Tactical Driving Behavior With Different Levels of Automation

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***Abstract*—This paper investigated how different types of automation affect tactical driving behavior, depending on trust in the system. Previous research indicates that drivers wait for automation to act, delegating the monitoring of traffic situations. This would be especially true for those who have more trust in automation. Behavioral and gaze data from 30 participants driving an advanced simulator were recorded in four driving conditions, namely, manual driving, intentional car following, adaptive cruise control (ACC), and ACC with adaptive steering. Measures of trust in the systems were recorded with a questionnaire. Three fairly common traffic events requiring a driver response were analyzed. Trust in automation was high among the participants, and no associations between trust levels and behavior could be found. Drivers seem to make informed choices on when to let the automation handle a situation and when to switch it off manually or via the vehicle controls. If drivers did not expect the system to be able to handle the situation, they usually resumed control before the automation reached its limits. If the automation was expected to be able to deal with the situation, control was usually not resumed. In addition, situations were dealt with in a tactically different manner with automation than without. Controlling the car with automation systems is thus accepted by drivers as being a different undertaking than driving in manual mode.**

***Index Terms*—Adaptive control, automation, behavioral science, vehicle control, vehicle driving.**

I. Introduction

WITH an increasing automation of the driving task, interest grows in how drivers adapt to automation. Handing over longitudinal control to the adaptive cruise control (ACC) system is a well-known example of partial automation. The system keeps a set speed, and in case of a slower moving vehicle ahead, it keeps a set time headway (THW) to that vehicle. Driver adaptation can occur in a number of different ways, with effects on different parts of the driving task. The driving task can be subdivided into operational, tactical, and strategic tasks [1]. The operational level consists of immediate longitudinal and lateral control. The tactical tasks can be described as rule-based decisions, such as overtaking or the negotiation of a junction. The selection of a suitable headway or the decision to go ahead or yield for another road user are other examples. We also subsume the driver's attention level and monitoring of the traffic situation under tactical behavior, as the driver's interpretation of the situation is the basis for tactical decisions and actions. Finally, strategic tasks contain higher level decisions such as mode choice and route planning.

Automation such that the support system completely takes over control for an extended period of time is currently most common on the operational level [2]. Longitudinal support by cruise control and, today, ACC is perhaps the most widely used type of automation. Increasingly, the automation of lateral control is also on the rise, such that the driver can be freed of all tasks on the operational level.

For experienced drivers, longitudinal and lateral control of their vehicle is a highly learnt skill and can be therefore characterized as automatic processing, which means that it can be carried out practically effortlessly [3]–[5]. Still, keeping the vehicle in the lane is essentially a tracking task with a constant need for updated information, such that the driver is forced to attend to the road frequently and adjust the vehicle's path [6]. Therefore, from the driver's point of view, the automation of tasks on the operational level can be a welcome riddance of boring duties, thereby increasing the level of comfort [7] and the possibility to direct attention to other things.

For the tactical level, there is typically no direct automation available. Rather, the support given on this level is an enhancement of information for potential hazard detection to help drivers with their tactical decisions [8]. For ACC, very limited tactical control exists; based on values previously set by the driver, the automation determines when to decelerate and when to accelerate again in a car-following situation. For systems offering assisted steering, the vehicle follows either the lane boundaries or the vehicle ahead or a combination of both, but up to date, there are no tactical decisions behind the lateral positioning algorithms, although current research explores possibilities to improve acceptance adapting support to driver state assessments [9]. Collision-avoidance systems can be viewed as belonging to the tactical level, but they take over control only for a very limited time period in tightly defined critical situations [10].

On the strategic level, control can be handed over to a navigation system [8]. This can also have some impact on the tactical level when the navigation system gives directions as to which lane to take in preparation for a turn. However, the automation only consists of advice to the driver on how to maneuver instead of taking direct control over the vehicle, as it happens during operational level automation. It was found though that the automation of navigation does reduce

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the driver's workload, particularly when driving in unfamiliar areas [11].

Giving up control over a part of the driving task does not necessarily mean introducing automation. It may also occur in a situation described as "intentional car following (ICF)," i.e., deliberately following another vehicle. ICF has been observed to lead to increased focus on the vehicle ahead at the expense of greatly diminished scanning for potential hazards such as pedestrians [12]. It was also observed that give-way violations significantly increased during ICF, which was partly explained as captured attention, resulting in reduced monitoring of the traffic situation. When following a lead car, it may also be the case that control on the strategic level and to a large extent on the tactical level is handed over to the driver of the vehicle ahead, such that the following driver does not check for hazards as much as they would otherwise. In addition, it is likely that the driver does not want to lose sight of the lead vehicle, such that an effort is made to stay close, although that may entail violating certain traffic rules.

When control is partially handed over to automation or another driver, the driving task changes in its nature. It not only means merely giving up of certain activities but it also means that the driver needs to monitor the agent that takes over control [13], [14]. This leads to restructuring of the task and may include a decision to change strategies on the tactical level [15]. One of the factors determining how the driver will deal with the changed situation is the level of trust the driver has in the agent who takes over partial control, be it an automation system or another driver [16].

If the driver trusts the automation, the felt need to monitor decreases [17]–[19] as the vehicle handles the immediate operational tasks. The driver may not only feel comfortable to attend to other things but it could also be argued that performance on the operational level should not be affected by an inattentive driver as long as the automation is functional. If the driver does not trust the automation, it can be expected that the driver closely monitors how the automation is performing in the current traffic situation, ready to intervene as soon as it is deemed necessary. Such behavior may even increase the driver's cognitive burden, and it clearly misses the purpose of automation, effectively leading to the driver no longer using the automation [16], [18].

In this paper, we examined how different levels and types of control delegation, namely, ACC, ACC with active steering (ACC-AS), and ICF would influence the drivers' tactical behavior in frequently occurring traffic situations and events. We also examined the effect on the drivers' eye movements, which were used as an indicator of attention. A questionnaire on subjective ratings of trust in automation [20] was administered as well in order to investigate whether trust was a mediator in possible behavioral changes.

The situations in the study were selected based on what was described in a survey as a typical scenario in which ACC did not respond in the way a driver would have done [21]. It was made sure that the minimum required actions differed between each of the two automation levels (ACC and ACC-AS) and the manual levels (fully manual and ICF). While the minimum required actions in the two manual levels were the same, the intention was to investigate whether behavior still differed, based only on the mental setting that the driver either followed another vehicle or not.

Based on the literature discussed above, it was assumed that drivers would be more likely to follow the lead vehicle more closely and that they would be less attentive to surrounding traffic in the ICF situation than when driving fully manually. It was also assumed that drivers, particularly those with high trust in automation, would partly delegate the monitoring of the situation to the automation and wait for the automation to act. Drivers trusting less in automation were expected to monitor traffic and automation performance more closely than more trusting drivers. A higher level of automation was expected to lead to a further delegation of control and, therefore, a further decrease in the felt need to act.

II. Material and Methods

A total of 31 drivers participated in the study. Twenty-four of them were male, and seven were female. One participant had to terminate the study early because of technical difficulties, and one driver experienced nausea and quitted before driving the last condition, which means that 29 participants completed the whole study and data from 30 participants could be used for three of the conditions.

The average age of the participants was 50 years (std $=$ 13 years). They had held their driver's license for 31 years on average (std $=$ 13 years), and excluding one outlier with a reported annual mileage of 120 000 km, their mean annual mileage was 27 000 km (std $=$ 13 000 km). Two thirds of the drivers were experienced with ACC.

The participants were recruited with help of Volvo Car Corporation and from a database of interested members of the public.

The study was conducted in a moving-base simulator with a high-performance linear motion system for simulation of lateral forces, roll-and-pitch movement of the whole simulator platform, and a vibration table for simulating bumps and road roughness. A Saab 9-3 passenger car cabin was installed in the simulator. The driving environment was presented by six HD projectors on a screen in front of the driver, providing a field of view of 115°. Three LCD screens acted as rear-view mirrors.

The human–machine interface (HMI) was placed on the steering column in front of the instrument cluster on a separate 7-in LCD screen and connected to the speedometer to show the simulated speed of the vehicle.

The drivers' eye movements were logged with the remote eye-tracking system Smart Eye Pro with four cameras. Gaze-tracking availability lies at more than 95%. Data from the simulator and the eye tracker were synchronized and logged at 50 Hz.

The ACC system kept a set distance to the vehicle in front by decreasing or increasing the speed of the vehicle autonomously up to the maximum set speed. In this paper, speed was preset at 75 km/h and THW was preset at 2 s. The system could lose contact with the vehicle in front if it is more than 10° off to the side or 3 s away to simulate the reach of a radar. If the ACC system no longer detected a vehicle in front, it accelerated the

Fig. 1. Illustration of the interface depicting the information that (above) the ACC system is active and that (below) the ACC-AS system is active.

vehicle to the set speed. On detecting a new vehicle, the system took a second to latch on and to begin regulating speed. The system was operated with the cruise control on–off switch on the indicator lever. The driver could also switch off the system by using the brake pedal.

The ACC-AS system has not only full ACC functionality but also active steering that allowed it to follow a lead vehicle laterally. The system followed a lead vehicle regardless of where that lead vehicle went, even across lane boundaries. If the yaw rate of the steering wheel was over 45°/s, the system simulates that it could not steer and issued a warning sound to indicate that the driver must immediately resume lateral control of the vehicle. The system was operated with the cruise control on–off switch on the indicator lever. The driver could also switch the system off by using the brake pedal. The main difference in the HMI compared with the ACC system was the addition of a wheel icon to indicate that system steering was active (see Fig. 1). Despite the driver taking control over the steering wheel or the system reaching its bounds and issuing a warning inactivated system steering, ACC functionality was still active. Neither of the ACC or ACC-AS system had forward-collision warning, which was pointed out to the drivers before the test run.

The participants drove on a rural road with moderate to dense traffic. In all the events investigated in this paper, there was one lane in each direction. The posted speed limit was 70 km/h. The road was made up of different segments, containing one event each. In each of the conditions, the participants encountered all events, but the order of the segments was balanced across conditions and participants.

Each participant drove in four different experimental conditions. The baseline condition, called "manual" from here onward, consisted of normal driving without any driver-support system. In the "ICF" condition, the participant was asked to follow a designated lead vehicle, as if he or she followed a friend. In addition, in this condition, no driver-support system was present. In the ACC condition, the participant drove with ACC on as default setting. After a system override, the driver was asked to switch the system on again as soon as possible. The ACC-AS condition was equivalent to the ACC condition.

The ACC and ACC-AS conditions were not run in direct succession to avoid any confusion between automation modes. Otherwise, the order of the conditions was balanced systematically across participants.

Five events happened during each trip, three of which are analyzed and presented in this paper. They were selected with the preconditions that they should be likely to occur rather frequently in regular driving and that they should lead either to a system action or into a situation in which drivers would be likely to expect system action. The events were more or less time critical, with none of them resulting in a crash. The events are described in more detail in Table I.

Prior to driving, each participant answered a questionnaire on his or her demographic background and experience with ACC. Then, the participant was given instructions about the experiment and the systems under investigation. The participant then signed an informed consent form.

The participant was seated in the simulator and shown where the system display was located and how to operate the vehicle. When the participant felt comfortable in the simulator, the eye tracker was calibrated to the participant's gaze. After this, both the ACC and ACC-AS functionality and operation were explained to the participant. He or she then completed a training route where the different system functions could be tested. The four experimental conditions were run successively, according to the balanced order described above. Each condition took about 15 min to complete. Before each new condition, the vehicle was stopped, and the experimenter informed the driver about the upcoming condition. After the first two drives (one of which was either the ACC condition or the ACC-AS condition), the participants filled out a questionnaire regarding their trust in the automated system they had just driven with.

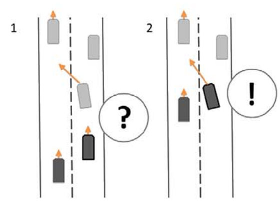
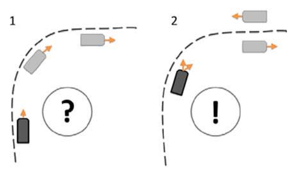
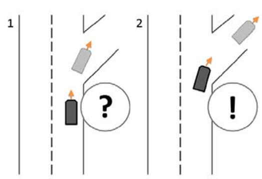
After the final condition, the participants left the simulator and were asked to fill out questionnaires on their trust in the second automated system, their experience of the scenarios, and their attitudes toward the automated systems.

For each of the three events analyzed in this paper, the data were extracted from the complete data set. For each event, it was determined whether and where the driver had braked and/or steered. The THW upon entering the event and in other critical locations was extracted as well.

For the curve event lane, exceedance was recorded. It was defined as the outside of the left front wheel entering the lane boundary. For the exit situation, the definition was equivalent on the right-hand side. When several exceedances occurred during one event, the accumulated distance and time spent exceeding the lane were used.

For gaze behavior, percent road center (PRC) was computed for the critical part of the event during the moment in which it could be detected that an action was required. The time during which the gaze cases were sampled varies both with event and individual but contains around 3–8 s. PRC is defined as the

TABLE I
ILLUSTRATION AND DESCRIPTION OF THE THREE EVENTS INVESTIGATED IN THE STUDY

	**Broken Down Car Event.** The participant drives in dense traffic in the right lane on a single carriageway. A vehicle is parked/stopped in the right lane, forcing traffic to merge to the left. The vehicles ahead of the ego vehicle merge left. Another vehicle travels in the left lane next to the ego vehicle, preventing the ego vehicle from merging. If the driver brakes to let the vehicle in the left lane pass, this vehicle brakes as well and lets the driver merge to prevent crashes. The driver can also accelerate and merge before the vehicle in the left lane. In the ACC condition the ego vehicle loses contact with the lead vehicle when the lead vehicle merges left, causing acceleration towards the set speed (75 km/h). The driver needs to steer or brake. In the ACC-AS condition the ego vehicle follows the lead vehicle, just making it past the vehicle in the left lane if the driver does not intervene. The "broken down car" event is defined to begin when the car in front of the lead vehicle starts to indicate a merge to the left and ends when the ego vehicle is passing the stopped vehicle.
	**Curve Event.** The participant drives through a sharp turn. In the ACC condition the ego vehicle may lose contact to the vehicle ahead, depending on lateral position and headway of the ego vehicle. If that happens, the ego vehicle accelerates to the set speed (75 km/h). In the ACC-AS condition the function loses contact to the lead vehicle at a specific location and issues a warning, if the driver has not reclaimed control beforehand. If the driver does not steer, the ego vehicle enters the oncoming lane. The curve event is defined to begin when the curve sign is first visible and ends when the road is straight again.
	**Exit Event.** The exit event always occurs a while after a new vehicle has merged into the gap between the ego vehicle and the lead vehicle. The cars drive along the road on a single carriageway. The new vehicle in front of the ego vehicle turns on its right indicators and leaves the main road via an exit. In the ACC condition the ego vehicle continues to go straight on. In the ACC-AS condition the ego vehicle would follow the exiting vehicle without driver intervention, therefore the driver is forced to steer actively in order to stay on the main road. The exit event is defined to start when the lead car turns on its indicators and ends when the ego vehicle has passed the exit.

The simulator vehicle driven by the participant (ego vehicle) is dark grey with a black border. Vehicles interacting with the ego vehicle are dark grey. Arrows indicate intended driving directions. Question marks indicate where drivers first have the possibility to realise the need for action on their part. Exclamation marks indicate where drivers need to act at the latest.

percentage of valid gaze cases located within a circle of 8° radius around the mode of the gaze distribution of the whole trip [22], [23]. The percentage of glances to the mirrors was also registered as an indicator for monitoring behavior.

In many instances, the driver's response to or interaction with the automation happened on several levels and in several steps. Therefore, analyses were made accordingly. For example, a driver may keep a large-enough THW to render quick brake reactions unnecessary. Drivers whose THWs are smaller may only need either to ease off the gas pedal or to brake actively. Others do not brake actively but rely on the system to do so. Others will brake when the system has started braking.

It would not be meaningful to subsume those different types of behavior to calculate means. Instead, the response pattern was analyzed, which entails that some of the resulting groups were rather small, not allowing the computation of inferential statistics. In each case, detailed explanations are provided on how the analysis was conducted.

III. Results

Analyses of tactical driver behavior were made separately for each event. Gaze behavior was analyzed for each event and also compared across events. The association of trust in automation with the observed driving behavior was analyzed per event.

When the car in front of the lead vehicle set its indicator in the broken-down-car event, headways were significantly longer in the two manual conditions than in the automated conditions where THW was fixed at 2 s ($F(3, 113) = 3.5$, $p < 0.05$; see Table II). No difference was found between the two manual situations or between the two automated situations, respectively. For all four conditions, it is of interest to see at which point, if at all, the driver chose to brake (and steer). Specifically, we investigated whether the driver took action before or after the car in front of the lead car changed lanes, before or after the lead car set its indicator to change lanes, and before or after the driver of the ego vehicle changed lanes. Table II indicates whether and how drivers handled the longitudinal control of the vehicle in each driving condition. In the fully manual condition, one driver kept his foot on the gas throughout the event; in the ICF condition, all drivers lifted their foot off the gas at some point in time. There was a trend for a difference in the distribution of how many drivers pressed the brake, depending on the condition ($\chi^2(3) = 6.9, p < 0.10$), with more drivers braking at some point in time in the conditions without automation. Furthermore, in the manual conditions, those drivers with a shorter THW had a higher likelihood to ease off the throttle earlier than those with a longer THW ($\chi^2 = 23.1, p < 0.05$), but they were not significantly faster in braking.

In the fully manual condition, drivers tended to react earlier by easing off the throttle than they did in the ICF condition (one-sided $\chi^2(2) = 3.6, p < 0.10$). Most drivers who braked did so after the lead car had switched on the indicators and before the driver changed lanes. Two drivers had already braked before the lead car turned on the indicators, and eight drivers braked only after having changed lanes, most of those in the ICF condition. This indicates that drivers accelerated before merging and then braked to adjust their speed once they were in the new lane. Four drivers stopped behind the stopped vehicle to let the traffic in the second lane pass. All of those had long THWs when entering the event.

TABLE II
AVERAGE THW IN THE BEGINNING OF THE EVENT AND COUNT OF DRIVERS DEPENDING ON THEIR ACTIONS TO CONTROL THE LONGITUDINAL MOVEMENT OF THE CAR

Condition (n)	average THW in s	no action with foot	no braking at all	off throttle btw. 2nd in lead changes lanes & lead car indicates	braking btw. 2nd lead car changes lanes and lead car indicates	braking btw. lead car indicates and ego car outside lane	braking after outside lane	standing still
manual (30)	2.4 ± 1.0	1	8	14	1	19	2	0
ICF (29)	2.4 ± 1.1	0	7	8	0	18	4	1
ACC (30)	2.0 ± 0.05	10	10		1	18	1	2
ACC-AS (30)	2.0 ± 0.04	16	16		0	13	1	1
Total	2.2 ± 0.8	1	41	22	2	68	8	4

TABLE III
AVERAGE THW WHEN THE CURVE SIGN BECAME VISIBLE AND AT THE CURVE ENTRANCE AND COUNT OF DRIVERS WHO DID NOT MOVE THEIR FOOT, WHO EASED OFF THE THROTTLE, AND WHO BRAKED, DEPENDING ON THE DRIVING CONDITION

Condition (n)	average THW in s when curve sign visible	average THW in s at curve entrance	no action with foot	off throttle	braking
manual (30)	2.7 ± 1.2	3.4 ± 2.2	6	24	8
ICF (29)	2.9 ± 1.6	3.5 ± 2.4	4	25	7
ACC (30)	2.0 ± 0.3	2.1 ± 0.7	19		11
ACC-AS (30)	2.0 ± 0.05	2.1 ± 0.4	24		6
Total	2.4 ± 1.1	2.8 ± 1.8	63	49	32

In the ACC-AS condition, drivers could either reclaim steering or not. Out of the 30 drivers, 24 reclaimed steering during the event, whereas 6 of them let the automation handle the situation. All drivers who braked needed to reclaim steering as braking also decoupled the assisted steering.

In the curve situation, the drivers had the option to decelerate or not, and in the ACC-AS situation, they could reclaim steering before the system lost touch with the lead car, or after the system lost touch, whereupon an auditive warning signal was given.

When the curve sign first became visible, as well as upon entering the curve, the THWs in the two automated conditions were significantly shorter than in the two manual conditions ($F(3, 115) = 6.0$ (sign visible), $F(3, 115) = 6.6$ (curve entrance); $p < 0.05$ for both). As shown in Table III, most of the drivers in the fully manual and ICF conditions eased off the throttle on their approach to the curve, with about a third of them also pressing the brake. This is also reflected in increasing THWs from the point where the curve signs become visible to the entering point of the curve. Both for the fully manual and ICF conditions, the average THW significantly increased between those two points (paired samples t-tests gave $t(29) = -2.9$ (manual) and $t(28) = -3.0$ (ICF); $p < 0.05$ for both).

TABLE IV
CROSS TABULATION OF LANE EXCEEDANCE OCCURRENCES AND DRIVING CONDITION FOR THE CURVE SITUATION

		Condition				
		manual	ICF	ACC	ACC-AS	Total
lane exceedance	yes	15	19	19	10	63
	no	15	10	11	20	56
	Total	30	29	30	30	119

In the two automated conditions, the only way to reduce speed below the speed of the lead vehicle was to brake, which was done by 11 drivers in the ACC condition and by 6 drivers in the ACC-AS condition. The number of drivers who did not take any active action to change the speed was much higher in the conditions with automated longitudinal control than in those with manual longitudinal control.

For those who braked, the maximum brake jerk depended significantly on the driving condition ($F(3, 111) = 67.7, p < 0.05$), with the two conditions with automation leading to much higher values (above 45 m/s^3) than the two manual conditions (10 m/s^3 and below).

The drivers' handling of the lateral control was examined as well. It was determined how many of the drivers exceeded the lane boundaries depending on the condition. As shown in Table IV, driving condition had a significant influence ($\chi^2(3) = 7.8; p < 0.05$) on how many drivers exceeded their lane, with the greatest number of exceedances in the ICF and ACC conditions and the smallest number in the ACC-AS condition.

For those drivers who actually did exceed the lane, the time spent outside of the lane ranged from 0.5 to 5.1 s, with a mean of 1.4 s. This translates into a mean distance of 27.4 m (6.5–98.9 m). There was no significant difference for time or distance spent outside of the lane between the conditions. The maximum lateral distance driven into the opposing lane was 24 cm on average (range of 2–84 cm). A significant difference for driving condition was found ($F(3, 55) = 2.9; p < 0.05$), with the ICF condition leading to lane excursions of 38 cm on average, whereas the mean values of the other three conditions lie between 19 and 24 cm.

A lane exceedance can either be planned (or at least tolerated) or unplanned. In order to investigate the likelihood for unplanned lane excursions, the maximum lateral jerk for

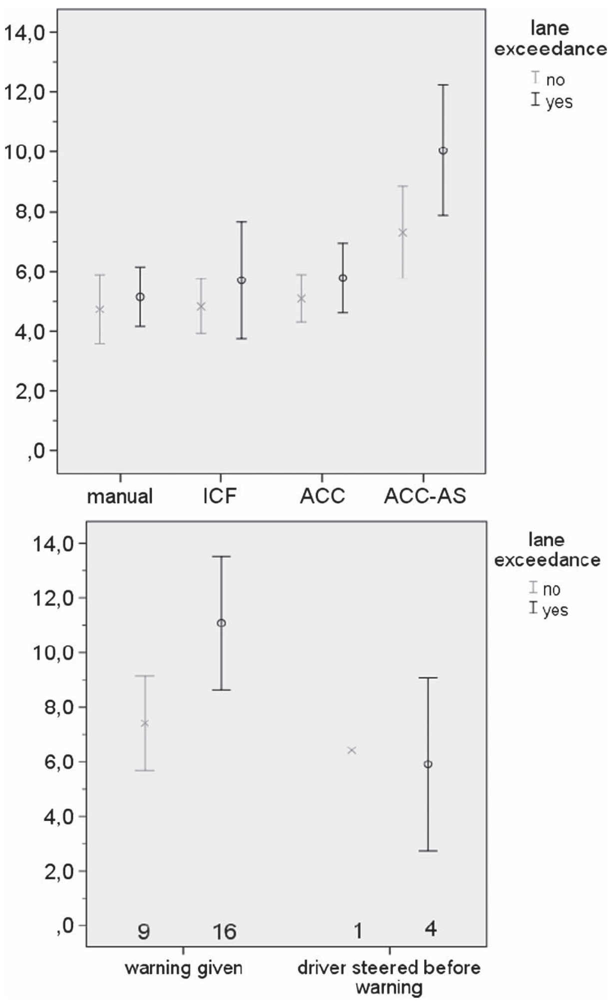


Fig. 2. Means with 95% confidence intervals for the absolute maximum lateral jerk (in meters per cubic second) in the curve situation (above) for all driving conditions, depending on whether a lane exceedance occurred or not, and (below) depending on whether the driver steered before or after the warning in the ACC-AS condition, also indicating the number of drivers in each subgroup.

the different conditions was analyzed. It was assumed that a higher lateral jerk indicates a stronger likelihood for an unplanned lane excursion. As illustrated in Fig. 2 (above), the maximum absolute lateral jerk was significantly higher in the ACC-AS condition than in the other three conditions ($F(3, 118) = 11.8; p < 0.05$), and the lateral jerks were larger when the lane was exceeded than when this did not happen ($F(1, 118) = 5.5; p < 0.05$).

The ACC-AS condition could be further broken down into drivers who had taken over steering before the active steering system had lost contact and drivers who had taken over steering first after the warning for lost contact had been issued. By doing this, the number of drivers in the cells became too low for inferential statistics, but the results are illustrative nevertheless (see Fig. 2). The largest jerks were observed for those drivers who had exceeded the lane and got a warning, whereas in all other conditions, the values were approximately equal.

It was found that higher brake jerks tended to be related to higher lateral jerks (Pearson's $r = 0.41$, $p < 0.05$).

TABLE V
AVERAGE THW PER CONDITION WHEN ENTERING EVENT AND COUNT OF DRIVERS DEPENDING ON WHETHER AND HOW THEY REACTED AND OR DEACTIVATED THE AUTOMATION

Condition (n)	average THW in s	driver does not turn off system	driver brakes	driver steers (only)	driver steers and then deactivates via button	driver deactivates via button (only)
manual (30)	4.7 ± 2.0		0			
ICF (29)	2.6 ± 1.0		1			
ACC (30)	(3.7 ± 0.6)	27	0			3
ACC-AS (30)	(3.6 ± 1.0)	11	0	1	2	16
Total	(3.6 ± 1.5)	38	1	1	2	

Average THWs are in parentheses for the automated conditions, as they were bimodal with peaks at 2 s and 4 s, depending on the preceding situation.

In the exit event, the vehicle right in front of the driver took an exit to the right. This vehicle was not the one the driver should follow in the ICF condition but rather a vehicle that had squeezed in between that lead car and the ego vehicle in an earlier event. The driver's task was to keep on going straight ahead, but in the ACC-AS condition, not reclaiming steering might lead into the ego vehicle leaving the road and following the exiting vehicle. Twice in the ACC condition and once in the ACC-AS condition, the ego vehicle immediately locked onto the next lead vehicle, thereby making it unnecessary for the driver to act. In another ten cases, in the ACC-AS condition, contact to the lead vehicle was lost while the lead vehicle exited, such that the ego vehicle did not follow the exiting car. Table V indicates how many of the drivers deactivated the system and how.

In the manual and ICF conditions, the driver did not have to do anything but to follow the road. In the ACC condition, the ego vehicle might accelerate to the set speed upon losing contact with the exiting vehicle. In the ACC-AS condition, the driver needed either to reclaim steering or deactivate the system to prevent the ego vehicle from following the exiting car.

Upon entering the exit event, the THW in the fully manual condition was significantly longer than in the ICF condition ($t(29) = 4.4; p < 0.05$). The THWs for the automated conditions were not analyzed as each of them was concentrated around two specific values (2 s when locked onto the lead vehicle and 4 s when still approaching at set speed), depending on the event that had occurred before the exit event.

In the ACC-AS condition, three drivers started following the exiting vehicle onto the exit ramp before reclaiming control either by steering (two cases) or by pressing the deactivation button (one case). In no other condition did the drivers follow the exiting vehicle over the lane marking.

For the conditions with automation, t-tests were carried out to investigate whether the type of automation was associated with other behavioral differences. It turned out that in the ACC-AS condition, a higher maximum brake jerk ($t(58) = -5.4, p < 0.05$) and a higher lateral jerk ($t(58) = -2.4, p < 0.05$) than in the ACC condition were reached.

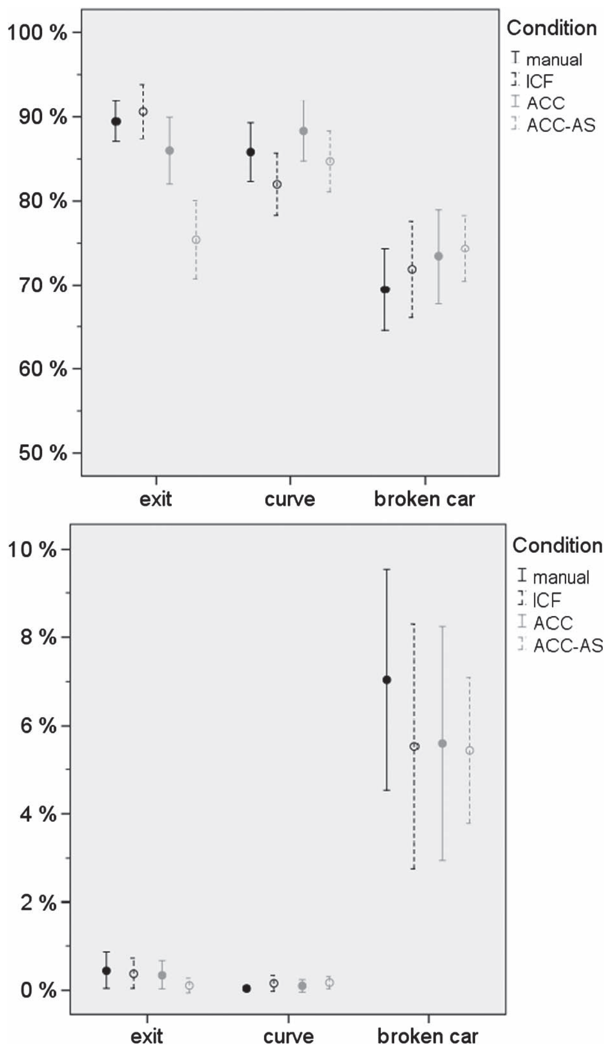


Fig. 3. Means and 95% confidence intervals for (above) the PRC values and (below) the total glance time at all mirrors per event and driving condition.

The drivers' gaze behavior was analyzed across event types and driving conditions. PRC and the percentage of glances directed at the mirrors during each event were investigated with univariate bifactorial analyses of variance. Overall, the PRC values lie at 70% and above, significantly varying with event type ($F(2, 330) = 54.5, p < 0.05$). There was also a significant interaction between event type and condition ($F(6, 330) = 6.1, p < 0.05$), as illustrated in Fig. 3. Only in the exit event that the PRC was lower in the ACC-AS condition than in the other conditions. The percentage of glances directed at mirrors significantly varied with event type ($F(2, 330) = 88.8, p < 0.05$), with practically no glances directed at the mirror in the exit and curve events and with around 6% of the glances directed at the mirrors in the broken-down-car event (see Fig. 3). The driving condition had no influence on the percentage of glances directed at the mirrors ($F(3, 330) = 0.5$).

The results from the trust in automation questionnaire show that the drivers generally tend to trust both systems; however, drivers have a significantly higher trust in the ACC system (73 on a scale from 0 to 100) than in the ACC-AS system (60 on the same scale; $t(28) = 4.5, p < 0.05$). The correlation between the two scores was low ($r = 0.26$) and not statistically significant, indicating that higher trust in one system was not necessarily associated with higher trust in the other system.

The drivers' propensity to act or wait out the system was investigated in relation to the reported level of trust in the systems for all three events analyzed above. However, no statistically significant association between the level of trust in the system and the likelihood to brake or steer could be found in any of the events. No relationship with any gaze-based variables could be found either.

IV. Discussion

The results from the three events together indicate that the type of automation does affect tactical behavior. Specific automation systems seem to affect specific aspects of behavior not only on the control level but also on the tactical level. Based on the data of this paper, we assume that drivers do not behave more or less safe, but rather, that they adapt their actions and reactions to what they find best suited for the situation at hand. This can be already observed upon entering the events, and it plays a role within the events. Drivers appear to make informed choices whether they let the automation handle the driving or whether they switch it off manually or via the vehicle controls.

Trust levels were higher for the ACC system than for the ACC-AS system, which is likely to be due to the drivers being more familiar with the ACC functionality. It fits in well with the finding that trust in ACC is built over time [24]. The difference can be also due to the feeling that also giving up lateral control either detaches the driver too much or presents a higher risk when automation fails. Drivers seemed to view the ACC and ACC-AS systems as quite dissimilar; high trust in one was not correlated to high trust in the other. We could not see that the level of trust influenced the observed behavioral adaptations. This may be due to the fact that all drivers exhibited comparatively high levels of trust in the systems, with mean and median values above 50. As previous research has shown that trust in automation does play a role when it comes to behavior [16], [18], [19], it is likely that the trust range observed here is not large enough to have an effect on behavior. If trust should be studied specifically, it is recommended to recruit into trust/no-trust groups.

The research questions put forward in the introduction are answered as follows. Only in one of the events the drivers followed more closely in the ICF condition than in the manual condition, which indicates that the way the behavior is adapted depends on the type of event, i.e., not only for automation in the usual sense but also for the type of "automation" afforded by following another vehicle.

The results indicate that it depends not only on the situation but also on the driver as varying responses were observed, e.g., how much drivers make themselves passive. In comparable situations, higher automation tended to lead to a more passive behavior, with fewer interventions with the brake foot.

We will now examine more closely a number of behavioral aspects that were affected by automation. First of all, it is of interest whether the automation was shut off or was kept running during an event. All in all, it is obvious that drivers employed different strategies on how they dealt with automation, depending on the situation at hand.

In the exit event where no speed reduction was necessary but where the ACC-AS would have continued on an unwanted course, the ACC-AS system was switched off manually. In three cases, the ego vehicle started exiting first, apparently without the driver expecting this behavior, which led to a manual system deactivation in all cases. In two of the cases, the driver started to steer back into the lane first. In the ACC condition, only three drivers deactivated the system, with the vast majority of drivers just letting the system proceed with its task. The expected behavior of the system is that the ego vehicle would start accelerating and then continue at the set speed when the lead vehicle left the lane, until it locked onto another lead vehicle, not necessitating any action on the part of the driver.

In the curve event, it was common to let the system keep the longitudinal control, and it was more common in the ACC-AS condition. No driver switched the system off manually; instead, the brake pedal was used for deactivation. In the ACC-AS condition, the driver was forced to take over steering eventually, and all but five drivers waited out the system and steered first when the limit of the system was reached.

In the broken-down-car event, speed reduction was a natural way to handle the event, and here, about half of the drivers used the brake to reduce speed and at the same time switch off both the ACC and ACC-AS systems. Other drivers, who apparently had planned to accelerate and pass the car in the left lane, did not experience any need to switch off ACC, as they accelerated over the set speed. Most drivers also reclaimed steering, which is necessary upon braking, as the system is switched off, but is also natural when not braking, as the situation was rather complex and the drivers were not very familiar with lateral automation. This combination makes it likely that drivers want to feel in control themselves.

Indications that drivers view driving with different types of automation as qualitatively different can be also found when looking at the headways they choose and at their speed reduction behavior in the different conditions. In the two conditions with system support, the headway control was completely handed over to the system, although it did not correspond to the headways chosen by the drivers in the manual conditions. In this paper, the drivers were not allowed to set their preferred headway, as all drivers should have the same preconditions; hence, we cannot know whether drivers would have chosen a somewhat longer headway if they had had the choice. The curve event provides the clearest indication that drivers switch strategy when driving with automation. In the two manual conditions, the mean headway increases with more than 1 s upon approaching the curve, showing that it feels natural under manual driving to decelerate before the curve, although this increases the distance to the car ahead. No difference was found between the manual and ICF situations either, although it was hypothesized that the ICF condition would produce smaller THWs, due to the psychological connection to the lead car. An explanation could be that there was no risk to get separated from the lead car; therefore, a temporary increase in THW did not come at a cost. In the two automated conditions, the headway remained the same set headway, with drivers not deactivating the automation. Drivers accepted headways that differed from their preference for the sake of keeping the automation switched on. Obviously, the drivers accepted that the automation handled the situation differently.

Upon entering the exit event, however, headways in the ICF condition were significantly shorter than in the fully manual condition. This can be due to the fact that, in the exit situation, there is a risk that the lead car may get separated from the following driver, particularly since another vehicle had squeezed into the gap beforehand, and therefore, the drivers get closer in the ICF condition. The headways in the automated conditions depended fully on the automation. The car was either at the preset headway or still in the approach phase, but the drivers did not intervene in any way. Otherwise, no big differences were found between the ICF and the fully manual condition, which can be due to the fact that the limitations in the simulated world made the navigation task very easy.

Interestingly, with ACC, a commonly used alternative to reduce speed, i.e., lifting the foot off the gas pedal, has been removed. The drivers either can stay in the automated mode and proceed at the set speed or have to decouple the system manually or brake actively. We assume that drivers are reluctant to change their speed drastically, and braking or a manual deactivation can be seen as a more "radical" intervention than just gently easing off the gas pedal. It may even be argued that the latter indicates a readiness to act upon changes in the environment, and this, together with the slight speed reduction achieved by easing off the gas, might reassure the driver that he or she is prepared. If the situation resolves such that no further action was necessary, the foot can simply be repositioned on the gas pedal, and no brake signal was visible from the outside. With ACC on, either the driver needs to switch off the system, which necessitates a movement of the hand and the foot to operate the pedals, or the driver can brake, disrupting the speed flow and necessitating a foot movement, or the driver can continue at the set speed, which may require additional attentional efforts to monitor the situation. In the curve and the broken-down-car event where a speed reduction was appropriate, the most common reaction in the manual conditions was initially easing off the gas, which was not always followed by braking. Compared with the behavior in the manual conditions, not doing anything with the foot was much more common in the automated conditions. Braking was approximately equally frequent, with some more braking in the ACC than in the ACC-AS condition. It is possible that the increased effort that is associated with deactivating the system leads to a tendency to keep the system on, although the vehicle will behave differently than in the manual condition. This can be seen as an adaptation to the changed mode of controlling the car.

Automated lateral control is not a feature that drivers are used to, and it may have felt scary for the drivers to let lateral control remain in the hands of the automation during the events. In those events where drivers decided to brake, the automatic lateral control was shut off anyway. Of the 16 drivers who did not brake in the ACC-AS condition in the broken-down-car event, only 6 did not steer either. Whether those six drivers decided not to steer or whether they did not realize that the situation could have easily demanded steering is not possible to tell. The eye-tracking-based PIs do not differ between those drivers who steered and those who did not.

In the curve event, it was necessary to steer eventually, also in the ACC-AS condition. Here, steering could be reclaimed either before or after the automation told the drivers to do so. Most drivers (25 of 30) waited for the warning to occur. Most of those drivers also exceeded their lane, but this was also true for four of the five drivers who did reclaim steering before it was necessary. The fact that a lane exceedance only led to a higher lateral jerk when drivers had not reclaimed control early may indicate that those drivers were surprised by the system warning and quickly jerked the vehicle back into the own lane. The lateral jerk value for drivers who reclaimed steering early and for those who received a warning but did not exceed the lane was comparable and not as high, indicating that drivers may have felt more in control over the situation and accepted a lane exceedance. It has to be remembered that the number of participants in some of the subgroups was rather small, such that it is recommended to investigate the interpretations provided here with a larger driver sample.

We do not have a good explanation as to why the drivers drove so much further into the oncoming lane in the ICF condition. A speculation might be that they felt protected by the car they were following, such that they did not take care themselves.

The investigated glance-related PIs differed between events but not between conditions, except that the ACC-AS condition led to a lower PRC value in the exit event. Drivers looked significantly less ahead and more into the mirrors in the broken-down-car event, where it was necessary to monitor the traffic in the left lane. This indicates that drivers adapt their glance behavior to the event at hand in general, regardless of the level of automation. The self-reported trust level was not associated with changes in the gaze-related PIs either. Several explanations exist for these findings. Possibly, the drivers would have needed more time and exposure to the conditions to develop condition-specific glance patterns. We know from earlier research [25] that the visual search pattern of experienced drivers differs from that of novice drivers, indicating that it takes time to develop visual strategies that suit the situation. In addition, the PIs used were somewhat blunt, limited by time and budget constraints. A more thorough analysis of search paths might yield additional results.

The lower PRC value in the ACC-AS condition in the exit scenario can be due to the fact that only in this condition the exiting vehicle influenced the ego vehicle, drawing the driver's gaze away from the road center. This would not constitute an adapted top–down search pattern but rather a bottom–up reaction to the exiting car.

V. Conclusion

To conclude, our results have indicated that drivers are conscious of the automation provided and actively include it in how they tactically approach different events; to some extent, this could be also observed for the ICF condition. The behavioral adaptations encompass headway and speed control, as well as how and when automation is switched off or not. Drivers do not just seem to react to automation but rather interact with automation, which changes the preconditions for behavioral evaluation. In the exit situation, drivers manually switched off the automation before it started heading off the road; in the broken-down-car situation, they made use of the slight deceleration that is linked to deactivating the automation using the brake pedal. This shows that drivers integrate the behavior of the automation into their tactical planning of the whole situation instead of only reacting to the responses of the automation.

If the concept of driving with automation is thus fundamentally different from the concept of driving without automation, it may not always be meaningful to compare performance indicators and subtasks without considering how the driver got into the situation in question.

References

[1] J. A. Michon, "A critical view of driver behavior models: What do we know, what should we do?" in *Human Behavior and Traffic Safety*, L. Evans and R. Schwing, Eds. New York, NY, USA: Plenum Press, 1985.

[2] M. S. Young and N. A. Stanton, "What's skill got to do with it? Vehicle automation and driver mental workload," *Ergonomics*, vol. 50, no. 8, pp. 1324–1339, Aug. 1, 2007.

[3] W. Schneider and R. M. Shiffrin, "Controlled and automatic human information processing: I. Detection search and attention," *Psychol., Rev.*, vol. 84, no. 1, pp. 1–66, Jan. 1977.

[4] R. M. Shiffrin and W. Schneider, "Controlled and automatic human information processing: II. Perceptual learning, automatic attending and a general theory," *Psychol., Rev.*, vol. 84, no. 2, pp. 127–190, Mar. 1977.

[5] R. M. Shiffrin and W. Schneider, "Automatic and controlled processing revisited," *Psychol., Rev.*, vol. 91, no. 2, pp. 269–276, Apr. 1984.

[6] H. J. Damveld and R. Happee, "Identifying driver behaviour in steering: Effects of preview distance," presented at the Measuring Behaviour, Utrecht, The Netherlands, 2012.

[7] M. Richardson, P. Barber, P. King, E. Hoare, and D. Cooper, "Longitudinal driver support systems," presented at the Automotive Environmental Impact Safety-Autotech, Birmingham, U.K., 1997.

[8] N. A. Stanton, M. S. Young, G. H. Walker, H. Turner, and S. Randle, "Automating the driver's control tasks," *Int. J. Cognit. Ergonom.*, vol. 5, no. 3, pp. 221–236, Sep. 1, 2001.

[9] N. Ovcharova, M. Fausten, and F. Gauterin, "Effectiveness of forward collision warnings for different driver attention states," in *Proc. IEEE IV Symp.*, 2012, pp. 944–949.

[10] J. D. Lee, D. V. McGehee, T. L. Brown, and M. L. Reyes, "Collision warning timing, driver distraction, and driver response to imminent rear-end collisions in a high-fidelity driving simulator," *Hum. Factors: J. Hum. Factors Ergonom. Soc.*, vol. 44, no. 2, pp. 314–334, Summer 2002.

[11] J. F. Antin, L. M. Stanley, and K. F. Cicora, "Conventional versus moving-map navigation methods: Efficiency and safety evaluation," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2138, pp. 34–41, 2009.

[12] D. E. Crundall, C. Shenton, and G. Underwood, "Eye movements during intentional car following," *Perception*, vol. 33, no. 8, pp. 975–986, 2004.

[13] M. R. Endsley and D. B. Kaber, "Level of automation effects on performance, situation awareness and workload in a dynamic control task," *Ergonomics*, vol. 42, no. 3, pp. 462–492, Mar. 1999.

[14] M. R. Endsley, "Toward a theory of situation awareness in dynamic systems," *Hum. Factors*, vol. 37, no. 1, pp. 32–64, Mar. 1995.

[15] J. E. B. Törnros, L. Nilsson, J. Östlund, and A. Kircher, "Effects of ACC on driver behaviour, workload and acceptance in relation to minimum time headway," presented at the 9th World Congr. Intelligent Transport Systems, Chicago, IL, USA, 2002.

[16] M. T. Dzindolet, S. A. Peterson, R. A. Pomranky, L. G. Pierce, and H. P. Beck, "The role of trust in automation reliance," *Int. J, Hum.-Comput. Stud.*, vol. 58, no. 6, pp. 697–718, Jun. 2003.

[17] O. M. J. Carsten, F. C. H. Lai, Y. Barnard, A. H. Jamson, and N. Merat, "Control task substitution in semiautomated driving: Does it matter what aspects are automated?" *Hum. Factors: J. Hum. Factors Ergonom. Soc.*, vol. 54, no. 5, pp. 747–761, Oct. 1, 2012.

[18] B. M. Muir and N. Moray, “Trust in automation: Part II. Experimental studies of trust and human intervention in process control simulation,” *Ergonomics*, vol. 39, no. 3, pp. 429–460, Mar. 1996.
[19] N. R. Bailey and M. W. Scerbo, “Automation-induced complacency for monitoring highly reliable systems: The role of task complexity, system experience, and operator trust,” *Theoret. Issues Ergonom. Sci.*, vol. 8, no. 4, pp. 321–348, Jul./Aug. 2007.
[20] J.-Y. Jian, A. M. Bisantz, and C. G. Drury, “Foundations for an empirically determined scale of trust in automated systems,” *Int. J. Cognit. Ergonom.*, vol. 4, no. 1, pp. 53–71, Mar. 1, 2000.
[21] A. F. L. Larsson, “Driver usage and understanding of adaptive cruise control,” *Appl. Ergonom.*, vol. 43, no. 3, pp. 501–506, May 2012.
[22] T. Victor, *Keeping Eye and Mind on the Road*, 2005.
[23] K. Kircher, C. Ahlstrom, and A. Kircher, “Comparison of two eye-gaze based real-time driver distraction detection algorithms in a small-scale field operational test,” presented at the 5th Int. Driving Symp. Human Factors Driver Assessment, Training Vehicle Design, Big Sky, MT, USA, 2009.
[24] M. Beggiato and J. F. Krems, “The evolution of mental model, trust and acceptance of adaptive cruise control in relation to initial information,” *Trans. Res. Part F: Traffic Psychol. Behav.*, vol. 18, pp. 47–57, May 2013.
[25] D. E. Crundall and G. Underwood, “Effects of experience and processing demands on visual information acquisition in drivers,” *Ergonomics*, vol. 41, no. 4, pp. 448–458, 1998.

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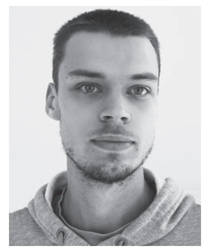

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