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Does Steering a Car Involve Perception of the Velocity Flow Field?

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1. Introduction

In 1950 Gibson introduced the idea of a flow-field – the pattern of velocity vectors in the field of view that results, in particular, from an organism's own motion. Since then there has been a continuing debate, evident from the chapters in this book, concerning the use of different cues in the guidance of locomotion. In crude terms these are viewed as being of two kinds. There are those based on the changing positions of identifiable features: thus "keep to the right of the row of trees and keep the church tower straight ahead". And there are those based on the pattern of velocity vectors in the flow-field. For example, the current direction of the traveller's heading – important for guiding locomotion – is represented by the location of the pole, or "focus of expansion" of the flow-field pattern, and the distances of objects in the surroundings can be recovered from their velocities across the retina. In the task I consider here, steering, the flow-field view of how we aim the vehicle was stated very clearly by Gibson (1950): "The behavior involved in steering an automobile, for instance, has usually been misunderstood. It is less a matter of *aligning the car with the road* than it is a matter of *keeping the focus of expansion in the direction one must go*."

This view was explored further by Lee and Lishman (1977), who showed that the correspondence between the edges of the road and the direction of motion on the retina (the locomotor flow lines) indicate whether or not the vehicle is on course. On the other hand, Land and Lee (1994) found that on winding roads drivers look at rather specific regions of the road, notably the "tangent point" on the inside of each bend (this is the point where the driver's line of sight is tangential to the road edge or centre line, and it moves around the bend with the driver. Its important attribute is that - like the focus of expansion on a straight road – it does not move laterally in the visual field provided the road curvature remains constant). This suggests that drivers may be using road *features* to steer by, rather than patterns of optic *flow*. In what follows I review what is known about the information drivers need and use when steering, with a view to resolving the vexed question of whether it is feature displacement or flow that is used in locomotor guidance (rev. Vishton and Cutting 1995).

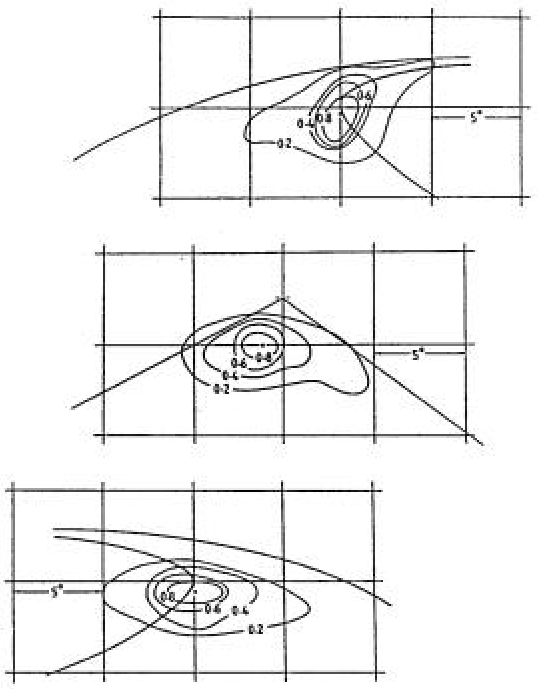

Fig. 1 Contour plots showing the location of fixations made on right and left-hand bends, and on straight road sections where no tangent point is visible. The contours give the density of fixations relative to the maximum (approximately 0.12 fixations / deg^{2}s^1). Measurements on bends were made from the tangent point and on the straight road from the vanishing point. The 0.2 contour includes about 65% of all fixations. Data from three 1km drives by different drivers. Note that on bends the highest fixation densities are within 1° of the tangent points. (Land and Lee 1994)

2. Where do drivers look?

Land and Lee (1994) used a head-mounted eye movement camera to determine the direction of drivers' gaze when driving on a winding road (Queen's Drive round Arthurs Seat in Edinburgh). The outcome was very clear; drivers looked at the region around the tangent point on the inside of each bend (Fig. 1) much more than anywhere else, and at the beginning of each bend they looked at it for about

80% of the time (Land and Lee 1994). There are a number of reasons why the tangent point might be particularly valuable to drivers, but perhaps the most important is that its direction, relative to the driver's current heading, gives a particularly simple measure of the curvature of the bend (Fig. 2). Since required steering-wheel angle is determined by bend curvature, this measurement provides an ideal visual input for any steering control system. The accuracy of this method depends to some extent on the driver keeping a constant, known, distance from the road edge, because this is a term in the curvature equation (Fig. 2), and so the tangent point direction needs to be supplemented by position-in-lane information, if it is to result in accurate steering. The other qualification is that the tangent point is some distance ahead, and provides information about the curvature between the driver and the tangent. For example, on a bend of 100 m radius with a driver 2 m from the lane edge, the tangent point is 20.1 m ahead of the driver, and so a delay is required. Land and Lee (1994) found that during the Edinburgh drives the maximum correlation between visual direction and steering-wheel angle occurred after a delay of 0.75 s, which is approximately the delay needed at moderate speeds.

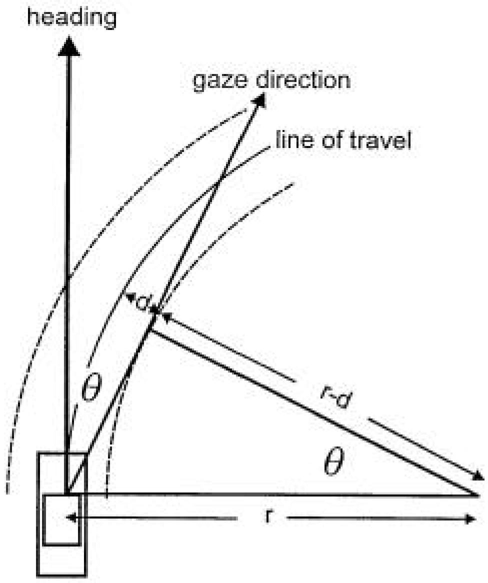

Fig. 2 Geometry of tangent-point steering. The curvature of the bend ($1/r$) can be obtained from the gaze angle ?, using the geometry of the right angled triangle. Here, cos? = $(r-d) / r$, where d is the distance of the driver from the lane-edge. However, the expansion of the cosine gives cos? ≈ 1 - ?² / 2. Substitution for cos? then gives: $1 / r$ ≈ ?² / 2d

As we will see later, it is not necessary for a driver to look at the tangent point, nor even to have the tangent point visible in the field of view. However, some part of the more distant region of the road does need to be visible, and provided that its distance is known (there are several cues that can be used for this) its direction relative to the driver's heading can be used in much the same way as the tangent point direction (Land 1998). This suggests that perhaps the significance of the tangent point is only partly to obtain curvature information, and that it may have another role. One thing that comes to mind is that in the region around the tangent point there no lateral motion of the flow-field, and in fact rather little vertical motion, as most of the structures in the region – lines and kerbs – are also oriented vertically in the flow field at this point. The tangent point is thus a place that the eyes can rest, without being "dragged around" by the optokinetic consequences of moving but irrelevant regions of the flow-field.

3. Simulator studies: which parts of the road does a driver need?

Although we have shown where drivers direct their gaze on bends, it is almost impossible to say where they are actually attending. We can, however, ask a related question: where should drivers look in order to get the best information to steer by? If this coincides with where they actually look, then this gives us grounds for thinking that they are attending there as well.

The method involved a simple simulator (Land and Horwood 1995), in which subjects drove round a skeletal version of the Queen's Drive road. Only the road edges were present, plus a horizon and a sketch of the car bonnet, but no other scenery. The drive could be run at a variety of constant speeds, from 12.5 to 19.7 m/s (28 to 44mph). Drivers found this similar to night driving, and had no difficulty negotiating the bends of the simulated road. The main measure of performance was the standard deviation of the subject's position in lane, taken over the whole 1km drive; under ideal conditions this was between 0.1 and 0.2m. After a few trials with the whole road outline visible, the view was restricted to either one or two 1° high segments of the road edge (Fig. 3) which could be located at varying positions between 1 and 10° below the horizon, corresponding to distances between 63 m and 6 m from the vehicle. These segments behaved exactly as they would had the whole road been present.

In the first set of experiments only one segment was visible The principal result was that at each speed there was an optimum (vertical) position of the segment that gave the best steering performance. It was nearer to the vehicle at slow speeds and further at high speeds, but in terms of "time ahead" it was close to 0.7 s at all speeds. Except for the slowest speed, however, the performance was not as good as when the whole road edge was present, and at faster speeds the difference was big enough to make the vehicle stray from its lane. This implies that any one segment of the road is not capable of providing the whole of the required control signal. Another disconcerting feature of this study was that the part of the road that provided the best performance was somewhat closer to the vehicle than the region containing the tangent point, and closer than the region where drivers usually looked when the whole simulated road was present.

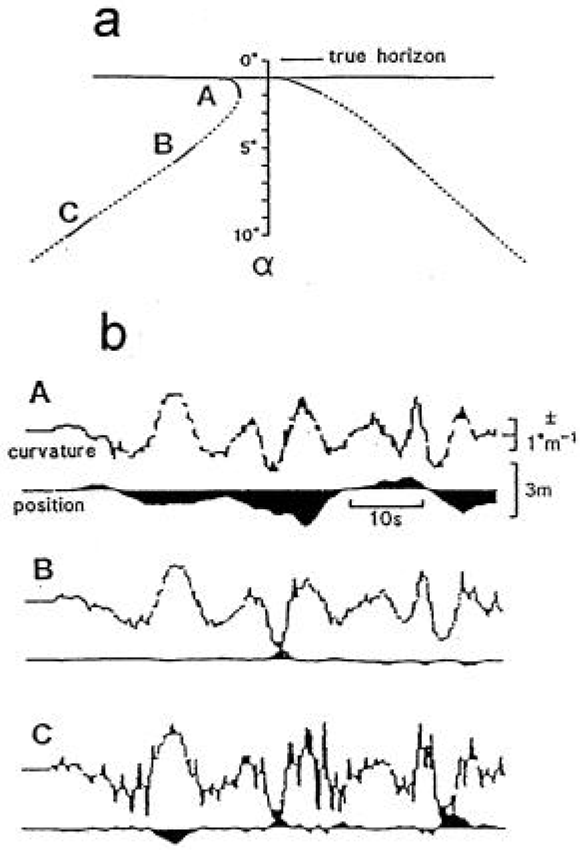

Fig. 3 Driving on a simulator with only parts of the road edge visible. **a** Appearance of simulated road, showing the angular scale used in Fig. 4 and the three road segments used in b, each subtending 1° vertically. **b** Differences in driver behaviour depending on the position of the visible segment. The upper trace in each pair gives the curvature of the road and the vehicle's track, with differences between them appearing as a solid black region. The lower trace shows position relative the road midline, with solid black indicating the extent of error. With only a distant segment visible (A) curvature matching is smooth and reasonably accurate, but position-in-lane accuracy is very poor. With only a near segment (C) curvature matching becomes jerky and unstable, although lane position is more accurate than in A. An intermediate distance (B) gives the best result. (From Land and Horwood 1995)

We also found that drivers behaved quite differently to near and far regions of the road. When only the far part of the simulated road was visible, drivers matched curvature well, but their lane keeping performance was poor; and when only the near part was visible lane keeping was better, but steering was unstable and jerky (Fig. 3b). The drivers' control system had changed from smooth to "bang-bang" (Land and Horwood 1995). This suggested that far and near regions contribute to the overall control system in different ways.

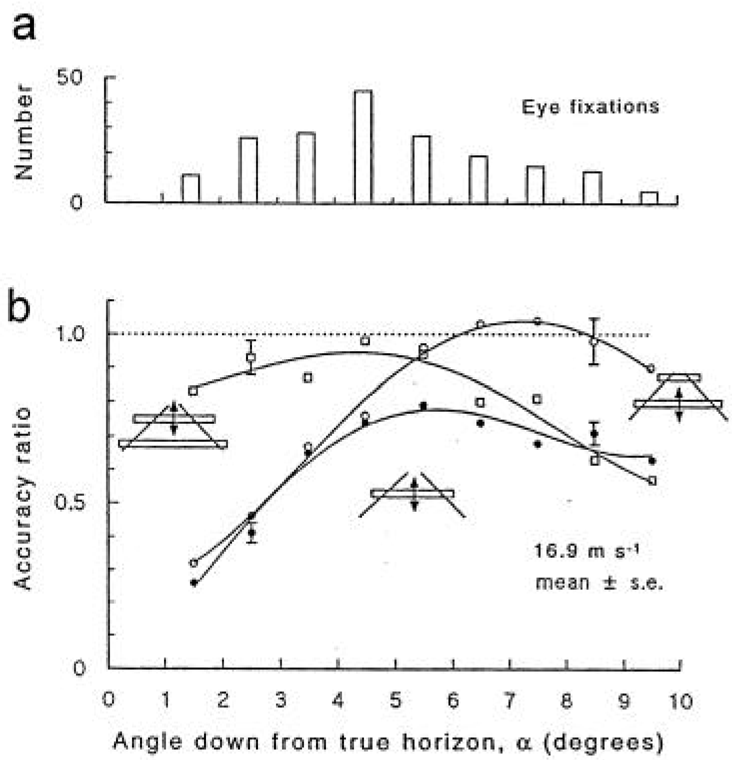

Fig. 4 Driver performance with two segments of road visible. **a** Distribution of vertical gaze direction when viewing the whole road. Abscissa as in b. The peak is 4-5° down from the horizon. (3 drivers) **b** With a single visible road segment (filled circles) the apparent optimum is 5.5° down from the horizon, but it is not as accurate as when the whole road is present (dotted line). Adding a second segment to the near part of the road (squares) greatly improves performance, but only when the first segment is in the far part of the road; when a second segment is added to the far part of the road (open circles) performance is enhanced for segment positions in the near part of the road. With two appropriately spaced segments, performance is as good as with the whole road edge visible. 5 drives each by 3 drivers. Abscissa is the angle down from horizon (a, Fig. 3a); Ordinate is the ratio of accuracy (1/s.d.) of the vehicle's position-in-lane under each condition, compared with the accuracy when the whole road edge is visible. (Land and Horwood 1995)

In a second series of simulations we added a second segment of road, and this improved performance provided that the two segments were well separated (Fig. 4). Taking out the “middle distance” region of the road, but leaving the more distant and nearer parts not only improved performance, but it made it indistinguishable from having the whole road present. In these simulations one visible segment was either at the most distant region (1-2° below the horizon) or the nearest (9-10° down), and the position of the other segment was varied. Broadly, the result shows that adding a second segment dramatically improves performance if and only if it is added to the opposite end of the road: the far segment if the near one is present, and vice versa. With the near-road segment present the optimum location of the far-road segment was about 4° down from the horizon (at 16.9 m/s), and with the far-road segment, the best location of the near-road segment was about 7° down.

The explanation of this is that the near and far regions of the road supply different and complementary information. The distant region (including tangent points where present) supplies feed-forward information about the future curvature of the road, and the near region supplies feedback information about position in lane. (A two-component model of this kind was originally proposed by Donges in 1978). Both are necessary. If only the far region is visible the driver may steer a course with a good approximation to the right road curvatures, but with no guarantee that he actually stays on the road. With only the near-road visible he can keep between the lane-edges easily at low speeds, but as speed increases and the lead time becomes short compared with his reaction time, the feedback becomes unstable. It is like driving too fast in fog. However, if the far-road feed-forward mechanism has already done most of the work, the near-road mechanism can work at low gain, and it is stable again.

4. Conclusions: features and flow

The locations of the edges of the road in the field of view appear to provide the principal visual cues for steering. They are necessary and sufficient, and the rest of the flow-field does not seem to be involved in any very direct or essential way. On poorly marked roads the differences in texture and motion at the road edge may substitute for discrete lines, but most drivers would agree that white or yellow lines provide a much better cue, and that when road markings are absent it is much harder to steer. However, “cross country” driving, which is normally undertaken at low speed, must involve other types of cue.

Are the edges of the road properly regarded as features, or components of the flow-field? They seem to have attributes of both. On a straight road, or on a road of constant curvature, their appearance and location in the visual field are constant, which makes them features. The direction of motion of their texture coincides with their orientation, so the “flow” appearance is weak, and is in any case irrelevant to the task of steering. However, when road curvature changes, or the vehicle strays from the lane centre, the lateral movements of the road edges in the field of view are of crucial importance. At that point one could regard them either as moving features, or as lateral components of the flow field. Perhaps the question should be: is it their instantaneous position or their velocity that matters? Again the answer is likely to be both. In this paper and its predecessors I have concentrated on the relation of the position of the road edge as an input to the human control system that turns the steering wheel, but in any practical control system the addition of a velocity input invariably improves performance, and that is undoubtedly also the case here. In a way the feature/flow argument is a sterile one. Features have both positions and velocities, and both are important control variables.

Another argument that is still active concerns the role of the focus of expansion of the flow field in providing moving observers with the direction of their heading (e.g. Gibson 1950; Cutting 1986, chap. 10). Drivers do need to know their heading, so that they can determine the angle between that heading and, say, the tangent point, in order to obtain a signal to steer by. A problem with this is that if drivers are actually looking at the tangent point (Fig. 1), their eyes will be rotating with the curve, and this means that there will be no focus of expansion, since this requires the eye to be in linear translational motion. On a curved trajectory the locations of the stationary points in the flow-field vary with distance, generating a curved line across the ground plane, not a single focus of expansion (see Raviv and Herman 1993). Thus to detect the direction of instantaneous heading in general requires the decomposition of the flow-field back into translational and rotational components. It seems this can be done in laboratory conditions, but with some difficulty. Warren et al. (1991) showed that under appropriate circumstances subjects can extract *circular* heading (i.e. their future curved path) from the sort of combined rotational and translational flow field that would result from driving on a curving road. However it isn't clear that this is actually relevant to the driving task, and the assumption that heading (linear or circular) needs to be obtained by visual means is very questionable. For a driver belted to the seat, the orientation of the trunk axis *is* the direction of the vehicle's instantaneous heading, and the measurement required for steering is simply the angle between the trunk and the tangent point, if that is the feature being used. This angle is the sum of two physiologically available measurements, the head/trunk angle and the eye/head angle, if the driver is actually looking at the tangent point (Fig. 1). Thus it is hard to find any information required for the task of steering that *must* come from the velocity flow-field.

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