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Driving as Night Falls: The Contribution of Retinal Flow and Visual Direction to the Control of Steering

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Summary

We have the ability to locomote at high speeds, and we usually negotiate bends safely, even when visual information is degraded, for example, when driving at night. There are three sources of visual information that could support successful steering. An observer fixating a steering target that is eccentric to the current heading must rotate their gaze. The gaze rotation may be detected by using head and eye movement signals (extra-retinal direction: ERD) or their retinal counterpart, visual direction (VD) [1]. The gaze rotation also transforms the global retinal flow (RF) field, which may enable direct steering judgments [2]. In this study, we manipulate VD and RF to determine their contribution toward steering a curved path in the presence of ERD. The results suggest a model that uses a weighted combination of all three information sources, but results also suggest that this weighting may change in reduced visibility, such as in low-light conditions.

Results and Discussion

Optic flow, the pattern of moving ground texture elements across a fixed image plane, is often described as the primary source of information for controlling the direction of locomotion [3]. In practice, there are problems with this simple solution to locomotor control. Gaze motion will introduce a rotation component into the optic flow projected onto the retina, and additional information may be needed to recover optic flow from this retinal flow field [4]. It is possible that steering could be accomplished by using pure retinal flow (RF) rather than optic flow [2, 5]. In some cases, however, RF information can be severely degraded or absent altogether, and visual direction information may become more important. For example, at night, a visual reference, such as the body of a car or bicycle handlebars, can provide a reference to the locomotor axis that clearly defines the visual direction (VD) of the steering goal at a retinal level. The direction and speed at which ground features, such as cats' eyes, move in relation to the visual reference can specify whether the current trajectory will take the driver around or over each obstacle [6]. If the mode of locomotion does not provide a fixed visual reference, an estimate of egocentric visual direction could be recovered from extra-retinal information (extra-retinal direction: ERD) arising from the control systems for the eyes and head. By aligning our head and eyes with the desired direction of travel, it is possible to steer accurately [7, 8]. In summary, there is considerable redundancy in the information provided by RF, VD, and ERD, and a steering system based on a combination of all three should be robust across changing conditions [6].

It has been demonstrated that walking a straight path toward a goal can be affected by both RF and ERD, but that the weighting attached may depend upon the quality or quantity of optic flow [9]. This walking task, however, required simple alignment of the observer with their perceived goal, whereas many everyday locomotor tasks require prospective judgment of more complex curved paths. In this paper, we examined the reliance on RF and VD in the context of high-speed steering of a curved path by introducing a subtle bias into each source of information that should result in steering errors if that source is being used. We then examined how reliance on RF and VD was influenced by three light levels, which simulated daylight, twilight, and night and reduced the salience of RF information. A further experiment examined the condition of complete darkness. We were therefore able to examine the changes in control strategy as the quality of optic flow was degraded, and we present a simple control model that exhibits equivalent behavior.

We simulated high-speed locomotion (8 m/s) in a direction that was eccentric to a target gate that was 60 m away. The task was to steer a smooth, curved path that would approach the gate and require a controlled and systematic reduction of the steering angle rather than direct target alignment [9]. In Experiment 1, an additional component was introduced into the ground plane motion (RF) that would promote either oversteering or understeering if RF was the primary source of information. The light levels for the environment were then manipulated to vary the quality of RF, in the presence of ERD (which occurred by default as the target moved relative to the observer), and thereby detect any associated shift in weighting. In Experiment 2, a vehicle emblem that provided a very strong reference for VD was introduced (Figure 1). An additional motion component that would promote oversteering and understeering, if the manipulated source was used, was then introduced into either the ground plane motion (RF) or emblem (VD) (Figure 2A). Each trial stopped 10 m from the target, and the steering errors were calculated by fitting a fixed curvature path to the final 1/3 of the trajectory, then extrapolating it to the 60 m mark to predict how close the trajectory would pass to the target.

In Experiment 1, there was retinal flow (RF) and extra-retinal direction information (ERD), but no emblem (VD). Control trials with no additional rotation were randomly interleaved with trials in which the ground plane texture was rotated around the steering goal. Positive texture rotation increased the RF rotation and caused participants to oversteer and overshoot the target, whereas negative texture rotation reduced the amount of rotation within RF and resulted in understeering ($F(1,7) = 34.5$,

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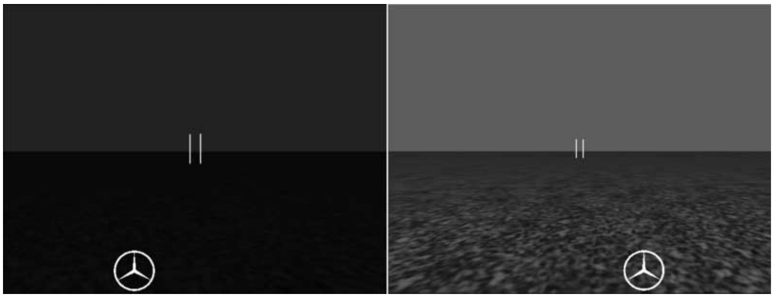

Figure 1. Examples of the Displays during the Nighttime and Daytime

These show conditions when RF (textured ground), VD (emblem), and ERD information was available. Note that the edges of the display were moved to always keep the target gate centered but that the whole display was displaced to offset the target from the observer by the correct degree on every frame; this gave rise to ERD when the target was tracked. Bias was introduced by rotating the ground texture around the point of fixation (RF) or by rotating the emblem around the observer (VD).

$p < 0.001$). As day turned to night, the mean error in the biased trials was reduced, indicating that the control strategy shifted from using RF to relying more on the unbiased ERD information (Figure 3, left bars)

In Experiment 2, an explicit visual reference for egocentric direction (VD) was supplied in the form of a white emblem located at the bottom of the viewing area equivalent to a car hood insignia. In addition to this, RF and ERD information were both available. When veridical VD information was present, errors resulting from RF bias were less than when VD was absent (Figure 3, compare RF and RF (VD); $F(1,7) = 7.4$, $p < 0.03$), indicating that, when VD is available, it is also factored into the steering control model. Combining the data of Experiment 1 and 2 confirmed that light attenuation caused a shift in weighting from RF to ERD (Experiment 1) or to VD + ERD (Experiment 2) as RF became degraded ($F(2,14) = 21.2$, $p < 0.001$). The errors during daytime, when RF was biased, however, show that, even with two strong veridical sources of information (VD + ERD), RF information still contributes to steering behavior.

Experiment 2 also introduced an equivalent bias into the VD information, while leaving RF unaffected (Figure 3, right bars). The resulting errors occurred less during the day than at night, reinforcing the finding that, as flow became more salient, the participants relied upon the biased emblem less; therefore, errors decreased ($F(2,7) = 4.8$, $p < 0.03$). This further demonstrates the shift in the weighting of VD and RF as lighting conditions changed.

Finally, to provide a measure of steering performance when participants were relying solely upon ERD and VD, a control experiment presented the environment in complete darkness (i.e., no sky or ground), with only the posts (ERD and no RF) or with the addition of the emblem (VD + ERD and no RF). The results (Figure 3, black bars) show that participants could still steer accurately when they only had access to ERD information or veridical VD + ERD. Figure 2B shows the path of a single observer in these conditions and demonstrates the marked dependence upon VD when it was available and the relatively accurate (though conservative) steering when only ERD was present.

A robust system for the visual control of locomotion is essential for survival. If the observer fixates the steering goal, there are three potential sources (RF, ERD, and VD) through which gaze rotation can be detected and used to control steering. In our definition, a retinal estimate of VD is only available to the observer if there is also a visual reference to the locomotor axis that defines

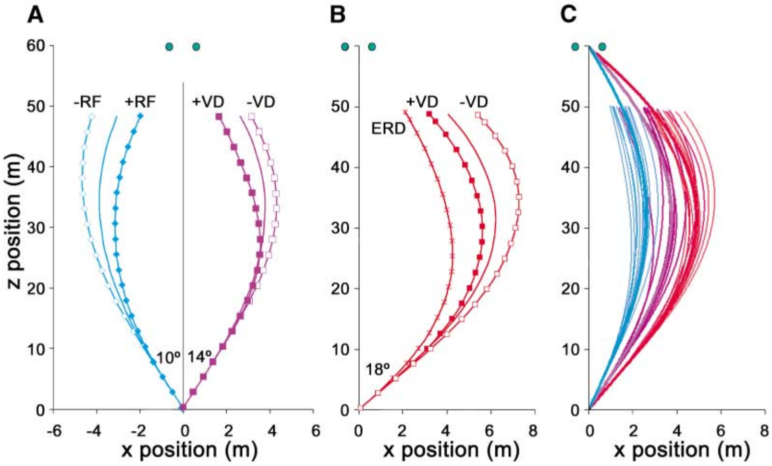

Figure 2. Examples of Individual Paths Taken in Experiment 2

In each panel, green circles represent the target posts.

(A) Bias in either visual direction (VD) or retinal flow (RF).

(B) Paths taken in darkness with ERD and VD, but no RF, information present. A path taken when steering was dependent upon just ERD information is also shown.

(C) Here, thin paths represent 36 paths taken by a single observer with veridical RF, VD, and ERD information available. There are three initial headings of 10°, 14°, and 18° (blue, purple, and red, respectively), jittered by ±1°, and the three thick lines are the modeled paths for these heading angles. We modeled steering behavior by using an equation that generated the rate of change of steering response ($\ddot{\theta}$) based on a combination of the three perceptual inputs that were estimates of the degree of rotation of the ground or target as perceived by the observer. Because the rotation components of RF, VD, and ERD are all functions of observer speed, target distance, and steering angle, there is no need to explicitly detect these parameters, but the model acts as an attractor to the point of gaze fixation that is scaled for speed and distance: $\ddot{\theta} = k(\beta_1 RF + \beta_2 ERD + \beta_3 VD) - b\dot{\theta}$. A first approximation applies equal weighting (β_{1-3}) to the three sources. The combined outputs are scaled by the response speed (k) of the steering system, and a damping factor ($-b$) is introduced to the current rate of turning ($\dot{\theta}$) to model the physical properties of the locomotor device.

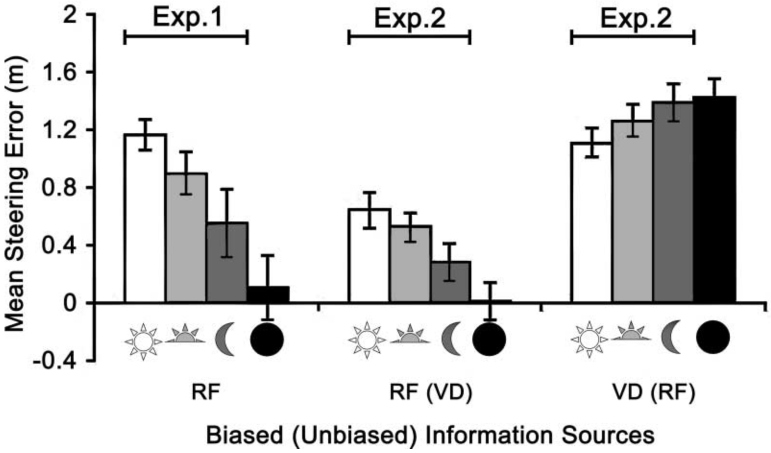

Figure 3. Mean Errors in Steering for Biased RF and VD Conditions

The sun and moon symbols indicate different light levels (day, twilight, night, darkness). Experiment 1 biased RF without a VD cue, and the results are shown in the three bars to the left. Experiment 2 biased either RF or VD, and the label in parentheses indicates which source was left unbiased and veridical. The black bars indicate the total darkness control condition with pure ERD (left), ERD with unbiased VD (middle), and ERD with biased VD (right) and are shown for reference.

the visual angle of the target. If there is no reference feature, the observer can fixate the target and recover an equivalent estimate extra-retinally (ERD) from the gaze control system. In our experiments, we introduced directional bias into sources of RF and VD information (in the presence of ERD) and varied the illumination, effectively controlling the quality of the RF information. The results support a model in which all three sources are combined. To evaluate the manner in which they are combined, we introduced the same RF and VD bias to a simple point attractor model. This model acts to null the combined rotation components and produced equivalent trajectories (Figure 2C). We then estimated the weighting for RF, VD, and ERD that would result in similar under/oversteering responses to those of human participants (Figure 4). This suggests that, when VD is available, it tends to be the dominant source of information. As night falls, however, it is clear that the weighting attached to each source also changes as a function of the salience of optic flow (Figure 3). To develop our understanding of the interaction between these inputs, further studies are needed to determine the extent to which biased ERD information, which is not currently manipulated, causes errors in the presence of veridical RF and VD information.

Experimental Procedures

A PC with Dual Xeon Pentium IV Processors and DirectX 8.1 graphics libraries generated images (50 Hz) at a resolution of 1248 × 984. They were projected with an Electrohome 7500 graphics projector with fast phosphor tubes within a light-excluded viewing booth with a large back projection screen (200 × 145 cm) providing a potential FoV of 90° × 72° when viewed from 1 m away. Care was taken to ensure that invariant frames of reference were absent. Computer-generated shutters were used to keep the target posts centered within the viewport and to remove the frame reference. The viewport dimensions were 127 × 94.5 cm (64.8° × 50.7°), allowing 12.6° (25.2° total) for lateral motion of the target and shutters. The screen edges were in the periphery (± 45°), but the screen edges were also covered in matte black tape; the room interior was matte black, and all incidental light was excluded from the projection booth. The participant wore a cape made of black nonreflective material to cover their shoulders, arms, and the steering wheel to prevent them from acting as a visual reference. Between each trial a bright screen was flashed for 2 s to prevent dark adaptation by the observer.

The eight participants, with normal or corrected-to-normal vision, used both eyes to view the nonstereo image and were naive to the experimental conditions. Gaze and head positions were left unrestricted since we desired natural gaze fixations upon the steering target. The presented scenes comprised a ground plane tiled with an image of gravel selected from a library of natural photographic textures. Placed within the scene, 60 m away from the observer, was a pair of posts (1 m apart), which were eccentric to the observer's initial direction of motion. The observer was instructed to

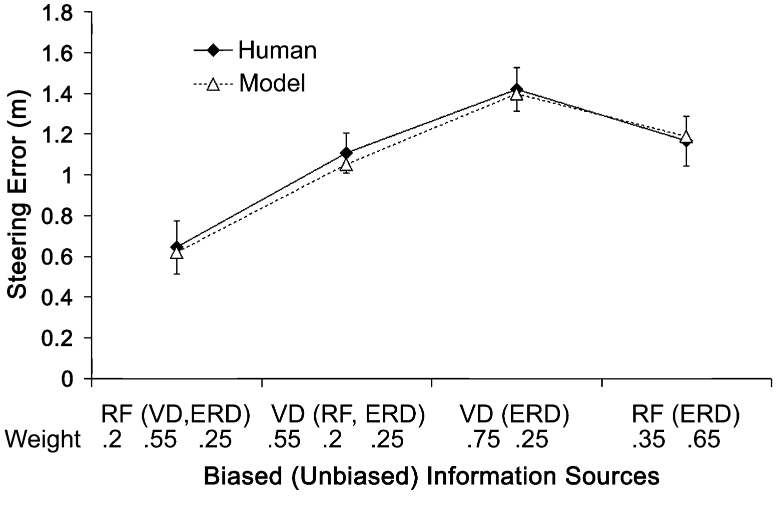

Figure 4. Steering Errors Caused by Biased VD and RF Conditions

Data for humans' (solid) and the model's (dashed) responses are shown with verdical information sources indicated by parentheses. Veridical ERD information is present in all cases. Model fit was achieved by using the same response speed (k) and damping ($-b$) terms as in Figure 2C. By introducing identical bias in the RF or VD components in the model, we can evaluate the accuracy of fit to human data. This procedure suggests an unequal weighting between the perceptual inputs. Most notably, VD dominates RF when both are available, keeping errors low when VD is veridical and high when VD is biased. The weighting of biased RF is surprisingly low in the presence of ERD, emphasizing the need for further examination of the role of ERD information in controlling steering.

fixate the posts and steer toward them in a smooth arc, making as few adjustments as possible, yet with the primary goal being accurate steering. Trials lasted 6.26 s and were stopped 10 m from the posts to prevent participants from receiving precise feedback as to the accuracy of their steering in each condition; this also negated the utility of binocular information. The final 2 s of each path was fitted with a curve of constant curvature, and this was extrapolated to provide a measure of steering accuracy at the 60 m mark. Velocity was constant at 8 ms^{-1}, and the initial direction of motion was offset to the right or left of the target posts by one of three basic angles: $\pm 10°$, $\pm 14°$, and $\pm 18°$, with an additional jitter of $\pm 1°$.

In Experiment 1, the rotation component of retinal flow was systematically biased to yield randomly interleaved conditions of negative bias (−RF), normal flow (RF), and positive bias (+RF). This bias was achieved by rotating the ground plane around the fixation target at a rate inversely proportional to the distance of the target by using a polar estimate of the gaze rotation ($\dot{\phi}$) that would result from a heading error of α: $\dot{\phi} = V \sin(\alpha)/F$, where V was the locomotor speed (8 m/s), F was the line of sight distance of the target calculated every frame (50 Hz), and α was chosen to be 20°. This introduced a bias into retinal flow equivalent to traveling on a more eccentric path, but without changing VD or ERD information. The rate of bias increased as F decreased from 0.95°/s in the first 250 ms to 4.1°/s during the final 250 ms, with an average over the trajectory of 1.9°/s.

In Experiment 2 an explicit source of visual direction (VD) was supplied, and bias was introduced by making the source of VD drift to the left or right (toward or away from the target destination) at a constant rate of 1°/s, yielding a potential offset from 0° in the first 250 ms to 6.2° in the final 250 ms. Conditions either contained veridical RF, VD, and ERD, or bias was added to RF or VD, yielding five combinations (RF:VD, −RF:VD, +RF:VD, −VD:RF, +VD:RF). Six trials in each condition were randomly interleaved, except for the unbiased RF:VD condition in which twice as many trials were presented.

The final control experiment removed sky and ground from the display so that no RF information was available. This provided baseline performance using only extra-retinal egocentric direction (ERD) and demonstrated the extent of error caused by VD bias in the absence of RF.

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