Steering with or without the flow: is the retrieval of heading necessary?

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A focus on the perceptual information required for tasks such as steering and approaching without collision was stimulated by Gibson1. He proposed that the task of steering could be accomplished by using properties of the optic flow field. A particular assertion was that ‘the centre of the flow pattern during forward movement of the animal is the direction of movement’. It is now accepted that this is only correct under limited conditions, because the retinal flow pattern may not reflect the pattern that Gibson described for optic flow1.

Linear translation across a textured ground plane, with the eye stable, produces a radial optic expansion that is symmetrical around the direction of heading, hence in this situation the focus of expansion (FoE) of the flow field indicates locomotor heading. But a gaze pursuit movement will introduce an additional rotation component into the retinal flow field that displaces the FoE from the direction of travel. Hence if a driver moves his/her eyes during locomotion then the FoE no longer specifies the direction of travel and the retinal flow field may approximate that produced by a curvilinear trajectory2,3.

This observation stimulated a prolonged debate on the issue of whether human participants can recover their direction of heading from retinal flow and whether they require additional (extra-retinal) information about eye movements. Lappe et al4 provided a comprehensive review of this research and three of the questions that were identified for future research were:

1. How is path information obtained from retinal flow and extra-retinal signals and how is the path predicted?
2. How are eye movements actively used to support heading perception and flow analysis?
3. How do eye movements actively influence locomotion?

These issues are central to the consideration of human locomotor control. This article outlines information that can specify future path (1), using retinal flow or extra-retinal information (2), combined with active gaze sampling (3). These are compared with the role of heading in making such judgments and it is concluded that heading is not a prerequisite for accurate locomotor control.

Path specification using visual direction and gaze rotation

In response to the review of Lappe et al5, Harris and Rogers6 highlighted evidence that observers used a visual direction strategy when walking to a target, even though this was in conflict with the visual flow information. They made the statement that ‘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’ (Ref. 5, p. 449). This challenge was based on the results of Rushton et al5 and Rogers and Dalton7 who demonstrated that if participants are asked to walk to a target, which is viewed through a prism, they take a distinctive curved path.

It is predictable that in this situation participants will set off in an eccentric direction because before they start to move, egocentric visual direction (i.e. the angle between the locomotor/body axis and direction of gaze) is the only information they have regarding the actual placement of the target and this is displaced by the prism. Once they are in motion, however, the retinal flow emanating from the fixated target should be weakly curved rather than radial (owing to gaze rotation)2 indicating that their trajectory is not towards the target. If participants are able to use flow information they should be able to fully compensate for their error and thereafter walk straight towards the target, rather than follow the curved path that Rushton observed. Hence, egocentric visual direction seems to be of primary importance in orienting locomotion directly towards a goal: in the prism experiment the curved trajectory results because the participant is iteratively adjusting walking direction so that the displaced image appears directly ahead.

In a natural steering task, where there is no prism displacement, the equivalent strategy would be to note the visual eccentricity of the target and then pivot around one’s locomotor axis such that a straight-line trajectory can be taken. This is one way of completing a locomotor steering task, but it is not a general solution. In many settings there may be path constraints, such as a roadway, that preclude a direct-line approach. Most vehicles have a wheelbase that restricts the turning arc, and even in running or skating, momentum makes a curved trajectory a necessity. In these cases we consider how visual direction might be used to plan and execute a curved trajectory approach.

The direction of gaze relative to the locomotor axis can be used to initiate a curved trajectory. Raviv and Herman8 presented a formal analysis of locomotor reference points arising from the inside or outside edges of a roadway,
There are two reasons for considering Eqs 1 and 2 as approximations, that may be used to set the initial steering response, but that this may require later confirmation or modification. The first issue is that parameters of $D$ and $D'$ are features of the environment that need to be recovered, possibly relying on the use of ‘known’ variables such as the driver’s eye-height. It is clearly feasible to estimate both $d$ and $D$, but some degree of error is likely. The second issue is that the curvature parameter ($1/R$) does not always map directly onto the required action to implement it. In the case of steering a car the angle through which the wheel should be turned is very closely related to curvature, but the degree of lean for a bicycle, or the edging of a ski, are mappings that must be learned and are therefore additional sources of error. The performer needs to monitor the consequences of their steering action to ensure it will meet the intended trajectory. In the case of a road bend of constant curvature, a trajectory that maintains a distance $d$ from the curb, will result in the tangent point having no horizontal motion in the field of view. Therefore:

$$d\frac{d\theta}{dt} = 0$$ (Eqn 3)

This would be a very simple and direct way of regulating the ongoing trajectory given that $d\frac{d\theta}{dt} > 0$ would indicate understeer and $d\frac{d\theta}{dt} < 0$ oversteer. On country roads with varying curvature, however, drivers could use a dual strategy in which the distant region of the road is used to estimate upcoming curvature (Eqs 1 or 2), but a nearer road region is used to keep $d$ constant. This strategy, however, does not provide a solution to the general case where locomotion is in a car park, field or forest and there is no explicit guide such as a curb or white line. One strategy would be to keep $\theta$ constant, although this results in an equi-angular spiral path, which would overshoot the target due to understeer. An alternative simple solution is available by using the rate of change of gaze angle ($d\theta/dt$) for a point on the intended path. As outlined in Fig. 1, if the observer fixates a point on his/her intended path and is holding a curved trajectory that will intercept that point then:

$$d\theta/dt = \pm 1/2R$$ (Eqn 4)

Where $V$ is the tangential velocity (locomotor speed) and $R$ the radius of curvature. If speed is constant then $d\theta/dt$ is constant for an appropriate trajectory. In simple terms this means the fixated point will sweep from its initial offset, to directly in front of the locomotor axis, at a constant rate. Lee proposed an alternative solution of keeping $\theta(t)$ constant. $\theta(t)$ is the derivative of the relative rate of change of $\theta$:

$$\theta(t) = \theta(t_0) + \int d\theta/dt \, dt$$ (Eqn 5)

$$\theta(t) = 1 - \int \frac{d\theta}{dt} \, dt$$ (Eqn 6)

Holding $\theta(t)$ is less where $0 < k < 1$ results in a controlled turn toward the goal direction with the constant $k$ dictating whether the angle $\theta$ is closed down early or late in the trajectory. In this respect the $\theta(t)$ proposal is elegant and adaptable, but because of its reliance on high order derivatives there are questions that arise relating to detection that are outlined below.

Detection of visual direction and gaze rotation

Just because $\theta(t)$ is a simple geometric variable it should not be assumed that it is a known variable. In the case of a car where there is a windscreens surround (or particularly a Mercedes with a ‘gun-sight’ on the bonnet), then both $\theta$ and $d\theta/dt$ may be visually specified with respect to a locomotor frame of reference and direction is very simple. It is also the case, however, that both $\theta$ and $d\theta/dt$ can be estimated extra-retinally without an external visual reference, other than that necessary to fixate the target.

You may test this by glancing to a peripheral feature, then closing your eyes and pointing to that feature. This task can normally be completed to within 1–2 degrees of error and confirms that we routinely recover an egocentric representation of visual direction from retinotopic and extra-retinal information. If we could not do so we would be somewhat impaired in many everyday tasks. There is some degree of error in estimating $\theta$ and as discussed above estimates of $d$ and $D$ may be prone to bias. This is consistent
Path specification using retinal flow

Despite the large volume of research on locomotor heading1 there has been a paucity of proposals as to how retinal flow and heading perception might be used in steering. Some options using heading are outlined in the next section, but it is of interest to note that retinal flow may guide steering without the need to judge instantaneous heading. A natural gaze response during locomotion is to look ahead to your future path. This is the strategy recommended for steering a bend by advanced driving manuals15,16. Gaze fixation of this type introduces a rotational component into the retinal flow field and the majority of the work reviewed by Lappe et al. is aimed at establishing how the visual system might recover linear heading in situations such as this.

The retinal flow field resulting from locomotion, plus gaze rotation, can be decomposed into rotation and translation components. The recovery of the translation (linear heading) component, however, does not 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. In this respect it is not clear that flow decomposition is particularly useful for the task of steering.

An alternative and simpler solution is to consider the raw retinal flow pattern that arises if the trajectory is appropriate for the steering task. If the observer fixates a point on the intended path and then adjusts steering to a curved path that will pass through that point (Eqn 2) then the flow-lines for ground elements will remain straight, but will move outwards asymmetrically from the observer’s future path (Fig. 2b). Points that lie on the observer’s future path move vertically in the projected field. If the observer is understeering the flow-lines curve away from the direction of steering error and oversteer is reflected in an opposite change in flow curvature (Fig. 2c,d). This heuristic revises Gibson’s assertions regarding steering with some general principles for using retinal flow that hold to the spirit of Gibson’s argument regarding optic flow: if you accurately direct gaze and fixate where you wish to go, then:

R1. If you are on a linear path to the point of gaze the retinal flow will be distributed radially.

R2. If the flow-lines 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.

R3. If you are on a curved path to the point of gaze the flow-lines for ground elements will be straight, but will be distributed non-radially.

R4. In both R1 and R3 the future path (straight or curved) to the point of gaze is indicated by elements that move with pure vertical motion or equivalently by the change in sign for horizontal flow (zero-crossings).

R5. If there is understeer or oversteer this will be reflected in an increasing degree of flow line curvature that indicates the direction of error as in R2.

Between R1 and R3 are a family of paths that will accomplish the steering goal with varying degrees of
Wann and Land – Steering and retinal flow

Detection of flow curvature and future path

The appeal of this approach is that the observer simply needs to detect the direction of any curvature in the retinal flow lines and there is no need to progress to a higher order perception of linear heading to control locomotion. Once again the issue of detection should be considered. Using R2 to detect understeer and oversteer does not require precise estimation of the acceleration components of the flow field. The visual system only needs to detect whether the direction of motion is changing for salient elements close to the path and the nominal direction of change. Werkhoven et al. confirmed that observers could detect changes in the direction of motion for dot elements with a Weber fraction of 9% (dv/dv).

Detecting changes in the direction of motion is fundamental to human vision and once again you may try a home test by fixating a point and asking a colleague to move their finger along either a straight or curved trajectory in your peripheral field. Most people do not experience difficulty in reporting the presence and direction of curvature. There is complementary evidence that instantaneous heading can be judged from a first order velocity flow field but accurate steering requires the rate of change of velocity flow vectors. The same principles that are presented to support the recovery of heading can be evoked for judging path directly from flow: cells in extra-striate area MT are sensitive to visual direction and a change in flow direction may be detected through a change in the relative firing rate of directionally tuned MT neurons, or through the detection of cortical motion for depth ordered points when these outputs are combined in area MST.

When steering does match the curvature of a bend, principle R4 means that a path of constant curvature, from under the driver to the disappearing point of the bend, will have no lateral motion on the retinal image. The percept of ‘reading the line’ might therefore equate to vertically tuned MT neurons being stimulated by the same points on the roadway throughout the trajectory. In the case of a steering error this vertical-flow line breaks away across the ground indicating understeer or oversteer (see Fig. 4). It is not essential to have visible elements on the intended path that move with pure vertical motion. In both Fig. 2a and Fig. 2b the locomotor path lies between ground elements that are moving close to vertical, but with opposite horizontal motion. In this respect the broad directional tuning of MT neurons could aid the perception of steering line.

Path specification from perceived heading

Prior to commencing a manoeuvre the recovery of linear heading could assist in specifying θ for use in Eqn 1 or 2 (Fig. 5). Once the steering manoeuvre is underway there are two strategies that would seem to arise from previous research on heading. The first would be to stabilize gaze with respect to the vehicle. If there is no gaze motion then the pattern of retinal flow reflects the locomotor translation and rotation and this pattern should indicate whether the current path will pass through the intended point. It has been demonstrated that observers can make circular path judgments to within 1–2 degrees when there was no additional gaze rotation within the simulated display. The problem with extrapolating from this finding is that trying to stabilize gaze with respect to the locomotor axis is a rather unnatural behaviour that requires the observer to allow their intended target to slip away from the focus. If the reader is bold enough to try this strategy they will find it very unnerving on all but the shallowest of curves and is certainly not recommended.

One advantage of fixating the tangent point (Fig. 1), if it is available, is that that gaze should be stable if the trajectory follows the curvature of the bend (Eqn 3); in which case retinal flow should provide a confirmation of the appropriate trajectory. It is debatable as to whether this should be classified as a strategy based on perceived heading. In this case the raw retinal flow is providing the observer with path information. As such it has more in common with R1–R5 outlined above, than with models that recover instantaneous heading through decomposition or compensation.

A strategy based on instantaneous heading can be considered:

H1. Fixate the steering goal and recover linear heading through flow decomposition
H2. Recover steering angle from the difference in subsequent headings
H3. Estimate the path from integration across instantaneous headings
There is strong evidence, however, that extra-retinal information may be required for the accurate recovery of linear heading from retinal flow in the presence of eye movements. In the previous sections we have demonstrated that the steering task could be completed using either the extra-retinal information or the raw retinal flow pattern. Combining these two sources to recover an approximate and transient estimate of heading, and then using this to compute H2 and H3 seems unnecessary and prone to additional error.

Detection of heading for steering

There is a considerable volume of research on the detection of direction from retinal flow or the raw retinal flow pattern. Combining these two sources to recover an approximate and transient estimate of heading, and then using this to compute H2 and H3 seems unnecessary and prone to additional error.

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the recovery of heading from optic flow. Previous state-
ments on optic flow and self-motion have implied that
the perception of heading is a pre-requisite in controlling
locomotion5,6,7, hence to the causal reader the perception
of heading and the control of locomotion may appear to
be synonymous. There are only a few specific models that
actually link the perception of linear heading to active
locomotor control (e.g. Le9), but given the volume of research
on the perception of linear heading this is surprising.

We have outlined how the task of changing locomotor di-
rection, such as steering around a bend, can be achieved using
information from either visual egocentric direction or ‘raw’
retinal flow. Visual direction (θ) can provide a simple means
of orienting the trajectory for either a straight or curved path.
In maintaining that path, however, there is redundancy
between the solutions available from visual direction infor-
mation (θ, dθ/dt) and the related retinal flow patterns (Fig. 5).
If a reliable tangent point is available on a roadway this
certainly simplifies the steering task, both in terms of the use of
dθ/dt or retinal flow. Even without this curvature guide there
is sufficient information in either dθ/dt or the ‘raw’ retinal
flow to confirm that the rate of turning is sufficient to main-
tain the intended path. Either input would be sufficient under
optimal circumstances, but it is facile for steering to be
guided by both the motion of the fixation point (dθ/dt) and the
retinal flow pattern arising from around that point of fixa-
tion. This would provide a robust system where the most
salient cue carries the most weight. Models that combine visual
direction and flow information are beginning to emerge8,9,10.

Irrespective of whether visual direction or retinal flow
patterns inform a specific type of steering, there is no re-
quirement in our analyses for heading to be recovered from
the flow field to direct locomotion. The perception of linear
heading, when gaze is stable and directed forwards (radial
retinal pattern), is certainly useful as a confirmation that
you are still on course. There appear to be very few advan-
tages, however, in recovering linear heading during pur-
suit/skating, which is the task that has been the focus for
much of the research. A ‘radial’ confirmation of a stable
linear trajectory can be provided by alternating gaze11, which
avoids attentional confounds in perceiving heading12, wherein
a change in course can be effected by using visual direction
information13,14 or retinal flow with appropriate gaze sampling15.
Hence, in the case of everyday locomotion in cars, on bikes or on foot it is not clear that heading,

Perspective
Wann and Land – Steering and retinal flow

References
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