The Effect of Driving Automation on Drivers' Anticipatory Glances

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Abstract. In this paper, we report a secondary analysis of data collected from two driving simulator experiments to understand the effects of SAE-Level 2 driving automation on drivers' glances in anticipation of traffic events. *Background*: Current state-of-the-art consumer vehicle automation requires drivers to monitor the road and intervene when automation fails. Limited research has investigated the effects of automation on drivers' anticipation of upcoming traffic events. We recently reported two driving simulator studies that focused on drivers' glance behaviors before such events; however, we did not compare the results of these two studies. *Methods*: In this paper, we report statistical analyses comparing the glance data from these two studies that had 32 participants each, half of whom were novices and the other half were experienced drivers. The two experiments were comparable in terms of the driving scenarios that required anticipation: the first experiment focused on driving without automation; while the second focused on driving with automation consisting of adaptive cruise control and lane keeping assistance. Further, half of the participants in each experiment were provided with a self-paced visual-manual secondary task. *Results*: In the no-secondary-task condition, drivers in the automation experiment spent a higher percent of time glancing at anticipatory cues that indicated an upcoming traffic event than did drivers in the no-automation experiment. In the secondary-task-condition, no such difference was observed between the two experiments. *Conclusion*: When there is no distraction to engage in, it appears that automation can allow drivers to have increased visual attention to anticipatory cues.

Keywords: Driving automation; anticipatory driving; driver behavior; visual attention; driving simulator.

1 Introduction

Although recent advances in technology have enabled the automation of lateral and longitudinal vehicle control, driving automation currently implemented in consumer vehicles still requires driver supervision and intervention. Previous research has found that compared to non-automated driving, driving automation that provides longitudinal and lateral control of the vehicle is associated with slower reactions to events without environmental precursors (e.g., sudden lead vehicle braking) that require driver intervention [e.g., 1, 2]. However, driving involves not only reacting to such unexpectedly-onset events, but also the anticipation of and reaction to traffic events [3]. Cues in the environment can enable the drivers to anticipate how the traffic can develop. For example, a slow-moving vehicle in relation to a faster vehicle approaching it from behind, can indicate that the approaching vehicle may change lanes before it starts signaling. Here, the signaling would indicate the approaching vehicle's intention to change lanes unambiguously, whereas the cues leading up to it can facilitate anticipation. Even when relieved from physically controlling the vehicle in automated vehicles, anticipatory drivers (i.e., drivers who can anticipate upcoming traffic events) would be better prepared for situations that require their intervention.

Through a driving simulator study investigating anticipation in non-automated driving, our group has found that experienced drivers glanced more toward anticipatory cues that indicated upcoming traffic events and exhibited more control actions in anticipation of upcoming traffic events (i.e., had more anticipatory actions) [4, 5]. Further, secondary task engagement was found to reduce drivers' attention to anticipatory cues, and thus impede their anticipatory actions [5]. Our group conducted a follow-up driving simulator study investigating anticipation, this time in automated driving, in the form of adaptive cruise control (ACC) and lane keeping assistance (LKA) combined. The results are currently under review by a journal but have also been reported in the PhD dissertation of He [6]. It was found that secondary task engagement impeded drivers' visual attention toward cues, while no effect of driving experience was observed. In the current paper, we report a secondary analysis on data collected from these two driving simulator experiments, investigating the effects of automation, and the moderating effects of driving experience and distraction, on drivers' glances on anticipatory cues.

In a simulator experiment by Merat and Jamson [7], it was found that compared to non-automated driving, driving automation in the form of ACC and LKA was associated with slower responses to a lead vehicle braking event that could have been predicted 3 seconds in advance based on the behavior of nearby traffic agents. However, we could not identify studies in the literature that compared drivers' visual attention toward anticipatory cues in vehicles with and without driving automation. Thus, the secondary analysis reported in the current paper provides further insights to the literature on the effects of driving automation on driver anticipation.

The two experiments that we compare in the current paper had very similar experimental designs. Half of the drivers in each experiment were allowed to engage in a self-paced visual manual secondary task, and half of the drivers in each experiment were experienced drivers and the other half were novice drivers. In both experiments, each participant performed four drives, each of which included a scenario that enabled drivers to anticipate a traffic event based on relevant cues in the environment. The driving automation in the second experiment could navigate these events without the driver's intervention. This was done to avoid over-exposing drivers to automation failures, which are generally rare in a real-world setting [8]. In the first experiment (no automation), however, drivers had to take action to avoid collisions. Thus, a comparison of drivers' actions in response to the traffic events across the two experiments would be unfair and the analysis presented in this paper only focused on drivers' glances towards cues that signal these events before event-onset.

2 Methods

2.1 Experiment Designs

As shown in Table 1, a 2×2 factorial design was used within each experiment, with driving experience (experienced vs. novice), and secondary task availability (yes vs. no) as between subject variables. In addition to these two variables, automation (Experiment 1: no automation vs. Experiment 2: automation with ACC and LKA combined) was included as an additional factor in the analysis presented in this paper.

Table 1. Experiment Designs and Participant Age

Automation	Experience	Secondary task availability	Mean age (min-max, SD)
Experiment 1: No automation (n = 32)	Experienced (n = 16)	Yes (n = 8)	30.3 (25-36, 3.9)
		No (n = 8)	33.9 (26-47, 7.1)
	Novice (n = 16)	Yes (n = 8)	21.8 (19-27, 2.9)
		No (n = 8)	25.3 (19-33, 5.2)
Experiment 2: ACC and LKA (n = 32)	Experienced (n = 16)	Yes (n = 8)	37.4 (28-58, 9.4)
		No (n = 8)	39.3 (28-52, 9.6)
	Novice (n = 16)	Yes (n = 8)	21.1 (18-27, 3.2)
		No (n = 8)	21.6 (18-24, 1.9)

Thirty-two participants completed each experiment, leading to 64 participants total. The novice drivers were required to have held a G2 license in Ontario (or equivalent in Canada or the U.S.) for less than 3 years, and to have driven less than 10,000 km in the past year; experienced drivers were required to have held a full license in Ontario (or equivalent in Canada or the U.S.) for more than 8 years, and to have driven more than 20,000 km in the past year. Participants were randomly assigned to secondary task levels, with 8 participants (4 female and 4 male) under each experimental condition. The secondary task used in the experiments was a self-paced visual-manual task developed by Donmez et al. [9] that simulates searching through options on an infotainment system.

The experiment was conducted in a NADS MiniSim fixed-base driving simulator. Participants wore a Dikablis head-mounted eye-tracker to record their eye movements. Driving and eye-tracking data were collected at 60Hz. Each participant completed four drives (each around 5 minutes long; two on rural roads with a speed limit of 50 mph and two on the highway with a speed limit of 60 mph), each including a distinct anticipatory scenario in which an upcoming traffic event could be anticipated based on the cues in the environment. The four anticipatory scenarios were repeated across the two experiments and they were always presented in the same order; the only difference between the two experiments was that in Experiment 1 participants controlled the vehicle whereas in Experiment 2 driving automation did. These scenarios include cues that indicate upcoming traffic events and the events themselves. For example, in the scenario depicted in Figure 1, the participant vehicle (in blue) followed a lead vehicle on a rural road. The vehicle behind it signaled left with high beams on, pulled into the opposite lane, and accelerated to overtake the participant vehicle. Because of an oncoming truck, the overtaking vehicle had to slow down and cut in front of the participant vehicle abruptly after signaling right. In this scenario, the anticipatory cues are left signal of the overtaking vehicle and its move to the opposite lane, followed by the emergence of the oncoming truck. Right signal of the overtaking vehicle is event-onset, clearly indicating its intention to change lanes, leading to a potential conflict with the participant vehicle. More details on these scenarios and the experiment procedures can be found in the PhD dissertation of He [6].

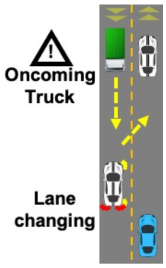

Fig. 1. Example anticipatory driving scenario used in the experiments.

2.2 Data Analysis

In this paper, we focused on drivers' glances to two areas of interest (AOIs), the roadway and the anticipatory cues, as previous research has shown that glances to these AOIs are related to driving safety in general [e.g., 10] and drivers' anticipation of upcoming traffic events in particular [4, 5, 11]. The two metrics reported in this analysis are the percent of time spent looking at each AOI, and the time until the first glance at the cues after cue onset (i.e., first cue becoming visible to the driver). Other glance metrics (e.g., the mean glance duration and the rate of glances) have been reported in the PhD dissertation of He [6], but are excluded from this paper, as they did not provide any additional insights. A glance was defined following the ISO 15007-1:2014(E) standard [12], i.e., from the moment at which the gaze started to move toward an AOI, to the moment it started to move out of the AOI. Glances shorter than 100 ms were excluded from the analysis [13]. Roadway glances include any glances to the forward roadway, the side mirrors, and the rear-view mirror. The roadway glances also include glances to the cues.

The data extraction period for glances towards the cues starts from the cue onset; the data extraction period for the glances toward the roadway is from 20 seconds before cue onset. The data extraction periods for both glances at the cues and glances at the roadway end at the event onset in Experiment 1 (no automation); while in Experiment 2, the data extraction period ends at the event onset or automation disengagement, whichever happened earlier. For glances that partially fall in a data extraction period, a fraction of the glances was utilized following the method in Seppelt, Seaman [14] (e.g., if 0.7 seconds of a 1-second glance fell in the period of interest, then this glance was counted as 0.7 glances). Percent of time looking at an AOI was the total time glanced at an AOI within the data extraction period divided by the length of the data extraction period. Further, if a participant never looked at an anticipatory cue before the event onset, their time until first glance to an anticipatory cue was from the first cue becoming visible (cue onset) to event onset.

All statistical analyses were conducted in SAS on-demand V3.8. Both dependent variables were modeled using mixed models with participants introduced as a random factor and variance-covariance structure chosen based on the Bayesian Information Criterion. For glances to anticipatory cues, the independent variables include automation, experience, secondary task availability, and their two-way interactions. In addition, for percent of time looking at the roadway, to investigate whether drivers' behavior changed after cues became visible (i.e., after cue onset), an independent variable, "cue-onset", was created. The cue-onset divided the data extraction period into two: before-cue-onset period, i.e., from 20 seconds before cue onset to cue onset; and after-cue-onset period, i.e., from cue onset to the end of the data extraction periods.

3 Results

Given that the focus of this paper is on automation, in the following text, we only discuss the significant main and interaction effects related to automation (Figure 2, Table 2). Other main and interaction effects have been reported in our previous publications [5, 15].

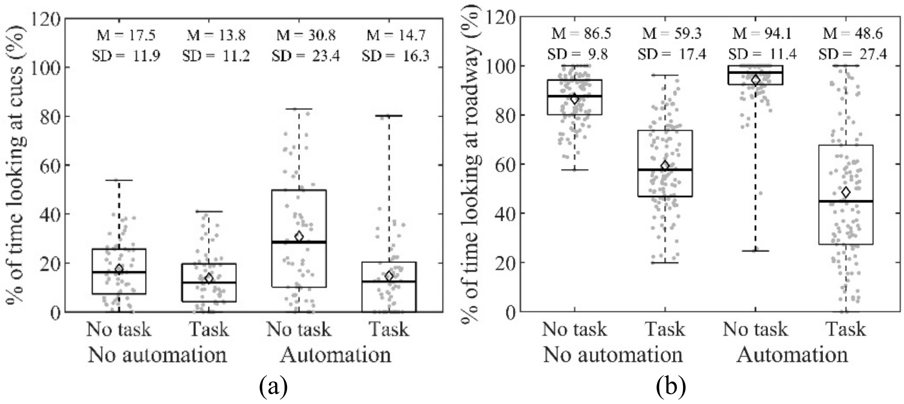

Fig. 2. Boxplots for the significant automation and secondary task availability interaction: a) % time looking at cues; b) % time looking at roadway. Boxplots present the five-number summary, along with the mean depicted through a hollow diamond. Mean (M) and standard deviation (SD) values are presented at the top of each figure.

Table 2. Statistical model results with significant effects (p<.05) bolded.

Predictor Variables	Time until first glance at cues (s)	% time looking at cues	% time looking at roadway
Automation	F(1, 57.1)=0.21 p=.6	**F(1, 57.2)=7.85 p=.007**	F(1, 57.1)=0.39 p=.5
Experience	F(1, 57.1)=3.38 p=.07	**F(1, 57.2)=6.91 p=.01**	F(1, 57.1)=1.13 p=.3
Secondary task	**F(1, 57.1)=10.81 p=.002**	**F(1, 57.2)=18.33 p<.0001**	**F(1, 57.1)=188.80 p<.0001**
Automation * Experience	F(1, 57.1)=0.19 p=.7	F(1, 57.2)=0.45 p=.5	F(1, 57.1)=0.02 p=.9
Automation * Secondary task	F(1, 57.1)=3.64 p=.06	**F(1, 57.2)=4.62 p=.04**	**F(1, 57.1)=11.80 p=.001**
Experience * Secondary task	F(1,57.1)=3.04 p=.09	F(1,57.2)=0.25 p=.6	F(1, 57.1)=0.01 p=.9
Cue-onset	-	-	**F(1, 57.1)=14.04 p=.0002**
Automation * Cue-onset	-	-	F(1, 429)=1.58 p=.2
Experience * Cue-onset	-	-	F(1, 429)=0.00 p=.95
Secondary task * Cue-onset	-	-	**F(1, 429)=5.69 p=.02**

3.1 Glances to Anticipatory Cues

An interaction effect was observed between secondary task and automation in terms of percent of time spent looking at cues (Fig. 2a). When there was no secondary task, drivers in Experiment 2 (automation) spent 10% more time looking at the cues compared to drivers in Experiment 1 (no automation), 95% Confidence Interval (CI): 4, 16, $t(57)=3.50$, $p=.0009$. No difference was observed between the two experiments when there was a secondary task. In Experiment 2, drivers in the secondary task condition spent 13% (95% CI: 7, 19) less time looking at the cues compared to drivers in the no-secondary-task condition, $t(56.6)=4.56$, $p<.0001$; while such a difference was not observed in Experiment 1.

3.2 Glances to Roadway

An interaction effect between secondary task and automation was also observed for percent of time looking at the roadway (Fig. 2b). When there was a secondary task, drivers in Experiment 2 (automation) spent 11% (95% CI: 3, 18) less time looking at the roadway compared to drivers in Experiment 1 (no automation), $t(56.9)=2.87$, $p=.006$; while no such effect was observed when there was no secondary task. In Experiment 1 (no automation), secondary task was associated with 27% (95% CI: 20, 35) less time spent looking at the roadway, $t(57)=7.29$, $p<.0001$. However, in Experiment 2 (automation), secondary task was associated with 46% (95% CI: 38, 53) less time looking at the roadway, $t(57.2)=12.14$, $p<.0001$.

4 Discussion

We conducted a secondary analysis on glance data collected in two comparable driving simulator experiments. The first experiment investigated anticipation of traffic events in non-automated driving, while the second investigated anticipation of traffic events with driving automation, in particular ACC and LKA combined. When there was no secondary task, drivers using ACC and LKA (combined; Experiment 2) spent a higher percent of time looking at anticipatory cues compared to those who did not have any driving automation (Experiment 1). As they were relieved from the physical demands of controlling the vehicle, it is possible that these drivers may have had more spare attentional capacity to observe the traffic situation, which may have enabled them to allocate more attention to areas of importance (i.e., anticipatory cues) that are relevant to the anticipation of traffic. However, when given the opportunity to engage in a visual-manual secondary task, drivers with automation seemed to shift their attention away from the driving task, as indicated by the drop in the percent of time looking at the roadway. Given the secondary task, these drivers' level of attention to anticipatory cues was no different than that of drivers without automation. This agrees with findings in previous research [e.g., 16, 17], in which an increased secondary task engagement was observed with the introduction of driving automation.

Interacting effects between automation and distraction have also been observed in previous research. For example, in a simulator study [18], it was found that when drivers were not distracted, the proportion of drivers who changed lanes in response to a critical event was the same in conditions with and without ACC and LKA. On the other hand, when drivers were distracted, few lane changes were made overall, especially in conditions without the ACC and LKA. Our results, which focus on glance behaviors, indicate that an interaction effect between distraction and automation exists also for glance behaviors, particularly anticipatory glances. This suggests that driver distraction can counteract the potential benefits of driving automation in terms of anticipation of traffic events. Given that drivers are more likely to be distracted when using automation like ACC and LKA [19, 20], interventions (such as display design and training) are needed to prevent and mitigate the effects of distraction on driver anticipation of traffic events when automation is being used.

Although this paper has provided some insights on the influence of automation on drivers' anticipatory glances, we have focused on scenarios that did not require drivers' intervention to avoid a crash when using ACC and LKA. Future research may be needed to explore more scenarios with different criticality as driver behavior might differ in scenarios where an intervention is needed to avoid collisions [21].

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