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RESEARCH ARTICLE

Changing lanes: inertial cues and explicit path information facilitate steering performance when visual feedback is removed

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Abstract Can driver steering behaviors, such as a lane change, be executed without visual feedback? In a recent study with a fixed-base driving simulator, drivers failed to execute the return phase of a lane change when steering without vision, resulting in systematic final heading errors biased in the direction of the lane change. Here we challenge the generality of that finding. Suppose that, when asked to perform a lane (position) change, drivers fail to recognize that a heading change is required to make a lateral position change. However, given an explicit path, the necessary heading changes become apparent. Here we demonstrate that when heading requirements are made explicit, drivers appropriately implement the return phase. More importantly, by using an electric vehicle outfitted with a portable virtual reality system, we also show that valid inertial information (i.e., vestibular and somatosensory cues) enables accurate steering behavior when vision is absent. Thus, the failure to properly execute a lane change in a driving simulator without a moving base does not present a fundamental problem for feed-forward driving behavior.

Keywords Locomotion · Vision · Vestibular · Motor control · Steering

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Introduction

How do humans use perceptual information to steer a vehicle? A highly practiced, well-learned skill involved in driving is changing lanes. The purpose of the present study was to investigate the role of visual feedback in the task of making a lane change. Drivers are often required to perform lane changes without continuous visual feedback as they monitor and attend to traffic, road signs, other passengers, scenery, and devices (radio controls, cell phones, etc.). If drivers demonstrate appropriate steering behavior despite opening of the control loop (i.e., briefly extinguishing the visual display so that they must use remembered information), feed-forward or predictive behavior, as we might expect, is playing a role. Predictive steering behavior can be experimentally evaluated by requiring participants to rely on previewed visual information in order to steer. Previous research indicates that steering a vehicle can be performed surprisingly well even with a temporary withdrawal of visual feedback (Cavallo et al. 1988; Godthelp 1985, 1986; Hildreth et al. 2000; Land 1998; Macuga et al. 2004). To perform well despite occlusions, it seems that one must maintain internal representations of the road and of the vehicle state with respect to the road (Loomis and Beall 2004). However, some visual feedback might be necessary to correct accumulated errors. In the case of a lane change, visual feedback may be especially important when realigning a vehicle back into the lane.

Do drivers rely on continuous visual feedback even for well-learned steering maneuvers such as lane changing? Most previous studies have modeled (Salvucci and Gray 2004) or described lane-changing behavior in the presence of full visual feedback, characterizing the phases (van Winsum et al. 1999) or the time course of driver behavior (Salvucci and Liu 2002) for this maneuver. However, Wallis et al. (2002) conducted a driving simulator study in which they removed visual feedback and found that participants failed to properly execute a lane change. The authors reported systematic final heading errors biased in the direction of the lane change, indicating that participants in their experiment behaved as if they were turning a corner when attempting to make a lane change without visual feedback. Here we challenge the generality of their finding with two experiments, and we also introduce a more representative quantitative measure (the return ratio) for describing the relative phases of the lane change maneuver.

For a typical terrain vehicle, a lane change maneuver has two phases: (1) an initial phase (a turn in the direction of the adjacent lane) and (2) a return phase (a turn equal in magnitude but opposite to the initial turn, which is necessary in order to realign the vehicle with the lane). In other words, the initial phase requires a change in vehicle heading to cross over into the adjacent lane. The return phase requires an equal and opposite change in vehicle heading to straighten the vehicle in that new lane. If the steering wheel is turned in the direction of the adjacent lane and then brought back to the center (initial phase), this will result in a change in heading. Unless an equal and opposite turn (return phase) is made, the vehicle will continue to head off in the direction of the initial turn. This return phase is essential for shifting the vehicle's heading back to the straight-ahead direction in the new lane.

As a measure of lane change performance, final heading error is not very informative about the relative phases of the maneuver. A more informative measure is the return ratio (RR), the ratio of the heading change of the return phase to the heading change of the initial phase:

$$\text{Return ratio (RR)} = \Delta\text{Heading}_{\text{Return}}/\Delta\text{Heading}_{\text{Initial}}$$

where:

$$\Delta\text{Heading}_{\text{Return}} = \text{final heading} - \text{max heading}$$

$$\Delta\text{Heading}_{\text{Initial}} = \text{max heading} - \text{initial heading}$$

and: max heading refers to the heading that differs most from the initial heading during the maneuver. Figure 1 depicts the correct response as well as the incorrect response typically made when executing a lane change maneuver without visual feedback. It also illustrates the corresponding return ratio for each.

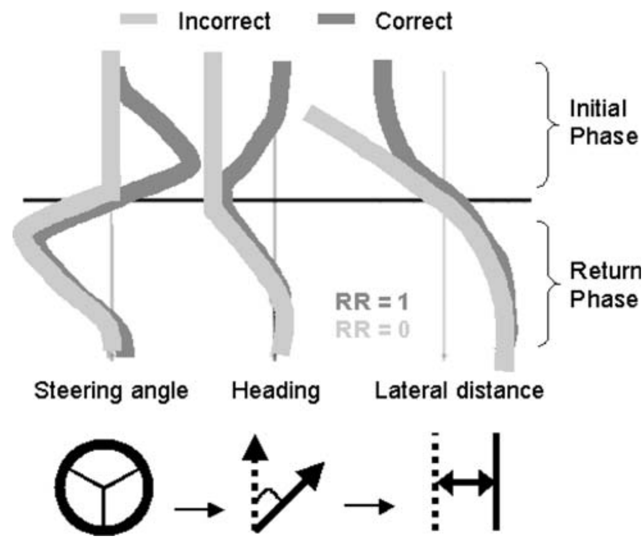

Fig. 1 Correct response (*dark gray*) as well as the incorrect response (*light gray*), illustrated for steering angle, heading, and lateral distance, that is typically made when executing a lane change maneuver without visual feedback. Corresponding return ratio (RR) for each is also depicted

Turning the steering wheel at even a modest angle can result in large heading changes and even larger position changes over time, since steering angle is integrated into heading and heading is in turn integrated into position. Given the double integral system dynamics, if drivers fail to execute the return phase, they will continue off the road in the direction of their initial turn, and obtain a return ratio close to zero. If they were to overcorrect with a return phase larger than the initial phase, their return ratio would be greater than one. In order to successfully complete the lane change, approaching a correct return ratio of one, drivers should make the return phase equal in magnitude to the initial phase.

Experiment 1: lane changing versus explicit path following in a stationary virtual reality-driving simulator

When walking, people can sidestep to change position, without changing heading. For that reason, they may not realize that, when steering a ground vehicle, they need to explicitly change heading in order to perform a lane change maneuver. In a ground vehicle, it is infeasible to sidestep. One must first change heading in order to change position. Figure 2 illustrates this point that in a vehicle (with the exception of a skid), one must first change vehicle heading in order to effectively change vehicle position. Most drivers may not be aware of this

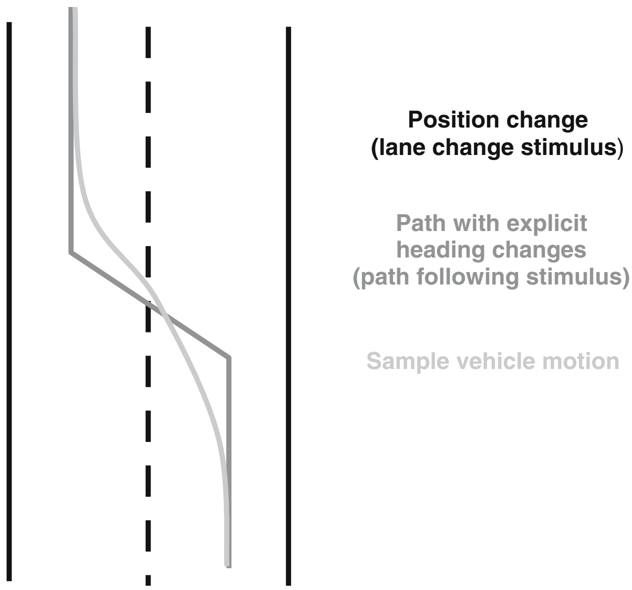

Fig. 2 Lanes (shown in *black*) imply a position change. Path (drawn in *dark gray*) explicitly depicts heading changes. In either case, the vehicle trajectory should look something like the *light gray line*

fact. In the Wallis et al. (2002) study, participants were asked to perform a lane (position) change. However, no information was provided with regard to prerequisite heading changes. A path would make required heading changes explicit, and thus should improve performance. To this end, the purpose of our first experiment was to investigate the role of visual feedback in the execution of a lane change, and to compare this to a path following case where required heading changes are made explicit and necessary heading changes are more apparent. In one task condition participants executed a lane change maneuver like that of Wallis et al. (2002). In the other task condition, participants steered a path consisting of three linear segments (corresponding approximately to a lane change maneuver), as depicted by the dark gray line in Fig. 2.

Method

Participants

Nine students (six men, three women) from the University of California, Santa Barbara volunteered to participate and gave their informed consent. All had driver's licenses, and their ages ranged from 18 to 22 years. All had normal or corrected-to-normal visual acuity and were naïve to the purposes of the experiment. The local ethics committee approved the experimental protocol.

Stimuli and procedure

The experiment was conducted using a driving simulator consisting of a Virtual Research V8 head-mounted display (HMD) with 640 × 480 pixel resolution LCD panels that simulated driver motion via computer-generated images in real time, and a steering wheel (Logitech Momo Racing) with a mild centering spring. The HMD provided stereoscopic viewing with a 50° horizontal by 38° vertical field of view, and the graphics were updated and refreshed at 60 Hz. Stereoscopic images were rendered by a dual 800 MHz processor computer with a nVidia Quadro4 550 XGL graphics card. Data from the steering wheel were sampled at 60 Hz. The driving simulator setup is shown in Fig. 3a, along with the two conditions (Fig. 3b, lane change and Fig. 3c, path following).

Prior to performing the experiment, participants were given an opportunity to familiarize themselves with the driving simulator. They steered five 500 m curving paths to get acquainted with the simulator steering dynamics. Then, in order to convey the task to the participants, we displayed an example of a lane change and a path following trial on the screen. Participants simply watched these example trials.

Roads and paths were 100 m long. For the lane change conditions, adjacent lanes were 4 m wide with a dashed stripe separating them as shown in Fig. 3b. The center stripe was at 0 m, and the lane centers were at –2 m (left lane) and at 2 m (right lane). Participants

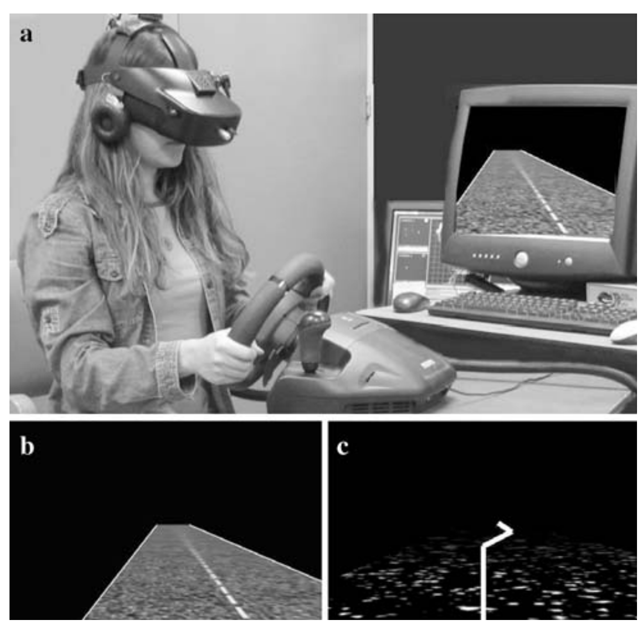

Fig. 3 Driving simulator used in Experiment 1 with sample frames of the experimental displays for both the lane change (*left*) and path following (*right*) conditions

started in the center of either the left or right lane. An auditory tone indicated when to begin the lane change. Upon hearing this auditory tone, participants attempted to move into the adjacent lane and then continued heading down the road in the new lane. For the path following conditions, path lines were centered at –2 m and at 2 m and crossed through 0 m at a 45° angle as shown in Fig. 3c. The simulated speed was held constant at 6 m/s. Accuracy in performing the maneuver was stressed. When participants felt that they had finished, they pressed a button to end each trial.

Participants performed the lane change and path following conditions both with and without visual feedback. Thus, on half of the trials, visual feedback was withdrawn, and participants had to continue driving while viewing a blank display. Nonetheless, despite this disruption, the participants were asked to steer as if the road or path was still present. On each trial after participants had previewed the stimulus for 3 s, the simulated vehicle began moving at a constant speed of 6 m/s. In all conditions, participants moved for 3 s along an initial straight segment with the road or path still visible. This was done in order to give participants an indication of their velocity. For the trials with visual feedback, participants continued to steer with the road or path present. However, for the trials without visual feedback, the entire display was occluded for the remainder of the trial. Participants were then instructed to continue driving as usual, though they were no longer able to see the road or path in this condition. For the lane change conditions, an auditory tone occurred after 3 s of steering, indicating that the participant should initiate the lane change. A typical trial lasted about 20 s. At the end of each trial, participants were reset to the start position and pressed a button on the steering wheel to start the next trial. As such, they did not receive any visual feedback, not even at the end of the trial for the no visual feedback condition. This was intended to prevent potential learning effects.

Participants performed 6 lane changes (3 left, 3 right) with visual feedback and 6 lane changes (3 left, 3 right) without visual feedback. The same set of trial conditions was administered for the path following condition. Trials were blocked and counterbalanced by task condition such that half of the participants performed the lane change condition first, and half of the participants performed the path following condition first. Within each block, feedback and no feedback conditions were alternated. For example, a sample of four lane changing trials would look like this: change left with feedback, change right without feedback, change right with feedback, change left without feedback. Each participant completed a total of 24 trials (6 trials × 2 feedback conditions × 2 task condition blocks).

Results and discussion

Figure 4 shows individual trajectories from a bird's eye view for all nine participants. When participants had visual feedback (solid lines), they changed lanes and accurately realigned themselves in the adjacent lane. Therefore, the following results will focus on the no feedback trials (dotted lines). Note the lack of a return phase for the lane change conditions (upper panels). Participants made the characteristic systematic heading errors in the direction of the lane change. For the path

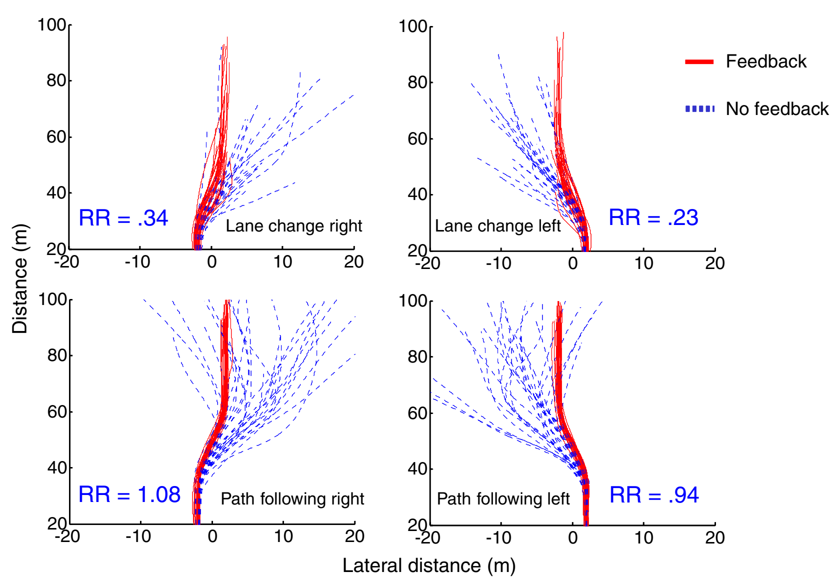

Fig. 4 Individual trajectories for nine participants. Adjacent lanes were 4 m wide. Thus, lane centers were –2 m (*left lane*) and 2 m (*right lane*). Note the lack of a return phase for lane change conditions (*upper panels*), but corrective realigning turns for path following conditions (*lower panels*), despite high variability. Return ratios are listed for the no feedback conditions

following conditions (lower panels), however, participants made corrective realigning turns, despite high variability in lateral position at the end of the trial. Signed mean final lateral position errors are plotted in Fig. 5. When visual feedback was unavailable, participants made lateral position errors in both lane change and path following conditions. However, as shown in Fig. 4, the trajectories for the path following condition and the lane change condition are qualitatively different. Only in the path following condition were participants attempting to realign themselves with the lane. This realigning behavior is best characterized by the return ratio measure.

Return ratios (RRs) for lane changing and path following conditions both with and without visual feedback are plotted in Fig. 6. Recall that a failure to produce the return phase would result in a return ratio of zero, and that a return ratio for the appropriate maneuver would be 1. Results shown are averaged across participants and collapsed over left/right trials. As expected, return ratios for the conditions with visual feedback have a value very close to one. Without visual feedback, the return ratio for the lane change was quite low, indicating that participants failed to produce much of a return phase. However, note the improvement in performance when necessary heading changes are made explicit in the path following trials without visual feedback. Return ratios for the path following trials without visual feedback are close to 1, similar to the trials with visual feedback. A repeated measures analysis of variance (ANOVA) revealed a significant difference between the lane change and path following conditions without visual feedback, $F(1,8) = 42.16$, $P < 0.001$, $\eta_p^2 = 0.84$, with a much

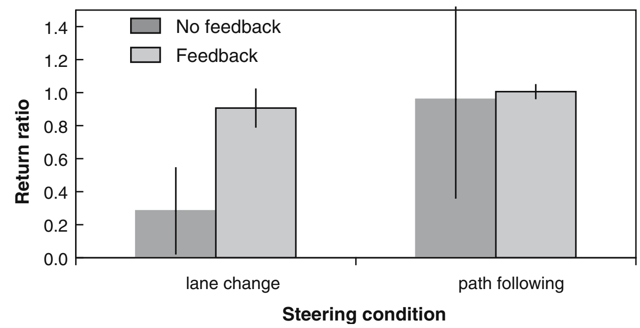

Fig. 6 Return ratios for lane changing and path following both with and without visual feedback. Results shown are averaged across participants and collapsed over left/right trials. *Error bars* are standard deviations. When visual feedback is present return ratios are very close to one. Lane change performance is poor without visual feedback, as indicated by a return ratio close to zero. However, note improvement in performance without visual feedback when necessary heading changes are made explicit in the path following trials

higher return ratio for the path following condition, as shown in Fig. 6.

To directly compare our results with those of Wallis et al. (2002), we also analyzed the data in terms of final heading error, as plotted in Fig. 7. We replicated their results for the lane change condition, as a repeated measures analysis of variance (ANOVA) revealed a significant effect of lane change direction on final heading, $F(1,8) = 34.07$, $P < 0.001$, $\eta_p^2 = 0.81$. This means that, in our driving simulator, participants also systematically deviated in the direction of the lane change. The important condition here, however, is the path following condition. In contrast to the results for the lane change condition, for the path following condition, we found that there was no significant effect of

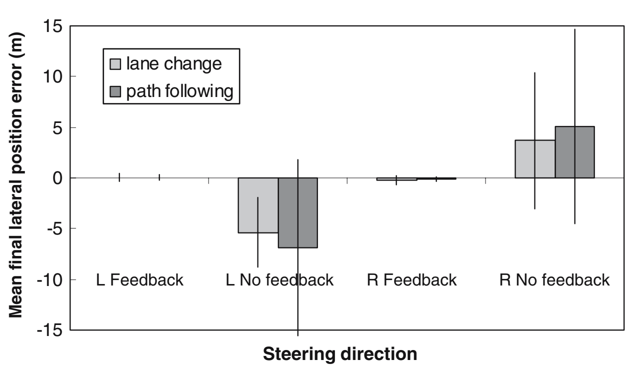

Fig. 5 Signed mean final lateral position errors for lane changing and path following both with and without visual feedback. Average lateral position at the end of the trial is shown for both left and right responses. With visual feedback, average lateral position errors are essentially zero. Without visual feedback, average lateral position errors are considerable and response variability is increased

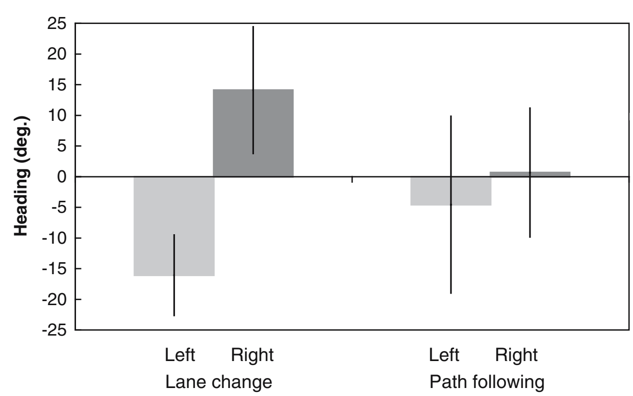

Fig. 7 Final headings (*left* vs *right*) for lane changing and path following without visual feedback. Results shown are averaged across participants. *Error bars* are standard deviations. For the lane change condition, final heading is significantly biased in the direction of the lane change. For the path following condition, however, final headings did not significantly differ

the path direction on final heading, $F(1,8) = 1.84$, ns. Average final headings for left and right paths were indistinguishable from one another.

So far we can draw the following conclusions. When required heading changes are initially made explicit by a demarcated path, on average, drivers do appropriately implement the required return phase without visual feedback. However, in driving simulators without a motion base, drivers seem unable to perform a lane change without visual feedback.

Experiment 2: lane changing versus explicit path following in a moving vehicle equipped with virtual reality

Do we still require visual feedback for steering if inertial cues inform us about changes in heading? The purpose of Experiment 2 was to explore the role of inertial information in steering. Results from Experiment 1 indicate that explicit paths can be followed without visual feedback, but that visual feedback is required for lane changing. Here, we perform the same study, but with the addition of vivid, valid inertial cues experienced while driving on an instrumented electric vehicle equipped with virtual reality.

Method

Participants

Eight students (3 men, 5 women) from the University of California, Santa Barbara served as volunteer participants with ages ranging from 19 to 28 years. The experimental protocol was approved by the local ethics committee, and participants gave their informed consent. All participants had drivers' licenses, and none had previously taken part in Experiment 1. Participants had normal or corrected-to-normal visual acuity, no history of vestibular problems, and were naïve to the purposes of the experiment.

Apparatus

Our new research tool depicted in Fig. 8 provided a wireless, mobile virtual reality motion base simulator by combining an electric vehicle (four wheel Victory model, Pride Mobility Products Corporation) with an onboard PC-based nVidia 5,200 dual-pipe graphics and a Virtual Research V8 HMD. The vehicle had a turn radius of 1.47 m. An onboard electronic compass (20 Hz sample rate) and a rear-axle optical encoder (60 Hz sample rate) provided input for precise dead

Fig. 8 Electric vehicle with onboard PC, tracking sensors, and Virtual Research V8 head mounted display provided wireless, mobile virtual reality motion base simulator. Participants performed the lane change and path following conditions both with and without visual feedback. However, they also have inertial information due to real movement of the vehicle

reckoning of the vehicle's track. A simple terrain vehicle was modeled by integrating instantaneous vehicle heading (provided by the compass and velocity (provided by the optical encoder) over time at 60 Hz and used to update the graphics. An Intersense IS-300 provided independent orientation tracking of the head. The vehicle also was equipped with two safety features: a remotely controlled kill switch and an ultrasonic obstacle detector. In future related studies, we will be able to simulate vehicle motion without delivering inertial cues by mounting the vehicle on a stationary platform while allowing its wheels to turn freely. We have also implemented steering actuation for remote control of the vehicle, although for this study it was left idle.

Stimuli and procedure

The lane change and path following displays were the same as in Experiment 1 except that the length of the road/path was reduced to 20 m due to outdoor space limitations. The outdoor space was a grassy field that was 30 m long × 15 m wide. The instructions and virtual display were also the same.

Prior to performing the experiment, participants were given an opportunity to acquaint themselves with the vehicle by driving around without wearing the HMD. We then made certain that they felt comfortable steering the vehicle through the physical environment while wearing the HMD and viewing a virtual environment. Then, in order to convey the experimental task to participants, we displayed an example of a lane change and a path following trial on the screen. Participants simply watched these example trials.

During the experiment, participants wore earphones that delivered white noise to eliminate any ambient auditory cues revealing direction of motion. On each trial, participants viewed the virtual road or path and then attempted to drive through the physical space at a constant speed of 1.9 m/s either with or without further visual feedback. At the end of each trial, participants were guided to the starting area without vision along a circuitous route to disorient participants, thus preventing error feedback. They followed verbal instructions delivered by the experimenter, heard through earphones that were also used to eliminate any auditory cues revealing direction of motion.

Participants performed 4 lane changes (2 left, 2 right) with visual feedback and 4 lane changes (2 left, 2 right) without feedback. The same trial conditions were administered for the path following condition. Trials were blocked and counterbalanced by task condition such that half of the participants performed the lane change condition first, and half of the participants performed the path following condition first. Within each block, feedback and no feedback conditions were alternated. For example, a sample of four lane changing trials would look like this: change left with feedback, change right without feedback, change right with feedback, change left without feedback. Each participant completed a total of 16 trials (4 trials × 2 feedback conditions × 2 task conditions).

Results and discussion

Individual trajectories from a bird's eye view for all eight participants are displayed in Fig. 9. As before, when participants had visual feedback (solid lines), they changed lanes and accurately realigned themselves in the adjacent lane. Therefore, the following results will focus on the no feedback trials (dotted lines). Remember that in Experiment 1 participants made the characteristic systematic heading errors in the direction of the lane change, though for the path following conditions they made corrective realigning turns, despite high variability in final lateral position. Here, however, participants' lateral position errors are minimal with low variability for both lane change and path following conditions. Signed mean final lateral position errors are plotted in Fig. 10. More importantly, when inertial cues are present, participants are properly executing the return phase for both lane change and path following conditions!

Return ratios for lane changing and path following conditions both with and without visual feedback are plotted in Fig. 11. When calculating the RRs, the heading data for each trial were median filtered (the window width was 0.83 s) to reduce extraneous noise generated by calculating vehicle heading as described earlier in the apparatus section. Again, recall that a failure to produce the return phase would result in a return ratio of zero, and that a return ratio for the appropriate maneuver would be one. As before, results shown are averaged across participants and collapsed over left/right trials. Once again, as expected, conditions with visual feedback have return ratios close to

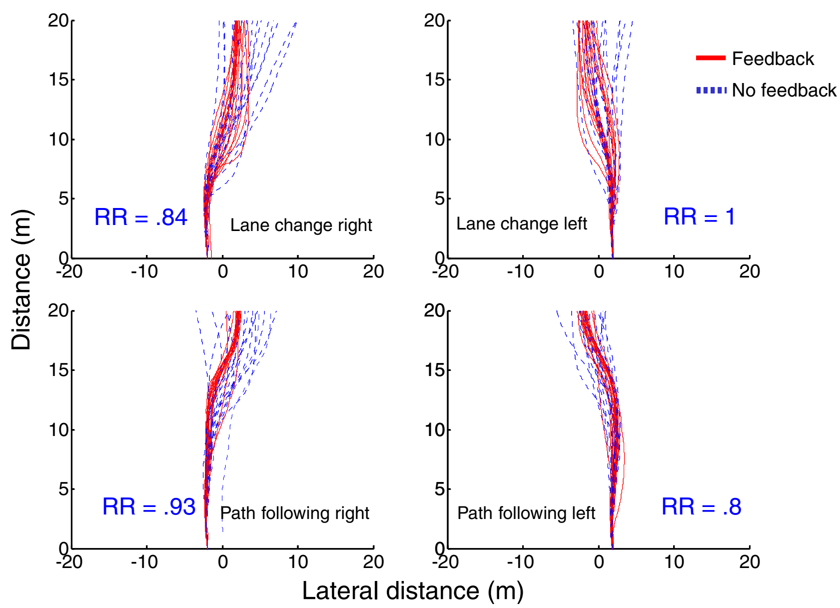

Fig. 9 Individual trajectories for eight participants. Note proper execution of return phase for both lane change and path following conditions. Return ratios are listed for the no feedback conditions

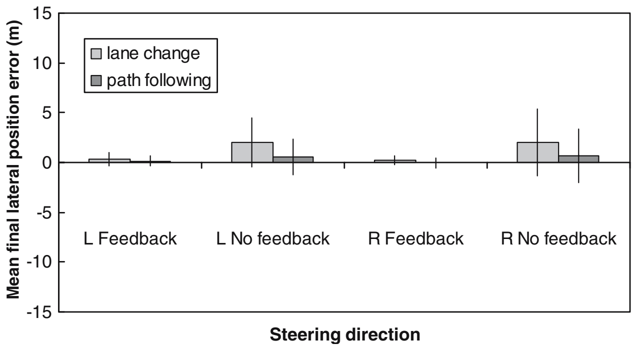

Fig. 10 Signed mean final lateral position errors for lane changing and path following both with and without visual feedback for *left* and *right* responses. With visual feedback, average lateral position errors are essentially zero. Without visual feedback, average lateral position errors are also quite minimal

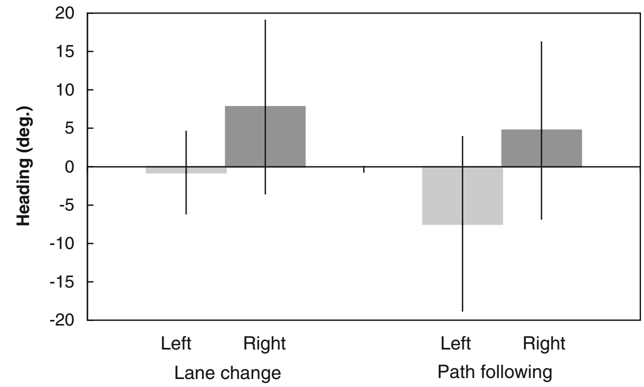

Fig. 12 Final headings (*left* vs *right*) for lane changing and path following without visual feedback but with inertial feedback. Results shown are averaged across participants. *Error bars* are standard deviations. Final headings did not significantly differ for either condition

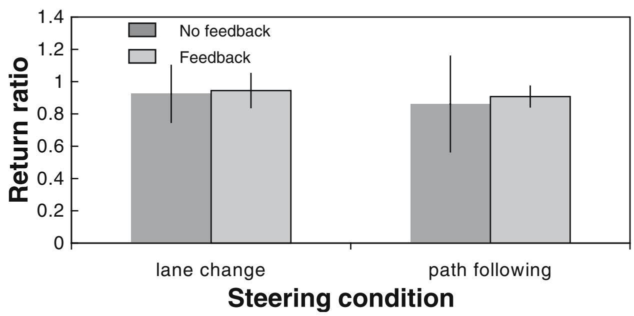

Fig. 11 Return ratios for Experiment 2 as displayed above for Experiment 1. *Error bars* are standard deviations. Note the proper execution of return phase, as evidenced by a return ratio close to one for both the lane change and path following trials when inertial cues are present, even despite complete lack of visual feedback in the no feedback conditions

one. However, this time, notice the proper execution of the return phase, as evidenced by a return ratio close to one for both the lane change and path following trials when inertial cues are present, despite a complete lack of visual feedback. A repeated measures analysis of variance (ANOVA) revealed that there was not a significant difference between the lane change and path following conditions without visual feedback, $F(1,7) = 0.63$, ns.

We also analyzed the results in terms of final heading error, the measure Wallis et al. (2002) used for their study. These results are plotted in Fig. 12. A repeated measures analysis of variance (ANOVA) revealed no significant effect of lane change direction on final heading, $F(1,7) = 2.89$, ns, when inertial cues were present. This means that, when inertial cues are available, participants do not systematically deviate in the direction of the lane change. As expected for the path following condition, there was also no significant effect of the path direction on final heading, $F(1,7) = 1.54$, ns, when inertial cues were present.

Inertial cues from vehicle motion seem to be supplying information about the linear accelerations and turns of the vehicle, thus improving the drivers' estimates of their movements with respect to the remembered visual scene.

General discussion

In driving simulators without a motion base, drivers seem unable to perform a lane change maneuver if visual feedback is not available. However, when required heading changes are initially made explicit by a previously viewed demarcated path, on average, drivers do appropriately implement the required return phase despite receiving no further visual feedback. Furthermore, inertial cues enable accurate steering behavior for making a lane change when vision is absent. In view of these results, the failure to properly execute a lane change maneuver in a driving simulator is an interesting finding, but is likely due to the lack of inertial cues typically experienced during vehicle motion.

How might these inertial cues be used to aid in the performance of a lane change when visual feedback is removed? To steer without visual feedback, drivers must estimate how they will move with respect to an intended path. This requires updating their position over time. Path integration is one strategy that can be used to update one's position in the absence of visual feedback. Path integration in a vehicle utilizes acceleration and/or velocity information sensed by inertial systems to update orientation and position according to turns and/or displacements. Path integration has been shown to be quite accurate for walking, given the accuracy with which people use perceptually directed action to walk without visual feedback to initially previewed targets (Loomis and Beall 2004; Loomis et al. 1999). Additionally, Grasso et al. (1999) report that after being passively moved along a path while blindfolded, people can accurately reproduce that path using path integration. Inertial cues possibly combined with priopriocepive cues and efference copy of motor commands can thus be used to update one's trajectory with respect to the remembered visual scene. In a vehicle, however, proprioceptive cues are removed, leaving only inertial cues and efference copy. In driving simulators without a motion base, only efference copy is available when visual information is removed. With this information alone, results indicate that drivers are unable to perform an accurate lane change. However, given a great deal of practice with the simulator, one might eventually be able to internalize the vehicle dynamics well enough to steer with efference copy alone to update one's trajectory with respect to the previewed visual scene (Loomis and Beall 2004).

The interaction between visual and vestibular information with respect to locomotor behavior has been recently explored. The relative contributions of each are determined by perturbing visual cues with prisms (as in Rushton et al. 1998), vestibular cues with galvanic vestibular stimulation (as in Bent et al. 2000; Fitzpatrick et al. 1999), or both cues to make them unreliable sources of information. Researchers find that when one source of information is ambiguous or unreliable, the other source has a greater influence on locomotor behavior (Carlson et al. 2005; Deshpande and Patla 2005). Kennedy et al. (2005) demonstrated that the weighting of vestibular cues increases just prior to a potential change in trajectory. This may be related to our results, such that changes in trajectory are required for completing both phases of a lane change, and that inertial information provided the additional information necessary for participants to initiate the return phase. So far it seems to be the case for steering, however, that when both visual and vestibular cues are available, vestibular information plays a relatively minor role (Wilkie and Wann 2005), as body rotation only had an effect when biased in the opposite direction to steering. Their vestibular manipulation was limited to rotations around the yaw axis, however, as participants were seated in a motorized chair, and steering was controlled with a joystick. While investigating the automaticity of spatial updating, Riecke et al. (2005) also examined visual–vestibular interactions for yaw rotations. They asked participants to either update or ignore passive rotations, and found that vestibular cues alone did not trigger automatic spatial updating, as they were as easy to ignore as to update. In contrast, participants did have trouble ignoring visual cues, and so the authors concluded that vestibular cues are not required for the automatic updating of rotations. Vestibular cues, however, have been shown to be important for judging traversed distances from passive linear self-motion (Harris et al. 2000), for reconstructing passively traveled trajectories with both linear and rotational components (Bertin and Berthoz 2004), and for driving simulation (Kemeny and Panerai 2003). However, in a recent extension to the Wallis et al. (2002) study, Wallis et al. (2006) repeated the original lane change experiment, this time with a motion-based simulator that introduced inertial stimulation by way of tilts to the left and right. The tilting of the simulator produced vestibular and somatosensory signals that mimiced those produced by lateral acceleration. The authors found no influence of the inertial cues on completion of a lane change; thus, as in the original study, participants failed to properly complete the lane change maneuver. It should be noted, however, that the simulator produced no yaw component, and that the inertial cues only approximate those of lateral acceleration. In our experiment, the vestibular cues were real, not simulated, and did indeed have an important effect on lane changing behavior.

In summary, drivers can make a lane change or steer an explicit path using visual feedback when it is present, but they are also able to update their vehicle movement with respect to a perceptual representation of an explicit path when the depicted path is occluded. On the other hand, in cases where heading changes are not made explicit (i.e., when only lanes are shown) and no physical motion is present, drivers have trouble intuiting how steering inputs affect vehicle position, seemingly neglecting the intermediate step of changing heading. Inertial information from real vehicle motion, however, supplies necessary information about vehicle turns when visual feedback is absent. The availability of vivid, valid inertial cues eliminates errors found in other lane changing experiments performed in driving simulators. Our results reveal the importance of inertial information, particularly when visual information is lacking.

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