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Active Gaze, Visual Look-Ahead, and Locomotor Control

Richard M. Wilkie
University of Leeds

John P. Wann
University of London

Robert S. Allison
University of York

The authors examined observers steering through a series of obstacles to determine the role of active gaze in shaping locomotor trajectories. Participants sat on a bicycle trainer integrated with a large field-of-view simulator and steered through a series of slalom gates. Steering behavior was determined by examining the passing distance through gates and the smoothness of trajectory. Gaze monitoring revealed which slalom targets were fixated and for how long. Participants tended to track the most immediate gate until it was about 1.5 s away, at which point gaze switched to the next slalom gate. To probe this gaze pattern, the authors then introduced a number of experimental conditions that placed spatial or temporal constraints on where participants could look and when. These manipulations resulted in systematic steering errors when observers were forced to use unnatural looking patterns, but errors were reduced when peripheral monitoring of obstacles was allowed. A steering model based on active gaze sampling is proposed, informed by the experimental conditions and consistent with observations in free-gaze experiments and with recommendations from real-world high-speed steering.

Keywords: locomotion, steering, gaze, eye movements, active vision

Active visual exploration is a crucial part of interacting with our environment and accurately perceiving the world around us (Wexler & van Boxtel, 2005). Effective locomotion is initiated through a series of online control movements, which are generated by a fast and efficient perception–action loop. This response system involves movement distributed across the body, invoking eye, head, and whole-body motion, which in turn affects the online information that is available to guide steering (Wilkie & Wann, 2002, 2005). Land and Lee (1994) and Land and Tatler (2001) highlighted the use of head and gaze orienting in directing steering during car driving; however, such behaviors could provide two sources of information stemming directly from the orienting action: gaze angle (the direction of your eyes and head relative to your body's midline, which is usually coincident with your direction of travel) and gaze rotation. Gaze angle gives some indication of the magnitude of rotation that would be required to reorient yourself in line with the steering target, whereas gaze rotation could be used to judge whether the rate of closure is appropriate (Wann & Land, 2000).[1]

The simplest way to travel toward a target that is offset relative to the current direction of motion is to turn to null visual direction (angle α) and then move along a straight-line path to reach the goal (Figure 1, black border between light gray and white zones). People often use this strategy at walking speeds because they are able to pivot on the ball of their foot without mishap. At higher speeds, for example when driving a car, such rapid changes to the direction of motion would cause skidding or, if cycling, would flip the cyclist over the handlebars. We argue that for general steering tasks, the goal is to close down α, the angle between the current direction of motion and the goal, at a smooth rate ($\dot{\alpha}$) that may, or may not, remain constant.

Another simple control heuristic is to base steering purely on the rate of change in egocentric visual direction of the goal ($\dot{\alpha}$). Rushton, Wen, and Allison (2002) put this theory into practice with a mobile robot and demonstrated that nulling any change in the visual direction of the target (canceling target drift) ensured smoothly curving paths that effectively steered the robot toward the target (Figure 1, black border between dark gray and white zones). It can be seen from the trajectories in Figure 1 that human participants actually steer more directly to the target than would be predicted if they simply nulled target drift. Rushton et al. (2002) proposed that more direct paths could be generated by overcom-

Richard M. Wilkie, Institute of Psychological Sciences, University of Leeds, Leeds, England; John P. Wann, Department of Psychology, Royal Holloway, University of London, London, England; Robert S. Allison, Centre for Vision Research, University of York, Toronto, Ontario, Canada.

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Correspondence concerning this article should be addressed to Richard M. Wilkie, Institute of Psychological Sciences, University of Leeds, Leeds LS2 9JT, England. E-mail: r.m.wilkie@leeds.ac.uk

[1] The role of retinal flow has been studied independently of extraretinal sources of information (e.g., Warren & Hannon, 1990). It is now clear, however, that retinal flow and extraretinal information support locomotor control via flexible combination (Warren et al., 2001; Wilkie & Wann, 2002).

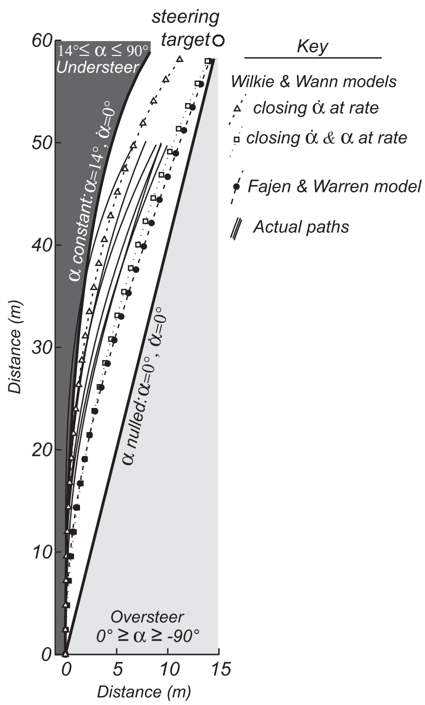

Figure 1. A plan view of real data (from Wilkie & Wann, 2003a, Experiment 3) and modeled data, for trajectories followed when steering to a single target offset by 14° (large open circle). Thin solid lines show actual paths steered by human participants. Dotted lines show modeled paths: the Fajen and Warren (2003) model (Equation 1: closed circles) and the Wilkie and Wann (2002) model using either $\dot{\alpha}$ (Equation 3: open triangles) or the extension of this model proposed here, which uses a combination of α and $\dot{\alpha}$ (Equation 4: open squares). Two gray zones sandwich a white central zone of "satisfactory" performance. The light gray zone represents the area of oversteer in which the target moves to the opposite side of the locomotor axis and in which we normally observe wild oscillations in steering. The thick black border of the light gray and white zones is demarcated by an α-nulling strategy whereby the angular offset of the target is nulled instantly and a linear path straight to the target is followed. This sort of path would only be possible at walking speeds at which momentum and inertia do not prevent changing direction on a pivot point. The dark gray zone indicates the area of understeer, in which the angle of the target gradually increases. It can be seen that one of the human paths lies in this area for the first half of the steering event; however, humans correctly perceive the increasing offset of the target and adjust their steering appropriately. After a certain time within this zone (depending on the dynamics of the vehicle), it becomes impossible to steer at a sufficient rate to compensate for the understeer, and successful locomotion to the target cannot be achieved. The thick black border between the dark gray and white zones shows the course when α is maintained at a constant 14° throughout the steering event and $\dot{\alpha}$ is nulled. This is not the safest strategy because error tending toward understeer during this course could cause irrevocable error.

pensating for target drift (e.g., steering at 200% target drift). Although simple solutions should always be considered, empirical data have shown that in more complex locomotor situations, a number of additional sources of information play a role in human control of steering (Warren, Kay, Zosh, Duchon, & Sahuc, 2001; Wilkie & Wann, 2002, 2003a, 2005).

A more sophisticated model is therefore required to provide a good fit for human steering performance that can take advantage of multiple information sources. A popular approach has been to use nonlinear dynamical models to couple perception to action (e.g., Fajen & Warren, 2003). In the Fajen and Warren (2003) model, the orientation and distance of both goals and obstacles are encoded and weighted by the goal–obstacle distance to set-up point attractors and repellors that then shape the resultant trajectory. This system, therefore, operates on the basis of the visual direction of the target or obstacle, not optic flow, but flow may be required to recover instantaneous heading if there is not a clear visual reference for the locomotor axis (such as handlebars). In the Fajen and Warren scheme, there is no proposal as to where the observer might look during locomotion. It would seem advantageous for the observer to fixate each target at least once to encode its location, but in their model there is no penalty for looking elsewhere during locomotion and no specific advantage gleaned from the timing or order of scene fixations. Wilkie and Wann (2002, 2003a) proposed a model whereby gaze fixation creates the point attractor; you look to where you want to steer, and steering is drawn to where you look. This is consistent with the recommendations of advanced steering guides: "Using your eyes correctly is critical in choosing the path you want your motorcycle to follow. You must discipline yourself to look where you want to go" (Ienatsch, 2003, p. 27). In our model, this process operates via a steering control system that acts to null perceived rotation rate ($\dot{\alpha}$):

$$\ddot{\theta} = k\dot{\alpha} - b\dot{\theta} \tag{1}$$

where $\ddot{\theta}$ is acceleration of response, $\dot{\theta}$ is the response rate, and $\dot{\alpha}$ is an estimate of rotation rate combined across multiple perceptual variables (as shown in Equation 2). The parameters *k* and *b* provide response-rate scaling and damping, respectively. We can expand Equation 1 by considering the perceptual information that reflects $\dot{\alpha}$: ${}_eRF$ is a perceptual estimate of the rotation within the flow field, and ${}_e\dot{ERD}$ is an extraretinal estimate of the rate of change of target direction (equivalent to gaze rotation for a fixated target). A third term, ${}_e\dot{VD}$, is included for situations in which there is a retinal estimate of the changing target direction, such as is provided by the visible bodywork of a car (Wilkie & Wann, 2002). Substituting in Equation 1 gives

$$\ddot{\theta} = k(\beta_1\, {}_eRF + \beta_2\, {}_e\dot{ERD} + \beta_3\, {}_e\dot{VD}) - b\dot{\theta} \tag{2}$$

where β_1–β_3 are informational weights and should sum to 1.0. This model proposes that observers exploit the redundancy in the visual scene and use flow field and visual direction information, but in cases of information drop-out (e.g., low light) may adjust their perceptual control strategy. The performance of the model compared with experimental data is show in Figure 1 (open triangles).

The data in Figure 1 are from 1 participant taking part in Experiment 3 of Wilkie and Wann (2003a), in which we generated a simulated visual environment and asked participants to steer to an offset target 60 m distant (thin solid lines). It can be seen that human paths cluster in a zone that lies in between a constant α strategy and an α-nulling strategy, but usually turn more rapidly than Equation 2. To capture this behavior, we propose an extension of our previous model in which both α and $\dot{\alpha}$ are used as inputs to the steering system:

$$\ddot{\theta} = k_1\dot{\alpha} + k_2\alpha - b\dot{\theta} \tag{3}$$

When we substitute perceptual variables into Equation 3, we therefore need ${}_{e}\text{ERD}$ and ${}_{e}\text{VD}$ as estimates of the gaze angle α, as well as the estimates of angular rotation (${}_{e}E\dot{R}D$ and ${}_{e}\dot{V}D$):

$$\ddot{\theta} = k_1(\beta_{1\,e}RF + \beta_{2\,e}E\dot{R}D + \beta_{3\,e}\dot{V}D) + k_2(\beta_{4\,e}ERD + \beta_{5\,e}VD) - b\dot{\theta}. \quad (4)$$

As with Equation 2, the $\beta_{4\&5}$ weights are the relative reliance on each source of information (which sum to 1.0), and k_2 is a response rate parameter. This model seems to be consistent with the everyday experience of steering: If we want to change our direction of motion to approach a target that has a large angular offset, we will steer more quickly than if the target is nearly straight ahead; however, we will still control the rate of change of steering to bring the target around smoothly. This is also consistent with the findings of Readinger, Chatziastros, Cunningham, Bulthoff, and Cutting (2002), who found that a simple gaze offset can lead to impairments in road positioning and steering.

If we compare the goodness-of-fit of paths generated using Equations 1 and 3 with human data (Figure 1; open triangles vs. open squares), then we can see that both generate paths that lie within the white central zone of satisfactory performance; however, Equation 3 turns earlier, which reflects the influence of the gross target angle. It can also be seen (Figure 1; open squares vs. filled circles) that Equation 3 produces very similar results to the model proposed by Fajen and Warren (2003); however, the primary difference between these models lies in their focus. Fajen and Warren make the case for considering the perception–action cycle as a dynamical system, but do not address the issue of the pickup of information or where someone might attend during locomotion. Wilkie and Wann (2002, 2003a, 2006) followed this lead and evaluated the information used to support steering. Our model suggests that appropriate patterns of gaze sampling can simplify the perceptual control of steering.

To examine further the role of active gaze in the control of steering, we carried out a series of experimental conditions with a particular emphasis on testing the applicability of the model described in Equation 4 to an extended steering task involving negotiation of a series of steering targets. We had three main aims: (a) Examine how natural gaze sampling is used to support human locomotor control when steering through a series of waypoints; (b) measure how steering is affected by altering gaze-fixation patterns (specifically, whether the length of fixation on the next steering waypoint changes steering and whether peripheral visual information has an input into steering control); and (c) examine the informational inputs that affect steering control. In addition, we examined whether the steering model outlined previously is consistent with the steering and gaze behaviors observed.

Active Gaze and Visual Look-Ahead

In everyday locomotion, people often have a single destination but are required to follow winding paths that are made up of many waypoints. In the real world, cat's eyes, lane markings, and road edges can all supply useful visual direction information. Land and Horwood (1995) examined steering along simulated roadways when the road edges in some areas were occluded. They identified two types of information use: Near-road information was used to aid centering, and far-road information aided curvature matching. Salvucci and Gray (2004) have proposed a visual control model of steering based on perceptual inputs from these two zones and have demonstrated a good fit to a variety of steering cases. Situation-specific use of visual direction information (such as the tangent point of a bend; Land & Lee, 1994) has also been proposed by Land (2004), although other situations seem to require a pronounced coupling between head and steering. For example, Land recently proposed that the combined use of gaze and vestibulocollic reflex may be the main mechanism behind negotiating 90° bends (Land, 2004).

The data on where people look during complex steering tasks is quite sparse. Land and colleagues (Land & Lee, 1994; Land & Tatler, 2001) have examined a small selection of skilled drivers approaching bends on real roads or tracks and highlighted the fixation of distinct geometric features. Wilkie and Wann (2003b) used a simulation setting to generalize these observations and demonstrated an advantage of free-gaze sampling over stabilized gaze in steering. However, these previous studies did not provide a direct test of whether advanced fixation is essential to the control of steering. With a continuous roadway, as used by both Land and colleagues (Land & Horwood, 1995; Land & Lee, 1994; Land & Tatler, 2001) and Wilkie and Wann (2003b), it is normal behavior to look ahead down the road or to look through the bend for oncoming hazards. It is also typical for drivers to stay within the confines of the roadway. A correlation between where drivers look and where they steer may simply be a consequence of these two habitual behaviors.

To examine the role of eye movements in steering, we have therefore moved to the challenging task of steering a slalom, in which participants can take any line that they desire provided they passed within a set of slalom gates (1 m wide) every 32 m (approximately 4 s apart). In this setting, there is no need for participants to continuously monitor a defined roadway. The Fajen and Warren (2003) model makes no requirement that such gates be fixated during locomotion, provided that these future targets or obstacles are in the visual scene and their bearing angle and distance can be encoded. In the steering model described in Equation 4, the observer can circumvent the problem of estimating the scene geometry by fixating each target in turn. In our model, sources of information in Equation 4 are yielded through the fixation of an upcoming target. Gaze fixation on the point to which you want to travel can supply all the information you need to successfully reach that target. In a situation containing multiple waypoints, each node could be treated in isolation, with no thought to future nodes until you have traveled past the most immediate waypoint. At best, this strategy would generate suboptimal paths; at worst, it could cause steering errors or collisions through inappropriate steering. To negotiate a series of tight, winding bends requires a degree of forward planning to ensure that the current path through an immediate steering target will also be appropriate for successful passage through future waypoints. One possible strategy would be to fixate the most proximal waypoint to establish an accurate steering course, and then switch gaze toward the next waypoint in the series. This is a strategy recommended in applied texts:

> As you approach a corner, you will be looking at a spot on the corner entrance, probably where you think it's a good place to turn. Leave your eyes on that spot too long, however, and the rest of the corner

> will either surprise you or rush you. Move your eyes off that entrance point and up into the corner. . . . as you approach that spot, rip your eyes up again to the exit. (Ienatsch, 2003, pp. 29–30)

This strategy would seem to require a stored estimate of where the most immediate steering target is located when fixation is to move to a more distal target. Peripheral vision could supply a low-resolution estimate of target location when gaze is directed away from the immediate steering goal, but this would be imprecise, and peripheral targets may be obscured in the real world at close proximities by the body of the vehicle. Land and Furneaux (1997) proposed that the information obtained from directed eye movements is entered into a temporal buffer, so that it might guide movements even if the eye has moved to a new target. They suggested that the required buffer length for driving may be of the order of 0.8 s, whereas in other tasks such as table tennis it may be somewhat shorter. Our prediction for negotiating a slalom course is that observers will fixate sequential gates well in advance of their approach and this will form an integral part of setting up the locomotor path. An example of this is shown in Figure 2, in which a set of cyclists can be seen sampling distinct features during a real slalom race. This illustrates the proposals of Wann and Wilkie (2004), which suggest that the key skills in steering are selecting appropriate waypoints (through which you wish to pass) and then fixating these in a tight temporal sequence. The prediction for the slalom task, however, is not simply that participants will look to check how many obstacles there are ahead, but that their fixation patterns will reflect their steering strategy, with gaze primarily directed toward the most immediate target with additional rapid fixations onto future targets when it becomes necessary.

To examine the use of gaze during locomotor control, we carried out a set of four behavioral experiments to compare our predictions with human performance. In Experiment 1, we undertook some observational analyses of where participants look when they are steering freely through a challenging slalom course to see whether they adopted a tight temporal gaze pattern when setting up their trajectories between gates. In Experiment 2, we examined gaze patterns experimentally to examine when participants preferred to move gaze from the immediate slalom gate to the next gate in the series. In Experiment 3, we explored what happened when gaze patterns were disrupted and participants were forced to move their gaze ahead earlier than they would prefer or were prevented from looking ahead as early as they would like. We also addressed whether participants monitored their current target alignment through peripheral vision or some form of visual–spatial buffer. In Experiment 4, we examined whether precise target fixation was important or whether the steering task could be completed when gaze is directed toward the approximate zone of a gate, but slightly offset. To probe the nature of the visual-spatial buffer, in Experiment 4 we also examined how well observers were able to monitor their time to passage for steering targets while still attending to future waypoints.

Figure 2. Natural gaze sampling during a real high-speed slalom. The two chasing riders are fixating a zone close to the bollard that they want to pass. The lead rider has switched gaze from the bollard to a point further ahead where she wishes to be in 1–2 s. The fixation of distinct features is not, in principle, essential to detect obstacles, locomotor heading, or the relation between the two, but the fixation of waypoints (that you wish to pass through) is a natural response in challenging steering tasks. The lead rider was the British National Circuit Race champion for her age group and rode for Great Britain in the Junior World Championships. From www.swarbrick.com. Copyright 2006 by Guy Swarbrick. Reprinted with permission.

General Method

Participants

Eight participants were recruited at the University of Reading (Reading, England), and the same participants took part in all experiments reported here. All gave their informed consent before their inclusion in the study, and the studies themselves were approved by the relevant ethics committee (the University of Reading) and were performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki. All participants had normal or corrected-to-normal vision and were unconnected with the study, but they did have some general experience of viewing motion displays in addition to having at least 2 years driving experience. Observers used both eyes to view the nonstereo image (bi-ocular viewing), and head and body position were not stabilized. Before taking part in the experimental conditions, participants were run through a number of training trials to allow them to get used to the device mapping of the steering device for visual control of self-motion, the display properties, and the format of the slalom course.

Apparatus

The experiments were conducted in the Action Research Laboratory at the University of Reading. Locomotor steering was controlled and captured through a bicycle fixed in an exercise training rig (TACX, Wassenaar, The Netherlands) with front forks attached to a rotating sensor apparatus that controlled direction of motion in the simulated world (rotation of the handlebars was sent to the personal computer via USB). In addition, both eye movements and head rotations were measured and recorded. An ASL 504 infrared remote optics eye tracker (Applied Science Laboratories, Bedford, MA) was used to record the point of gaze. Gaze coordinates were streamed via serial port to the image generation workstation and recorded at 50 Hz in synchrony with the steering response. Additional responses could also be collected from two electronic clickers positioned like bicycle index gear shift levers on the handlebars for ease in pressing with the left or right index fingers. These were used in Experiment 2 to adjust world properties and in Experiment 4 for participants to indicate when they passed through each gate.

Displays

The projection system presented a wide field of view (90° × 45°) virtual environment to the observer, with an eye height on the bicycle that was adjusted to a standard 1.55 m and an eye-to-screen distance of 1.0 m. The computer-generated images of the simulated environment were rendered at 50 Hz using custom-written Visual C++ code and DirectX libraries. The personal computer was a Dell XPS Dimension Workstation with Pentium 4 processor (Extreme Edition) running at 3.46 GHz. The simulated slalom course consisted of a series of gates that consisted of two tapered blocks (height falling from 0.3 m at the inside edge to 0.1 m at the outside edge; width = 1 m) with a 1-m gap between them, with an additional green marker positioned in the center point that provided both a fixation and a steering target for the participants. Layout of the slalom course placed the gates at the apex of the bends of a sum-of-sines path (based on the roadway used in Wilkie & Wann, 2003b), and the locomotor speed was kept at a constant 8 ms^{-1}.

Procedure

The participants were asked to steer smoothly and accurately and attempt to pass safely through a series of slalom "gates." Participants were advised to avoid contact with the blocks (although no feedback about collision was given) and to steer as closely as possible to the position of the green marker (midway within the gates) while maintaining a smooth trajectory.

Trials lasted 37.5 s, and an average trial took the participant through nine gates. The first gate was always visible to give the participant a concrete initial steering target for the course, so for analysis the first gate was always ignored. A single format of slalom course was used to allow comparison between trials and conditions in the experiments outlined here and also with previous experiments that have used the same underlying sinusoidal pattern as a basis for the steering course. The course was sufficiently sparse and irregular to minimize learning of specific bends or the generation of explicit cognitive strategies. In addition, courses were randomly mirrored around the long axis so that trials began with either an initial leftward turn or an initial rightward turn that was required to steer to the first gate. This stopped the motor response from becoming too familiar while preserving an equivalent level of difficulty across trials.

Data Analysis

The primary measure was steering behavior, from which we generated a measure of steering error and steering smoothness. Steering error was calculated by finding the smallest passing distance from midway within each gate. Steering smoothness was calculated on the basis of the average acceleration of steering rate (°/s/s). Rather than taking the average across the whole trial, we calculated smoothness for the trajectory leading up to each gate. This allowed us (in Experiment 2) to examine whether smoothness was influenced by particular properties of each gate. We could also average smoothness across all the gates in a trial to examine the influence of each experimental condition on steering smoothness.

Eye-movement behavior was also recorded, and the details of the analysis of these data are contained in individual *Method* sections. Similarly, analysis of the data from the two electronic clickers are described in the *Method* sections for Experiments 2 and 4.

Experiment 1: Natural Gaze Fixations

Land and Lee (1994), Land and Tatler (2001), and Wilkie and Wann (2003b) examined gaze patterns when steering along a continuous roadway on which there were an indeterminate number of potentially useful fixation points and constant visual feedback for steering performance. With continuous roadways, a suitable locomotor path may be maintained by using near and far sections of the road edges to continually adjust steering (Land & Horwood, 1995). In many settings, however, human and animal steering systems need to generate smooth paths that "spline" between a set of locomotor goals.[2] Here, we wanted to determine typical gaze behaviors when steering around a number of discrete waypoints that required the generation of a smooth path. In addition, we wanted to obtain a measure of "optimal" steering performance from participants steering while looking wherever they liked in the scene.

Method

Experiment 1's method was as described in the General Method section. Eight participants steered down 12 full slalom courses with their gaze and steering behavior monitored but with no restrictions on where they could look.

[2] It is our contention that on-road steering is a restrictive paradigm when exploring locomotor control. For very obvious reasons, we have engineered vehicles and roadways to minimize the skill required to steer the former along the latter. The solutions that are observed do tend to be specific to maintaining a safe in-lane position. The remarkable skill and flexibility that humans can exercise in steering only become apparent in situations akin to a driver on a racetrack, a cyclist descending an alpine road, or a person running at speed in a forest.

Results and Discussion

Steering strategy. Figure 3 presents some examples of steering strategies with a greater or lesser forward planning component. DP generated a course through the first gate (G_n) that neatly set up the trajectory for the gate beyond (G_{n+1}). This strategy is effective (minimum distance between position and center of gate, or errors = 0.12 m), but it is hard to execute because it requires a large degree of forward planning (reflected in a relatively high standard deviation of 0.06). EL consistently took a more direct route to G_n, but this did not take into account the position of G_{n+1} and made it more difficult to ensure safe passage through the gate beyond (errors = 0.18 m, SD = 0.02). CH carried out a low-risk, intermediate strategy that was safe and effective because she exhibited the smallest errors of all participants (errors = 0.08 m, SD = 0.02). The overall mean steering error for the group was 0.2 m (SD = 0.12), and we use this value as the baseline measure of steering accuracy for the experimental conditions that follow.

In addition to calculating steering errors, we can also examine a measure of steering smoothness. Land and Horwood (1995) created an instability index to examine smoothness; however, their data contained many spikelike steering behaviors linked with maintaining position on the road using the near-road edges. Our steering data were all comparatively smooth because immediate error feedback was absent from our task; however, we might still expect differences in the rates of steering between individuals on the basis of the paths seen in Figure 3. To evaluate smoothness for each participant, we calculated the average absolute value of angular acceleration (°/s/s). For steering, there is no need to go to the third derivative (jerk) to estimate smoothness. If heading and forward velocity are constant, then the trajectory is optimally smooth. If steering velocity is constant, then the trajectory is around a smooth arc. If there is angular acceleration, it reflects the sharpness with which a participant initiates or completes a turn or any adjustments to turning rate during the trajectory. In all cases, high values would jolt a passenger, so a lower absolute value of angular acceleration indicates smoother steering. The results show that the smoothest steering was exhibited by CH (25.7°/s/s) and DP (25.8°/s/s), with EL exhibiting slightly less smooth steering (26.3°/s/s). The mean steering smoothness across participants was 27.7°/s/s (SD = 4.1), and this can be used as a baseline for later comparison.

Gaze strategy. Because a person's head and eyes can only be directed toward one location at a time, there is competition for gaze resources between the current set of gates (G_n) and the next set (G_{n+1}). Figure 4 contains an example of the gaze strategy of CH, who produced the intermediate steering strategy shown in Figure 3. The sawtooth profile in the top panel of Figure 4 shows the basic switching pattern of the vertical gaze angle, tracking one set of gates as it approaches the bicycle before jumping back up to fixate the next set of gates. The horizontal gaze angle plot (lower panel of Figure 4) shows an equivalent effect whereby each gate is fixated and brought in from an offset position toward the center. CH maintained fixation on G_n, then she jumped ahead to the next gate (G_{n+1}). This strategy was common across trials and participants, but with differing degrees of look-ahead. Also, in Figure 4 there is some evidence of a strategy we label *gaze polling*. Between 18 s and 20 s, CH made a saccade to briefly fixate G_{n+2} before returning to track G_{n+1}. This is also seen between 22 s and 24 s as she polled G_{n+3} before returning to fixate G_{n+2}. This dual-sampling strategy has been illustrated previously by Land (1998) for dealing with road hazards, such as pedestrians. We anticipated that this might be used more widely by participants, but observed this pattern only intermittently. Ideally, we would be able to calculate the look-ahead distance from the free-gaze data; however, this proved to be problematic because eye blinks often accompany saccades, and gaze polling could have reduced the imperative to fixate the next gate in the series. It was therefore difficult to resolve a useful estimate of preferred look-ahead distance. To resolve this issue, Experiment 2 obtained a measure of comfortable gaze-switching behavior using an experimental manipulation.

Summary. The Wilkie and Wann (2002) model of steering describes a system whereby gaze fixation onto the point to which you want to travel can supply all the information you need to

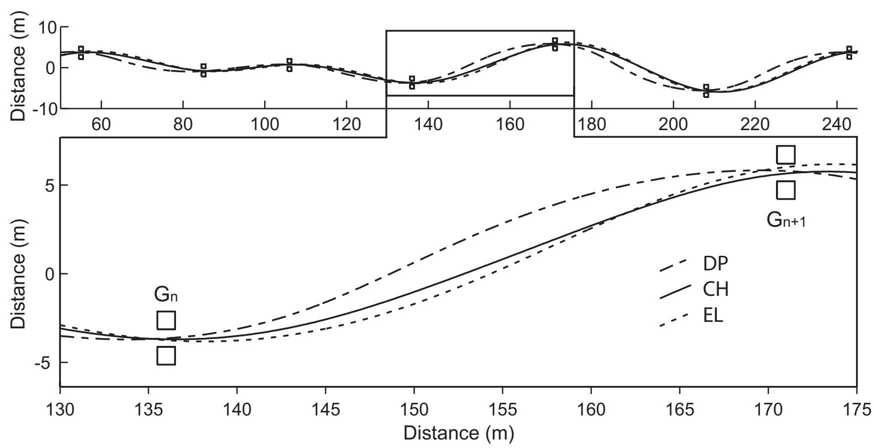

Figure 3. A plan view of steering paths through a gated slalom course when gaze is free. Single trials from 3 participants are shown (DP, dot-and-dash line; EL, dotted line; and CH, solid line) to demonstrate contrasting steering strategies. Upper panel: Trajectories through seven gates. Lower panel: Expansion of the section between two gates.

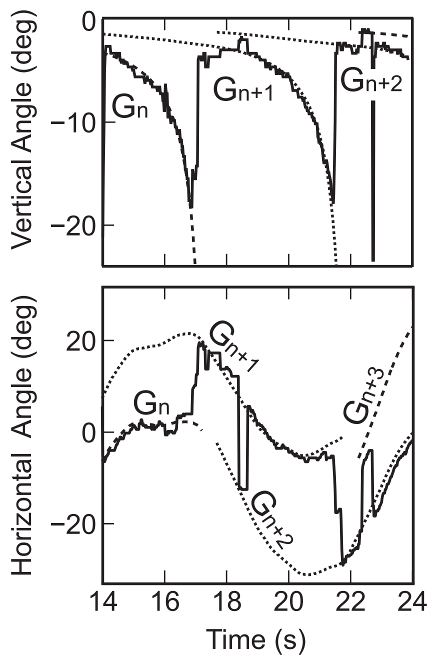

Figure 4. Gaze behavior (solid lines) for participant CH when steering around a number of slalom gates (broken lines indicate the midpoint of each gate). The first two gates (G_n and G_{n+1}) match those shown in the lower panel of Figure 3. The top panel shows CH tracking each target gate as it approaches and moves vertically down the screen. Gaze switching on to the next gate can clearly be seen in the sawtooth pattern of the solid line. The bottom panel shows the horizontal angular position of gaze and the midpoint between the slalom gates as CH approaches each in turn. Her gaze tracks the center of each gate before jumping to the next target. Gaze polling (see the text for explanation) can also be seen at about 18.5 and 23.5 s into the trial

successfully reach that target. One way to handle multiple waypoints would be to treat each set of gates as a single target in isolation, with no thought to the next until the current target has been reached. However, to successfully steer smooth paths through a series of waypoints requires a degree of path planning to ensure that current steering carries you via the immediate steering target without precluding safe passage through future waypoints. Experiment 1 showed that measures of steering error and smoothness can effectively describe the different steering strategies being used by individual participants. The group data also provide useful baseline measures (error = 0.2 m, smoothness = 27.7°/s/s) for optimal visual conditions. Gaze recordings revealed systematic patterns of gaze behavior whereby gaze was primarily directed toward the most immediate slalom gate with fixation moving onto future gates when it became necessary.

Experiment 2: Manually Adjusted Gaze Fixation

Natural gaze behavior is highly dependent on the complexity of the task and the resources that need to be brought to bear. For example, cycling at high speed down a mountain bike track is a taxing task with very little room for error. In this situation, gaze fixations tend to be brief, efficient, and directed to rapidly pick up information crucial to the current steering maneuver. It is not easy to simulate such a time-critical steering task while retaining tight behavioral control. In the free-gaze condition (Experiment 1), even though only one pair of gates could be fixated at any one time, saccades could be made between gates (gaze polling) to help set a smooth line for gates further down the course. In this experiment, we wanted to establish the "comfortable" temporal pattern for gaze shifts between slalom gates, without the potential confound of gaze-polling strategies. More specifically, we wanted to know when the near-steering obstacle was no longer required for comfortable steering.

To examine the timing of comfortable gaze shifting, we presented the same slalom course as for Experiment 1 but ensured that only one gate was visible at any time. We then made it possible for participants to adjust the distance at which the nearest gate (G_n) disappeared, at which time the next gate (G_{n+1}) in the series simultaneously appeared. We might expect increased steering precision when passing through gates that remain visible for longer (switched late) because there would be more time to ensure correct alignment; however, this would also restrict the advance information about the location of the next gate, and so could have an impact on smooth splining of the trajectory between waypoints. In contrast, increasing the distance at which the near gate (G_n) disappeared would mean that G_{n+1} would become visible sooner, which might allow a smoother path to be followed, but with the possible consequence of some alignment errors when passing the invisible G_n. We examine the final clipping distance setting for each trial as chosen by participants to establish the comfortable gaze-switch time when shifting gaze from the immediate slalom target to the next gate in the slalom.

Method

The slalom course was laid out in the manner outlined in the General Method section except that only one slalom gate was visible at a time. The participant used handlebar index buttons to adjust the distance at which the nearest gate (G_n) disappeared, at which time the next gate in the series (G_{n+1}) simultaneously appeared. By depressing the left button, the participant could gradually reduce the clipping distance so that G_n disappeared later on the approach and could therefore be tracked for longer. In contrast, depressing the right button increased the clipping distance with the opposite effect. The 8 participants from Experiment 1 took part in 16 trials, with each trial starting with gates at a random clipping distance. They steered through a slalom course for 37.5 s and passed through an average of nine gates. The participants adjusted the clipping distance over the course of the trial so they were comfortable when the near target disappeared and the next target simultaneously appeared. The clipping distance at the end of each trial was taken as the participant's judgment. Steering smoothness was calculated as described in the General Method section.

Results and Discussion

Figure 5 presents the mean lead time at which participants chose to switch their gaze to the next slalom gate in the series (e.g., causing G_{n+1} to appear and G_n to disappear). The mean times are shown in the figure, bracketed by the maximum and minimum switch times chosen by each participant. Taking 1.45 s as an

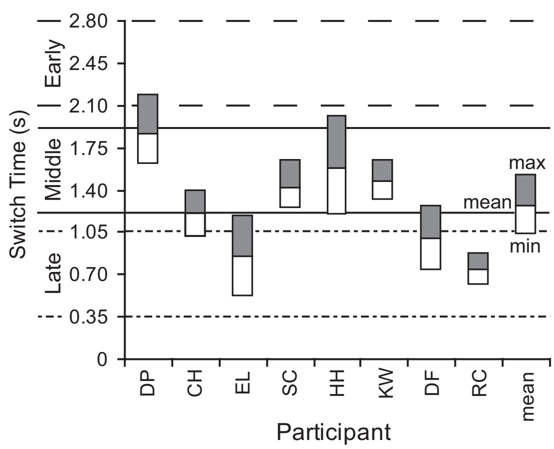

Figure 5. Mean preferred switch times for 8 participants. The maximum (gray bar) and minimum (white bar) switch times chosen by each participant are also shown to represent the range of comfortable fixation zones. The switch times were adjusted by the participants to match their preferred gaze switching during the slalom steering task. There is some variation between participants, with some preferring earlier switch times (e.g., DP) and some later (e.g., EL). The vertical axis also shows the bands of switch times (late, middle, and early) as used later in Experiments 3 and 4 when switch times were enforced.

approximate midpoint for these responses, it appears that EL, DF, RC, and CH switched to G_{n+1} later than 1.45 s. Participant DP switched to G_{n+1} earlier than 1.45 s, and the other participants (KW, SC, and HH) fell within the 1.45-s window. It is not necessarily the case that these individuals make up three distinct groups because they are neither homogeneous in mean or range; however; the differences in steering performance between individuals such as DP and EL (as noted in Experiment 1) may well be linked to their preferred steering strategy. This is illustrated in Figure 3, in which DP's steering line appears to be adjusted toward G_{n+1} at an early stage in the approach to G_n. We can examine these characteristics more closely by calculating how rapidly the participant turned the wheel to make steering corrections. If participants leave their steering adjustments until they are close to the gate, then they will need to implement a higher rate of change to steering, which in the natural world would incur increased lateral forces and the potential to skid. A more conservative early turn need only be implemented with a lower rate of change of steering. We calculated the acceleration of steering adjustments (in °/s/s) for the trajectories leading up to each gate for all trials and participants and then performed a correlation with their degree of look-ahead (indicated by the chosen switch time for each trial). There was a small but significant negative correlation ($r = -.13$, $p < .01$), indicating that trials that exhibited greater rotational accelerations were associated with a near looking strategy (late switch times). We then grouped the rate of change of steering for trials on which switch times were chosen to be late (<1 s), middle (1–1.45 s), and early (>1.45 s). This resulted in three bins with approximately equal numbers of trials in each (42, 49, and 44 trials, respectively), although these were sampled unequally across participants (because the switch times were controlled by the participant). Late-switch trials showed the least smooth steering (31°/s/s), and although early switching was only slightly more smooth (29°/s/s), middle switching resulted in the smoothest steering (25°/s/s).

Experiment 2 showed that on average participants felt comfortable switching their gaze from the current slalom gate to the next gate around 1–1.5 s before the target was reached. Individuals' preferred switch times did vary, however, with earlier gaze switching being linked to smoother steering performance.

Experiment 3: Constrained Gaze Fixation

In Experiment 2, the participant's primary goal was to manually adjust the switch time of the slalom gates into a comfortable spatiotemporal zone. Steering performance was therefore not the primary task, although this was clearly being carried out to some degree in parallel with the manual control of switch timings. In Experiment 3, we wanted to examine in detail the effect of different switch times when steering through the slalom course and look specifically at whether enforced switch times influenced accuracy and smoothness of steering behaviors.

The steering errors that occur when obstacles are only visible within certain temporal ranges should demonstrate the limits of the system for steering accurate paths. In Experiment 2, all participants fell within the 0.75-s to 2-s zone for mean switch-time preference. The closest clipping distance of the slalom gates (when gates left the bottom of the screen) was 0.35 s, so for Condition 1 of Experiment 3, we grouped the switch times using the following time-to-passage (TtP) bands: late (0.35- to 1.05-s TtP), middle (1.225- to 1.925-s TtP), and early (2.1- to 2.8-s TtP). We anticipated that when enforced, these bands would cause selective changes to steering behavior, with greater positional errors linked to early switch times (greater look-ahead) than late switch times (less look-ahead). We then planned to probe the cause of any steering errors by running two further conditions in which additional information was available. In Condition 2, we added peripheral information about the position of the (previously invisible) near target that would allow us to examine the role of information available from unfixated sources. A comparison of steering performance with and without peripheral information would indicate the impact of visual direction information specified in the retinal periphery (and not extraretinally via fixation). In Condition 3, we relaxed the fixation requirement and allowed the participants to look back to targets that had disappeared. The aim was to allow participants to exercise any buffered information by using active gaze fixation to maintain and update any stored representation of the near (invisible) gate. Comparison of steering performance between Conditions 1 and 3 should permit us to demonstrate whether allowing a remembered spatiotemporal location to be revisited with gaze can enhance steering behavior.

In addition to steering errors, we were also able to examine measures of steering smoothness, and these could be influenced by a number of factors. A previous study that examined steering along simulated roadways showed that far-road information was associated with maintaining a smooth locomotor path, and near-road information ensured successful lane keeping (Land & Horwood, 1995). On this basis, we might predict reduced smoothness when gaze was switched to future targets late in the trajectories. This would be broadly in line with the results from Experiment 2 (conceding the limitations of the measure in that experiment). These slalom conditions are not directly comparable to on-road steering, however, because there is no equivalent to the near-road error signal available on roads. Paths that are taken without the constraints of a continuous road edge are by their nature more free form, and as was shown in Figure 3, it is usually possible to carry out sufficient steering either further from or nearer to each slalom gate and still successfully complete the task. Although we might predict that late gaze-switching conditions should be less smooth than when gaze switches earlier in the trajectory, we would also expect these differences to be relatively small.

Method

Condition 1: Target removal. Using the general method, we presented participants with the same basic slalom course layout as in Experiments 1 and 2, but in this case the switch times were preprogrammed and controlled by software. Participants were required to look at the fixation mark lying at the center of the visible gate (G_n) and switch their gaze to the fixation mark on the next target (G_{n+1}) when G_n was removed from the scene. They were also instructed to steer as accurately and as smoothly as they could through the slalom course. They were presented with a block of six trials for each of the three bands (early, middle, or late switch times), with block order randomized across participants. For each slalom gate, the precise switch time was randomly picked from within the range of that band to prevent predictive preemptive gaze switching.

Condition 2: Color-cued switch. To determine whether unfixated peripheral information was useful for accurate steering, we repeated Condition 1, but instead of forcing a target switch by removing G_n, we prompted the participant to look at G_{n+1} by means of a color change. Participants were required to fixate the set of gates that were presented in red. Compliance with the fixation requirement was assessed by monitoring gaze, using the ASL 504 eye-tracker output overlaid on the visual scene. If unintentional saccades took place, the participant was reminded of the fixation requirements. The same switch times were induced as in Condition 1, but the unfixated (near) target remained available in peripheral vision.

Condition 3: Target removal with free gaze. Finally, we also repeated Condition 1 (in which G_n was removed and G_{n+1} appeared at a preprogrammed time), but participants were allowed free gaze to fixate as they wished (although no additional instructions were given as to where to look or when). This meant that if they wanted, they could try to fixate the ground where G_n used to be even after it was no longer visible, although, of course, this would mean that G_{n+1} was not foveated.

Results and Discussion

Figure 6 presents the change in steering errors (the passing distance from midway within each slalom gate) for conditions in which the participants negotiated the slalom under different enforced switch times. There was a general increase in gate alignment errors as participants were pushed toward earlier switch times under Conditions 1 and 3, but apparently not under Condition 2, for which peripheral visual information was available. Binned into the three bands of early, middle, or late, a two-way analysis of variance (ANOVA) of Switch Time × Condition (3 × 3) for steering errors confirmed that there was a significant influence of switch time on steering error, $F(2, 14) = 41.18$, $p < .001$, $\eta^2 = .86$; a significant change in error resulting from condition, $F(2, 14) = 23.15$, $p < .01$, $\eta^2 = .77$; and a significant interaction, $F(4, 28) = 22.51$, $p < .001$, $\eta^2 = .76$.

A closer look at the steering errors when peripheral information was available (Condition 2) shows there was a small but signifi-

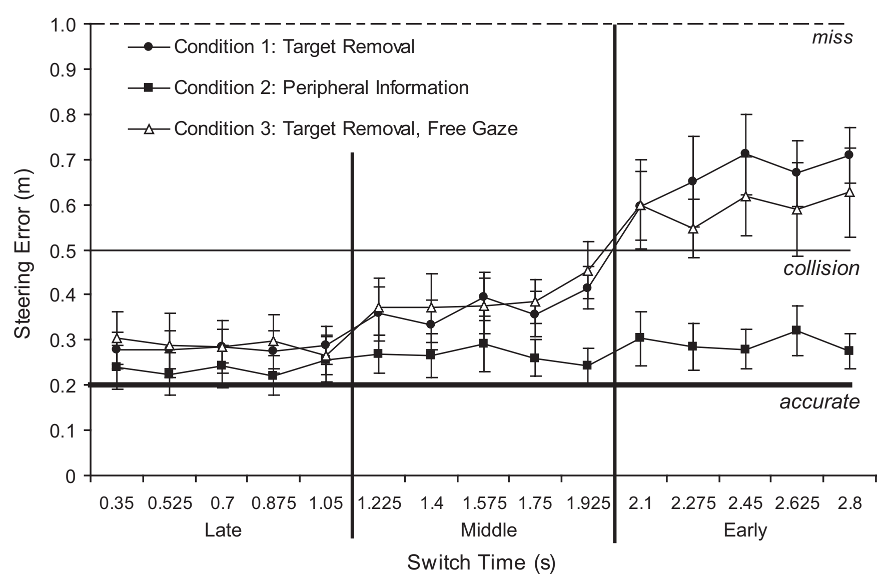

Figure 6. Steering errors when negotiating individual slalom gates for three viewing conditions at a variety of enforced fixations (Experiment 3). The horizontal reference lines indicate three levels of error. Errors are measured from the center of slalom gates (1 m wide). An error of 0.5 m would result in a potential collision with a gate (thin solid line), and an error of more than 1 m would be a complete miss of the gates (dashed line). Good steering performance when gaze was unconstrained and all slalom gates were visible (Experiment 1, Condition 1) resulted in errors of about 0.2 m, which is represented as a constant baseline (bold line).

cant, $t(7) = 2.53$, $p < .05$, increase in errors for the earliest switch times compared with the latest switch times (equating to a distance of approximately 0.36 m from the gate midway). This indicates that even though peripheral information had a strong influence on maintaining accurate performance, active fixation also played a role in accurate locomotion. Because of this, we may have expected an improvement under free-gaze conditions (Condition 3), in which gaze could be directed to the most appropriate point in the scene. No improvement was evident except at the earliest switch times. We took the average error for each participant across the four earliest switch times (2.275–2.8 s) and found that this was significantly reduced when gaze was free, $t(7) = 1.92$, $p < .05$. The large variability (demonstrated by the size of the standard error bars) was partially because of the differential effects of free gaze. Two participants (DP and CH) who exhibited the smallest errors (approximately 0.4 m) for early switch trials during Condition 1 showed no improvement with free gaze, whereas those exhibiting larger errors (approximately 0.5–1 m) showed an average improvement of 0.11 m. The results from Conditions 2 and 3, therefore, indicate that both peripheral vision and active gaze fixation contribute to successful control of steering.

Examination of how steering smoothness changes across each switch time can be achieved by calculating steering acceleration (°/s/s). Collapsing smoothness measures into late, middle, and early switching shows that for Condition 1, there seemed to be an advantage of early and middle switching (*M*s = 28.4 and 27.6°/s/s, *SD*s = 2.6 and 2.3, respectively) over late switching ($M = 29.3$°/s/s, $SD = 2.6$). Comparison with Experiment 1 ($M = 27.7$°/s/s) indicates that as predicted, late switching reduces smoothness. A one-way ANOVA revealed a marginal effect, $F(2, 14) = 3.58$, $p = .056$, $\eta^2 = .34$, linked to a significant increase in steering acceleration (decrease in smoothness) for late-switch times compared with middle-switch times, $t(7) = 2.83$, $p < .05$. No differences in steering smoothness were found across switch times for Conditions 2 and 3, with an average smoothness of approximately 28°/s/s. This indicates that although there may be some disadvantage for late gaze switching in terms of steering smoothness when information is tightly controlled, this disadvantage vanishes when additional information becomes available from either free eye movements or peripheral view of slalom gates.

Summary. Experiment 3 shows that experimentally manipulating when participants switch their gaze from the current steering target to the next causes systematic changes to steering performance. Steering errors increase as switch times become earlier, but providing additional peripheral or free-gaze information mediates the increase in errors. This indicates that both peripheral vision and active gaze fixation contribute to successful control of steering. When these sources are absent, it also appeared that (as in Experiment 2) smoothness decreases for late switching in comparison to earlier switch times.

Experiment 4: Multitasking While Steering

Method

Condition 1: Monitoring signposts. The previous experiments examined various permutations of fixating parts of the slalom course with or without additional retinal or extraretinal information. However, these conditions did not indicate whether it is the angle of gaze and foveation of the future steering target that is important or the successful tracking of this target that supports the steering maneuver that is being carried out. The results from the peripheral information trials (Experiment 3, Condition 2) may suggest that foveation, per se, is relatively unimportant, so here we tested this more directly. We repeated the basic paradigm described in Experiment 3, Condition 1, but with an alternative fixation requirement. This fixation ensured that an appropriate gaze rotation ($\dot{\alpha}$) signal was available for controlling steering; however, the absolute gaze angle (α) was biased. The pattern of steering errors will inform whether α is an important informational input and also whether $\dot{\alpha}$ can be sufficient for accurate steering control.

A signpost was rendered near to the slalom gate, on the horizon, offset horizontally by either 7° or 14°. This offset was always toward the “inside” of the slalom, to the right of leftward gates and the left of rightward gates (relative to the z-axis). As the slalom gate moved on the screen relative to the observer, so the signpost was shifted to maintain a constant horizontal offset from the gate on the screen. When G_n was made invisible, the signpost was moved to be positioned with the same offset from the now visible G_{n+1}. Fixation of the signpost ensured that the rate of change of horizontal gaze angle was the same as would have been experienced if fixating the visible gate, but with a constant error in the absolute angle of visual direction. This also prevented the steering target from being foveated. Two angular offsets (7° or 14°) were used for this experiment, interleaved randomly. This condition is similar to the real-world situation of looking at a signpost except that the sign did not increase in size, nor did it move vertically in the scene. The rationale for omitting vertical movement of the sign was twofold. First, positioning the sign over the ground would have obscured texture elements that could contribute to the retinal flow information used to control steering, so any impairment in steering would be difficult to interpret. Second, in pilot work we found that the task of refixating the signpost was very difficult when the sign moved vertically because of the need to search the scene visually and locate the new sign before refixation. Even without vertical motion, the fixation requirements were potentially tiring, so to prevent fatigue a short rest was given halfway through the trials, with each block lasting 16 min.

Condition 2: Judging arrival time. We also wanted to examine the amount of effort required to maintain any internal representation of the position of the slalom gates and to probe the possible units of storage. We repeated the target removal condition of Experiment 2 and asked each participant to indicate (with a button click) when they thought that they had passed through or by the slalom gate while continuing to steer as normal. This would supply an explicit measure of where the participants believed G_n to be when fixating G_{n+1}. It would also act as a secondary task, tapping cognitive resources and forcing attention to be directed toward the invisible steering target. To ensure participants’ gaze did not follow the target, their gaze behavior was monitored, and if unintentional saccades took place the participant was reminded of the fixation requirements.

Results

Figure 7 shows steering errors averaged across 8 participants. Errors are shown across switch times for the two conditions in Experiment 4 (signpost and TtP) and for the standard target removal condition from Experiment 3 for comparison. Steering performance in the TtP button-press task matched previous performance well, with the same general increase in gate alignment errors as switch times became earlier. The signpost fixation task presented an offset fixation target in addition to clipping the slalom course, as in the other condition. Two signpost offsets were used, but there were no consistent differences between them so data were pooled across both conditions. Signpost fixation markedly impaired performance across all switch times compared with equivalent trials when fixating the future target gate. For middle switch times, fixating an offset target increased errors to cause a collision with the gates; for early switch times, it raised errors into a complete miss of the gates. For analysis, we recombined the switch times into the three original bands in which they were presented during trials: late (0.35- to 1.05-s TtP), middle (1.225- to 1.925-s TtP), and early (2.1- to 2.8-s TtP). A two-way ANOVA of Switch Time × Condition (3 × 2) for steering errors confirmed that there was a significant influence of switch time on steering errors, $F(2, 14) = 42.53$, $p < .001$, $\eta^2 = .86$; a significant change in errors resulting from condition, $F(1, 7) = 16.83$, $p < .01$, $\eta^2 = .71$; and a significant interaction, $F(2, 14) = 13.39$, $p < .01$, $\eta^2 = .62$. These analyses show that not only was steering influenced more by the signpost condition than by the TtP condition, but that errors were differentially elevated at middle and early switch times in signpost conditions.

We also examined a measure of steering smoothness by considering the rate of change of steering (°/s/s). The data showed that rotational accelerations increased for later switch times. A two-way ANOVA revealed that the main effect of condition was not significant, $F(1, 7) = 1.34$, *ns,* $\eta^2 = .16$; however, both switch time, $F(2, 7) = 20.62$, $p < .01$, $\eta^2 = .58$, and the interaction were significant, $F(1, 7) = 7.67$, $p < .01$, $\eta^2 = .52$. We examined the interaction further by carrying out a one-way ANOVA on each condition independently. The effect of switch time on smoothness was greatest in the signpost conditions (late = 29.9°/s/s; middle = 28.03°/s/s; and early = 26.4°/s/s), and the one-way ANOVA was highly significant, $F(2, 14) = 11.31$, $p < .001$, $\eta^2 = .62$. A similar pattern was seen in the TtP condition (late = 29.7°/s/s; middle = 28.22°/s/s; and early = 28.9°/s/s), although the effect was smaller, $F(2, 14) = 4.25$, $p < .05$, $\eta^2 = .38$.

To investigate further how target location may be represented by the steering system, we examined how well participants explicitly judged their TtP of the slalom gate. First, we analyzed steering errors to see whether the secondary task impaired steering performance and found no differences between steering errors during conditions with or without additional TtP judgments, $F(1, 7) = 0.11$, *ns,* $\eta^2 = .015$. The actual TtP judgments appear to be reasonably accurate (Figure 8); however, it is clear that there is a gradual increase in errors as switch times become earlier. The temporal errors observed here (when moving at 8 m/s) equate to a spatial error of about 1.2 m for the latest switch time (look-ahead of 0.35 s) and about 3.1 m for the earliest switch time (look-ahead of 2.63 s), with a bias toward responding early. In fact, all the participants except 1 made early TtP responses in this task, and this

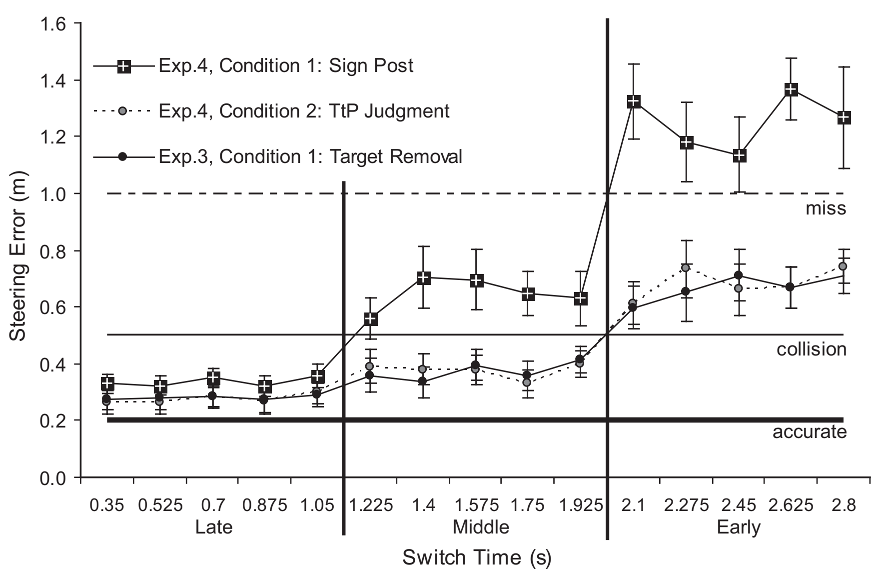

Figure 7. Steering errors when negotiating slalom gates for three viewing conditions at a variety of enforced switch times: target removal (Experiment 3, Condition 1); target removal with a time-to-passage (TtP) judgment task (Experiment 4, Condition 2); and fixating a signpost offset from the steering target (labeled *Sign Post*; Experiment 4, Condition 1). Errors are measured from the center of slalom gates (1 m wide). An error of 0.5 m would result in a potential collision with the gate (thin solid line), and an error of more than 1 m would be a complete miss of the gate (dashed line). Average steering performance from Experiment 1 when gaze was unconstrained and all slalom gates were visible resulted in errors of about 0.2 m (bold line). Exp. = Experiment.

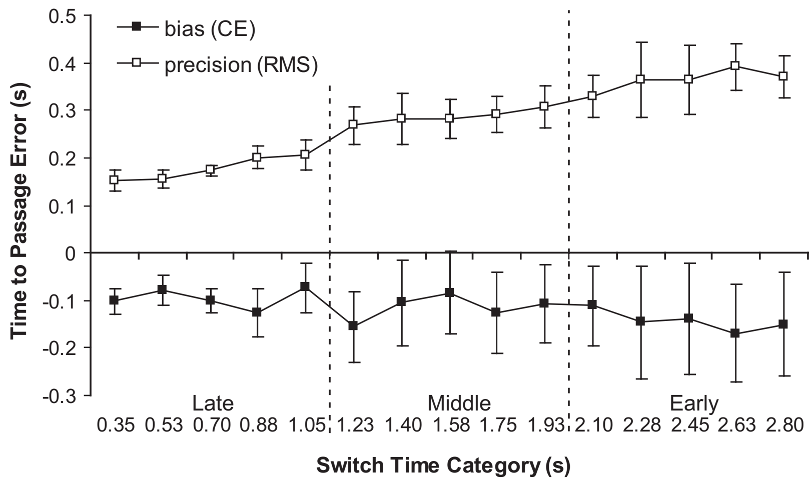

Figure 8. Errors in time-to-passage (TtP) judgments when steering via slalom gates at a range of switch times. Data shown are averaged across 8 participants, with the bars indicating standard errors across the group. Open symbols show root-mean-squared error (RMS), which provides a measure of precision. The closed symbols show the mean constant errors (CE), with negative values indicating the TtP judgment made before passing the steering gate (i.e., an early response).

is reflected in the negative bias apparent in their judgments (Figure 8). The increase in the size of standard error bars for earlier switch times reflects the increase in variability between participants, which may also be related to increased uncertainty in judgments.

Discussion

The increase in steering errors in the signpost condition showed that a steering target provides more useful information when it is properly fixated. There was, however, a marked improvement in performance as switch times became later and buffer times decreased, suggesting that an appropriate gaze-rotation signal on its own still contributes significantly to steering. The vertical angle of gaze remained constant during signpost fixation (unlike target fixation), and for late switch times this may explain the difference in the size of steering errors between Conditions 1 and 2. It is, however, unlikely that the increase in errors for signpost fixation at middle and early switch times can be explained by this missing vertical gaze component. The signal difference from the vertical angle of gaze at the early switch times (fixating obstacles approximately 2–3 s ahead) will be relatively small compared with late switch times (<1 s ahead); however, the size of steering errors increased markedly. The results show that the availability of $\dot{\alpha}$ in addition to a limited (peripheral) source of α are insufficient to support accurate steering except at late switch times. We therefore propose that both visual direction information (α supplied by the fixation) and gaze rotation ($\dot{\alpha}$) are used during active steering.

Summary. Experiment 4 confirms the main pattern of results observed in Experiment 3, in that both the signpost and the TtP conditions cause steering errors and smoothness to increase as switch times become earlier. In addition, the signpost condition reveals that the direction of gaze has a powerful influence over steering accuracy. When gaze is offset from the direction of the steering target (and moves at an appropriate horizontal rate), this markedly increases the magnitude of steering errors. As gaze switching occurs earlier, the increase in steering errors grow, until at the earliest switch times errors are twice as large as when fixating the steering target. The TtP condition provided additional information about the properties of the internal representation of gate location. Participants were able to explicitly identify the location of the (invisible) gate; however, accuracy was poorer than behavioral measures, suggesting that behavior is not driven by a cognitively penetrable representation of gate location.

General Discussion

We carried out a series of experiments to identify the crucial spatiotemporal characteristics of gaze sampling when negotiating a slalom course containing multiple steering targets. To help compare results across these experiments, we plotted the mean steering error for each of the conditions (Figure 9). Baseline performance when all slalom gates were visible and gaze was free resulted in errors of 0.2 m (shown on the graph as the bold horizontal line labeled *accurate*). The standard target removal condition, in which gaze was directed toward a single slalom gate with no view of the other gates, is indicated on the graph with filled black bars (target removal). Steering performance across all switch times under target removal conditions was poorer than baseline, with errors gradually increasing as switch times became earlier. Early switch times (>2 s) caused steering errors that would have resulted in actual collisions with the slalom gates, demonstrating a lack of accurate buffering of gate position for such long time periods. Matched conditions when TtP was indicated with a button press (TtP judgment) showed a similar pattern despite the additional cognitive load. The third constrained gaze condition made additional near peripheral information available (i.e., the near gate did not disappear when refixating on the next gate; this is labeled *peripheral information* on the graph), and this improved steering performance considerably. This shows that a peripheral view of road obstacles can provide an important cue to steering. Interest-

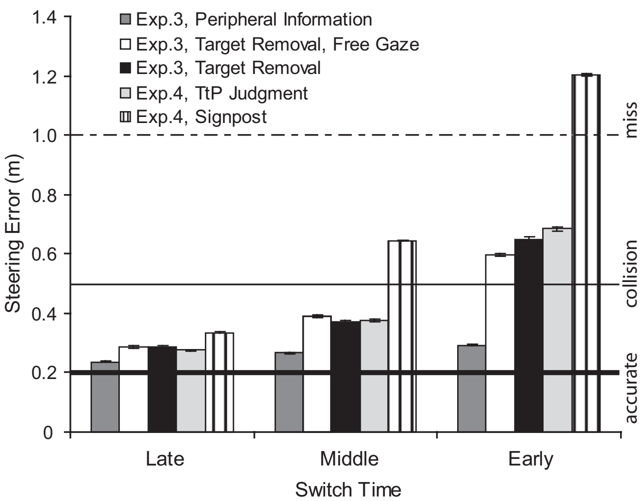

Figure 9. Three groupings of switch times are shown: late (0.35–1.05 s), middle (1.225–1.925 s), and early (2.1–2.8 s). These switch times are when the current steering and fixation target (slalom gate G_n) disappears and fixation is directed onto the next target (slalom gate G_{n+1}). The participant is instructed to take a path via the gate that is no longer visible, despite fixation on the next gate. Exp. = Experiment; Ttp = time-to-passage.

ingly, under these conditions there was evidence of degraded performance at earlier switch times, which took gaze away from the most immediate target. This can be most easily seen by examining the small increase in errors compared with the accurate baseline in late switching and then contrasting that with the larger increase in errors for early switching. This statistically significant difference shows that foveation of the target does have added value for improving steering accuracy even when peripheral monitoring is possible.

To see whether active gaze could aid steering in the absence of peripheral information, we ran conditions when gaze was unconstrained (target removal, free gaze conditions, white bars). These conditions did not change steering in late and middle switch times despite the freedom to refixate the remembered position of the slalom gates that had been removed if the participant wished. There did seem to be some advantage of free gaze for the earliest switch times, which suggests that gaze can help in coarse spatiotemporal localization of a hidden target, although not with pinpoint accuracy.

The final condition (signpost, striped bars) re-presented the task from Experiment 3, Condition 1 (no peripheral information for near targets), but also introduced an offset fixation target. Fixating the offset target markedly impaired performance across all switch times compared with equivalent trials when fixating the gate. For middle switch times, fixating an offset target raised errors to cause a collision with the gates, and for early switch times, it raised errors into a complete miss of the gates. These results tell us two things: First, the angle of gaze (α) does contribute to steering accuracy, and it is therefore crucial to include it in any model of steering control. Second, the evidence also suggests that sources that provide information about the rate of rotation relative to gaze position are also used, as is proposed in Equation 4.

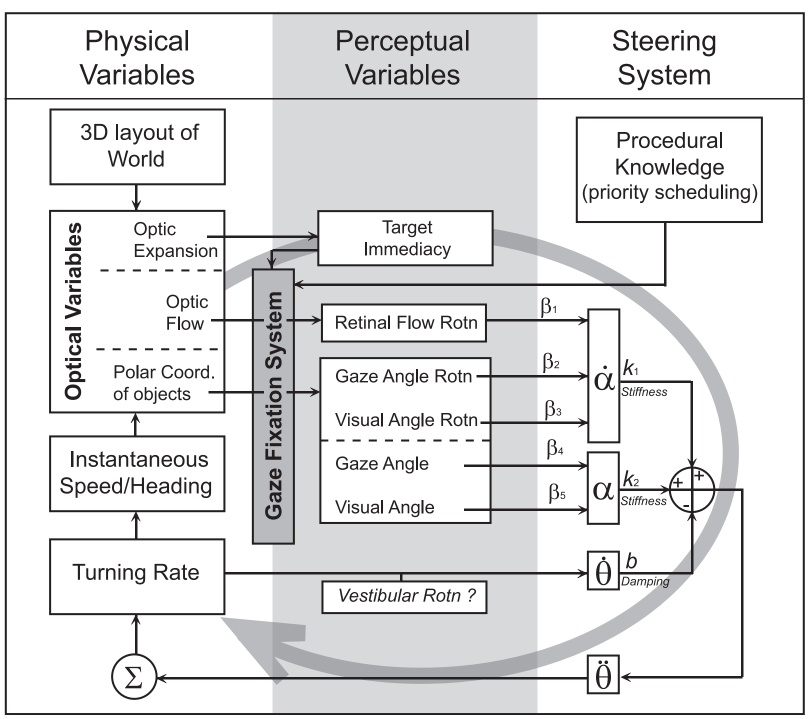

Figure 10. A model of locomotor steering centered on the active gaze fixation system. Gaze fixation is driven by the immediacy of upcoming targets or obstacles and may also be shaped by experience (procedural knowledge of where to look and when). The steering module responds to the specific visual motion components that result from fixation (see Wann & Wilkie, 2004, for further explanation). Coord. = coordinates; Rotn = rotation.

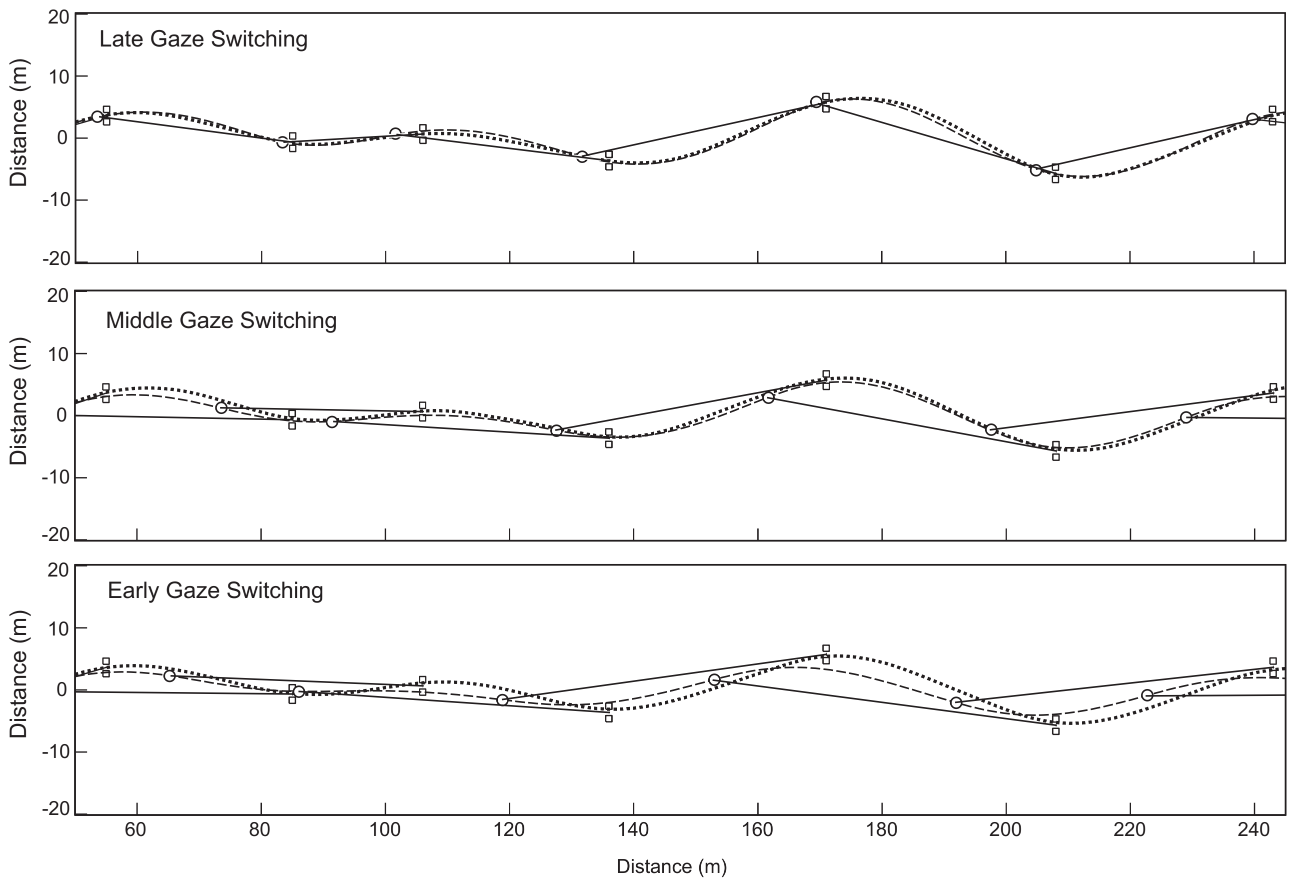

Figure 11. A plan view of steering paths through a slalom course with different switch times (as in Experiment 3, Condition 1, target removal). Open squares indicate the size and location of slalom gates. Dotted curved paths show single example trials for participant CH, whereas dashed paths demonstrate those taken by the extension of the Wilkie and Wann (2002) model put forward in this article (Equations 3 and 4). Open circles mark the position at which gaze switches from one slalom gate to the next. Solid straight lines connect the open circles to the new gaze being fixated. The top panel shows paths with late gaze switches (<1 s), the middle panel shows paths with middle gaze switches (1–2 s), and the bottom panel shows paths with early gaze switches (>2 s).

In Figure 10, we schematically represent the flow of information from perception through to action to generate the behavior characterized by Equation 4. Gaze fixation shapes the information (optical variables) arising from the three-dimensional scene. The perceptual system can weight and combine information on the basis of experience or changing conditions (Wilkie & Wann, 2002). The resultant steering response alters the optical variables of the scene, and the steering loop repeats. Within this scheme, target immediacy is a variable that may be detected from object looming or through changing height in the scene, but in general observers have few problems discerning which road feature they will pass first. We allow procedural knowledge to act to specify the priority of each approaching feature and shape the gaze sampling. We also allow for vestibular inputs to shape the detection of $\ddot{\theta}$, although our previous study found that incorrect vestibular stimulation (with locomotor speeds of 8 ms^{-1}) had little effect on steering accuracy (Wilkie & Wann, 2005).

The general patterns of data suggest that steering is driven by perceptual correlates of α and $\dot{\alpha}$, but the findings do not exclude the possibility that some representation of the spatiotemporal location of target may be required when switching early to more distant targets. We have two reflections on this. Any such representation seems to have a limited lifespan, and the steering errors gradually increase for longer look-ahead periods. First, broadly, participants preferred a buffer period of about 1.5 s, whereas temporal periods of more than 2 s generally resulted in collisions with the slalom gates. Second, within this 2-s window, the need for an internal spatial representation to maintain steering when gaze is switched ahead is debatable. Wann and Wilkie (2003) presented the effect of different gaze-switching times, in effect changing the priority scheduling in Figure 10 to effect earlier or later fixation of future steering targets. This is reproduced in Figure 11, in which trajectories are shown from a single participant steering with three different sets of switch times (as described in Experiment 3, Condition 1) compared with the trajectories taken by the model proposed in Equation 4 when fixating gates at switch times identical to the participant's. The top panel of Figure 11 shows the trajectories that result when gaze is maintained on the most immediate target as in late switching conditions (between 0.35 and 1.05 s ahead). The middle panel shows switching gaze to a future target when the most immediate target is between 1.225 and 1.925 s ahead, and the bottom panel shows early switching when gaze is moved ahead between 2.1 and 2.8 s before the most immediate target is passed. What can be seen is that the steering exhibited by the model remains acceptable when the gaze lead is less than 2 s and only starts to miss the gates at more than 2-s gaze lead. There is no spatiotemporal storage of target locations in this model, and it operates purely on instantaneous perceptual parameters as in Equation 4. The tolerance for gaze switching results from the balance between the stiffness and damping terms (k and b in Equation 4) that are necessary to make the model stable and suppress oscillatory behavior (these values were kept constant for all the modeled paths in Figure 11). However, the balance between stiffness and damping also results in a certain degree of momentum in the steering output. The observer will carry on toward a previously fixated target for a period of time, even when gaze is switched elsewhere. This tradeoff is fortuitous because it allows gaze to be directed ahead by 1-2 s, as recommended by some advanced driving guides and as observed in previous research (Land & Lee, 1994; Wilkie & Wann, 2003b) without the need for a buffered representation of targets previously fixated, but not yet passed.

The information contained in advanced driving manuals is not scientific data, but it represents a different class of knowledge that has been distilled through extensive practice in real-world settings, in which the strategy adopted has critical consequences. It is satisfying when lab-based theory converges with experience-based heuristics. The model we have presented seems to meet this litmus test. Guides such as that of Ienatsch (2003) recommend fixating on key waypoints in the road and "ripping" gaze up to new waypoints as you progress. They also warn against allowing your gaze to settle on a hazard such as a crack or stone lest you be drawn toward it. These strategies have been refined through real-world experience, but this does not provide an explanation for why these gaze strategies work. The steering control algorithm in Equation 4 and the schematic in Figure 10 provide a formal basis for explaining the "go-where-you-look" strategies. In addition, our current work is also documenting the neural systems engaged in delivering the online control of steering (Field, Wilkie, & Wann, 2007). An important feature of the proposed flow of information (Figure 10) is that there is room for task-specific knowledge to influence the manner in which fixations are used to sample from the scene. This accounts for an experienced cyclist's successfully taking the racing line around a hairpin bend compared with following the lane on the motorway. Each situation requires that you bring to bear your knowledge of the environment, the locomotor device, and the most appropriate fixation strategy for those conditions.

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