The role of visual and non-visual feedback in a vehicle steering task

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Abstract

This paper investigates vehicle steering control, focusing on the task of lane changing and the role of different sources of sensory feedback. Participants carried out two experiments in a fully instrumented, motion based simulator. Despite the high level of realism afforded by the simulator, participants were unable to complete a lane change in the absence of visual feedback. When asked to produce the steering movements required to change lanes and turn a corner, participants produced remarkably similar behavior in each case, revealing a misconception of how a lane-change maneuver is normally executed. Finally, participants were asked to change lanes in a fixed-based simulator, in the presence of intermittent visual information. Normal steering behavior could be restored using brief but suitably timed exposure to visual information. Our data suggest that vehicle steering control can be characterized as a series of unidirectional, open-loop steering movements, each punctuated by a brief visual update.
Introduction

Many everyday motor control tasks require the coordination of multiple phase movements. In the case of motor-vehicle control, any maneuver more complex than turning a corner requires multiple, active steering movements. Whilst there is general agreement in the literature that corner turning can be performed in an open-loop manner, only requiring visual feedback at the end of the maneuver, other simple tasks such as lane changing and lanekeeping have proven a source of considerable debate. As lane changing and lanekeeping are two of the most fundamental aspects of driving they have often been used as a testbed for models of steering control. In this paper we focus on the task of lane changing. We used a driving simulator to investigate the role of both visual and non-visual cues in guiding this maneuver.

A large number of models of steering control have been advanced over the years. These differ in many ways, but can be categorized in part by the degree to which they require visual feedback (McRuer, Allen, Weir, & Klein, 1977; Donges, 1978; Reid, Solowka, & Billing, 1981; McRuer & Weir, 1969; Modjtahedzadeh & Hess, 1993; MacAdam, 2003). The importance of visual information in driving is indisputable (MacAdam, 2003), even if the exact proportion of its influence remains a matter of often poorly substantiated debate (Sivak, 1996). Over and above its level of importance, however, the question arises as to whether the feedback which it provides need be continuous or not. In real driving situations, drivers have to attend to other road users and interior controls or gauges without this adversely affecting their ability to control the vehicle. It therefore seems reasonable that many common steering tasks will incorporate a certain degree of open-loop control, free from the need for continuous visual input (Salvucci, 2001). Consistent with this idea, several more recent studies have demonstrated the ability of humans to carry out basic steering maneuvers in the absence of visual feedback either during lane corrections (Hildreth, Beusmans, Boer, & Royden, 2000; Godthelp, Milgram, & Blaauw, 1984), lane changing (Godthelp, 1985) or curve driving (Godthelp, 1985; Land, 1998). This work, in particular the first three studies, suggests that a driver who intends to make a multi-phase steering movement such as a lane change or lane correction, prepares his/her steering movements in advance, executes these movements with the appropriate timing and force, and only at the end of the maneuver does he/she require visual feedback to compensate for accumulated errors. The results are consistent with models of steering control which incorporate at least some degree of planning (McRuer et al., 1977; Donges, 1978) and reveal the limitations of models that make use of closed-loop control (Reid et al., 1981; McRuer & Weir, 1969; Modjtahedzadeh & Hess, 1993). Hildreth et al. (2000) highlight two models of vehicle control capable of reproducing lane corrections in the absence of visual feedback. The first is constrained by lateral position and steering-wheel amplitude (Dorf & Bishop, 1995),
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the other by the pursuit of a virtual target at the center of the lane (Boer, Hildreth, & Goodrich, 1998). Both models require drivers to be able to estimate the change in specific visually perceived variables during periods of visual occlusion.

In a recent article, Wallis, Chatziastros, and Bülthoff (2002) observed that all of the earlier studies of open-loop control did not (often for safety reasons) remove visual feedback for more than a few seconds. The main problem with this approach is that participants were able to see the result of their attempt at the task. This type of visual feedback may have led to adaptations or strategic changes (Schmidt, 1988). It is possible, therefore, that participants in earlier studies adapted their behavior on the basis of visual feedback, and that this obscured their inability to complete the task in the absence of such learning. Wallis et al. (2002) went on to test this possibility using the lane-changing maneuver studied by (Godthelp, 1985), using a fixed-base simulator consisting of a table mounted steering wheel placed in front of a large projection screen. Use of a simulator allowed participants to be placed in a preset starting position at the beginning of each trial, and could prevent them from receiving visual feedback as 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. This work demonstrated that drivers cannot perform lane-changing maneuvers in the complete absence of visual feedback, as other studies have suggested. Wallis et al. (2002) went on to conclude that a lane change can be characterized by two phases of opposite steering motion, the second of which is substantially reduced or entirely missing in the absence of visual feedback - see figure 1.

The study described here aims to extend the original study by improving several aspects of the methodology used. The original studies used a simulator which afforded only a limited field of view, only a limited internal reference frame in times of darkness, and no non-visual sensory feedback other than the force-feedback supplied by the steering wheel. As Kemeny and Paneri (2003) point out, this lack of non-visual feedback could well have influenced performance in the lane-change task. Certainly, vestibular and somatosensory systems have the potential to provide important feedback control signals (Hosman & Vaart, 1990), and in driving simulations it has been shown that physical motion can augment driver performance (McLane & Wierwille, 1975; Kemeny & Paneri, 2003).

All of the experimental issues listed above can be addressed directly by allowing participants to drive a real vehicle, but it then becomes all but impossible to avoid providing some element of unwanted task performance feedback. In a real vehicle it is not safe to allow the driver to become disoriented, as inevitably happens after periods of more then a few seconds of darkness (Hildreth
et al., 2000). Also, the vehicle has to be returned to the starting point in each trial, potentially providing non-visual information about heading at the end of the previous trial. This paper reports data from a series of experiments which sought to greatly improve the level of realism whilst retaining the tight experimental control offered by conducting experiments in a driving simulator.

One other important issue not addressed in the original study by Wallis et al. (2002) is the assumption that participants are attempting to complete the lane-change maneuver in a truly symmetric manner. Returning to figure 1, it should be noted that any number of biphasic steering movements could be used to produce a lateral shift in vehicle position. The only constraint is that the area under the steering wheel profile (top trace in the figure) sum to zero, producing an overall zero heading change. It is quite possible that drivers normally introduce a degree of asymmetry in the two steering phases when changing lanes. If, for example, subjects have a tendency to produce a first phase which is more pronounced in terms of maximum steering-wheel amplitude than the second, then it may simply be the weak nature of the second phase that allows it to be overlooked by drivers in the absence of visual feedback. This issue is tested empirically as part of the first two experiments.

The first major hypothesis of this paper is that non-visual cues play a role in guiding steering behavior, and that by providing proprioceptive feedback via a moving-base motion platform, correct, two-phase steering behavior will be produced, even in the absence of visual feedback. This question forms the focus of the first two experiments which test steering behavior at numerous velocities in a high-fidelity driving simulator. Analysis of the experiments includes a model of the likely levels of proprioceptive stimulation at the different simulated vehicle speeds. In practice, the first two experiments provide compelling evidence that in the absence of visual feedback, drivers effectively turn a corner rather than change lanes. These results then motivate a third experiment in which the question is raised as to whether participants will alter their erroneous lane-changing behavior if they are required to enact corner turning as well as lane-changing maneuvers. The final experiment considers the second major hypothesis, that lane changing can be said to consist of two, open-loop control movements. A new task is tested in which brief exposure to visual feedback is provided at the crossover point between the first and second phases of the lane-change maneuver, to see if such a brief exposure is sufficient to restore normal behavior.
Experiment 1: Lane changing in a driving simulator

Introduction

This experiment was intended as a direct replication of the original experiment by Wallis et al. (2002), but using a fully instrumented, tilting motor vehicle placed in a driving simulator with 240° wrap-around screen. By increasing the level of realism in this way we aimed to ascertain the role of non-visual cues in lane changing, as well as the possible use of a visual reference frame provided by a vehicle windshield and dashboard.

Methods

Ten volunteers, aged between 26 and 39 years, took part in the experiments. All had at least three years of driving experience although four had over fifteen years. All ten participants were naive as to the purpose of the experiment. Experiments were conducted at the Monash University Accident Research Center in Melbourne - see figure 2A. The simulator consists of a fully instrumented vehicle mounted on a 3 degrees of freedom motion platform, capable of simulating natural vehicle roll, pitch and elevation (See figure 4). Elevation control is useful for simulating the rumble of tires on a natural road surface. The participants completed 20 trials each: ten lane changes to the left and ten to the right. The road itself consisted of a divided highway with two lanes running in either direction. Consistent with standard driving practice in Australia, the drivers were asked to drive in either the left or right-hand lane on the left-hand side of the four lane highway - see figure 2B. The vehicle’s steering-wheel produces realistic return forces of up to 3Nm. In the simulator the level of return force was calculated on the basis of both static and dynamic vehicle properties ranging from tire type to vehicle speed and acceleration. In practice, the overall return force generated rose approximately linearly with steering angle (up to a saturation point of around 3Nm), in a manner similar to a family car, and in accord with comparable driving simulators (Toffin, Reymond, Kemeny, & Droulez, 2003).

Testing was alternated on each trial between the two lane-change directions. Each trial was initiated by the participant, who was instructed to accelerate the vehicle to obtain a vehicle speed of 50 km/h, whilst positioning themselves in the appropriate starting lane. Instructions for each trial were provided by the simulator operator via an in-vehicle intercom. Whilst still under normal viewing conditions, the drivers were asked to complete one lane change. This helped confirm their ability to produce the correct steering behavior under normal viewing conditions, but also served
to remove any effects of disorientation caused by the latter half of the preceding trial. During this latter part the participants were asked to produce steering movements in the absence of visual feedback. Visual feedback was removed by allowing the participants to enter a dark tunnel which rapidly reduced road visibility to zero meters. Once in the tunnel, the participants were requested to return to the lane they had just left, i.e. produce the complementary lane change to that conducted under normal viewing a few moments earlier. The participants were asked to slow the vehicle to a stop once they were satisfied that they were in the correct lane. Simulator state parameters including vehicle speed, tilt, steering-wheel angle and vehicle heading were recorded at a rate of 30 Hz. The final heading of the vehicle, once stopped, was used as the main dependent variable of the analysis.

Results

Results from the first experiment appear in figure 3. Figure 3A provides a bird’s-eye view of the road and the trajectories followed by the ten participants. All ten repetitions of each lane change are shown (left in light lines and right in dark). It appears that when changing lanes to the left our drivers veered off the road to the left, and when changing to the right they veered off right. Comparison of the first phase steering amplitude of lane changes conducted with visual feedback (before reaching the tunnel) and those without, revealed that they did not differ significantly from one another, $F(1, 9) = 1.46, \, d = 0.50$, not significant. This in turn suggests that the first phase of the maneuver is invoked satisfactorily, and that it is the second phase which is incorrectly executed. To test this further, maximum steering amplitudes were compared from the two steering phases of the maneuver completed without visual feedback. The second phase amplitude was found to be less than half of the first phase ($20.1^\circ$ versus $10.2^\circ$) and of much shorter duration (approximately 3.5 times shorter). A repeated measures ANOVA was run with steering phase and lane-change direction as independent variables and steering-wheel amplitude as dependent variable. The analysis confirmed that the difference in steering phase amplitudes was highly statistically reliable, $F(1, 9) = 14.84, \, d = 1.26, \, p < .005$.

The results are in general agreement with the results reported by Wallis et al. (2002). Although there are perhaps two or three occasions in which subjects do regain their original heading, they represent no more than 1% of the total number of trials driven. Figure 3B summarizes the behavior by presenting the drivers’ average heading as a function of time, from the moment they entered the tunnel. In this case the average heading is remarkably left-right symmetric. In the earlier report by Wallis et al. (2002), there was some evidence of a slight asymmetry, but it is not evident
here. Under the current conditions, with a large number of repetitions, the final heading in each case appears equal in magnitude and variability. A repeated measures ANOVA with lane-change direction as a main factor and final heading as the dependent variable, revealed a statistically reliable difference, \( F(1, 9) = 21.82, \ d = 2.4, \ p < .01 \).

Based on the recorded vehicle rotation angles it is also possible to estimate the level of non-visual stimulation which our drivers would have experienced, with particular reference to the issue of whether stimulation would have been above known detection thresholds. To assess this we need to consider the degree of body rotation experienced by the participants about the three major axes (see figure 4). Figure 5A presents the average body roll separated into left and right lane changes. It is apparent that at this moderate vehicle velocity the amount of vehicle roll is very small, with a maximum amplitude of around 0.3 deg. If these changes in vehicle roll are to be influential in performance they must be above threshold. Thresholds for detection of body rotations depend on many factors including posture, exposure levels and the presence of visual cues (Warren & Wertheim, 1990; Benson & Brown, 1989; Benson, Hutt, & Brown, 1989). The most relevant measures have been made by Benson and Brown (1989). Their study focused on seated participants who experienced a single sinusoidal forcing function, similar to that experienced by a driver during a lane change. The relationship between angular acceleration \( \ddot{\theta} \), angular velocity \( \dot{\theta} \), and angular displacement \( \theta \) for a sinusoidal forcing function are as follows:

\[
\ddot{\theta} = A \sin(\omega t) \\
\dot{\theta} = \frac{A}{\omega} (1 + \cos(\omega t)) \\
\theta = \frac{A}{\omega^2} (\omega t - \sin(\omega t))
\]

The function \( \theta \) has a maximum, \( \dot{\theta} \), at

\[
\dot{\theta} = \frac{2\pi A}{\omega^2}
\]

An example of this function applied to the roll axis, \( \theta_r \), appears in light gray in figure 5A, fitted to the mean of the actual roll angles produced by our volunteers. The actual rotational movement about the roll axis approximates well to \( \theta_r \), suggesting that the outward rotation of the steering wheel was approximately sinusoidal in form. In this particular case, the maximum body roll displacement, \( \dot{\theta}_r \), was 0.25 deg. This maximum is achieved in approximately five seconds, i.e. \( \omega_r = 1.257 \). The corresponding cosine bell velocity profile \( \dot{\theta}_r \) (see second equation above) has
an amplitude $A/\omega_r = 0.16$. The thresholds described by Benson and Brown (1989) are given in terms of this velocity amplitude and hence the ability of the stimulation to be detected by our participants can be deduced. In practice, however, rather than fitting the average vehicle roll data, a more appropriate measure is obtained by applying this technique to individual trials. Using the same methodology, all 200 individual trials were fitted with $\theta_r$ functions and the amplitude of $\dot{\theta}_r$ deduced. The results appear in figure 5B. The values given by Benson and Brown (1989) vary as a function of frequency. In the range 0.1 - 0.5 Hz, thresholds are around 2 deg/s. This value is much higher than the amount of roll produced in these experiments. That said, the conditions described by Benson and Brown (1989) are not identical to those used here, in as far as our drivers had their eyes open and could see the interior of the vehicle. Benson et al. (1989) report a decrease in thresholds by a factor of five or more in the presence of a visual reference frame which rolls with the driver. As a result, thresholds as low as 0.4 deg/s are possible in the experiments described here.

A similar process can be used to estimate rotation about the pitch and yaw axes. For fixed vehicle velocities, changes in pitch are minimal and so they are not considered further here. Changes in yaw, on the other hand, can be quite large. Unfortunately, physical yaw cannot be reproduced by the simulator as it does not possess the ability to rotate the vehicle. It is nonetheless interesting to consider the size of the yaw signal which a driver would experience, if only to gauge its potential for influencing lane-change maneuvers. Returning to figure 3B, the $\theta_y$ function achieves a maximum displacement $\dot{\theta}_y = 2\pi A_y/\omega_y^2 = 9.1$ deg, with angular frequency $\omega_y = 0.628$. The maximum heading is equivalent to yaw rate amplitude, i.e. $A_y/\omega_y = 0.91$. For the final estimates of $\dot{\theta}_y$ maximum heading values were extracted for each of the 200 individual trials. The results appear in figure 5B. The thresholds described by Benson and Brown (1989) vary once again as a function of frequency. In the range 0.1 - 0.5 Hz, thresholds are around 1.5 deg/s, which is similar to the measured yaw rates.

Another source of non-visual input to the lane-change control system is lateral acceleration. As with yaw, a standard driving simulator is unable to simulate (long-lasting) lateral accelerations. Nonetheless, some simulators are able to mimic lateral acceleration using a brief tilting motion in the opposite direction to the natural vehicle roll (Reymond, Kemeny, Droulez, & Berthoz, 2001). The Monash simulator was designed to include such cuing and it was the experimenters’ subjective impression that such accelerations were noticeable at high rates of heading change. However, analysis of the subject’s data suggests that the levels generated by our drivers changing lanes were rarely greater than the cyclical rumble deliberately placed on the actuators to simulate a natural road surface. Bearing in mind the limited nature of the lateral acceleration simulated here, one can nonetheless consider its potential for influencing behavior. Benson, Spencer, and Stott (1986) have
made measurements of detection thresholds in which they subjected their participants to sinusoidal lateral accelerations of the type experienced by drivers when carrying out a lane change. Lateral acceleration was estimated from the maximum yaw rate (based on maximum heading angle) and the vehicle’s speed, the product of which is equal to the amplitude of the lateral acceleration sinusoid. Estimates of this amplitude were made for all 200 trials. The average acceleration amplitude was 0.59 m/s^2 which is well above the threshold level of around 0.06 m/s^2 reported by Benson et al. (1986).

Finally we now consider another issue raised at the beginning of the paper, namely the question of maneuver symmetry. The model of Wallis et al. (2002) tacitly assumes that the two steering phases are approximately equal and opposite. If they are not, and the second phase is actually weaker, this may serve to explain why the second phase is so easily overlooked by our drivers in the absence of visual feedback. To test this, driver behavior in the task was collated during the first lane change in each trial, i.e. the lane change conducted under normal viewing conditions. Figure 6A presents the average maximum steering amplitudes during the two phases. The interesting point to draw in both cases, is the fact that far from being smaller, the second phase amplitude was actually larger than the first. For a left lane change the difference was not significant \( t(9) = 1.98 \), not significant, whereas for a right lane change it was \( t(9) = 4.34, d = .61, p < .025 \).

**Discussion**

The focus of this first experiment has been to test the findings of Wallis et al. (2002) using a considerably improved level of realism, both in terms of the driving simulator and vehicle controls used. The main result is clear. The errors seen in previous studies have been successfully reproduced and the average heading error of 8.5 deg, is larger than the 5 degrees which they reported. Given the high level of realism offered by the driving simulator it seems that the evidence for the simple ‘turn and see’ approach to vehicle control is reliable. This permits us to draw two major conclusions. First, that providing a visible reference frame in the form of a windshield and dashboard makes no difference to the overall lane-changing behavior. Second, that moderate levels of non-visual stimulation also fail to promote initiation of the second steering phase. Clearly, the levels of non-visual stimulation offered by the simulator are small, and given the inability of the simulator to reproduce yaw, and the relatively low roll rates achieved, only moderate levels of non-visual feedback were available to our subjects. Nonetheless, on the basis of this experiment, we can conclude that for speeds up to 50 km/h, the findings are consistent with the earlier findings.

The results also revealed evidence for a small, but systematic difference in steering amplitude between the first and second phase of a lane change, when performed under normal viewing con-
ditions. In contrast to the suggestion raised at the beginning of the paper, far from being a weak counterpart to the first phase, the second phase was either indistinguishable or slightly larger in amplitude than the first. This serves to dispel any suggestion that the failure of our drivers to complete the second phase in the absence of visual feedback is somehow related to the fact that the second steering phase is of smaller amplitude and longer duration than the first.

Experiment 2: The effects of vehicle speed

Introduction

The previous experiment established that the systematic errors in final heading seen in earlier studies were not due to a lack of realism. Certainly one can conclude that inclusion of a realistic visible reference frame does not motivate drivers to initiate a second steering phase, and nor does moderate levels of proprioceptive feedback. The purpose of this second experiment is to test whether this effect spans the entire range of normal driving speeds at which somatosensory and vestibular input are likely to be much larger. This study was therefore directed at testing this issue by measuring driver behavior over a range of speeds up to 120 km/h.

Methods

Ten participants took part in the study. All had corrected to normal vision and were aged between 23 and 48 years. There was a fairly large range of driving experience, with one driver having only driven for three years, whereas four others had been driving for over 20 years. All ten participants were naive as to the purpose of the experiment.

The participants’ task was identical to that in experiment 1 except that on any given trial they were instructed to accelerate their vehicle to one of five set velocities (40, 60, 80, 100 and 120 km/h). Each participant completed a total of six trials at each velocity (three right and three left), making a total of 30 trials each. Care was taken in selecting the length of the visible section of road (before the tunnel) to ensure that even at the highest velocity, the drivers had time enough to complete each part of the instructed maneuvers. At just over 600 m in length it allowed over 20 seconds for the acceleration phase and first lane-change maneuver to be carried out before entering the tunnel.
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Results

Before analysis began, all of the final headings obtained from the ten participants were grouped by direction and speed. Outliers were calculated across individuals on the basis that they were more than 3 standard deviations from the group mean. Seven outliers were identified from the 300 trials on the basis of this criterion and excluded from subsequent analysis.

The average heading over time for the remaining 293 trials appears in figure 7, as measured from the moment the vehicle entered the tunnel. The figure is split into six panels, one for each of the five vehicle speeds. The sixth panel displays the final heading of the vehicle at the moment the subjects halted the vehicle, indicating that they believed they were facing straight ahead in the appropriate lane. As in experiment 1, the participants are attempting to produce an overall change in heading qualitatively equivalent to the second plot of figure 1. However, there was a strong tendency for the vehicle to veer left when changing lanes to the left, and right, when changing to the right, once again in accord with the findings in experiment 1. This represents a systematic departure from the correct behavior. As before, this cannot simply be attributable to accumulating errors because of the distinction between the average final headings for a left versus a right lane change. Five separate, repeated measures ANOVAs were conducted at the five individual vehicle speeds with lane-change direction as independent variable and final heading as dependent variable. All of the final headings were significantly different, with the lowest difference recorded at 120 km/h, \( F(1, 9) = 26.93, d = 0.8, p < .01 \). A two-way repeated measures ANOVA with speed and lane-change direction as main factors confirmed that the overall difference in final heading was statistically significant, \( F(1, 9) = 24.75, d = 1.24, p < .01 \).

One of the expected effects of speed is that steering amplitudes will be reduced and hence heading errors. The two-way ANOVA described above did indeed reveal a significant effect of speed \( F(4, 36) = 3.567, MS_e = 24.43, p < .05 \) corresponding to a decrease in final heading error with increased speed. The analysis also revealed a significant interaction \( F(4, 36) = 3.44, MS_e = 25.9, p < .05 \). The interaction was mainly attributable to a large asymmetry in final heading at the most extreme speeds (40 km/h and 120 km/h) as compared with intermediate speeds - see bar chart in figure 7. At the two extreme speeds, final heading for a right lane change, whilst on average negative, does not differ significantly from the correct response: a heading of zero degrees. In contrast, the final heading for a left lane change is consistently greater than zero, and significantly different from that for a right lane change. Overall, there appears to be a tendency in our drivers to veer left, and although most pronounced at the extreme speeds, it appeared under most conditions. One possible explanation for this is that the size of the heading errors differ for the two lane-change types. In order to test this, the final headings were converted into magnitudes as a new dependent
variable, with lane-change direction and vehicle speed as main factors. There was a main effect of vehicle speed $F(4,36) = 4.91$, $MS_e = 25.6$, $p < .01$, but there was no significant effect of lane-change direction $F(1,9) < 1$, not significant. The trend was for final heading error to decrease approximately linearly from 11 deg at 40 km/h to 5 deg at 120 km/h.

Reexamining figure 7, it is evident that our drivers did not enter the tunnel heading exactly straight ahead when making a right-hand lane change at 40 km/h or 120 km/h. Instead they headed off to the left (the darker trace has a small peak at or before zero seconds). It seems, therefore, that when the participants began the actual lane change under these two conditions, they were already heading slightly left of straight ahead. This has the effect of dragging the final heading response (which would ordinarily show a rightward bias) closer to zero degrees. Quite why this happens is unclear, but one can say that it only happened under the two most extreme conditions and does not alter the fact that the final headings were significantly different.

The development of vehicle roll with time appears plotted in figure 8 for the five vehicle speeds. Whereas peak heading amplitude tended to shrink as a function of speed, vehicle roll tended to increase. This is reflected in the sixth panel of the figure in which yaw and roll rate are plotted against vehicle speed. These angular rotation velocities were calculated using the same procedure described in experiment 1. Table 1 presents mean values of roll and yaw rate rather than medians, and reports the average duration of the fitted roll rotation. The roll rate and movement frequency increase fairly linearly as a function of speed, as does yaw frequency. Yaw rate, on the other hand, decreases with speed. The decrease does not appear to be linear, forming instead, a relatively smoothly decelerating function. The table also provides figures for the peak lateral acceleration. From 80 km/h and above, the roll rate is potentially large enough to be perceptible and hence influence behavior. There is no evidence for such an influence however, since the drivers continue to consistently head right when making a lane-change to the right, and left when making a lane-change to the left.

The final analysis to be conducted was on steering amplitudes during normal visual feedback (conducted before the participants entered the darkened tunnel) - see figure 6B. Amplitudes were very similar across a wide range of speeds, and were comparable to those reported in the results measured at 50km/h in experiment 1. The main pattern to emerge was a tendency for the first-phase amplitude to decrease as velocity increased, but for the second-phase amplitude to remain constant. Ten pair-wise comparisons were made of first versus second phase maximum steering amplitudes under the conditions of lane-change direction and speed. None of the comparisons produced a significant effect at an adjusted alpha level of .005.
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The findings of the first experiment were replicated over a wide range of vehicle speeds and in the presence of sizable, above threshold body roll. Overall there was a slight tendency to veer left, especially at the lowest and highest speeds, but it did not alter the fact that the final headings were reliably different. A slight bias in final heading direction has been reported before in these types of experiments (Wallis et al., 2002). A short analysis of some earlier data from an experiment conducted in Germany (n=6) also revealed a bias, in the same direction to drivers in Australia: 10.5 deg when right to left, and -6.7 deg for left to right, which was significant $t(5) = 3.50, d = 2.215, p < .01$. The fact that the bias is in the same direction irrespective of which side of the road one drives serves to discount several possible explanations for such a bias. For example, it is inconsistent with the suggestion that the drivers were veering away from oncoming traffic or that the relationship between lane-change direction and type of maneuver (overtaking versus returning to the inside lane) affects final heading errors. There was also no evidence that the handedness of our participants had any systematic effect on this bias. Despite its apparent consistency the effect may still be no more than noise. As we saw in experiment 1, given a sufficiently large number of repetitions of a particular condition, the effect disappears.

The discussion of minor biases aside, the main finding of this experiment is that final headings recorded in the experiment differed significantly across a wide variety of speeds. Results at the higher speeds are of particular interest because participants experienced suprathreshold body roll which apparently failed to alert them to the systematic steering errors they were making. The results also provide further evidence to support the assumption that under normal viewing conditions, drivers typically produce steering movements that approximate the idealized sinusoid displayed in figure 1, at least in terms of the max steering-wheel amplitudes being of the same size in each phase, irrespective of speed or lane-change direction.

Experiment 3: Enacting a lane change

Introduction

One of the surprising consequences of the results of previous two experiments is that in the absence of visual feedback, participants only perform the first phase of a lane-change maneuver, which is equivalent to turning a corner. One question which arises is whether participants would have produced this behavior if they had been allowed to conduct a normal array of steering movements.
including turning corners, or if this might have prompted them to realize that their lane-changing response must be incorrect. This short experiment looked at the simple task of enacting both turning and lane changing in the absence of visual feedback.

**Methods**

Five participants were chosen for this task, each with a minimum of 2 years driving experience. All five were naive as to the purpose of the experiment. Participants sat in front of a force-feedback steering wheel. The wheel produced a return force equivalent to a small family car with power assisted steering, traveling at a fixed speed of 60km/h. Return force was modeled as a linearly increasing function of 4.5Nm/rad, saturating at around 4Nm. Participants could see the steering wheel but were provided with no other form of visual feedback. The participants were told that they would be required to perform the steering movements which they would normally make in carrying out a lane-change maneuver to the right or to the left as well as the steering movements required to turn a corner to the left or right. Before conducting these maneuvers the participants were given the opportunity to practice them for three minutes. Participants were then asked to carry out each of the four maneuvers in a random order determined by the experimenter exactly once. Steering movements were recorded with an accuracy of 0.01 deg at a rate of 30 Hz.

**Results**

The recorded steering movements appear in figure 9. Each trace presents the single trial steered by each of our five participants. As is immediately clear from the figure, their responses were qualitatively identical under the four conditions. They produced a large initial steering movement in the appropriate direction, followed by little or no return-phase steering movement. The only subject to produce a small return-phase steering movement also chose to make much larger amplitude steering movements. Given the damped (but not critically damped) spring-like properties of a force-feedback steering wheel, it is unclear whether the return steering motion measured was due to overshoot of the self-realigning wheel or a deliberate second phase, counter-steering movement of the subject. The fact that the same subject also produced a small amount of counter steer when turning a corner (when it was not required) would tend support the idea that it was due to overshoot. Overall, it is apparent that drivers produce little or no counter steer irrespective of whether they were being asked to turn a corner, in which case this response was correct, or lane change, in which case it was incorrect. The only systematic difference between the two maneuvers was a tendency to make larger amplitude movements for turning a corner (mean peak amplitude = 64°) than for a lane change (28°).
Discussion

In the absence of any visual information, drivers can enact a corner turning maneuver seemingly normally. However, when faced with the task of changing lanes, they consistently omit the counter-steering phase required to straighten the vehicle and regain their original heading. This occurs despite their having the opportunity to carry out the two maneuvers in close succession. Such behavior is consistent with the idea that even experienced drivers have only a very rudimentary knowledge of the steering movements required to carry out the relatively simple task of lane changing. More specifically, it suggests that normal behavior requires visual feedback in order to motivate the second, counter-phase steering movement.

Experiment 4: Lane change with intermittent visual feedback

Introduction

One tentative conclusion which Wallis et al. (2002) sought to draw from their work is that a lane-change maneuver can be regarded as a pair of open-loop steering movements. The fact that the first phase is completed normally certainly suggests that once activated, a unidirectional steering movement does not require further visual feedback. However, it is not yet certain that the entire maneuver can indeed be characterized in this way. If it can, one might predict that a driver would be able to complete the second phase of the steering movement correctly if briefly exposed to visual information at an appropriate moment during, and possibly just subsequent to, the first steering phase. The purpose of this experiment was to ascertain at what moment and for how long, drivers require visual input to motivate initiation of the second steering phase, and then to go on to complete the maneuver normally.

Methods

For the final study we used a fixed-base simulator. Given the broad consistency between the results described in experiment 1 and 2, and those obtained in a fixed-base simulator (Wallis et al., 2002), we felt able to return to a fixed-based model without loss of generality. Six participants, aged between 20 and 29 years took part in the experiment. All but one held current driver’s licenses, with driving experience varying from 2 to 11 years. The drivers had normal or corrected-to-normal vision, and were naive as to the purpose of the experiment. Participants started a trial in one of
the two left-most lanes of the highway used in experiments 1 and 2, traveling at a fixed velocity of 72 km/h. Eight seconds after the trial started, the drivers passed a pair of red-white cones, indicating the starting point of the lane-changing maneuver. A stationary car was placed at a distance of 80 m beyond the marking cones. Participants were requested to steer between the cones and then to change lanes in order to draw alongside the vehicle in the middle of the adjacent lane - see figure 10A. By restricting the format of the steering maneuver in this manner, it was possible to produce a more stereotypical steering profile and hence exact better control over the moment at which significant stages in the maneuver were reached - such as lane-crossing point and first to second phase crossover point (see fig 1). Each trial lasted approximately 20 seconds. As in the first two experiments, the actual starting lane and direction of lane change was alternated between trials.

The participants viewed the scene and controlled their driving direction seated in the center of a large (7 m diameter), half-cylindrical projection screen. The front-projected scene subtended an angle of $180^\circ \times 50^\circ$. The simulation refresh rate and rate of data acquisition was set at 36 Hz. The experiment consisted of two sections. In the initial, familiarization section, participants executed 30 lane changes under normal viewing conditions. Subsequently, another 30 lane changes were carried out under reduced visual feedback.

The experiment was designed to establish a threshold time window within which participants were able to gain enough visual feedback in order to complete the lane-change maneuver accurately. This was achieved via an adaptive staircase procedure in which successful completion of the task (a heading at 4000 ms of within 1.5° of zero degrees) led to a reduction in duration of the time window by 50 ms. Failure to complete the task accurately brought about a lengthening of the time window by 100 ms. All timing was recorded with reference to the moment participants passed the traffic cones. After 500 ms, visual feedback was removed and only returned at 1750 ms, before being removed again for the remainder of the trial after 2250 ms. Hence, from the outset of the experiment the midpoint of the visual window lay at 2000 ms (the approximate center point of the complete maneuver). In subsequent trials, as adjustments to the time window were made on the basis of participant performance, this midpoint was maintained. In other words, increases in the time window were made symmetrically either side of 2000 ms.

**Results**

The drivers’ heading as a function of time from the onset of the maneuver is illustrated in figure 10B. As is evident from the figure, the heading deviation acquired during the lane change was corrected almost perfectly within the predefined period of four seconds. Accordingly, an ANOVA
failed to reveal any significant difference in the final heading (t = 4 s) between the two lane change directions $F(1, 5) = 1.21$, not significant.

The duration of the viewing window required by our participants to achieve this level of performance varied quite considerably. Table 2 reports summary statistics for all of the participants. The mean of the feedback duration over all trials was 675 ms, the mean of the minimal individual duration in successful trials (with absolute heading error less than 1.5 deg) amounted to 417 ms.

This second figure indicates that on average, less than half a second of intermittent visual feedback at the midpoint of the maneuver was sufficient to generate an appropriate return steering movement, such that final heading was within 1.5° of straight ahead. In practice, the absence of feedback at the end of the trial (in keeping with the earlier experiments) meant that the performance of participants did not asymptote over the series of trials, and hence accurate thresholds could not be established. Nonetheless, the minimum figures in the table indicate that even the most inaccurate of our participants were able to produce the correct behavior with a time window of as little as 800 ms.

Despite the confines which the task placed on our participants, there was also a degree of variability in the peak heading deviation ($h_{\text{max}}$) both between participants but also across the repetitions of a particular participant. In order to take into account variations in $h_{\text{max}}$, we computed a performance measure which we henceforth refer to as the heading compensation ratio (HCR), defined as $(h_{\text{max}} - h_{\text{final}})/h_{\text{max}}$, where $h_{\text{final}}$ is the heading direction at $t = 4$ s. The HCR can be taken as a measure of the extent to which drivers exhibited a steering response in the second phase of the lane change: A heading compensation ratio of 1.0 indicates perfect resumption of their original heading. A HCR less than unity indicates a less pronounced steering response, such that a heading error in the direction of the lane change remains.

In order to investigate the role of the visual window further we sought evidence for a relationship between temporal parameters of the window and the HCR. The first parameter to be investigated was window duration, but analysis failed to reveal any systematic relationship, $r = .061$, $t(178) < 1$, not significant. Focus now switched to window onset time. In order to perform this analysis a new variable $\tau_{\text{H}}$ was calculated. This was taken as the period between window onset and the moment at which maximum heading deviation was achieved in that particular trial - see figure 11. Using this measure ensured that onset time was measured relative to a driver’s actual steering profile on a specific trial, rather than more arbitrary, fixed referents such as occlusion onset time or the moment of passing the traffic cones. Ultimately this served to provide a more standardized measure of onset time, as well as serving to decorrelate window onset time (relative to passing the cones) from window duration. Correlating $\tau_{\text{H}}$ with the HCR yielded a significant negative relationship ($r = -.252$, $t(178) = -3.47, p < .01$ - see figure 11. Thus, an early window onset time
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relative to the maximal heading, tended to elicit a more pronounced second phase heading change, producing slight over compensation for the first phase. Over compensation (HCR > 1) actually occurred on 41% of the trials, strongly suggesting that unlike the previous three experiments, final heading error was no longer systematically related to the direction of lane change.

Discussion

The main result of this experiment is that in contrast to the results of the three previous experiments, heading error was almost completely eliminated when a brief amount of visual feedback was provided midway through the maneuver. Some participants were capable of straightening their car on the basis of visual information being provided for less than half a second.

The absence of a correlation between the duration of intermittent visual feedback and heading compensation accuracy is particularly interesting in this regard. This finding is in accordance with the view that visual feedback provided during execution of the lane change gives information about the instant heading error, and that drivers can prepare and execute a steering movement which depends on the magnitude of that error. However, the execution of the steering movement itself does not need to be monitored continuously, since an extended period of feedback is of little use for the ongoing steering movement. The lane-changing process as a whole can be regarded as a succession of two turns in opposite direction, each of which can be executed visually open-loop, as long as some information about the direction and timing of the next turn is available before initiation of the second phase.

Consistent with this idea is the negative correlation between feedback occurrence time and the HCR. It seems to be of some importance in which phase of the lane change drivers receive visual information: In the present experiment, heading was compensated best when intermittent feedback was given shortly (100 - 200 ms) after drivers had reached their maximal heading. This corresponds to the point in time when a driver has returned the steering wheel to the central position at the end of the initial pull-out phase, and is consistent with the idea that visual feedback can be best utilized when this first phase (executed in open-loop) is completed.

One of the interesting results to emerge from this experiment is apparent in figure 10, namely that the peak deviation in heading was reached briefly before the period of visual feedback occurred (on average 220 ms earlier). It is conceivable that our participants adapted their behavior in order to ensure that the feedback began shortly after the end of the first phase - a point in time at which they could make optimal use of the information.

We conclude that a brief period of visual information is required to instigate the second phase
of the steering movement, consistent with the proposal that a two-part, open-loop model of lane changing best describes normal drivers’ behavior. The period of the required visual information can be very brief for some drivers, but has to be administered at a specific moment in time within the overall maneuver.

General Discussion

Summary of the findings

The results as a whole speak against models of steering behavior which involve multiple, pre-programmed steering movements. That is not to say that drivers are incapable of carrying out multiple steering movements in the absence of visual information, but only after suitable training (Wallis et al., 2002). Without such training drivers appear not to implement motor programs that involve more than a single-phase steering movement. The results therefore provide strong support to the preliminary findings of Wallis et al. (2002), having now been reproduced in a more compelling and realistic environment. Their preliminary suggestion that the complete maneuver can be regarded as involving a pair of open-loop steering movements has also received new and detailed support in the final experiment.

In the first and second experiments, despite sizable, suprathreshold vestibular and somatosensory stimulation, participants continued to produce the same systematic errors in their steering behavior. It seems, therefore, that drivers are equally unaware of the need to counterbalance their lateral body tilt and lateral accelerations during the lane-change maneuver. As described in these two experiments, on the basis of these results alone one cannot rule out a role for yaw or prolonged lateral acceleration in guiding steering behavior, but the fact that roll and simulated lateral acceleration were not utilized, suggests that these sources of information may well also fail to activate the second phase of the steering movement. In contrast to the inability of non-visual, continuous feedback to elicit a return phase steering movement, the final experiment revealed that even brief periods of visual feedback approximately midway through the lane change were sufficient to instigate full-sized return steering movements. These results support the view that visual information is of vital importance in initiating the second phase of the lane change.

One obvious question that arises is how these results might be reconciled with earlier reports of drivers being able to complete lane-change tasks without visual feedback. Apart from the issue of learning described in the introduction, other issues also arise. Returning to the work of
Hildreth et al. (2000), they reported (experiment 4) that prolonged (4 second) visual occlusion greatly degraded overall task performance. Since the authors mainly focused on variability as a performance measure, some systematic heading deviation may have been present. That study also focussed on a somewhat different task (lane correction). In practice the similar two-phase nature of the task would lead us to predict that similar findings would emerge in the absence of task performance feedback. In an earlier study, Godthelp (1985) describes how periods of visual occlusion during the task can produce deviations from normal behavior, consistent with the view that the maneuver is not wholly open-loop in nature. For example, he reported that if feedback was removed for a short period (1 second) during the first phase of the lane change, drivers tended to produce exaggerated steering-wheel movements, which led to an increase in maximum heading deviation compared to normal driving. In a more recent series of real world experiments, in which different phases of curve driving were occluded, visual feedback was found to be indispensable, especially at the end of the curve: Novices as well as experts started to recenter the steering wheel too early, effectively producing a curve with enlarged radius (Cavallo, Brun-Dei, Laya, & Neboit, 1988). Indeed, although it has been reported that drivers can tolerate occlusion times of three to five seconds at low speeds (Godthelp et al., 1984), these values were derived during straight road driving, where drivers were not required to execute any steering movements.

Overall, we can conclude that models of vehicle steering control can most likely be considerably simplified, since there is no longer the requirement that steering movements can involve a direction reversal without appropriate visual stimulation. Despite this simplification, any successful model of steering behavior would still have to retain much of the sophistication included in modern models. Presumably some form of motor program exists to generate a single-phase steering movement of appropriate duration and amplitude which is scaled to the dynamics of the vehicle, its current speed and the type of steering maneuver being undertaken (lane correction, lane change, corner turning) (Modjtahedzadeh & Hess, 1993; Reymond et al., 2001; MacAdam, 2003). At a higher level, decisions need to be made as to the path a driver will take along the road (Prokop, 2001; MacAdam, 2003). Nonetheless, the crucial point of this study is that humans take a relatively simple approach to steering which we have characterized as ‘turn and see’. Extrapolating from these results we would argue that under a wide range of driving situations, drivers use short discrete visual updates to control steering, rather than continuous feedback.

**Models of steering behaviour**

In their recent paper, Hildreth et al. (2000) described two models, both of which were designed to elaborate the control of lane correction and lane changing tasks. One of their models, the final
target model, incorporates the anticipation of the driver. According to this model, the driver pursues a virtual target on the road, adjusting the steering-wheel in order to pass the target. During lane changing the lateral position of the target and its distance to the driver varies. At the beginning of the lane change, until the first steering-wheel maximum, the driver approaches the target, which is stationary in the lane the driver wishes to enter. This approach leads to the pull-out of the car. After this, the virtual target moves along the mid-line of the new lane with a speed less than the driver’s forward speed. By approaching the moving target, the driver initiates the realignment into the new lane. This phase covers the end of the first and start of the second phase (see figure 1), up until the second maximum steering-wheel deflection. Finally, the virtual target starts to move faster than the driver. In this phase, the driver recenters the steering wheel so as to drive straight in the new lane. According to the final target model, the driver extrapolates the target motion during occlusion periods.

If this model is correct, the failure of our participants to execute an entire lane change under total occlusion may be related to difficulties in extrapolating the motion of the virtual target. Specifically, in the second phase of the lane change the driver has to imagine approaching a moving target, which at some point in time speeds up and reverses its motion direction. During occlusion, the driver would be confronted with mentally extrapolating this non-linear trajectory with changes in speed and direction. Experimental findings suggest that humans are very good at extrapolating the linear motion of an object when its speed is constant, but that changes in speed are not predicted accurately (Bootsman & Oudejans, 1993; Runeson, 1975). When a more complex trajectory consists of both changes in speed and direction, mental extrapolation contains systematic errors, especially when not accompanied by spontaneous eye movements (Huber & Krist, 2004). The reason for the failure to complete a lane change may then lie in an inability to imagine a relatively complex future trajectory of the virtual target. If so, one would still have to explain how drivers are able, after just one or two trials, to adapt their behavior in the presence of visual feedback at the end of the maneuver (Wallis et al., 2002).

If, as we are suggesting, drivers choose to reduce heading control to a series of single phase open-loop steering movements, there is presumably a reason for this. One possibility is that constructing motor programs for multi-phase steering movements is less efficient, less accurate and less flexible for coping with a wide range of driving situations. Timing, duration, and amplitude of steering will vary enormously as a function of driving speed, lane width, environmental conditions, vehicle dynamics and so forth. It is certainly conceivable that in the presence of highly varied response requirements, internal models are too inflexible to cope, and a more piecewise approach is employed. That is not to say that the movement need, as a result, be disjointed or jerky. By extracting visual information at the appropriate moment, the second phase of the movement can
be prepared to dovetail with the end of the first. What it does mean is that failure to receive
the update at the appropriate moment can lead to catastrophic mistakes, as witnessed in the first
three experiments.

Although there is more research required on this topic, we would argue that the type of model we
are proposing for lane changing characterizes all vehicle driving behavior: Periods of automated
feed-forward control, punctuated by a visual update used to motivate the next single-phase steering
movement. The rate at which new updates are made would most likely be quite regular under
normal driving conditions but would almost certainly increase in frequency along windy or busy
roads, or in the event of unexpected deviations due to sudden side winds, tire blow-outs etc. It
seems likely that if vestibular cues ever play a dominant role in control, it is in instigating a rapid,
corrective response to such sudden surprise events. Under normal driving conditions, however,
their influence seems to be far less apparent. As we saw in experiment 1, subjects produce a
first steering phase of both normal amplitude and duration without any sensory input beyond the
feedback provided by the steering wheel.

The single-phase ‘turn and see’ model of steering control seems to do a good job in accounting for
the results described here but it is as yet unclear as to what extent these results will generalize to
other driving situations or other forms of locomotion. We know from previous studies that drivers
can perform multi-phase steering maneuvers given suitable training (Wallis et al., 2002; Hildreth
et al., 2000; Godthelp, 1985). It seems likely that this capacity may be of use in situations not
considered in this study. For example, during rapid obstacle avoidance maneuvers, which may
involve unusually large and rapid steering amplitudes (Reid et al., 1981), there may be too little
time for the use of visual feedback. Beyond the realm of motor vehicles it seems likely that pilots
may well learn to employ preprogrammed, multi-phase steering patterns due to the relatively poor
level of visual feedback which can occur when flying into a featureless sky, in cloud, or at night. It
is also true that studies with pedestrians suggest a sophisticated internal model of our environment
which can be reasonably accurately updated on the basis of proprioceptive cues (Philibeck, Loomis,
& Beal, 1997; Loomis & Beall, 2004). Hence, overall the implications for these results may well
be limited to the sphere of motor vehicle control.

Implications for applied research

One of the most surprising and telling conclusions to draw from these studies is that drivers are
naive as to the effect a steering wheel has on their direction of heading. This may have very
practical implications for vehicle design. As Wallis et al. (2002) point out in their paper, steering
wheels are a serious aggravating factor in motor vehicle accidents (Parkin, MacKay, & Cooper,
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Thomas & Bradford, 1995; NHTSA, 1997) even though, or indeed sometimes because, an air-bag is installed (Segui-Gomez, Levy, & Graham, 1998; Duma, 1996; NHTSA, 1999). A recent review of accident figures indicates that ten times as many deaths are due to inappropriate deployments of steering-wheel housed airbags than passenger-side airbags. The ‘turn and see’ approach to steering, suggests that we do not build sophisticated, multi-phase models of steering devices and that we are somewhat naive as to the effects which a steering device has on our heading over time. These facts in turn suggest that adaptation to other steering devices would be easier than more complicated models would predict, since complex internal models do not need to be learned. As a consequence the introduction of safer alternative steering devices may be considerably more feasible than previously thought.

Conclusions

Whatever the eventual implications for vehicle design, the fundamental message of this and our previous study, is that it may be possible to simplify models of human steering control given a driver’s reliance on visual feedback to initiate each phase of the lane-change maneuver. Needless to say, there are still several aspects of this story which requiring further investigation, such as its generalization to other modes of locomotion as well as to other steering maneuvers. It also remains to be seen what role more naturalistic lateral acceleration may play, especially considering its central role in some models of steering control (Modjtabazadeh & Hess, 1993; Reymond et al., 2001). Nonetheless, it remains the case that over a reasonable range of speeds and steering amplitudes, our drivers failed to produce even the most simple, biphasic steering movement when asked to carry out the everyday task of lane changing. Ultimately, our results imply that drivers - some of whom have spent 30 years and more at the wheel - are perfectly capable of carrying out complex steering movements despite a surprisingly poor understanding of the relationship between steering-wheel angle and changes in vehicle heading. We would argue that to do so, they use neither complex multi-phase steering patterns, nor continuous visual feedback, but rather, suitably timed samples of visual information which instigate brief periods of unidirectional, open-loop steering motion.

Notes and Acknowledgments

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References


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Fig. 1: Concurrent plots of idealized steering-wheel angle, heading change, and lateral displacement required to change lanes, plotted as a function of time. Note the biphasic nature of the steering-wheel movement required to shift the vehicle laterally from one lane to the next.

Fig. 2: (A) The Monash University Accident Research Center driving simulator, featuring 240° visual angle screen, fully instrumented vehicle, and motion platform. (B) Rendering of the simulated highway upon which the participants drove. Trials alternated the start position from left to right lane.

Fig. 3: Results from experiment 1 in which participants drove at 50 km/h and attempted to change lanes to the left or right. (A) Trajectories for all ten participants during ten left lane (light) and ten right lane changes (dark). (B) The same results plotted as average heading over time - the dotted lines indicate ± one standard error of the mean heading. Zero seconds corresponds to the moment of entering the tunnel at which point visual feedback was removed.

Fig. 4: Summary of the three primary axes of rotation of a motor vehicle. Rotations about these axes produce three distinct types of rotatory motion referred to as: Yaw (equivalent to a heading change), Pitch (tipping forwards or backwards), and Roll (tipping to the left or right).

Fig. 5: (A) Average vehicle body roll angle versus time. The dotted lines indicate ± one standard error of the mean angle. The minor, high-frequency oscillation is a result of simulating road noise. Superimposed over the plot, the equation for the best fitting half sinusoid used to estimate roll velocity. (B) Amplitude of role and yaw velocities experienced during the lane-change maneuver. Bars indicate the median value over the 200 trials. Error bars indicate the upper and lower quartiles.

Fig. 6: (A) Maximum steering amplitude in the two phases of a left and right lane change, conducted with normal visual feedback at 50 km/h. The two amplitudes are very similar, suggesting that participants adhere reasonably closely to a symmetric steering pattern during normal execution of the maneuver. (B) Maximum steering amplitude in the two phases of a left and right lane change, conducted with normal visual feedback at a range of vehicle speeds.

Fig. 7: Average heading versus time for five different test velocities. The dotted lines indicate ± one standard error of the mean heading. The bar chart displays the final headings chosen by the participants. The asterisks indicate the level of significance of the difference in each case (* = p < .05, ** = p < .01, *** = p < .001)

Fig. 8: Average vehicle body roll angle versus time for the five different test velocities. The dotted lines indicate ± one standard error of the mean angle. The bar chart displays the maximum angular velocity for yaw and roll in deg/s. Bars indicate the median value. Error bars indicate the upper and lower quartiles.
Fig. 9: Results from experiment 3 in which participants were asked to act out lane-change and corner turning maneuvers using a force-feedback steering wheel. The figure displays steering-wheel movement with each trace corresponding to a single subject conducting a single trial for each of the four turning maneuvers. The responses are qualitatively the same, only differing in amplitude. Our participants were clearly unable to reproduce the steering movements required to change lanes successfully, consistently omitting the second phase of the biphasic movement.

Fig. 10: (A) Plan view of the steering task of experiment 4. The curved line indicates an idealised trajectory which one of our subjects might have steered along during a single trial. The line appears dotted to indicate approximate periods of visual occlusion. The orange hexagons represent the pair of traffic cones through which the participants passed before drawing alongside the stationary motor vehicle. (All dimensions of the parked vehicle and cones are drawn to the scale of the width axis). (B) Time course of the overall heading from experiment 4, in which lane changes to the left (light) and to the right (dark) had to be executed within a four second period. Grey areas depict periods without visual feedback. Between the two occlusion periods, intermediate visual feedback was provided for a variable amount of time. In this figure the grand mean time of 675 ms is illustrated. Grey dashed lines indicate the required start and end of the maneuver, and dotted lines show ±1 standard error of the mean heading. The value $\tau_H$ illustrated in the figure was used to gauge window onset time relative to the midpoint of the first steering phase. The value of $\tau_H$ was calculated on a trial by trial basis for each subject.

Fig. 11: Heading compensation ratio as a function of feedback occurrence time, $\tau_H$ (onset of intermittent feedback relative to the maximal heading). A heading compensation ratio greater (smaller) than one indicates over-compensation (under-compensation) of heading direction. The straight line shows the best linear fit over all trials. Different symbols denote trials of different individuals.

Table 1: Average yaw and roll velocity amplitudes and frequency of the rotational movement for five different vehicle speeds. Also the average, maximum lateral acceleration experienced during the attempted lane change.

Table 2: Steering performance as indicated by the required duration of the intermittent visual feedback. A trial was defined as successful, if the heading error at the end of the maneuver ($t = 4$ s) was within $\pm 1.5$ deg. Since the update rate of the simulation was 36 Hz, the real durations of visual feedback may vary by $\pm 28$ ms.
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FIGURE 1

[Diagram showing time, lateral position, heading, and steering angle over phases 1 and 2]
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FIGURE 2

A

B
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FIGURE 3

Displacement along road axis (m)

Heading (deg)

Displacement along road axis (m)

Heading (deg)
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The role of visual and non-visual feedback in a vehicle steering task

**FIGURE 5**

**A**

Body Roll (deg)

- **LEFT**
- **RIGHT**

**B**

Maximum Angular Velocity (deg/s)

- **Roll**
- **Yaw**

\[ 0.05(t - 1.5 - \frac{5}{2\pi} \sin(\frac{5}{2\pi}(t - 1.5))) \]
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FIGURE 6

A

Maximum steering-wheel amplitude (deg)

Steering phase

0 5 10 15 20

1

2

LEFT

RIGHT

B

Maximum steering-wheel amplitude (deg)

Vehicle speed (km/h)

40 60 80 100 120

40 60 80 100 120

Phase 1

Phase 2

LEFT

RIGHT
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FIGURE 7

- **40 km/h**
  - Left
  - Right

- **60 km/h**
  - Left
  - Right

- **80 km/h**
  - Left
  - Right

- **100 km/h**
  - Left
  - Right

- **120 km/h**
  - Left
  - Right

- **Velocity (km/h)**
  - **Heading (deg)**
  - **Time (sec)**

- **Bar chart**
  - Heading (deg) vs. Velocity (km/h)
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**FIGURE 8**

![Graphs showing body roll (deg) vs. time (sec) for different speeds and conditions.](image)

- **40 km/h**
  - Right: Blue line
  - Left: Red line

- **80 km/h**
  - Right: Blue line
  - Left: Red line

- **120 km/h**
  - Right: Blue line
  - Left: Red line

- **60 km/h**
  - Right: Blue line
  - Left: Red line

- **100 km/h**
  - Right: Blue line
  - Left: Red line

![Bar chart showing maximum angular velocity (deg/s) vs. velocity (km/h).](image)

- Roll
- Yaw

![Graph showing time (sec) vs. velocity (km/h).](image)
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FIGURE 9
The role of visual and non-visual feedback in a vehicle steering task

FIGURE 10

Displacement from start position (m)

Width (m)

Heading (deg)

Time (sec)

Displacement from start position (m)

Width (m)

Heading (deg)

Time (sec)
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FIGURE 11

Heading Compensation Ratio vs. \( \tau_H \) (msec)
The role of visual and non-visual feedback in a vehicle steering task

<table>
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<th>Vehicle Speed (km/h)</th>
<th>Vehicle Yaw Speed (deg/s)</th>
<th>Vehicle Yaw Freq. (Hz)</th>
<th>Vehicle Roll Speed (deg/s)</th>
<th>Vehicle Roll Freq. (Hz)</th>
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The role of visual and non-visual feedback in a vehicle steering task

<table>
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