18. How do We Control High Speed Steering?

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1 INTRODUCTION

We routinely travel at high speed, in a car or on a bicycle, and also steer complex paths with relatively little conscious processing or explicit procedures as to how we 'judge a bend'. The consequences of an error, however, could be considerable. Within this chapter we tackle the issue of how optic flow and other sources of information can enable locomotor animals to steer effectively. Although there has been a strong body of research into how we might judge locomotor *heading* we will argue that this does not equate to active locomotor control and that there is relatively little research into effective steering, despite the latter being the ecological skill that all locomotor animals need to achieve. We have written this chapter in a tutorial style to try and make a difficult field accessible to undergraduate and postgraduate students. In this respect we do not attempt to cite every contribution on the use of optic flow or other information sources, but provide some basic background and then concentrate on the components that we believe can be linked into a coherent account of high speed steering.

1.1 Optic Flow, Retinal Flow and Heading

In a seminal paper in the British Journal of Psychology, Gibson (1958) tabled the agenda that vision research should be tackling ecological tasks such as steering & aiming; approaching without collision; and steering amongst obstacles. He proposed that the task of steering could be accomplished by using properties of the optic flow field. A particular assertion was that "*the center of the flow pattern during forward movement of the animal is the direction of movement*" and *"to aim locomotion at an object is to keep the*

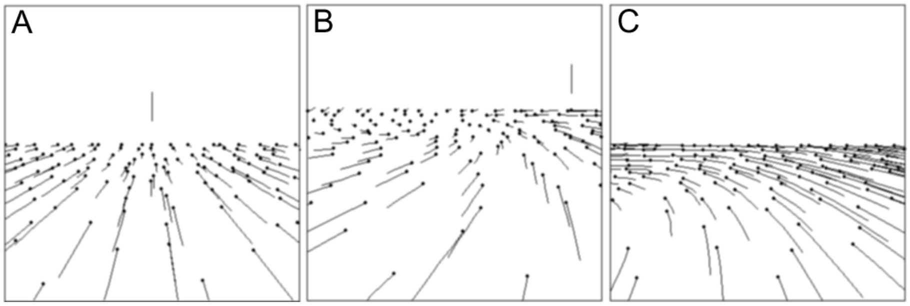

Figure 1. Retinal flow patterns for a) Radial Flow with gaze fixed forward, actual destination indicated by the vertical line above the horizon. b) The same straight line trajectory as in (a), but with gaze fixed on a ground feature to the left of the path, so on the retinal the destination is displaced to the right and there is a local focus of expansion at the point of gaze. c) A curved path with fixed gaze demonstrating locomotor flow lines.

center of flow of the optic array as close as possible to the form which the object projects", (p. 187). These statements are true for *optic flow* when the observer is on a straight path, in which case the flow field will be radial with a clear focus of expansion (FoE) in the direction of heading (Figure 1a). These principles are suitable for *maintaining* heading towards a particular goal, when the observer has a stable gaze position. The problem that arises in ecological tasks is that humans, and many other locomotor animals, have fast, mobile gaze systems that are used to sample from the environment and fixate future targets during locomotion. For a mobile eye the fundamental problem is that *optic flow* (as discussed by Gibson) is not equivalent to the *retinal flow* that will be received at the back of the observer's eye. The classic description of the problem is that if the observer is traveling on a straight-line path so the optic flow is radial, but fixates a feature to the side of locomotor path, then the flow field on the retina is not radial (Figure 1b). It is of particular note that the FoE at the point of heading is now masked and a new local expansion point occurs at the point of fixation (Regan & Beverley, 1982). To recover optic flow from the retinal pattern, processing would be required to subtract the gaze rotation component, render an unbiased flow field with an identifiable FoE and thereby provide an estimate of *heading*. The premise is that once optic flow is recovered the control strategy would be one of keeping the focus of expansion on the target object in order to maintain your heading towards it.

The task of recovering heading from retinal flow has been the main focus of research in this area during the last 15 years. The approaches may be crudely divided into those that propose the use of decomposition algorithms or template methods (Warren & Hannon, 1988; 1990; van den Berg, 1993; Stone & Perrone, 1997; Li & Warren, 2000) and those that propose the extraction of the gaze rotation component using of extra-retinal signals specifying the head and eye motion (Royden et al., 1994; Banks et al., 1996; Crowell et al., 1998). The main difference between the two approaches is the extent to which the eye-movements are incorporated. Decomposition algorithms work solely upon the retinal image, relying upon contrasting properties of the rotation and translation components of the flow field to recover optic flow. These methods are limited by the quality of the retinal information and have problems with some potentially ambiguous flow fields. In contrast extra-retinal signals provide a direct measure of the magnitude of motion, but this would require muscle motor commands to be combined with visual information.

The majority of heading research has been applied to the case of a straight-line path. Similar issues do arise for curved trajectories (Figure 1c), and while there is no FoE for optic flow it may be possible to discern 'locomotor flow lines' (Lee & Lishman, 1977). A simple generalization of Gibson (1958) would be that you could steer by keeping the target object centered within the locomotor flow lines, irrespective of whether they are radial (linear path) or curved. But once again if the observer fixates an object in the direction of travel the locomotor flow lines will be biased by gaze rotation. In this case the use of decomposition algorithms is more problematic because there is a potential confusion between the rotation in the flow field that is due to the curvature of the path and the component produced by gaze rotation.

In summary if a driver or cyclist moves his/her eyes during locomotion then this masks any clear specification of the direction of travel in the retinal flow field. This has led to a prolonged debate as to how human participants can recover their direction of heading from retinal flow. The problem with this debate is that it has taken a tangent to Gibson's original agenda. Rather than addressing the issue of active steering using optic flow, it has focused on the recovery of instantaneous heading. Even if the observer is able to recover their instantaneous heading from retinal flow it is still the case that to *steer* they need to implement a procedure to change that heading and perceive whether the rate of change of heading is sufficient to achieve their goal. In this respect perceiving heading can at best be an intermediate stage in the control of locomotion. Our argument will be that it may not be necessary at all, and that active steering can progress without the need to recover heading per se.

In reviewing the previous research on optic/retinal flow Lappe at l. (1999) posited that the questions for future research were: How is path information obtained and how is the path predicted? How is optic flow combined with other navigational strategies? How are eye movements actively used? This chapter outlines the retinal or extra-retinal information that can specify the future path, and how gaze fixation can be used in combination with retinal flow and extra-retinal information to provide a robust steering mechanism.

2 IS FLOW NECESSARY FOR STEERING?

Although there is a strong body of research into the perception of heading from flow, considerably less research has been directed toward exploring the use of retinal flow and/or extra-retinal information in steering. The role of flow in active steering has been questioned: Rushton et al. (1998) demonstrated that participants asked to walk to a target, which was viewed through a prism, took a distinctive curved path. The prism caused the target to be shifted in relation to the observer's head, but the pattern of flow was unchanged by the prism since all scene elements were shifted equally. In this situation, it is predictable that participants set off in the wrong direction. Before they started moving the angle between their body axis and direction of gaze (Visual Direction: VD) was the only information they had regarding the placement of the target, and this was displaced by the prism. Once they were in motion, however, the retinal flow emanating from the fixated target would have been weakly curved, due to gaze rotation, indicating that they were not walking towards the target. If participants were able to use flow information they should have been able to fully compensate for the error and then walk straight towards the target. Instead, Rushton et al. (1998) observed participants fixating the target and then closing down the angle between their body axis and direction of gaze, hence VD seemed to be the primary source of information in walking directly towards a goal. Based on this and a number of follow-on studies (Rogers & Dalton, 1999; Wood et al., 2000; Harris & Bonas, 2002), Harris & Rogers (1999) stated, "*We challenge flow researchers to provide some compelling evidence for a significant role of optic flow in the control of the direction of locomotion on foot*", (p. 449). In response Warren et al. (2001) conducted equivalent walking experiments in a large scale virtual environment, where they could manipulate the quality of optic flow, and proposed that VD and optic flow are both used, but the reliance on either depends upon the strength of optic flow. Warren et al. responded to the challenge by stating, "*contrary to previous claims humans indeed make use of optic flow to walk to a goal*", (p. 216).

In evaluating this debate it is useful to note that in the prism experiment the curved trajectory results because the participant is iteratively adjusting walking direction so that the displaced image appears directly ahead, so from the participants viewpoint the trajectory was 'straight towards the target'. In an everyday steering task, with no prism displacement, the equivalent strategy would be to register the visual angle of the target and then pivot around to cancel that angle so a straight-line trajectory can be taken. This is a very simple solution to some locomotor steering tasks, but it is not a general solution. Most vehicles have a wheelbase that restricts the turning arc, and even in running or skating, momentum makes a curved trajectory necessary and precludes an instantaneous target alignment. In other cases (e.g. a roadway) there may be a course that precludes a direct line approach that has to be followed to avoid obstacles and reach the target. The VD strategy and heading-from-flow strategies that have been debated only provide solutions for the rather simplistic task of walking in a straight line towards a target at low speeds (1-2 m/s). For a more general solution we consider how VD or optic flow might be used to plan and execute curved trajectories, including those of minimal curvature (i.e. almost straight) during higher speed approaches.

The VD strategy can be used for curved trajectories. Land & Lee (1994) and Land (1998) proposed that car drivers fixate the tangent point of a bend (apex of the inside curb) and use the angle of the tangent point to estimate the degree of steering required

$$Curvature = 1/R = \theta^2/2x \qquad (1)$$

where R is the radius, θ is the angle of gaze (visual direction relative to the locomotor axis) and x is the distance of the inside of the curve from the intended path. The tangent point can then be used to maintain a curved trajectory that will keep them equi-distant from the curb, and hence within their traffic lane, by keeping the tangent point at a constant VD angle. The gaze velocity (change in gaze angle $d\theta$ divided by the change in time dt) therefore would be zero

$$d\theta/dt = 0 \qquad (2)$$

If the gaze velocity is greater than zero this would indicate an understeer whereas $d\theta/dt < 0$ would indicate an oversteer. This technique uses the visual direction of a single road feature and does not require any contribution from global optic flow. This strategy, however, does not provide a solution to the general case where locomotion is in a car park, field or forest where there is no explicit guide to your path such as a curb or white line. Wann & Land (2000) proposed a variant of the tangent point strategy that would be applicable for roads that do not have a clear tangent point, or if the driver wishes to “cut-the corner”, or for open field steering. If the observer fixates a point at a distance ahead (d_f) that they wish to pass through then a constant curvature path that will take them to that point is specified by

$$Curvature = 2 \sin \theta/d_f \qquad (3)$$

If this trajectory is maintained then as the observer progresses toward the target

$$d\theta/dt = V/2R \tag{4}$$

where V is the locomotor speed (tangential velocity) and R the radius of curvature. Hence if locomotor speed is constant then $d\theta/dt$ is constant for an appropriate trajectory. The observer does not need to know V or R, they simply need to recognize that for an appropriate 'safe' trajectory the fixated point will sweep from its initial offset, to directly in front of the locomotor axis, at a constant rate. If it accelerates towards their midline then they are oversteering, if it slows, or moves away, then they are understeering. In summary equations 1-4 provide solutions to steering a range of curved paths, using fixation of a single environmental feature, without the use of optic flow. It is therefore appropriate to ask what optic flow can provide in addition to egocentric visual direction.

2.1 Retinal Flow, Gaze Fixation and Steering

Although there has been a considerable amount of research into the perception of heading, there appears to have been an assumption that the recovery of heading equates to locomotor control. But as discussed earlier there have been very few proposals as to how perceived heading is used to control steering. In addition, as highlighted by Lappe et al. (1999), there is a dearth of research investigating how eye-movements and gaze fixation can play an active part in steering judgments. The classic heading studies have treated gaze fixation as a confounding variable rather than an active component of control. We propose that "where you look" is an essential component of visually guided steering. A natural gaze response when steering a bend is to look ahead to your future path and advanced driving manuals recommend this strategy. Fixation of a ground feature that you wish to pass through that is eccentric to your current trajectory will introduce a gaze rotation component into the retinal flow field (Figure 2a). Rather than subscribe to the theme that the observer has to recover heading from this flow field[1], we propose that a simpler solution is to consider the raw retinal flow pattern that arises if the trajectory is appropriate for the steering task (Kim & Turvey, 1999; Wann & Swapp, 2000). If the observer fixates a point on the intended path and adjusts steering to a curved path that will pass through that point (e.g. using Eq. 3) then the flow-lines for ground elements will remain

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[1] The retinal flow field could be decomposed into rotation and translation components, to recover heading. The recovery of the translation component, however, cannot indicate whether the current rate of change of heading is sufficient to achieve the intended trajectory, whereas the rotation component includes both the locomotor rotation and the gaze counter-rotation. So it is not clear that flow decomposition is particularly useful for the task of steering.

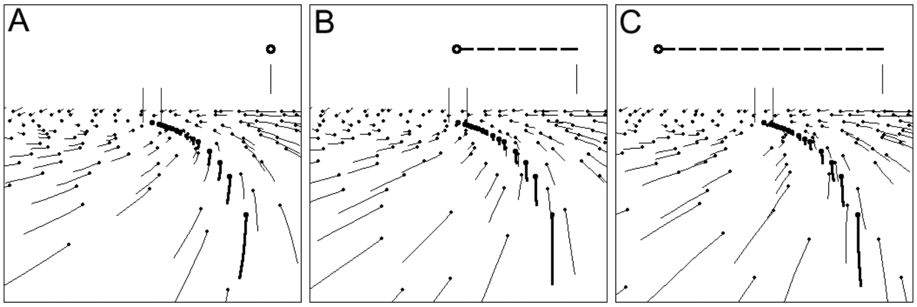

Figure 2. Retinal flow patterns for different steering responses. Simulations display the flow arising over 0.1s while traveling at 30 mph and fixating between the pair of vertical posts, which represent a gate that the observer wishes to steer towards. Initial heading is indicated as a vertical line above the horizon with a horizontal dashed line indicating changing heading due to steering. a) If the observer understeers and is on an eccentric heading, but fixating the target gate then the pattern of curvature is centered around the point of fixation (as in Figure 1b). b) If steering is set to a circular course that will pass through the gate, and fixation is maintained on the target, the flow lines are straight but asymmetrically displaced. c) If the observer oversteers, such that the future trajectory will pass in front of the target then the flow is still centered around the fixation point, but displays curvature in the opposite direction to the understeer and the curvature is correlated with the degree of steering error. See Wann & Swapp (2000) for further details.

straight, but will move outwards asymmetrically from the observer's future path (Figure 2b). Points that lie on the observer's future path move vertically in the projected field. If the observer is under-steering, the flow-lines curve away from the direction of steering error and over-steer is reflected in an opposite change in flow curvature (Figure 2a,c).

Wann & Land (2000) proposed that if the observer fixates a point on the future path then a set of principles hold that extend Gibson's original assertions about the use of optic flow to the use of retinal flow (RF):

RF1: If the retinal flow-lines for ground elements curve then you are not on a path to where you are looking and your steering error is in the direction opposite to the flow curvature

RF2: Once you are on a curved path to the point of gaze the flow-lines will be straight, but will be distributed non-radially.

RF3: If you are on a linear path to the point of gaze the flow-lines will be straight and will be distributed radially.

RF4: In both RF2 and RF3, points, which move with pure vertical motion in retinal flow, indicate the future path for the current steering angle (Figure 2b).

Irrespective of whether the trajectory is straight or curved to the point of gaze, RF4 suggests that the observer may be able to detect the future path by elements that move with pure vertical motion, or equivalently by the zero-crossings for horizontal flow[2]. This proposal has been questioned by van den Berg et al. (2001), who commented that in passive tasks observers have perceived changes in path when transformations that do not disrupt the vertical motion properties have been applied to the flow field. There needs to be further research to investigate, in an active control setting, whether there is sensitivity to flow-line shape, over and above the global speed and motion of retinal flow.

We do not propose that the everyday driver explicitly knows principles RF1, RF2, RF3 & RF4, but they do reflect simple principles that any skilled driver or cyclist will recognize. Consider some distinct components of ground flow, such as the near-side curb and the white line: During a safe trajectory around a bend, principle RF2 specifies that their projection on the retina should move outwards to either side of the drivers intended trajectory with no change in their direction of motion. If either of them starts to curve and break inwards we propose that any driver with a modicum of experience would recognize a steering error (principle RF1) that will result in the vehicle crossing the white line or curb in the near future.

2.2 Using Retinal Flow, Visual Direction & Gaze Motion Signals

There is a notable similarity between the strategy we have proposed for the use of visual direction (VD) and the strategy for the use of retinal flow. With VD we proposed that if the observer fixated a point on their intended path, the gaze angle can specify the degree of steering required (Eq. 3) while the rate of change of that angle can confirm if steering is appropriate or if there is under/over-steer (Eq. 4). For the same situation, however, we have argued that retinal flow can also provide some indication of the steering required and can confirm if steering is appropriate or if there is under/over-steer. There is redundancy in the information available through VD and retinal flow and the use of both sources of information should ensure a robust control system across a range of steering tasks and environmental conditions.

We propose that VD information can be considered as having two main components. When there is a clear visual indication of the locomotor axis,

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[2] The zero-crossing is the point where left/right motion changes sign and vertical motion would occur. In principle it is not essential to have texture elements that move with pure vertical motion. The notion of "zero-crossings" is that the observer may perceive the path as being midway between a rightward flow vector and a leftward flow vector.

Figure 3. A car supplies strong visual references for the locomotor axis in the form of the mirror, windscreen and dash.

such as your body or vehicle, this can provide a retinal reference for the target angle (RRD: Retinally Referenced Direction). If there is no visible reference for your body/vehicle, but the observer fixates the target, then the target angle could be recovered from somato-sensory information about head & eye direction relative to the body (GAD: Gaze angle direction).

Consider the differences in the information available when steering a car, motorbike, bicycle or roller-blades. In a car there is a very strong visual reference for the locomotor axis. The VD of a steering target can be coded with respect to the windscreen surround or the front of the car (Figure 3). In such a vehicle the steering task can be reduced to a pure VD strategy of bringing the target to the center of the windscreen. A curious situation occurs with a motorbike: The use of a full-face helmet provides a peripheral visual frame, similar to the car windscreen, but the frame moves with the head, providing a false reference (Figure 4). On larger bikes, however, there are still relatively strong references to the direction of locomotion provided by the mirrors, dash and screen of the bike. In contrast to this, when riding a bicycle, all visual references (such as the handlebars) will be very low in the peripheral field (Figure 5). It is debatable as to whether a horizontal feature in the peripheral field can provide a strong retinal reference for visual direction (RRD). A front bicycle light illuminating the path could provide limited information, but this information is not consistently yoked to the locomotor axis. An alternative strategy for the cyclist is to use proprioception to sense their head angle relative to their body and the angle of the handlebars relative to their body and thereby recover an estimate of target angle from somatosensory (gaze-angle) information. This requirement is amplified with

Figure 4. Left Panel - A motorcycle approaching a bend. Note the driver's head is offset from his locomotor axis supplying GAD information. *Right Panel* – The view from the motorcycle with the point of gaze marked as a black disc. In addition to the visual reference supplied by the windshield and mirror, the helmet both limits the field of view and supplies a visual reference that is fixed to the head angle not the locomotor axis.

something like roller blades, where vision of your own body is in the far periphery and extra-retinal, proprioceptive information should be of primary importance. We argue therefore that in steering a car, motorcycle, bicycle or roller blades the quality of VD information will vary and more or less emphasis may be placed on non-visual sources of information (GAD).

In principle some optic flow is always available, but this will also vary across environmental conditions. Quantifying flow is not straightforward since the optimal texture density to generate flow depends upon the speed of locomotion and the eye height in the world. In principal the higher the contrast between adjacent elements the better, but conventional tarmac is too fine grained to provide rich optic flow at speed, and a driver on a wide highway or racetrack may have considerably less flow information available than a driver on a narrow paved street. As night falls the quality of optic flow will also change for the pedestrian or cyclist and the erratic beam of a bicycle headlight does little to offset the loss of ambient light. So although modern highway designs have introduced devices to enhance ground-flow, such as retro-reflective cats-eyes and road markings, we have evolved to cope with environments where the quality of flow may change and we still encounter these in everyday situations.

Figure 5. Left Panel - A bicyclist approaching a bend. Again the cyclist's head is offset from her locomotor axis supplying GAD information. *Right Panel* – The view from the bicycle with the point of fixation marked with a black disc. There is more optic flow available to the cyclist since it is not obscured by a helmet or the vehicle body, and peripherally the handlebars only supply a weak retinal reference (RRD) for the locomotor axis.

To explore the weighting attached to either retinal flow (RF), retinally referenced direction (RRD) or gaze angle direction (GAD) Wilkie & Wann (In Press) created a virtual environment steering task where each information source could be manipulated. The participant's task was to steer a smooth, curved trajectory (speed: 18 mph) to a pair of target gates, so the retinal flow and VD information discussed in this chapter was available to them. During some of the trials the texture on the ground plane was rotated around the target at a rate that was equivalent to them being on a different trajectory. Hence on the RF-bias trials they received veridical RRD and GAD information, but the RF information suggested that they were either over-steering or under-steering. The participants displayed steering errors in the direction predicted by their use of RF as steering information. Wilkie & Wann also manipulated the availability of GAD information and the availability of RRD information such as a windscreen surround. Key findings were:

i) When Retinal flow (RF) was severely degraded, participants could steer accurately using gaze angle direction (GAD) information from somatosensory signals (head and eyes).

ii) Adding a strong retinally referenced direction (RRD) information source such as a windscreen or hood-mascot resulted in very accurate steering.

iii) If a rotational bias was added to RF in condition (ii), however, errors confirmed that RF was still being used for steering control.

iv) RF was not sufficient for accurate steering when GAD was absent, or RRD information was in conflict.

v) Introducing a similar bias into RF or RRD on interleaved trials allowed the estimation of the reliance that the participants placed on each source. As a first approximation RF, RRD and GAD appear to be weighted equivalently.

Wilkie & Wann (2002) took this paradigm one step further and estimated the change in reliance on RF, RRF and GAD as the ambient lighting in the scene changed from day to night. As might be expected RF is relied upon less, and VD (GAD and/or RRD) more, as the light levels fall. But surprisingly, even when the nighttime illumination made the ground texture very difficult to perceive in a static scene, there was evidence that the low-contrast flow pattern was still influencing steering when other sources of information were available. In the context of actively negotiating curved paths at relatively high speed we concur with Warren et al. (2001) that the reported demise of flow as a primary control variable in locomotion was premature.

3 A MODEL USING FLOW AND VISUAL DIRECTION DRIVEN BY ACTIVE GAZE

The model proposed by Wilkie & Wann (2002; In Press), follows the lead of Warren et al. (2001) and Fajen & Warren (In Press) by using a point attractor system. A point attractor, in simplified terms, is a control system that acts like a spring:

$$F = k(x - x_o) \tag{5}$$

where F is the force generated by a spring with a current length of x, a natural rest length of x_o, and a stiffness defined by k. If $x > x_o$ then a restoring force is generated until $x = x_o$ and F drops to zero. An undamped spring such as this will respond very quickly but tend to overshoot and oscillate around its equilibrium position. By adding a second damping term b to the rate of response (speed: $\dot{x}$) the system will respond more slowly but reach its equilibrium position in a steady manner:

$$F = k(x - x_o) - b\dot{x} \tag{6}$$

An example of a damped spring system such as this is a hydraulic door mechanism, that always returns the door to a closed position (an "attractor"), but does so without allowing the door to slam into the frame. Such systems can also be set up as repellors, such that the force F pushes the state away from a specified position. Mass-spring models such as this have been used to describe the behavior of neural systems such as agonist and antagonist muscle pairs (e.g. biceps and triceps). Fajen & Warren (In Press) propose that such models can be used to describe the coupling between perception and action in steering. This is not proposing that there are any actual "springs" in the system, but that certain classes of information act to push the system towards a particular state or trajectory. Their model is quite complex and includes attractors (goals you wish to move to) and repellors (obstacles you wish to avoid), in simplified form this is equivalent to

$$\ddot{e} = -k_g\,(goal\ VD) + k_o\,(obstacle\ VD) - b\dot{e} \tag{7}$$

In this case the output of the system is not a force F, but a turning response specified by angular acceleration ($\ddot{e}$), where θ is the instantaneous heading and $\dot{e}$ is the rate of change of steering. In this case k_g and k_o tune the response strength of the goal and obstacle respectively. The system acts to cancel the offset angle for attractors (goals) while maximizing the passing angle for repellors (obstacles). For the Fajen & Warren model the locations of both goals (ψ_g) and obstacles (ψ_o) are referenced to instantaneous heading (θ). This system actually operates on the basis of the VD of the target or repellor, not flow, but flow may be required to recover instantaneous heading if there isn't a clear reference to the locomotor axis (e.g. Figures 3-5). To account for observed performance the VD angles ($\theta-\psi_g$ and $\theta-\psi_o$, respectively) are weighted by exponential functions that include goal distance (d_g) and obstacle distance (d_o). The resulting model is then equivalent to:

$$\ddot{e} = -k_g(\theta-\psi_g)(e^{-c1dg}+C_2) + k_o((\theta-\psi_o)(e^{-c3\,|\theta-\psi o|}))(e^{-c4dg}) - b\dot{e} \tag{8}$$

Although this model seems very complex, we should accept that neural systems can exhibit behavior that may appear complex when described mathematically. But there are limitations of the model in that it does require the recovery of heading (θ) and absolute distance of both the goal (d_g) and all obstacles (d_o). It is questionable as to whether we can access heading in an "instant", as opposed to after 0.5s of viewing (at which point a maneuver may have been completed). It is also debatable as to whether we can judge absolute distance with precision when targets are beyond 3-4m from the observer.

Our version of a point attractor steering model avoids these issues by operating on the rate of change of VD and/or the rotation component in retinal flow that arise when the observer fixates their intended target. We have already discussed that steering on the basis of VD requires the VD angle to be cancelled in a steady systematic manner (Eqs. 3, 4). We have also outlined that rotation in the retinal flow field indicates that the observer is not heading to the point of fixation (principle 1), so a goal is also to cancel the rotation component. The rotation components of VD and retinal flow are both functions of $V\sin\theta/D$, where V is the travel speed, d_f is the distance of the fixated target and θ the offset of the fixated target from the current direction of travel. So if inputs to the system are the rotation components of VD and flow, then there is no need to specify V, d_f or θ as these are reflected in the rotation rates. This may be represented as

$$\ddot{e} = k\,(\beta_1 RF + \beta_2 VD) - b\dot{e} \tag{9}$$

where β_1 and β_2 are the respective weights or reliance placed on the two inputs. As discussed previously, VD may in turn be split into pure retinally referenced direction (RRD) when there is a visible reference for the target angle (Figure 3) and a non-visual gaze angle direction signal (GAD) when the observer must rely upon head, eye and body position information. A limitation for the model in Eq. 9 might be the extent to which an observer can accurately estimate the rotation component in retinal flow (RF) or even the rotation component of VD. Wilkie & Wann (In Press) demonstrated that precise estimates are not required. The model will achieve a smooth curved trajectory even when the RF and VD inputs are crudely quantized into a 0–3 point integer scale[3]. We argue that the observer does not need to precisely estimate RF rotation, but just recognize between "on-course" (0) a small (1), medium (2) or major (3) steering error and whether it is an understeer (-ve) or oversteer (+ve) error. The retinal flow principles outlined in the previous section provide the basis for such judgments. The β weighting factors allow for adjustments in reliance on RF or VD as conditions change, such as the onset of night (Wilkie & Wann, 2002).

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[3] Irrespective of what the rotation rate might be at the eye (deg/s) it will be encoded into different co-ordinate systems at the retina or by the head-eye GAD system. Irrespective of the units, we can scale the input down to integers of 3, 2, 1, 0, -1, -2, -3 and the system still steers effectively demonstrating that high sensitivity is not required by either the RRD or GAD system.

3.1 Application of the Model to Ecological Contexts

An important difference between the Fajen & Warren model, in Eq. 8 and Eq. 9, is that once the *k* and *b* parameters are set the trajectory that results from equation 8 is dictated by the location of the targets and repellors, not by the performer. The model we propose in Eq. 9 is an attractor to the *point of fixation.* This puts trajectory control in the eye of the beholder. The task for the driver is to fixate the future locations that he/she wishes to pass through at appropriate times during the forward trajectory. This provides the driver with the option of executing a safe lane-following strategy or taking a “racing-line” and cutting the corner. The skill is in identifying the where the critical via-points lie on a path and when to direct attention to each in turn. In our model (Eq. 9) parameters *k* and *b* dictate the response speed and may reflect a combination of the characteristics of the vehicle and the performers input. A high *k* and low value of *b*, would equate to a driver who decides to snatch at the wheel, causing the car to pivot sharply towards the target, but at the risk of a loss of control and oscillation. The optimal values of *k* and *b* can be acquired through experience and will change as the performer adopts different modes of transport. For example a commuter bicycle has a very different steering geometry from a lightweight racing bicycle, a family saloon has different steering characteristics from a sports car. A driver may respond in a manner equivalent to a high *k* if they have failed to notice a turning (or are trying to impress a passenger), but the perceptual inputs to the system remain unchanged. So the selection of path fixations and response speed (*k*) allow the performer to tackle a bend in an aggressive or relaxed manner. Learning to take a racing-line in a car or on a bicycle[4] would be to learn the optimal path settings for characteristic bends.

How well does this model correlate with what we can observe, experimentally or anecdotally, about steering in natural contexts? The inclusion of both retinal flow (RF) and visual direction (VD) inputs is based on the findings of Wilkie & Wann (2002, In Press). We don’t know of any evidence that rules out either of these inputs. The weighting factors (β) allow for environmental changes such as thick fog, where the reliance on global RF may be zero and the driver may just follow an illuminated feature. Gaze fixation as the mechanism for trajectory aiming would seem to conflict with

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[4] The turning rate of a bicycle it dictated primarily by the lean of the rider with a small amount of handlebar adjustment. So on a bicycle, or on skis, $\ddot{\text{è}}$ results from the controlled shift in weight, rather than a steering wheel. The parameters *k* and *b* are still valid, the rate at which weight is shifted is critical to the stability of the bicycle, but there is the need for an additional control system that incorporates the maximum degree of lean that is possible at a given speed of travel.

the findings of Land & Lee (1994). In our model looking at the tangent point would cause you to steer towards the tangent point. The Land & Lee study, however, was conducted on a one-way road around a mountain (Arthur's Seat in Edinburgh). Hence there was no requirement for the driver to stay in the offside lane and because the inside verge of the road was steeply banked, it is difficult to differentiate between looking *at the apex* and looking *through the apex* to the most distant point on the path that was visible.

We have repeated a similar study in a simulation setting with open field bends, where the performer could look across the apex, and found that although participants looked to the tangent point for 64% of the time, they fixated their future path 32% of the time, as coded by naive observers (Wann & Swapp, 2001). Land & Tatler (2001) recently observed that racing drivers, on a closed circuit, did not fixate the tangent point but oriented to the bend with their head. This is generally consistent with our model, but suggests that they may be using VD as a stronger input than RF, which may in turn be due to the lower quality of flow that arises on a broad racing circuit with smooth tarmac and no central road markings. This is speculation until we have further data of eye-movements from natural contexts such as these. If drivers do habitually seek out points on their future path, we might suppose that they can identify these more effectively than their instantaneous heading, which we have suggested is not essential. Wilkie & Wann (2002) did find that participants' ability to fixate a point on their future path was significantly more accurate than their ability to fixate their instantaneous heading. Finally, a control mechanism based on gaze fixation seems to be reflected in the advice given in advanced driver manuals (1992; 1998). These discuss orienting gaze on approaching a bend and also warn that if an unexpected obstacle is encountered, the motorcyclist/driver should not look at the obstacle, because they will hit it, but look to the side of the obstacle that they wish to pass. This seems very much in tune with the mechanisms we propose.

In summary there are multiple sources of information that can be used to control direction of motion when locomoting through the world. These can be broadly categorized as either retinal flow or visual direction information (both egocentric and exocentric), but all can be encoded as a rate of change of rotation, which directly informs the required degree of adjustment to the current course. This also allows multiple estimates from different information sources to be pooled providing robust steering estimates across varying visual conditions (Figure 6).

A series of articles and letters in Trends in Cognitive Sciences saw a heated debate over the roles of retinal flow and visual direction information in human locomotion (Harris & Rogers, 1999; Lappe et al., 1999a,b; Fajen & Warren, 2000; Wann & Land, 2000; Harris, 2001; Rushton & Salvucci, 2001; Wann & Land, 2001). This highlighted the variety of explanations that are available to describe the everyday activity of locomoting through the world.

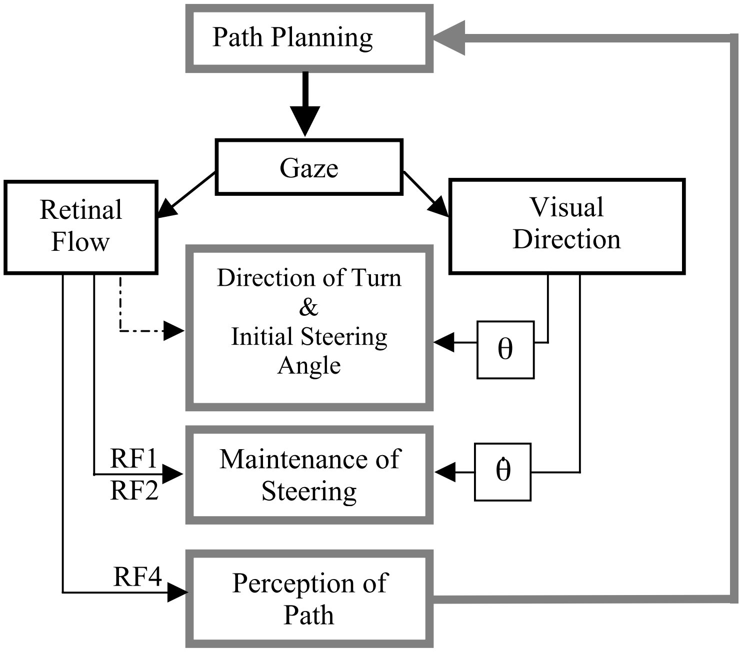

Figure 6. Potential inputs from retinal flow or visual direction for planning and controlling steering behaviour. RF1, RF2, RF4 indicate the use of the principles outlined earlier.

Significantly, there was considerable agreement over which information sources are used, even if there was not agreement as to the weighting attached or the actual method for using them. Many of the comments support the combined use of both retinal flow and visual direction information, and there was consensus that empirical evidence needs to be gathered to discover the true role if vision in steering.

The future agenda for investigating the control of locomotion is twofold:

i) to determine how we use gaze to sample from the world, and the way in which this simplifies the information received.
ii) to determine how the information that is made available to the visual system as a result of directed gaze can be used flexibly to control direction of motion.

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