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The effect of visual degradation on anticipatory and compensatory steering control

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It has long been held that steering a vehicle is subserved by two distinct visual processes, a compensatory one for maintaining lane position and an anticipatory one for previewing the curvature of the upcoming road. In this study, we investigated the robustness of these two steering control processes by systematically degrading their visual inputs. Performance was measured at the level of vehicle position and at the level of the actions on the steering wheel. The results show that the compensatory process is more robust to visual degradation than the anticipatory process. The results are also consistent with the idea that steering is under the supervision of a combination of compensatory and anticipatory mechanisms, although they suggest that the quality of the sensory information will determine how information is combined.

Keywords: Visuomotor control; Driving; Visual degradation; Steering.

Driving along a winding road is a seemingly effortless task, much of which relies on visual information. It has long been suggested that there are two distinct visual processes to vehicle steering control (Donges, 1978; Godthelp, 1986, see Figure 1a). One process manages *compensatory* corrections of the vehicle's lateral deviation from the intended path. The primary visual information for this mechanism is acquired at a distance relatively near to the vehicle. This mechanism presumably relies on peripheral vision encompassing the edge lines related to the road (Summala, Nieminen, & Punto, 1996). However, as it is dependent on closed loop feedback, steering guided by this process alone inevitably becomes unstable and jerky at high speeds as the process can no longer deal with feedback delays (Land & Horwood, 1995). To be stable, the control system needs an *anticipatory* process. The primary visual information for this process is acquired at a distance relatively far from the vehicle. Several hypotheses have been proposed to explain where drivers preferentially direct their gaze to preview road curvature. The most prominent hypotheses suggest that drivers track the road's tangent point situated on the inside edge of the upcoming road (Authié & Mestre, 2011; Land & Lee, 1994). It has also been argued that drivers track points in the world through which they wish to pass (Wann & Swapp, 2000; Wilkie, Kountouriotis, Merat, & Wann, 2010). Recently, Mars and Navarro (2012) suggested that drivers track the tangent

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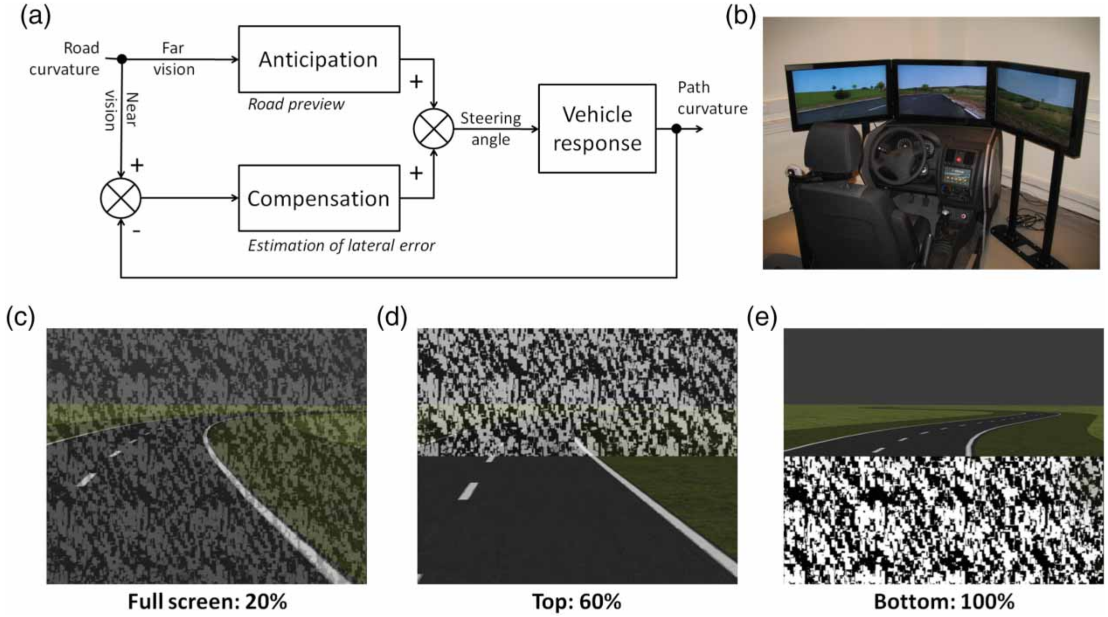

Figure 1. *Apparatus and material. (a) Generic version of two-level model of steering control featuring an anticipation and compensation process. (b) The fixed-base driving simulator. Panels c–e show examples of the mask, mask opacity, and mask placement. (c) Full-screen mask with 20% opacity. (d) Top mask with 60% opacity. (e) Bottom mask with 100% opacity. The mask was a static, black-and-white, marble-like, mottle pattern. To view a colour version of this figure, please see the online issue of the Journal.*

point to stabilize the eyes close to the edge line in a position on the roadway that they do not want to cross—in other words, to establish a boundary of safe trajectory. Irrespective of the exact visual input, the anticipatory process depends on accurate calibration of the relation between the continuously changing visual array and the steering wheel angle (Land, 1998; Mars, 2008).

A number of influential models of visual steering control incorporate both the compensatory and anticipatory processes (Donges, 1978; Land & Horwood, 1995; Mars, Saleh, Chevrel, Claveau, & Lafay, 2011; Salvucci & Gray, 2004). These so-called two-level models of visual control essentially differ in their mathematical realization (Plöchl & Edelmann, 2007; Steen, Damveld, Happee, van Paassen, & Mulder, 2011). Both processes are thought to independently specify steering wheel angles that are added together to formulate the actually desired steering wheel angle (Figure 1a). The desired angle, in turn, has to be converted into an action by the motor system. This conception of steering control has been successfully applied to the automation of lateral control of vehicles (Mars et al., 2011; Saleh, Chevrel, Claveau, Lafay, & Mars, 2013).

Some support for two-level models has recently come from a number of functional magnetic resonance imaging (fMRI) studies exploring the neural substrates of steering control (Billington, Field, Wilkie, & Wann, 2010; Billington, Wilkie, & Wann, 2013). Billington et al. (2010), for instance, found that the posterior parietal cortex is involved in the processing of future path information, which is necessary for anticipatory control, and they found that the so-called motion complex (MT+) is involved in maintaining current lane positioning —that is, compensatory control. Experimental behavioural support was presented by Donges (1978), although the most influential study was by Land

and Horwood (1995) who investigated the steering performance of participants driving along a virtual track at ~60 km·h^{-1} while watching the visual scene through small 1°-high segments. Steering performance was highly dependent on the location of the segment. When only the distant part of the road was visible, the curvature of the road was smoothly matched; however, the vehicle's lateral position was not well maintained as it deviated widely from the centre of the lane. When only the near region was visible, steering was difficult and jerky as the driver resorted to a bang-bang control strategy. Interestingly, while steering performance decreased as the segment was displaced below the horizon, the addition of a second fixed segment showing a part of the far-away information restored stability. Recently, Cloete and Wallis (2011) argued that Land and Horwood's particular results may reflect technical limitations of the experimental set-up rather than driving behaviour. Because the simulation was run at 7 Hz, significant time lags were introduced between the actions on the steering wheel and the consequent visual feedback, which can severely affect steering behaviour. Nevertheless, most researchers agree that the visual control of steering incorporates both a compensatory and an anticipatory process.

While occlusion manipulation has been instrumental in demonstrating the dual character of visual control of steering in particular, and the role of visual feedback on steering control in general (e.g., Wallis, Chatziastros, & Bülthoff, 2002), it does not allow us to understand how steering behaviour changes when the information used by the anticipatory and compensatory processes is partially degraded. For instance, consider the fact that real-life driving is set in a continually changing environment full of disturbances that affect the quality of the visual information to various degrees. Examples of such disturbances include rain, fog, and changes in illumination level (night vs. day, or entering a tunnel), but also partial occlusions from moving traffic and environmental obstacles. All these factors introduce uncertainty (i.e., noise) in specific parts or the entire visual array. An experimental approximation of this would entail systematically degrading the information in the visual array. An example of such an approach is a study by Kountouriotis, Floyd, Gardner, Merat, and Wilkie (2011), who were interested in the interaction between the driver's gaze and the feedback information from the road's boundary edges. They systematically varied the visibility of the inner and outer edges by showing them fully, fading them, or completely removing them. Interestingly, they found evidence that is reminiscent of current models of perception that hold that we integrate information from across various sources in a weighted fashion such that the more reliable source is attributed a higher weight (e.g., Wolpert, Diedrichsen, & Flanagan, 2011; Yuille & Kersten, 2006).

Our goal was to investigate the response of the steering control processes to various levels of visual noise. Noise was added to the visual information by means of a semitransparent mask. The mask could cover the entire screen, thus degrading the visual field evenly. Alternatively, the mask covered either the near or the far visual scene, thus degrading for the most part the visual information to the compensatory and anticipatory process, respectively. According to the two-level control model (Donges, 1978; Salvucci & Gray, 2004), anticipatory control should be highly sensitive to the quality of visual information as it is used to preview road curvature and to orient gaze to salient and useful visual cues. Thus we expect that the larger the visual noise put on the far mask, the harder it would get for the driver to steer the vehicle. On the other hand, compensatory control is expected to be more robust to visual degradation. We expect this robustness as the steering solution relies more on the perception of the near road and edge lines through peripheral vision. Visual acuity is not as crucial here, and lateral error detection may be performed even with moderately noisy visual signals. Thus, we hypothesized that steering perturbation would only appear for high levels of visual noise on the near mask.

Method

Participants

Three females and 12 males, between 19 and 38 years of age, volunteered for the experiment. They had been licensed drivers for a minimum of 1.5 years. All had normal or corrected-to-normal vision. The experiment was conducted in accordance with the ethical standards specified by the 1964 Declaration of Helsinki, and all participants gave informed consent.

Apparatus and material

The study took place in a fixed-base driving simulator, consisting of a single-seat cockpit with full instrumentation (Figure 1b). It was equipped with an active steering system for realistic force-feedback. The visual environment was displayed on three 32″ LCD monitors, one in front of the driver and two laterals, inclined at 45° from the front one. The monitors were viewed from a distance of about 1 m and covered 115° of visual angle in width and 25° in height. The SCANeR™ Studio software package (OKTAL) was used for creating the track and controlling the experiment. Data were recorded at 500 Hz, but were down-sampled to 20 Hz for further processing.

The experimental track was a two-lane road (lane width 3.5 m) with 24 curved segments each followed by a 50-m straight segment (see Figure 2). A curved segment could have one of two radii (100 or 200 m) and one of three lengths (39.3, 78.5, or 157.1 m). The road markings were standard continuous white lines to mark the road edges and an interrupted line to mark the centre. The track had no other traffic and was placed in a grassy but otherwise flat and featureless terrain with a monochrome grey sky. Its total length was 3887 m and took around 2:45 min to complete.

The mask was a static, black-and-white, roughly marble-like, mottle pattern (see Figure 1c–1e for examples). Five levels of mask opacity where created using a transparency function of an image processing software; 20, 40, 60, 80, 100% (i.e., the last level being completely opaque).

Procedure

After settling in the simulator, the participants read the prepared instructions, which specified to keep in their lane without cutting bends to the point of crossing the edge lines. Note that participants were not told to stay in the centre of the lane. Such instruction, although not uncommon in driving simulator studies, constrains the drivers in a way that precludes natural driving behaviour, in particular, people's use of the width of the lane when negotiating bends. Before the experiment, participants were allowed a period of practice until they became comfortable driving the simulator, and their driving performance had stabilized.

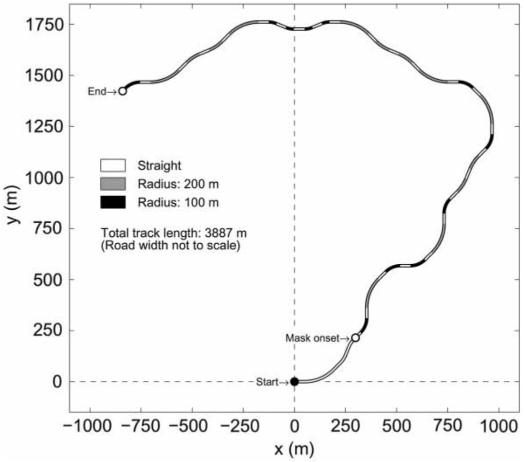

Figure 2. *Top-down representation of the track. The road markings were standard continuous white lines to mark the road edges and an interrupted line to mark the centre (not shown). Note that for clarity the lane width is not to scale but has been exaggerated by a factor of 1.7.*

All participants drove along the track 15 times, each time under a different condition. Conditions were tested in quasirandom order with short breaks in between each run, although participants were free to take longer breaks if necessary. The entire experiment was completed in a single session and never lasted more than 75 min. In the baseline condition, there was no visual mask. The other 14 conditions were created by combining five levels of opacity (20, 40, 60, 80, and 100%) of the masks with three possible locations of the mask (top half, bottom half, and full screen), minus the 100% full-screen mask condition for obvious reasons.

With this experimental setting, the tangent point area was virtually always located on the top half of the screen (see, for instance, Figure 1d).

Given that most of anticipatory gaze behaviour is directed toward this area and beyond when driving in a bend, the mask on the top half of the screen effectively ensured that the anticipatory process was affected. Conversely, with the mask at the bottom, only the near field (Figure 1e), was degraded. The visual mask did not come on immediately but at around 400 m into the track (see also Figure 2), at which point the car had already accelerated to cruising speed. The speed of the car was controlled by the simulation and was set at a constant speed of 90 km·h^{-1}, which was a comfortable speed on this track.

Data analysis

A number of performance measures are available for describing steering control. Here we used measures that quantify performance at the level of vehicle positioning as well as at the level of the driver's actions on the steering wheel. First, the *standard deviation of the lateral position* of the car is computed from the lateral position of the car. Second, we calculate the *mean lateral position* of the car with respect to the inner edge line of the curve; thus straight parts are not considered for this measure. These measures are typically considered as indicators of steering variability and bias, respectively. However, while this holds true when the task is to stay close to the road centre when driving in a straight line, in bends drivers naturally cut corners. Hence, one can expect greater standard deviations of lateral position when adopting a racing line than when keeping the trajectory close to the road centre. Thus, a greater variability of lateral positioning may represent a less stable control of the vehicle, but it may also represent the tendency of drivers to adopt a more efficient path. We therefore included another measure based on the drivers' action on the steering wheel. The *steering wheel velocity* is the median (absolute) velocity at which the steering wheel was turned. This measure is associated with rougher corrective actions as steering control becomes harder.

The first 400 m, where there was no mask, were not used for analysis, which left approximately 2:20 min of data per condition for each participant. Analyses were done in Matlab 7.7 (MATLAB). Statistical testing was conducted in RStudio using R Version 2.15.1 (Team, 2010). Dunnett's tests were conducted in Statistica 8 (Statistica, 2007).

Results

In this section we discuss the three dependent measures one by one and in the order presented in Figure 3. The effect of mask opacity on the standard deviation of the lateral position is shown in Figure 3a. It showed a smooth and (near) monotonous sensitivity to opacity for all three masks. The results were analysed separately for each mask in 3 one-way analyses of variance (ANOVAs) that also included the baseline condition. The effect of opacity was significant for the full mask, $F(4, 56) = 21.3$, $MSE = 0.012$, $p < .0001$, the top mask, $F(5, 70) = 32.4$, $MSE = 0.018$, $p < .0001$, and the bottom mask$(5, 70) = 53.0$, $MSE = 0.009$, $p < .0001$. We followed up on significant ANOVAs using Dunnett's post hoc tests comparing the baseline with each level of mask opacity. Instead of listing the results here we incorporated them into the figure where uniformly filled markers indicate significant differences with respect to baseline while grey filled markers indicate nonsignificant differences. We can observe that each mask affected the standard deviation of the lateral position at different points. Whereas the full mask had an effect starting at 40% opacity, the top and bottom masks started to show an effect at 80% and 60%, respectively.

The mean lateral position (Figure 3b) showed an overall tendency to move away from the lane centre and towards the inside of the curve (i.e., "curve cutting"). This bias was on average −14 cm, $t(14) = 2.30$, $p < .05$. The effect of opacity was significant for the full mask, $F(4, 56) = 3.76$, $MSE = 0.025$, $p < .01$, and the top masks, $F(5, 70) = 133.3$, $MSE = 0.013$, $p < .0001$, but not for the bottom mask, $F(5, 70) = 1.77$, $MSE = 0.025$, $p = .13$. The results from Dunnett's post hoc tests showed relatively few deviations from baseline. For the full mask at 60% and 80% opacity was there a significant change in mean lateral position towards cutting the bend more.

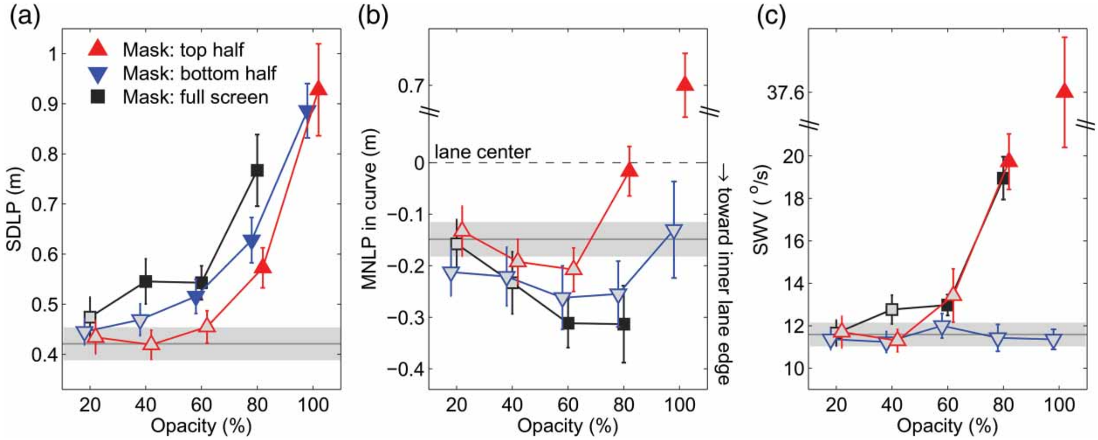

Figure 3. *The effect of visual degradation on steering control. (a)* Standard deviation of the lateral position (SDLP). *(b)* Mean lateral position (MNLP) *in curves with respect to the centre of the lane. Negative values indicate a location towards inner edge of the curve. (c)* Steering wheel velocity (SWV). *Error bars represent the standard error of the mean* (SEM), *and the shaded areas represent the baseline condition* ± 1 SEM. *The different shading of the markers reflects the results of Dunnett's post hoc tests. Uniformly filled markers indicate a significant difference with respect to the baseline, while grey filled markers show nonsignificant differences. To view a colour version of this figure, please see the online issue of the Journal.*

For the top mask, on the other hand, we found a relative move towards the outer lane edge at 80% and 100% opacity.

Finally, the steering wheel velocity (Figure 3c) was highly sensitive to the opacity of the full mask, $F(4,\ 56) = 40.8$, $MSE = 3.46$, $p < .0001$, and the top mask, $F(5,\ 70) = 105.7$, $MSE = 15.2$, $p < .0001$, but showed no sign of an effect for the bottom mask ($F < 1$). Deviation from baseline was significant at 80% opacity for the full mask and top mask.

Discussion

We investigated how steering control of a vehicle is affected by systematically degrading the entire field of view, the near field of view, or the far field view. In the following discussion, we integrate the results obtained from the different dependent measures by discussing the effects of each type of mask with respect to the two-level visual control model.

The top mask manipulation showed that, at the level of the vehicle behaviour, the drivers managed to maintain a trajectory similar to that of the baseline with noise up to 60%. From that point, it seemed that drivers failed to anticipate changes in road curvature as they moved away from the centre line in the direction of the inside edge line, which increased the variability of lateral position. In terms of the participants' actions on the steering wheel, the anticipatory mechanism showed some robustness but only up to relatively low levels of degradation and became erratic as degradation increased. Indeed, we found increasingly more and faster (Figure 3c) actions on the steering wheel as the mask opacity increased. Thus, it appears that with an increase in noise in anticipatory control there is a progressive transition from smooth anticipatory to jerky reactive control, up to a point where compensation is not sufficient. With full occlusion of far vision, Land and Horwood (1995) also observed an increased number of short-term corrective actions, which made steering jerky but also allowed maintaining a central lane position. This may be due to the fact that the speed relative to the road curvature was low enough to allow for driving with near vision only. Our study expands those results by showing a progressive degradation of anticipatory control with level of visual noise.

The results obtained with the bottom mask showed that compensatory steering did not depend on the level of visual noise as much as anticipation did. No significant effect of visual degradation at all was observed on steering wheel velocity and mean lateral position. The variability of the vehicle's lateral position increased as a function of the magnitude of visual noise on the bottom mask, just like for the top mask (Figure 3a). However, in the case of the bottom mask this increase in variability of lateral position cannot be interpreted as the consequence of an increasing steering wheel velocity. It rather appears that the participants moved further away from the centre line in the direction of the inside edge line, except with the full opacity case in which the mean lane position differed considerably across participants. This suggests that drivers showed a tendency to cut bends more sharply when near vision was degraded, but they only showed difficulties in remaining within the lane boundary when near vision was completely occluded.

Our observations add to Land and Horwood's (1995) findings that an impairment of near vision allows smooth steering but yields large lateral position errors. Here, it is demonstrated that the control of lateral position remains relatively robust even with poor visual input. At the same time, there are some notable differences between our results and those of Land and Horwood that can reasonably be traced back to differences in experimental methods. As described in the introduction, the manipulations on the visual array in the Land and Horwood study were rather different from ours. Also, the speed we used is considerably higher ($25\ \text{m}\cdot\text{s}^{-1}$ vs. $16.9\ \text{m}\cdot\text{s}^{-1}$). Higher speeds are more likely to engage the anticipatory control process (Salvucci & Gray, 2004). For instance, we observed large lateral deviations when far vision was masked, whereas drivers in Land and Horwood's study managed to stay very close to the lane centre. This can be explained by the fact that their participants drove at a lower speed, which meant that they did not rely as much on anticipation. In spite of these differences, it is more important to note that the results of both studies can be understood within the same two-level framework.

There is one caveat in generalizing the results of this study that should be mentioned. Although the mask was effective in targeting the anticipatory and compensatory control processes, the mask did not fully take into account the spatial frequency content of the respective parts of the visual scene. That is, although the mask's density was uniform, the more distant parts of the scene carry more high-frequency information than the near parts. This could mean that the mask was masking details in the far and near field differently. The extent to which this difference affected the results should be addressed in further studies.

As could be expected, most indicators showed larger degradation of performance with the full mask condition. However, the observed results are unlikely to be the product of a simple addition of the top and bottom mask influence. For instance, it is remarkable that drivers strayed further from the inner edge of the curve in the top mask condition with high levels of opacity, as if the lack of anticipation prevented them from steering into the bends in time. However, the reverse was true in the full mask condition when far vision was degraded, and near vision was also no better. This time drivers stayed closer to the inner edge. This suggests that drivers heavily relied on near vision and completely disregarded far vision when it was degraded, which induced some delay in the steering actions. On the other hand, drivers may have tried to take advantage of both types of visual cues when both were equally unreliable. This flexible use of information most probably reflects that far and near visual cues do not receive equal weighting in steering control, which may be related to the perceptual system's ability to reweight cues depending on the quality and availability of sensory information (Wolpert et al., 2011; Yuille & Kersten, 2006). On a more speculative note, it may be that compensatory and anticipatory steering control are not purely visual, but are also dependent on the motor system in charge of performing the steering wheel movements. There are now studies showing that (planning) motor actions can affect visual perception such that information processing needs for action control are met at the earliest possible stage (e.g., Craighero, Fadiga, Rizzolatti, & Umiltà, 1999; Gutteling, Kenemans, & Neggers, 2011; Shin, Proctor, & Capaldi, 2010). Thus, whereas two-level models propose that the visual system produces a steering solution that is propagated to the motor system (see Figure 1a), we might consider that the motor system is not just a recipient but also a determinant in the steering solution (Mars & Navarro, 2012). In all cases, this goes against the idea that the combination of compensatory and anticipatory visual control in the two-level models (Donges, 1978; Land & Horwood, 1995; Mars et al., 2011; Salvucci & Gray, 2004) should be considered as a simple additive process.

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