Optic Flow

Optic flow refers to the image motion of the environment projected on the retina during our movement in the world. The term was first coined by James J. Gibson, and played a key role in the development of the ecological approach to visual perception, an approach that emphasizes studying human perception in the natural environment rather than in a controlled laboratory setting. Ever since James Gibson proposed that the optic flow field contains cues for the perception and control of self-motion, much research in cognitive psychology and neuroscience has investigated what specific cues from optic flow that people use for the perception and control of self-motion. The major findings are summarized below.

Perception of self-motion

The optic flow field is normally represented by a velocity field with each velocity vector depicting the motion of a reference point in the environment. Any optic flow field is composed of two components, a *translational component* of radial flow, which is the pattern of flow due to observer traveling on a straight path with no eye, head or body rotation (pure translation, Figure 1a), and a *rotational component* of lamellar flow, which is the pattern of flow due to observer eye, head, or body rotation and/or observer traveling on a curved path (Figure 1b).

[Figure 1 about here]

Figure 1. Sample velocity fields for movement over a ground plane. Each line represents a velocity vector depicting the motion of a reference point on the ground. (a) Translational component of radial flow produced by observer translation toward the "x". (b) Rotational

component of lamellar flow produced by eye rotation to the right about a vertical axis. (c) Retinal flow field produced by translating toward the "x" while fixating "o" on top of a post.

Source: Li, L., & Warren, W.H. (2000). Perception of heading during rotation: Sufficiency of dense motion parallax and reference objects. *Vision Research, 40*, 3873-3984.

Translation

When traveling on a straight path with no eye, head, or body rotation, the focus of expansion (FOE) in the resulting radial flow ("x" in Figure 1a) indicates one's instantaneous direction of self-motion (heading), and can thus be used for the control of self-motion. To illustrate, to steer toward a target, we keep the FOE on the target; to stay in the lane during driving, we keep the FOE at the center of road; and to steer to avoid an obstacle, we make sure the FOE is not on the obstacle etc. Research by William Warren and others has shown that humans can indeed use the FOE in optic flow to estimate their heading within 1˚ of visual angle during simulated translation. Note that good heading performance for pure translation may not involve the perception of self-motion, because the task could be performed by locating the FOE in the 2D velocity field on the screen without any 3D interpretation of the velocity field.

Translation and rotation

When one is traveling on a curved path or is traveling on a straight path but rotating one's eyes to track an object off to one side, the retinal flow pattern is not radial any more. The flow field now contains both translational and rotational components, and the lamellar flow generated by the path or eye rotation (Figure 1b) shifts the FOE in the retinal flow field away from the heading direction (Figure 1c). To recover heading in this case, many mathematical models have been proposed that use information such as global flow rate and motion parallax in the flow field to compensate for the rotation, a computation that has been implemented with neurophysiological models of primate extrastriate visual cortex.

To determine whether humans are capable of recovering heading from combined translational and rotational flow, a number of behavioral studies have examined heading perception during translation with simulated eye movements (the display is generated in such way that the retinal image of the display on a stationary eye is the same as if the eye had moved). While some behavioral studies by Martin Banks and others show that observers need extra-retinal information (such as occulomotor signals about eye movement) to remove the rotational component in the flow field for accurate heading estimation at a high eye rotation rate, more studies by James Cutting, Leland Stone, Li Li, and others find that observers can estimate their heading within 2° of visual angle by relying on information solely from optic flow, especially when a large field of view and realistic complex 3D scenes are provided.

Path perception

Apart from heading, an equally important feature of self-motion is one's future trajectory of traveling (path). The common locomotion control tasks that can be achieved using heading can be similarly accomplished using path. Heading and path coincide when one travels on a straight path but diverge when one follows a curved path of motion, as in the latter case, heading is the tangent to the curved path (Figure 2).

[Figure 2 about here]

Figure 2. An illustration of the relationship between heading and path for (a) traveling on a straight path and (b) traveling on a curved path.

While heading can be perceived from a single 2D retinal velocity field of optic flow, path recovery requires more. The instantaneous velocity field during translation and rotation is associated with one heading direction but is consistent with a continuum of path scenarios ranging from traveling on a straight path with eye, head, or body rotation to a circular path with no eye, head, or body rotation. This path ambiguity problem can only be solved using information beyond a single retinal velocity field such as the acceleration in the translational flow field, dot motion over an extended amount of time, reference objects in the scene, or extra-retinal signals. All these cues can be used to determine whether the rotational component in optic flow is due to eye, head, body, or path rotation. However, up to now very few studies have examined how these cues are used for the perception of path trajectory.

For the relationship between heading and path perception, given heading is the tangent to the curved path (Figure 2) and observers can infer heading as soon as they perceive path, recent studies from Li Li's lab have found that while heading and path perception are two separate processes, path does help heading perception when the display does not contain sufficient optic flow information for accurate heading estimation. Furthermore, accurate perception of path but not heading from optic flow depends on where we are looking, thus supporting the claim that heading is a more reliable cue for the on-line control of locomotion.

Neural basis

Many species have neural pathways that selectively respond to optic flow patterns. The neurophysiological basis of heading perception includes several cortical areas. Earlier single-neuron studies by Charles Duffy, Robert Wurtz, and others report that neurons in macaque dorsal medial superior temporal cortex (MSTd) selectively respond to radial, lamellar, and spiral patterns of optic flow. More recent functional magnetic resonance imaging (fMRI) studies on macaque and human brains by Frank Bremmer, Andrew Smith, David Burr, and others reveal that the ventral intraparietal area (VIP) is also involved in heading perception as well as a human homologue of primate MST, the MT complex (MT+).

For the cortical areas involved in path perception, recent brain imaging work on humans by David Field and others reports that the presence of road markers, which clearly defined the path trajectory, activates the superior parietal lobe (SPL) bilaterally in addition to the MT+ area. Presenting observers with distant road markers during heading judgment reproduces the SPL activation, while presenting observers with near road markers results in activation only in the MT+ area.

Control of self-motion

James Gibson proposes that we use the information that we perceive from optic flow to guide our movement in the world. The main research findings on optic flow cues used for visual feedback-driven control of self-motion are summarized below.

Walking toward a target

James Gibson states that to steer toward a target, we move in such way to keep the FOE in optic flow (i.e., heading) on the target. However, work by Simon Rushton and others has challenged this claim. They find that when observers wearing a prism are asked to walk toward a target, they walk on a curved rather than a straight path. The prism deflects the visual direction of the target from the observer but it does not deflect the FOE in the optic flow pattern from the target. The results thus support the idea that observers rely on the visual direction of the target but not the FOE in optic flow to walk toward the target. Nevertheless, testing people in a virtual environment in which optic flow information can be rigorously controlled, recent work by William Warren and others find that both the FOE in optic flow and the visual direction of the target contribute to control of locomotion on foot. The FOE appears to increasingly dominate control as more flow and motion parallax information is added to the scene.

Braking

The rate of expansion in optic flow specifies the time-to-contact with objects and can thus be used for the control of braking during driving. David Lee proposes that by adjusting deceleration so that the rate of change in time-to-contact is near the margin value of -0.5, one would stop at the moment of contact. Several naturalistic studies by David Lee and others report that hummingbirds indeed follow this strategy in docking on feeding tubes. A behavioral study from William Warren's lab also confirms that observers adopt this strategy to control the direction and magnitude of braking for a linear brake with no higher order control dynamics during simulated driving. However, recent work by Brett Fajen shows that observers do not rely on a single optical variable for braking control during driving. As the dynamics of the controlled system influences the visual cues observers see in the display due to their control actions, observers rely on different optic flow cues (such as global flow rate) to modulate deceleration during braking depending on the dynamics of the braking system (i.e., the mapping between brake position and deceleration).

Lane keeping

Another commonly experienced control of self-motion task is lane keeping on a straight path during driving, riding a bicycle, or walking down a path. There are at least three types of cues from optic flow that we can use for lane keeping. The first one is again, the FOE in radial optic flow. Lane keeping can be achieved by keeping the FOE (i.e., heading) centered on the far end of the lane. The lane edges provide two other cues for lane keeping: bearing and splay angle. Bearing refers to the direction from the observer to a reference point on the lane edge, measured with respect to a reference direction such as the gaze direction or meridian, and splay angle refers to the angle between the optical projection of the lane edge and a vertical line on the image plane. To maintain traveling in the center of a lane, observers can adopt the strategy of keeping the left and the right bearing or splay angle equal. The further away the reference point on the lane edge, the less useful bearing information because the harder it becomes for the observer to detect a change of bearing. On the other hand, as the near and the far parts of the lane edges provide the same splay angles, unlike bearing, splay angle information is a property of the whole image plane, independent of distance.

The FOE in the radial flow, bearing, and splay angle strategies for lane keeping in the real world are usually redundant and lead to the same lane-keeping behavior. Early research in human factors has reported that human operators use heading more than the vehicle's lateral position (which defines bearing and splay angle) for lane keeping. Later work by Andrew Beall and Jack Loomis has found that people rely mainly on the splay angle for lane keeping. A recent work by Li Li challenges this finding and shows that heading from optic flow is used for lane keeping regardless of the presence of spay angle information. Several other studies reveal that equating the speed of radial flow in the left and right lateral field of view also contributes to maintaining a centered position in the lane.

In summary, in support of James Gibson's proposal that optic flow contains cues for the perception and control of self-motion, research in cognitive psychology and neuroscience over the last four decades has not only identified the cues in optic flow that we use to perceive and control our self-motion in the world, but also the underlying neural mechanisms responsible for the detection of these cues. As our detection of information in optic flow puts us in direct contact with the world without the need of mediating representations, optic flow provides the key supporting evidence for the concept of direct perception.

Li Li

See also Direct and Indirect Perception; Vision, Neural Basis

Further Readings

Fajen, B. R. (2008). Learning novel mappings from optic flow to the control of action. *Journal of Vision*, *8*(11):12, 1-12, http://journalofvision.org/8/11/12/, doi:10.1167/8.11.12.

Gibson, J.J. (1979). *The ecological approach to visual perception*. Boston: Houghton Mifflin.

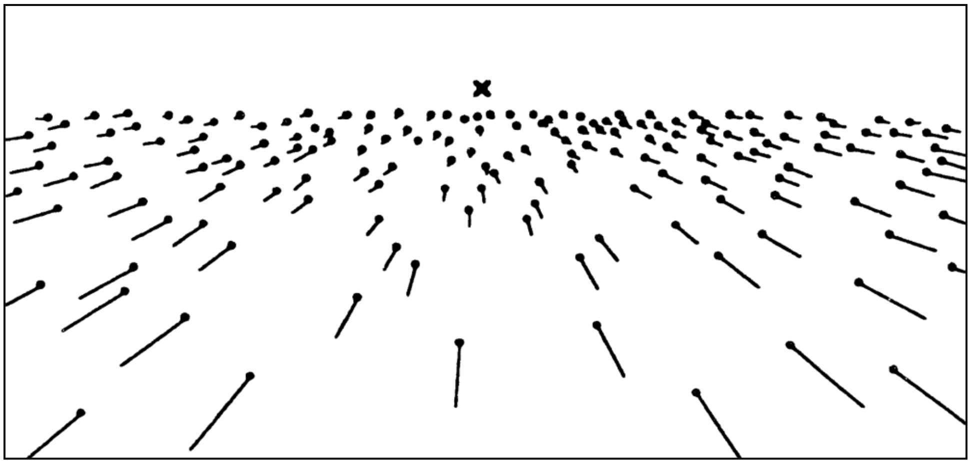
Li, L., Chen, J., & Peng, X. (2009). Influence of visual path information on human heading perception during rotation. *Journal of Vision*, *9*(3):29, 1-14, http://journalofvision.org/9/3/29/, doi:10.1167/9.3.29.

Rushton, S., Harris, J., Lloyd, M., & Wann, J. (1998). Guidance of locomotion on foot uses perceived target location rather than optic flow. *Current Biology*, *8*, 1191-1194.

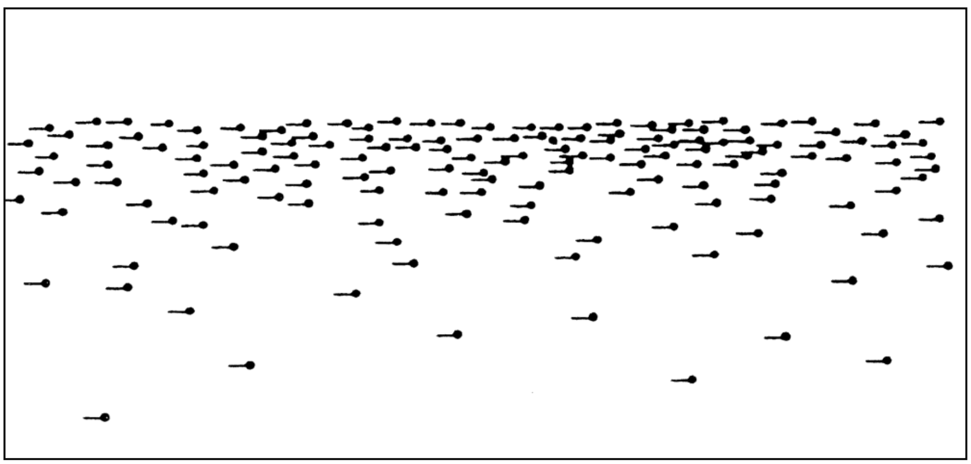
Wall, M. B., & Smith, A. T. (2008). The representation of egomotion in the human brain. *Current Biology*, *18*, 191-194.

Warren, W. H. (2008). Optic flow. In A.I. Bashaum, A. Kaneko, G.M. Shepherd, & G. Westheimer (Eds.), *The senses – a comprehensive reference: Vision II* (Vol. 2, T.D. Albright & R. Masland, Eds). Oxford, UK: Academic Press, 219-230.

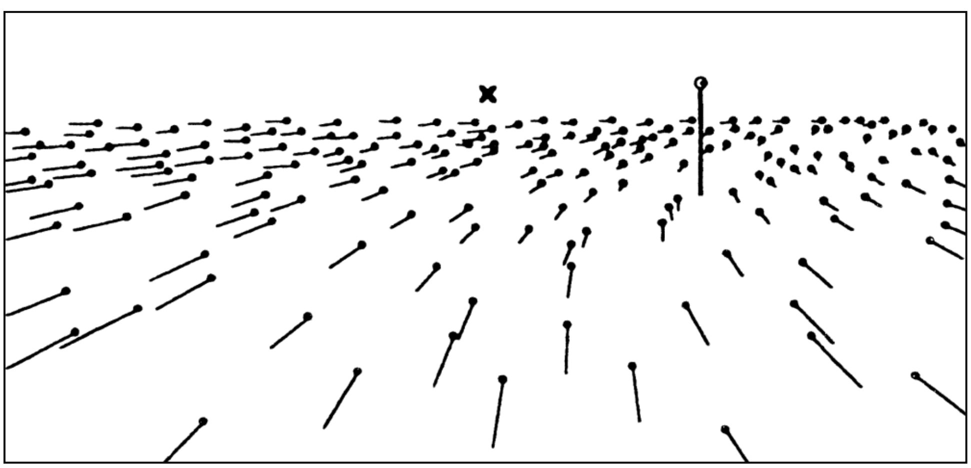
Warren, W. H., Kay, B. A., Zosh, W. D., Duchon, A. P., & Sahuc, S. (2001). Optic flow is used to control human walking. *Nature Neuroscience*, *4*, 213-216.



(a)



(b)



(c)

Figure 1.

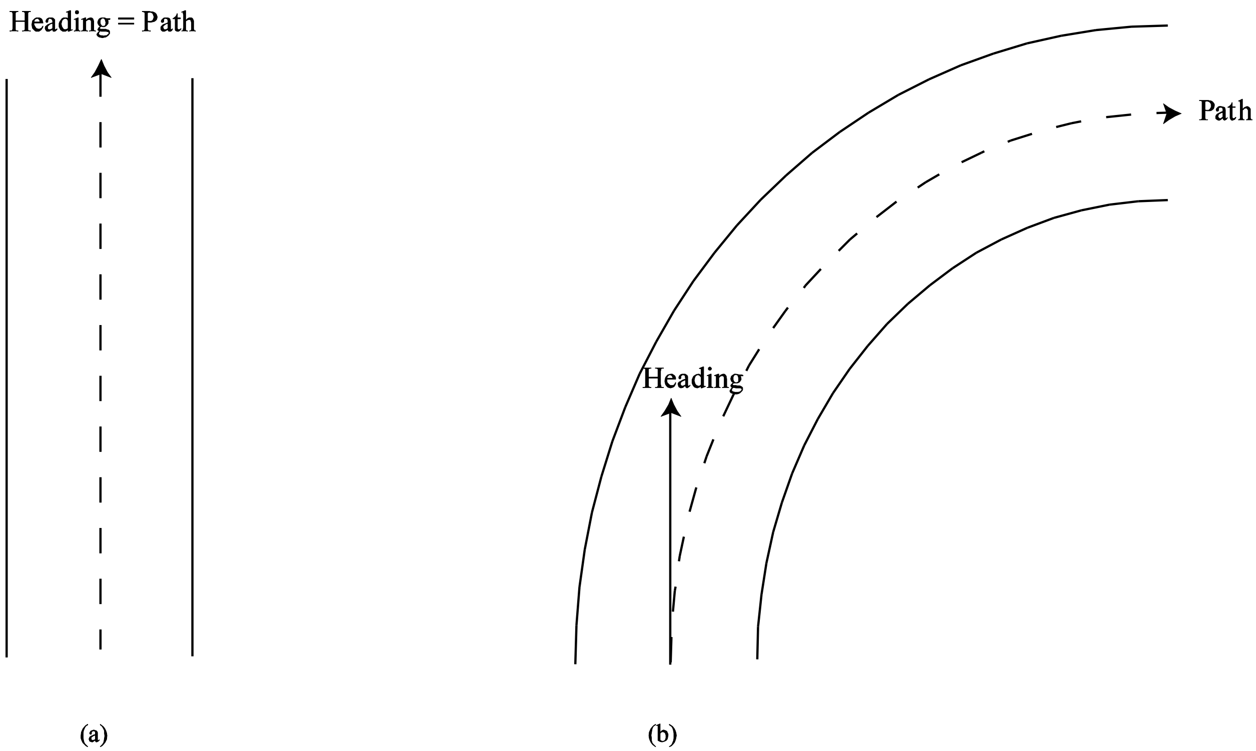


Figure 2.