



Pursuing motion illusions: A realistic oculomotor framework for Bayesian inference

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ABSTRACT

Accuracy in estimating an object's global motion over time is not only affected by the noise in visual motion information but also by the spatial limitation of the local motion analyzers (aperture problem). Perceptual and oculomotor data demonstrate that during the initial stages of the motion information processing, 1D motion cues related to the object's edges have a dominating influence over the estimate of the object's global motion. However, during the later stages, 2D motion cues related to terminators (edge-endings) progressively take over, leading to a final correct estimate of the object's global motion. Here, we propose a recursive extension to the Bayesian framework for motion processing (Weiss, Simoncelli, & Adelson, 2002) cascaded with a model oculomotor plant to describe the dynamic integration of 1D and 2D motion information in the context of smooth pursuit eye movements. In the recurrent Bayesian framework, the prior defined in the velocity space is combined with the two independent measurement likelihood functions, representing edge-related and terminator-related information, respectively to obtain the posterior. The prior is updated with the posterior at the end of each iteration step. The maximum-a posteriori (MAP) of the posterior distribution at every time step is fed into the oculomotor plant to produce eye velocity responses that are compared to the human smooth pursuit data. The recurrent model was tuned with the variance of pursuit responses to either "pure" 1D or "pure" 2D motion. The oculomotor plant was tuned with an independent set of oculomotor data, including the effects of line length (i.e. stimulus energy) and directional anisotropies in the smooth pursuit responses. The model not only provides an accurate qualitative account of dynamic motion integration but also a quantitative account that is close to the smooth pursuit response across several conditions (three contrasts and three speeds) for two human subjects.

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1. Introduction

Motion illusions help us to better understand how motion information is processed by the visual system. In particular, they illuminate how the brain processes ambiguous information to infer the most probable source from the external world (Kersten, Mamassian, & Yuille, 2004). The aperture problem, and its perceptual consequences, is one of the most investigated cases of motion illusions since it can be investigated at both perceptual, motor and neuronal levels (see Masson and Ilg (2010) for a collection of reviews). Motion sensitive cells in early visual stages have small receptive fields and, therefore, a limited access to the motion information present in the images. Neurons with receptive fields located at different positions along a simple moving stimulus such as a bar will provide different velocity measurements as illustrated in Fig. 1a.

Consider two frames of a tilted line translating horizontally but seen through three small, circular apertures (locations 1–3). The translation vector in the 1st and 3rd apertures is unique as there is only one possible way to recover the translation of the line between the two frames, thanks to the two-dimensional (2D) profile of luminance information. Thus, motion recovered from the translation of these line-endings (also called features, terminators, or local 2D motion) is unambiguous, as illustrated by the small gaussian-like distribution of the most probable velocities in the (v_x, v_y) space, for a high signal-to-noise ratio (Lorceau & Shiffrar, 1992; Pack, Hunter & Born, 2005). On the contrary, analyzing the translation of a one-dimensional luminance profile as seen in the 2nd aperture yields to an infinite number of possible velocity vectors. Such 1D motion is highly ambiguous (Movshon, Adelson, Gizzi, & Newsome, 1986) leading to the aperture problem. One can compute the 1D velocity likelihoods in the same (v_x, v_y) space, which under some assumptions about noise properties, would correspond to an elongated Gaussian distribution crossing an entire quadrant (Simoncelli, Adelson, & Heeger, 1991; Weiss et al., 2002). Understanding how purely horizontal motion of the entire

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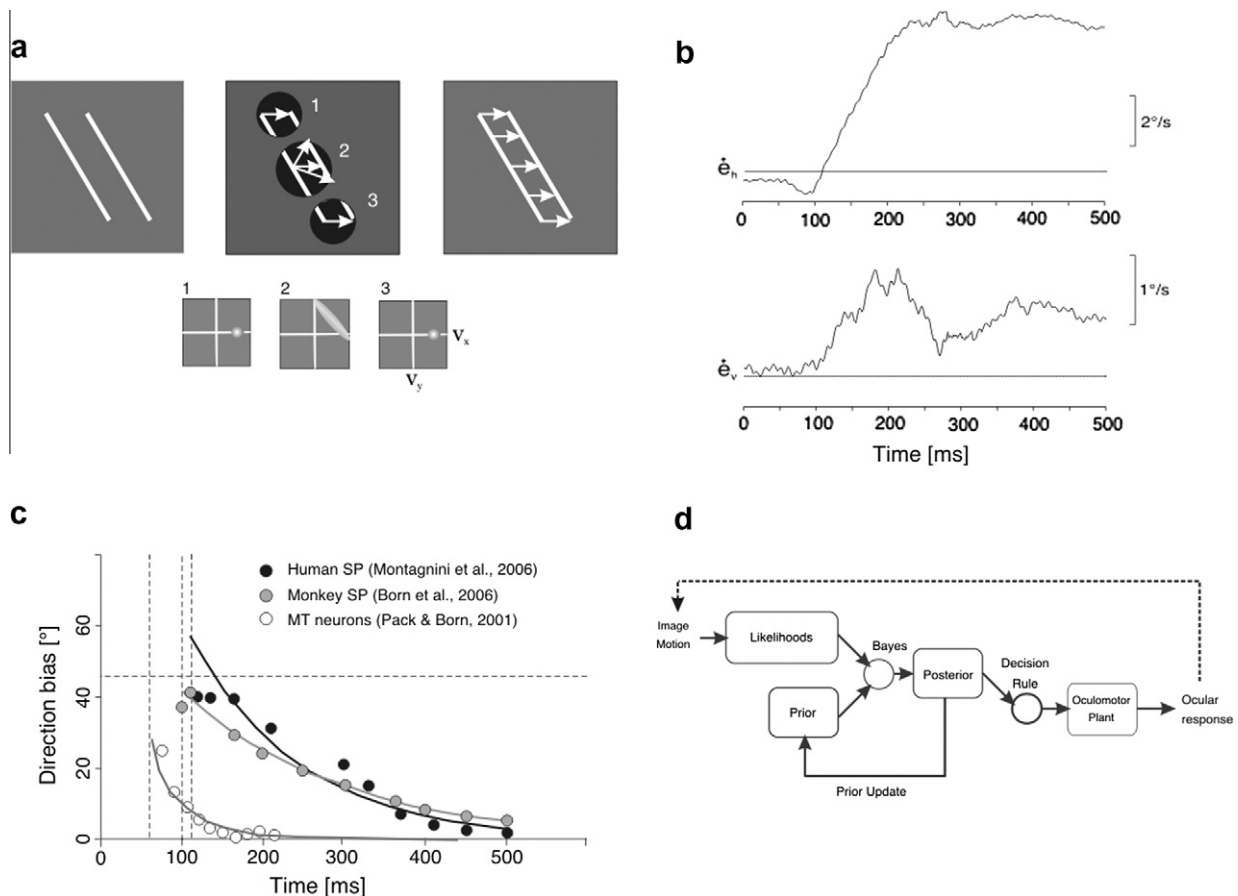


Fig. 1. Aperture problem and dynamics of motion integration. (a) Upper row illustrate the aperture problem during translation of a single tilted line. From left to right: two successive frames of a pure horizontal translation; velocity vectors extracted through three different apertures; the correct solution of the aperture problem is reached when global motion consistent with translation of a rigid object is obtained. Shown are three different instances of a tilted line. Lower row illustrates the velocity likelihoods computed at the three locations (ambiguous (2) and unambiguous (1, 3)). (b) Mean smooth pursuit eye velocity traces (horizontal (\dot{e}_h) and vertical (\dot{e}_v)) for a tilted line translating to right at $7^\circ/s$. (c) Pursuit direction error plotted against time for human (black dots) and monkey (gray dots) pursuit of a 45° tilted line. Open circles plot the time course of direction estimate from a population of MT neurons presented with a set of small tilted lines translating in the classical receptive field. (d) Block model of the model for motion inference and pursuit. The front-end infers optimal motion estimation using a Bayesian model. Such estimate is dynamical due to prior updating, implementing a recurrent Bayesian network. The decision rule extracts the optimal image velocity at a given point in time and feeds two independent oculomotor plants, driving horizontal and vertical eye velocity.

visual pattern is recovered has been the goal of dozens of psychophysical and physiological studies (see Bradley & Goyal, 2008; Masson and Ilg (2010) for reviews) but several key aspects remain unclear such as the role of feature motion (Lorceau & Shiffrar, 1992; Pack, Gartland, & Born, 2004), the rule governing the integration of 1D and 2D local motion (Weiss et al., 2002) or the exact physiological mechanisms used to reconstruct global motion (see Rust, Mante, Simioncelli, & Movshon, 2006; Tlapale, Masson, & Kornprobst, 2010; Tsui, Hunter, Born, & Pack, 2010, for recent computational studies).

A key observation with the aperture problem is that perceived direction of a single tilted bar translating horizontally is biased towards the oblique direction, corresponding to the velocity vector orthogonal to the bar orientation (Casted, Lorceau, Shiffrar, & Bonnet, 1993; Wallach, 1935), at least for short stimulus durations and low contrast. Such observations also hold for motor actions such as voluntary pursuit. Example of smooth pursuit eye movements driven by a rightward motion of a 45° tilted line is shown in Fig. 1b. At pursuit onset, there is always a transient vertical component, reflecting the directional bias induced by the aperture problem. Once that 2D motion information begins to be integrated along with 1D motion, there is a slow reduction in the directional bias. Such observation was made both in humans (Masson & Stone, 2002; Montagnini, Spring, & Masson, 2006; Wallace, Stone, &

Masson, 2005) and monkeys (Born, Pack, Ponce, & Yi, 2006). Fig. 1c plots the time course of the tracking direction error (i.e. the difference between the instantaneous 2D eye movement direction and the 2D translation of the bar) observed in either monkeys (closed symbols) or humans (open symbols). At high contrast, tracking error decays with a time constant ~ 90 ms so that, after 200 ms of pursuit both eye and target motions almost perfectly matched. Gray symbols plot the time course of the population vector of direction-selective cells recorded from macaque area MT using a somewhat similar stimulus. MT neurons initially respond primarily to the component of motion perpendicular to a contour's orientation, but over a short period of time (time constant: ~ 60 ms) their responses gradually shift to encode the true stimulus direction 100–150 ms after stimulus onset (Pack & Born, 2001).

Numerous mechanisms such as vector averaging (VA), Intersection of Constraints (IOC) and 2D features (2DFT) (see Bradley & Goyal, 2008, for a review) have been proposed as solutions to the aperture problem. The Bayesian framework, based on the idea that the visual system makes inferences from noisy signals offers a simple explanation for two-dimensional motion illusions observed with a large pool of stimuli (Weiss et al., 2002). Their seminal suggestion was that primate visual system prefers slow and smooth motions. In the Bayesian framework of probabilistic inference, such preference can be instantiated as a Prior distribution centered at

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