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Drive first or yield? Effect of complexity on cooperation behavior at deadlock-situations at T-intersections

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ABSTRACT

Deadlock-situations at intersections, where the right-of-way is not clearly regulated, pose challenges for automated vehicles (AVs) in mixed traffic. For AVs to show behavior that is accepted by all traffic participants, it is important to understand the cooperation behavior of manual drivers in these situations. Three studies were conducted where the effect of complexity on cooperation behavior at deadlock-situations was examined. Participants watched videos of approaches to T-intersections where a deadlock-situation occurred but was not yet resolved. After each video they reported their intended behavior, the perceived difficulty and visual clutter of the situation as well as the anticipated behavior of the cooperation vehicles. Complexity was manipulated with visual built clutter, pedestrians and additional traffic. Results show minimal effect of complexity on perceived difficulty and visual clutter as well as cooperation behavior. However, cooperation behavior was significantly influenced by approach position. When approaching from below drivers are more likely to yield compared to approaches from left or right. Additionally, when a vehicle is driving through the intersection directly in front of the driver they show higher probabilities of driving first through the intersection. The anticipated behavior of the cooperation vehicles is influenced both by their approach position and the right-of-way rule from the driver's perspective, suggesting that the right-of-way rules are not correctly understood and therefore the deadlock-situation is not recognized as such. Recommendations for the behavior of automated vehicles in these situations are derived from the findings of the studies.

1. Introduction

The development of autonomous vehicles (AVs) continues to advance and holds great potential for road safety. According to a study by Prognos (2018), it is projected that by 2050, 50–70 % of all newly registered vehicles in Germany will have automation features. However, the proportion of these vehicles that will be able to drive autonomously in inner city traffic is estimated to be only 20–30 %. This means that for a long time to come, there will still be mixed traffic consisting of manual and autonomous vehicles, particularly in urban settings. This mixed traffic presents new challenges, especially in urban traffic, where there is a higher risk of accidents (Statistisches Bundesamt, 2022). Deadlock situations pose a particular challenge in inner-city traffic. In Germany, these situations occur, for example, at equal narrow passages or intersections with right-before-left priority rule, where three or four vehicles arrive at the same time (Fig. 1). Deadlock situations are not the most frequent, but they do occur regularly in real traffic. For example, in a 5-hour observation of a T-intersection, about 9 % of vehicle interactions were deadlock situations (Imbsweiler et al., 2016). In these

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situations, none of the road users has the right of way. According to the German Road Traffic Regulations, road users must cooperate in these situations to find a solution. These situations, though less common, present unique challenges in urban traffic that warrant closer investigation, particularly as AVs are expected to operate in mixed traffic. However, research on deadlock situations remains limited. Many existing studies on driver behavior focus on interactions at intersections but do not specifically address deadlock situations (e.g. Björklund & Åberg, 2005; Liu, Chen, Lu, & Wang, 2017; Pollatschek, Polus, & Livneh, 2002; Yang et al., 2019). These situations, however, require cooperation since right-of-way is not clearly regulated. In contrast, cooperation is not necessary when right-of-way is clearly defined. Understanding drivers' cooperation behavior at deadlock situations is therefore essential. This is especially important for AVs, as they must also cooperate in such scenarios. To do so, they need to accurately predict the intentions of human drivers.

One approach for automated vehicles in such ambiguous situations could be to simply come to a stop and let the other road users drive first, as this would be the safest course of action. However, this behavior may not always be optimal or accepted. If another road user drives defensively and prefers the cooperation partner, such as the AV, to proceed first, it would result in a standstill. This scenario is undesirable, and the behavior of the autonomous vehicle might be unexpected. In situations where the behavior of other road users cannot be accurately predicted, unsuccessful cooperation may occur, potentially leading to conflict (Svensson & Hydén, 2006). This could decrease the acceptance of AVs by both their users and interaction partners (Deng et al., 2020; Zhang et al., 2021). For successful cooperation, it is crucial that both the manual driver and the AV can anticipate each other's behavior to react accordingly. Therefore, understanding how human drivers behave in deadlock situations is essential.

In previous studies the cooperation behavior of drivers in deadlock situations at equal narrow passages and T-intersections was investigated (Imbsweiler et al., 2017; Imbsweiler et al., 2018). To the best of our knowledge, these are the only studies that have specifically addressed cooperation behavior at deadlock situations. The term 'cooperation behavior' in this context refers to whether drivers choose to proceed as the first of the involved road users or wait to let another driver go first. The results of these studies show that cooperation behavior is influenced by the behavior of the cooperation partners. When the cooperation partners display defensive behavior, such as braking or flashing headlights, drivers tend to resolve deadlock situations by proceeding first. Conversely, when a cooperation partner displays offensive behavior, such as maintaining speed, drivers typically come to a stop and yield to the other vehicle. However, cooperation behavior is influenced not only by the behavior of cooperation partners but also by the complexity of the deadlock situation. In simpler deadlock situations, such as at equally narrow passages, drivers prefer to drive first, whereas in more complex situations, such as at T-intersections, drivers feel more secure when the cooperation partner drives first (Imbsweiler, 2019). Building upon the understanding that the complexity of the deadlock situation influences cooperation behavior, this paper aims to investigate how variations in complexity within the same type of deadlock situation affect drivers' cooperation behavior. To achieve this, the complexity of deadlock situations at T-intersections was varied.

1.1. Complexity of traffic situations

The influence of complexity on drivers and their behavior has been studied across various driving scenarios. However, many studies investigating complexity do not explicitly define the concept of complexity or explain their rationale for its operationalization and classification (for example high and low complexity). Often, they simply state that they manipulated complexity, describing which variables they altered (e.g. Cantin et al., 2009; de Craen et al., 2008; Oviedo-Trespalacios et al., 2017; Rudin-Brown et al., 2014). When studies do provide a rationale for how complexity was manipulated, they frequently reference Fastenmeier (1995) framework. Fastenmeier offers a classification of traffic complexity based on demands placed on information processing and vehicle handling. However, this classification is broad and does not provide a specific definition of complexity itself, leading to varied interpretations and operationalizations across studies. As a result, researchers classify traffic scenarios differently, further contributing to the variability in how complexity is operationalized. For instance, Faure et al. (2016) classify driving in rural environments as having low demands on information processing and high demands on vehicle handling. In contrast, Patten et al. (2006) categorize driving in rural environments as having low demands on both factors. Faure et al. (2016) classify urban driving as having high demands on both dimensions, whereas both Patten et al. (2006) and Jahn et al. (2005) classify driving in urban environments as having low demands on both, with only city center driving classified as having high demands. Furthermore, the classification of traffic situations does not always align with the measured outcomes. Objective workload parameters in Faure et al.'s (2016) study revealed that rural driving was more demanding than urban driving, contradicting the initial classification. This unexpected outcome was attributed to the absence of

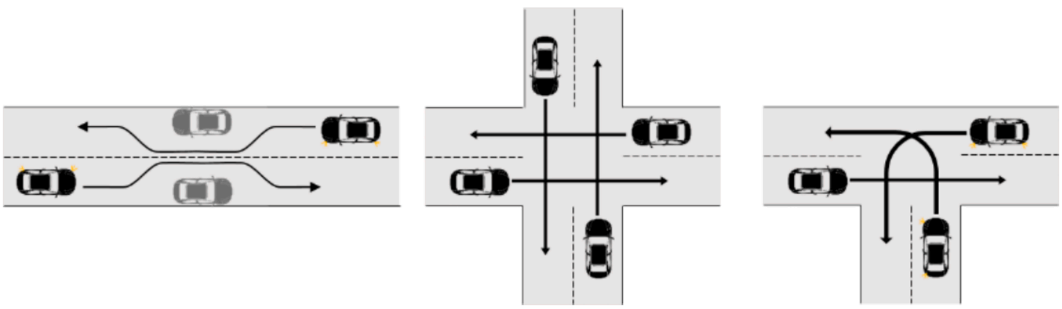


Fig. 1. Deadlock-situations according to German road traffic regulations.

other traffic participants in the urban scenario, which reduced the demands on information processing. However, the findings of Oviedo-Trespalacios et al. (2017) challenge this explanation, demonstrating that urban areas impose higher demands on drivers compared to rural areas, even in the absence of other vehicles. These discrepancies in classification highlight the limitations of Fastenmeier (1995) framework and show that a more detailed description of traffic scenarios and the operationalization of the variables affecting complexity is necessary.

1.2. Task-capability interface model

A more nuanced model capable of describing the relationship between complexity and driving behavior is Fuller (2011) task-capability interface model which explains and predicts driver behavior in various traffic situations. A central concept within this model is task difficulty, which primarily arises from the interaction between (perceived) task demands and driver capability. When capability remains stable, task difficulty can be understood as workload. Capability includes factors such as knowledge of traffic rules, the mental representation and anticipation of the traffic situation, as well as physiological characteristics such as information processing capacity or reaction time. It varies individually and depends on factors such as training, experience, fatigue, or distraction. The task demands can have both information input and response output character. The incoming information of the task demands consist of environmental characteristics, other road users and vehicle characteristics. While driving, drivers constantly make decisions to maintain their perceived difficulty within certain limits. When perceived difficulty exceeds their individual threshold, drivers employ compensatory measures to reduce the difficulty. This is often achieved by reducing the task demands, for example by reducing the speed. Applied to cooperation behavior at deadlock situations, drivers should thus tend to stop when task demands and therefore task difficulty increase (assuming capability remains constant). For our studies, we define complexity as the task demands of the traffic situation (from which perceived task difficulty arises), specifically the environmental characteristics and other road users. This distinction is crucial, especially considering the inconsistencies noted in the previous paragraph, where many studies fail to provide a clear definition of complexity or a theoretical foundation for its operationalization.

1.3. Visual clutter

The environmental factors within the task-capability interface model are not defined in detail. However, these factors play an essential role in describing the complexity of the environment in a deadlock situation. To address this gap, we also incorporated the concept of visual clutter, as proposed by Edquist (2008), to further describe the environment. Visual clutter is closely related to the concept of task difficulty but offers the advantage of distinguishing factors that influence driving behavior in greater detail than Fuller's model. Visual clutter is divided into two broad categories: objects that must be attended to for safe driving, and objects that distract from safe driving. Objects that require attention for safe driving can be further categorized into two subcategories: situational clutter and designed clutter. Situational clutter includes vehicles, cyclists, and pedestrians, and corresponds to Fuller's category of "other vehicles". Designed clutter refers to road markings, traffic signs, and signals, among others. On the other hand, objects that distract from safe driving are categorized as built clutter. Examples for built clutter are billboards, advertising or shops. Background complexity, including buildings and other infrastructure, is also considered part of built clutter. The broad category of environmental characteristics in Fuller's model can thus be further divided using Edquist's taxonomy into designed clutter, built clutter, and background complexity. According to Edquist's taxonomy, it can be further specified for each type of clutter whether the objects obscure other objects.

A substantial body of research has examined the influence of visual clutter on driving behavior and mental workload. These studies have consistently demonstrated that in urban environments characterized by a dense array of buildings, shops, sidewalks, advertisements, parked cars, traffic, pedestrians, etc., drivers experience higher subjective workload measures, reduce their speed, and exhibit slower reaction times compared to suburban or urban environments with minimal visual information (e.g. (Horberry et al., 2006; Oviedo-Trespalacios et al., 2017; Stinchcombe & Gagnon, 2010; Törnros & Bolling, 2006). These studies do not differentiate between situational and built clutter and combine them. However, focusing solely on built clutter reveals similar results. Drivers allocate a substantial portion of their attention to irrelevant objects such as those found on sidewalks, buildings, vegetation, and billboards (Hughes & Cole, 1986). Billboards and roadside advertisements have been shown to negatively affect workload and lateral control, leading drivers to reduce their speed (Meuleners et al., 2020; M. S. Young & Mahfoud, 2007). Furthermore, drivers exhibit lower speeds and report higher subjective ratings of mental workload when navigating streets lined with buildings and shops directly adjacent to the sidewalk, compared to streets where buildings are set further back (Rudin-Brown et al., 2014). Similarly, the same effects are observed in areas where cars are parked at the roadside compared to streets with no parking spaces or empty parking spaces (Edquist et al., 2012). In addition to these distracting objects, other road users (situational clutter) also influence drivers. One factor that is crucial in this regard is traffic density, which increases workload both when driving on highways and at intersections (Bitkina et al., 2019; Loeches De La Fuente et al., 2019; Manawadu et al., 2018; Shakouri et al., 2018; Teh et al., 2014; Xie et al., 2021). Additionally, driving behind a vehicle or overtaking one, leads to increased workload compared to free driving (Cantin et al., 2009; Oviedo-Trespalacios et al., 2017). Pedestrians, as part of the urban environment, also contribute to drivers' workload (e.g. Cantin et al., 2009). However, no studies have been conducted that examine the impact of pedestrians in isolation, apart from other factors.

1.4. Research aims

The complexity of the environment evidently influences the behavior of drivers across various scenarios. However, the impact of complexity on cooperation behavior in deadlock situations has yet to be explored. This research gap will be addressed in this paper by examining a deadlock scenario at a T-intersection. This paper aims to investigate how built clutter and situational clutter affect perceived difficulty and visual clutter as well as cooperation behavior. We expect that deadlock-situations with either situational or built clutter will be perceived as more difficult and visually cluttered, thereby reducing the likelihood of drivers to drive first through the intersection. To assess the independent effects of these clutter components, three separate studies are conducted. In the first study, built clutter was manipulated by objects on the sidewalk and different house facades (the latter contribute to background complexity as part of built clutter in Edquist's (2008) taxonomy). Additionally, in one condition, the objects on the sidewalk obscure the view of the intersection, and thereby the view of other vehicles on the street. This approach was used because, according to Edquist's taxonomy, types of clutter can be further differentiated based on whether they obscure the view of other objects. The second and third study focus on different aspects of situational clutter. As explained earlier, situational clutter consists of dynamic objects that must be attended to for safe driving, including vehicles and pedestrians (Edquist, 2008). Study 2 examines the impact of other vehicles at the intersection and study 3 focuses on the influence of pedestrians. As discussed earlier, traffic density can influence driver behavior. In study 2, traffic density was manipulated by adding vehicles during the approach to the intersection, as well as vehicles following behind the cooperation vehicles. Additionally, a leading vehicle was introduced, as following a vehicle has been shown to impact driver workload (as previously dicussed). In study 3, the number of pedestrians was varied. Pedestrians are considered objects that must be attended to for safe driving, which implies they could interact with the traffic environment, especially if they were to step onto the road. To investigate this, pedestrians were either positioned close to the road or near the building facade. Additionally, a barricade was introduced to separate the pedestrian path from the road, which could potentially reduce the risk of pedestrians stepping into the street.

As the T-intersection allows drivers to approach from three different directions, the effect of the approach position will also be examined. While the approach position is not directly related to the concept of complexity, as defined by either Fuller (2011) or Edquist's (2008) model, it is still relevant for analyzing cooperation behavior for two reasons. Firstly, the time during which drivers can see the other cooperation vehicles varies depending on the approach. When approaching from the left or right, one of the cooperation vehicles is visible throughout the approach, but the vehicle from the intersecting street becomes visible only shortly before reaching the intersection. In contrast, when approaching from below, both cooperation vehicles are visible only shortly before reaching the intersection. Secondly, different priority rules come into play depending on the approach position. Drivers approaching from the left or below must give way to the vehicle to their right, while those approaching from the right must give way to the vehicle whose path they are crossing.

At an intersection, priority rules as well as current and future behavior of the other cooperation partners are crucial for how drivers anticipate and respond to traffic situations (Björklund & Åberg, 2005; Imbsweiler et al., 2018). Therefore, this paper also investigates drivers' expectations regarding the behavior of the other cooperation partners, and how these expectations vary across the three approach positions.

2. Method

2.1. Participants

Three separate studies were conducted to investigate the effects of different aspects of visual clutter on perceived difficulty, perceived visual clutter and cooperation behavior. In study 1 N = 34 participants (13 male, 19 female, 2 did not answer) aged 20 to 60 years ($M = 29.47$, $SD = 10.66$) participated in the study. All subjects held a valid driver's license for an average of 11.76 years ($SD = 10.55$). On average participants drove 7444.85 km per year ($SD = 9687.76$). In study 2 N = 34 participants (22 male, 12 female) aged 18 to 80 ($M = 31.85$, $SD = 15.84$) participated in the study. All subjects held a valid driver's license for an average of 14.26 years ($SD = 15.86$). On average participants drove 7559.62 km per year ($SD = 8842.48$). In study 3 N = 30 participants (15 male, 15 female) aged 22 to 83 ($M = 36.63$, $SD = 17.01$) participated in the study. All subjects held a valid driver's license for an average of 18.67 years ($SD = 16.51$). On average participants drove 6285.13 km per year ($SD = 8138.08$).

Each participant was only allowed to participate in one of the three studies, ensuring that there was no overlap between participants in different studies.

2.2. Procedure and material

The studies were conducted as online surveys using the software LimeSurvey. Participants were instructed to complete the surveys on a laptop or desktop computer, rather than a mobile device. They viewed videos that depicted scenarios at a T-intersection leading to a deadlock situation. The videos were created using the Silab® 6.0 driving simulation software.

Participants observed an approach to a T-intersection, simulating a 50-meter drive from the driver's perspective. An arrow shown at the bottom of the video indicated the direction in which the ego vehicle would navigate at the intersection. The vehicle approached the intersection at a constant speed of 30 km/h and began decelerating at a constant rate 25 m before the intersection, coming to a complete stop at the intersection. The vehicle began braking 25 m before the intersection, as this distance corresponds to the start of the cooperation zone at intersections (Imbsweiler, 2019).

At the same time, a vehicle approached the T-intersection from each of the other two access roads. These vehicles traveled the same distance from the intersection as the ego vehicle, matched its speed, and applied the same braking. According to Imbsweiler et al. (2018) this represents a defensive cooperation behavior. The direction of travel for each vehicle was indicated by the turn signal of the respective vehicle. The video abruptly ended and a black screen was displayed one second before all vehicles came to a stop, leaving the situation unresolved. Each video lasted for 9 s and was shown only once to each participant.

2.3. Dependent variables

After viewing each video, participants answered questions about the scenario. First, participants were asked to rate how likely they thought it was that they would be the first vehicle to cross the intersection. This probability was rated on a scale from zero to 100 %. Participants were then asked to rate the perceived difficulty of the traffic situation and the perceived visual clutter on a scale from one to seven. For both ratings, 1 represented “not difficult at all” and “not visually cluttered at all,” respectively, and 7 represented “very difficult” and “very visually cluttered,” respectively.

Additionally, they were asked about their expectations for the behavior of the other two cooperation vehicles, specifically whether they expected the other vehicle to slow down and stop, or continue driving. In study 3, participants were also asked in which direction the two cooperation vehicles would travel. The findings for this are not reported.

The procedure was consistent across all three studies. The studies differed in the independent variables manipulated in the videos.

2.4. Independent variables

In study 1, the variable visual built clutter was manipulated by two factors. One independent variable was the presence of objects on the sidewalk. There were three conditions of this variable: first, the absence of objects on the sidewalk, second, the presence of objects that did not obstruct the view, and third, the presence of objects that did obstruct the view into the intersection. Additionally, house facades were varied as another independent variable. In one condition, the house facades were identical, while in another condition they were from different houses. Fig. 2 shows example screenshots of two of the videos shown.

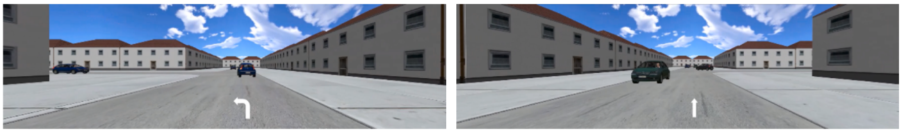
Study 2 focused on the variation in traffic conditions at the intersection. Traffic was manipulated by varying three independent variables. The first independent variable involved the presence of a leading vehicle in front of the participant’s own vehicle (leading vehicle vs. no leading vehicle). This leading vehicle traveled in the same direction as the participant’s vehicle and crossed the intersection just before the arrival of other vehicles from the intersecting streets. The second independent variable considered whether there were other vehicles driving behind the two cooperating vehicles (with vehicles driving behind vs. without vehicles driving behind). The third independent variable addressed whether the participant encountered traffic while approaching the intersection (additional traffic vs. no additional traffic). This traffic, however, did not directly interact with the participant’s vehicle or the cooperating vehicles. In Fig. 3 screenshots of the videos are depicted.

In study 3, the focus shifted to the variation in pedestrian activity at the intersection. One independent variable involved the number of pedestrians present. This variable had three levels: no pedestrians at the intersection, a low number of pedestrians (20 pedestrians), and a high number of pedestrians (80 pedestrians). To our knowledge, no benchmark exists in the literature for pedestrian density in relation to driver behavior. Therefore, the numbers 20 and 80 were chosen based on our subjective assessment of the scenario, with 20 pedestrians representing a low but noticeable presence, and 80 pedestrians representing a more crowded condition. Additionally, the position of the pedestrians was manipulated as another independent variable. Pedestrians walked either close to the road or close to the buildings surrounding the intersection. Furthermore, the presence of a barrier on the sidewalk was varied as an independent variable. This barrier, which consisted of a fence that physically separated the sidewalk from the street, served to prevent pedestrians from crossing onto the street. See Fig. 4 for example screenshots of the videos.

In all three studies, the position of the ego vehicle’s approach to the intersection was also manipulated. The videos were shown from all three possible directions of approach to the intersection: left, right, and below. Each subject saw each possible scenario, resulting in a 3x2x3 within-design with a total of 18 videos for study 1 and a 2x2x2x3 within-design with a total of 24 videos for study 2. In study 3, a 2x2x2x3 design was used. A 3x2x2x3 design might be expected due to the described variables, however, certain factors were limited by the nature of the pedestrian scenarios: in the scenario with no pedestrians, the position of the pedestrians cannot vary, and the presence of a barrier is only meaningful when pedestrians are present. Therefore, the design includes a total of 24 scenarios plus an additional scenario without pedestrians for each approach position, resulting in a total of 27 scenarios. The order of the videos was randomized.


(a) (b)

Fig. 2. (a) Screenshot depicting the ego perspective as the participant’s vehicle approaches a T-intersection from the right side with objects that don’t obstruct the view into the intersection and (b) screenshot depicting the ego perspective as the participant’s vehicle approaches a T-intersection from below with objects that obstruct the view into the intersection. Both screenshots were taken when the participant’s vehicle was approximately 10 m away from the intersection.



(a) (b)

Fig. 3. (a) Screenshot of a scenario depicting the ego perspective as the participant's vehicle approaches a T-intersection from the right side with a lead vehicle driving through the intersection in front of the ego vehicle and (b) screenshot of a scenario depicting the ego perspective with the participants' vehicle approaching from the left with traffic that does not directly interact with the ego vehicle. Both screenshots were taken when the participant's vehicle was approximately 10 m away from the intersection.

(a) (b)

Fig. 4. (a) Screenshot depicting the ego perspective as the participant's vehicle approaches a T-intersection from the left side with many pedestrians walking close to the road and (b) screenshot depicting the ego perspective as the participants' vehicle approaches the T-intersection from below with few pedestrians walking close to the buildings and a barrier. Both screenshots were taken when the participant's vehicle was approximately 10 m away from the intersection.

2.5. Data analysis

To analyze the data the software R 4.3.2 was used with packages rstatix, ordinal, RVAideMemoire, rcompanion, emmeans and PMCMRplus. As the residuals in the regression models for the probability to drive first were not normally distributed, non-parametric tests were performed for this variable.

The values of the variable visual clutter were inverted for clarity. This adjustment was necessary because the study was conducted in German, where the term used for visual clutter (Übersichtlichkeit) has the opposite meaning. To facilitate data interpretation in this paper, the values were reversed.

3. Results

3.1. Difficulty and visual clutter

To assess the effect of the manipulated variables on the perceived difficulty and visual clutter, ordinal regression models were calculated for all three studies. To account the within-design of the studies multilevel models with a random intercept for participants were used. The null-models with the random intercept proved to be significantly better than the null-models without a random intercept for both difficulty and visual clutter in all three studies. This supports the use of random intercept models to account for the within-subject design.

Mean rated values and standard deviation for difficulty and visual clutter for the three approach positions of the ego vehicle to the intersection can be seen in Table 1. The position did not have a significant effect on difficulty ($\chi^2(2) = 0.164$, $p = 0.921$) or visual clutter ($\chi^2(2) = 2.144$, $p = 0.343$) in study 1. In contrast, study 2 showed a significant effect of position for both difficulty ($\chi^2(2) = 8.780$, $p = 0.012$) and visual clutter ($\chi^2(2) = 13.030$, $p = 0.001$). Bonferroni-corrected post-hoc tests show that difficulty was rated significantly higher from below than from the left ($p = 0.001$) and visual clutter was rated significantly higher when approaching from below than from the left ($p = 0.004$) and right ($p = 0.006$). However, pseudo R-squared values indicate very small effect sizes for both difficulty (Nagelkerke's $R^2 = 0.020$) and visual clutter (Nagelkerke's $R^2 = 0.045$). In study 3, approach position had no significant effect on difficulty ($\chi^2(2) = 1.184$, $p = 0.553$), but did have a significant effect on visual clutter ($\chi^2(2) = 13.579$, $p = 0.001$). Approaching from the left was rated significantly less visually cluttered than from the right ($p = 0.009$) or below ($p = 0.002$). The effect size for the approach position on visual clutter was very small (Nagelkerke's $R^2 = 0.034$).

Table 1
Mean values (and standard deviation) for difficulty and visual clutter for the three approach positions to the intersection for all three studies.

	Study 1		Study 2		Study 3	
Approach position	Difficulty	Visual clutter	Difficulty	Visual clutter	Difficulty	Visual clutter
Right	3.42 (1.57)	3.36 (1.48)	3.23 (1.37)	3.27 (1.31)	3.93 (1.45)	3.97 (1.45)
Left	3.45 (1.64)	3.51 (1.60)	3.18 (1.45)	3.28 (1.44)	3.86 (1.53)	3.74 (1.50)
Below	3.45 (1.65)	3.38 (1.52)	3.41 (1.41)	3.50 (1.41)	3.87 (1.46)	3.99 (1.47)

Note. Difficulty and visual clutter were measured on a 7-point-likert scale from 1 to 7.

Objects on the sidewalk did not have a significant effect on difficulty ($\chi^2(2) = 0.605$, $p = 0.739$), but on visual clutter ($\chi^2(2) = 9.714$, $p = 0.008$). Scenarios with objects that obstruct the view into the intersection were rated to be more visually cluttered than scenarios without any objects on the sidewalk ($p = 0.008$). The effect size for this is very small (Nagelkerke's $R^2 = 0.021$). The different house facades did not significantly affect difficulty ($\chi^2(2) = 0.128$, $p = 0.721$) or visual clutter ($\chi^2(2) = 0.169$, $p = 0.681$). Descriptive statistics can be seen in Table 2.

Under different traffic conditions, only the presence of a leading vehicle has an impact on the perceived difficulty and visual clutter (see Table 2). If a vehicle drives through the intersection in front of the ego vehicle, the situation is perceived as significantly more difficult ($\chi^2(1) = 5.909$, $p = 0.015$) and visually cluttered ($\chi^2(1) = 18.229$, $p < 0.001$). Pseudo R-Square values show that these effects are very small (Nagelkerke's $R^2_{\text{difficulty}} = 0.019$, Nagelkerke's $R^2_{\text{visualclutter}} = 0.045$). Other vehicles behind the two cooperating vehicles have no significant effect (difficulty: $\chi^2(1) = 0.340$, $p = 0.560$; visual clutter: $\chi^2(1) = 1.140$, $p = 0.286$). Neither does traffic approaching the intersection (difficulty: $\chi^2(1) = 0.010$, $p = 0.920$; visual clutter: $\chi^2(1) = 2.588$, $p = 0.108$).

Pedestrians walking on the sidewalk and their number did not have a significant effect on perceived difficulty ($\chi^2(2) = 5.229$, p = 0.073), but did have a significant effect on visual clutter ($\chi^2(1) = 13.226$, p = 0.001, Nagelkerke's $R^2 = 0.034$). Scenarios with a lot of pedestrians were rated more cluttered that without pedestrians ($p = 0.003$). However, the position where they walked ($\chi^2(1) = 3.339$, $p = 0.068$) and whether there was a barrier between the sidewalk and the street ($\chi^2(1) = 0.008$, $p = 0.931$) did not affect these ratings. All descriptive statistics for difficulty and visual clutter can be found in Table 2.

3.2. Probability to drive first

Overall, the subjects rated their probability of being the first to cross the intersection as relatively low in all three studies. The average probability was 18.90 % for study 1, 23.64 % for study 2, and 24.05 % for study 3. At the same time, there was a large variance in the answers and the range of the answers was from 0 to 100 % in all three studies ($SD_{\text{study1}} = 30.71$, $SD_{\text{study2}} = 32.77$, $SD_{\text{study3}} = 29.79$). Similar to difficulty and visual clutter, the three studies also showded a slightly different picture regarding the influence of the approach position on the probability to drive first. In study 1, the probability of driving first was highest when approaching from the right ($M = 29.63$, $SD = 36.45$), followed by left ($M = 16.60$, $SD = 27.97$) and below ($M = 10.47$, $SD = 23.14$). As can be seen in Fig. 5, the range as well as the interquartile range are considerably larger for the right approach position than for the left and bottom positions, and there are no outliers. Friedman test results showed a significant effect of approach position on the probability to drive first, $\chi^2(2) = 12.94$, $p = 0.002$. Bonferroni-corrected post-hoc tests revealed that the probability was significantly higher for the approach position right than for the approach position from below ($p = 0.002$).

Study 2 shows a slightly different pattern in some cases. The approach position again had a significant influence on the probability of being the first to drive, $\chi^2(2) = 18.74$, $p < 0.001$. Approaching from below was still associated with the lowest probability ($M = 11.77$, $SD = 25.03$). Post-hoc tests showed that this was significantly lower compared to the right ($p = 0.001$) and left ($p < 0.001$). In contrast to study 1, approaching from the left resulted in a slightly higher probability of driving first ($M = 32.03$, $SD = 35.88$) than approaching from the right ($M = 27.12$, $SD = 33.05$). In addition, the interquartile range is considerably larger and there are no more outliers for the left approach. However, as in study 1, the difference between the left and right approaches is not significant.

In line with study 1, the approach from the right was again associated with the highest probability of being the first to drive in study 3 ($M = 36.84$, $SD = 36.81$). However, the median in study 3 is notably higher than in studies 1 and 2 (see Fig. 5). The approach from below was rated the lowest ($M = 12.19$, $SD = 17.03$), i.e., participants most rarely indicated that they want to be the first to drive through the intersection in this situation. A Friedman test confirmed that the approach position had a significant effect on the probability of being the first to drive, $\chi^2(2) = 14.81$, $p < 0.001$. Post-hoc tests revealed that the approach from below was significantly

Table 2
Mean ratings (and standard deviation) for difficulty and visual clutter for the independet variables in studies 1 to 3.

Independent variable	condition	difficulty	visual clutter
Objects on the sidewalk	no objects	3.45 (1.59)	3.33 (1.57)
	objects that do not obstruct the view	3.40 (1.60)	3.37 (1.50)
	objects that obstruct the view	3.47 (1.67)	3.54 (1.53)
House facades	identical	3.41 (1.59)	3.42 (1.52)
	different	3.47 (1.64)	3.41 (1.55)
Leading vehicle	no	3.18 (1.38)	3.19 (1.33)
	yes	3.37 (1.44)	3.51 (1.43)
Vehicles behind cooperation vehicle	no	3.29 (1.39)	3.38 (1.37)
	yes	3.25 (1.44)	3.32 (1.42)
Oncoming traffic while approaching the intersection	no	3.28 (1.41)	3.29 (1.39)
	yes	3.27 (1.42)	3.40 (1.40)
Number of pedestrians	0	3.82 (1.53)	3.63 (1.50)
	20	3.81 (1.50)	3.81 (1.45)
	80	3.98 (1.44)	4.06 (1.50)
Walking position of pedestrians	house	3.88 (1.43)	3.85 (1.40)
	street	3.90 (1.51)	4.02 (1.55)
Barricade between road and side walk	no	3.95 (1.49)	3.93 (1.47)
	yes	3.83 (1.46)	3.94 (1.49)

Note. Difficulty and visual clutter were measured on a 7-point-likert scale from 1 to 7.

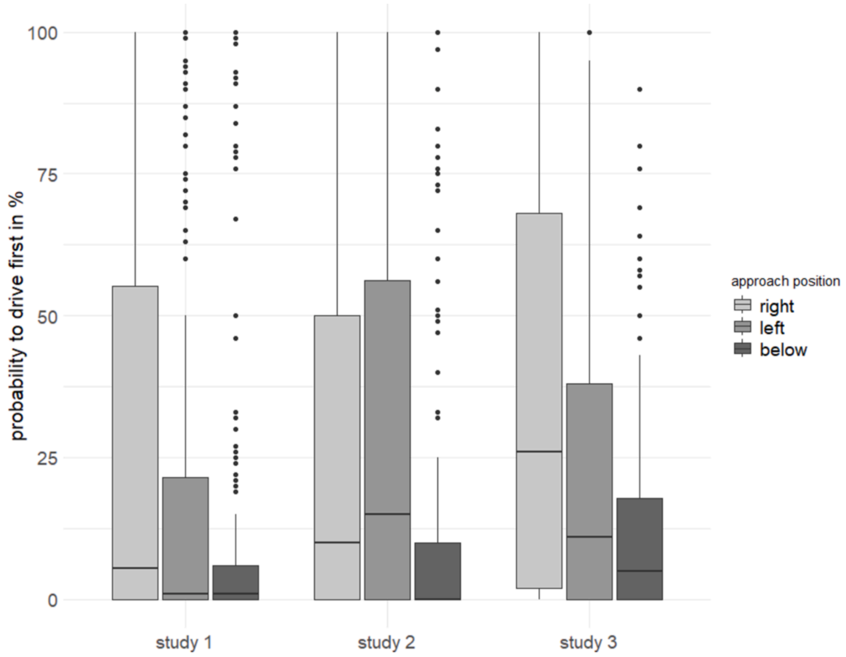


Fig. 5. Boxplot of the probability to drive first in the three studies.

less associated with the intention to be the first to drive compared to both the left ($p = 0.015$) and right ($p < 0.001$) approaches.

The manipulation of the environment did not affect the reported cooperation behavior. Neither the visual built clutter on the sidewalk ($\chi^2(2) = 1.85$, p = 0.397) nor the different building facades ($v = 233.5$, $p = 0.784$) significantly influenced the probability of being the first to drive (see Table 3 for descriptive statistics). While descriptive trends showed slightly higher probabilities of driving first in scenarios with no pedestrians (27 %) compared to situations with few (24 %) or many pedestrians (23 %), these differences were not statistically significant ($\chi^2(2) = 5.96$, $p = 0.051$).

The presence of other vehicles only partially affected the reported cooperation behavior (Table 4). When a vehicle directly in front of the ego-vehicle drove through the intersection, it significantly increased the probability of driving first through the intersection oneself (z = -3.223, $p < 0.001$). However, neither vehicles behind the cooperative vehicles (z = -1.310, p = 0.190) nor traffic approaching the intersection (z = -1.249, p = 0.212) had a significant influence on cooperative behavior.

3.3. Anticipated behavior of the cooperation vehicles

Overall, participants anticipated the cooperation vehicles to stop substantially more often than to proceed. This was the case both when the cooperation vehicle had right-of-way over the participant and when it had to yield to the participant (see Fig. 6 and Table 5). However, participants' expectation that the cooperation vehicle would stop was higher when it had to yield to the participants than when it had the right of way before the participant. Conversely, participants expected the car to drive ahead more often when it had the right-of-way than when it had to yield to the participant. This effect of the influence of right-of-way on anticipated behavior was significant for study 1 ($\chi^2(1) = 32.01, p < 0.001$) and study 2 ($\chi^2(1) = 38.91, p < 0.001$), but not for study 3 ($\chi^2(1) = 0.15, p = 0.701$).

An interesting pattern emerges in the anticipated behavior of the cooperation vehicle based on its approach position and right-of-way rule relative to the participants' perspective. Fig. 7 illustrates the percentage distribution of situations in which participants anticipated the cooperation vehicle to stop in study 1. Firstly, when the cooperation vehicle is approaching from below, the vehicle is expected to stop considerably more often than when approaching from the left and, conversely, from the right. Secondly, when the cooperation vehicle is approaching from the left or below, the right-of-way regulation affects the participants' expectation. For both approach positions (i.e., the cooperation vehicle coming from the left and below), the participants expect the cooperation vehicle to stop significantly more often if it is required to stop relative to the ego vehicle according to the right-of-way regulation than if it has the right-of-way (left: $\chi^2(1) = 16.52, p < 0.001$; below: $\chi^2(1) = 14.67, p < 0.001$). In contrast, the approach position from the right does not

Table 3
Mean probabilty (and standard deviation) to drive first through the intersection in study 1.

Objects on the sidewalk			House facades	
No objects	Non-obstructing objects	Obstructing objects	identical	different
19.46 (31.76)	18.32 (29.96)	18.92 (30.53)	18.93 (30.56)	18.87 (30.91)

Table 4
Mean probabilty (and standard deviation) to drive first through the intersection in study 2.

Leading vehicle		Vehicles behind cooperation vehicles		Oncoming traffic while approaching the intersection	
no	yes	no	yes	no	yes
21.23 (31.32)	26.05 (34.03)	24.26 (32.92)	23.02 (32.65)	24.87 (33.17)	22.41 (32.37)

Fig. 6. Anticipated behavior of the cooperation vehicle in study 1.

Table 5
Percentage of situations where the cooperation vehicle was anticipated to stop or continue driving depending on the right-of-way relative to the ego vehicle for studies 2 and 3.

Anticipated Behavior	Right-of-way of cooperation vehicle	Study 2	Study 3
Vehicle slows down and stops	Has to yield to ego vehicle	76.5 %	78.0 %
	Has right of way	65.7 %	75.3 %
Vehicle continues driving	Has to yield to ego vehicle	23.5 %	22.0 %
	Has right of way	34.3 %	24.7 %

show a significant difference in the expected frequency of the vehicle stopping depending on the right-of-way regulation ($\chi^2(1) = 1.78$, $p = 0.180$).

Study 2 shows a largely identical pattern with a slight deviation (see Fig. 8). In line with the findings of study 1, there are significant differences of how often the cooperation vehicle is expected to stop depending on the right-of-way regulation (from the ego vehicle's perspective) for the approach positions from the left ($\chi^2(1) = 13.39$, $p < 0.001$) and below ($\chi^2(1) = 13.09$, $p < 0.001$). No significant differences were found when the cooperation vehicle approached from the right ($\chi^2(1) = 2.96$, $p = 0.086$). Study 2, though, shows that when the cooperation vehicle approaches from the left, it is anticipated to stop less often than in study 1.

In study 3, a similar pattern to study 1 can be seen again: when the cooperation vehicle approaches from the left, it is more frequently expected to stop compared to when it approaches from the right. However, unlike the previous studies, study 3 shows no significant difference across all three approach directions of the cooperation vehicle regarding whether the cooperating vehicle has to yield or has the right-of-way before the ego vehicle (right: $\chi^2(1) = 0.03$, $p = 0.856$; left: $\chi^2(1) = 1.84$, $p = 0.175$; below: $\chi^2(1) = 2.29$, $p = 0.131$). The percentage of situations where participants expected the vehicle to stop when it must yield to the ego are: 66 % for right, 76 % for left and 93 % for below, and 66 % for right, 70 % for left and 89 % for below when the cooperation vehicle has the right of way.

4. Discussion

The goal of the studies was to investigate the influence of a varying complexity on the cooperation behavior of drivers in deadlock situations at T-intersection. To this end, it was first examined whether changes in the environment and the approach position affect subjective difficulty and visual clutter. Next, it was investigated if these changes in environment and approach position have an effect on the probability that drivers would choose to drive first in deadlock-situations. Finally, it was investigated how drivers anticipated the cooperation vehicles to behave depending on their approach position and right-of-way relative to the ego perspective.

4.1. Difficulty und visual clutter

The results of the influence of the approach position vary slightly between the three studies. Study 1 showed no effect of the approach position on perceived difficulty or perceived visual clutter. Study 2, on the other hand, found that approaching from below was perceived as more difficult and more visually cluttered than the other two approach directions. Study 3, in turn, showed no

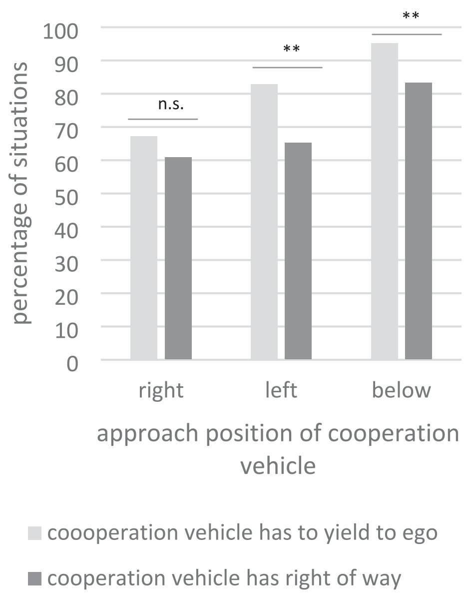


Fig. 7. Percentage of situations where participants anticipated the cooperation vehicle to slow down and stop dependent on the approach position and the right-of-way of the cooperation vehicle relative to the ego vehicle for study 1.

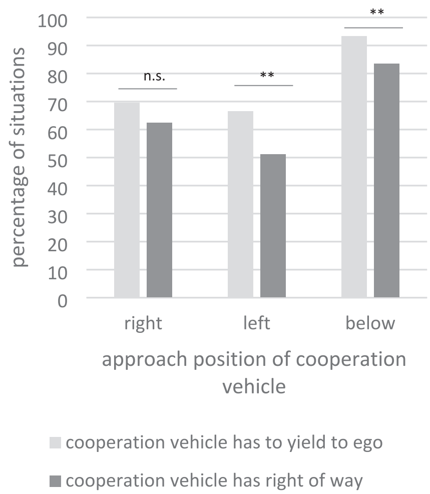


Fig. 8. Percentage of situations where participants anticipated the cooperation vehicle to slow down and stop dependent on the approach position and the right-of-way of the cooperation vehicle relative to the ego vehicle for study 2.

differences in the difficulty ratings of the three approach positions, but approaching from the left was rated as more visually cluttered than the other two approaches. The effect sizes of all effects were very small, which is also evident from the relatively small mean differences. Overall, the approach position does not seem to have a substantial impact on perceived difficulty and visual clutter. However, there is a slight tendency for the approach from below to be perceived as slightly more visually cluttered.

Regarding the changes of the environment, there are only few and minor significant influences on the perceived difficulty and visual clutter. Objects on the sidewalk and variations in building facades did not result in a perceived change in difficulty. The latter also had no impact on visual clutter. However, objects on the sidewalk obstructing the view into the intersection led to a higher perceived visual clutter compared to scenarios with no sidewalk objects. Nevertheless, this effect was relatively small. Interestingly, the presence of objects itself did not influence visual clutter; rather, it was the obstructed view into the intersection that contributed to the altered perception of the situation. This finding contradicts the initially expected hypothesis and other research that found built clutter to increase workload.

However, there are some differences between these studies and the one presented here. Some studies focused on built clutter on highways (Horberry et al., 2006; Meuleners et al., 2020), which might not directly translate to intersection situations in urban areas. While differences in driving parameters indicating higher workload were observed in some studies, subjective workload measures did not differ significantly (Horberry et al., 2006). Additionally, the operationalization of visual clutter differed. Most studies tested environments with very high levels of visual information, combining different aspects of clutter (e.g., buildings, shops, billboards, parked vehicles, and pedestrians) against environments with minimal visual information (e.g., no objects). In the present study, the contrast in conditions may not have been as pronounced as only one aspect of the built clutter was varied, potentially leading to different outcomes.

Furthermore, the findings may not be transferable to a situation as specific as the deadlock scenario at an intersection in an urban setting. Intersections, compared to driving on open roads, pose increased challenges for drivers due to the higher cognitive demands involved (Teasdale et al., 2004). Deadlock-situations at T-intersection, in particular, represent even more demanding scenarios (Imbsweiler et al., 2018). As such, these situations demand high levels of attention from the drivers to ensure that they navigate these situations safely. Intersections are typically visible to drivers well in advance, unlike sudden events such as a child running onto the road. This allows drivers to anticipate the upcoming situation and direct their attention accordingly. When approaching intersections, drivers predominantly focus their attention and fixations on task-relevant areas of interest, namely the road ahead and the intersecting streets (Lemonnier et al., 2015). Attention is directed purposefully toward the intersection, with less or no attention given to irrelevant aspects. The objects on the sidewalk in the present study are not immediately relevant to the driver and the driving task. Although this study did not directly measure attention (e.g., via eye-tracking), it can be reasonably inferred, based on previous research, that while drivers are aware of these objects, they do not need to consciously direct their attention to these objects. This allows full focus on the relevant traffic event, potentially explaining why the presence of objects on the sidewalk did not significantly increase perceived difficulty. Further research using eye-tracking would provide a more precise insight into where drivers' attention is focused on in deadlock-situations.

This explanation aligns with research on built clutter, particularly the impact of billboards on driving situations with high demands. K. L. Young et al. (2017) found that drivers directed attention to billboards when driving demands were low. However, when driving demands were high, requiring drivers to focus on the driving situation, attention to billboards decreases, demonstrating drivers' ability to self-regulate their attention allocation. This finding is consistent with studies examining eye gaze patterns concerning the presence of billboards. S. E. Lee et al. (2007) demonstrated that the percentage of time spent looking at the road did not differ significantly between sections with billboards and sections without billboards or other signs. S. E. Lee et al. (2003) even showed that the eyes-off-road time is higher in the absence of billboards and buildings compared to their presence, suggesting that billboards may improve the visual behavior of drivers.

The findings of this study suggest that drivers in deadlock situations may primarily focus their attention on the intersection, the relevant traffic event. This aligns with the results regarding the effect of pedestrians. Similar to objects on the sidewalk, the presence of pedestrians did not significantly affect perceived difficulty at the deadlock-situations. However, a high number of pedestrians did lead to increased perceived visual clutter compared to no pedestrians. Conversely, a low number of pedestrians did not yield this effect. This suggests that there may be a threshold or minimum number of pedestrians required to affect drivers perception of clutter, which was not met with the presence of 20 pedestrians. That pedestrians are not perceived as immediately relevant to the driving task in these situations is further supported by the result that there is no effect whether pedestrians walk close to the road or if there is a barrier separating the sidewalk from the street. If drivers anticipated pedestrians potentially stepping onto the road and thereby affecting traffic, a barrier or the fact that pedestrians walk close to the buildings (thus far from the road) should reduce this risk and consequently, the perceived difficulty. However, since this was not the case in the present study, it seems that pedestrians in deadlock situations are not considered immediately relevant to the traffic situation. This contradicts the categorization of pedestrians as road users in the models of Fuller (2011) and Edquist (2008). Perhaps this classification needs to be adapted for different situations. For example, Divekar et al. (2012) distinguish between pedestrians as either passive or active hazards. Passive hazards were defined as pedestrians who were clearly visible on the sidewalk and not moving towards the street. Dynamic hazards, in contrast, were defined as pedestrians who suddenly ran out from behind a tree towards the street and then continued walking on the sidewalk. If one were to follow this classification, the pedestrians in the present study would merely be passive hazards and therefore have little influence on drivers. Although Divekar et al. (2012) did not specify the type of pedestrians (e.g., adults or children), it is reasonable to assume that the study predominantly used adult pedestrians, as no mention of children was made. In our study, the pedestrians were predominantly adults. However, children might influence driver behavior, as they may be perceived as dynamic hazards due to their unpredictable behavior. Future research should explore how different types of pedestrians, such as children, impact drivers' behavior at deadlock-situations.

When considering other road users as traffic, it also becomes evident that traffic only has a limited influence on the perception of the situation. Both traffic approaching the intersection before the cooperation vehicles, as well as vehicles following the cooperation vehicles, do not have a significant effect on perceived difficulty or visual clutter compared to situations where only the two cooperation vehicles are present. However, a vehicle that crosses the intersection directly in front of the participant significantly increases the difficulty and visual clutter, although this effect is very small. This lack of effect is surprising, as it was initially assumed that increased traffic, and thus more relevant visual information to process, would lead to a more difficult situation. The specific nature of the situation could again provide an explanation as to why the expected result did not occur. Lemonnier et al. (2015) examined the eye movements of drivers approaching an intersection while varying the traffic density (no traffic, light and heavy traffic). Interestingly, when drivers had to yield at the intersection, no differences were found between the traffic densities in terms of dwell time on the road ahead and intersecting roads, nor in the transitions between these two roads. They explained this result by suggesting that the relevant information at an intersection lies in the two intersecting roads. Drivers need to look for a gap between incoming vehicles that they can merge into. Finding this gap requires the same frequency of information sampling, regardless of the amount of other traffic present. Even if no other vehicles are visible, the intersecting roads must still be monitored to ensure that no additional vehicles are approaching. The same might apply to the participants in the present study. To correctly understand the deadlock-situation, both intersecting roads need to be carefully observed, regardless of whether other vehicles are on the road in addition to the cooperating vehicles or not.

4.2. Probability to drive first

Overall, there was a relatively low probability that participants would choose to be the first to drive through the intersection across all three studies, with rates between 19 % and 24 %. Initially, it was expected that increased complexity of the traffic situation, due to more built clutter and additional road users, would increase the perceived difficulty of the situation. According to Fuller's (2011) model, an increase in difficulty should then lead drivers to take compensatory measures, such as being more likely to stop at the intersection. However, since no significant changes in perceived difficulty were found for built clutter and other road users (except for the vehicle driving in front of the participant), the first part of the hypothesis (increased complexity due to more built clutter and road users increases the perceived difficulty of the situation) must be rejected. In line with Fuller's model however, elements that did not impact perceived difficulty also did not influence reported driving behavior. Objects on the sidewalk, pedestrians, and additional traffic in front of or behind the cooperating vehicles did not affect the likelihood of participants indicating they would be the first to drive through the intersection. Interestingly, when a vehicle crossed the intersection directly in front of the participant, it significantly increased the likelihood for participants to drive first even though this situation was perceived as more difficult. Contrary to Fuller's model, a more difficult situation in this setting leads to more offensive behavior. One possible explanation for this behavior is that participants may not correctly recognize or understand the right-of-way rules in a deadlock situation, leading to uncertainty about which vehicle should proceed first. This uncertainty may cause to drivers to simply follow the car in front of them. When people encounter ambiguous conditions or problems, they tend to follow the cues of others. This phenomenon, a form of rational conformity known as abidance in social behavior studies (Song et al., 2012), may also apply to drivers in deadlock situations. A closely related phenomenon in Germany is the Mitzieheffekt, which can be roughly translated into English as the pull-along effect. It refers to the tendency of drivers to be influenced by the behavior of other drivers, even when it deviates from their original intentions. For instance, drivers may follow a different route than planned simply because they observe others doing the same, or they may drive faster in foggy conditions, aligning their speed with that of the cars ahead (Debus et al., 2005; Wermuth and Wulff, 2008). The effect is even acknowledged in traffic law: for example, it can mitigate penalties if a driver inadvertently runs a red light, believing that they have the right of way because vehicles in an adjacent lane have a green light and begin moving (Krumm, 2011).

The uncertainty in understanding the right-of-way rules can be inferred from the reported behavior depending on the direction of approach. In all three studies, the approach position from below showed the lowest probabilities of being the first to drive through the intersection. As with the other independent variables, Fuller's model does not fit its assumption here, as only one of the three studies indicated that the approach from below was also the most difficult or visually cluttered. In the other studies, there was no significant difference, or the bottom approach was not rated as the most difficult. The lower probability of being the first to drive from the approach from below might be due to a misinterpretation of the deadlock situation, with participants possibly assuming they do not have the right of way from this position. In this case, the straight-through road would be perceived as the main road with the right of way. This main road effect was described by Björklund and Åberg (2005), though it referred to intersection situations without a deadlock. If we apply the main road effect to the deadlock situations in the present studies, the vehicle approaching from the left would have the right of way, and therefore, the probability to drive first should be the highest at this position. However, this is not consistently reflected in the data. In study 2, descriptively, the highest probability of being the first to drive is indeed reported for the left approach. In studies 1 and 3 though, the probability of being the first to drive is higher for the approach from the right, which contradicts the right-of-way rules if we assume a main road effect. Overall, it appears that participants do not have an accurate understanding of the right-of way rules at deadlock-situations at T-intersection. This becomes also apparent when examining the anticipated behavior of the two cooperating vehicles based on their positions.

4.3. Anticipated behavior of the cooperation vehicles

Participants were asked to indicate whether they anticipated the cooperating vehicles to stop or continue driving after each video. In every video, both vehicles actually decelerated and would come to a complete stop one second after the video was cut off. Overall, participants significantly more often anticipated the vehicles to stop rather than continue driving.

However, there were differences in these expectations based on whether the cooperation vehicle had the right-of-way or had to yield to the participant. When the cooperating vehicle had to yield to the participant, it was significantly more likely that participants expected the vehicle to stop compared to when it had the right-of-way before the participant. Conversely, participants more often expected the cooperation vehicle to continue driving when it had the right-of-way. Thus, the right-of-way rule from the participant's perspective influenced how the behavior of the cooperating vehicles was anticipated. Notably, only the right-of-way rule from the ego perspective was considered—meaning, who had the right-of-way relative to the participant. The right-of-way rule between the two cooperating vehicles was not taken into account; if it had been, participants would have recognized the deadlock situation at the intersection. Examining the expectations based on the right-of-way rule for the three different approach positions of the cooperation vehicle, differences were only observed for approaches from the left and bottom. When the cooperating vehicle approached from the right, there were no differences in expected behavior regardless of whether the vehicle had the right-of-way or had to yield to the participant. This suggests that the right approach position is more commonly perceived as the one with the right-of-way, regardless of the participant's position.

The approach position of the cooperating vehicles itself also influenced the anticipated behavior. When the cooperation vehicle approached from the bottom, participants most often expected it to stop, considerably more than when the vehicle approached from the left or right. This expected behavior aligns with the behavior participants would display themselves. Participants would stop when approaching from below, and they expect the same from other vehicles approaching from below. However, differences emerged when looking at the other two approach directions across the studies. In studies 1 and 3, participants more frequently expected the cooperating vehicle to stop when it was approaching from the left than from the right, whereas in study 2, the opposite was true. These different expectations, though, were consistent with the participants' own behavior. In studies 1 and 3, participants were less likely to drive first when approaching from the left compared to the right, and they expected the same behavior from the cooperating vehicle. In study 2, participants were less likely to drive first when approaching from the right compared to the left, and they expected other vehicles to stop more when approaching from the right. Overall, therefore, the behavior shown in all cases is that which is also expected of the other cooperation partners.

The expectation that the vehicle from the right would continue driving, and the higher likelihood that participants would drive first themselves when approaching from the right, supports the conclusion that the right approach position is perceived as having the right-of-way. However, in study 2, the left approach position seems to be perceived as having the right-of-way, leading to no clear consensus across the studies on how right-of-way at the intersection is understood. It can be concluded that the participants did not demonstrate a consistent or accurate understanding of the right-of-way rules, nor did they accurately identify the deadlock situation.

Further research is therefore required to explore drivers' understanding of deadlock situations in greater depth. This could be explained by two factors. First, participants may recognize only one of the two traffic rules that apply in such scenarios (the right-before-left rule and the rule to yield when crossing the path of an oncoming vehicle) or fail to consider that both rules are equally valid in the situation. Second, misinterpretations of the intended travel directions of the cooperating vehicles may play a role. For instance, if one vehicle is assumed to be turning rather than driving straight (or vice versa), the situation is no longer a deadlock, and the right of way becomes clearly regulated. To what extent the intended driving directions were accurately recognized, or the right-of-way rules were incorrectly applied, and how these differing perceptions of right-of-way in deadlock situations may influence behavior should be investigated in future studies.

5. Limitations

While these studies offer valuable insight in the perceived difficulty of deadlock-situations and the cooperation behavior, it is important to acknowledge certain limitations that may influence the interpretation of the findings.

The primary limitation lies in the use of videos to represent real-world traffic scenarios. While this approach offers the advantage of standardized stimuli, ensuring that all participants experience identical situations, it also introduces potential biases that could affect the perceived difficulty and visual clutter assessments. According to Fuller's (2011) model, both the traffic situation and the driver's own behavior contribute to the task difficulty. In this study, the likelihood that participants would drive first was relatively low, thus potentially influencing the perceived difficulty: When a driver decides to yield, the situation may become less difficult, regardless of the surrounding environment. The use of video simulations might also have an influence in how situations involving pedestrians are perceived. Participants might not fully anticipate pedestrian to walk onto the road in a simulated environment, leading to an underestimation of their potential risk and a reduced influence on the difficulty assessment. Furthermore, the hypothetical nature of the task, where participants indicate their intended behavior rather than actually driving, introduces a cognitive element that may not fully reflect real-world decision-making. Participants have time to contemplate their responses and are not subject to the same level of risk and consequences as in actual driving situations.

Despite these limitations, the findings of the studies can be considered transferable to real-world traffic scenarios. Research has demonstrated that video-based studies can produce results comparable to those obtained in real-world settings. For instance, Y. M. Lee and Sheppard (2016) found that participants could accurately assess the intentions of vehicles at intersections when presented with videos or even only static images. Similarly, Imbsweiler (2019) conducted a study where participants where shown videos of approaches to a deadlock-situation at T-intersections and participants had to indicate what behavior they would show and answer several questions regarding this situation. These videos were recorded in a previous study where participants drove with a real vehicle through these scenarios and answered the same questions. The results showed a high degree of consistency between the patterns of responses in the both studies, suggesting that video stimuli can effectively be used to investigate deadlock situations. Nonetheless, further studies should examine driving behavior, for example, in driving simulators during deadlock situations to gain a more comprehensive understanding of cooperation behavior in these situations.

6. Conclusion

This paper aimed to gain a deeper understanding of drivers' cooperation behavior in deadlock situations within inner-city traffic. This knowledge is crucial for the development of automated vehicles so that they can (1) show cooperation behavior similar to human drivers and (2) better predict the intentions of manual drivers, ensuring that both passenger and manual drivers accept the automated vehicles' behavior.

Complexity only partially influences cooperation behavior in deadlock situations. The environmental characteristics (objects on the sidewalk and building facades), as well as most other investigated road users (pedestrians, vehicles behind the cooperation vehicles, and additional traffic approaching the intersection), had no effect on the reported cooperation behavior. However, a leading vehicle had a significant impact on cooperation behavior. When a leading vehicle drove in front of the ego vehicle, participants were significantly more likely to report driving first compared to when no leading vehicle was present. The approach position also had a significant effect. When approaching from below, participants reported a significantly lower probability of driving first compared to the other approach positions. An AV should therefore consider the presence of a leading vehicle and the approach direction to the intersection. However, the other aspects of complexity explored in this study do not need to be taken into account.

Complexity also only partially influences perceived difficulty and visual clutter in deadlock situations. The environmental characteristics and other road users that had no effect on cooperation behavior also had no effect on perceived difficulty or visual clutter in these situations. However, a leading vehicle increased the perceived difficulty of the situation. For the approach position, there were inconsistent results across the studies. In two of the three studies, no difference was found in perceived difficulty depending on the approach position. In one study, however, the approach from below was perceived as more difficult.

No consistent pattern could be observed when examining the relationship between cooperation behavior and perceived difficulty. For the leading vehicle, higher perceived difficulty was associated with a higher probability of driving first. In contrast, for the approach position from below, higher perceived difficulty was associated with a lower probability of driving first in one study. For factors that had no influence on perceived difficulty, cooperation behavior also showed inconsistent patterns: in some cases, no change in behavior (e.g., for objects on the sidewalk), while in others, a lower probability of driving first (e.g., the approach position below from the other two studies). These inconsistent patterns suggest that perceived difficulty alone may not be sufficient to predict driving behavior in deadlock situations. A possible reason for this could be the incorrect understanding and different interpretations of deadlock situations.

Overall, participants exhibited relatively low probabilities of being the first to drive through the intersection. This suggests that an AV could adopt defensive behavior, such as stopping, to replicate human behavior. Defensive behavior may be particularly appropriate in scenarios where another vehicle passes through the intersection ahead of one of the two cooperation vehicles. In such cases, the AV can reasonably assume that the cooperation vehicle will follow the preceding vehicle and drive first, making stopping a suitable strategy.

However, the relatively low probabilities reported by participants for being the first to cross the intersection do not imply that an AV should always stop. This becomes evident when considering drivers' behavior and the anticipated behavior of the cooperation vehicles based on the approach position. Participants approaching from below displayed a preference to stop rather than proceed through the intersection. The cooperation vehicle approaching from below was also anticipated to stop. This expectation was observed among participants approaching from both the left and the right. Notably, participants approaching from the right anticipated the cooperation vehicle to stop even more frequently, given that the vehicle from below must yield to them. Therefore, an AV approaching the intersection from below should stop and allow one of the other two vehicles to drive first. Even when the vehicle on the right slows down and stops, theoretically giving the AV an opportunity to proceed, stopping remains consistent with drivers' expectations in this scenario.

In contrast, when the AV approaches from the left or right, driving first may be a more appropriate action than stopping. In such cases, the AV can reasonably assume that the vehicle from below will stop. In a deadlock situation, one vehicle must eventually drive first to prevent a standstill. This leaves the vehicles on the left or right to resolve the situation. Participants approaching from the left or right indicated significantly higher probabilities of driving first compared to those approaching from below. Furthermore, the anticipated behavior of the cooperation vehicles suggests that vehicles from the left or right are expected to drive first and thereby resolve the deadlock situation. However, the difference between left and right approaches could not be conclusively determined due to differing results across the studies. In two of the three studies, the approach position from the right seems to be the position where drivers would drive first and also expect others to do the same. In one study, however, this pattern was observed for the approach from the left. These differences may stem from misunderstandings of the right-of-way rules or a failure to recognize the deadlock situation. Some drivers appear to mistakenly assume that vehicles from the left or right have the right-of-way, as suggested by the findings. An AV must therefore anticipate that drivers approaching from the left or right may perceive themselves as having the right-of-way and act accordingly. Intention prediction methods, such as those described in Weinreuter et al. (2022) can be employed to predict whether the cooperation vehicle actually shows offensive behavior and might attempt to drive first. However, the likelihood of a manual driver approaching from the left or right actually driving first is relatively low. Therefore, an AV should attempt to drive first through the intersection if it is approaching from the left or right (and intention prediction indicates that the opposing vehicle slows down and stops). This behavior aligns with most drivers' expectations for vehicles approaching from these two approach positions and offers a viable strategy to prevent standstills in deadlock situations.

These insights in cooperation behavior at deadlock-situations can be used to enhance the intention prediction of manual drivers at intersections. Additionally, they can provide recommendations on behavior for autonomous vehicles, ensuring they exhibit cooperation behavior in deadlock situations that satisfies all involved road users.

CRediT authorship contribution statement

Nadine-Rebecca Strelau: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Barbara Deml:** Writing – review & editing, Supervision, Conceptualization.

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.

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Data availability

The authors do not have permission to share data.

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