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Louw, T orcid.org/0000-0001-6577-6369, Madigan, R orcid.org/0000-0002-9737-8012, Carsten, O et al. (1 more author) (2017) Were they in the loop during automated driving? Links between visual attention and crash potential. Injury Prevention, 23 (4). pp. 281-286. ISSN 1353-8047

https://doi.org/10.1136/injuryprev-2016-042155

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Louw, Madigan, Carsten, & Merat. (in press). Were they in the loop during automated driving? Links between visual attention and crash potential. *Injury Prevention.*

Were they in the loop during automated driving? Links between visual attention and crash potential

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ABSTRACT

A proposed advantage of vehicle automation is that it relieves drivers from the moment-to-moment demands of driving, to engage in other, non-driving related, tasks. However, it is important to gain an understanding of drivers' capacity to resume manual control, should such a need arise. As automation removes vehicle control-based measures as a performance indicator, other metrics must be explored. This driving simulator study, conducted under the EC-funded AdaptIVe project, assessed drivers' gaze fixations during partially-automated (SAE Level 2) driving, on approach to critical and non-critical events. Using a between-participant design, 75 drivers experienced automation with one of five out-of-the-loop (OOTL) manipulations, which used different levels of screen visibility and secondary tasks to induce varying levels of engagement with the driving task: 1) *no manipulation*, 2) *manipulation by light fog, 3) manipulation by heavy fog*, 4) *manipulation by heavy fog plus a visual task,* 5) *no manipulation plus an n-back task*. The OOTL manipulations influenced drivers' first point of gaze fixation after they were asked to attend to an evolving event. Differences resolved within one second and visual attention allocation adapted with repeated events, yet crash outcome was not different between OOTL manipulation groups. Drivers who crashed in the first critical event showed an erratic pattern of eye fixations towards the road centre on approach to the event, while those who did not demonstrated a more stable pattern. Automated driving systems should be able to direct drivers' attention to hazards no less than 6 seconds in advance of an adverse outcome.

1. Introduction

The first generation of partially-automated vehicles (SAE Level 2)[1] is already on our roads. The Volvo XC90, for example, combines Lane Keeping Assist (LKA) and Adaptive Cruise Control (ACC) in 'IntelliSafe Autopilot' mode.[2] However, drivers are still required to supervise the system and resume control, for instance due to system limitations. Studies suggest that prolonged monitoring of an automated system can take drivers out of the loop,[3] inducing passive fatigue,[4] thereby reducing drivers' attentional capacity[5] and ability to detect, evaluate and respond to critical events thus increasing the likelihood of crashes.[6-8]

Concomitantly, drivers may choose to engage in non-driving related activities,[9] which distract from the supposed primary task of monitoring the vehicle. Therefore, passive fatigue and task disengagement are two factors that may hamper drivers' ability to safely resume control from an automated system in driving.[10,11] Previously, in a series of studies designed to investigate this concept, we used various OOTL manipulation techniques, including altering drivers' visibility of the road scene during automation while they completed visual and non-visual tasks, thereby varying drivers' level of awareness and engagement in the driving task.[12,13] We found a differential effect of OOTL manipulation on the standard deviation of horizontal gaze position, where drivers looked around more when their view of the driving scene was completely blocked, and horizontal gaze was more concentrated when drivers performed a visual secondary task presented on the road scene, but these differences actually resolved within three seconds after removal of the OOTL manipulation. However, while gaze dispersion provides an overview of drivers' visual attention, it is not as informative as point and duration of eye fixations for identifying the focus of drivers' visual attention. Previous studies have shown that sudden changes to the road environment capture drivers' attention, resulting in reduced visual scanning of the scene and increased fixations towards changes therein,[14,15] which link directly to an increase in crashes.[16] Therefore, this study considered drivers' eye fixations in the seconds after removal of the OOTL manipulations, to assess how each manipulation affected the pattern of visual attention allocation, and whether this was predictive of drivers' ability to avoid crashes in critical scenarios. Finally, although many studies have considered driver behaviour after take-over from automation in response to a take-over request[17,18] we introduced an 'uncertainty alert' in this study to portray potential system limitation, which required drivers to assess the need to resume manual control, allowing us to evaluate drivers' trust in the system, assessing their visual attention on approach to each of the six events.

2. Methods

2.1. *Participants*

75 drivers (41 male), aged 21-69 years (M=36.16, SD=12.38) were recruited via the participant database of the fully motion-based University of Leeds Driving Simulator (UoLDS) and were reimbursed £20 for partaking. Participants had normal or corrected-to-normal vision, an average annual mileage of 8290.46 (SD=6723.08), a full driving licence for at least three years (M=16.22, SD=12.92), and drove at least twice a week.

2.2. *Design and Procedure*

2.2.1. *Materials*

The experiment was conducted in the UoLDS, which consists of a Jaguar S-type cab housed in a 4m spherical projection dome with a 300° field-of-view projection system. A v4.5 Seeing Machines faceLAB eye-tracker was used to record eye movements at 60Hz.

2.2.2. *Design*

A 5 X 2 repeated measures mixed design was used, with OOTL Manipulation (No Fog, Light Fog, Heavy Fog, Heavy Fog+Quiz, No Fog+n-back) as between-participant factor and Event Number (1-6) as within-participant factor. The automated drive lasted about 20 minutes and encompassed six discrete car-following events, within a free-flowing three-lane motorway with ambient traffic. As shown in Figure 1, the drive contained two critical events (2,6), where the lead vehicle decelerated at a rate of 5.0 m/s^2 with a 3 s time-to-collision (TTC), and four non-critical events (1,3,4,5), where the lead vehicle either sped up or changed lane. Crash with the lead vehicle was inevitable in the critical events, if drivers failed to resume control. Participants completed two experimental drives, a manual drive and an automated drive, which were counterbalanced across participants. As this paper is focused on comparing the effect of different types of OOTL manipulation on performance in automation, results from the manual drive are not included.

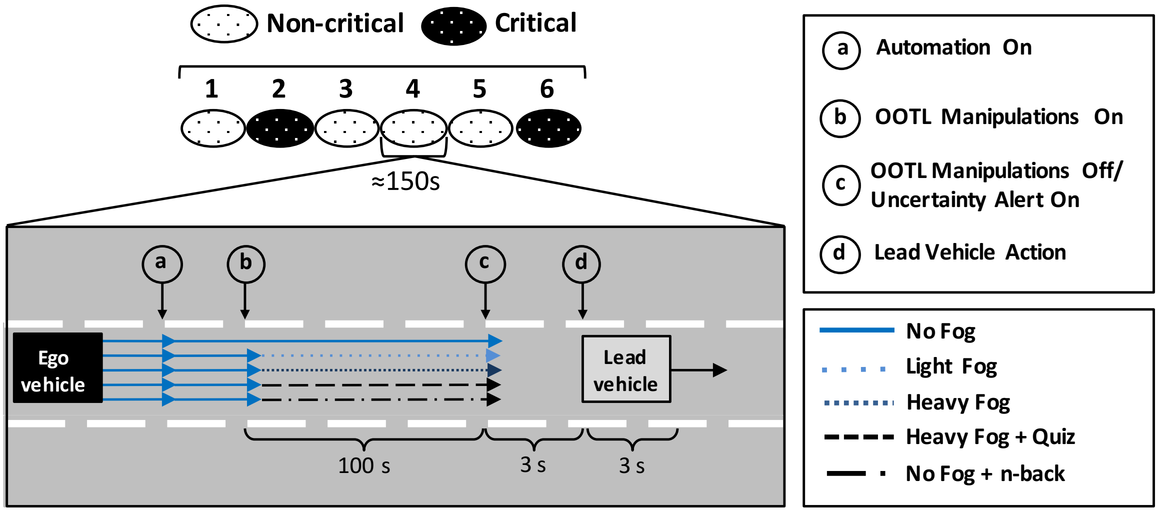

Figure 1. Schematic representation of each discrete event in the experimental drive. (a) to (d) represent various phases of the drive.

2.2.1. *Automated driving system*

The partially-automated driving (PAD) system was only available when the vehicle was travelling between 65 and 75 mph in the middle lane. The system was engaged via a button on the steering wheel and disengaged by either pressing the same button, turning the steering wheel more than 2°, or depressing the brake pedal. If participants did not engage automation, the system engaged automatically after 5 s. Once engaged, the system assumed lateral and longitudinal control and adjusted the vehicle's speed to maintain 70mph.

Automation status was indicated by the colour of a steering wheel symbol located in the vehicle's central display unit. It was solid grey when automation was unavailable, flashed green when available, and appeared solid green when active. A flashing yellow symbol indicated automation was 'uncertain', and drivers were expected to monitor the roadway and intervene if they deemed necessary (see [13] for further details of the HMI). If the driver deactivated the automation, the symbol appeared solid red for 2 s. Automation activation and deactivation was accompanied by an auditory tone (1000Hz, 0.2 s). A forward crash warning symbol included to the left of the automation status symbol gave drivers a visual estimate of the lead vehicle headway and a continuous alarm sounded if drivers reached a 2 s TTC.

2.2.2. *OOTL Manipulations*

To vary the level by which drivers were aware of, and engaged with, the driving task during automation, we applied one of five OOTL manipulation techniques to briefly alter their vision of the road scene. In the No Fog condition, the road scene was not manipulated in any way. In the Light Fog condition, a translucent grey filter superimposed the road scene, allowing drivers to perceive elements in the road environment in the immediate vicinity, but not further afield. This manipulation aimed to simulate situations where drivers' primary focus towards the OOTL is partially hindered due to interaction with other non-driving related tasks. In the Heavy Fog condition, an opaque grey filter overlaid the road scene, blocking all visual information from the road environment, with the aim of simulating situations where the driver is completely looking away from the road scene and is unaware of the traffic conditions. In the Heavy Fog+Quiz condition, a visually presented secondary task was overlaid on the opaque grey OOTL, and participants were required to provide verbal answers to a series of multiple-choice questions relating to visuospatial shape-matching, general knowledge questions, and moderately challenging mathematics. These questions were sourced from various web-based IQ tests and were used to assess how a visual secondary task affected performance. In the No Fog+n-back task condition, there was no OOTL manipulation, and participants completed the verbal response delayed digit recall task (n-back)[19,20] during automation. Participants were presented with a sequence of single digit numbers and were expected to repeat out loud the last number presented. This was used to assess how engagement in a non-visual task during automation would affect eye-movements, resumption of control and crash avoidance.

2.2.3. *Procedure*

Upon arrival, participants read a handout with details of the experiment. After signing consent, participants completed a 15-minute familiarisation drive, consisting of non-critical events only. This began with a short manual drive. Once familiar with the simulator controls, participants practiced activating/deactivating the automation, were shown how the HMI communicated automation states, and experienced the OOTL manipulations. Participants then completed the two experimental drives.

2.2.4. *Data analysis*

Data were analysed with SPSS V.21 (IBM, Armonk, NY, USA). A α-value of .05 was used as the criterion for statistical significance and partial eta-squared was computed as an effect size statistic. Least Significance Difference (LSD) pairwise comparisons ($\alpha = .05$) were used to determine the difference between levels of OOTL Manipulation and Event Number.

3. Results and discussion

Our aim was to explore drivers' visual attention during the resumption of control from PAD, after experiencing different OOTL manipulations designed to vary drivers' awareness of, and engagement with, the road scene. The following research questions were addressed: (i) how does each OOTL Manipulation affect the location of drivers' first fixation after the uncertainty event, (ii) how are drivers' fixations distributed over time, and (iii) what is the relationship between fixations during the uncertainty alerts and crash frequency. Fixations were calculated based on a 200ms threshold with a standard deviation of gaze position below 1^{o}. Fixation location was based on five spatial areas of interest (AOIs) anchored by the road centre region, which was defined as the mode of gaze fixations that fell within a 6° circular region of the road centre area (See Percent Road Centre (PRC)).[21,22] The Top, Left, Bottom and Right regions of this AOI account for an equal division of the remainder of the road scene (for details see [12]).

3.1. *Where do drivers look first?*

Our results show that the OOTL manipulations influenced the AOI region first fixated by participants after the manipulations ceased (Figure 2). To assess how dispersed the groups' fixations were between the AOIs for each group and across all events, we calculated a dispersion index (D),[23] defined as, *"the ratio of the number of pairs in the data which are found to be different to the maximum number of such pairs, given the total number of observations"*.[24] This produces a value from zero to one, where zero indicates the observations are concentrated in one category and one indicates the observations are distributed evenly among the categories:

$$D = \frac{\mathrm{k}(N^2 - \sum_{i=1}^{k} N_i^2)}{N^2(k-1)}$$

Where k = the number of categories,

N = number of observations,

N_i = number of observations in the ith category.

Since some fixations coincided with the start of the uncertainty event, only those starting 200ms after the cessation of the OOTL manipulations were analysed. In the Heavy Fog+Quiz and No Fog+n-back group fewer drivers fixated on the central region immediately after the screen was removed, and the dispersion index shows there was more variance in these groups compared to others. Fixations between participants were least dispersed in the Light Fog and Heavy Fog condition, with the majority of first fixations located in the central region. These results suggest that, irrespective of screen visibility, performing a secondary task during automation caused more variation in drivers' first fixation, when they were required to reengage in the driving task.

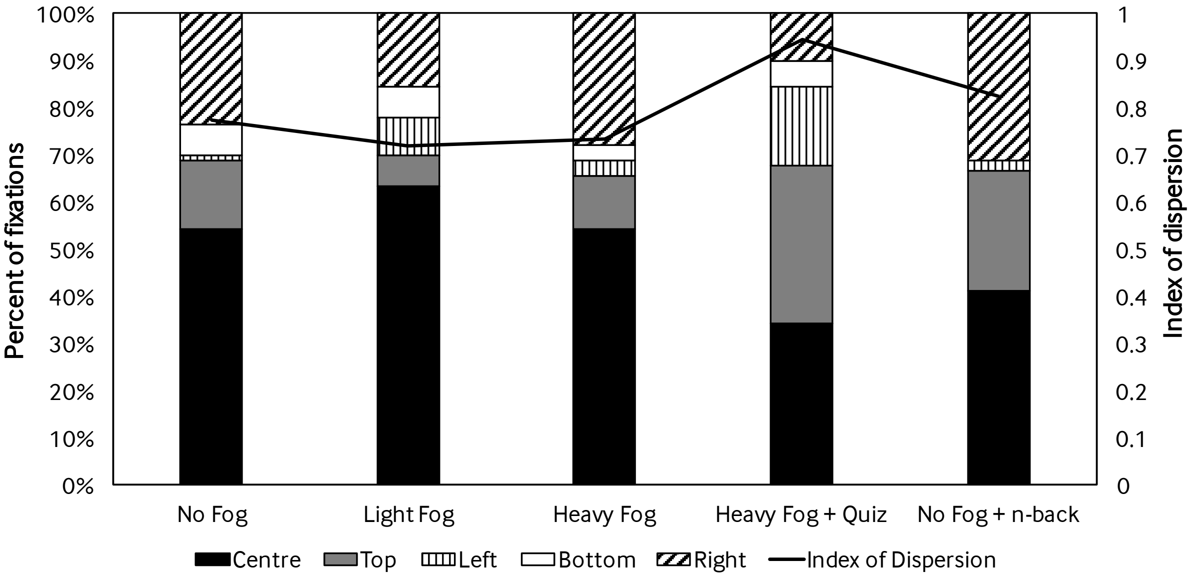

Figure 2. Location of participants' first fixation after the OOTL manipulations ceased, for all events.

3.2. *Effect of OOTL Manipulations on fixations*

To understand how drivers distribute their visual attention while the automated system was in an ‘uncertain’ state, an index of PRC was calculated for three 1 s time windows, immediately after the OOTL manipulations ended. These were compared using a three-way ANOVA, with Event Number (1-6) and Time (1s-3s) as within-participant factors and OOTL Manipulation (5 Conditions) as between-participant factor.

Results showed an effect of Event Number (F(5,350)=3.179, p<.01, η_p^2=.043), where, as shown in Figure 3A, drivers’ visual attention distribution changed with successive events. Post-hoc comparisons revealed that PRC scores for Events 1 and 3 were significantly different. There was also an effect of Time (F(2,140)=10.329, p<.001, η_p^2=.129), and Figure 3B shows that PRC scores rose significantly from the first to the second and third second after the OOTL manipulations ended. There was an interaction of Event Number and Time (F(10,700)=19.162, p<.01, η_p^2=.215). However, post-hoc comparisons failed to show any meaningful patterns. Consistent with our previous results,[11] there was no effect of OOTL Manipulation on fixations to the road centre in the first three seconds, however there was an interaction of Time and OOTL Manipulation (F(8,140)=2.772, p<.05, η_p^2=.137). To investigate this interaction, two-way ANOVAs were conducted for each of the three seconds, with OOTL Manipulation as between-participant factor and Event Number as within-participant factor. A main effect of OOTL Manipulation was observed only for the first second (F(4,70)=2.997, p<.05, η_p^2=.146). Post-hoc comparisons showed that during the first second, PRC scores were significantly lower in the Heavy Fog and Heavy Fog+Quiz group compared to the others. This indicates that drivers were scanning the environment more after not having seen the road beforehand, but at the expense of focusing on the lead vehicle.

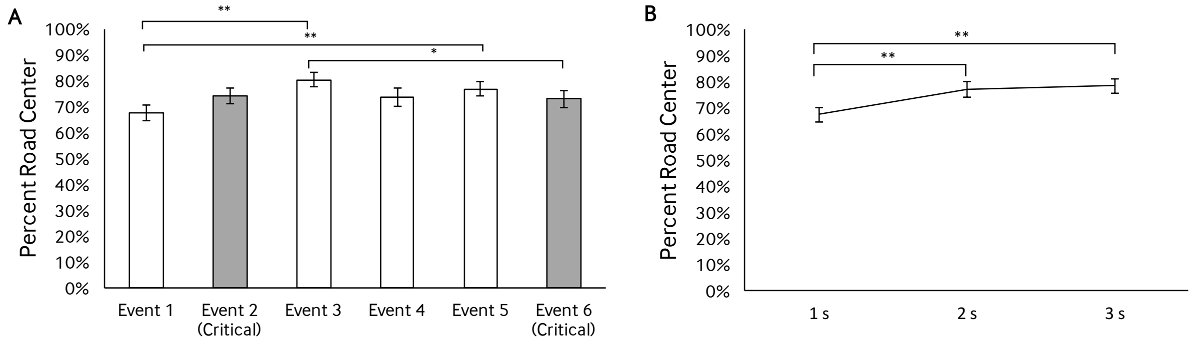

Figure 3. A) Average Percent Road Centre frequency after the uncertainty alert, for each of the six events alert, and B) Average Percent Road Centre frequency for the first three seconds after the uncertainty alert (right) * p<.05, ** p<.001.

3.3. *Fixations in the Critical Events*

The number of crashes in Critical Event 1 (CE1) and Critical Event 2 (CE2), did not differ significantly between the Conditions (CE1, p=.073; CE2, p=.064), as calculated by χ^2 tests (Table 1). This suggests that crash propensity may not necessarily be linked to drivers' first point of fixation. To test for a relationship between fixations during the uncertainty alerts and crash frequency, PRC scores were calculated for six 1 s periods after the OOTL manipulations ceased. We compared PRC scores in CE1 using a two-way ANOVA, with Time Window (1s-6s) as within-participant factor and Event Outcome (crash/no crash) as between-participant factor. We focused on CE1 as there were only four crashes in CE2. Not included in the analysis but important to note is that in the second before the OOTL manipulations ceased there was no difference in PRC scores between participants (Figure 4), therefore any changes in PRC can be attributed to drivers' strategies for coming back into the loop.

Table 1. Crash counts out of 15 cases for Critical Event 1 (CE1) and Critical Event 2 (CE2) for each group in the automated drive.

	CE1		CE2	
	No Crash	Crash	No Crash	Crash
No Fog (*N*=15)	10	5	15	0
Light Fog (*N*=15)	14	1	14	1
Heavy Fog (*N*=15)	8	7	12	3
Heavy Fog + Quiz (*N*=15)	13	2	15	0
No Fog + n-back (*N*=15)	11	4	15	0
Total	56	19	71	4

There was a significant effect of Time Window (F(5,325)=5.287, p<.01, η_p^2=.075), where post-hoc comparisons revealed significantly higher PRC scores in the third to sixth second, and immediately after the brake light, compared to that of the first second. There was no effect of Event Outcome (p=.526), however there was a significant interaction between Time Window and Event Outcome (F(5,325)=5.125, p<.01, η_p^2=.073), where PRC scores over time were clearly different for the event outcome groups (Figure 4). This is highlighted by results from independent sample t-tests comparing PRC scores between the Event Outcome groups for each of the six 1 s Time Windows. For the crash group, only 51% of total fixations in the first two seconds were on the road centre region, which compares to 70.5% and 84% in the same periods for those who did not crash, the latter being significatly different (t(73)=3.141 p<.01). However, in the third second, the crash group's PRC score rose to 97%, which was significantly higher compared to the no crash group at 71.3% (t(73)=2.238 p<.05).

In terms of preparation to respond to the hazard, it seems that drivers who crashed, left it too late. They maintained a high PRC score during the fourth and fifth second before dropping in the sixth possibly reflecting a late attempt at avoiding a crash. This was in contrast to the no crash group, whose PRC score rose gradually over the same period. Therefore, drivers with a smoother pattern of eye movements focused towards the point of the potential hazard (the road centre) and were more likely to avoid a crash than those with more erratic eye movement behaviour. The PRC pattern for the crash group could be a result of these drivers either succumbing to an 'automation surprise'[7] leading to increased cognitive demand,[25] or over-trusting the system to handle the hazard,[26] which led to them not feeling the need to distribute their attention in preparation for a response until it was too late. As a comparison, Figure 4 shows that the PRC trend for non-colliders in CE1 is remarkably similar to that of the 71 non-colliders in CE2.

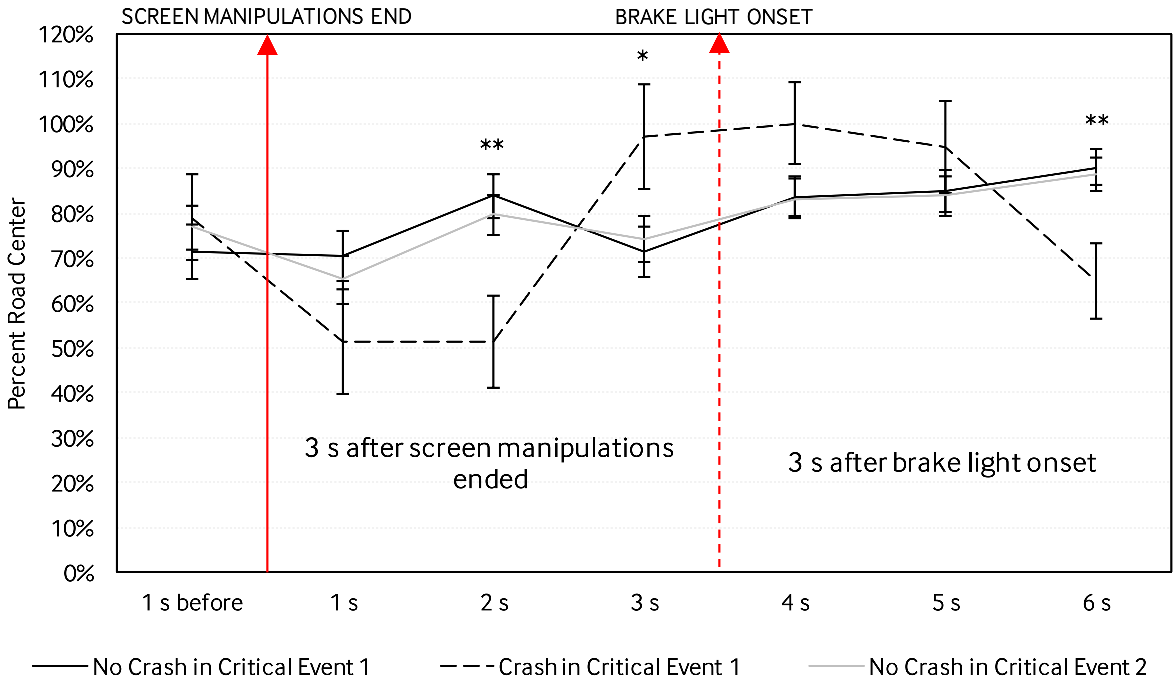

Figure 4. Percent Road Centre scores in Critical Event 1 for the crash (N=19) and no crash group (N=54) for seven 1 s time windows from the second before the OOTL manipulations ceased. Those who did not crash in Critical Event 2 (N=71) are also shown. * p<.05, ** p<.01 (applies to comparisons for Critical Event 1).

4. Conclusions

The aim of this study was to investigate drivers' visual attention patterns during the resumption of manual control from PAD, and whether these link to crash potential. Following [11], we hypothesised that drivers who crashed would have different patterns of visual attention towards the road centre, compared to those who did not. OOTL manipulations influenced drivers' first point of gaze fixation after they ceased, yet these differences resolved within two seconds, and there was also no association between OOTL manipulation and crash outcome. Key to bringing a driver back into the loop who then responds appropriately is directing their attention as early as possible towards the hazard that may lead to an automation disengagement. This avoids erratic eye scanning and improves information acquisition and processing, which supports better decision making, and action execution.[27]

As vehicle automation evolves from SAE Level 2 to SAE Level 3, so the decisions that drivers will have to take regarding their involvement in the driving task will shift from being about *when* to intervene to *whether* to intervene. Considering that we do not have a well-defined understanding of drivers' competence to resume control safely, previous studies argued that drivers should remain engaged with the driving task during automation to intervene quickly if necessary.[3] This justifiably conservative recommendation results in drivers not being relieved of the workload that automated driving promises, highlighting a familiar irony of automation.[28] This paper provides two recommendations that might help realise the potential for PAD to reduce workload: 1) automated driving systems needs to be able to direct drivers' attention towards the cause of a system limitation at least six seconds in advance of an adverse outcome, and 2) drivers need to possess an accurate and confident understanding of their role and the capabilities of their PAD systems.[29] These are especially relevant for time-critical situations, and where drivers are ultimately responsible for safety. A possible limitation of this study is that the automated drive duration used may not have been long enough to induce the out of the loop states. Therefore, and with a view to developing a more complete understanding of drivers' capacity to resume control, a natural progression of this work is to investigate links between longer durations out of the loop, visual attention, takeover times, vehicle control, and crash outcome.

What is already known on this subject

- In the coming decades, the driving task will become increasingly automated. Irrespective of the level of automation, drivers will likely engage in non-driving-related tasks, which may impede their ability to avoid crashes if they are expected to resume manual control, should the vehicle reach a limitation.
- Little is known about drivers' visual attention during such instances, yet this is especially important as automation renders traditional metrics of driver behaviour inadequate.
- The design of safe automated driving systems can and should be informed by a clear understanding of how drivers' visual attention is distributed in the moments after they are expected to resume control.

What this study adds

- This research improves and expands upon previous research by comparing how varying levels of drivers' awareness of, and engagement with, a partially automated driving system influences their visual attention distribution during critical and non-critical road events.
- A detailed insight into drivers' eye fixation behaviour in these events is presented, and differences in visual attention patterns between those who crashed and those who did not is shown.

- Our results suggest it is imperative that automated driving systems are able to direct drivers' attention no less than 6 s in advance to the cause of a manual take-over request, especially if this is a traffic threat that may lead to a crash. This is a conservative estimate, however, with the threshold likely to rise with increasing road and traffic complexity.

Acknowledgements The authors would like to thank Michael Daly, Tony Horrobin and Andrew Tomlinson for their assistance in implementing the simulator scenarios.

Funding This research was conducted as part of the AdaptIVe project, co-funded by the European Commission under the 7th Framework Programme, grant agreement number 610428.

Disclaimer The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the European Commission.

Competing interests None declared.

Ethics approval University of Leeds Research Ethics Committee (Reference Number: LTTRAN-054).

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