An Unexpected Role for Visual Feedback in Vehicle Steering Control

Guy Wallis,[1,2,3] Astros Chatziastros,[1]
and Heinrich Bülthoff[1]
[1]Max Planck Institute for Biological Cybernetics
Spemannstraße 38
Tübingen
Germany
[2]Perception and Motor Systems Lab
School of Human Movement Studies
University of Queensland
Queensland, QLD 4072
Australia

Summary

Some motor tasks can be completed, quite literally, with our eyes shut. Most people can touch their nose without looking or reach for an object after only a brief glance at its location. This distinction leads to one of the defining questions of movement control: is information gleaned prior to starting the movement sufficient to complete the task (open loop), or is feedback about the progress of the movement required (closed loop)? One task that has commanded considerable interest in the literature over the years is that of steering a vehicle, in particular lane-correction and lane-changing tasks. Recent work has suggested that this type of task can proceed in a fundamentally open loop manner [1, 2], with feedback mainly serving to correct minor, accumulating errors. This paper reevaluates the conclusions of these studies by conducting a new set of experiments in a driving simulator. We demonstrate that, in fact, drivers rely on regular visual feedback, even during the well-practiced steering task of lane changing. Without feedback, drivers fail to initiate the return phase of the maneuver, resulting in systematic errors in final heading. The results provide new insight into the control of vehicle heading, suggesting that drivers employ a simple policy of "turn and see," with only limited understanding of the relationship between steering angle and vehicle heading.

Results

Background

Imagine changing lanes on a motorway/freeway. In particular, try to recall the series of angles through which the steering wheel passes in completing the maneuver. The vast majority of us describe turning the wheel out to 20° or 30° and then returning the wheel to the middle position. Our intuition in this case is, however, wrong. It is wrong because we have failed to describe the appropriate symmetrical movement of the steering wheel in the opposite direction required to straighten the car. To better characterize this apparent omission, we conducted a pilot study in which we asked ten subjects to

[3] Correspondence: gwallis@hms.uq.edu.au

act out the steering movements required to change lanes. All ten demonstrated little or no evidence of a symmetric steering movement in the opposite direction of the initial steering movement. What is more, when asked to act out turning a corner, they produced exactly the same steering pattern, but with a larger maximum amplitude (means: 30.9° and 64.0°, respectively) (see the Supplementary Material available with this article online). In order to better understand the significance of this mistake, it is instructive to consider the relationship between steering wheel movement and lane position in this type of task. Figure 1 conveys this relationship, revealing the biphasic nature of the task. The aim of this paper is to investigate whether an inability to imagine the correct motor behavior transfers to an inability to complete the maneuver in a real driving situation. Our results reveal that subjects do indeed make the same mistakes in a driving simulator when no visual feedback is provided and that this reveals something fundamental about how humans steer vehicles.

Various models of vehicle steering control have been advanced, most of which assume the availability of regular, if not continuous, visual feedback [3–7]. Despite this, a considerable number of studies have demonstrated the ability of humans to carry out basic steering maneuvers in the absence of such feedback [1, 2]. In real driving situations, drivers have to attend to other road users and interior controls or gauges, and it therefore seems reasonable that many common tasks will incorporate a certain degree of automation [8]. Indeed, in contrast to our pilot study, Godthelp [1] and Hildreth et al. [2] provide evidence that some subjects can complete an entire lane correction in complete darkness, consistent with models of steering control that incorporate some degree of planning [3, 5] and revealing the limitations of models that make use of constant visual feedback [4, 6, 7]. Hildreth et al. [2] argue that their results are consistent with two possible models of steering control: one constrained by lateral position and steering wheel amplitude [9], the other, by the pursuit of a virtual target at the center of the lane [10]. Both models require drivers to estimate the change in relevant, visually perceived variables during periods of visual occlusion.

One explanation for the discrepancy between our pilot study and the results of Hildreth et al. [2] and Godthelp [1] may be that, in these studies, vision was only occluded for a few seconds. This allowed subjects to see the result of their attempt at the task and hence potentially to adapt their behavior [11]. Such adaptation runs the risk of obscuring the subjects' actual inability to complete the task in the absence of such learning. To test this possibility, our experimental work was conducted in a driving simulator that allowed subjects to be placed in a preset starting position at the beginning of each trial, without being privy to their success or failure in the previous trial. It also allowed the entire maneuver, from briefly before its inception though to completion, to be safely conducted in complete darkness.
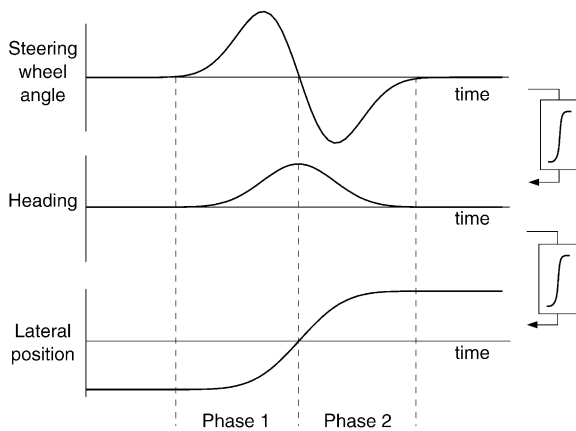
Figure 1. Lane-Changing and Lane-Correction Tasks Are Characterized by a Pair of Steering Movements, Phase 1 and Phase 2

In the case of a lane change, the first phase involves changing the vehicle's heading, so as to cross into the adjoining lane. The second phase involves an equal and opposite heading change required to straighten the vehicle.

Experiment 1: Without Task Performance Feedback

In the first experiment, we focused on the question of whether subjects can complete a lane change in the absence of visual feedback and, in particular, on their ability to regain their original heading. Eight subjects took part in the study, each completing a total of ten trials. All had corrected to normal vision and had held their driver's license for at least 2 years. The driving simulator consisted of a driver's seat and a console-mounted steering wheel. The steering wheel produced a return force proportional to its deflection from 0°, equivalent to that produced in a small family car. The simulated velocity of the vehicle was held constant at 65 km/h, with subjects being only required to steer. The simulated scene was generated by a Silicon Graphics Onyx II computer running at an update rate of 36 Hz, which was fast enough to prevent any motion artifacts in the projected image. The scene was projected onto a semicircular screen 7 m in diameter. Each subject was placed at the center of curvature of the screen, providing a 180° × 50° field of view. Before formal experimentation began, subjects were allowed to familiarize themselves with the simulator until they reported feeling comfortable with the controls. To familiarize the subjects with the task itself, they were twice shown a recording of a complete trial, driven earlier by one of the investigators.

At the beginning of each trial, subjects found themselves moving down either the left or right lane of a dual-carriage way, as shown in the top half of Figure 2. On the appearance of a green bar in the top 10° of the visual field, subjects were required to move into the adjoining lane and to continue heading down the road. The bar appeared for a total of 4.5 s. At the end of the road, a tunnel appeared in which visibility rapidly dropped to 0 m. Once it was completely dark, subjects once again saw the green bar, indicating that they should once again change lanes, but now back to the lane in which they originally started the trial. Thus, subjects were required to perform a lane change once with
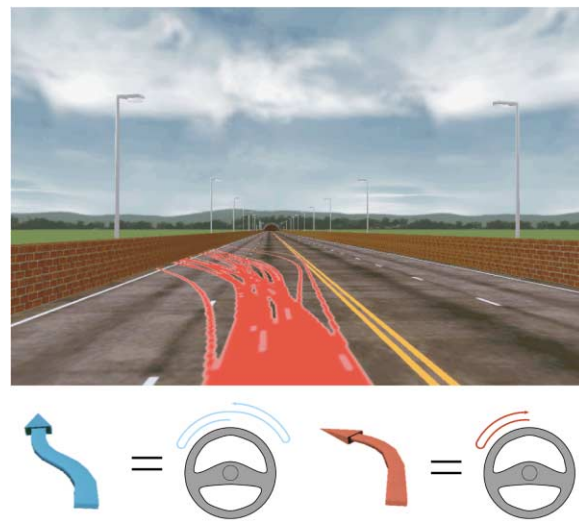

Figure 2. The Simulated Highway along which the Subjects Drove

Superimposed upon it, the first segment of 25 trajectories driven by subjects who were asked to move over from the right to left lane without visual feedback. The steering wheels below depict the movements necessary for a lane change on the left and to turn a corner on the right. In the absence of visual feedback, our subjects failed to produce a sufficient counterphase steering movement, resulting in a systematic deviation in final heading in the direction of the lane change.

visual feedback and once without visual feedback in every trial. The lane change with feedback was intended to give the subjects the opportunity to execute the maneuver successfully before each attempt in darkness. Each trial ended when the subject indicated that they were now pointed straight ahead, along the lane they originally started in. Subjects started the next trial by pressing a button attached to the console. At no time, from the onset of darkness to the start of the next trial, was any visual or other form of information provided to the subjects that might indicate their final position or heading at the end of the trial.

In the presence of full visual feedback, all subjects had no difficulty producing the biphasic steering movements required to change lanes successfully. However, in the absence of visual information, subjects showed an increase in the variability of their final heading. Such an increase is in and of itself unsurprising, because one would expect small errors to accumulate in the absence of visual information. However, the distribution of final headings was by no means random. Instead, subjects demonstrated a clear, systematic deviation of heading toward the direction of the lane change: $F(1, 7) = 33.443$, MSE (mean squared error) $= 14:75$, $p < 0.001$. Figure 3A shows the 80 trajectories driven by the 8 subjects, separated into left and right lane changes, and Figure 4A summarizes the final heading data for all trials, revealing the strong correlation between direction of lane change and final heading error. Figure 4B presents the results of Figure 4A broken down by trial, from which it is clear that the behavior remains consistent across trials.

Further studies of steering wheel angle revealed no measurable difference in the initial swing across the lane
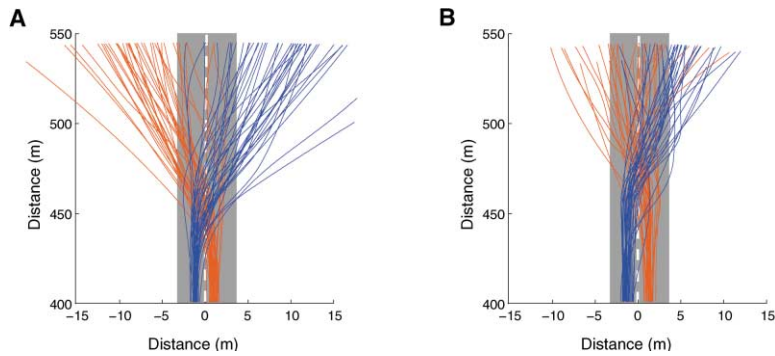
Figure 3. Overhead View of the Trajectories Steered by the Subjects in Both Experiments Covering a Period of 8 s from the Onset of the Lane Change

The entire 8 s were driven in complete darkness. Lane changes to the left appear in red, and those to the right appear in blue.

(A) Results for experiment 1. Note the systematic relationship between lane-change direction and final heading.

(B) Results from experiment 2 in which visual feedback was given at the end of the trial. Note the appearance of corrective steering movements as the subjects adapt their behavior from trial to trial.

from that under normal vision, but almost a complete lack of any return steering movement. In other words, the first steering phase appeared normal, whereas the second, straightening phase, was totally missing. Figure 5A presents steering wheel angle profiles for a particular subject broken down across trials. Comparison with the profile required to complete a lane change, given in Figure 1, clearly reveals the absence of the second phase of the steering movement. The subject repeated this behavior on all five repetitions of the left lane change presented, despite carrying out the maneuver successfully under normal viewing conditions before each trial.

It is worth adding that the data reported in the paper by Hildreth et al. [2] strongly suggest that, in the absence of visual feedback, any task requiring more than 2 s to complete leads to serious levels of driver disorientation. This is certainly consistent with the high variability of final headings obtained but makes the findings of this first experiment all the more remarkable. Despite the large variability in final heading, the distributions for left and right lane changes are still clearly differentiable.

Experiment 2: With Task Performance Feedback

The first experiment revealed a strong correlation between direction of lane change and final heading, suggesting that our subjects failed to complete the turning maneuver. This is at odds with other studies that demonstrate that subjects can complete the task. As described above, the main difference in experimental technique was that the previous studies provided visual feedback after completion of the maneuver, and we have argued that this was sufficient to alter the subjects' behavior

after even a single trial. To test this hypothesis, experiment 1 was repeated, but with the return of normal vision at the end of each trial.

The experiment proceeded exactly as before, except that 8 s after receiving the turn signal in the tunnel, normal visibility was restored. After the simulator familiarization phase, subjects once again watched a successfully completed trial twice to familiarize themselves with the task. By not actively steering in the task familiarization phase, they remained naïve and therefore comparable to the subjects in experiment 1. Subjects were instructed to complete the steering maneuver well before visual feedback was restored.

The 80 trajectories driven by the subjects appear in Figure 3B. In contrast to the results in experiment 1, the final headings appear randomly distributed around $0°$ (corresponding to the longitudinal axis of the road). The means of these final headings are given in Figure 4A. An analysis of variance revealed no significant effect of lane-change direction on final heading: $F(1, 7) = 1.83$, $MSE = 26.88$, $p = 0.218$. There was a slight tendency to oversteer right, which was nearly significant at the 5% level: $F(1, 7) = 4.78$, $MSE = 31.9$, $p = 0.065$. The source of this bias is currently unknown. It may be due to handedness (seven of the eight were right-handed), or it may be affected by which side of the road one drives on (Australians drive on the left and therefore overtake to the right). These and other possibilities are the subject of further studies. Figure 4B portrays the results of experiment 2 broken down by trial. It is clear that, in contrast to experiment 1, the final heading rapidly converges to $0°$ as more experience is accrued. In Figure
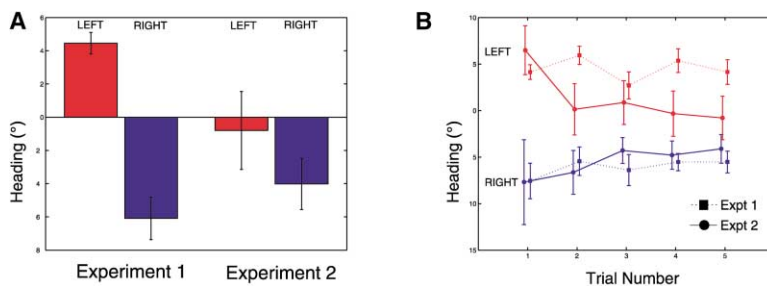

Figure 4. Summary of the Final Heading Data for All Subjects Separated by the Direction of the Lane Change

Error bars indicate standard error of the mean.

(A) Results averaged over trials, revealing a clear link between final heading and the direction of the lane change in experiment 1. Results for experiment 2, in contrast, reveal that the final headings for left and right lane changes were indistinguishable both from one another and from $0°$ (i.e., straight ahead).

(B) The same results broken down into individual trials, revealing no learning in experiment 1, but a trial by trial reduction in final heading error in experiment 2.
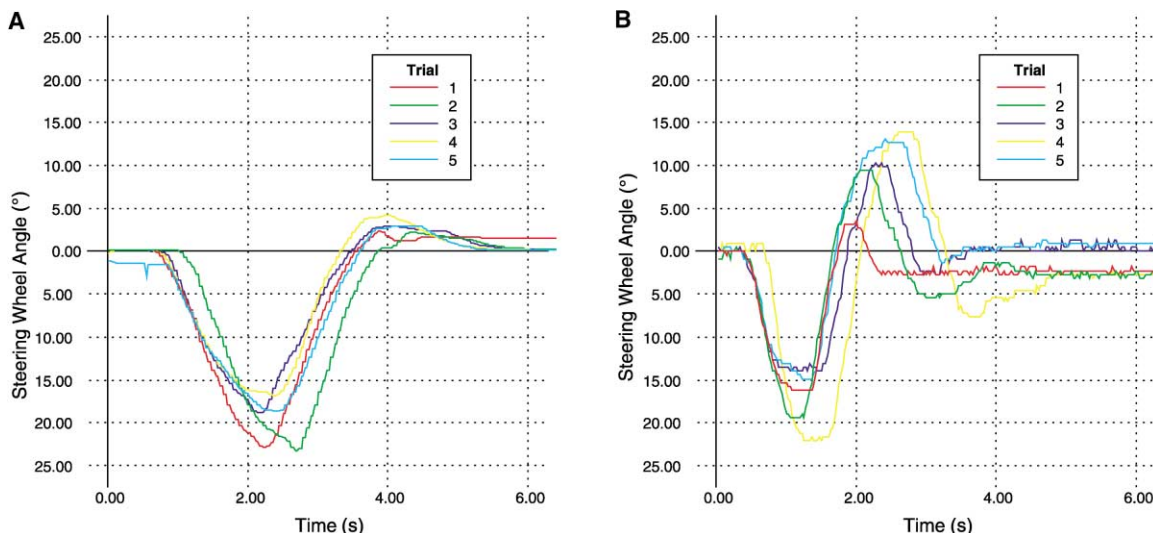
Figure 5. Steering Wheel Angles Adopted by Two Subjects When Executing a Series of Lane Changes from the Right- to the Left-Hand Lane

(A) Subject A participated in experiment 1. The subject received no visual feedback during the experiment and, as a result, repeatedly failed to regain the vehicle's original heading.

(B) Subject B took part in experiment 2. The subject failed to steer strongly enough to regain original heading in the first two trials but rapidly increased the return steering amplitude as more experience was accrued. After two or three trials, the typical behavior for the no feedback condition disappears.

5B, the steering wheel angle profile is reported for a subject who took part in the second experiment. While trials 1 and 2 show a weak second steering phase comparable to performance by subjects in experiment 1, by trial 3 the second phase is well established. In other words, only one or two trials suffice to completely alter this subject's behavior in the presence of visual feedback. Note that this makes the results of experiment 2 all the more striking. Clearly, the subjects in experiment 2 were just as naïve as those in experiment 1 when they started. Hence, the first few trials contained the same systematic errors, which led to the effect measured in that experiment. This is a major contributing factor to the residual difference in heading measured in experiment 2.

Unlike the results of experiment 1, the results are now consistent with those of Godthelp [1] and Hildreth et al. [2], in as far as the final heading shows no consistent patterning as a function of lane-change direction. Hence, we can conclude that providing visual feedback at the end of each trial causes drivers to alter their steering behavior. Evidently, drivers are able to change lanes without visual feedback, but only by learning to alter their behavior in this way. Normally, drivers must have further visual information at some point during the maneuver to initiate the second phase of the steering maneuver.

Discussion

This paper has revealed that, without specific training, even experienced drivers are unable to complete a lane-change maneuver in the absence of visual feedback. While the initial phase of a lane-change maneuver can be conducted apparently normally, the second is almost entirely lacking. As such, lane changing appears to be neither exclusively open nor closed loop in nature. More work will be required to establish the precise nature of the control process, but it appears that the first phase can proceed without visual feedback, suggesting that the second can too, but that it must first be initiated via a second, brief exposure to visual information. Taken as a whole, the results suggest that humans rely on a "turn and see" approach to steering control, in which they steer once and then prepare the next steering movement on the basis of their new heading. Models of steering control that attempt to explain human behavior have, until now, attempted to explain how multiple steering movements can be generated in the absence of visual feedback. By incorporating the results described here, the models stand to become both simpler and more compact.

The inability of our subjects to complete the lane-change maneuver also tells us that drivers are naïve as to the effect a steering wheel has on their direction of heading. While this may at first seem surprising and possibly disturbing, such naïvety is typical of driving behavior. Land and Tatler [12] describe a comparable naïvety in racing drivers who consistently but unknowingly rotate their heads when negotiating a bend. Under normal viewing conditions, our subjects' naïvety is unimportant because a second steering movement is naturally initiated once they perceive their incorrect heading.

As a final aside, the results also have potential ramifications for vehicle design. If the steering wheel is not the intuitive steering device we all imagined, is there a more intuitive or safer alternative? Steering wheels are a serious aggravating factor in motor vehicle accidents [13–15] even though, or indeed sometimes because, an airbag is installed [16–18]. Certainly alternatives exist. Joysticks, for example, are used in the mining and farming industry to steer specialist vehicles, as well as in

the aviation industry in the form of the European Airbus. However, choosing an alternative is not trivial. A steering wheel provides information about the current angle of the front wheels, it allows various grasping positions to be adopted, reducing fatigue, and the driver can grip the wheel firmly on rougher road surfaces. For these reasons, further investigation will be required to isolate a truly advantageous alternative.

Supplementary Material
Supplementary Material including preliminary results from a follow-up experiment is available at http://images.cellpress.com/supmat/ supmatin.htm. The purpose of this experiment was to test the validity of the original work that was conducted in a fixed-base simulator. In the new experiments, the same steering task was conducted, but in a whole-car driving simulator, incorporating a motion platform, a fully instrumented car, and all-around vision.

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