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Go with the flow

In a recent article, Wann and Land cast rhetorical aspersions upon the idea that optic flow is used to guide human locomotion[1]. They were especially critical of the notion that the perception of heading (one's instantaneous direction of translation) from optic flow is required for locomotor control in general, and for the task of steering a curved trajectory in particular. Their argument strikes us as full of straw, for to our knowledge no one has actually proposed that heading is required for all locomotor tasks, and researchers have already identified other variables that could be used to steer a curved path to a goal. In this reply we urge the gentle reader not to be swayed by the authors' disputation, and we bring to bear some empirical evidence that rules out their data-free conjectures.

Consider first the significance of optic flow. The authors approvingly cite Harris and Rogers' statement[2] that there is no compelling evidence that optic flow plays a significant role in the control of locomotion on foot. To the contrary, Warren *et al.*[3,4] have shown that when the heading direction specified by optic flow is offset from the walking direction in a virtual environment, it strongly influences the path taken to a target. The data reveal that both optic flow and the visual direction of the target contribute to locomotor control, but the former increasingly dominates as flow and motion parallax are added to the display. This has recently been confirmed in open-field experiments using displacing prisms to offset the flow[5,6]. Another experiment conducted in our laboratory demonstrated that both heading judgments and joystick steering are biased by a moving object in the same manner[7]. These results strongly imply that heading is not merely a '*post-hoc* percept', as Wann and Land suggest, but plays a functional role in guiding locomotion on straight paths.

Next consider the authors' portrait of a heading hegemony. They are surely correct that linear heading is not analytically required for steering a curved path, but then no one has argued that it was. Indeed, a number of alternatives, some based on other flow properties, already exist in the literature[8–11]. Wann and Land favor two purportedly heading-less strategies, one based on the visual direction of the goal (θ) and the other on 'the raw retinal flow'[12], (although they fail to cite the prior publication of the retinal flow theory by Kim and Turvey a year ago[13]). We hasten to point out, however, that θ is defined as the visual angle between the target and heading (Fig. 1), so perceived heading actually *is* required by their visual direction theory. Although Wann and Land argue that heading in a vehicle might be given by the center of the windscreen or a hood ornament, this is clearly a special case. Heading on foot might be given by pedal proprioception, but it is also influenced by optic flow; and heading is not given in numerous other activities (bicycling, skating, skiing, diving, sailing, flying…). Optic flow offers a proven solution, for heading can be accurately judged from flow, on both straight and curved[14] paths. Even the authors later admit that heading from optic flow could be used to specify θ.

We believe that different locomotor tasks are likely to involve different informational variables and task-specific control laws. The point is that this is an empirical matter, and the authors' hypotheses should be regarded as such until they are tested experimentally. As it happens, one of us has recently carried out such tests for steering a curved path[15]. The data

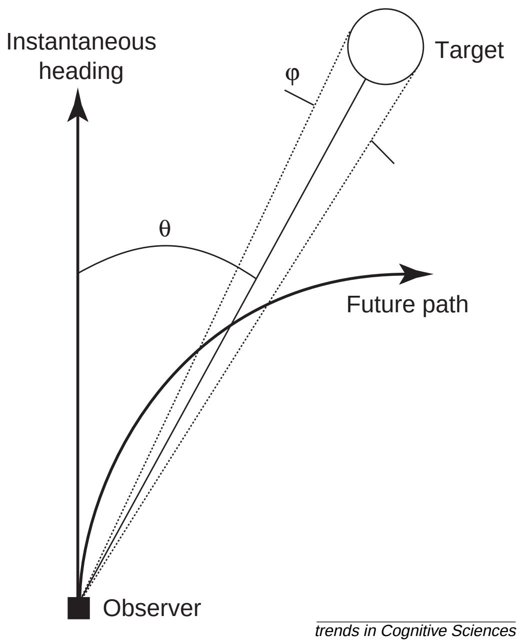

Fig. 1. Plan view of an observer moving along a curvilinear path towards a target. θ is the angle between the target and instantaneous heading; φ is the local optical angle of the target. The future path is the path that the observer would follow by continuing to move with constant curvature. (See text for discussion.)

militate against Wann and Land's preferred strategies. More generally, the results contradict any strategy that generates a path of constant curvature leading to the target.

Their first 'visual direction' strategy (Wann and Land, Eqn 4) is derived from the fact that, for an observer moving on a circular path that intercepts a target, θ decreases at a constant rate ($\ddot{\theta} = 0$). Accordingly, when $\ddot{\theta} > 0$, the observer is oversteering and should decrease curvature, and when $\ddot{\theta} < 0$, the observer is understeering and should increase curvature. Given that this strategy is based on θ alone, an obvious test is whether θ, by itself, is sufficient to control steering. Note, however, that the observer must null θ before reaching the target, and the closer one is to the target, the less time one has to do so. Thus, information about the time-to-passage of the target (TTP), which is based on θ and the optical expansion of the target's visual angle φ (Ref. 16) (Fig. 1), might also play a role.

Fajen[15] had participants use a computer mouse to steer a curved path over a ground plane to three sorts of targets: (1) a floating cross that did not optically expand; (2) a floating sphere that optically expanded, providing TTP information; and (3) a grounded post that optically expanded, providing both TTP and distance information. The initial target distance was 60 to 180 m, and simulated observer speed was 15 ms^{-1}. Because θ was available in all conditions, performance should have been equivalent. The final steering error (which corresponded to θ at the end of the approach, when the observer was 5 m from the target), however, was considerably worse in the cross condition (1), showing that steering is not based on θ alone. The equivalence of the sphere and the post conditions (2 and 3) indicates that TTP information is adequate and target distance is not needed. Thus, both θ and φ are jointly necessary and sufficient for accurate steering. Note that the necessity of φ is also inconsistent with Lee's $\dot{\tau}(\theta)$ hypothesis[10] (Wann and Land, Eqn 6), which is based on θ alone.

Moreover, the observed steering profiles in Fajen's experiment were inconsistent with the simple θ strategy. Observers systematically oversteered during the initial portion of the approach, increasing curvature until the target was outside the future path ($\ddot{\theta} > 0$). Following a brief period of constant curvature that was too steep to follow to the target, observers gradually reduced curvature for the remainder of the approach to control the closure of θ, arriving at the target along a linear or nearly linear path. By contrast, Wann and Land's strategy predicts that observers will initially increase curvature only until the future path intercepts the target ($\ddot{\theta} = 0$), then maintain constant curvature to the target. But the data reveal that observers never followed a circular path to the target.

The second, 'raw retinal flow' strategy[13] (Wann and Land, Fig. 2) is based on the fact that when an observer fixates a point on the future curved path, the trajectories of ground elements that lie on the path are all vertical in the image plane, while those on either side of the path move outwards from it asymmetrically. Understeering and oversteering are indicated by trajectories that curve in the direction opposite to the steering error. Contrary to the data, this strategy also predicts that observers will follow a path of constant curvature to the target, and it cannot account for improved performance with TTP information. Indeed, Fajen's results appear to rule out any strategy that produces a circular path to the target, including the θ hypothesis, raw retinal flow, the locomotor flow line[8], and flow field curvature[9].

How might TTP information contribute to steering? Fajen[15] proposes that observers coordinate the time-to-closure of θ [$\tau(\theta) = -\theta/\dot{\theta}$] with the TTP of the target [designated by $\tau(\theta, \varphi)$]. By keeping $0 \le \tau(\theta) \le \tau(\theta, \varphi)$, the observer is guaranteed to arrive at the target. This is consistent with the improvement in actual performance when TTP information was available. Moreover, observers tended to null θ more gradually when TTP was greater, suggesting that they adjusted curvature so as to coordinate $\tau(\theta)$ with $\tau(\theta, \varphi)$.

Wann and Land argue that heading and optic flow play little role in locomotor control, and replace them with visual direction and fixation-based strategies. However, our data indicate that optic flow and visual direction both contribute to steering straight paths, and that steering curved paths relies on $\tau(\theta)$ (based on heading) and TTP (based on target expansion, a local flow property). Other locomotor tasks are similarly likely to be governed by task-specific information and control laws. The role of optic flow in locomotion is an empirical matter, and reports of its demise are greatly exaggerated.

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