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The detection of moving objects by moving observers

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ABSTRACT

When an observer moves through the world, he or she must detect moving objects in order to avoid or intercept them. Accomplishing this task presents a problem for the visual system, because the motion of the observer causes the images of nearly all objects in the scene to move across the retina. We tested observers' abilities to detect a moving object when its angle of motion deviated from the radial optic flow pattern generated by observer motion in a straight line. To test whether global information is important for this task, we compared the results for a radial pattern with those for a deformation pattern. The results show that observer accuracy depends on the global pattern of the optic flow. In addition, we tested the effects of the duration of the trial, the number of objects, the eccentricity of the moving object and the speed of the observer.

1. Introduction

Observer motion through a scene causes images of objects in the scene to flow across the retina. Observers are able to use information from this 2D image motion, known as optic flow, to ascertain their direction of motion through the 3D world around them. One important task for a moving observer is to detect moving objects. For example, during a soccer game a player must maneuver across the field in the presence of other players and locate and track the moving soccer ball. Psychophysical research has shown that people judge their heading well from visual motion information alone (Royden, Banks, & Crowell, 1992; Royden, Crowell, & Banks, 1994; Warren & Hannon, 1988; Warren & Hannon, 1990), even in the presence of moving objects (Royden & Hildreth, 1996; Warren & Saunders, 1995), which do not affect heading judgments under most conditions and cause only a small bias in heading judgments under some conditions. It has often been assumed that one must identify moving objects before computing heading so that the effect of their motion would not bias the heading computation (e.g. Hildreth, 1992). However, Royden (2002, 2004) showed that a model for computing heading based on motion subtraction gives results very similar to those of human observers without removing the moving objects from the computation. Thus, the detection of moving objects in the scene does not appear to be a prerequisite for reasonably accurate heading computations.

The problem of the detection of moving objects by a moving observer has been less well studied. Because the images of stationary items in the world move across the retina when the observer is moving, it is unclear how a moving object can be distinguished from the other moving images in the scene. Several models of heading computation have addressed the problem of moving objects in the scene, often identifying moving objects in order to minimize their effects on the heading computation. For example, Thompson and Pong (1990) noted that one could make a preliminary estimate of observer motion parameters, and then identify regions that are inconsistent with the image motion pattern expected from these observer parameters. Hildreth (1992) proposed a heading model that computed the headings predicted from multiple localized regions of the image, identifying the location consistent with the majority of those local computations as the overall heading of the observer. The model then identified any local regions that computed a different heading as potential locations of moving objects. This is a similar idea to that of Thompson and Pong (1990), in that it identifies regions that are inconsistent with the image motion expected from the computed heading estimate.

Several studies have shown how the presence of an optic flow field generated by simulated observer motion can affect the perceived trajectory or the time to contact of a moving object within the scene (Gray, Macuga, & Regan, 2004; Gray & Regan, 2000; Matsuyima & Ando, 2009; Warren & Rushton, 2007; Warren & Rushton, 2008; Warren & Rushton, 2009). In a series of studies, Warren and Rushton (2007), Warren and Rushton (2009) showed that, under the conditions used in their experiments, the perceived trajectory of a moving object is dependent on the perceived depth of the object relative to the stationary items in the scene. Their

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hypothesis is that the visual system subtracts out the motion generated from the observer motion, a process they have labeled "flow parsing," and any remaining motion must be due to moving objects. Because many of their simulations involve observer rotations as well as translations, information about the relative depths of items in the scene is necessary for an accurate estimate of the image motion to be subtracted. The subtraction of the optic flow due to observer motion leads to predictable changes in the perceived motion direction of the moving object. However, none of the above studies examined how observers detect the moving object within an optic flow field. Object detection must be done before one can establish the object's trajectory.

Rushton, Bradshaw, and Warren (2007) have shown that, under some conditions, in a scene that simulates an observer translation and rotation about a set of stereoscopically presented cubes, a moving object "pops out", meaning that the reaction time to signal its presence is constant as the number of stationary (distractor) cubes increases. Royden, Wolfe, and Klempen (2001) also examined visual search for a moving object in a scene through which an observer was moving. They examined search for an object whose image motion was stationary within a radial optic flow field. While the object did not pop out, the search for the object was more efficient within a structured flow field, either a radial, deformation or translational field, than a search for the object within a field of randomly moving distractors. These studies showed that moving objects can be detected within the flow fields generated by moving observers, but neither study examined the parameters necessary for observers to detect that object. In the current study, to understand more about how people detect moving objects, we examined how several factors affect an observer's ability to detect moving objects in a scene through which he or she is moving.

The difficulty in detecting moving objects is illustrated in Fig. 1. For observer motion in a straight line through a stationary scene, the image velocities of all objects in the scene form a radial optic flow pattern (Fig. 1a). The center, or focus of expansion (FOE), away from which all image velocity vectors radiate, coincides with the observer's direction of motion, or "heading" (Gibson, 1950; Gibson, 1966). The heading can be easily determined by extending lines through the image velocity vectors and determining their intersection. Fig. 1b shows how the presence of a moving object in the scene could affect the flow field. A moving object in the scene could have an image that is moving in the same direction on the retina as the image of a stationary object. For example, the image of the moving object depicted in Fig. 1b is moving upward, which is the same direction as the image of one of the other items in the scene. How then do observers detect moving objects if they themselves are moving? As suggested by Thompson and Pong (1990) and Hildreth (1992), one method would be to locate items that are moving inconsistently with the optic flow field. For example, an object that is moving in a different direction from the radial flow lines generated within the optic flow field must be moving relative to the other stationary items in the scene. Thus, one would expect that human observers could detect objects moving at different angles from these radial patterns generated by observer motion. This would require the visual system to make use of the global pattern of image motion, in order to establish the radial pattern from which the object motion differs. An alternative hypothesis is that the visual system might use local motion differences to determine the presence of a moving object. In this case, the visual system might signal the presence of a moving object if its angle of motion differs significantly from that of the neighboring objects, independent of the global pattern.

One complicating factor in analyzing optic flow fields arises from eye movements made by the observer. The rotation of the eyes adds a component to the flow field and changes the pattern of optic flow on the retina (Gibson, 1950; Longuet-Higgins & Prazdny, 1980). Wilkie and Wann (2003) have presented evidence that the accuracy of steering is affected by whether the driver is allowed free eye movements or required to fixate. However, in terms of perception of the flow field, experiments in heading perception suggest that the motion due to real eye movements is discounted by the brain, so that heading accuracy is largely unaffected when observers move their eyes (Royden et al., 1992; Royden et al., 1994; Warren & Hannon, 1988; Warren & Hannon, 1990). This could be done by way of a motion-subtraction mechanism (Longuet-Higgins & Prazdny, 1980; Royden, 1997) or by way of a mechanism that may use an efference copy of the eye movement signal to eliminate the rotation effects within the flow field (Royden et al., 1994). It is not the aim of this study to examine the role of eye movements in moving object detection. Because the presence of a fixation point may add an additional cue for observers to use while judging the presence of a moving object, for most of the experiments presented here we chose to allow free eye movements with no fixation point, conditions that better emulate conditions observers would encounter in the real world. To verify that eye movements were not a big factor in the results, in experiment 2 we added a fixation point and instructed observers to maintain fixation during the trials.

In order to test how the angle of 2D image motion is used to detect moving objects in the flow field, we conducted psychophysical experiments to examine the effects of various factors on the ability to detect moving objects based on their angle of motion. Specifically, we determined the threshold angle of deviation from a 2D radial pattern of motion for which a moving object can be detected.

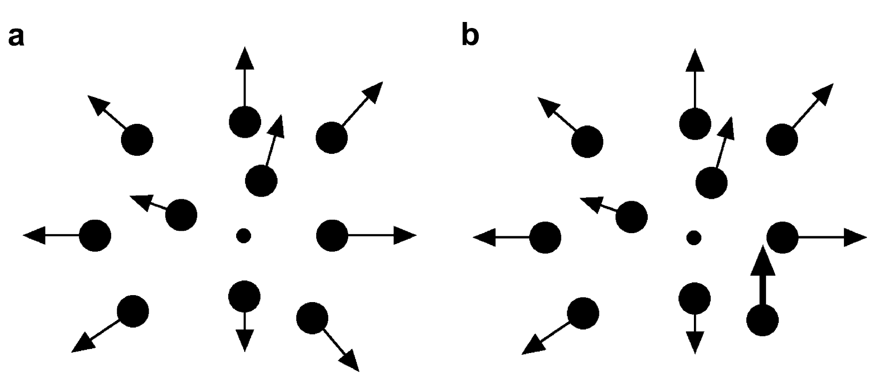

Fig. 1. Radial optic flow fields generated by an observer moving in a straight line toward a set of disk shaped objects. The small circle in the center indicates the FOE, which coincides with the direction of observer motion. Arrows indicate the direction of motion of each disk in the image. (a) Optic flow field with no moving object in the scene. (b) Optic flow field with one moving object in the scene. The moving object is in the lower right corner, indicated by the thick arrow.