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The Effect of Motor Control Requirements on Drivers' Eye-Gaze Pattern During Automated Driving

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Abstract

This driving simulator study compared drivers' eye movements during a series of lane-changes, which required different levels of motor control for their execution. Participants completed 12 lane-changing manoeuvres in three drives, categorised by degree of manual engagement with the driving task: Fully Manual Drive, Manual Intervention Required, Fully Automated Drive (Manual drive, Partial automation, Full automation). For Partial automation, drivers resumed control from the automated system and changed lane manually. For Full automation, the automated system managed the lane change, but participants initiated the manoeuvre by pulling the indicator lever. Results were compared to the Manual drive condition, where drivers controlled the vehicle at all times. For each driving condition, lane changing was initiated by drivers, at their discretion, in response to a slow-moving lead vehicle, which entered their lane. Failure to change lane did not result in a collision. To understand how different motor control requirements affected driver visual attention, eye movements to the road centre, and drivers' vertical and horizontal gaze dispersion were compared during different stages of the lane change manoeuvre, for the three drives. Results showed that drivers' attention to the road centre was generally lower for drives with less motor control requirements, especially when they were not engaged in the lane change process. However, as drivers moved closer to the lead vehicle, and prepared to change lane, the pattern of eye movements to the road centre converged, regardless of whether drivers were responsible for the manual control of the lane change. While there were no significant differences in horizontal gaze dispersion between the three drives, vertical dispersion for the two levels of automation was quite different, with higher dispersion during Partial automation, which was due to a higher reliance on the HMI placed in the centre console.

Keywords: Vehicle automation, Gaze patterns, Transition of control, Visual-motor coordination, Lane change.

Introduction

The motivation for this study comes from a well-known challenge in the field of Human Factors in Transportation, which is that the introduction of vehicle automation to the driving task can remove drivers' involvement in the decision-making and control loops (Louw & Merat, 2017), and this removal may ultimately compromise drivers' capabilities to make decisions, and act appropriately, whenever their intervention for system control is required (Young, 2012). Due to their limited Operational Design Domain (ODD), some vehicles are unable to perform certain complex manoeuvres, which involve decision-making elements, such as changing lane on a busy motorway. Therefore, some authors have argued that, in these situations, drivers might need to re-acquire sufficient situation awareness (Endsley, 1995) in order to safely and accurately resume control from the system, and accomplish the desired task or manoeuvre (see e.g. Louw & Merat, 2017; Zeeb et al., 2015; Dambock et al., 2013).

According to Gartenberg et al. (2014), the process of situation awareness recovery relies heavily on visual search, where the automation's operator (a driver in the context of this research) distributes their visual attention between relevant sources of information, to create the right mental model, in a goal-directed approach, for the correct execution of a given task. In the context of the information processing required for driving a vehicle, Sivak (1996) has also stated that this is mainly a visual task, that is achieved via tight coordination with the drivers' motor control systems, allowing them to guide the vehicle in the right direction, at the desired speed. The links between gaze-based measures, attention to, and successful completion of, tasks have been established for some time in studies on human behaviour. For example, Carrrasco (2011) and Posner (1980) demonstrated that longer fixation durations towards one specific point of interest are a good indicator of where drivers are placing their attention. However, drivers' visual attention is also known to vary depending on the scenario in hand (Borji & Itti, 2013), and can also change based on the different demands imposed by the driving environment (Crundal et al., 2003). In a similar line of thought, Sullivan et al. (2012) demonstrated through a simulated driving task that drivers had increased gaze time and frequency towards a particular information source while under conditions of higher levels of uncertainty. In that sense, it is to be expected that drivers, whenever recovering control of the vehicle (assuming low levels of situation awareness), are more likely to gaze longer and more frequently towards the areas which they expect to find the most relevant information. For example, Salvucci, Liu & Boer (2001) have demonstrated that drivers' gaze during a lane change task is generally characterised by an increased number of fixations towards the side mirrors, followed by a concentration of gaze towards the vehicle's heading - the destination lane.

In terms of lane-changing behaviour, Tijerina et al. (2005) report on two distinct phases of eye-tracking patterns. Defining a lane change as "(…) a deliberate and substantial shift in the lateral position of a vehicle with the intent to cross a lane boundary to enter an adjacent lane (…)", these authors link eye movement patterns to two main phases of the lane changing manoeuvre. The first phase, which occurs prior to the manoeuvre itself, is characterised by the acquisition of safety-related information, allowing the driver to decide if it is safe to overtake. Examples of such safety-related information include gap acceptance, the relative speed of their vehicle, distance to the vehicle ahead, and distance to the designated location in the adjacent lane (Gipps, 1986; Zheng, 2014). In terms of eye movements, Tirjerina et al. (2005), and Doshi & Trivedi (2009) report that this phase is generally characterised by a high frequency of glances to the mirrors, as well as over the shoulder checks. The second phase, on the other hand, termed the execution phase, is extremely demanding in terms of vehicle control and requires drivers to be aware of their vehicles' acceleration, steering control, and relative position on the road (Chovan, 1994). When it comes to eye movements, using results from a naturalistic driving study, Salvucci & Liu (2002) showed that drivers generally shift their primary visual focus from their own lane to the destination lane, immediately after the onset of the lane change. This study also showed a reduction in drivers' attention to the mirrors and road ahead at this stage of the manoeuvre.

On the topic of situation awareness acquisition, Louw et al. (2015) suggest that automated driving reduces situation awareness by taking drivers "out of the loop", with two different loops involved: "(…) we suggest that "being in the loop" can be understood in terms of (1) the driver's physical control of the vehicle, and (2) monitoring the current driving situation (…)" (Merat et al., 2019, p 6.). In this broad view of the problem, drivers are not only required to look towards the road to acquire the right information for appropriate situation awareness, but also need to apply the correct visuomotor control coordination (see Wilkie & Wann, 2010; Mole et al., 2019a), and consider the correct strategic planning of their future actions (Land et al., 2006). Endsley (2006) suggest this as a critical challenge of situation awareness acquisition in automation, where high levels of, spatially dispersed, information might exceed the operators' (drivers') capabilities, limiting their ability to attend to all relevant information, enforcing the prioritisation of certain information, above others.

Following the issues described above, it is of interest for the current state of the art on Human Factors in Automation research to understand if, and how, drivers' gaze behaviour is affected when they relinquish control from the vehicle (which is thought to fundamentally change the context of the task, see Parasuraman et al., 2000). It is also important to establish whether different levels of motor control, as determined by the level of automation, have different effects on this gaze behaviour, and, therefore, drivers' strategies for gaining situation-awareness, and ultimately, safe resumption of vehicle control. In this paper, motor control requirements is defined as the need for drivers' to actively monitor and guide the lateral and longitudinal movement of the vehicle, by interacting with the vehicle controls (cf. Merat et al. 2019). In this sense, it is expected that tasks with higher motor control requirements would demand the driver to coordinate their steering wheel and pedal movements to match their desired goal, based on the visual information acquired from the vehicle's movement (visual-motor coordination, Wilkie & Wann, 2010).

Previous simulator studies, investigating the lack of physical control during the driving task (generally caused by engaging automation) have reported an increased gaze dispersion away from the centre of the road, whenever drivers were not in control of the vehicle (Mars & Navarro, 2012; Mackenzie & Harris, 2015; Louw & Merat, 2017). Such patterns are even seen to be true for highly demanding phases of the driving task, such as curve negotiation. Mole et al. (2019a) suggest this change in gaze behaviour can be problematic since the interruption of the perceptual-motor coordination used in tasks such as driving can reduce the association between drivers' eye fixations and the vehicle's heading, which can reduce safety if automation fails (see also Mole et al. 2019b).

However, according to Mars and Navarro (2012), drivers' gaze behaviour pattern during curve negotiations in automation does not change significantly, compared to that seen during manual control, with drivers diverting a similar proportion of gaze to the same locations in given periods of time. The authors suggest that the eyes seem to follow the movement of the vehicle's heading, even when drivers are not in manual control, arguing that the placement of drivers' vision is not just affected by the bidirectional coordination between the eye and arm-motor systems, but also by kinematic cues caused by the visual perception of motion. However, an increased dispersion in drivers' gaze was also observed in this study, which, as suggested by Mole et al. (2019a), might affect drivers' ability to resume motor control, whenever required, especially after long periods of automated driving.

For less demanding driving situations, Mackenzie & Harris (2015) observed that drivers not in manual control of the driving task tend to prioritise scanning activities (e.g. looking for hazards in the periphery) over control-related gaze monitoring, such as looking towards vehicle heading. According to these authors, the importance of some information falls in favour of others, when we are not actively in control of the task, since, we as drivers tend to gaze towards what it is important to us.

However, it is important to note that the above studies were conducted in quite simple driving environments, in order to focus specifically on the effect of motor control of the vehicle as a dependent variable. The limitation of such an approach is that it lacks applicability for more complex scenarios, such as automated lane change manoeuvres, which might impose new demands on the driver, leading to a change in gaze behaviour patterns, as suggested by previous literature (see Crundal et al., 2003; Borji & Itti, 2013). Therefore, to understand how different levels of engagement with the control loop affect the way drivers disperse their gaze to acquire situation awareness for a response to a given task, it is necessary to isolate the need for motor control as a dependent variable, but in more complex scenarios, which require higher levels of decision-making that may influence gaze scanning behaviour.

Current study

This study forms part of a larger research programme related to the EU-funded AdaptIVe project (Grant Agreement No. 610428), the aim of which was to provide a deeper understanding of drivers' behaviour during transitions of control from automation to manual driving. The goal of the current study was to investigate drivers' visual scan patterns during a number of lane changing tasks, which, based on the level of automation engaged, differed in terms of the level of motor control, and decision-making required. It was hypothesised that drivers with different motor control demands would give priority to different kinds of information, such that drivers in active control of the vehicle would focus more on the vehicle's heading. In contrast, drivers without motor control of the task would focus on hazard perception routines, characterised by a higher lateral gaze dispersion during task execution.

Method

Participants

A total of 30 fully-licenced UK drivers were recruited for this study, using the University of Leeds Driving Simulator (UoLDS) participant database. One person withdrew from the study, and results are, therefore, based on the remaining 29 participants (15 male and 14 female). All participants had at least 2 years' driving experience (M = 13.62, SD = 9.62) and varied in age between 21 and 60 years (M = 34.21, SD = 8.94). Participants received a full set of instructions for the study and were compensated £20 for taking part. The study received approval from the University of Leeds Ethics committee (Reference Number LTTRAN-054) and took just under two hours to complete.

Materials

The experiment was conducted using the University of Leeds Driving Simulator, which consists of a Jaguar S-Type cabin, with fully operational controls, located inside a 4m spherical projection dome, with 300° projection angle and equipped with an 8 degrees of freedom motion system (see Figure 1). A Seeing Machines FaceLab eye tracking device (v4.5) was used to record participants' eye movements at 60Hz.

Figure 1 The University of Leeds Driving Simulator

Design and Procedure

The experiment followed a 3 (automation level) x 12 (lane changing manoeuvre) repeated-measures, within-subjects, design, where all participants had to perform the same task under three different levels of automation condition: Manual drive, Partial automation, and Fully Automated Drive (Full automation). These were presented in a fully counterbalanced order.

The experimental scenario involved travelling on a three-lane motorway, with a speed limit of 70 mph, where automation (if present), was available in the middle lane. There was a regular flow of traffic (70 mph) in lane one of the motorway (to the left of the ego vehicle), and no vehicles in lanes 2 or 3 (see Figure 2). For automation to be activated, participants were required to enter the middle lane (lane 2) and maintain the speed limit, while also driving in the centre of the lane. The 80.64 km long road depicted a typical UK motorway, and consisted of straight sections of road, with a few gentle curves (252 m with a 1km radius).

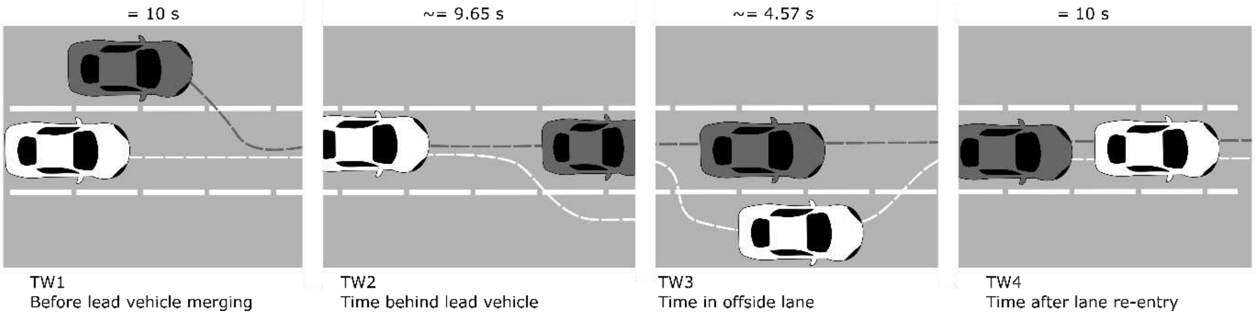


Figure 2 Representation of the various phases of the traffic scenario during the Lane Change experiment (Avg. 34.22 seconds duration).

During each of the three drives, 12 events were choreographed, where a vehicle from the left lane (lane 1) entered the middle lane (lane 2) and gently reduced its speed (to around 50 mph), slowing the ego vehicle down and prompting the need for a lane-changing manoeuvre by participants. Here, participants were asked to change lane, if they so wished, and if they did not overtake the lead vehicle, no critical event ensued, and drivers were simply caught behind this slow-moving vehicle. After overtaking the lead vehicle, participants were required to move back into the middle lane, as soon as it was safe to do so and return their speed to 70 mph, in order to reengage the automated system (for the two automated drives).

For the two automated drives, participants were told that they were not required to monitor the environment. They were instructed to only interact with the steering wheel during the manual sections of the drives, or during the take-over situations (whenever required). The Human-Machine Interface (HMI), located in the centre cluster, presented different information related to the behaviour of the system. The HMI was developed in conjunction with CRF (Fiat) as part of the AdaptIVE project (see also Madigan et al., 2018 for further details). Details of the HMI for each driving condition are outlined below:

Manual drive: The driver was entirely in control of the vehicle's lateral and longitudinal position (SAE level 0; SAE, 2018). All the overtaking manoeuvres and vehicle control were performed manually by the participants. In terms of HMI, as automation was not available throughout the manual condition, no automation-related information was displayed (see Figure 3).

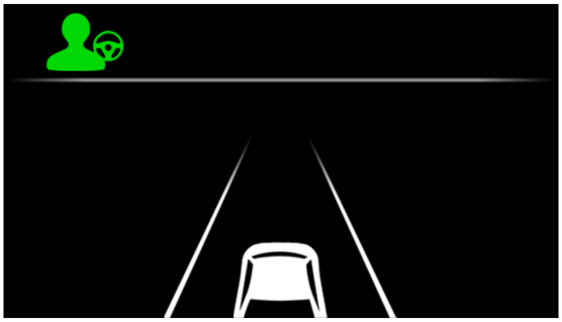
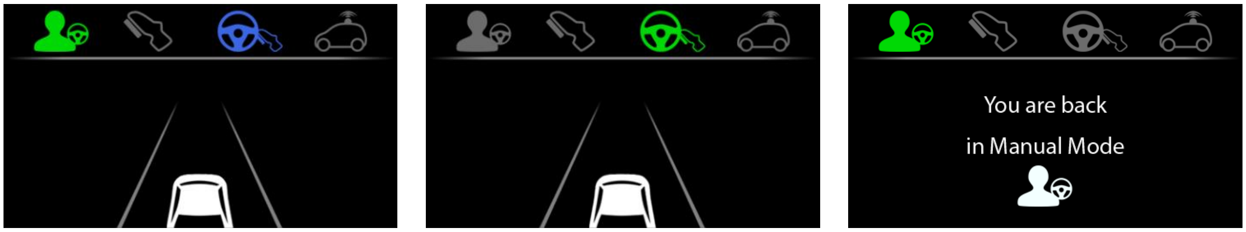


Figure 3 HMI for Fully Manual Drive (no automation available). Designed by: CRF.

Partial automation: Here, both lateral and longitudinal control of the vehicle in the centre lane were managed by the system, with a combination of an Adaptive Cruise Control (ACC) and a Lane-Keeping System (SAE level 2). The system maintained the vehicle position in the centre of the middle lane at 70 mph unless there was a lead vehicle, in which case it would slow down, maintaining a 2 seconds headway. In this condition, the system was not able to perform an overtaking manoeuvre. Therefore, drivers were expected to regain control of the vehicle and change lane when they wished to overtake the lead vehicle. In this condition, the system could be disengaged using three different methods: 1) by pulling the right indicator stalk (as with engaging the system); 2) by pressing the accelerator pedal; 3) bymoving the steering wheel more than 2 degrees. In terms of HMI, the system started with the same information as in manual driving and informed drivers when the automation was available, by means of a flashing blue steering wheel icon (see Figure 4). Once the automation was engaged by the driver, the colour of the steering wheel icon changed to green. When the automation was disengaged by the driver, the HMI would present a written message stating, "You are back in Manual Mode". The system in this condition also provided a "beep" sound whenever the automation was engaged or disengaged.



You are back
in Manual Mode

Figure 4 HMI for Manual Intervention Required condition. Designed by CRF. Left: automation available, Middle: automation on, Right: driver back in manual control.

Full automation: Similar to the previous condition, this system also assumed lateral and longitudinal control of the vehicle. The main difference between this system and Partial automation was that, here, the system could perform the overtaking manoeuvre. The only intervention required from the driver was to move the indicator lever in the direction they wanted the lane change to occur, and the system would then perform the manoeuvre. Regarding the HMI, when the automation was on, a green car icon appeared on the screen (instead of the steering wheel from the Partial automation condition), and the background also turned to green, distinguishing itself from the Partial automation condition. When participants moved the indicator stick, an arrow icon appeared on the screen, pointing to the direction of the manoeuvre.

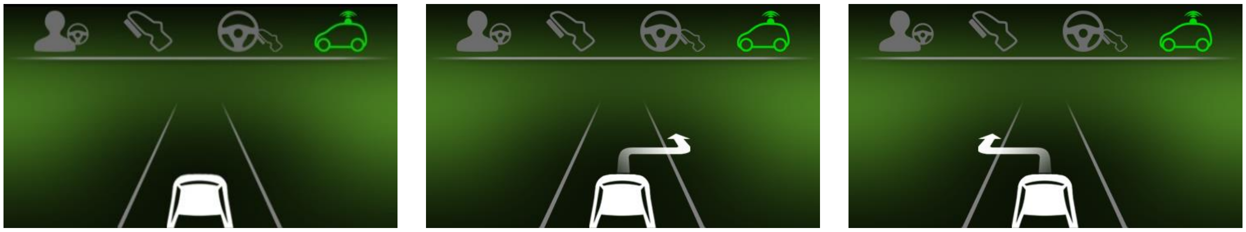


Figure 5 HMI (Human-Machine Interface) for Fully Automated Driving condition. Designed by CRF (Centro Ricerche Fiat). Left: Automation on, Middle & Right: vehicle changing lane automatically.

Statistical Analysis

The data was compiled and treated using MatlabR2016a and analysed using IBM SPSS v21. Kolmogorov-Smirnov tests (Conover, 1999) were used to check for normality and showed that part of the data was not normally distributed and presented a slight positive skew. In order to apply parametric statistical tests, logarithmic transformations were made in cases where it was applicable. All the plots presented below are based on the untransformed data, but the ANOVA test results are based on the corrected/transformed samples. An α-value of 0.05 was used as the criterion for statistical significance, and partial eta-squared was computed as an effect size statistic. Where Mauchly's test indicated a violation of sphericity, degrees of freedom were Greenhouse-Geiser corrected.

Research Variables

Eye-tracking measures can be noisy and prone to loss of quality. Therefore, data filtering and selection were applied, using Facelab's algorithms, to avoid biasing the results with low-quality data. The first criterion was gaze quality, which excluded from the dataset all cases with less than 75% good gaze tracking, according to Facelab's algorithm (quality levels < 1). Also, due to some possible detection failures (e.g. when drivers' head was down), some of the data points suggested that drivers looked outside the simulator's projection field. A filtering algorithm was, therefore, applied, excluding all data points that were consistently far away from the interior of the vehicle, or the projection scene inside the simulator dome.

In this study, two main eye-tracking measures were used to assess drivers' visual attention to the road, and vehicle controls, during the 12 lane-change manoeuvres. The first measure involved calculating the percentage of drivers' eye fixations to five main areas, including the road centre (PRC – Percentage Road Centre; see Victor, 2005; Carsten et al., 2012; and Louw et al., 2017). As in all previous studies conducted in our laboratory, the reference point for this metric was defined for each participant as the mode of their gaze fixations within a 6° circular limit (Carsten et al., 2012; Louw et al., 2017; Merat et al., 2014; Louw et al., 2017). The other four areas of interest (AoIs) were defined as diagonal sections equally divided from the road centre. The top AoI includes both the far road ahead and the rearview mirror; the left and right AoIs include the view of the side lanes, as well as the wing mirrors and the shoulder checks; and the bottom AoI constitutes both drivers close view of the road ahead and their view of the instrument cluster (where the system's HMI is located). Any variations in this measure over time, and across the three different drives were explored. Fixations were calculated based on a 200 ms threshold.

Drivers' fixations to the AoIs were analysed for each overtaking event, and divided into 17 intervals of 2 s, using the time for exiting the middle lane as a reference starting point. The remaining time windows were decided based on the mean duration of each step of the lane changing manoeuvre performed by the drivers (as can be seen in Figure 2). This resulted in 10 intervals before and 7 after the lane change. It must be noted that several different time intervals were tested here (between 1s and 5s), but smaller chunks of time led to fixation percentages of 100% or 0% - suggesting that one second was too short for drivers to deviate their eyes. Larger intervals of 3 or 5 s did not reveal the subtle changes in drivers' gaze behaviour (e.g. from the planning to the execution phase of the manoeuvre, when drivers changed their strategy in a very short period). Therefore, observing changes in 2-second intervals, which started 10 seconds before the mean point at which the lead vehicle began its manoeuvre to the middle lane (flagged by the simulator software) until 10 seconds after the mean point at which the ego vehicle re-entered lane 2 after the overtaking manoeuvre (mean duration of 34.22 seconds) was chosen to assess fixation patterns in this study.

The second metric used was an investigation of drivers' vertical and horizontal gaze dispersion. This was calculated using the mean of the standard deviation of raw gaze and pitch values. A similar approach was used by (Chapman & Underwood, 1998), as an indicator of drivers' scanning behaviour for strategic-based information, due to increasing demands imposed by the driving environment. An increase in dispersion was expected during the planning and execution of the lane-changing manoeuvre in this study, to denote drivers' scanning behaviour during decision-making. We were particularly interested in establishing if this pattern was different across the three drives. It was hypothesised that, at least in manual driving, increasing demands of the drive, such as those required during lane changing, would increase the dispersion of fixations, as drivers moved their visual attention between the lead vehicle, the adjacent lane, the destination lane, and the vehicle HMI, to gather information about their eminent manoeuvre. Understanding whether the same pattern was present for the two levels of automation and similar to that seen in manual driving, was relevant here. Therefore, it was important to establish whether the timing and type of dispersion varied between the three drivers, as drivers' responsibility, decision-making, and levels of motor control, changed across the three different drives. However, using overall gaze dispersion based on short time intervals (as the two seconds used in the previously mentioned analysis) could lead to potential data quality issues and, therefore, limitations when interpreting our results. The reason is that gaze dispersion is sensitive to the overall number of observations in the dataset, as it is recalculated at every time interval, ignoring the deviation which happened in the previous iterations. To address this issue, average levels of vertical and horizontal dispersion were plotted for the three drives, based on four main time windows (the size of these time windows was different for each driver, as it was based on the time they spent in each step of the manoeuvres). The four Time Windows were identified as follows: 1) 10 seconds before the lead vehicle entered the middle lane; 2) from the lead vehicle's arrival in the middle lane, until the time when participants started the lane change (*M* = 9.65 s, *SD* = 2.91 s); 3) from the point participants exited the middle lane, until they returned to it, thereby completing one lane change manoeuvre (*M* = 4.57 s, *SD* = 3.88 s); and 4), 10 seconds after return to lane 2 (see Figure 2Figure 3). The division of those four time windows (TW) is based on Tijerina et al.'s (2005) definition of a lane change task , as the visual attention demands for the task may vary in the different stages of a lane change. TW1 was used to understand how drivers disperse their visual attention during a free drive with no vehicle in front; TW2 is the representation of the decision-making phase of the lane-changing task; TW3 represented the execution phase, and the TW 4 is the point where drivers confirm the appropriate execution of the manoeuvre and return to free driving.

Results and Discussion

Percentage Road Centre

First, assess whether there were any learning effects in the data sample, a Two-way repeated-measures ANOVA was conducted on the percentage of fixations to the road centre to measure the effect of the order of the overtaking events (13) and DRIVE (Manual drive, Partial automation, Full automation). There was no significant effect of the order of the events [F(4.566,123.281)=0.965, *p*=.48, ηp^2 =.034], or interaction effects [F(6.273,150.548)=1.526, *p*=.122, ηp^2 =.06]. This result suggests that there was no significant learning effect during the whole experiment, indicating that drivers behaved similarly during the whole experiment.

A two-way repeated-measures ANOVA was conducted on the percentage of fixations to the road centre, to measure the effect of Drive (Manual drive, Partial automation, Full automation) and Time Interval (17 intervals of two-second length) (see Figure 6). There was a significant effect of Drive on PRC [F(1.408,33.796)=5.46, *p*<.05, ηp^2 =.180], where Bonferroni *post hoc* tests (Tabachnick & Findell, 2001) revealed an overall higher percentage of fixations to the road centre during Manual drive (~60%), compared to Full automation (~53%). However, there was no difference between Full automation and Partial automation, or between Partial automation and Manual drive, for this measure.

There was also a main effect of time interval (TI) on PRC scores [F(5.162,161.846)=8.898, *p*<.001, ηp^2=.270]. As can be seen in Figure 6, *post hoc* tests identified that PRC in the 9th TI was significantly lower than TIs 1-8 and TIs 10-13. This shows how, for all three automation conditions, drivers' visual attention moved away from the road centre immediately (2 seconds) before exiting the middle lane, presumably in preparation for the overtaking manoeuvre. A sharp rise in PRC is then seen during the lane exit phase (TI 11), which was significantly higher than TIs 7-10, 15 and 16. This rise in PRC just before returning the vehicle to the middle lane is expected, showing drivers' attention to the road centre, and particularly the road area relevant for correct repositioning of the vehicle (Tijerina et al., 2005), before automation could be reengaged.

A significant interaction between TI and Drive was also seen [F(10.859, 260.624)=2.929, *p* <.001, ηp^2=.109], where PRC values for the two automation conditions, Full automation and Partial automation, were generally more aligned, and lower, before the lead vehicle entered the middle lane, i.e. when there was no major interaction required from the driver regarding the lane changing manoeuvre, and the automation was engaged (TIs 1-4). Eye movement patterns then converged for the three driving conditions, when the lead vehicle was in the middle lane, ahead of the ego vehicle, and remained similar until 2 seconds after lane exit (TIs 11-17), where drivers' attention to the road centre then dropped in Full automation, immediately after the manoeuvre execution, since less physical engagement with the vehicle was required.

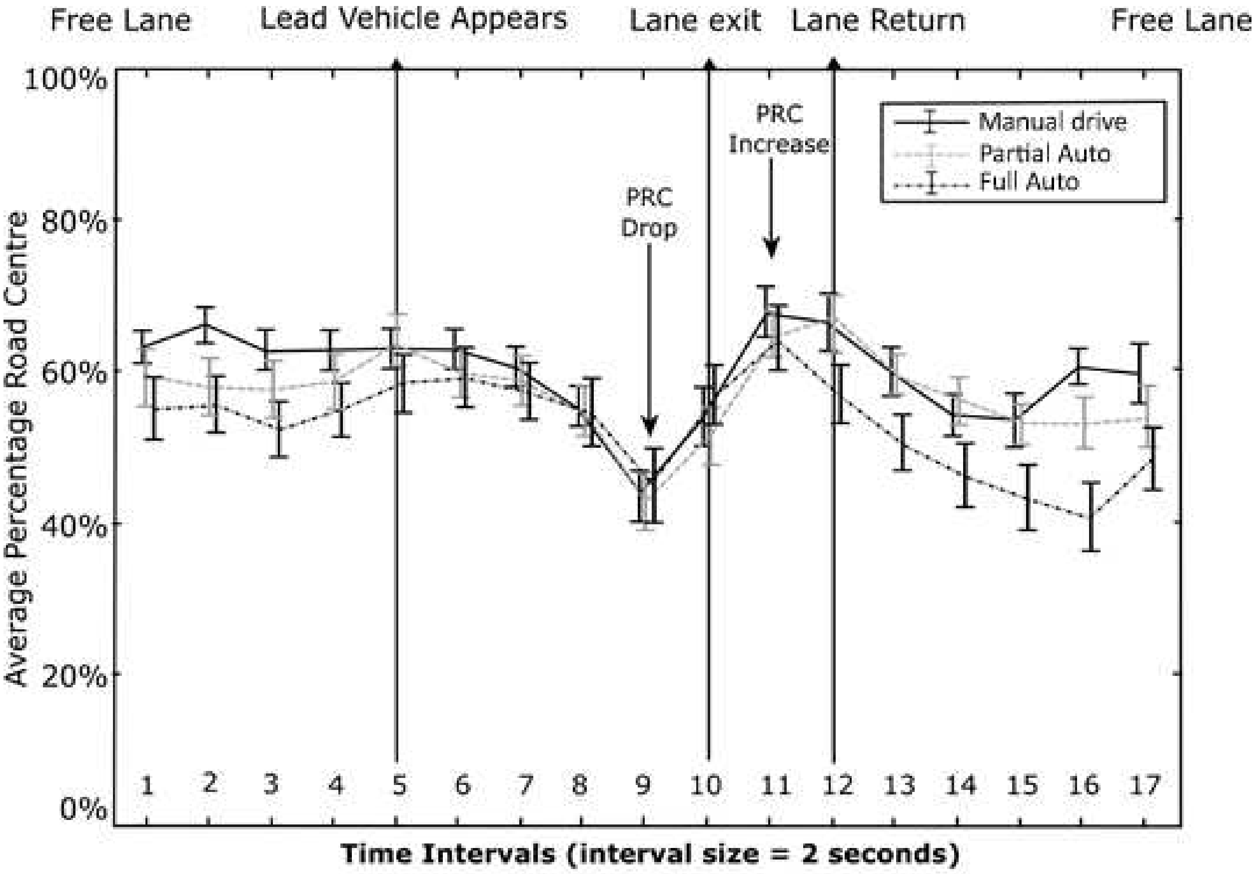


Figure 6 Average Percentage Road Centre scores over time during the three drives. The vertical lines represent the starting points for the different phases of the overtaking manoeuvre, which are based on the average duration of each phase for all drivers. The error bars represent the standard error within each distribution.

Taken together, these results suggest some general patterns regarding drivers' information acquisition for these three types of lane-changing task, as governed by the level of automation. For the two automation drives, after attending to the requirement to intervene, drivers exhibit a sudden drop of visual attention towards the road centre, which is similar to that of the manual drive, presumably because they continue to sample information from the road environment, for example looking towards the side mirror and destination lane, to decide whether it is safe to overtake. Further analyses performed indicated that most of the drivers fixated to the right AoI (where the wing mirror is located) before the initiation of the manoeuvre, during TIs 8, 9 and 10, where the drop of PRC was registered. However, this was much higher for the manual drive (Percentage of drivers looking at the right AoI during these time periods pattern: Manual drive = 100%, Partial automation = 89.96%, Full automation = 86.17%). Once they acquired the relevant information, there was a sharp increase in the amount of attention towards the central AoI, for all three drives. An increase in fixations to the road centre is seen for all drives, after lane exit, which shows that, regardless of automation level, all drivers were looking to the destination lane, which they are merging into. This is presumably in order to ensure the path ahead in their destination lane is free, or to coordinate their visual-motor control of the task. Similar results have been reported for lane changing in manual driving by Salvucci & Liu (2002), Salvucci Liu & Boer (2001) and by Tijerina et al. (2005), who showed a reduction in drivers' attention to the side (mirrors and shoulder check) and a focus on the target lane, located in the centre of their field of view. Figure 6 also shows that from 2 seconds after they returned to the middle lane, there is a steady reduction in drivers' PRC values, especially for the Full automation condition, with this reduced PRC remaining lower for this drive for 5-8 seconds after lane re-entry (TI 13-17).

Overall, these results illustrate that, even when drivers were not engaged in the physical act of changing lane, their visual attention to the road ahead, and the adjacent lane, was quite similar. These findings are similar to those reported by Mars and Navarro (2012) and suggest that drivers maintain the same level of attention to the driving environment, even when the perceptual-motor connection with the vehicle is broken. Considering that drivers are more likely to gaze towards the most informative information for the given task (Spargue & Ballard, 2004; Sullivan et al., 2012), it seems that the need for decision-making oriented information (such as the ones found in the speedometer and right-side mirrors) overcome the effects of the lack of motor control in lane change tasks. However, it is worth noting that similarities in gaze patterns were only observed during the moments of high decision-making demand, as the drivers' PRC values seem to diverge between the groups the further time away from the actual lane-change task. An analysis of PRC data over the 12 lane-changing manoeuvres showed no significant differences in this pattern over time during TIs 8-10 (which, according to Tijerina et al. (2005) are considered to be the moments of the preparation for a lane-change, [F(11,44)=.667, p > .05, ηp^2 = .014], nor in drivers' fixation percentage to the right AoI [F(1.690,7.823)=1.665, p >.05, ηp^2 = .029]. It remains to be seen if longer-term experience with the system affects this pattern.

Horizontal and Vertical Gaze Dispersion

To understand which other areas of the road drivers attend to during lane changes and whether this is different for manual versus automated driving, we analysed the standard deviation of gaze yaw and pitch, plotting the dispersion of gaze for each phase of the lane change manoeuvre. Two repeated-measures, two-way ANOVAs (one for pitch and the other for yaw gaze dispersion) were conducted, to assess the effect of Drive (Manual drive, Partial automation, Full automation) in one of four Time Windows: 1) before the lead vehicle entered the middle lane; 2) time spent behind the lead vehicle; 3) time in offside lane, and 4) time after the overtake manoeuvre was complete (ego-vehicle returns to the middle lane, see Figure 2). Regarding horizontal gaze dispersion, the data for drivers' standard deviation of yaw was not normally distributed, showing a slight positive skew, which was corrected through logarithmic transformation.

Analyses of results showed that there was no main effect of Drive [F (2,32) =.845, *p* >.05 ηp^2=.050] on yaw gaze patterns. However, there was a significant main effect of Time Window [F(3,48)=21.803, *p* <.001, ηp^2=.577], where horizontal gaze dispersion was significantly higher for TWs 2 and 4 (*M* = 7.690; 8.348, before and after the manoeuvre, respectively). Based on the results from the previous section (Percentage Road Centre), there was an increased amount of fixations to the side AoIs (left and right, where the wing mirrors are located) during the period of time equivalent to TW 2 (see TIs 8-10, in Figure 6). This increased lateral dispersion can be explained by the fact that drivers were inspecting the side lanes in order to decide how to act. These results reaffirm what was found for the PRC analyses, where drivers' visual attention to the road centre varied across time in the same way for the three Drives. These findings reinforce the idea that the nature of the task – in this case, overtaking a lead vehicle – has a strong influence on drivers' horizontal gaze patterns, regardless of the automation condition.

There was also a significant interaction between Time Window and Drive [F(6,96)=2.235, *p* < .05, ηp^2=.123], with *posthoc* Bonferroni tests showing the highest dispersion in yaw gaze for Full automation, during TW 3, i.e. when the vehicle was in the offside lane. As stated above, even if the overall pattern of dispersion was similar since this stage of the lane change was managed by the automated system in Full automation, drivers have no real reason to pay attention to the vehicle's heading, showing more gaze dispersion and less attention to the road centre.

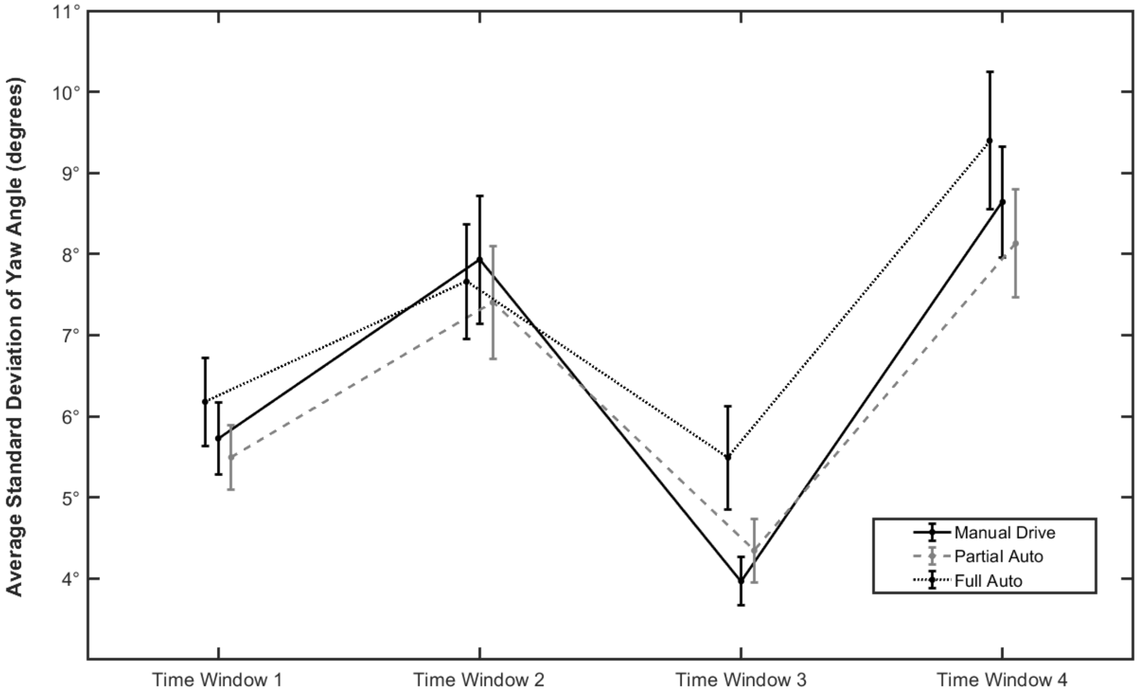


Figure 7 Average standard deviation of gaze Yaw over time, during the different automation conditions. TW 1 represents the time 10 seconds before the entrance of the lead vehicle on the middle lane, TW 2 is the time that the ego vehicle spent behind the lead. The error bars represent the standard error within each distribution.

An analysis of drivers' vertical gaze dispersion showed a significant main effect of Drive [F(2,34)=6.361, *p*<.001, ηp^2=.272], where SD of Pitch was higher overall in Partial automation, compared to Full automation. Results also showed the least degree of variability in gaze pitch for both Full automation and Manual drive. There was a significant effect of Time Window [F(3,51)=7.606, *p*<.001, ηp^2=.309] on SD of Pitch, which was higher in TWs 2 and 4 (before and after the manoeuvre) than in TW 1 (before lead vehicle entering the middle lane). Finally, there was a significant interaction between Drive and Time Window [F(3.180, 54.151)=9.973, *p*<.001, ηp^2=.370], where SD of Pitch in Manual drive was higher than Partial automation and Full automation in TW 1, the period before the merging of the lead vehicle into the middle lane.

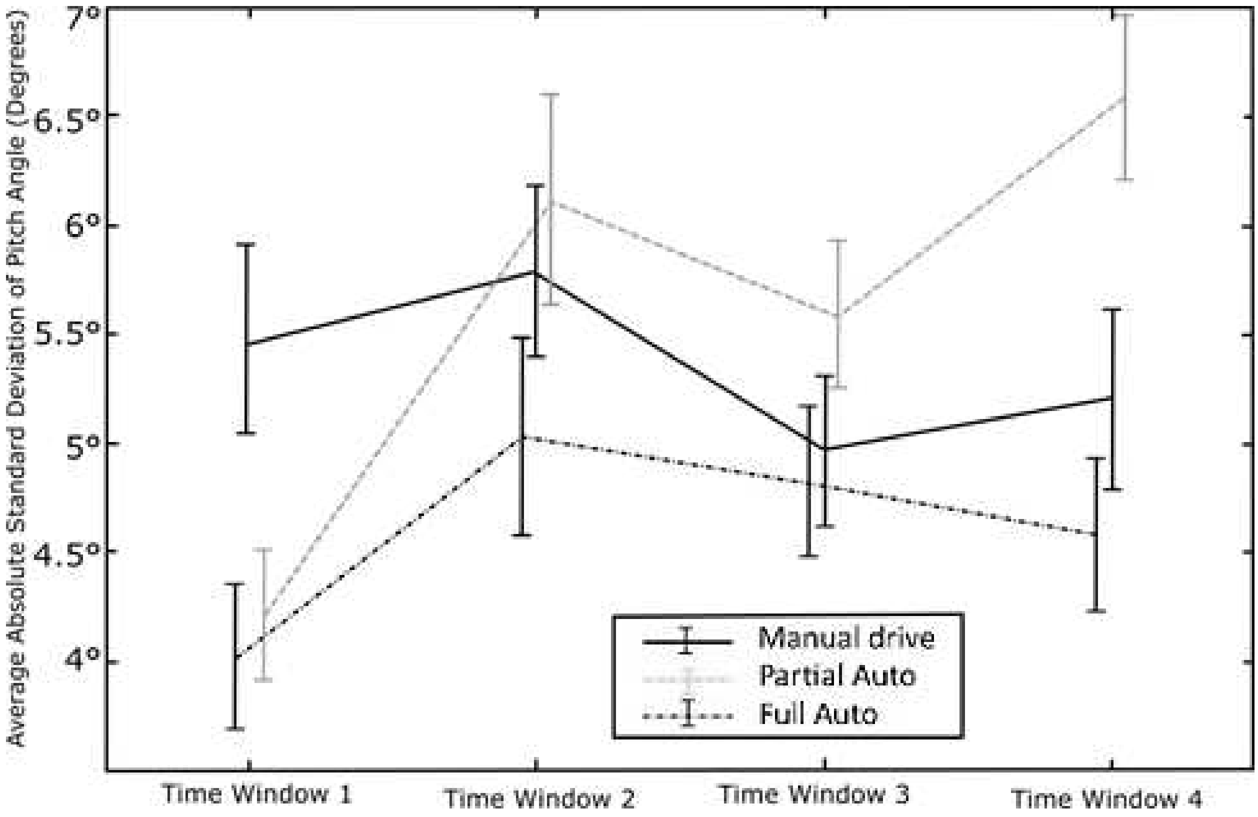


Figure 8 Average standard deviation of gaze pitch over time, during the different automation conditions. TW 1 represents the time 10 seconds before the entrance of the lead vehicle on the middle lane, TW 2 is the time that the ego vehicle spent behind the lead. The error bars represent the standard error within each distribution.

A higher SD of Pitch was also observed for Partial automation in TWs 2-4. Further analyses showed that during this time, the place most fixated (after the road centre, which was always the most fixated area) by the drivers in Partial automation condition was the bottom (11% in TW2 and 15.45% in TW4). These results suggest that drivers' need to acquire additional information was highest during the Partial automation condition when their attention to the actions of the lead vehicle and information provided by the HMI (located in the bottom AoI) was highest. As this was the only condition where a transition of control to manual was required, the significant increase of drivers' gaze dispersion towards the bottom AoI during TW1 and TW4 suggests that drivers used the vehicle HMI mostly during Partial automation, to assist with information about the disengagement/re-engagement of the system. On the other hand, the low levels of Pitch SD in Full automation suggest a lesser urgency for drivers to access the information presented in the instrument cluster (both the automation HMI and speedometer), also suggesting that drivers trusted the automated system, perhaps even pressing the 'lane changing button' on the steering wheel, without looking down at the HMI. Following the same logic used in Sullivan et al. 's (2012) study, assuming high uncertainty of specific information (due to the induced OOTL state), drivers seemed only to see value in the HMI information during moments of transitions of control.

Figure 8 shows how drivers' pitch gaze dispersion is affected by the different demands imposed by the DVE (Crundall et al., 2003), and that this is not the same for the three different drives. In TW1, where there was no vehicle in the middle lane, the only condition which required attention to heading and speed control was Manual drive, which shows the highest vertical gaze dispersion. As outlined above, for TW 2 and 4, drivers in Partial automation had one extra task, when compared to the two other conditions: transition of control from automation to manual mode, and vice versa, which accounts for the higher SD of gaze in this condition, and highlights the need for reliable and timely information for drivers for such transitions of control.

Conclusion

The goal of this paper was to evaluate the impact of different levels of motor control requirements for task execution on drivers' gaze behaviour during lane changing manoeuvres assisted by vehicle automation. To do so, drivers' percentage of eye fixations to the road centre, as well as gaze dispersion metrics were compared between different test conditions in a lane change task. For each condition, drivers were required to intervene manually with different intensities (control the whole task, transition control to overtake, push the indicator lever to allow automated lane change) in order to complete the manoeuvre.

Percentage road centre (PRC) analyses showed that, during moments of low task demand, drivers' attention to the road centre was lower whenever they were not in active control of the driving task. On the other hand, the differences in their gaze behaviour were quickly resumed (as also reported by Louw et al., 2017) whenever drivers moved closer to the lane change event. Regardless of the level of vehicle automation, drivers' visual attention was directed away from the centre of the road at the same time, immediately before the initiation of an overtaking manoeuvre, which was then refocused towards the road centre during its execution. The observed pattern is similar to that reported in previous literature on manual lane change (Gipps, 1986; Salvucci & Liu, Boer 2001). This result leads us to the assumption that, regardless of drivers' manual engagement with vehicle control, the demands imposed by the task in hand seem to directly affect the way they sample their surroundings for information (Spargue & Ballard, 2004), even if they do not have to actively interact with such information.

In general, drivers' horizontal gaze dispersion was not significantly affected by the different levels of motor control requirements. On the other hand, drivers' vertical gaze dispersion was higher during times when a transition of control was required, with further analysis confirming that this dispersion was generally targeted to the bottom AoI, where the system interface was located. This result suggests that HMI information is especially useful during moments of transitions of control, probably to confirm whether the transition was successful or not, as the interface was the only information source about the system status. Therefore, system designers should consider prioritising a clear identification of system status on vehicle HMI since our results suggest such information encourages drivers to move their eyes towards that area.

This study supports Mackenzie & Harris' (2015) assumption that drivers not in physical control of the driving task change the focus of their visual attention, based on new monitoring priorities. The results observed also suggest that system-based information on an interface is generally not a priority for drivers in automation, outside moments where a transition of control is required, with drivers preferring to direct their attention towards the outside road environment. The implications of these findings are an important consideration for road safety, if drivers become complacent and over trust system information (Miyajima et al., 2015), especially during silent automation failures, where a Take-over-Request by the automation is absent (Louw et al., 2019).

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