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# Detecting moving objects in an optic flow field using direction- and speed-tuned operators

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ABSTRACT

An observer moving through a scene must be able to identify moving objects. Psychophysical results have shown that people can identify moving objects based on the speed or direction of their movement relative to the optic flow field generated by the observer's motion. Here we show that a model that uses speed- and direction-tuned units, whose responses are based on the response properties of cells in the primate visual cortex, can successfully identify the borders of moving objects in a scene through which an observer is moving.



## 1. Introduction

When an observer moves through the world, the motion of images on the retina form a dynamic pattern known as the optic flow field. This motion contains a wealth of information about the world around the observer, including information about the observer's direction of motion, the relative distance to objects in the visual field and whether or not objects are moving relative to the rest of the scene (Clocksin, 1980; Gibson, 1950; Longuet-Higgins & Prazdny, 1980; Nakayama & Loomis, 1974; Royden & Picone, 2007; Thompson & Pong, 1990). In terms of recognizing moving objects, it is clear that moving observers can detect objects that are moving relative to the scene, but it is unclear how the visual system accomplishes this task. The difficulty arises because the observer's own motion creates motion throughout the visual image, even for images of stationary items, and thus the image motion of the self-moving object is not unique. While there have been several theoretical models proposed that could detect moving objects within the optic flow field (Hildreth, 1992; Thompson & Pong, 1990), there has been no analysis of how these mechanisms could be implemented by biological neurons. In the current study, we show how a model that is based on the response properties of neurons in the primate visual system, using operators with speed- and direction-tuned responses to motion, can be extended to detect moving objects in the visual scene.

### 1.1. Theoretical considerations

When an observer moves in a straight line through a stationary scene, the optic flow field forms a radial pattern (Fig. 1a). The center of this pattern, where the image motion is zero, is known as the focus of expansion (FOE) and corresponds to the observer's direction of motion, or heading. A moving object in the scene may introduce image velocities that are inconsistent with this pattern (Fig. 1b), and this inconsistency, in theory, can be used to detect the presence of a moving object. Thompson and Pong (1990) proposed a computational model in which one could identify a moving object if its motion differed in direction or speed from the expected optic flow field generated from a given camera motion. In their analysis they noted that knowledge of the relative depth of points in the scene, either from binocular stereo or monocular depth cues such as familiar size, can aid in detecting moving objects based on motion discontinuities.

When the observer is rotating as well as translating, such as when moving on a curved path or tracking an object with eye or head movements, the optic flow field becomes considerably more complex (Fig. 1c), making it more difficult to detect a moving object. Longuet-Higgins and Prazdny (1980) presented a mathematical analysis that showed how one could use local motion subtraction of image velocities to eliminate image motion due to rotation. The resulting difference vectors form a radial pattern with a center coinciding with the observer's translational direction of

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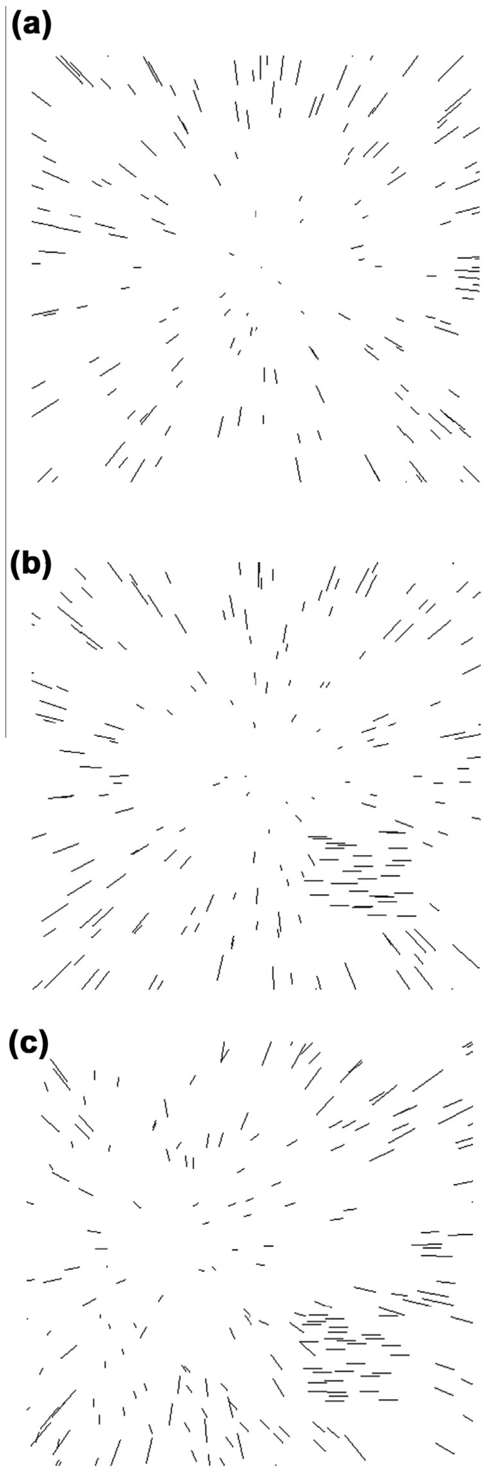


**Fig. 1.** Optic flow fields. (a) Radial optic flow field generated by an observer moving toward the center of a scene consisting of two planes at different depths. (b) Radial optic flow field with an object located in the lower right. (c) Optic flow field for an observer who is both translating and rotating, with a moving object in the lower right.

motion. Rieger and Lawton (1985) further showed that one could compute heading reasonably accurately using motion subtraction for two points separated on the image plane by a small amount. Hildreth (1992) showed that one could use local motion differences to determine an observer's direction of motion. Once the direction of motion is known, moving objects can be identified based on difference vectors whose angle does not fit the expected radial pattern for that observer heading.

The theoretical models discussed above rely on accurate measurements of both the direction and speed of 2D image velocities within a region of the visual field to compute the heading and the location of moving objects. This might lead one to assume that biological visual systems would also need to compute image velocities relatively accurately to accomplish these tasks. Because the initial neural processing of motion in primate visual cortex involves tuned responses to the direction and speed of motion (Maunsell & van Essen, 1983), an additional stage of processing would be required to compute the actual speed and direction of motion. For example, Priebe and Lisberger (2004) and Perrone (2012) have shown how this can be accomplished. Here, we ask whether one can accomplish these tasks without calculating speed and direction of image motion explicitly.

The model presented here is an extension of a model (Royden, 1997; Royden & Picone, 2007) that is based on the analysis of Longuet-Higgins and Prazdny (1980), but uses mechanisms that are based on the response properties of neurons in the primate visual system, such as speed- and direction-tuning, to compute heading. Here we extend the model to identify the borders of self-moving objects in the scene, by identifying locations where local motion differences lead to responses that differ from those expected for motion through a stationary scene.

### 1.2. Psychophysical evidence

It is clear from everyday experience that people can detect and interact with moving objects in a scene. Sports players can track moving balls and other players, and drivers can identify other moving vehicles or pedestrians in the scene. Royden and Connors (2010) showed that people can detect a moving object whose angle of motion differs from the radial flow pattern generated by an observer moving in a straight line. They reported a threshold detection angle of 10.3 deg deviation from the radial flow lines. They also noted that the global pattern was important for this detection, since people performed much more poorly when detecting an object deviating from a deformation pattern. Royden and Moore (2012) showed that people can also detect moving objects based on their speed. In their experiments, people detected objects whose speed was either 1.4 times faster or 0.6 times slower than it would be if it were part of the optic flow field (a 40% change in each case). From these two studies it is clear that people can detect an object for which the image motion varies in angle or speed from the optic flow field generated by an observer's straight line motion.

Warren and Rushton (2007, 2008, 2009; Rushton & Warren, 2005) have examined people's judgments of object trajectory when they are moving, and shown that the visual system appears to subtract out the optic flow due to the observer's own motion when computing the trajectory of the moving object. How this subtraction is accomplished by the visual system is an open question. Here we examine one potential model for motion subtraction to detect moving objects based on the response properties of neurons in the primate visual cortex.

## 2. The computational model

### 2.1. Mathematical derivation

The model for computing heading has been described in detail previously (Royden, 1997; Royden & Picone, 2007), but we provide a description of the main features here. To understand the mechanisms used by the model, we first review the mathematical underpinnings for determining heading for an observer undergoing