COGNITIVE LOAD DURING AUTOMATION AFFECTS GAZE BEHAVIOURS AND TRANSITIONS TO MANUAL STEERING CONTROL

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Summary: Automated vehicles (AVs) are being tested on-road with plans for imminent large-scale deployment. Many AVs are being designed to control vehicles without human input, whilst still relying on a human driver to remain vigilant and responsible for taking control in case of failure. Drivers are likely to use AV control periods to perform additional non-driving related tasks, however the impact of this load on successful steering control transitions (from AV to the human) remains unclear. Here, we used a driving simulator to examine the effect of an additional cognitive load on gaze behavior during automated driving, and on subsequent manual steering control. Drivers were asked to take-over control after a short period of automation caused trajectories to drift towards the outside edge of a bending road. Drivers needed to correct lane position when there was no additional task (“NoLoad”), or whilst also performing an auditory detection task (“Load”). Load might have affected gaze patterns, so to control for this we used either: i) Free gaze, or ii) Fixed gaze (to the road center). Results showed that Load impaired steering, causing insufficient corrections for lane drift. Free gaze patterns were influenced by the added cognitive load, but impaired steering was also observed when gaze was fixed. It seems then that the driver state (cognitive load and gaze direction) during automation may have important consequences for whether the takeover of manual vehicle control is successful.

INTRODUCTION

Automated vehicles (AVs), controlled by a “safety driver” are currently being road-tested in many locations around the world, and there are plans for large-scale deployment of such vehicles in the not-so-distant future. Whilst some AVs aim to completely remove the need for a human driver, many are designed to support the driver and improve comfort, relying on a human to remain vigilant and responsible for taking control of the vehicle, when required (Level 2 and 3; SAE, 2018). One of the purported benefits of AVs is that they should free up the driver to perform other tasks, although this would seem to compete with the requirement to remain vigilant. It seems likely that drivers will use periods of AV control to perform a range of non-driving related tasks, confirmed by both real-world cases reported in the news and driving simulator studies (Merat et al., 2014). There has been growing interest in understanding how secondary tasks distract drivers regaining control of their vehicle (Merat et al., 2012). Human cognition can be conceptualized as a system with limited capacity, whereby attempting to perform multiple concurrent tasks leads to competition for limited resources: when functions are in use performing one task they will be unavailable for use for concurrent tasks, particularly those that are not highly learned (Wickens, 2002; also see Engstrom et al., 2017, for a review).

One way in which distracting tasks could interfere with successful take-over of control is the demands placed on the functions of the visual system, with the competing demands in this case being the direction of gaze: when reading an email, gaze is no longer directed to the road ahead, rather the driver is looking at a display screen. The visual system is therefore no longer sampling the requisite information for vehicle control. Even without direct competition over visual function, there is evidence that non-visual cognitive tasks can alter gaze behaviour, with additional load reducing the distribution of gaze patterns (Wang et al., 2014; Victor et al., 2005; Recarte & Nunes, 2003). Because eye-movement patterns are integral to successful control of steering (Lappi & Mole, 2018; Wilkie et al., 2010) such changes could have an impact on successful resumption of manual steering control (Mole et al., 2019).

To examine these issues, the aim of this study was to test the effect of adding a non-visual cognitive load during automated driving on subsequent manual steering control using a simplified and highly controlled simulated driving task. Drivers were asked to take-over control after a short period of automation and correct any lateral drift that occurred, bringing the vehicle back to the center of the road. There was either no additional task ("NoLoad"), or an auditory detection task ("Count" or "Nback" tasks) that were used to add a "Load". Previous research has shown that this kind of load alters gaze patterns (Kountouriotis et al., 2016). To control for this, we used either: i) Free gaze, or ii) Fixed gaze constrained to a point on the center of the road ahead. The results indicate the extent to which cognitive load impairs the ability of drivers to correct lane position, and whether gaze patterns interact with successful steering control.

METHOD

Participants

20 University of Leeds students and staff took part in this experiment (10 Males & 10 Females, mean age=24.75yrs). All participants held driving licenses. Ethical approval was from the University of Leeds, School of Psychology Research Ethics Committee (ref: PSC-184).

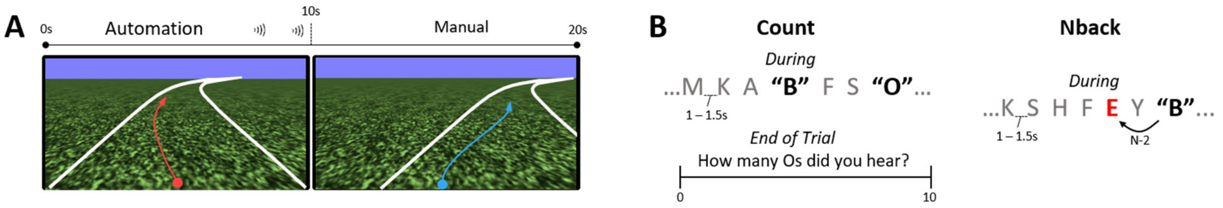

Figure 1. A) Trials consisted of approximately 10 s of automated driving, followed by 10 s of manual driving. During automation the vehicle drifted gradually to the outside of the bend. Following a short tone, the driver was prompted regain a firm grip, and 2s later to take over manual control of steering and return the vehicle to the road center. B) The auditory cognitive load tasks: *Count* and *Nback* (see main text for explanation).

Apparatus

Perspective correct visual stimuli were generated using Vizard 3.0 (WorldViz, Santa Barbara, CA) running on a PC with Intel i7 3770 (3.40 GHz), and back-projected onto a large projection screen (h × v field of view = 89 ° × 58 °) with black surroundings. Participants sat on a fixed-based adjustable seat, with eye position 1.2 m high and 1 m away from the display (w × h: 1.95

m × 1.1 m). Similar to Mole et al. (2016) the scene consisted of a textured ground-plane with super-imposed white lines demarcating the road (Figure 1A). Display refresh and data recording was synchronized at 60 Hz. Steering was via a force-feedback wheel (Logitech G27, Fremont, CA). Eye-tracking was performed using Pupil labs version 1.2.7 (Kassner et al., 2014). A brief report of this experiment was released using the Open Science Framework (osf.io/wdvku).

Driving Scenario

Drivers experienced many short (20 s) trials of steering a constant curvature bend (60 m radius). Each trial began with 10 s of automation. The AV began in the center of a 6 m wide road, and gradually drifted towards the outside road-edge, adopting a position with a lateral error of -2.5 m relative to the centerline (.5 m away from the outside edge). The drivers were asked to correct this positional error once they regained manual control, bringing the vehicle back to the center of the road. During automation the wheel was turned by the AV, but drivers kept their hands loosely on the wheel so that they could respond to the cognitive tasks. Take-over was prompted by two high-pitched tones occurring 2 s apart (Figure 1A). On the first tone the participant regained a firm grip on the wheel. On the second tone the driver regained sole manual control of the vehicle. At the end of 10 s of manual driving a further tone sounded, prompting the driver to remove their hands from the wheel, the trial ended, and the visual scene was reset.

Manipulating Cognitive Load

Three conditions were used to impose either a “Load” (“Count”, “Nback”) or “NoLoad”:
i) **Count** (Figure 1B): Participants listened for two target letter sounds ‘B’ & ‘O’ amid a stream of distractor letters (1–1.5 s interval), responding using a button on the steering wheel. At the end of trials participants estimated how many times each target occurred. Target occurrence: 40%.
ii) **Nback** (Figure 1B): Based on tasks reported by Reimer et al. (2014), keeping most characteristics similar to *Count*. Participants listened for targets (‘B’), but responded only if the letter two places before had been a vowel (‘A’, ‘E’, ‘I’, ‘O’ or ‘U’). Target occurrence: 12.5%.
iii) **NoLoad:** Participants were presented with the same auditory sequence of letters but without a requirement to respond or remember the letters.

Cognitive tasks were blocked and counterbalanced as follows: all participants completed a NoLoad block (NoLoad1), then the Nback and Count blocks were performed, in an order counterbalanced across participants. A second NoLoad block was completed at the end (NoLoad2). Results were averaged across both NoLoad blocks to provide a baseline measure of steering without additional cognitive load.

Constraining Gaze

The direction of gaze can influence steering control (Wilkie et al., 2010), and cognitive load can alter eye-movements (Victor et al., 2005). To determine whether changes in steering after resumption of control result directly from cognitive load during automation, or whether gaze patterns also influence steering, we measured and constrained gaze. In half of the trials gaze was left unconstrained (*Free*) to assess whether increased cognitive load affected eye-movements. Based on previous research it is expected that gaze might become more concentrated towards the future path (Victor et al., 2005; Recarte & Nunes, 2003). In the other half of trials, gaze was constrained to a tracking fixation point (*Fixed*) lying over the future path (as per Mole et al., 2016). This controlled for any differences in gaze behaviour across conditions to determine the pure effect of Load on steering performance.

Experimental Design

Participants received 5 practice trials before each block to become familiar with the simulator and task instructions. There were 6 trials repeated for each level of Gaze and Cognitive Load. Similar behavior was observed in both Cognitive Load conditions and also in both NoLoad conditions, therefore, for analysis purposes, central tendency was estimated from mean values calculated across trial repetitions and also across Load (Count, Nback) or No Load (NoLoad1, NoLoad 2) conditions. Repeated measures ANOVA were applied to steering measures in a Load (Load, NoLoad) × Gaze during Automation (Free, Fixed) × Gaze during Manual (Free, Fixed) design. Partial Eta Squared (η_p^2) is reported as a measure of effect size.

RESULTS

Oversteering bias (OSB) was calculated to assess directional deviation from the road-center (Wilkie et al., 2010). Positive values signal a position towards the inside edge (oversteering), and negative values indicate a position towards the outside edge (understeering). Simulator error meant that 3.12% of trials were removed (described in *Supplementary Materials* in osf.io/yzgra). Average steering bias and steering wheel corrections for Load and NoLoad conditions are shown in Figure 2. Load caused understeering relative to NoLoad ($F(1,19) = 59.3$, $p<.001$, $\eta_p^2 = .76$), consistent with reduced correction of the vehicle position relative to the road center (Figure 2A). There was a general propensity to not fully correct the lane drift that had occurred during Automation (-2.5 m), with all trajectories exhibiting understeering bias.

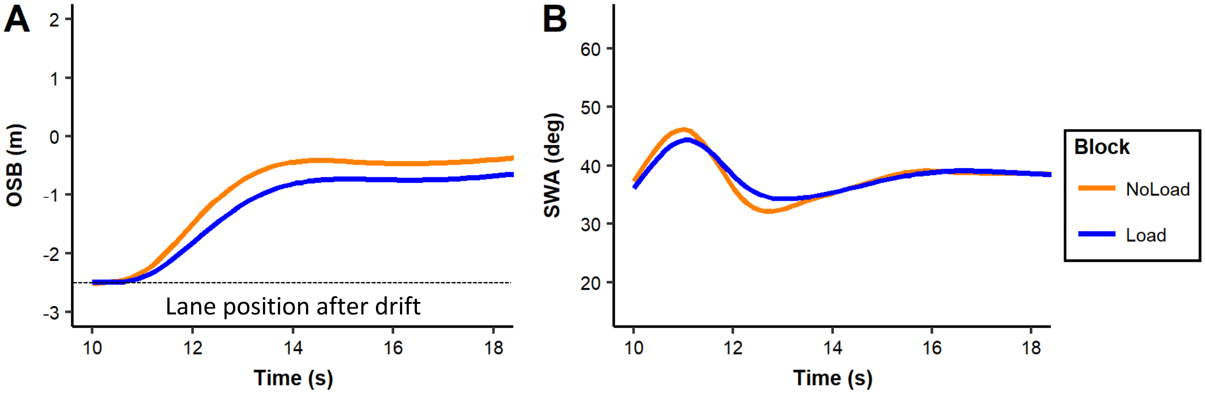

Figure 2. A) Average trajectories showing oversteering bias (OSB) over time, collapsed across Fixation Conditions. Negative values indicate understeering, zero values indicate a center of lane position and positive values indicate oversteering (cutting corners). B) Steering wheel angle (SWA) over time.

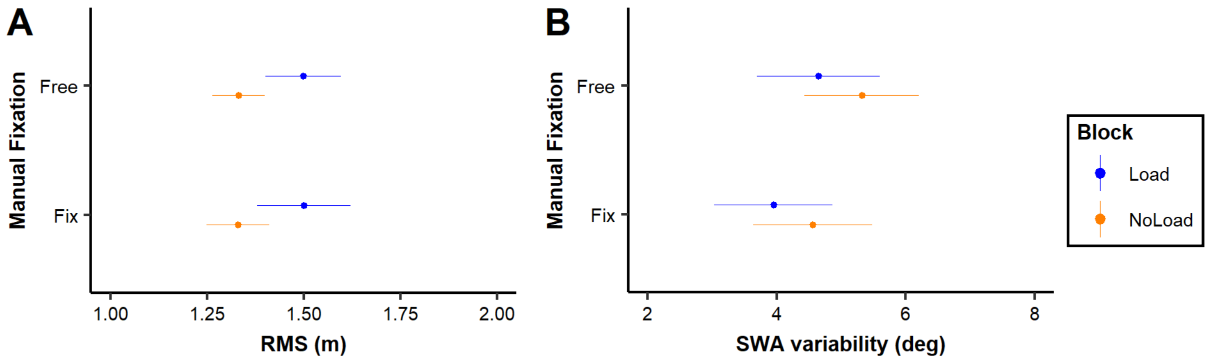

Figure 3. Steering performance for Free or Fix gaze conditions during manual driving, shown for Load (Blue) and NoLoad (Orange) conditions. A) Root Mean Square (RMS) of steering bias. Higher values equal greater error. B) Steering Wheel Angle (SWA) variability is calculated using the standard deviation of wheel angles within each trial. Lower values indicating smoother steering with fewer corrections. Bars are 95% CIs.

Figure 3A shows Root Mean Square (RMS) deviation from road midline (an unsigned measure of steering error) for all fixation conditions. Load caused consistently greater RMS errors compared to NoLoad (F(1,19) = 54.2, p<.001, η_p^2 = .74). Greater RMS errors could result from a failure to correct lane position, but could also occur if corrections were made, but in the wrong direction or of the wrong magnitude. To determine whether corrections were being made, steering wheel angle (SWA) variability was calculated (Figure 3B). Load caused smoother steering (lower steering wheel variability) than NoLoad (F(1,19) = 14.04, p<.001, η_p^2 = .43), suggesting that the increased steering error in Load was caused by failing to make sufficient corrections for the understeering introduced during automation (Figure 2B), a finding consistent with Kountouriotis et al. (2016) and Li et al. (2018). The steering measures appeared to produce patterns that were similar across gaze conditions (Figure 3), suggesting that the effects of Load on steering did not interact with whether gaze had been Fixed or Free (e.g. for OSB there was no reliable interaction between load and gaze conditions, F(1,19) = .018, p>.05, η_p^2 = .001). Whilst this indicates that the differences in steering responses were unlikely to be driven by changes in gaze patterns, cognitive load has been reported to lead to gaze sampling constricted towards the road center (Victor et al., 2005, Wang et al., 2014). Figures 4A shows that the variability of gaze along the horizontal dimension was indeed reduced during Load (F(1,16) = 21.89, p<.001, η_p^2 = .58), accompanied by an increased number of saccades and a reduced range of gaze dispersion, compared to NoLoad. Although we observed more constrained sampling of the scene when there was an additional cognitive load, we did not observe drivers looking more closely to the road center which is in contrast to some previous findings (Victor et al., 2005, Wang et al., 2014).

Figure 4B shows average gaze bias relative to the road center during automation. For this measure there are no reliable differences between Load and NoLoad. Nevertheless, it is intriguing that during automation drivers look close to the current lane position of the vehicle, rather than to the road center (or elsewhere). The phenomenon of 'looking where you are going' is well reported during active control of steering (Wilkie et al., 2010), but here we observe a similar phenomenon during automated driving.

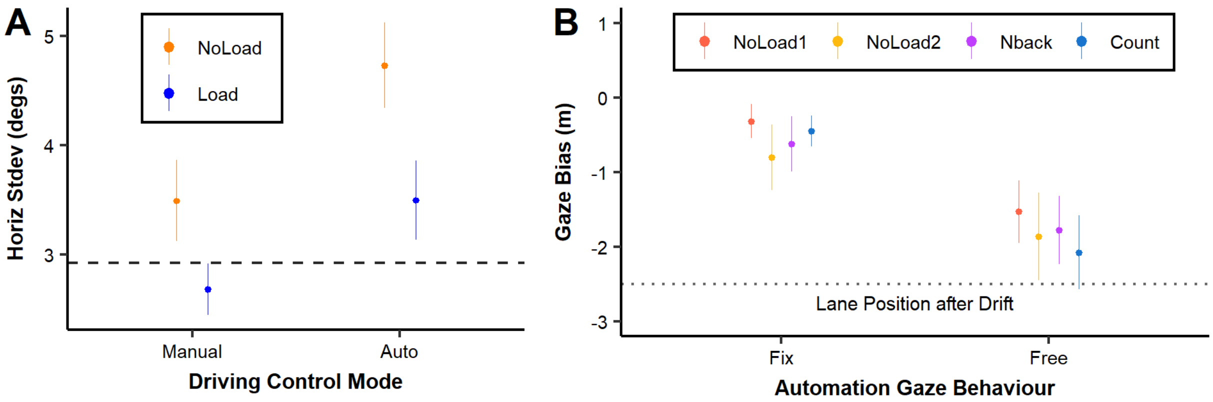

Figure 4. A) Standard deviation of horizontal gaze angle (Horiz Stdev) in degrees, relative to the center of the projection screen during NoLoad or Load and for Manual or Automated (Auto) control modes. Only data for Free gaze conditions are shown; the dashed line indicates the grand mean for Fix gaze conditions. B) Gaze bias (signed distance of the point of gaze in world coordinates relative to the road center) for NoLoad or Load (Nback, Count) when gaze was Fix or Free. Zero gaze bias indicates looking toward the road center (where the fixation cross was positioned) and negative gaze bias is toward the outside of the bend in the direction of the drift that occurs during automation (position marked by the dotted line). Bars are 95% CIs.

CONCLUSIONS

Previous research on cognitive load during automation has focused primarily on safety-critical situations after take-over (Merat et al., 2012). The present study tested drivers correcting subtle positional errors introduced by the AV. Steering and gaze behaviors were recorded with or without a cognitive load. Cognitive load reduced the magnitude of steering corrections, resulting in smoother steering, but drivers did not sufficiently correct the AV error (compared to no load). It has been suggested that cognitive load may impair participants' ability to remember and comply with task instructions (cf. Engstrom et al., 2017) however this was not the case for the present experiment. Participants made steering corrections in all conditions, however the magnitude of the correction was insufficient when there was a cognitive load (Figure 2). This finding suggests that the load did not inhibit the generation of steering responses, rather it was somehow attenuating the magnitude of response. One possible mechanism for this interference is via gaze behaviors being inhibited, leading to insufficient steering. Consistent with previous research, both cognitive load tasks did indeed cause restricted gaze sampling throughout trials (Wang et al., 2014; Recarte & Nunes, 2003; Victor et al., 2005) which may have disrupted the gaze behaviors necessary for executing sufficient steering corrections, but the effects of cognitive load on steering were observed even when gaze was fixed on the future path (Figure 3). This suggests that increased gaze concentration when cognitively loaded may be independent of the reduced magnitude of steering response. When considering the potential impact of these findings it should be highlighted that the scenario examined was tightly controlled, but in many ways provided an optimal takeover situation - the driver was given clear and explicit advanced notice of the need to take over control of the vehicle. In real-world situations there may well be 'silent' failures of AV systems (e.g. the AV drifts in lane). It should be expected that a concurrent cognitive load would have greater impact in these sorts of scenarios, with a cognitively loaded driver struggling to respond to takeover situations where there are many hazards (that a driver with restricted gaze may not detect) or where there is a greater need to alter the vehicle's trajectory.

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