WHERE YOU LOOK DURING AUTOMATION INFLUENCES WHERE YOU STEER AFTER TAKE-OVER

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Summary: When driving a vehicle, gaze direction (where the driver is looking) is tightly coupled with steering actions. For example, previous research has shown that gaze direction directly influences steering behavior. In the context of transitions of control from automated to manual driving, a new question arises: Does gaze direction before a transition influence the manual steering after it? Here we addressed this question in a simplified simulated driving scenario, for maximum experimental control. Participants (N=26) were driven around a constant curvature bend by an automated vehicle, which gradually drifted toward the outside of the bend. An auditory tone cued manual take-over of steering control and participants were required to correct the drift and return to the lane center. Gaze direction was controlled using an onscreen fixation point with a position that varied from trial to trial horizontally and/or vertically. The results showed that steering during manual control was systematically biased by gaze direction during the automated period, but notably in the opposite direction to what might have been expected based on previous research. Whilst further research is needed to understand the causal mechanisms, these findings do suggest that where a driver looks during the seconds preceding a transition to manual control may be critical in determining whether the subsequent steering actions are successful.

INTRODUCTION

Where drivers look and where they steer are tightly coordinated during manual curve driving. Visual direction information supplied by the *act of looking* appears to be used during steering control whereby the angle of gaze relative to the body midline indicates the required steering response (Wilkie & Wann, 2003). Current models of human steering control suggest that gaze behaviors shape the sensory cues that inform steering adjustments (Wilkie & Wann, 2003; Salvucci and Gray 2004; Lappi & Mole 2018). This is supported by the observation that drivers not only look to where they wish to steer (Wilkie et al., 2010), but they also steer in the direction they are looking, even unintentionally (Robertshaw & Wilkie, 2008; Kountouriotis et al., 2012).

Highly automated vehicles are being designed to remove the requirement for drivers to actively provide steering inputs to the vehicle. However, many automated systems will require drivers to monitor system operation and occasionally take-over control of the vehicle. During automated driving the gaze behavior of drivers appears to diverge from that seen during manual driving, even when looking at the road (Louw & Merat, 2017), and even when not engaging a secondary task (Navarro et al., 2016). In general, drivers are expected to look less often towards the road ahead, and instead direct gaze more often at objects inside the car (Jamson et al., 2013). This raises the interesting question of whether gaze direction during automation can influence subsequent steering actions after there has been a transition to manual control (Mole et al., 2019).

If gaze direction information during automated driving can 'carry-over' to manual steering control after a handover, it may pose a fundamental challenge to drivers' ability to successfully provide appropriate steering inputs. The current experiment examined whether 'carry-over' effects exist by manipulating where drivers looked (using an on-screen marker, cf. Robertshaw and Wilkie, 2008) during periods of automation in a simplified and highly controlled steering task in a driving simulator. Drivers' trajectories immediately after the handover were examined to see whether they were biased in the direction of gaze during the preceding automation period. Such patterns would be consistent with previous research into manual steering (without automation), whereby individuals steer in the direction they are looking (Robertshaw & Wilkie, 2008; Kountouriotis et al., 2012). If carry-over effects do not exist then gaze direction during automation should not influence manual steering trajectories.

METHOD

Participants

26 University of Leeds students (24 females: 2 males, 18-22 years, mean=19.38 years) with full UK driving licenses took part in this study. Ethical approval was granted from the University of Leeds School of Psychology Ethics Committee (reference: PSC-122).

Apparatus

Participants sat on a fixed-based driving seat in front of large projection screen (field of view 89° x 58°). The virtual environment (Figure 1) was generated using Vizard 3.0 (WorldViz, Santa Barbara, CA), running on a PC with Intel i7 3770 (3.40 GHz). The driving seat was adjusted so that eye-height was 1.2 m and 1 m away from the display. Steering was via a force-feedback wheel (Logitech G27, Logitech, Fremont, CA), which was linearly mapped onto rate of change of heading through a minimum step size of 0.36°/s. The steering dynamics used a point mass model that was not matched to a particular vehicle. The first three participants were eye-tracked using Pupil labs version 1.2.7 (Kassner et al., 2014). This confirmed that participants were able to comply with gaze instructions (Figure 1B) while driving.

Simulation Scenario

Each participant experienced a series of trials where they steered a constant curvature bend of 60 m radius and 6 m road width. The first 10 s of the bend were automated, with the automated vehicle purposely drifting towards the outside edge of the road to a position of -2.5 m (.5 m from the outside edge), reached at 5.5 s and then held constant (Figure 1). Participants started each trial with their hands off the wheel which automatically turned with the bend. Take-over was signaled by two separate tones of .5 s duration. On the first tone (7.5 s) participants returned hands to the wheel. The second tone (9.5 s) signaled that the vehicle was in manual control mode. After a further 10 s of manual control the trial ended, and the participant removed their hands from the wheel.

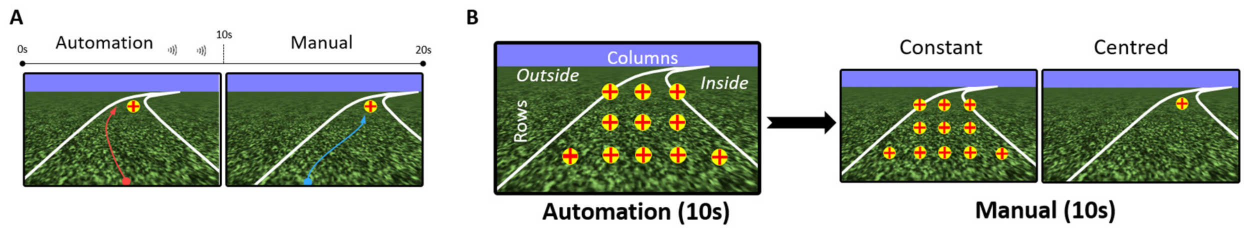

Figure 1. A) Trials consisted of approximately 10 s of automated driving, followed by 10 s of manual driving. During automation the vehicle drifted gradually to the outside of the bend. The driver is prompted regain a firm grip, and 2 s later to take over manual control of steering and return the vehicle to the road centre. B) Fixation conditions. During automation a single fixation direction was chosen from a possible 11-point grid, *in columns near to the Outside, Middle or Inside of the bend* (leftmost panel). The fixation cross during automation was randomly selected from this grid. During Manual control (post automation) each *fixation condition* had different requirements *(shown right of black arrow)*: fixations were either kept Constant (*no change from* automation), or Centred (a *change to a* single fixation point location over the road centre).

Fixation Grid

Gaze direction was controlled throughout the whole trial using single point selected randomly from an 11-point fixation grid (Figure 1B) arranged in three rows (Top, Middle or Bottom row) and across five columns (Far Outside, Outside, Middle, Inside, Far Inside; relative to the direction of the bend). Depending on the condition, fixation points were placed in either world coordinates (where the optical angle of the fixation point changed depending on the driver's lane position) or in screen coordinates (so that the optical angle was fixed regardless of driver position in the world). During automation, after some initial drift, a constant lane position was adopted, so world and screen coordinates gave equivalent fixation directions. The top-middle fixation was always placed so it would be over the road-centre during the automation period, regardless of the coordinate system, at a point 5° below the horizon. The top-left and top-right fixations were 11.3° either side of the road-centre (over the Outside and Inside road-edges respectively during the automation period). The mean time headway for the top row of fixations was 1.08 s. Outside, Middle and Inside fixations with the same horizontal separation but a vertical angle separation of 5° were used to create a core 3 x 3 grid allowing assessment of three vertical and horizontal eccentricities (mean time headway for middle and bottom rows was .53 s and .36 s, respectively). The bottom row added two extreme eccentric fixation positions located optically closer to the outside and inside road edges (Far Outside and Far Inside, 22.6° away from the road centre), creating the full 11-point grid of possible fixation points. These were used to create two different types of Fixation conditions (Figure 1B):

Constant gaze fixation condition **-** fixations placed in screen coordinates caused a constant gaze angle regardless of vehicle trajectory. A single point of fixation (out of the 11-point grid) was used and was kept constant across both manual and automation periods.

Centred gaze fixation condition **-** fixations were the same as in *Constant*, but *only* during the automation period. At manual take-over the fixation point was immediately switched to the road-centre. This new fixation was placed in world coordinates so as to continuously track the road centre. Previous studies using this type of fixation has shown successful and reliable steering

(Robertshaw & Wilkie, 2008), therefore any systematic deviations of steering trajectories based on fixation direction during automation would indicate carry-over effects.

Procedure

The fixation conditions (*Constant*, *Centred*; Figure 1B) were blocked, and participants experienced 5 practice trials at the start of each block, to avoid instructions from one condition contaminating the following condition. The blocks were counterbalanced across participants. The fixation cross location (across the grid) varied from trial to trial in a random fashion, with 6 repetitions of trials fixating each point on the grid. Participants were instructed to fixate on the visible marker throughout and to return the vehicle to the centre of the road upon manual control. Mean performance across trial repetitions were taken as the estimate of central tendency.

RESULTS

To assess whether gaze influenced steering position "OverSteering Bias" (OSB in meters) was calculated, which represents directional deviation from the road centre during manual steering control (Figure 2). OSB was calculated from the average signed distance between current position and the nearest point on the road centre at each frame (Robertshaw & Wilkie, 2008). Positive values signal a position toward the inside road edge (oversteering), and negative values indicate steering toward the outside road edge (understeering). Trials were removed if there was clear evidence of simulator error (incorrect trajectories taken due to the automation algorithm) or large steering errors interpreted as atypical mistakes (e.g. hands slipping on the wheel). In total 1.26 % of trials were excluded (see *Supplementary Materials* of osf.io/yzgra).

Modelling Results

For inference a Bayesian multi-level modelling approach was adopted. A 3-factor multi-level model was used, with Horizontal and Vertical Fixation position and fixation block (*Constant, Centred*) as predictor variables that varied between participants. For condition means and inferential contrasts the 95% highest density interval is reported (HDI; McElreath, 2016): an interval in which the posterior suggests there is a 95% probability that the population mean falls.

The effect of gaze direction during automation on manual steering

To determine whether gaze direction during automation affected manual steering trajectories after a transition requires a comparison across fixation conditions. Specifically, comparing the trajectories when gaze had been directed *Outside* or *Inside* during automation. Figure 2A displays raw steering trajectories for the *Centred* fixation conditions, when participants looked at fixation points along the top row (Outside, Middle, Inside) during automation. In all these trials gaze returned to 'Centre' fixation during manual control. Despite this, there are clear differences in OSB according to fixation direction during automation: *Outside* fixations lead to the least understeering, and *Inside* fixations lead to the most understeering. These differences develop over the first four seconds, then the driver gradually corrects for the error (though not completely).

The systematic differences between Outside and Inside conditions were consistent across both *Centred* and *Constant* conditions, with Outside fixations (Orange) always producing less negative OSB than Inside fixations (Light Blue). Figure 2B displays the posterior means collapsed across *Centred* and *Constant* conditions. Whilst one might expect that the 'Far' (*Top row*) fixations would amplify steering biases, there was no clear evidence for this. The global trend is least clear in the Bottom Row of Figure 2B because these conditions included extreme fixations (*FarOutside* & *FarInside*). It is possible that drivers failed to comply consistently with fixation requirements in these extreme conditions. Whilst broad compliance with gaze instructions was observed for the three participants that were eye-tracked, even subtle changes across the group could have reduced the impact of these fixations.

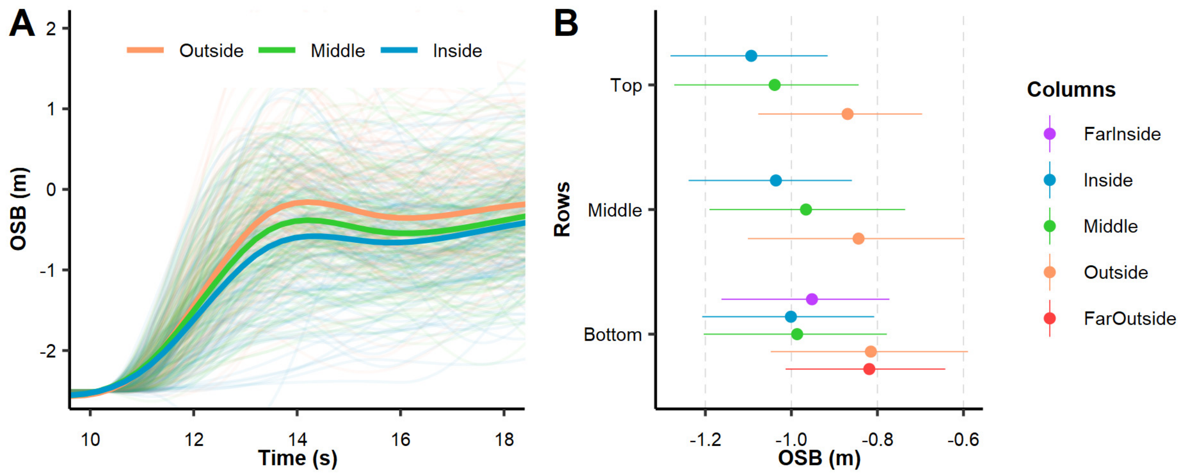

Figure 2. A) Raw trajectories showing oversteering bias (OSB) during manual driving, for the *Centred* Fixation Condition, top-row fixations only. Colours show fixation placement during automation. All conditions had an identical fixation placement (road-centre) during manual driving. B) Posterior means for data collapsed across *Centred* and *Constant* conditions, with 95% HDIs shown. Vertical fixation position is on the Y-axis, and the horizontal fixation position is shown through the colours. Columns are different fixation placements after take-over (see Figure 1 for Fixation conditions).

To assess the apparent differences in active steering caused by gaze direction in the automated driving period, contrasts were performed between the Outside and Inside fixation position, collapsed across vertical fixation row, for each Fixation Condition (Figure 3). This shows the estimated difference between the condition means. When the contrast's 95% HDI (black lines in Figure 3) excludes zero there is a high probability of a difference between means.

The critical condition is *Centred* (Figure 2A), where participants looked at different fixation points during automation but always looked at a fixation pointed located at the road centre during manual control. The 95% HDI ranges from .003 m to .32 m (mean is .161 m), with 98.1% of the posterior mass above zero, indicating a high likelihood of a non-zero difference between Outside and Inside fixations in *Centred* conditions. This is clear evidence of the presence of 'carry-over' effects: gaze location during automation has a direct effect on steering bias immediately after handover to manual control (Figure 3). Systematic biases were also observed during *Constant* conditions (Figure 2B, 95% HDI from .051 m to .43 m, with 99.5% > 0). This was expected, since the fixation position is biased during manual driving. The 95% HDI of the difference between the contrast distributions shown in Figure 2B (i.e. the interaction) lies between -.21 m and .29 m, with 61.2 % > 0, indicating that one cannot be certain that the magnitude of the differences in steering bias for the inside and outside fixation locations vary across *Centred* and *Constant* conditions.

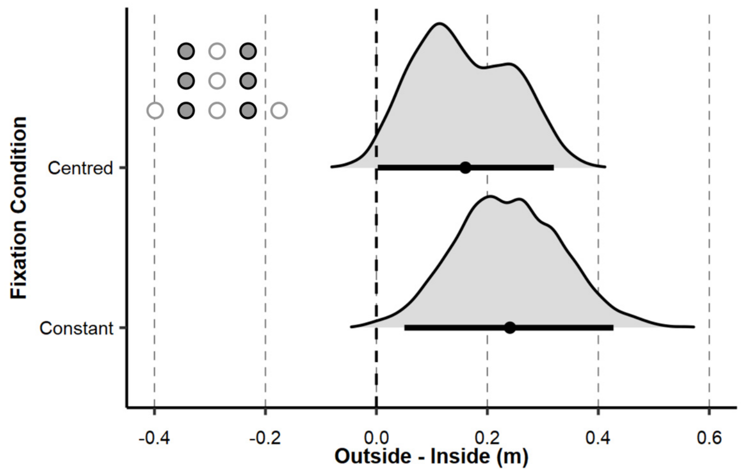

Figure 3. Posterior distributions for the contrast between OSB in Inside and Outside fixations (collapsed across vertical fixation rows), shown for each Fixation Condition. The black point-ranges are 95% highest density intervals. Inset shows fixation placements used in the contrast (filled circles).

CONCLUSIONS

These findings suggest that the direction of fixation during automation can bias steering during subsequent manual control recovery. Whilst gaze direction did influence steering it is worth highlighting that in all cases the direction of these effects were opposite to that predicted by much of the literature. Drivers systematically steered in the *opposite* direction to fixation, a reversal of the previously reported 'steer where you look' effect (Kountouriotis et al., 2012). One explanation may lie in the optical relationship between the on-screen fixation and the underlying road. Since the fixations were primarily fixed to the screen (rather than in world coordinates such as in Kountouriotis et al., 2012), in order to bring the road information into view the driver may have altered their steering to effectively bring fixation closer to the centre of the road (and also bringing road-edge information into peripheral view). Drivers therefore may have been engaged in a trade-off between the requirement of fixating in a particular direction and the need to keep road-edges in view, so it will be worthwhile assessing whether the result generalizes to other road geometries that may place different optical constraints. Whilst this might explain the direction of steering bias when drivers were holding gaze eccentric in manual control (*Constant* conditions), it does not easily explain why the same systematic biases were observed when drivers fixated on the road-centre during manual control (*Centred* conditions*)*. The observed 'carry-over' effects in the *Centred* condition suggests that there is a critical period in steering and gaze coordination where drivers are influenced by where they have *previously* been looking, not where they are *currently* looking. It may be that where drivers look in the few seconds *before* taking over control is of critical importance to the success of that takeover. This finding has clear applied consequences for handing over control of automated vehicles. Gaze behavior leading up to hand-over of control may predict the quality of subsequent steering actions, which has clear safety implications. The types of eccentric gaze fixations that would be expected during automated driving can be broadly classified as in-world (looking toward road-signs or other scene features either side of the road) or in-vehicle (looking to an in-vehicle information display). The findings presented here most directly relate to in-world fixations, and it has already been demonstrated that the gaze patterns present during automation differ compared to manual driving (Louw & Merat, 2017; Navarro et al., 2016). It is possible that in-vehicle fixations could also cause similar issues to those observed here, however further investigation is required to confirm whether this is indeed the case. Irrespective, our findings raise the possibility that monitoring gaze during automation may enable the steering actions immediately after handover to be predicted and modelled. Future research will test whether gaze behavior can be used to predict drivers' capability to safely take over control of automated vehicles.

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