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Discovering driver-vehicle coordination problems in future automated control systems: Evidence from verbal commentaries

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Abstract

A critical question being asked by many vehicle manufacturers is what actually happens when the driver finds themselves being “hands and feet free” within their vehicles. This small exploratory case study was used to investigate the possible functionality of a Driver-Initiated Command and Control System of Automation. Verbalizations and subjective reports of mental workload and stress revealed evidence of different driver-vehicle coordination problems (i.e. mode error and automation surprise) based upon driver familiarity in driving with the system engaged.

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1. Introduction

The future of Advanced Driver Assistance Systems (ADAS) points to a higher level use of automation; largely driven by claims that automation can improve road safety and overall system performance [1,2,3]. This will mean that the driver will be able to relinquish a greater degree of control transfer to the vehicle, allowing them to essentially become “hands and feet free”. However, despite claims that the driving system will be enhanced by the introduction of intelligent ADAS, negative effects of automation have also been widely reported. These include issues surrounding driver complacency [4], decreased situation awareness [5] and mental over- and under- load [6].

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If as Stanton & Marsden [7] suggest we are to overcome and not replicate the problems of automation posed in aviation, more specific research is needed in the area of driver-vehicle coordination and cooperation.

According to Cuevas et al. [8] a human-automation team can be defined as the coupling of both human and automated systems that must work both collaboratively and in coordination to successfully complete a task, for instance; driver and ACC [9,10]. It is important that the principle of complementarity is adopted, with the allocation of tasks between system agents serving to maintain control whilst retaining human skill [11]. Driving automation poses many challenges for systems designers with regards to operational functionality and system management because there may be confusion over “who” has authority over “what” controls at any given time. Whilst previous research by Banks et al [12, 13, 14] has modelled driver-vehicle interactions within automated system networks using the Distributed Cognition approach [15], very little research to date has explicitly observed and captured driver-vehicle coordination problems in a naturalistic driving environment involving high levels of automation.

In the near future, full automation of longitudinal and lateral control will be achieved through the combination of traditional Adaptive Cruise Control and Lane Keep Assist technologies to create a new hybrid of Cruise Assist Technology suitable for motorway or highway driving (CAT). However, there is growing concern that controlling technologies such as this may mean that manual override in unanticipated and unexpected situations that are due to system malfunction or dropout will be difficult for the driver to manage [16]. According to Palmer [17], an automation surprise can be a contributory factor to human error especially if the human operator has grown complacent with the functionality of the automated subsystem [18]. This paper utilises direct observation methods to investigate the effects of unexpected driver-vehicle coordination problems occurring in a naturalistic driving environment on subjective levels of driver stress and workload post hoc.

2. Method

2.1. Selection of participants

Two participants with Advanced Driver Training were recruited to take part in this study due to the exploratory use of a highly automated prototype technology. One participant was an experienced user of a new form of CAT having built up a number of hours using the subsystem the preceding week whilst one participant was a novice, first time user of the subsystem.

2.2. Experimental design and procedure

Prior to study, both drivers were instructed to complete a much condensed version of the Dundee Stress State Questionnaire (DSSQ: [19]) that included the Energetic Arousal (EA), Tense Arousal (TA) and Task Irrelevant Interference (TII) scales. According to Matthews et al. [20], EA can be seen as similar to the level of task engagement whilst TA can infer levels of distress. With automation having the propensity to decrease driver workload, TII can be a useful indicator of increased or spare attentional resource. The three sub-scales consisted of 39 items that were coded per usual instruction [19]. In addition, the novice user was also given a brief introduction to the CAT subsystem and was introduced to images of the HMI interface to familiarise themselves with the controls. It was felt that given common practice dictates that new vehicle consumers do not receive any additional training in the use of vehicle subsystems, a description like this was sufficient. Upon completion of the pre-drive DSSQ, drivers were able to familiarise themselves with the host vehicle as they made their way from the University of Warwick campus to the A46; a distance of approximately 2 miles.

The test vehicle was a left hand drive, medium sized family saloon car that was equipped with a prototype system of Driver-Initiated Command and Control automation consisting of both radar and LIDAR sensors and other stereo equipment that analysed the surrounding environment and monitored for other road obstacles and lane markings. The test route consisted of a 16 mile stretch of the A46 between Coventry and Warwick that took approximately 20 minutes to navigate. Throughout this time, drivers were invited to complete a verbal commentary recorded using Smart Voice Recorder version 1.7. Upon joining the A46, drivers were invited to use CAT given the understanding that drivers would manually override the subsystem when necessary (e.g. in the case of malfunction,

automation dropped out). An expert sat beside the driver in the passenger seat who could answer any questions that the driver posed whilst the experimenter sat in the rear of the vehicle. Upon return to the University of Warwick campus, drivers were instructed to complete the post drive DSSQ and NASA-TLX [21].

2.3. Data reduction and analysis

Once verbal commentaries had been transcribed, an initial coding scheme based upon systemic situation awareness research (e.g. [22]) was used to analyse the content of verbal reports. Refinement of this coding scheme ensued using a hybrid of theory-driven and data-driven approaches. The iteration process continued until the verbal reports were judged to be adequately categorised into the coding scheme. The final coding scheme consisted of seven categories (see Table 1 for descriptions and examples).

Table 1. Coding Scheme for Verbal Commentaries.

Code	Description	Example
Behavioral Disparity	Disparity in system performance and what the driver would normally do	“See really I would have pulled over by now”
Driver Knowledge	Reference to driver knowledge of system behavior / operation	“This wouldn't let me do that”
Other Traffic	Any reference to the behavior of other traffic	“You can never really second guess what other people are going to do”
Driver Behavior	Statements referring to own behavior	“Quite happy to take my hands off the wheel”
Manual Override	Evidence of the driver regaining manual control of the vehicle	“I'll just do it manually”
System Behavior	Overt references to system operation	“It's keeping me in the lane”
Functionality Issues	A lack of understand surrounding system function	“So it's still working now?”

3. Results

3.1. Verbal Protocol Analysis

Figure 1 indicates the total number of observations made for both the experienced and novice CAT users. Unsurprisingly the novice user generated evidence of a greater number of functionality concerns characterized by an increased number of questions posed to the expert to seek validation on system behavior. These questions typically focused on clarification of system behavior, the meaning of HMI content and system limitations.

If we analyse the ‘spread’ of these results as a percentage of total coding (Table 2), we can see that the novice user of CAT was heavily focussed upon functionality issues and building their knowledge database of system functionality whilst the experienced user was more evenly spread.

3.1.1. Evidence of driver-vehicle coordination problems

Interestingly, the verbal commentary provided some evidence of mode error on behalf of the novice user:

“Thanks for telling me because I didn't spot the lines [on the HMI display]. So because I'm unsure of what state it's in, what I'm going to do is press the brake and I'm going to start all over again...”

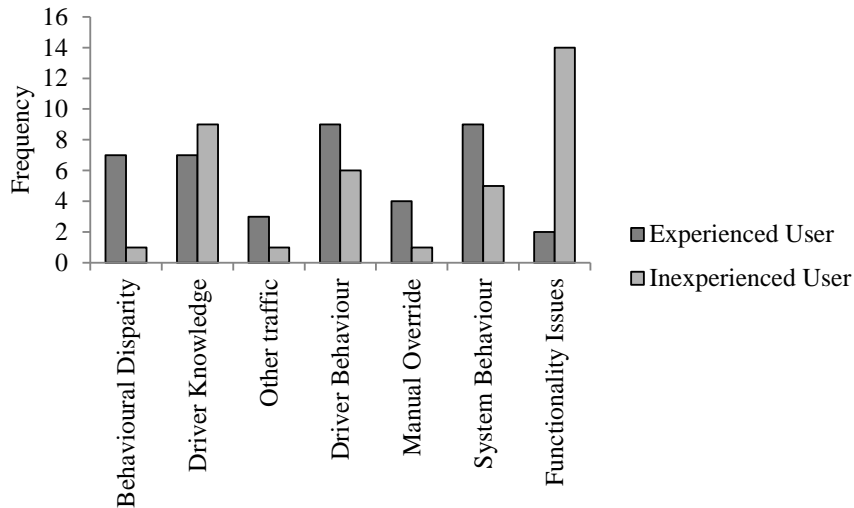


Fig. 1. Frequency of code occurrence.

Table 2. Coding frequency (%) by user

Code	Experienced User	Novice User
Behavioral Disparity	17	3
Driver Knowledge	17	24
Other Traffic	7	3
Driver Behavior	22	16
Manual Override	10	3
System Behavior	22	13

Mode error occurs when the human operator of a system fails to understand the current and future state or behaviour of automated subsystems (see [23]). In this case, the driver believed that the system was on when actually it was not (e.g. [24]). This statement implicates the importance of HMI design and suggests that the current prototype lacked transparency (Stanton & Marsden, 1996) although these types of error may reduce over time as experience in using the system increases:

“I think it’s quite clear and precise really. You know exactly what you’re being offered and when”

The experienced user of CAT provided evidence of a good working knowledge of the vehicle subsystem and appeared at ease throughout the drive apart from when the automation behaved in a way that was unexpected (e.g. automation surprise; [16]) and deviated from their mental model of system operation signalling a breakdown of driver-automation coordination. At this point, the driver sought clarification from the expert and appeared anxious:

“What happened there?I’m just a bit more aware, there’s a few things that happened back there that makes me definitely keep in control of it”

This unanticipated system behaviour challenged internal mental models surrounding system functionality and disrupted normal data-driven and knowledge-driven monitoring of the system [25]. It is errors like these that have the potential to result in future accidents especially if the automation behaves consistently for prolonged periods enabling drivers to become complacent which may have been the case for the experienced user of CAT:

“I was thinking it’s going to be a breeze on the way down, not a problem and then it went and did something like.... But like you say, on the way back I felt a lot more comfortable. It’s knowing exactly what it’s going to do and what it’s capable of”

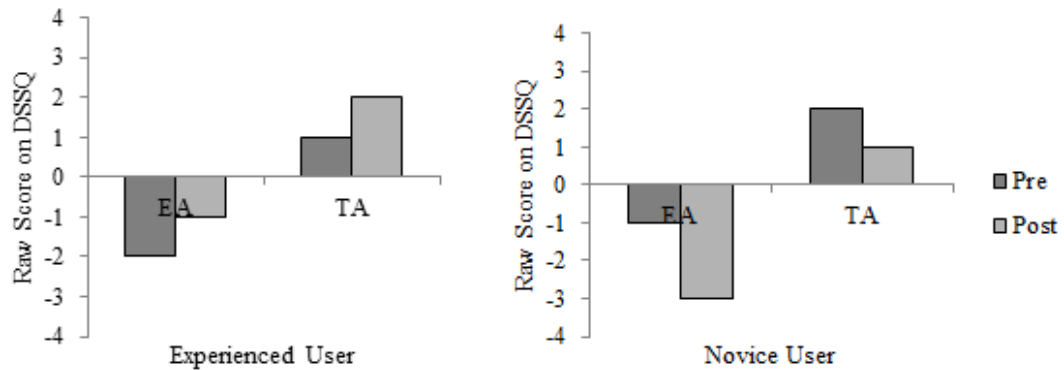


Fig. 3. Scores on DSSQ for Energetic Arousal (EA) and Tense Arousal (TA)

3.2. Subjective stress and workload

The results of the DSSQ are presented in Figure 3 and show a shift in EA and TA by both users of CAT. Although these differences are not statistically significant, post drive scores indicate that the experienced user of CAT became more energetically aroused and tensely aroused whilst the novice user became less energetically aroused and tensely aroused. Desmond & Matthews [26] reported that prolonged driving can produce a loss of task engagement and the control transition that took place between the novice user and CAT appeared to lower task demand and subsequent stress levels. In contrast, subjective levels of task engagement and stress as reported by the experienced user suggested that greater knowledge of system functionality and its limitations can actually increase driver monitoring of subsystem behavior. This may be attributed to a greater degree of behavioral disparity between driver and subsystem behavior, as evidenced by the VPA, and also the capability of the driver to know when the subsystem is behaving unusually.

With Hockey [27] suggesting that the degree of effort required to sustain system performance being directly related to the level of task demand, it comes as no surprise that the novice user reported lower scores on all but one dimension of the NASA-TLX (Figure 4). This means that the automation surprise was deemed to be more stressful than a mode error because it challenges pre-existing mental models (e.g. [28]) whereas the mode error is most likely to occur when mental models are still being constructed. It has been previously suggested that the workload imposed

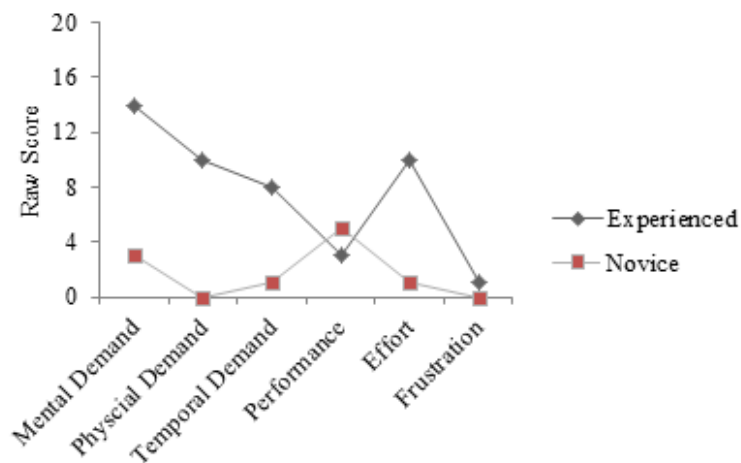


Fig. 4. Subjective Workload Results

by a task can have a direct effect on objective performance and subjective stress response [19]. These results support this claim.

Interestingly, despite the literature suggesting that drivers are more likely to engage in secondary tasks or become disengaged from the primary driving task when automation is engaged (e.g. [29]), TII scores were lower than the scores documented for the pre-drive state. This suggests that the activation of CAT did not allow for unrelated task thought processes to continue to the same degree as they were able to before the experimental trial began. This may be attributable to the new monitoring function incorporated into the driving task by the addition of CAT and the difficulties in driver-vehicle coordination as evidenced above. Drivers may not have had the attentional capacity to succumb to unrelated task thought content as their workload was heavily weighted by monitoring the behaviour of the automated system.

4. Discussion

Although the use of verbal reports are highly debated [e.g. 30,31, 32], they offer a means to explore the behavioural effects of driver-vehicle coordination problems, namely the stress effects of sudden demand transition which can be supported through use of subjective measures (e.g. [33]). Without verbal commentary, it seems unlikely that the problems experienced by the drivers would have been captured. This is because through observation alone, driver-vehicle coordination appeared to continue flawlessly. It was only upon the analysis of the verbal commentary that these coordination problems became apparent.

Much like in aviation, automation surprises within driving are likely to be a phenomenon that can be experienced by all drivers regardless of their experience in using the system but more likely to cause greater stress to those with greater usage [16]. This is because experienced users have created robust mental models about how the system functions and in turn, have developed trust in the system due to its perceived reliability. In contrast, new users of a system remain flexible to change as new experiences that would otherwise be perceived as 'unexpected' help create these robust models in the first place. In other words, the authors suggest that experienced users are more susceptible to an automation surprise than novice users. As integrated ADAS becomes more common on the road to full vehicle automation, it seems likely that the prevalence of automation surprise in a driving environment will become more common. This is because automation remains incapable of coping with all driving eventualities [34]. In contrast, mode error is less relevant to driving because drivers can quickly learn the different states of automation through experience [35]. If mode error were to consistently occur, it would signal an issue in the design of HMI. Even so, the occurrence of mode error in this study calls into question the need for advanced driver training in using intelligent ADAS such as CAT. It would seem that a brief introduction to CAT was not sufficient enough to avoid driver error.

In any case, the results of this study highlight the importance of maintaining the driver in-the-loop to ensure they remain sensitive to changes within their environment [36]. If drivers were to lose their situation awareness, they would be less able to recognise abnormal system behaviour which will only seek to exaggerate the effects of system malfunction or dropout. If control is transferred back to the driver when they are least expecting it, their ability to take back control may be restricted and system performance will be significantly affected. Encouragingly, the results of this study demonstrate that far from being removed from the control-feedback loop [37], the setup of CAT maintained pre-automation driver status meaning that driver-vehicle coordination problems were quickly and effectively overcome. The irony of automation as discussed by Bainbridge [38] is that highly automated systems still require human operators as automated subsystems have restricted functional envelopes [39]. However, as long as automation remains 'adaptable', the division of labour between the driver and automated subsystems can remain dynamic and flexible [5]. This means that any deviation from normal system behaviour can be quickly addressed through a swift control transfer back to the driver as was the case of the driver-vehicle coordination problems found in this study.

4.1. Evaluation and future research

This study offered a very unique opportunity to observe driver-vehicle coordination problems in a more naturalistic driving setting than those afforded by traditional driving simulator studies. However, there were a number of practical constraints that limited the feasibility of data collection. These included issues surrounding

commercial sensitivity, time and legal constraints. Even so, the authors felt that the opportunity to observe driver behaviour in a naturalistic “hands and feet free” driving system was worthwhile especially when considering that there has been growing concern about what drivers may do if they are not in active control. For example, with concerns growing over how well drivers will cope in the event of system failure (e.g. [28]), this research provided some encouraging results. Although it seems unlikely that the final CAT product would elicit the same sort of automation surprise observed in this study, both drivers were quickly and efficiently able to regain control of the vehicle despite a sudden increase in subjective stress levels.

Future research should make use of a larger sample size of mixed age, gender and experience in use of reliable CAT systems. It seems likely that the greatest obstacle to overcome in terms of driver-vehicle coordination problems is issues surrounding driver complacency. It is evident that keeping the driver in-the-loop does not safeguard against the development of this phenomenon. Continued research is needed to ensure that overall system safety can be maintained after prolonged periods of reliable automation.

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