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Influence of cognitive processes on driver decision-making in dilemma zone

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ABSTRACT

In the past, research, which addressed driver behaviour in dilemma zone while approaching signalised intersections, did not focus on cognitive processes underlying stop/go decisions and collision risk after yellow-onset. Therefore, a study in a dynamic driving simulator with 20 participants was conducted to examine cognitive processes as basis of decision-making at signalised intersections. The study followed a 2×2 design with repeated measures. First, cognitive processes were triggered by perceptual cues, like the onset of yellow and a car in a leading position. Second, a cognitive distracting secondary task, the drivers had to solve interfered with cognitive processes. The results show, that a car in a leading position increases the probability not to stop after yellow-onset. Furthermore, the cognitive distracting secondary task leads to longer perception-response times (PRT) after yellow-onset, but only if there was no car in a leading position. Additionally, pupillary responses of the drivers during cognitive loading driving conditions are supporting this pattern of results. Finally, the concept of coupled motion is suggested to explain the underlying stop/go pattern of drivers after yellow-onset.

1. Introduction

Intersections compared to other road areas are potential crash blackspots (e.g., Campbell et al., 2004; Mahalel and Prashker, 1987; Vollrath et al., 2006). According to the National Highway Traffic Safety Administration (National Highway Traffic Safety Administration, 2021) 49% of all roadway crashes in 2019 occurred at intersections or intersection-related sites in the United States. Considering all crashes, 23% happened at signalised intersections (NHTSA, 2021). In this context, traffic safety must be addressed at signalised intersections to reduce crashes.

At signalised intersections, two major crash types can be differentiated. First, rear-end collisions occur when two successive drivers make conflicting decisions after the traffic light has changed from green to yellow (yellow-onset). Consequently, the risk of rear-end collisions are the highest if a driver in a lead car decelerates abruptly and the driver in the following car decides to cross the intersection and accelerates because he/she does not anticipate the behaviour of the driver in the lead car (Mahalel and Prashker, 1987). Second, right-angle collisions occur if a driver decides too late after yellow-onset not to stop. The driver runs the red light and clears the intersection too late, which can result in a crash with the crosswise traffic (cf. Lum and Wong, 2003). According to Yang and Najm (2007), the decision not to stop and thus risking a possible red-light violation was one of the major causes for right-angle collisions at signalised intersections.

Both crash types can occur when a driver is trapped in the so-called “dilemma zone” (cf. Gazis et al., 1960). Two types of dilemma zones can be differentiated. Dilemma zone type I, where a driver after yellow-onset can neither safely stop using a normal braking rate nor safely cross at a speed below the speed limit (cf. Gazis et al., 1960; Liu et al., 1996) and dilemma zone type II (option zone), where drivers can both, stop and cross (cf. Köll et al., 2004). But also additional factors, which influence driver behaviour after yellow-onset were addressed.

1.1. Factors influencing driver behaviour after yellow-onset

Rear-end and right-angle collisions can be avoided in case drivers make correct stop-or-go-decisions within seconds after yellow-onset while approaching a signalised intersection. The decision-making process underlying the stop/go decision, thus stop/go behaviour is influenced by a variety of different factors: Early research focused on the dilemma zone and the relationship between acceleration/deceleration, width of intersections, length of cars and duration of yellow intervals (e.g., Gazis et al., 1960; Olson and Rothery, 1961; Liu et al., 1996; Zhang et al., 2014). For instance, the duration of the yellow interval determines whether or not a driver is trapped in the dilemma zone type I (e.g., Liu et al., 1996). Further research took account of the dilemma zone type II (e.g., Köll et al., 2004; Mahalel and Prashker, 1987; Hurwitz et al.,

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2011). For example, the dilemma zone type II can be extended to reduce dilemma zone type I, but if the trade-off between dilemma zone type I and II is not good the crash risk also increases (cf. Köll et al., 2004).

Factors determining stop/go behaviour in the dilemma zones include approach speed and distance from stop-line at yellow-onset (Allos and Al-Hadithi, 1992; Chang et al., 1985). The stop/go behaviour of a driver was influenced by traffic volume (Mahalel and Prashker, 1987; Porter and England, 2000), intersection width (Chang et al., 1985), intersection type and layout (Allos and Al-Hadithi, 1992; Ng et al., 1997), or if red light cameras were installed at intersections (e.g. Lum and Wong, 2003; Retting et al., 1999b).

In addition, the position of cars in a platoon during car following in the dilemma zone was investigated in a variety of different studies. For instance, Moon and Coleman (2003) used car-following theory to model the driver-vehicle behaviour in platoons and found that the values of gate delay and gate interval times in car-following situations are greater than those with a single vehicle approach. Rakha et al. (2011), for example, investigated three platooning scenarios: car in a leading position, car in a following position, and no other vehicles. Rakha et al. (2011) found that drivers in a leading position are more likely to go through the signalised intersection after yellow-onset to avoid rear-end crashes. Furthermore, for drivers in a following position the probability to go through the signalised intersection is also higher after yellow-onset compared to the scenario with no other vehicles around (Rakha et al., 2011). Additionally, Ren et al. (2016) collected data from three signalised intersections during a time interval of nine months. Ren et al. (2016) found that if a car in the leading position or on an adjacent lane passed the signalised intersection after yellow-onset the following car has a significant higher probability to also run the intersection, which fits to the findings of Gates et al. (2007).

Supplementary, Mohammed et al. (2022) found that drivers in a platoon ran signalised intersections more frequently when they had a shorter tailway to a following vehicle. This result is in line with Al-Mistarehi et al. (2021), who state that the presence of a car with a short headway has an impact on the following driver's behavior. Additionally, Al-Mistarehi et al. (2021) found that almost 70% of vehicles in a platoon have a higher percentage of running the signalised intersection compared to vehicles not in a platoon. For example, Yousif et al. (2014) found that 17% of vehicles following a lead car, which decides to pass a signalised intersection after yellow-onset also runs the intersection. Furthermore, Papaioannou et al. (2021) showed that 71% were platoon leaders, 23% were first followers, and 6% were second followers who passed the intersection after yellow-onset in their study. In addition to this Knoflacher (1973) focused in his work on the followers in a platoon and observed the so-called "Mitschlepp" effect in an observational study. According to this effect, a driver of a following car was less likely to stop at an intersection if a lead car did not stop at an intersection after yellow-onset. This effect was confirmed by Elmitiny et al. (2010) and also by Van der Horst and Wilmink (1986). For further research in the context of cars in a platoon during car following at signalised intersections see also Konecni et al. (1976), Zimmerman and Bonneson (2004) or Yan et al. (2022).

In summary, many configuration-specific factors are well known to influence stop/go decisions at intersections. Yet, they explained only 35% of the variance in crashes at signalised intersections (Hubacher and Allenbach, 2004). Other factors related to characteristics of drivers, like age, gender, and attitude, accounted for the variance in crashes at signalised intersections (Hubacher and Allenbach, 2004). In several different studies, a relationship between the age of a driver and his/her stop/go decision after yellow-onset was found (e.g., Caird et al., 2007; Porter and Berry, 2001; Retting et al., 1999a; Retting and Williams, 1996). Another demographic factor is gender: Male drivers were more likely not to stop than female drivers (e.g., Papaioannou, 2007; Retting et al., 1999a). In addition, driving records (e.g., Retting et al., 1999a; Retting and Williams, 1996), aggressiveness (Papaioannou et al., 2021) and whether or not drivers were accompanied determined the stop/go probability (Porter and Berry, 2001).

1.2. Influence of cognitive processes during intersection approach

Broad insights are available about the effects of driver-related characteristics on stop/go decisions (see previous section). Yet, only little is known about the exact effects of cognitive processes which may explain the effects of driver-related characteristics: Why, for instance, do drivers who are accompanied, exhibit a different stop/go behaviour? The theory of action selection (cf. Cooper and Shallice, 2000; Cooper et al., 2005; Norman and Shallice, 1986) can be used to answer such questions. Here, this theory was used to identify the cognitive mechanisms involved in the decision-making of stop/go behaviour in the dilemma zone at signalised intersections. This theory was chosen as it has already been applied in the context of driving (cf. Groeger, 2016). According to this theory, actions (stop, go) are represented by a set of different action schemas with different activation levels (Norman and Shallice, 1986). The action schema with the highest level of activation is chosen for implementation. The activation level is influenced by bottom-up and top-down processes. Bottom-up processes are a linear flow of information from perception to action (Norman and Shallice, 1986). Perceptual cues (e.g., a lead car, the ego car is following) can activate triggers. These triggers are stored in a data base and can increase the activation level of a schema, if the perceptual cues, triggers, and the schema fit together. If different schemas are activated at the same time with the same activation level, conflicts occur. To solve such conflicts, an additional top-down control structure is activated (cf. Norman and Shallice, 1986). This so-called "Supervisory Attentional System" (SAS) activates or inhibits activation levels of schemas for instance by allocating attentional resources. If attention is shifted to a particular schema, its activation level increases. Herewith, this mechanism attention can modulate the activation level of a schema and thus its selection for implementation (Norman and Shallice, 1986).

One factor that may be able to shift attention to a secondary task (e.g., talking on a hands-free phone while driving) is cognitive distraction. Due to this shift, the activation level of a schema irrelevant for the primary task (e.g., stopping after yellow-onset) is increased. In contrast, the activation level of the relevant schema is decreased. As soon as the activation level of the schema, which controls the secondary task, is higher than the one of the schema, which controls the primary task, an inappropriate action, for example not stopping after yellow-onset, can result. In this situation, the action selection originates from bottom-up processes, perceptual cues (e.g., a lead car, the ego car is following), because the top-down mechanism is distracted by a secondary task (cf. Norman and Shallice, 1986). In this context the secondary task plays a central role because cognitive processes can be investigated, if the driver's performance in distracted and undistracted driving situations (yellow-onset) are compared to conclude underlying processes, which afterwards result in actual stop/go behaviour. Thus, in this work first drivers' behaviour was tested without impairing driving performance in order to have a baseline. Then it was tested with impairing driving performance in order to compare it with the baseline and conclude on the effects of cognitive distraction.

1.3. Pupil dilation and cognitive distraction

As one way of investigating cognitive processes in demanding driving situations while approaching signalised intersections, pupil dilation of the drivers can be evaluated. Using pupillary responses as a measurement of cognitive loading tasks has a long history in research (cf. Hess and Polt, 1964; Kahneman and Beatty, 1966; Schaefer et al, 1968). Research concerning pupil dilation and cognitive load shows a stable, positive relationship between both factors (Laeng et al., 2012). The higher the cognitive load, the wider the pupil (see e.g. Beatty, 1982; Hyönä et al., 1995; Jainta, and Baccino, 2010; Karatekin, 2004). In the automotive context pupil dilation is also used as a psychometric measurement of cognitive load while driving (Kun et al., 2011; Schwalm et al., 2008). Pupil dilation is used in this work to indicate cognitive demanding driving situations (i.e. wider pupil dilation) while approaching signalised intersections, especially during secondary task conditions.

Research aim and hypotheses

The objective of this work is to investigate the influence of cognitive processes on drivers' decision-making in dilemma zone while approaching signalised intersections. In this context it is of particular interest how bottom-up processes triggered by perceptual cues are integrated with top-down processes. Especially, cognitive distraction as a major factor of interference and its effects on decision-making processes were investigated. Considering the theory of action selection and the work on pupil dilation and cognitive distraction, a variety of hypotheses can be derived:

H1: Bottom-up process and specifically perceptual cues trigger go behaviour in case top-down processes are not present.

H2: Top-down processes trigger stop behaviour, if they are not impaired by cognitive distraction.

H3: Cognitive distraction impairs top-down processes, thus triggering go behaviour.

H4: It is assumed that the more demanding (driving) situations will result in wider pupillary responses because top-down processes, which impair bottom-up schema selection are present. Based on the research and literature on cognitive demanding tasks and pupil dilation (Jainta and Baccino, 2010; Kun et al., 2011; Laeng et al., 2012; Schwalm et al., 2008) it is assumed that in the condition with secondary task drivers' pupil should be wider compared to the condition without secondary task. Considering the car-following condition (with vs. w/o lead car) a non-directional hypothesis is postulated.

2. Method

2.1. Study design

A study was designed to test the hypotheses. This study followed a 2×2 design with repeated measures. The first factor was the perceptual cue *lead car* with the two stages "no lead car" vs. "lead car". The second factor was the *cognitive distraction* with the two stages "no *1*-back task" vs. "*1*-back task". As dependent variables the stop/go behaviour, the perception-response times (PRT), the number of correct answers in the *1*-back task, as well as the pupil dilations were recorded and analysed. A within-subject design was realised.

2.2. Apparatus

The experiment was conducted in a dynamic driving simulator (Fig. 1a) with a hexapod motion system (Suikat, 2005). Pupil dilation was recorded (Fig. 1b) by the head-mounted eye-tracking system Dikablis (Lange et al., 2009). The pupils of the drivers' left eyes were measured. The eye-tracker uses "dark-pupil technique" for measuring pupil dilation (Duchowski, 2007; Long et al., 2007). Additionally, optical markers as reference points for head-tracking were used (Lange et al., 2009).

2.2. Driving scenario

Two urban driving scenarios were designed that differed with regard to the existence of a lead car. In the first scenario the ego car followed a lead car and in the second scenario there was no lead car. In the first scenario, the participants had to drive for 10.1 km (6.3 mi) in a city. The speed limit in town was 50 $^{km}/_{h}$ (31 mph). During the drive, the participants approached 20 signalised x-shaped intersections on a straight road section, which was between 300 m (328 yd) and 900 m (984 yd) long. Between the straight sections, ten right and ten left turns were implemented. Eight out of 20 traffic lights (critical traffic lights) changed their signal from green to yellow when the participants were approaching the intersection (Fig. 2).

The signal changed when the participants were 2.9 sec away from the stop-line (yellow-onset). The lead car passed the intersection after yellow-onset. The yellow-interval duration of 2.9 sec was identified during a pilot study to adjust the yellow-interval duration to the motion system of the dynamic driving simulator. The pilot study was conducted with 10 participants, who did not participate in the actual study. The participants of the pilot study drove the exact same route as the participants of the actual study. The only difference in the pilot study was that different traffic lights had different yellow-onsets, varying from 2,0 sec to 3,8 sec, increasing with 0,3 sec steps. The evaluation of the stop/go behaviour in the pilot study showed that with yellow-onsets the same or shorter as 2.6 sec nearly all participants did not stop after yellow-onset. With yellow-onsets the same or longer as 3.2 sec nearly all participants did stop after yellow-onset. At intersections with a yellow-onset of 2.9 sec nearly half of the participants stopped and nearly half

Fig. 2. Third-person view of simulation at intersection with lead car after yellow-onset (Copyright: DLR). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(a) (b)

Fig. 1. Dynamic driving simulator and control station (Copyright: DLR). (a) Hexapod system with car. (b) Eye-tracking setup in the control station.

did not stop, indicating a decision conflict. The aim of the pilot study was to catch the participants in the dilemma zone type I, assuming that with a yellow-onset of 2.9 sec the cognitive conflict to make a stop/go decision is highest in the driving simulator.

In the actual study, if the participants stopped after yellow-onset and the lead car went through the intersection, the lead car waited behind a bend, so that the participants could catch up again. The position of the critical traffic lights was randomly distributed between the 20 intersections. The remaining 12 traffic lights changed their signals randomly so that the participants could not predict the behaviour of the traffic lights. Five of 12 traffic lights were always green, five changed from green to yellow to red, when the participants were 5–9 sec away from stop-line, and the first and last traffic light changed from red to yellow. While approaching ten out of 20 intersections, the participants were cognitively distracted by a secondary task (see next section). The participants were instructed not to overtake the lead car and the maximum speed of the lead car was 50 $^{km}/_{h}$ (31 mph). Other traffic included oncoming traffic and crosswise traffic at intersections. The traffic volume was of medium intensity. These specifications were exactly the same for the first and second scenario with the exception of the existence of the lead car (with vs. w/o lead car). Furthermore, the distribution of the critical traffic lights among the 20 intersections and the intersections where the participants were cognitively distracted by a secondary task was different in the second scenario to avoid learning effects.

2.3. Cognitive distraction

As a secondary task, an auditory version of the *n*-back task (see e.g. Kirchner, 1958; Dobbs and Rule, 1989) was presented. The participants had to respond to the task while driving. Single letters, like H, K, D, F, etc. were presented auditorily in a random sequence. The interstimulus interval was 4 sec. While driving, the participants had to compare a letter with its predecessor in the sequence (*1*-back task), and had to decide whether or not both letters were the same or not. Such secondary tasks can produce cognitive load, influence working memory processes, reaction times, and response accuracies (Basak and Verhaeghen, 2011; Jaeggi et al., 2010; Oberauer, 2006; Smith and Jonides, 1997). If both letters were the same, the participants had to press a button with their thumb located on the right half of the steering wheel. If both letters were not the same, the participants had to press a button located on the left half of the steering wheel. To avoid a connection between the presentation of the *1*-back task and traffic light behaviour the assignment of *1*-back task to traffic lights was balanced and randomised. The *1*-back task was presented at four of the critical traffic lights. Furthermore, the *1*-back task was presented at six of the remaining 12 non-critical traffic lights. The *1*-back task was presented when the participants were 300 m in front of the stop-line and was stopped 100 m after the stop-line was crossed. The distance between two intersections without secondary task varied between 100 m and 900 m.

2.5. Participants

Twenty participants were included in the experiment. All participants were paid 8 € (8.13 $) per hour for participation. The entire experiment lasted between 1 and 1½ hour. The age of the participants varied from 28 to 47 ($M = 36.6$, $SD = 6.5$) years. Gender was balanced among the participants (50 % female and male). The driving experience of the participants varied from 10 to 29 ($M = 18.1$, $SD = 6.4$) years with a minimum of 5000 and a maximum of 50,000 ($M = 19325$, $SD = 11585$) driven km (3107 – 31,069 mi, $M = 12008$, $SD = 7199$) per year.

2.6. Procedure

At the beginning of the experiment, the participants were informed of the facts, risks, and alternatives of the driving study and gave their written consent. Afterwards, the participants answered a demographical questionnaire. Before the participants started with the driving scenarios, they completed a familiarisation drive to get used to the driving dynamics of the simulator and to the *1*-back task. The familiarisation drive lasted up to 15 min and the participants drove in an urban area. The participants were told to drive as they normally would in their own car and to obey all rules of the road (e.g., traffic lights, speed limits). One driving scenario lasted up to approximately 20 min (including stops at traffic lights). A pause of 5 to 10 min between two scenarios was made. The order of the driving scenarios was counterbalanced for both participant and gender.

2.7. Data collection and statistical analyses

Data were analysed for the 16 signalised intersections with a yellow-onset of 2.9 s (both driving scenarios). Analyses addresses the interval between yellow-onset either till crossing of stop-line by the ego car for those who did not stop and or till the stop of the ego car for those who stopped. As dependent variables the stop/go behaviour, the perception-response times (PRT), the number of correct answers in the *1*-back task, as well as the pupil dilations were recorded and analysed.

To analyse the influence of the lead car and the *1*-back task on stop/go propensity and perception-response time (PRT) after yellow-onset, the group of those who stopped was separated from the group of those who did not stop. Olson and Farber (2003) defined the perception-response time as the interval that starts when a visual cue becomes visible and ends when a “discernable response” is initiated. Accordingly, the PRT for acceleration was defined here as the time after yellow-onset until the accelerator was pressed down >3% (discernable change in CAN data compared to the initial position at yellow-onset) before crossing the stop-line. The mean PRT for acceleration was calculated only for those who did not stop after yellow-onset. Changes in the accelerator position smaller than 3% were removed from the analyses. An analysis of the PRT for deceleration (time from yellow-onset to the foot contacting the brake – see e.g., Caird et al., 2007; Caird et al., 2008) was not calculated due to small cell sizes in the group of those who stopped.

To investigate how car following influenced the allocation of cognitive processes, the performance of the drivers in the *1*-back task was analysed. For this purpose, the number of correct answers during the whole driving scenario was set in relation to the maximum number of trials for each participant. Means were calculated for the conditions “lead car” and “no lead car”.

To investigate how pupillary responses of the drivers were influenced by *1*-back task and car following, mean pupil dilation was computed for the interval between secondary-task onset till crossing of stop-line by ego car for those who did not stop and till stop of ego car for those who stopped. These intervals were compared with the same intervals of the condition without secondary-task, identified by ego-car position.

To test the H1 and H2 hypotheses, a chi-square test of stop/go behaviour after yellow-onset and an ANOVA for repeated measures of drivers’ perception-response time (PRT) were conducted. To test the H3 hypothesis, a *t*-test for repeated measures was used to analyse the performance in the *1*-back task. To test the H4 hypothesis, an ANOVA for repeated measures was used to analyse the influence of cognitive load on drivers’ pupil dilation.

3. Results

3.1. Stop/go propensity

Significantly less drivers stopped after yellow-onset with lead car (31.25 %) compared to the condition without lead car (68.75 %), $\chi^2(1, 80) = 11.25$, $p < .001$. Based on this result the hypothesis that bottom-up processes, especially perceptual cues, trigger go behaviour (H1) can be confirmed. There was neither a significant influence of the *1*-back task on actual stop/go behaviour nor a significant interaction ($p > .05$). Based on this result the hypothesis that cognitive distraction impairs top-down processes, thus triggering go behaviour (H3) cannot be meaningfully answered at this point because it is not fully clear whether cognitive distraction was induced by the *1*-back task (for a detailed discussion see the final chapter). Fig. 3 shows the stop/go propensity by the existence of lead car and *1*-back task in more detail. Less participants stopped (13.75 %) in the condition with *1*-back task and lead car compared to the condition with *1*-back task and without lead car (36.25%), $\chi^2(1, 40) = 8.10$, $p < .01$ (see Fig. 3). This result confirms H1, that bottom-up processes like a perceptual cue (i.e. lead car) trigger go behaviour. If the participants solved the *1*-back task and followed a lead car, significantly less drivers stopped (13.75%) compared to the condition without *1*-back task and without lead car (32.50%), $\chi^2(1, 37) = 6.08$, $p < .05$. This result also confirms H1, that bottom-up processes like a perceptual cue (i.e. lead car) trigger go behaviour (see Fig. 3).

A similar behaviour was visible if the participants performed the *1*-back task and followed lead car. Then, significantly less participants stopped (17.50%) after yellow-onset compared to the condition with *1*-back task and without lead car (36.25 %), $\chi^2(1, 43) = 5.23$, $p < .05$. This pattern of results also confirms H1, that bottom-up processes like a perceptual cue (i.e. lead car) trigger go behaviour. Finally, if the participants did not solve the *1*-back task and followed a lead car fewer participants stopped (17.50%) compared to the condition without *1*-back task and without lead car (32.50 %). This result was marginally not significant ($p = .058$). Still, its tendency fits in the overall stop/go pattern.

The two combinations in Fig. 3, which indicate the influence of cognitive distraction (*1*-back task) on the stop/go behaviour after yellow-onset, were statistically not significant ($p > .05$). There was no difference in stop/go behaviour if the participants followed a lead car and solved the *1*-back task (13.75%) or did not solve the *1*-back task (17.50%). Meaning that the hypothesis that top-down processes trigger stop behaviour, if they are not impaired by cognitive distraction (H2) cannot be confirmed. And there was no difference if the participants did not follow the lead car and solved the *1*-back task (36.25%) or did not solve the *1*-back task (32.50%). Meaning that the hypothesis that cognitive distraction impairs top-down processes, thus triggering go behaviour (H3) cannot be confirmed. Thus, the *1*-back task had no influence on the actual stop/go behaviour, regardless whether or not the participants followed a lead car.

3.2. Perception-response time (PRT) at accelerator

The statistical analyses of PRT revealed a significant main effect of the *1*-back task for acceleration after yellow-onset ($F(1, 19) = 5.898$, $p < .05$, $\eta^2 = 0.237$) and a significant interaction of the factors lead car and *1*-back task ($F(1, 19) = 10.955$, $p < .01$, $\eta^2 = 0.366$). There was no significant main effect of the factor lead car ($F(1, 19) = 0.953$, $p = .341$, $\eta^2 = 0.048$). The mean PRTs for acceleration by lead car and *1*-back task are shown in Fig. 4.

If the participants did not follow a lead car and were cognitively distracted by the *1*-back task, the perception-response time was significantly slower ($M = 1.039$, $SE = 0.184$) compared to the baseline

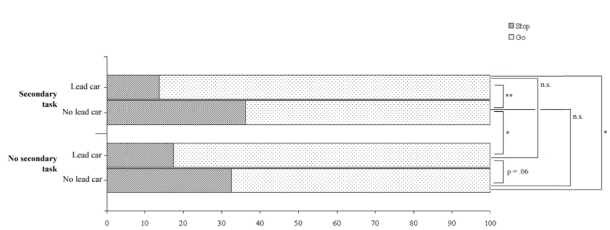

Fig. 3. Percentage of drivers stopping and going by lead car and secondary task (**p < .01; *p < .05; n.s. p > .05).

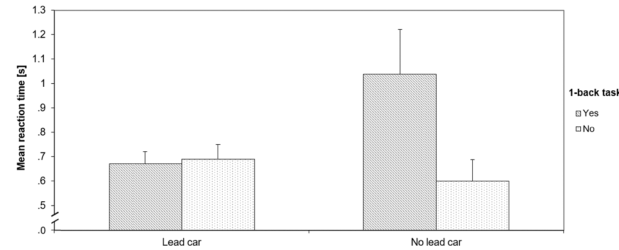

Fig. 4. PRT for acceleration by lead car (lead car vs. no lead car) and 1-back task (task performed: yes vs. no).

condition without lead car and without cognitive distracting *1*-back task ($M = 0.601$, $SE = 0.088$). This result indicates that the cognitively distracting *1*-back task has an impairing effect on PRT supporting the H3 hypothesis.

But if the participants followed a lead car and were cognitively distracted by the *1*-back task, the PRT was significantly faster ($M = 0.671$, $SE = 0.050$) compared to the condition without lead car and with *1*-back task. This result indicates that bottom-up processes, like perceptual cues (i.e. lead car) improve PRT supporting the H1 hypothesis. Finally, if the participants followed a lead car and were not cognitively distracted ($M = 0.671$, SE $= 0.061$) there is no difference in PRT compared to the condition with lead car and with *1*-back task. This result also fits in the overall pattern, that perceptual cues (i.e. lead car) facilitate bottom-up processes, thus also supporting the H1 hypothesis.

The statistical analysis of the PRT for deceleration was not possible due to the small cell sizes, but the calculated mean PRTs for deceleration show a similar pattern, indicating the same influence of lead car and *1*-back task on both PRT for acceleration and deceleration.

3.3. 1-back task

If the participants followed a lead car, the mean number of correct answers in the 1-back task was significantly higher ($M = 0.674$, $SE = 0.009$) compared to the condition without lead car ($M = 0.563$, $SE = 0.013$), $t(19) = 7.455$, $p < .001$ (see Fig. 5). Thus, in the condition with lead car more cognitive resources were used to solve the *1*-back task compared to the condition without lead car. Both, the mean number of correct answers in the condition with lead car ($t(19) = 19.095$, $p < .001$) and in the condition without lead car ($t(19) = 4.916$, $p < .001$) was significantly higher than the probability of guessing the correct answer ($p = .5$).

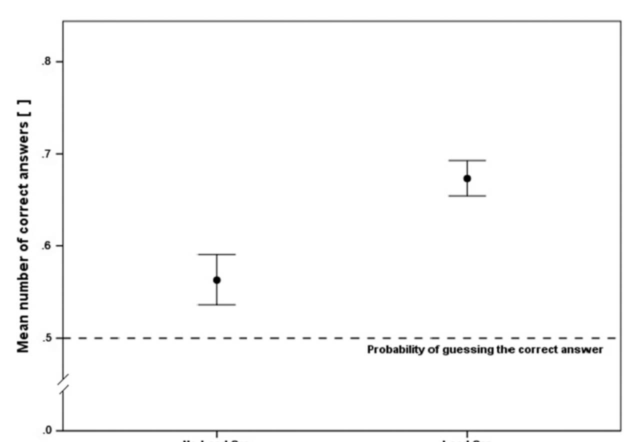

Fig. 5. Mean number of correct 1-back answers by lead car.

3.4. Pupil dilation

The statistical analyses of the pupillary responses of the drivers showed a significant main effect of the *1*-back task on their pupil dilation ($F(1, 19) = 37.217$, $p < .001$, $\eta^2 = 0.662$) and a tendency of the lead car, which is slightly above significance level ($F(1, 19) = 4.181$, $p = .055$, $\eta^2 = 0.180$). There was no significant interaction of the factors *1*-back task and lead car ($F(1, 19) = 0.727$, $p = .404$, $\eta^2 = 0.037$). This means, if the participants solved the cognitive loading *1*-back task while approaching signalised intersections their pupil was significantly wider ($M = 52.772$, $SE = 2.437$) compared to the baseline condition without cognitive loading secondary task ($M = 50.630$, $SE = 2.332$). This result confirms the hypothesis that demanding driving situations result in wider pupillary responses because top-down processes, which impair bottom-up schema selection are present (H4).

Furthermore, if the participants followed a lead car, there was a tendency that the pupil was not that wide ($M = 51.110$, $SE = 2.386$), compared to the condition without lead car ($M = 52.291$, $SE = 2.406$). Finally, there seems to be no interdependency between solving the *1*-back task with ($M = 52.067$, $SE = 2.479$) or without car following ($M = 53.477$, $SE = 2.449$) and no *1*-back task with ($M = 50.154$, $SE = 2.315$) or without car following ($M = 51.106$, $SE = 2.379$) on pupillary responses of the drivers (Fig. 6).

4. Discussion and conclusions

Previous research, which addressed driver decisions in dilemma zone did not focus on cognitive processes as a possible explanation of stop/go behaviour. The objective of this study was to investigate cognitive mechanisms, influencing the decision-making process after yellow-onset at signalised intersections. Therefore, a study was conducted to explain stop/go decisions based on the theory of action selection by Norman and Shallice (1986). It was hypothesised that a perceptual cue, like a lead car, the ego car follows, triggers go behaviour via bottom-up processes, leading to a higher propensity not to stop at the intersection after yellow-onset (H1). Additionally, it was assumed that top-down processes trigger stop behaviour, if they are not impaired by cognitive distraction, like the *1*-back task (H2). Furthermore, it was expected, that cognitive distraction, like the *1*-back task, binds attentional resources of top-down processes, which were needed to switch from a go to a stop schema by inhibiting the current active go schema, resulting in a higher propensity not to stop at the intersection after yellow-onset (H3). Finally, it was assumed that the more demanding the driving situation the wider pupillary responses are because of top-down processes, which impair bottom-up schema selection (H4).

The results of the data analyses revealed that the existence of the perceptual cue "lead car" predicted the stop/go decision of the drivers.

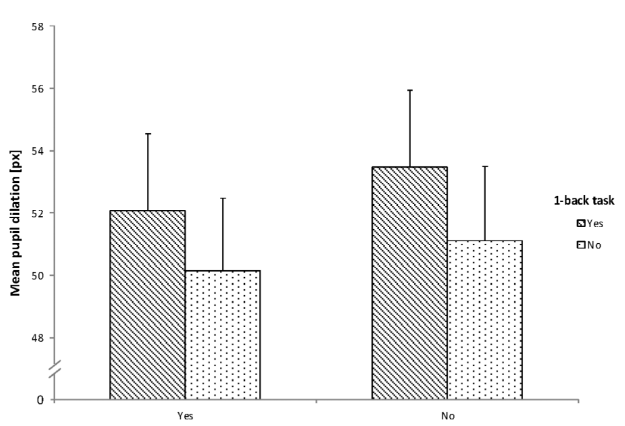

Fig. 6. Mean pupil dilation by lead car and 1-back task (task performed: yes vs. no).

The probability not to stop after yellow-onset was significantly higher if the drivers followed a lead car compared to the condition without a lead car. Furthermore, if the drivers drove behind a lead car, crossing an intersection after yellow-onset, significantly more drivers did not stop. This result fits to the so-called "Mitschlepp" effect reported for example by Knoflacher (1973), Van der Horst and Wilmink (1986), and Elmitiny et al. (2010). An explanation in accordance with the theory of Norman and Shallice (1986) can be, that the perceptual cue "lead car" triggers a go schema via bottom-up processes, resulting in a higher activation level of the go-schema and as a consequence a higher go-propensity.

Considering the second factor, cognitive distraction, there was no significant influence of the *1*-back task on the stop/go behaviour after yellow-onset. Based on this result, it can be concluded that the *1*-back task had no influence on the actual stop/go behaviour. Yet, there was a significant main effect of the *1*-back task on PRT at the accelerator. Compared to the baseline condition (no lead car and no cognitive distraction), the PRT was significantly slower if the participants did not follow a lead car and were cognitively distracted by the *1*-back task. One possible explanation might be that the comparison of only one letter back was not difficult enough to impair higher cognitive processes, but produced distraction on a lower cognitive level, affecting PRT. According to research concerning the *n*-back task, *1*-back tasks affect lower cognitive processes, whereas $n > 1$ impairs higher executive-control mechanisms (Jaeggi et al., 2009; Smith and Jonides, 1997; Verhaeghen and Basak, 2005). This is because the *1*-back comparison can be performed based on familiarity of the two letters, but if $n > 1$ the preceding letters must be retrieved actively from working memory (Oberauer, 2005). Within the framework of Norman and Shallice (1986), this means that the auditory cues (i.e., letters) trigger corresponding schemas increasing its activation level. But to solve simple *1*-back comparisons bottom-up processes are sufficient and no further attentional resources are needed. This means that the *1*-back task did not bind enough attentional resources of top-down processes to inhibit a firmly established go behaviour (respectively the switch from a go to a stop schema). However, enough attentional resources are bound to slow down PRTs by inhibiting bottom-up processing.

Another result concerning PRT is the interaction between cognitive distraction and existence of a lead car. If the drivers were cognitively distracted and followed a lead car their PRTs were faster compared to the condition with distraction and without lead car. A possible reason for this effect is, that in the condition with lead car, the drivers coupled their responses to the behaviour of the lead car by activating a corresponding driving schema, resulting in faster PRTs. This effect is of particular importance in combination with the results from the performance of the drivers in the *1*-back task. When the participants followed a lead car, the number of correct answers was significantly higher compared to the condition without lead car.

One possible conclusion of this pattern of results is that drivers in a following position manually couple their longitudinal control to the behaviour of the lead car. By coupling longitudinal control to the lead car, a driver can reduce the cognitive demands of the driving task. This coupling makes attentional resources available for other cognitive processes and tasks. Coupling longitudinal control to the lead car enables the drivers to shift free attentional resources away from the driving task and to the *1*-back task (driving-unrelated task), resulting in a better performance in the secondary task. This coupling is comparable to a "cognitive-cruise control". Drivers in such traffic situations seem to use simple driving heuristics, like follow the lead car as basis for their driving. The result of coupling the own decision-making process to the behaviour of the lead car is a higher go-propensity at signalised intersections, faster PRTs after yellow-onset as well as better performances in the *1*-back task.

The mechanism of coupling longitudinal control to the behaviour of the lead car is a possible cognitive explanation of the so-called "Mitschlepp" effect. To emphasise the cognitive-coupling process, the term "coupled-motion" effect is suggested, describing a driver in the following position of a platoon manually connecting his/her longitudinal control to a lead car and not only being pulled ("Mitschlepp") by the lead car. Related with the coupled-motion effect at signalised intersections is the risk of unexpected critical traffic events. The decision-making process is coupled to the lead car and attentional resources are shifted to a cognitive distracting secondary task, like talking on a hands-free car phone. If the driver in the lead car decelerates abruptly and the driver in the following car does not anticipate this manoeuvre because attentional resources are shifted to a secondary task, the risk of rear-end collisions increases.

Furthermore, this over-all pattern of results is supported by the pupillary responses of the drivers. First, the pupil was significantly wider in the condition with *1*-back task what means that the *1*-back task was cognitively loading. The secondary task did not have an effect on actual stop/go propensity, maybe because it was too easy for an effect on actual stop/go behaviour, but impaired cognitive processing of the drivers to an extent which is visible in slower reaction times and additionally wider pupils. Second, a tendency is discernible that in the condition with lead car pupillary responses of the drivers are smaller compared to the condition without lead car. This indicates that the driving task might be easier with lead car, maybe due to the coupling of longitudinal control during car following. Elmitiny et al. (2010) argued that the chance to be in a following position is higher at intersections with higher traffic volumes. This means in turn, that the probability of the coupled-motion effect and accordingly the risk of rear-end collisions increases at intersections with higher traffic volumes. Furthermore, the PRTs show that longer PRTs are related with a higher propensity not to stop after yellow-onset. This go decision of drivers, based on longer PRTs, can lead to longer yellow-entry times, resulting in a higher risk of red-light running, correspondingly right-angle collisions (Elmitiny et al., 2010).

This study is the first experimental approach to investigate cognitive factors involved in decision-making processes while being in the dilemma zone after yellow-onset. The results presented in this work can contribute on the one hand to the dimensioning and parameterisation of the infrastructure at signalised intersections on the other hand to the development of advanced intersection assistance systems to support drivers' decision-making process and action-selection after yellow-onset by considering the coupled-motion effect and driver distraction. This, in turn, can reduce the risk of rear-end and right-angle collisions in conflicting action-selection situations after yellow-onset.

On the part of infrastructure at signalised intersections up to now the calculation of the dilemma zone boundaries, the signal timing settings, as well as the speed limit and their modelling are based on a variety of different factors, also including drivers' characteristics, like gender and aggressiveness, as described in the studies of Papaioannou (2007) and Papaioannou et al. (2021). But a cognitive factor is not included by now, neither in current calculations of dilemma zone boundaries, signal timing settings or speed limit nor in the modelling of drivers' decision-making after yellow-onset. Therefore, it is proposed to take cognitive factors into account, which can be investigated by secondary tasks (e.g. n-back task) in future research activities to address dilemma zone boundaries, the signal timing settings, and speed limits. This is of special relevance because under cognitive distraction the PRTs are longer, thus the propensity not to stop after yellow-onset is higher.

Furthermore, vehicle-to-infrastructure (V2X) communication can be used as technology at signalised intersections to cover the whole intersection infrastructure, including all intersection arms. Based on V2X communication the status of the signal and the duration of its phase can be communicated to surrounding vehicles. Additionally, vehicles approaching an intersection can register at the intersection via V2X, sending information of its velocity, acceleration, location, dimensions, and position in a platoon to the signalised intersection. This can also be supported by additional sensors of the infrastructure and the vehicle itself. Based on information available via V2X the development on the part of assistance systems can be advanced to support drivers' decision-making process and action-selection after yellow-onset.

For example, an adaptive dilemma zone assistance system can use the V2X information described above in combination with information from in-vehicle camera systems, which are tracking drivers' pupil dilation to identify cognitive distraction, for example during a talk on a hands-free car phone while driving. If the adaptive dilemma zone assistance system realises, based on the information via V2X and the pupil dilation of a driver, that the driver is caught in a dilemma zone and cognitively distracted by a secondary task (e.g. talking on the phone) at a signalised intersection the adaptive dilemma zone assistance system can first mute the entertainment system of the vehicle, put phone calls on hold and advises the driver to halt the vehicle in front of the stop line. Beside a warning strategy an adaptive dilemma zone assistance system might also provide automatic deceleration for the vehicle to come to a halt in front of the stop line to support a driver, who is caught in a dilemma zone and cognitively distracted.

Especially in the context of the coupled-motion effect and driver distraction, as described in this work, a warning and actively assisting system, like the adaptive dilemma zone assistance system can support drivers in cognitively demanding driving situations in the dilemma zone. In particular if a driver is first or second follower in a platoon and is caught in a dilemma zone and cognitively distracted the adaptive dilemma zone assistance system might prevent drivers to run the signalised intersection after yellow-onset, thus reduce the number of passes after yellow-onset while driving in a platoon during car following as described by Papaioannou et al. (2021). In this context an adaptive dilemma zone assistance system would decouple the cognitive connection of a driver following a lead car. For the development, dimensioning, and parameterisation of an adaptive dilemma zone assistance system it is important that the warnings and active assistances in a dilemma zone are due to human factor aspects, traffic regulations and always consider the surrounding traffic, especially in a platoon, so that violations of regulations and collisions with others vehicles at signalised intersections, for example due to an abrupt deceleration in a platoon, are avoided.

Finally, some limitations of the current work have to be addressed. First of all, as mentioned before, the *1*-back task was not cognitive loading enough. Although a pre-study was conducted to test the adequacy of the *n*-back task (1 vs. 2), it would have been better to use the *2*-back instead of the *1*-back task. The *2*-back task impairs higher executive-control mechanisms and should show a clearer result pattern, supporting especially hypothesis H2 and H3. Furthermore, the results mentioned here have to be seen in the context of a driving simulator study. Although Abdel-Aty et al. (2009) could show that driving simulators are reliable instruments to investigate stop/go decisions to assess the crash risk at signalised intersections it is important to validate the results in a controlled driving study at a closed test area to further investigate stop/go behaviour and PRTs in combination with a *2*-back task in an equipped test vehicle after yellow-onset.

In this context further research is needed to clarify the cognitive mechanisms involved in the decision-making process after yellow-onset, especially using equipped test vehicles at closed test areas. In a potential setup at a test area particularly the interaction between subjectively perceived yellow-interval duration, distance to stop-line and speed of car under cognitive distraction (e.g. *2*-back task) after yellow-onset are of special interest for further research to investigate decision-making and action-selection at signalised intersections. For example, prospective duration estimation plays a major role in the context of highly dynamic environments, like driving vehicles. Prospective duration estimation is influenced by cognitive workload, like performing a cognitive distracting secondary task while driving. If the prospective duration estimation is impaired by a cognitive distracting secondary task subjectively perceived durations, for example the yellow-interval at a signalised intersection can differ from the objective duration (e.g. yellow-onset setting of a signal). The difference between subjectively perceived duration and objective duration can lead to an erroneous decision-making of a driver at signalised intersection, thus resulting in an inadequate stop/go behaviour after yellow onset. Therefore, the subjective perception of duration is a relevant aspect of decision-making at signalised intersections and also the work presented here. The mechanisms underlying subjective perception of duration at signalised intersections and the influence of cognitive distraction are described in more detail by the authors in a publication, which is under preparation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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