Visual control of steering in curve driving

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This pair of studies investigated steering in the absence of continuous visual information. In a driving simulator, participants steered a curving path that was displayed either continuously or intermittently. Optic flow conditions were manipulated to alter the nature of the heading information with respect to the path being steered. Removing or biasing heading information had little effect on steering even during long and frequent path occlusions as long as turn rate was available. This demonstrates that participants can use intermittent views of the path to plan their steering actions and optic flow to accurately update vehicle turns with respect to that path.

Introduction

A fundamental skill in driving is steering with respect to a path. Quite often, curved trajectories are preferred or necessary, such as when driving on a winding road. The purpose of the present study was to investigate the role of visual feedback in the task of steering a curving path. Drivers are often required to maintain steering control while performing other visual tasks. For instance, they might sample their path intermittently while looking at traffic, road signals and signs, passengers, scenery, or electronic devices (e.g., audio controls, cell phones, navigation systems, etc.). Thus, visual feedback from the path is often intermittent rather than continuous. Drivers may also encounter situations for which they have optic flow information in the form of ground texture, but the path is not visible. This could occur with faded path markings, or when drivers look away from the road but still have optic

flow available in the periphery. Here we were specifically interested in the role of visual feedback from optic flow when views of the path were intermittently occluded.

Visual information for steering

Heading based upon optic flow variables has previously been implicated in steering curved paths toward a stationary target (e.g., Fajen & Warren, 2000). Gibson (1950, 1958) first proposed the solution that locomotor behaviors could be carried out on the basis of optic flow information. Optic flow has been defined as the changing angular positions of environmental points caused by any relative movement between the observer and the environment. While some researchers have followed in Gibson's footsteps, heralding optic flow as the dominant cue for locomotion (Fajen & Warren, 2000; Li & Chen, 2010; Warren, 1998; Warren, Kay, Zosh, Duchon & Zahuc, 2001; Zhao & Warren, 2015), others have disputed the privileged status of optic flow as a determinant in the visual control of locomotion (Beall & Loomis, 1996; Loomis & Beall, 1998; Loomis & Beall, 2004; Loomis, Beall, Macuga, Kelly, & Smith, 2006; Macuga, Loomis, Beall, & Kelly, 2006; Rushton, Harris, Lloyd & Wann, 1998; Salvucci & Gray, 2004; Wann & Land, 2000). One proposed alternative to the heading-based optic flow strategy is the active-gaze-based strategy, developed by Wann and colleagues (Wann & Swapp, 2000; Wilkie, Kountouriotis, Merat, & Wann, 2010; Wilkie & Wann, 2002, 2003, 2006; Wilkie, Wann, & Allison, 2008), whereby one can fixate the intended path, judge the steering error based upon the curvature of ground

element trajectories, and then reorient the ground trajectory toward the target. Thus, the steering of curved paths can be executed without having to recover translational heading from optic flow. However, when others have compared these two approaches in paradigms that examined perceived future path judgments, they found evidence in favor of a heading-based optic flow strategy (Li & Cheng, 2011; Saunders & Ma, 2011). It is possible that the tasks of steering toward a target or making perceptual judgments may be guided by different sources of information than the active steering of curving paths. In fact, Kountouriotis & Wilkie (2011) have revealed differences between heading judgments and active steering under degraded visual conditions. Another proposed gaze-based alternative was based on the discovery that drivers often direct their eyes to the tangent point when steering curving roads (Land & Lee, 1994). Boer (1996) presented a tangent point-oriented model that uses distance to the tangent point and heading relative to the tangent vector to control steering. For this model, the driver must identify and track the tangent point. However, more recent work questions the generality of the tangent point strategy, and suggests that drivers fixate and use their future path instead to steer curving paths (Itkonen, Pekkanen, & Lappi, 2015; Lappi, 2014; Lappi, Lehtonen, Pekkanen, & Iktonen, 2013). Finally, several prominent driver steering models have been based on far and near road regions (Donges, 1978; Kountouriotis, Floyd, Gardner, Merat, & Wilkie, 2012; Salvucci & Gray, 2004), with the far region used for predictive control and the near region used for feedback control. However, the quality of the visual input may determine how the information from these regions is combined (Frissen & Mars, 2014). As such, an important and unresolved question is what visual information guides the steering of curving paths. Furthermore, none of the aforementioned studies have addressed or attempted to explain steering behavior in the absence of continuous visual feedback.

Steering in the absence of continuous visual feedback

Godthelp (1986) established that steering a vehicle over a constant curve could be performed well even when vision was occluded just upon curve entry. Similarly, Cavallo, Brun-Dei, Laya, and Neboit (1988) occluded vision at different stages of the curve and found that visual feedback was not necessary during curve entry. However, they demonstrated that such feedback became necessary for accurate steering toward the end of the curve. Hildreth, Beusmans, Boer, and Royden (2000) conducted experiments in a driving simulator, in which they assessed steering performance during periods of visual occlusion while participants performed a simple lane correction, and then developed steering models to account for their data. Participants performed accurately with a short 1–2 s occlusion at the start of the steering maneuver. However, longer occlusions produced a marked decrease in lane correction performance. In summary, drivers can continue to steer following brief visual occlusion, but performance rapidly degrades.

We aimed to explore the more complex behavior of steering extended curving paths. If participants demonstrate appropriate locomotor behavior despite the opening of the control loop (i.e., briefly blanking the visual display so that they must use remembered information), feed-forward or predictive behavior, as we might expect, is playing a role. We seek to understand the nature of this predictive control. Predictive steering behavior can be experimentally evaluated by requiring participants to rely on previously viewed visual information in order to steer. If participants are able to retain accurate performance and update their behavior, then they are indeed effectively utilizing predictive strategies for path planning. Implementation of this manipulation involves periodically blanking the entire visual display (intermittency), thereby interfering with optic flow, and then monitoring performance (e.g., Senders, Kristofferson, Levison, Dietrich, & Ward, 1967). Another manipulation is to occlude the path to be followed, while continuing to provide optic flow cues that result from the driver's actual steering inputs. Thus, although the path may be occluded, participants can still get visual feedback, in the form of optic flow, regarding how their steering actions move them through the environment. Others have demonstrated that biased optic flow can influence steering (Kountouriotis et al., 2013; Kountouriotis, Mole, Merat, & Wilkie, 2016; Mole, Kountouriotis, Billington, & Wilkie, 2016), though in those studies path information was continuously available. Here, the selective manipulation of path occlusion and optic flow enabled us to experimentally control the information that was available to the driver. In a series of experiments, we considered the predictive visuomotor control involved in curve driving. Specifically, is path prediction more important than current instantaneous heading, and if so, how is path prediction used to control steering?

Visual control of steering with intermittent display

The roles of both optic flow and updating with respect to a previously viewed path were thus studied in a series of two experiments. In Experiment 1, path intermittency and ground texture flow were manipu-

lated to examine how misleading or absent optic flow might impair steering when the path is intermittently occluded. In Experiment 2, the ground texture flow was manipulated in two additional ways to investigate turn rate as a source of information for steering during intermittent path occlusion.

Experiment 1: role of optic flow when steering with intermittent path display

Experiment 1 was designed to address two questions. Is there a limit beyond which path occlusions cause major degradations in performance, and can drivers use optic flow information to make steering corrections when their path is occluded? To answer these questions, we employed a large-screen, high-definition driving simulator as shown in Figure 1.

The highway simulation was programmed and run using Vizard software (WorldViz, Santa Barbara, CA) and depicted a single-lane road 4 m wide, with many bends on a textured ground plane (see sample frame in Figure 2). An additional line between the two lane edges defined the center of the road.

Participants were first given several practice trials to acquaint themselves with the simulator steering dynamics. To ensure that steering accuracy could be properly evaluated with respect to the center line, participants were instructed to steer and maintain their vehicle's position in the center of the road as accurately as possible. The measure of steering accuracy was root mean squared error from the center of the road. In the following experiments, we independently manipulated the visual intermittency of path occlusion and the availability and type of optic flow from ground texture present during occlusion. There were 10 intermittency conditions ranging from continuous viewing to having the path visible for slightly less than one frame every 2 s. The intermittencies are depicted in Figure 3, and will be described in more detail in the methods section. By varying intermittencies, we can further probe the nature and extent of drivers' predictive control. At some level of intermittency, participants should reach a performance limit, and be unable to maintain sufficient steering control. The representations for path prediction may be transient; therefore, for longer intervals of screen blanking in the intermittency conditions, representations may degrade or be poorly updated. If optic flow information, produced by ground texture when view of the path is intermittent, can be used by drivers to update their trajectories during path occlusion, we should also see differences in performance related to the availability and type of optic flow. Specifically, we

Figure 1. Driving simulator used in both experiments.

predicted that optic flow should enhance performance during path occlusion. On the other hand, altering or removing optic flow information should impair steering, particularly as the path is occluded for larger proportions of time.

Method

Participants

Six graduate students (three men, three women) at the University of California, Santa Barbara, gave their informed consent and served as paid participants. Their ages ranged from 24 to 28 years. All had driver's licenses and normal or corrected-to-normal visual acuity. Participants were naïve to the purposes of the experiment. The local ethics committee approved the experimental protocol.
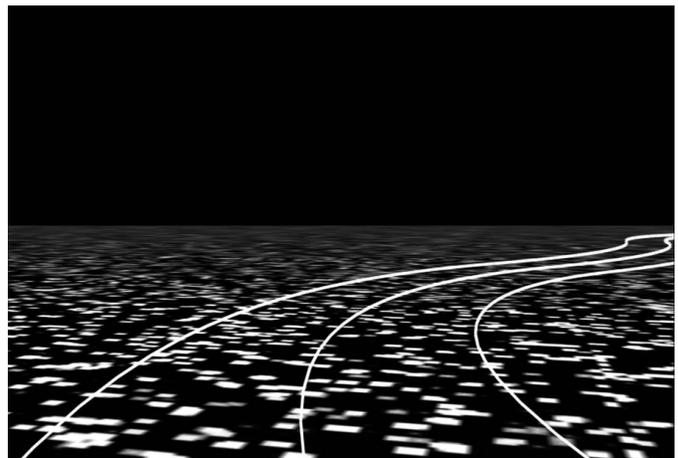

Figure 2. Sample frame of the experimental display used in Experiments 1 and 2. Figure is altered slightly for publication purposes. In the actual simulator display, the ground texture was black with red texture elements, and the path lines were bright green.
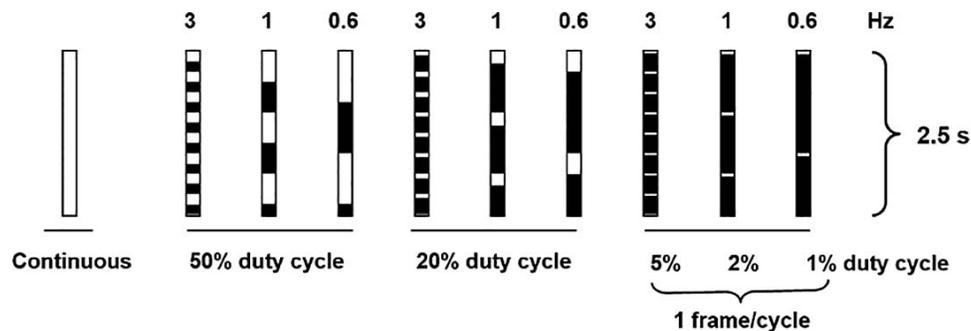
Figure 3. The intermittency conditions are illustrated using black and white symbols, with white representing the period of path visibility and black representing the period of path occlusion. The bars depict a 2.5 s time interval.

Stimuli and procedure

Experiments were conducted using a driving simulator with a wide-screen (58-in. diagonal) high-definition television (HDTV, Pioneer Electronics, Torrance, CA), mounted with the center of the display at a height of 90 cm, and a steering wheel (Logitech Momo Racing, Newark, CA) with a mild centering spring. Vehicle heading was updated by integrating the steering wheel angle and scaling by both a constant and the vehicle's forward speed. We did not model tire friction or other inertial properties. Participants were seated so that their eyes were 1 m away from the screen, with a 60° horizontal by 47.5° vertical field of view. Display resolution was 1,920 (horizontal) by 1,080 (vertical) pixels. A Dell PC (Round Rock, TX) and an NVIDIA-based graphics card (Santa Clara, CA) enabled high-speed rendering (60 Hz update rate). Display frame rate was 60 frames per second. Participants were required to steer to keep the vehicle in the center of the path. Solid lane markers with a center line demarcating the center of the road designated the path to be steered. The path was a curving single lane road with smooth lane markers, 4 m wide, defined by the sum of 3 spatial sinusoids with periods of 37 m, 47 m, and 67 m and starting phases of 0°, 90°, and 180°. All sinusoids had amplitudes of 10 m. The integrated length of each path was about 500 m. The ground texture was a highly textured dot pattern. Participants did not control speed, which was held constant at 6 m/s. Because the turns were fairly tight, the speed was relatively slow. Speed control and braking are other interesting facets of driving performance, but here we wanted to isolate steering behavior. Steering accuracy was assessed using root mean squared lateral position error from the centerline (RMS error). This is the square root of the sum of squared deviations between vehicle position and path position, summed over sampled positions and divided by the total number of sampled positions. Data were sampled at 60 Hz and processed with MATLAB software (MathWorks, Natick, MA). Statistical tests were conducted in SPSS.

Experiment 1 had two main manipulations. One manipulation was path intermittency. The path to be steered was either always visible (continuous) or periodically occluded (intermittent). In addition to the continuous condition, nine levels of intermittency (Figure 3) were used in which the frequency (3.0 Hz, 1.0 Hz, 0.6 Hz) and duty cycle (1 frame/cycle, 20%, 50%) were crossed. Frequency represents the rate of intermittency in terms of cycles per second (Hz). Duty cycle represents the proportion of time the path was visible as frames per cycle. The design was not fully crossed, however, as the 1 frame/cycle actually corresponds to different duty cycles for each frequency (5%, 2%, 1%, respectively). Nevertheless, we felt that it was important to include this 1 frame/cycle condition because this allowed us remove path flow and look more specifically at the role of optic flow. When the path disappeared during occluded intervals, path information was removed, but drivers still had access to some information about their vehicle movement from ground texture. Thus, the other manipulation pertained to the ground texture information. Ground texture can provide information independent of that provided by path information. This situation is not typical, but it allows us to independently manipulate available visual cues. Three ground texture conditions were used. In the consistent flow condition (see Figure 4A), the ground texture was rigidly associated with path. Thus, the ground flow corresponded to the path being steered both when the path was visible and when it was occluded. In the inconsistent flow condition (see Figure 4B), the ground flow was only partially correlated with the path being steered since it contained two separate components. For one component, the ground flow corresponded to motion along a different path, which was being steered by a "ghost driver." These "ghost driver" paths were artificially created by simulating trajectories appropriate for separate roads different from the ones generated for the participants (see Figure 4D for a bird's eye view of the "ghost driver" path shown along with the actual path). The "ghost driver" paths were defined by the sum of three spatial sinusoids with periods of 23 m, 53 m, and 71 m and initial phases of 0°, 90°, and 180°. All sinusoids had amplitudes of 10 m. The other component of the
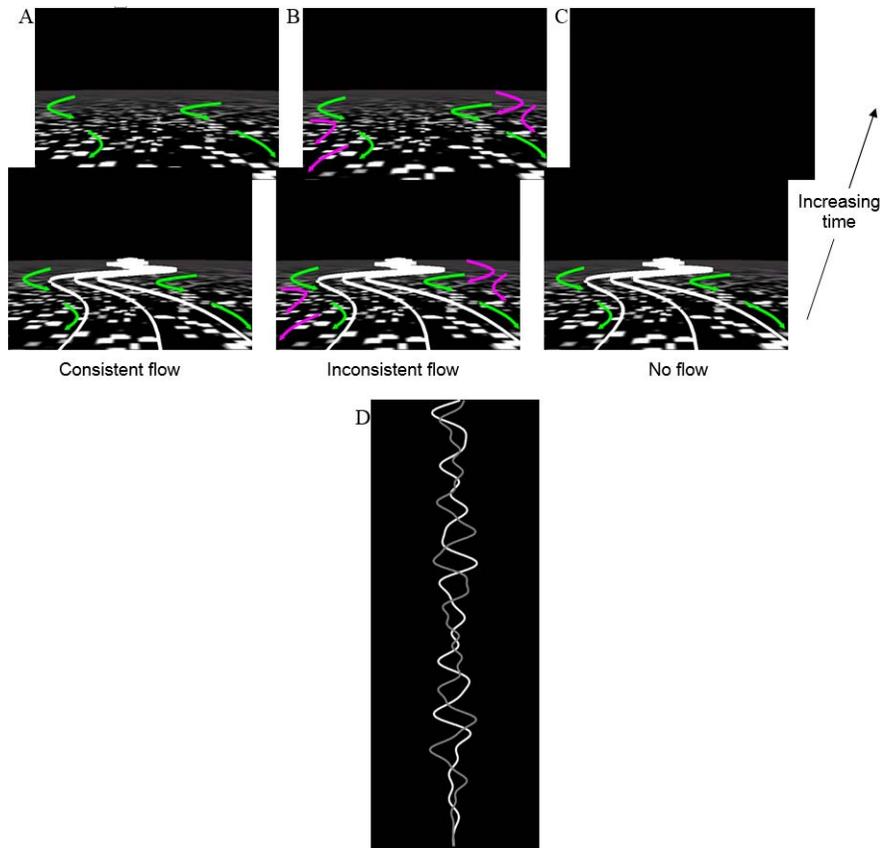
Figure 4. General design of optic flow conditions in Experiment 1. In all conditions, the path was intermittently occluded, as illustrated here over time. The first frame shows the path displayed and the second frame shows the path occluded. Arrows depict components of the optic flow: green arrows correspond to the component of flow associated with actual steering inputs while magenta arrows correspond to the component of flow associated with the experimental manipulation. (A) In the consistent flow condition, green arrows show flow corresponding to participants' actual movements. (B) In the inconsistent flow condition, arrows show flow corresponding to participants' actual movement (green arrows) plus movement from an artificially simulated trajectory over a "ghost" path (magenta arrows). (C) In the no flow condition, green arrows show flow corresponding participants' actual movements as in the consistent flow condition, but the flow disappeared when the path disappeared. (D) Bird's eye view of the inconsistent flow condition. White lines illustrate the actual path, and gray lines depict the simulated "ghost" path.

inconsistent flow was the rotational flow arising from the participant's actual steering behavior. Because the changes in ground flow were partially correlated with steering behavior, participants could potentially use changes in the ground flow to estimate their turn rate (i.e., yaw rate or angular velocity). The inconsistent flow was present both when the path was visible and when it was occluded, as it was for the consistent flow. In the no flow condition (see Figure 4C), the ground texture was occluded with the path. Thus, the entire display was blank during the occluded intervals. This would be like temporarily turning off one's display monitor.

Participants were instructed to try to stay in the center of the path. Performance accuracy was stressed. They were given two blocks of all three conditions (2 blocks × 10 intermittencies × 3 flow conditions = 60 total trials), presented in a random order. A two-way repeated-measures analysis of variance (ANOVA) was conducted to evaluate the interaction between intermittency (10 levels) and flow condition (three levels).

Results and discussion

Performance was quite good despite intermittency. Mean RMS values appear in Figure 5. Drivers could tolerate visual occlusions without a severe degradation in steering performance. Notice that when the path viewing was continuous, RMS values were small with little variation, and there was no effect of flow condition. Furthermore, when the path was frequently visible for sufficient intervals, it did not matter whether heading was consistent. However, when the path disappeared for long intervals, we began to see the effects of flow from ground texture, as confirmed by the interaction between intermittency level and ground
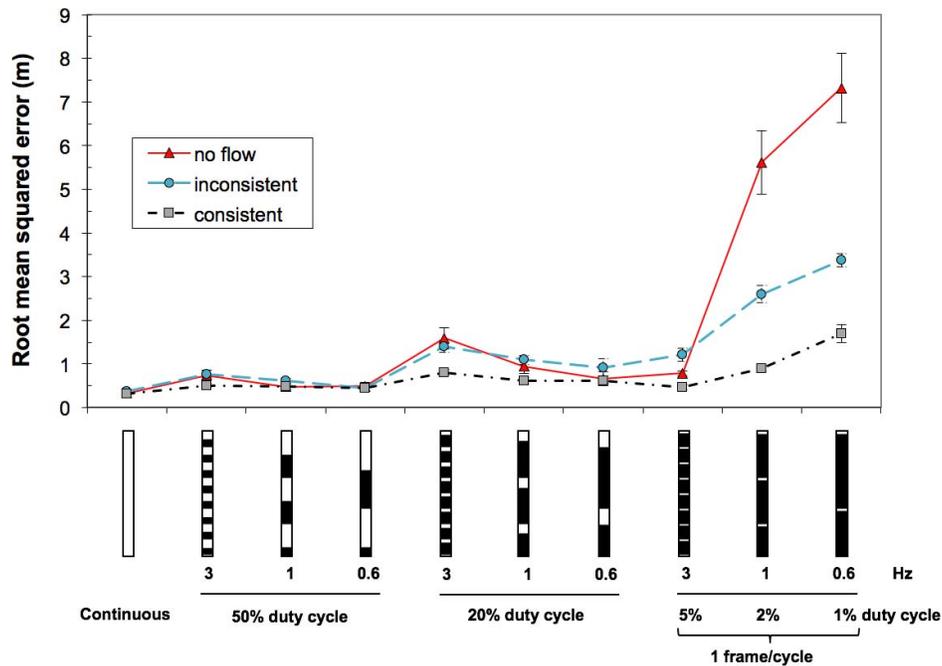
Figure 5. Effects of intermittency for different optic flow conditions in Experiment 1. Intermittency conditions are illustrated using black and white symbols, with white indicating periods when the path was visible. Mean RMS error values are plotted as a function of intermittency for the consistent, inconsistent, and no flow conditions. Error bars are standard errors.

texture condition, $F(18, 90) = 31.08$, $p < 0.001$, $\eta_p^2 = 0.86$, obtained with a two-way repeated-measures ANOVA. An alpha level of 0.01 was used in all statistical tests except in post-hoc comparisons where the alpha level was adjusted using a Bonferroni correction. Post-hoc tests revealed differences between ground texture conditions in only those cases where there was only 1 frame/cycle of path exposure. For the 1 frame/cycle at 3.0 Hz condition, consistent flow was better than both inconsistent flow ($p = 0.002$) and no flow ($p = 0.005$). As one can see on the right side of Figure 5, there were clear differences between all ground texture conditions for the 1 frame/cycle at 1.0 Hz (all ps < 0.005) and the 1 frame/cycle at 0.6 Hz (all ps < 0.005) conditions, with consistent flow resulting in better performance than inconsistent flow and no flow being worse than both inconsistent flow and consistent flow. Thus, as we pushed the driver's limits by introducing long blanking intervals, performance became severely degraded without access to flow from ground texture during the blank intervals. A surprising result, however, was the participants' moderate performance with inconsistent flow. Remember that in the inconsistent flow condition, heading was not correctly specified via movement of the ground texture. Nevertheless, in this condition, the ground texture was composed of two different flow components. One component corresponded to the complex motion over the "ghost driver's" path. The other component, however, was rotational flow, which moved in accor-

dance with the participant's turn rate. Given the results, participants seemed to be able to use aspects of the degraded flow, perhaps including these rotational cues that were embedded in the inconsistent flow, to make more appropriate steering actions.

In summary, drivers steered accurately, despite intermittent visual feedback and misleading or absent flow from ground texture. However, for long and frequent path occlusions, differences between ground texture conditions began to emerge. When ground flow was inconsistent, performance began to degrade. Furthermore, for the more extreme intermittencies, absence of flow caused even greater degradations of steering performance than inconsistent flow. Why did drivers tend to perform better with inconsistent flow than they did with no flow? One possibility is that they were able to use aspects of the degraded inconsistent flow, such as turn rate, to steer during path occlusions. In Experiment 2, we wanted to replicate the results for the consistent and no flow conditions with more participants and further isolate the rotational flow.

Experiment 2: Turn rate information for steering

A surprising result from Experiment 1 was that drivers steered better with inconsistent flow than they did with no flow for the more severe path intermittency

conditions. The proposed explanation was that drivers were able to use aspects of the degraded flow, such as turn rate information to improve their steering performance in the inconsistent flow condition. The goal of Experiment 2 was to isolate and investigate some of these aspects, such as turn rate, as a source of information for steering. To explore the potential role of turn rate information in steering curving paths, two new conditions (canted flow and rotational flow) were tested and compared with the consistent flow and no flow conditions from Experiment 1. These new conditions both supplied turn rate information, but the ground flow provided an incorrect (canted flow) or an ambiguous (rotational flow) heading direction. If turn rate information improves steering, then performance in both of these two new conditions should be better than performance in a no flow comparison condition. More specifically, we predicted an interaction between ground texture condition and intermittency, such that the no flow condition would result in worse performance than the other flow conditions as the path is occluded for larger proportions of time.

Method

Participants

Ten students (five men, five women) at the University of California, Santa Barbara, gave their informed consent and served as paid participants with ages ranging from 19 to 29 years. None had previously taken part in Experiment 1. All had driver's licenses and normal or corrected-to-normal visual acuity. Participants were naïve to the purposes of the experiment. The local ethics committee approved the experimental protocol.

Stimuli and procedure

Two new conditions were tested and compared with the consistent flow and no flow conditions from Experiment 1. Instead of the inconsistent flow condition from Experiment 1, we generated and tested canted flow and rotational flow. In these new conditions, optic flow revealed either an incorrect (canted flow) or an ambiguous (rotational flow) heading direction. In the canted flow condition, the ground texture moved so that it was always canted 15° with respect to the long axis of the display, which we called virtual North. Therefore, the ground flow revealed a heading direction that was misaligned with respect to the actual heading direction (see Figure 6A), which felt a bit like a side-slip. Nevertheless, turn rate information was available in the display, since the participants' steering inputs determined the turn rate of the ground flow, despite the heading direction offset. In the rotational flow condition, no ground texture was
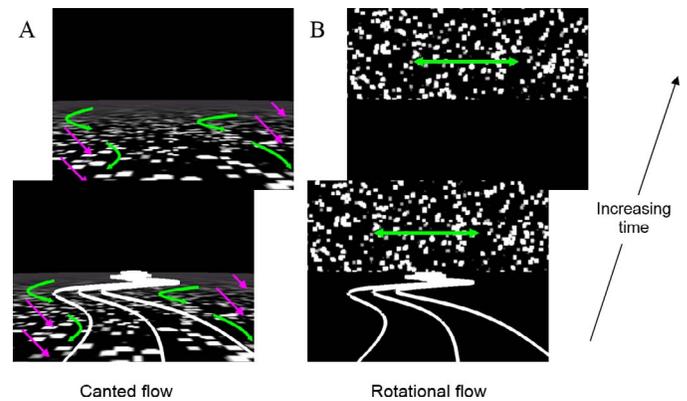

Figure 6. Illustration of the two new optic flow conditions included Experiment 2. In both conditions, the path was intermittently occluded, illustrated here over time. The first frame shows the path displayed and the second frame shows the path occluded. As in Figure 4, arrows depict components of the optic flow: Green arrows correspond to the component of flow associated with actual steering inputs while magenta arrows correspond to the component of flow associated with the experimental manipulation. (A) In the canted flow condition, arrows show flow corresponding to participants' actual movements (green arrows) plus flow canted 15° with respect to the long axis of the display (magenta arrows). (B) In the rotational flow condition, green arrows show flow corresponding to participants' actual turning movements, though this flow only appears in the upper portion of the display. For the consistent flow and no flow conditions also included in Experiment 2, refer back to Figure 4.

present. Instead, the ground texture was mapped onto a cylindrical surface above the horizon. As the driver steered, the display delivered accurate rotational cues about turn rate. However, there was no translational component, as the cylindrical surface remained at a fixed distance. Thus, no heading information was available, just turn rate from the rotational movement of the upper portion of the display (see Figure 6B). The no flow and consistent flow conditions were equivalent to those in Experiment 1. Task, procedure, and intermittency values were also identical to those used in the first experiment.

As before, participants were instructed to try to stay in the center of the path. The design was within-participant with 10 intermittencies × 4 flow conditions = 40 total trials, presented in random order. A two-way repeated-measures ANOVA was conducted to evaluate the interaction between intermittency (10 levels) and flow condition (four levels).

Results and discussion

Results are summarized in Figure 7. As in Experiment 1, performance was quite good despite path occlusions.
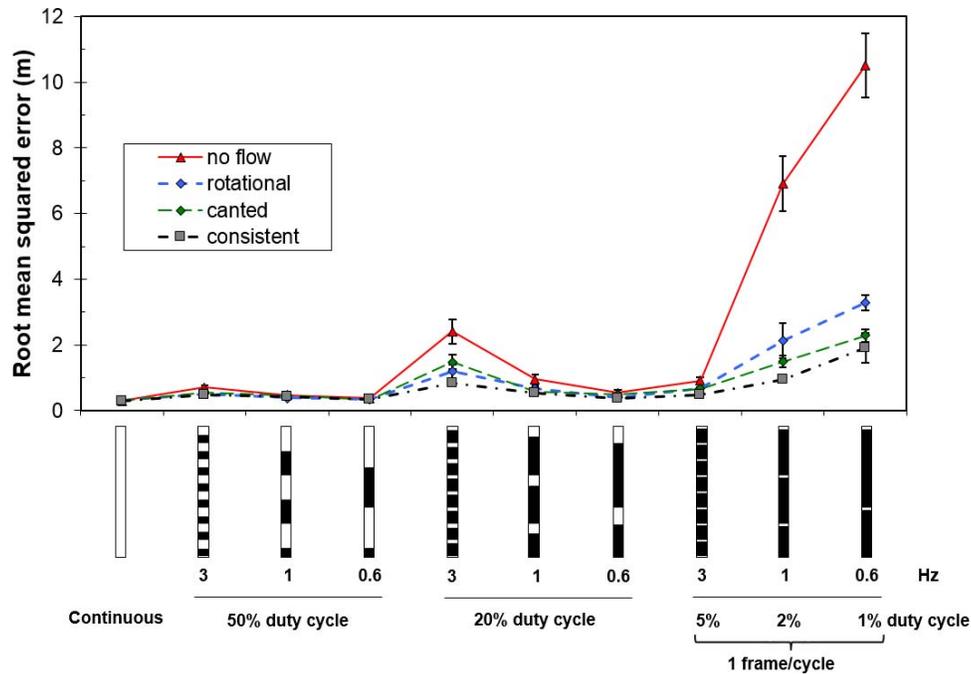
Figure 7. Effects of intermittency for different optic flow conditions in Experiment 2. Intermittency conditions are illustrated using black and white symbols, with white indicating periods when the path was visible. Mean RMS error values are plotted as a function of intermittency for the consistent, canted, rotational, and no flow conditions. Error bars are standard errors.

Once again, as the path disappeared for long and frequent intervals, differences emerged between the ground texture conditions as evidenced by the interaction between intermittency level and ground texture condition, $F(27, 243) = 33.28$, $p < 0.001$, $\eta_p^2 = 0.79$, confirmed using a two-way repeated-measures ANOVA. Thus, Experiment 2 replicated the results from Experiment 1 for the no flow and consistent flow conditions. As for the new flow conditions, both the canted flow and rotational flow conditions were better than the no flow condition for these difficult intermittent viewing trials, as displayed on the right side of Figure 7. Post-hoc tests revealed that for the 1 frame/cycle at 1.0 Hz and the 1 frame/cycle at 0.6 Hz path intermittency conditions, performance in the no flow condition was worse than performance in all other conditions (consistent, canted, and rotational, with all ps < 0.001). Optic flow from ground texture supplies information about turn rate that helps to guide vehicle control, even if heading information is ambiguous or misleading, as in the canted flow condition. Thus we conclude that heading information from optic flow is not needed for the active steering of curving paths. Turn rate information is sufficient. This claim is further supported, since turn rate was the only cue available in the rotational flow condition. In the rotational flow condition, heading relative to the path could not be directly acquired from the stimulus. We should mention, however, that for 1 frame/cycle at 0.6 Hz, performance in the rotational flow condition was slightly worse than in the consistent flow ($p = 0.009$) and

canted flow ($p = 0.001$) conditions. This could be due to the fact that in the rotational condition, no ground flow was available to give subjects a sense of their forward velocity during the long intervals without path information. Therefore, the timing of their steering inputs may have been more difficult. An additional result was that performance in the no flow condition was worse than performance in the consistent flow condition for the 3Hz, 20% duty cycle intermittency ($p = 0.002$). There was a similar, though nonsignificant, pattern in Experiment 1, which suggests that it might be interesting to investigate these effects at higher frequencies. Higher frequencies might not give drivers as much of an opportunity to encode the path layout.

Overall, however, these results (i.e., excellent performance when the path was occluded except for extreme levels of intermittency) indicate that participants steered using the path when it was available, but could also update their vehicle's movement with respect to a perceptual representation of the path when it was occluded during intermittent presentation. We therefore conclude that participants were using their perception of the path layout to plan their steering inputs as well as flow from the ground texture to sense vehicle motion.

Conclusions

Drivers were able to use path information that was continuously viewed or intermittently viewed to per-

ceptually represent the path to be steered. They then steered in accordance with the visible path when it was present, but were also able to update their vehicle movement with respect to a perceptual representation of the path when it was not present. To steer when the path was not present they must perceive the path, represent it in memory, sense their self-motion, and spatially update their position with respect to the remembered path. Optic flow from ground texture supplied information about the turn rate of the vehicle, generally improving the drivers' estimates of their movement with respect to the path.

General discussion

Despite the extensive research on heading perception, its utility for steering remains questionable. Research on the visual control of steering has not yet reached a consensus. Models that rely on optic flow (e.g., Fajen & Warren, 2000) and or visual direction (e.g., Wilkie & Wann, 2003, 2006) strategies are the tentative compromise, though other avenues are also being pursued. The shifting movement toward predictive strategies during active tasks is a promising one that may provide insight into the nature of locomotor behavior.

Implications for steering control models

To incorporate predictive control, some models of steering also include a feed-forward or look-ahead component. McRuer, Allen, Weir, and Klein (1977) stressed the importance of both feed-forward and feedback components for steering control models. The feed-forward component transforms future road curvature into steering wheel inputs at the appropriate time to reproduce the desired path. The feedback component uses visual information to null accumulated errors and to correct for unpredictable disturbances. If the feed-forward component is accurate, the feedback component has little to do. Similarly, Donges (1978) proposed a double control system steering model with feed-forward predictive control (based on the future road curvature) and visual feedback. The feed-forward mechanism could anticipate and match upcoming road curvature, while online feedback mechanism could be used for online error correction. Thus, the components of this dual system are complementary. Land and Horwood (1995) empirically supported this type of control system by demonstrating that participants reached near optimal performance with one far and one near section of the road. However, more work in this area is needed, as Cloete and Wallis (2011) were not

able to replicate Land and Horwood's results with a faster update rate. Salvucci, Boer, and Liu (2001) have constructed an integrated driver model that uses a simple two-level steering model based on two optimal control points: a far point that guides predictive steering, and a near point that guides steering within the lane. This model has been generalized and extended to model empirical data for curve negotiation, corrective steering, and lane changing (Salvucci & Gray, 2004). In our study, views of the path supplied feed-forward information, similar to the far section, to allow drivers to match the road curvature. Optic flow provided concurrent visual feedback, similar to the near region, which allowed drivers to fine-tune their steering and correct any errors.

Feed-forward control updated with turn-rate information

As noted in the introduction, a growing body of research has indicated that predictive information may be used for steering behavior, though the visual feedback control model still dominates the literature. Our results indicate that both sources of control are used, in line with a hybrid model (e.g., Zhao & Warren, 2015), though the important visual feedback source need not be heading information. In fact, when drivers were only provided with information about their turn rate, they were able to steer well even in the face of path occlusions. By introducing occlusions and opening the control loop, we found that continuous visual feedback was not necessary for accurate steering, which is consistent with previous studies that used curve entry (Cavallo et al, 1988; Godthelp, 1986) and lane correction tasks (Hildreth et al., 2000). Here we showed that drivers could use intermittent views of the path ahead to plan their steering actions. This finding is related to research on perceptually directed action, which demonstrated that participants can control their locomotor actions without visual feedback by implementing feed-forward control (see Loomis & Beall, 2004, for a review). Though visual feedback was removed, participants were able to update an estimate of their position and orientation with respect to their desired trajectory derived from previously viewed visual information. To do this, they could use path integration, based on velocity and/or acceleration information from inertial cues (e.g., vestibular information) to update their position and orientation in the absence of visual feedback (Macuga, Beall, Kelly, Smith, & Loomis, 2007). In the present study, drivers were able to use turn rate information (available via optic flow in the visual display) to update their trajectory despite visual occlusion of the path. While steering during visual occlusion, drivers must assess

how their steered path will change over time given their steering input and attempt to steer with respect to the previously viewed path. For this, the driver could use an efference copy of the steering response along with an internal model of the vehicle dynamics to continuously (Loomis & Beall, 1998, 2004) or intermittently (Markkula, 2014) update their trajectory. Turn rate information from optic flow seems to ease this updating process, perhaps by allowing drivers to recalibrate their internal models of the vehicle dynamics following any drift over time (e.g., Fajen, 2005, 2007). Online visual feedback may play an essential role in more complex maneuvers such as obstacle avoidance (Cloete & Wallis, 2009) or lane changes (Wallis, Chatziastros, & Bulthoff, 2002). However, even lane changes can be performed without visual feedback if path information is specified or if vestibular feedback is available (Macuga et al., 2007).

Additionally, we found an interaction between intermittency and optic flow information. Intermittency was more deleterious when no turn rate information was available. Turn rate information could also be supplied by inertial cues; however, as our simulator lacked a motion-base, this issue was not investigated here. We have explored such questions in other studies using a vehicle that allowed us to deliver accurate inertial cues to participants (e.g., Macuga et al., 2007). Further research of this kind is needed to better understand how path prediction is used along with visual feedback as well as inertial information to control steering.

Keywords: locomotion, optic flow, steering, visuomotor control, visual feedback

Acknowledgments

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