion signals. Using this stimulus it is now possible to create pure FO and SO signal elements and if the two are processed by independent motion systems then the extraction of motion signals using one should not be affected by noise carried by the other stimulus type. Thus the asymmetry in masking observed when using moving dots as stimuli is not expected if the systems are independent. The results of this test of independence will be presented for both translational and circular global-motion to determine whether the complexity of the motion solution impacts on the conclusions.

2. Experiment 1: no interaction of FO and SO signals in translational global-motion extraction

The aim of the first part of this experiment was to determine whether SO noise had an effect on global-motion extraction from FO local-motion signals. The procedure used was based on the finding that as the total number of Gabors of the same kind (either first- or second-order) increases, the number of signal Gabors required to determine the global direction of motion also increases. This is the same as what happens with dot stimuli (Edwards & Badcock, 1994, 1995; Edwards, Badcock, & Smith, 1998; Williams & Sekuler, 1984) and is broadly consistent with maintaining a constant signal-to-noise ratio at threshold. The experiment had three conditions in which the numbers of FO and SO Gabors were varied: (i) 50 FO Gabors (50FO); (ii) 100 FO Gabors (100FO); and (iii) 50 FO and 50 SO Gabors (50FO/50SO). In the 50FO/50SO condition (iii) only the FO Gabors carried the global-motion signal, the SO stimuli were always noise.

If there are separate FO and SO global-motion systems, adding pure-noise SO Gabors should have no effect on FO global-motion extraction, so thresholds for the 50FO and the 50FO/50SO conditions should be equivalent. However, if FO and SO signals are pooled prior to global-motion extraction, and if this single global-motion system was equally sensitive to the FO and SO signals used here, then the threshold for 100FO and 50FO/50SO conditions should be similar.