Analysis of intersection accidents - An accident causation and prevention perspective

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Abstract

Analyses of intersection accidents have shown that in most cases drivers failed to notice other traffic participants who had the right of way at that time. In-depth surveys have found that improper attention allocation by drivers could be among the main reasons for this kind of driver error. As this cannot be examined in accident situations easily, the aim of a first study was to better understand drivers' attention allocation and driving behaviour in different intersection situations. Therefore, a T-intersection was varied by two environmental characteristics. In a next step, this required knowledge was used to develop effective visual warning signals which support drivers in their actions. This was aim of a second study. Results of the studies indicate that depending on the intersection situation drivers systematically adapted their attention allocation and driving behaviour which can lead to an accident. Warning signals which were already presented to drivers when approaching a critical intersection were most useful to avoid a collision. The results of the studies contribute to a better understanding of the psychological processes leading to driver errors at intersections. This can be used to derive requirements for warning strategies to effectively support drivers in these kinds of intersection situations.

Introduction

Numerous accident studies have shown that over 36% of all severe accidents happen at intersections (for Germany, e.g., Vollrath et al., 2006). In most of these cases, drivers failed to notice other traffic participants, e.g. crossing vehicles, cyclists, and pedestrians, who had the right of way at that time. In-depth surveys of bicycle–car accidents (e.g., Räsänen & Summala, 1998) have shown that the cause of these accidents could be attributed to drivers not looking in the appropriate direction of the other party ("failed to look"). Furthermore, Räsänen and Summala (1998) conclude that these improper visual scanning patterns by drivers could be described in terms of unjustified expectations for hazards in these situations.

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One typical situation is when drivers want to turn right at an unsignalized T-intersection and have to yield to oncoming cars on the main road (Räsänen & Summala, 1998). Here, drivers often report that they failed to notice a cyclist on a two-way cycle track on their right-hand side who has the intention of crossing the road, by focusing their attention mainly on the road to their left-hand side where they expected potential hazards (oncoming cars with the right of way). The two-way cycle track is barely attended by them. It indicates that drivers tend to allocate their attention only to certain areas of the intersection which are task-relevant for their current driving manoeuvre. Hence, other areas of the intersection are barely attended by them whereby other traffic participants are difficult to notice.

Due to the fact that most of these in-depth analyses (e.g., Räsänen & Summala, 1998) are done post hoc, a direct observation of drivers' attention allocation was not possible. Consequently, research is needed to examine the psychological processes of drivers' attention allocation and their driving behaviour when driving at different intersections with critical incidents, and thus to establish their role in the causation of intersection accidents. As a next step, this input can be used to specify drivers' needs with regards to collision avoidance systems which warn drivers about potential critical incidents at intersections.

From an accident causation and prevention perspective, two key research questions have been identified: (1.) What causes accidents in which other traffic participants with the right of way are neglected by drivers? When this is understood, requirements for effective countermeasures (e.g., collision warning systems) can be derived to reduce the occurrence of accidents. Thus, research question (2.) was how can drivers be adequately warned when driving in a critical intersection situation and which warning strategy is most effective.

To investigate these two research questions, two driving simulator studies were conducted. The aim of study I was to examine how drivers' attention allocation and their driving behaviour depend on different environmental characteristics (e.g., traffic density) in a T-intersection situation, and how this influences the occurrence of (simulated) accidents using a critical incident presented near the intersections. This provided the input for study II. The aim of study II was to derive concepts for effective visual warning signals in cars, which influence drivers' attention allocation and their driving behaviour in a way which leads to a better control of the critical situation. In the following, the method and results of the two driving simulator studies are described.

Study I: Drivers' attention allocation and driving behaviour at intersections

Aim and method

In order to investigate drivers' attention allocation and their driving behaviour at intersections, a give-way T-intersection was used where drivers had to yield to oncoming cars from the left-hand side of the intersection. The main driving task was to turn right. This intersection situation was varied using two environmental factors: (1.) traffic density of oncoming cars from the left (low and high density) and (2.) number of high task-relevant information sources (in addition to the oncoming cars from the left, *with* or *without* pedestrians on the right; 1 and 2 important areas). In Fig. 1, the four intersection situations are shown. As Fig. 1 shows, there were intersection situations in which drivers' attention was attracted to two important areas of the intersection before making a right turn: oncoming cars from the left-hand side and pedestrians with a pedestrian crossing on the right-hand side (2 important areas; Fig. 1 intersection 3 and 4). In other intersection situations, there were only the oncoming cars from the left-hand side and driving straight (1 important area; Fig. 1 intersection 1 and 2).

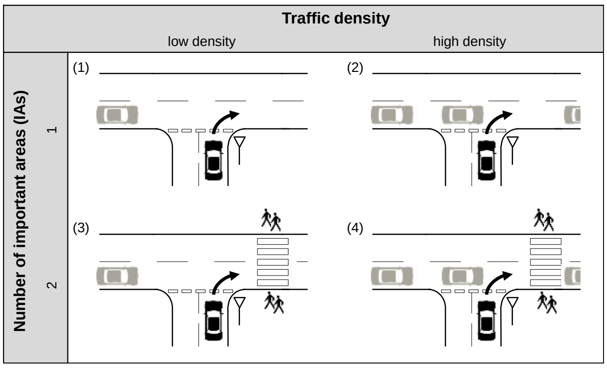

Fig. 1: The four T-intersection situations with a variation of traffic density of oncoming cars from the left and number of important areas (IAs)

Additionally, it was examined how well drivers could recognize and react to critical incidents in these four intersection situations (Fig. 1) which occurred shortly after drivers had entered the intersection. In the study, two critical incidents were introduced: either a ball bounced across the road from the right to the left sidewalk or a vehicle that had parked at the right-hand side of the road suddenly left the parking space and entered the road (Werneke & Vollrath, 2012). The two critical incidents were presented to each driver in one of the four intersection situations.

In total, two driving scenarios consisting of a number of urban segments were driven by the participants. Here, one urban segment comprised the four intersection situations (Fig. 1) and was driven five times so that the participants got to know these situations quite well. At the end of each driving scenario one of the two critical incidents occurred at the last of the four intersection situations. The order of the two driving scenarios with one of the two critical incidents at the end was randomized between the participants. Overall, forty drivers (26 men, 14 women) participated in the study and they ranged in age from 19 to 55 years (M = 31.0 years, SD = 11.9 years).

Drivers' gaze and driving behaviour were analysed. In particular, the number of drivers' gazes towards the right-hand side while approaching the intersection was examined. With regard to drivers' reactions to the critical incidents, velocity while turning right and collision frequency in the four intersection situations were computed. For more detailed information about the entire analysis and results of the study, see Werneke and Vollrath (2012).

Results

Analyses of the collision frequency showed that the first critical incident (the entering vehicle or bouncing ball in the first driving scenario) was so unexpected and difficult for drivers that no clear effects of the influencing factors could be found. In the first driving scenario, only four drivers could avoid a collision ($Chi^2_{(3)}$ = 2.2, p = .528). Thus, results of drivers' gaze and their driving behaviour only in the second driving scenario are presented here.

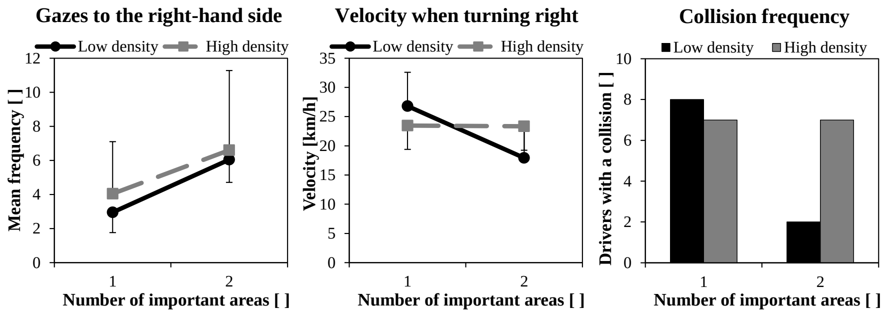

Fig. 2: Mean and standard deviation of (left) frequency of drivers' gazes to the right-hand side and (middle) velocity when turning right as well as (right) collision frequency at the four intersections in the second driving scenario

There was a significant main effect of the number of important areas (IAs) on drivers' gaze behaviour to the right-hand side ($F_{(1, 36)}$ = 9.3, p = .004). Neither the effect of traffic density nor the interaction between traffic density and number of IAs was significant (traffic density: $F_{(1, 36)}$ = 0.8, p = .379; interaction: $F_{(1, 36)}$ = 0.1, p = .768). In Fig. 2 (left) the main effect of drivers' gazes to the right-hand side is shown. As Fig. 2 (left) shows, at intersections with pedestrians on the right-hand side (2 IAs), drivers made clearly more gazes to that side, as compared to the intersection situations when there were no pedestrians present (1 IA). On average 6.3 gazes (SD = 3.4 gazes) to the right-hand side were made by drivers, as compared to 3.5 gazes (SD = 2.3 gazes) at intersections with only one important are (1 IA).

For the velocity when turning right (Fig. 2 middle), there was a significant interaction of both factors ($F_{(1, 36)} = 7.3$, $p = .010$) and an effect of the number of IAs ($F_{(1, 36)} = 7.7$, $p = .009$). The effect of traffic density was not significant ($F_{(1, 36)} = 0.4$, $p = .524$). As Fig. 2 (middle) shows, drivers reduced their velocity only at intersections with a low traffic density of oncoming cars from the left and with pedestrians on the right (M = 17.9 km/h, SD = 6.1 km/h).

Fig. 2 (right) shows the collision frequencies in the second driving scenario (combined for the two critical incidents). There was a significant difference between the four intersection situations ($Chi^2_{(3)} = 9.2$, $p = .027$). This effect was mainly due to the intersection with pedestrians on the right-hand side (2 IAs) and low traffic density of oncoming cars from the left. Here, 80 % of the drivers (n = 8 out of 10) could avoid a collision. At all other intersections, accident rates were quite high.

Overall, the results of study I confirmed that the two environmental factors had clear effects on drivers' attention allocation and their driving behaviour when entering the intersections. This played a major role in their recognition of critical incidents in these situations and their reaction to them. When the traffic density was low and there were two areas of interest, drivers shifted their attention more to the right, started more slowly when entering the intersection and were then able to avoid a collision. When the traffic density of oncoming cars from the left was high and there were two areas of interest, drivers also shifted their attention to the right but started clearly faster, probably in order to prevent crashes with oncoming cars from the left. Then, they were not able to avoid a collision. Similarly, when there was only one area of interest (only oncoming cars from the left in high traffic density condition), drivers focused their attention mainly to the left, started faster, and were then not able to avoid a collision.

How can these results be used to design warning systems to prevent these kinds of accidents? One approach could be to support drivers to shift their attention to the critical areas. This could lead to a more cautious driving behaviour and could be useful to prevent these kinds of accidents. Accordingly, the aim of study II was to compare different warning strategies of collision warning systems to influence drivers' attention allocation and their driving behaviour. This is described in the next section.

Study II: Warning strategies at intersections

Aim and method

In study II, two approaches to influence drivers' attention allocation were investigated: (1.) using top-down processes to change drivers' expectations about the current driving situation and (2.) using bottom-up processes to automatically redirect drivers' attention towards salient stimuli. Thus, the two warning strategies varied in their timing: The former warning strategy (top-down) presented a warning signal when drivers were approaching the critical intersection so that they could shift their attention to the appropriate intersection area (early warning). The latter warning strategy (bottom-up) presented a warning signal directly before the critical incident (late warning). Here, two different design concepts of the late warning signal were examined (Fig. 3).

For this comparison, one intersection situation with the highest collision frequency from the first driving simulator study (see study I) was used. This was the situation with low traffic density of oncoming cars from the left and no pedestrians on the right (Fig. 1, intersection 1). The critical incident at the intersection was similar to study I: A car parked on the right-hand side of the road, suddenly pulled out from the parking space and entered the road. In Fig. 3, the three warning signals are shown. All were presented in the middle of a simulated head-up display (HUD) or sidewise as an augmented reality.

Fig. 3: The three warning signals examined in study II: (left) early warning signal presented in the middle of a HUD; (middle) late warning signal presented in the middle of a HUD; (right) late warning signal presented sidewise in augmented reality.

The early-middle warning signal (Fig. 3 left) was presented to drivers as they approached the critical intersection situation, approximately 70 m before the intersection. The warning signal presented a view of the approaching intersection construction where a flashing orange warning circle signalized danger at the right-hand side of the intersection.

The two late warning signals (Fig. 3 middle and right) were given directly before the critical incident. In the late-middle warning, a view of the road was presented to drivers and a flashing orange warning circle showed the danger at the right-hand side of the road. The late-sidewise warning signal was presented directly at the spot where the critical incident occurred. The idea of the late-middle warning was that it should be easy to see by drivers as the signal was in the focus of drivers' view. The idea of the late-sidewise warning signal was to attract and direct drivers' attention directly to the critical incident.

Four experimental groups (control group without a warning signal, group with the early-middle, late-middle, and late-sidewise warning signal) were used. A total of 48 subjects (32 men, 16 women) participated in the study with an average age of 27.3 years (SD = 7.4 years). They were randomized to the four groups.

Each participant drove one driving scenario which was similar to the driving scenario from study I. The scenario consisted of seven urban segments composed of the four T-intersection situations (Fig. 1) and took 45 till 50 minutes. The critical incident occurred two times in this driving scenario. This was done to examine if drivers would adapt their gaze and driving behaviour over time. This was clearly the case as in the second critical incident, all except one driver (n = 47) could avoid a collision. Thus, in order to compare the effects of the different warning signals, further analyses were only done for the first time a critical incident occurred.

Minimal distance to the entering car was analysed. In order to better understand the effect of the different warning signals, drivers' gaze (e.g., percentaged glance proportion) and their driving behaviour (e.g., velocity when turning right) were examined in three intersection epochs: Approaching, Waiting, and Accelerating. The paper presented here focuses only on the percentaged drivers' glances to the right- and left-hand side during waiting and accelerating at the critical intersection as well as their velocity when turning right. More detailed information on the experimental design, method, and analysis of study II is given in Werneke and Vollrath (submitted).

Results

In order to examine differences between the warning signals, it has to be mentioned that when approaching and waiting at the intersection, only the group with the early-middle warning received a warning signal, and thus differed from the other three groups which were combined (no signal, late-middle, and late-sidewise). With regard to drivers' glances to the right-hand side of the intersection, the analysis showed a significant main effect of the group factor ($F_{(1, 46)} = 12.1$, $p = .001$). With regard to drivers' glances to the left-hand side no significant effect was found ($F_{(1, 46)} = 2.6$, $p = .116$). Fig. 4 (left) shows the percentaged drivers' glance proportion to the right-hand side while waiting and accelerating at the critical intersection.

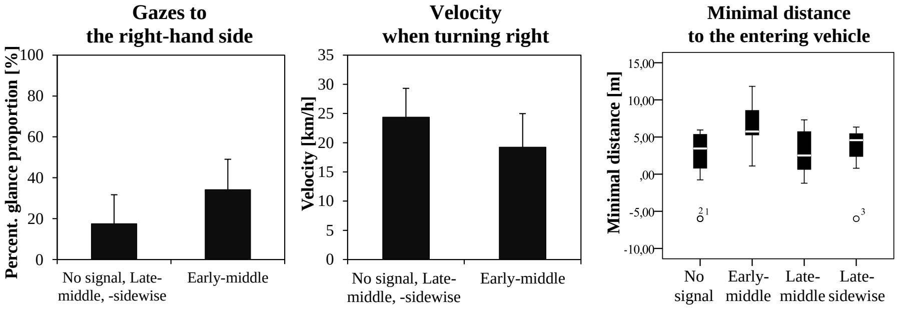

Fig. 4: Mean and standard deviation of (left) drivers' glances to the right-hand side of the intersection while waiting and accelerating at the intersection; (middle) velocity when turning at the intersection; (right) Box plot of the minimal distance to the entering vehicle.

As Fig. 4 (left) shows, when driving with the early-middle warning signal on average a higher proportion of drivers' glances to the right-hand side (M = 34.2 %, SD = 14.9 %) was found, as compared to the group with any signal in that time (no signal, group with the late-middle and late-sidewise warning signal; M = 17.5 %, SD = 14.2 %). Additionally, drivers with the early-middle warning signal did not differ in the percentage of their glances to the left-hand side of the intersection (in total: M = 28.7 %, SD = 15.7 %).

With regard to drivers' mean velocity when turning right (Fig. 4 middle), the analysis showed a significant main effect of the group factor ($F_{(1, 46)} = 9.0$, $p = .004$). Here, drivers with the early-middle warning signal were much slower (M = 19.2 km/h, SD = 5.8 km/h), as compared to the other group (M = 24.4 km/h, SD = 4.9 km/h).

In the analysis with regard to the minimal distance to the entering vehicle, all four groups were compared. There was a significant main effect of the group factor ($F_{(3, 44)} = 3.7$, $p = .018$). Fig. 4 (right) shows the drivers' minimal distances to the entering vehicle. In the group with the early-middle warning signal the largest minimal distance was found (pairwise comparison to the control group: p = .003; to the group with the late-middle warning signal: p = .017; to the group with the late-sidewise warning signal: p = .031). On average, drivers with the early-middle warning stopped 6.5 m (SD = 2.8 m) before the entering vehicle. Drivers with the later warnings had a mean minimal distance of approximately 3.2 m (SD = 3.2 m) and the control group approximately 2.1 m (SD = 4.2 m).

Discussion and conclusion

The aim of the two studies presented here was to better understand drivers' attention allocation and their driving behaviour when driving at different T-intersections, varied in two environmental factors, both in the role of accident causation (study I) and prevention (study II).

Results of study I showed that the two environmental factors had clear effects on drivers' attention allocation and their driving behaviour. With the presence of another important information source in the situation (e.g., pedestrians on the right), drivers directed their attention more towards that intersection side, as compared to intersections with no pedestrians and pedestrian crossing on that side. It indicates that drivers adapt their gaze behaviour in accordance with the situational requirements to gather more and task-relevant information. It also supports the idea of strategies in drivers' attention allocation which are specific for certain situations. However, if dangers arise at locations where drivers' attention is not directed at, these may not be managed adequately, and thus resulted in a large number of collisions (study I).

Thus, in study II it was examined how different warning strategies can be used to re-direct drivers' attention, and thus prevent an accident. The results of study I showed an adaptation of drivers' gaze and their driving behaviour with regard to the intersection situation. Thus, drivers could react faster to a critical incident when their attention was already allocated to the side of the critical incident and when they turned right with lower velocity. This was shown in intersection 3 (Fig. 1). In contrast, the highest collision frequency was shown at intersections with only oncoming cars from the left and no pedestrians with a pedestrian crossing on the right (Fig. 1, intersection 1). Due to the missing information source on the right-hand side, less attention was allocated to that side by drivers. Additionally, at this intersection the highest velocity was found. Based on this acquired knowledge, different approaches of warning systems which support drivers in their attention allocation and driving behaviour were compared in study II.

The results of study II showed that the early-middle warning signal (top-down) was very effective. Here, most collisions were avoided by drivers. In addition, this warning signal was effective to shift drivers' attention as drivers had more gazes to the side of the critical incident as compared to the groups without a warning signal at that time. With regard to the driving behaviour, drivers adapted their behaviour towards safer driving by turning right with a lower velocity. In contrast, the late warnings (bottom-up) were not able to improve drivers' reactions to the critical incident. Obviously, these warnings were too late for drivers to react in time. As the warnings were presented at the same time when the car started to enter the road, it may be that these warnings just provided no additional information for drivers. If it is possible to give these warnings a bit earlier it might be that these warnings would also prove effective. Furthermore, one could try to increase the strength of these warnings be using multi-modal warnings and adding a warning tone.

As a next step, it would be important to examine these warning strategies for older drivers. As perception and attention errors are assumed to be the main reasons why older drivers are involved in accidents (e.g., Bao & Boyle, 2009), especially when driving at intersections, warning systems which assist drivers in their attention allocation might be useful for these groups of drivers.

In general, due to the somewhat artificial surrounding and missing motion in the driving simulator, findings of the two studies should be validated in real road-traffic situations. Further limitations concerning the implementation of those warnings in practice and effects of false alerts are discussed in Werneke and Vollrath (2012, submitted).

In conclusion, the results of the two studies support the idea that driver errors leading to intersection accidents are at least in some part the results of systematic psychological processes, involved in mechanisms of drivers' attention allocation, their expectation, and driving behaviour. The studies are important input for the following: (1.) a better understanding of the psychological processes leading to driver errors at intersections with regard to their attention allocation and driving behaviour (study I), (2.) the design of effective warning signals in these situations, and (3.) their evaluation which further contributes to a better understanding of drivers' behaviour in critical intersection situations (study II). This can be used to reduce injuries and fatal accidents at intersections, and thus increase driving safety.

Acknowledgments

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