Perception of Heading and Driving Distance From Optic Flow

Markus Lappe, Antje Grigo, Frank Bremmer, Harald Frenz

Zoology & Neurobiology, Ruhr–University, 44780 Bochum, Germany

Tel. +49/234/32-24350, Fax. +49/234/32-14278

email: lappe@neurobiologie.ruhr-uni-bochum.de

www.ruhr-uni-bochum.de/neurobiol/mitarbei/markus_lappe/e_mlappe.htm

Rene J. V. Bertin, Isabelle Israël

College de France / L.P.P.A., 11, place Marcelin Berthelot, 75005 Paris

Among the sensory signals available to control driving (or walking), the induced visual motion pattern, the optic flow, is a powerful source of information. The role of optic flow in visual navigation has been increasingly researched over the last ten years. The basic questions are: which information can be obtained from the optic flow, and how does the human visual system do it? I will concentrate on two tasks for which optic flow analysis can be used during driving. The first is the perception of heading (the direction of self-motion) from optic flow. The second concerns the perception of driving distance from optic flow.

Many perceptual experiments have shown that heading can be perceived from optic flow. They have identified important requirements for accurate analysis as well as sources of error. A particular concern are eye movements which are induced by optic flow and which, by distorting the structure of the flow field projected in the eye, compromise heading detection. The nature of these eye movements and their influence on optic flow analysis in the visual system will be discussed. The perception of driving distance from optic flow is less well studied. Recent experiments, however, showed that humans can reliably discriminate driving distance on the basis of optic flow provided they can make valid assumptions about the structure of the visual environment. This new finding may point to a previously overlooked role for optic flow in driving.

Driving comprises many subtasks. The driver has to monitor the status of the road and the car, has to estimate and anticipate the car's heading with respect to the road, steer, analyse road signs, observe the behavior of other drivers or pedestrians, and register his own speed and travel distance. In all of these tasks the generation of appropriate behavior requires the analysis of sensory information. Almost always visual information is involved, often accompanied by other sensory sources such as somesthetic, vestibular, or auditory signals. Hence, an important step for understanding driving behavior — and for building realistic driving simulators — lies in studying the perceptual processes that support the analysis of driving–related sensory information. In the following, I will review recent research on the sensory perception of heading and driving distance. I will concentrate on visual information provided by the optic flow but also include related sources of information that are not of visual origin.

Optic flow is the pattern of visual motion that one experiences during one's own movement. When driving along a straight road and looking straight ahead, the optic flow has the well–known characteristic structure of an optical expansion. All visual motion is directed radially away from the focus of expansion, which lies in the direction of the heading of the car. In this situation, one may ask whether the driver can use the location of the focus of expansion to estimate his or her heading. Several studies have shown that humans can accurately locate the focus of expansion in the optic flow and suggested that this capability may contribute to driving behavior [1, 2, 3]. In order to restrict the information available to the subject to pure optic flow, these studies have not used realistic driving simulations but rather impoverished controlled displays that consisted only of random dots moving in an expanding pattern. Observers can equally well locate estimate their heading in more realistic displays [4]. But the observation that good performance can be obtained with impoverished displays makes clear that simply the visual motions in the optic flow contain sufficient information.

The structure of the optic flow pattern changes when components of rotation are added to the movement. One particular situation is driving in a curve. In this case, there is no focus of expansion in the optic flow. Rather the flow resembles of a collection of curved lines. Yet, human observers are quite capable to estimate the degree of curvature [5] and their curvilinear heading [6, 7] from the optic flow.

A second way by which rotational components may enter the optic flow is through the occurrence of tracking eye movements. Although eye movements clearly do not influence the course of the car, they do influence the projection of the relative movement between the world and the driver (the optic flow) in the driver's eye. The visual input that the driver experiences is therefore the retinal projection of the optic flow, or the *retinal* flow. The structure of the retinal flow is different from the structure of the optic flow because of the additional transformation due to eye movements. In particular, the retinal flow often does not contain a focus of expansion even for linear movement, or, if it does, the focus of expansion is not synonymous with heading [8, 9, 10]. Thus it is not clear whether the described ability of human observers to locate the focus of expansion in an expanding optic flow has any relevance to the normal driving situation at all. Two important questions arise from these considerations. First, what eye movements occur during driving? Second, if tracking eye movements occur, can observers estimate heading from the retinal flow?

Like most behaviors driving is accompanied by eye movements and gaze shifts. During open road driving gaze is most often directed straight ahead, a lower percent of the time to the far scenery on the side or to other vehicles, or, very infrequently, to the near parts of the road [11]. But the percentage of time spent looking in these directions depends on the scene and on the task or objective of the driver. More gaze shifts to eccentric positions are made when the driver is asked for instance to attend to all the road signs, memorize the travel area, etc. [11, 12, 13]. Frequent and large gaze shifts occur, for instance, when crossing an intersection [14]. A further characteristic and consistent relationship between gaze direction and driving behavior has been described for the negotiation of curves [15]. During approaching and driving a curve, gaze is directed towards a specific point at the inner edge of the road, the 'tangent point'. This is the point where the tangent to the edge of the road reverses direction, the innermost point of the road edge seen from the driver. During driving in a curve, gaze is directed towards the tangent point on average 80% of the time.

Gaze shifts are used to gather essential visual information through scanning of the scene. But in addition, eye movements during self–motion serve a further important function, namely to maintain stable vision in the presence of large–field visual motion (optic flow). Because of the retinal image motion induced by optic flow the eye needs to be moved along to stabilize the image of the scene. Several types of compensatory eye movement reflexes attempt to counteract the self–motion induced visual motion and keep the retinal image stable [16]. They act on vestibular, proprioceptive, or visual input. When human observers look at an optic flow stimulus their eye movements show a regular alternation of gaze shifts and slow tracking movements at a frequency of about

2Hz [17, 18]. Eye movements in the slow tracking phases follow the averaged motion near the direction of gaze. Hence these slow phases stabilize the retinal image in a small area around the direction of gaze. However, while such tracking eye movements are beneficial for stable vision in the central field they create problems for the analysis of optic flow in the peripheral field. Tracking eye movements induce motion of the retinal image such that the optic flow in the central visual field is cancelled. However, the same image motion is also added to the peripheral parts of the visual field such that the total retinal motion pattern becomes a combination of radial optic flow with retinal motion induced by the eye movement. The resulting retinal motion pattern is quite different from the simple expansion that one normally associates with optic flow. In particular, eye movements usually destroy or transpose the focus of expansion on the retina (e.g. [8, 10]). The question then becomes whether such distorted flow patterns still signal information relevant for driving, and in particular whether it is still possible to perceive heading from such retinal flow.

Human observers have been asked to estimate heading while they watched an optic flow stimulus and performed tracking eye movements. Heading accuracy was almost as good as when subjects located the focus of expansion during fixation [8, 19]. However, in this condition two sources of information are available to the subject. The first is the motion pattern of the retinal flow. The second is non–visual information about the eye movement, which may be provided by eye muscle proprioception or by an efference copy signal of the brain command driving the eye movement. Therefore, it is not clear whether the ability to estimate heading in this situation is based on the optic flow or an a combination of optic flow with non–visual eye movement signals. To tear these two possibilities apart, investigators have used the paradigm of simulated eye movements. In this paradigm, the visual display does not only simulate the forward movement of the observer but also a tracking eye movement. To the fixating eye, the display would present the same retinal flow as a real eye movement, but the eye proporioception and efference copy signals are eliminated because the eye is physically motionless. Data from these experiments are mixed. Some researchers found that the lack of non–visual eye movement signals prevented correct estimates of heading (e.g. [19]). Others found accurate judgements, supporting the view that retinal flow alone contains sufficient information (e.g. [8, 20]). A detailed overview of the discussion can be found in [10].

To take the rotation problem a step further, we have recently begun to investigate the perception of entire movement trajectories in the presence of rotational components

[21]. Observers were asked to estimate the trajectory of a simulated movement from an optic flow display. The trajectory was either straight or semicircular. In some trials, a rotation about the vertical axis was added as if subjects turned during their movement. In this situation, the change in heading, or, equivalently, the trajectory curvature, must be dissociated from a true change in orientation, i.e., a rotation about the vertical axis. It turned out that subjects in some condition were unable to perform this task. Accurate performance required that the simulated orientation either stayed constantly tangential to the trajectory, or remained constant in space. When neither of these requirements was fulfilled, subjects strongly overestimated the curvature of the trajectory. This suggests that assumptions about normal conditions in locomotion and driving ("orientation is mostly tangential to the path") can strongly influence our interpretation of the visual input.

Next to heading, the optic flow may provide other information relevant for driving. Speed, travel distance, and time–to–contact with obstacles in the scene would all be of interest to the driver. Strictly speaking, optic flow alone carries only information about the last, time–to–contact [22, 23]. Because visual velocities in the optic flow are determined from the product of forward speed and the distance of the respective visible object from the observer, neither speed nor distance can directly be inferred without knowing the other. However, if one can make valid assumptions about the speed or about the structure of the environment it may becomes possible.

We have recently started to evaluate the conditions under which human observers can make reliable estimates of travel distance from optic velocities [24, 25]. Test persons were presented with two successive optic flow displays that simulated forward motion with variable speeds and duration. Their task was to compare the travel distances of the two movements and tell whether the second movement went further or less far than the first. From a sequence of trials we calculated the point of subjective equality (PSE) of the two distances (i.e., when both appear to be of the same length). In a series of experiments we determined the dependence of the PSE, and hence the distance estimation ability, on the speed and duration of the two movements and on the structure of the environment. We found that observers could consistently discriminate between movements of different distance, even if the speed in the two movements was different. Some subjects exhibited individual over– or underestimation of driving distance when speed changed, but the average data was quite accurate. Variation of the structural cues in the environment revealed that the main contribution to this ability was an integration of optical velocities experienced over the duration of the sequence. These results suggest that optic flow may play a role also in the perception of driving distance.

References

[1] W. H. Warren, M. W. Morris, and M. Kalish. Perception of translational heading from optical flow. *J.Exp.Psychol.: Hum.Percept.Perform.*, 14:646–660, 1988.

[2] J. A. Crowell and M. S. Banks. Perceiving heading with different retinal regions and types of optic flow. *Percep.Psychophys.*, 53:325–337, 1993.

[3] S.F.T. te Pas, A.M.L. Kappers, and J.J. Koenderink. Locating the singular point in first-order optical flow fields. *J.Exp.Psychol.: Hum.Percept.Perform.*, 24:1415–1430, 1998.

[4] J. E. Cutting, P. M. Vishton, M. Flückinger, B. Baumberger, and J. D. Gerndt. Heading and path information from retinal flow in naturalistic environments. *Percep.Psychophys.*, 59:426–441, 1997.

[5] K. Turano and X. Wang. Visual discrimination between a curved path and straight path of self motion: Effects of forward speed. *Vision Res.*, 34:107–114, 1994.

[6] W. H. Warren, D. R. Mestre, A. W. Blackwell, and M. W. Morris. Perception of circular heading from optical flow. *J.Exp.Psychol.: Hum.Percept.Perform.*, 17:28–43, 1991.

[7] L.S. Stone and J.A. Perrone. Human heading estimation during visually simulated curvilinear motion. *Vision Res.*, 37:573–590, 1997.

[8] W. H. Warren and D. J. Hannon. Eye movements and optical flow. *J.Opt.Soc.Am.A*, 7:160–169, 1990.

[9] A. Grigo and M. Lappe. An analysis of heading towards a wall. In L. R. Harris and M. Jenkin, editors, *Vision and Action*, pages 215–230. Cambridge University Press, 1998.

[10] M. Lappe, F. Bremmer, and A. V. van den Berg. Perception of self-motion from visual flow. *Trends.Cogn.Sci.*, 3:329–336, 1999.

[11] R. R. Mourant, T. H. Rockwell, and N. J. Rackoff. Driver's eye movements and visual workload. *Highway Res.Rec.*, 292:1–10, 1969.

[12] P. K. Hughes and B. L. Cole. The effect of attentional demand on eye movement behaviour when driving. In A. G. Gale, editor, *Vision in Vehicles II*. Elsevier, 1988.

[13] J. Luoma. Drivers' eye fixations and perceptions. In A. G. Gale, editor, *Vision in Vehicles II*. Elsevier, 1988.

[14] M. F. Land. Predictable eye-head coordination during driving. *Nature*, 359:318–320, 1992.

[15] M. F. Land and D. N. Lee. Where we look when we steer. *Nature*, 369:742 – 744, 1994.

[16] F. A. Miles. The neural processing of 3-d visual information: evidence from eye movements. *Eur.J.Neurosci.*, 10:811–822, 1998.

[17] T. Niemann, M. Lappe, A. Büscher, and K.-P. Hoffmann. Ocular responses to radial optic flow and single accelerated targets in humans. *Vision Res.*, 39:1359–1371, 1999.

[18] M. Lappe and K.-P. Hoffmann. Optic flow and eye movements. In M. Lappe, editor, *Neuronal Processing of Optic Flow*, Int.Rev.Neurobiol.44, pages 29–47. Academic Press, 2000.

[19] C. S. Royden, J. A. Crowell, and M. S. Banks. Estimating heading during eye movements. *Vision Res.*, 34:3197–3214, 1994.

[20] A. V. van den Berg. Perception of heading. *Nature*, 365:497–498, 1993.

[21] R. J. V. Bertin, I. Israel, and M. Lappe. Perception of two–dimensional, simulated ego–motion from optic flow. Comparison with a vestibular study. *Vision Res.*, 2000. (in press).

[22] D. N. Lee. The optic flow field: The foundation of vision. *Philos.Trans.R.Soc.Lond. B*, 290:169–179, 1980.

[23] J. R. Tresilian. Visually timed action: time-out for 'tau'? *Trends.Cogn.Sci.*, 3:301–310, 1999.

[24] F. Bremmer and M. Lappe. The use of optical velocities for distance discrimination and reproduction during visually simulated self–motion. *Exp.Brain Res.*, 127:33–42, 1999.

[25] H. Frenz, F. Bremmer, and M. Lappe. Wahrnehmung von Distanzen visuell simulierter Eigenbewegungen in unterschiedlichen Umgebungen. In H. H. Bülthoff, M. Fahle, K. R. Gegenfurtner, and H. A. Mallot, editors, *Beiträge zur 3. Tübinger Wahrnehmungskonferenz*, 2000.