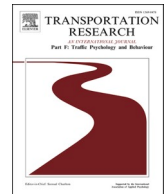




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Effects of a frontal brake light on (automated) vehicles on children's willingness to cross the road

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ABSTRACT

In this study, the effect of a frontal brake light (FBL) on children's willingness to cross the road was investigated. While recent studies have investigated effects of an FBL their samples consisted exclusively of adults. The results and conclusions of these studies may not be applicable to children due to their partially less developed cognitive capabilities. Accordingly, the aim of this study was to investigate the effects of an FBL on children's willingness to cross a vehicle's path. In a mixed design simulation study, participants were assigned to an experimental condition (EC), in which vehicles were equipped with an FBL, or to a control condition (CC), in which vehicles were not equipped with an FBL. Children aged six to twelve watched videos from the perspective of a pedestrian standing at the curb. A vehicle with an initial speed of 30 km/h approached either by maintaining the speed or by decelerating. In the latter case, the braking onset was varied (55 m or 32 m from the pedestrian's position). Participants' task was to indicate their willingness to cross the road in front of the vehicle at five different distances. Results show that FBL affected the willingness to cross the road, especially at an early braking onset (i.e., 55 m). If the vehicle decelerated (i.e., the FBL was activated in the EC), the willingness was significantly higher in the EC than in the CC. In case the vehicle maintained its speed (i.e., the FBL was not activated in the EC), the opposite effect appeared. However, children did not exclusively rely on information gained by the FBL, but still paid attention to distance to the vehicle and braking onset. In conclusion, the effects of an FBL on children are similar to the effects on adults identified in prior studies. Nevertheless, more research in complex scenarios is needed to draw general conclusions about the impact of FBL on road safety in differently aged children and adults.

1. Introduction

Many different road users encounter each other in public traffic, each with their own tasks to reach their destination safely. Road traffic can be especially challenging for vulnerable road users (VRU) such as pedestrians, cyclists, or users of mobility devices. When crossing a road, VRU need to be aware of their environment, other road users, and the infrastructure. They are less protected than motorized participants. Therefore, there are many aspirations to increase safety for VRU (BMVI, 2021), e.g., with the help of assistance systems like Autonomous Emergency Braking or Intelligent Speed Assistance (DGVP Verkehrspsychologie, 2017). Another approach is

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to improve communication between motorized participants and VRU (DGVP Verkehrspsychologie, 2017). Several authors argued that increasingly automated vehicles provide an opportunity in this regard, as they could use so-called external human–machine interfaces (eHMI) to explicitly communicate to surrounding traffic (Dey et al., 2020; Eisele & Petzoldt, 2022). However, some eHMIs are not limited to automated vehicles. They could also help to enhance the communication capabilities of any other motorized (non-automated) traffic participant. Therefore, the discussion and research about external eHMI increases continuously.

1.1. Related work

According to Tabone et al. (2021), eHMIs should primarily be used to support implicit communication like perceivable changes in vehicle speed. One possible and simple approach to support communication between motorized participants or automated vehicles and VRU could be a frontal brake light (FBL) as an eHMI, which does exactly the same what brake lights on the rear of a vehicle do: indicate a deceleration of the vehicle (Schubert & Kirschbaum, 2018). It lights up simultaneously with the rear brake lights when the vehicle is decelerated and deactivates as soon as the vehicle is no longer decelerated. As far back as the 1920s there were considerations about a frontal brake light (Douglass, 1924; Pirkey, 1925). Post and Mortimer (1971) conducted a study regarding the usefulness of an FBL by equipping private vehicles with an FBL for a month. After that period, participants were asked about their experience and their opinion about that technology. In addition, participants of a control group, who had no experience with an FBL, were also asked about the concept. Both groups characterized the FBL as positive and useful, especially in situations with poor visibility. Another study of Petzoldt, Schleinitz, and Banse (2018) investigated the detection of decelerations with and without an FBL, implemented as a green light, and the potential benefit of an FBL. They reported that the FBL not only facilitated the identification of a deceleration but also led to more conservative reactions when the FBL was not activated. Monzel, Keidel, Schubert, and Banse (2021) investigated possible effects of a green FBL on the airside of the Berlin Tegel Airport in a longitudinal field study. Over a period of 3.5 month, about 100 vehicles were equipped with an FBL. The perceived safety increased with FBL and participants showed a positive attitude towards the FBL. Authors concluded that FBL improve communication between road users and that FBL could contribute to anticipate critical situations and prevent accidents. In order to assess whether an FBL not only facilitate the detection of decelerations and is perceived positively but also affect the behaviour of a pedestrian waiting at the curb to cross the road, Eisele and Petzoldt (unpublished results) conducted a laboratory study where participants should indicate their willingness to cross the road at different distances to approaching vehicles with and without an FBL. When vehicles yielded, the (activated) FBL contributed to a higher willingness to cross in comparison to interactions with vehicles without an FBL. However, an inactivation of the FBL (i.e., no deceleration of the vehicle) led to a lower willingness to cross in comparison to interactions without an FBL. In all these studies, however, adults participated. Therefore, it remains unclear, how children would interact with such an FBL or if an FBL even evokes negative effects.

Children are particularly vulnerable in road traffic and therefore represent a special part of VRU. They not only want to use road traffic to go from point A to point B but also to play, to meet friends or to communicate (Limbourg, 2010). Children have less experience and the development of required skills for safe participation in road traffic continues into adolescence (Schlag, Richter, Buchholz, & Gehlert, 2018). The ability of visual perception develops early; however, the comprehension of the perceived situation requires experience and more cognitive abilities, which partially develop later (Kröling, Schlag, Richter, & Gehlert, 2021) and are necessary for safe participation in road traffic. For instance, depth perception is not completely developed until the age of eleven (Uhr, 2015). This also entails size constancy, which describes the capability to perceive the size of objects constantly independent of their distance (Uhr, 2015). The literature differs on the age at which size constancy is fully developed. Sperandio (2021) assumed that it is already present in early childhood, whereas according to metacognitive theory it develops between ages seven and eleven (Kavšek & Granrud, 2012). Before this age, younger children have been shown to perceive distant objects as smaller than they actually are (Kavšek & Granrud, 2012). The depth perception as well as size constancy affect distance and speed estimation Schmied (2018), whereby perception of distance develops earlier (Uhr, 2015). The integration of distance and speed information requires higher cognitive capabilities, which can be reached at eleven years (Matsuda, 2001). Children make their decisions to cross a street especially based on distance information and less to the velocity of an oncoming vehicle (Connelly, Conaglen, Parsonson, & Isler, 1998; Wang et al., 2020). While adults also mostly rely on distance information, they make safer crossing decisions than children (Simpson, Johnston, & Richardson, 2003) and take the time gap into account (Dommes et al., 2015). Due to this, especially younger children make riskier crossing decisions (O'Neal et al., 2018; Schwebel, Gaines, & Severson, 2008).

Children also need to learn that other persons have another perspective, which is necessary to understand the behaviour of others (Limbourg, 2010). The ability to take another person's perspective develops in different stages (Selman, 1984). The insight that one cannot assume that others behave according with rules and regulations therefore only improves with age (Foot et al., 2006). The comprehension of other persons' intentions is associated with the ability of hazard perception. Horswill and McKenna (2004) describe hazard perception as "situation awareness for potentially dangerous incidents in the traffic environment" (p. 156). It has been shown that children's hazard perception and awareness develop gradually. Limbourg (1997) identified three stages. The first stage is acute hazard awareness. At this stage, children are able to recognize dangerous situations but only when they are already endangered. The second stage describes an anticipatory, forward-looking hazard awareness, which means children are able to anticipate hazardous situations. The last stage is the awareness of prevention. Children learn to avoid dangerous situation through preventive behaviour. However, having developed these skills is not sufficient for a safe participation in road traffic (Kröling et al., 2021; Limbourg, 1997). Another important factor influencing the perception of danger in traffic is attention (Limbourg, 1997). Attention greatly influences cognitive skills (Schlag et al., 2018). However, children are highly distractible (Kröling et al., 2021; Tapiro, Oron-Gilad, & Parmet, 2020). They do not necessarily turn their attention to objectively important information, but rather to information that is interesting to them (Kröling et al., 2021). The higher the visual stimulation the more likely children are distracted and need longer to cross a road

(Tapiro et al., 2020). Also, children who are distracted cross a road in a riskier manner (Dunbar, Hill, & Lewis, 2001). The interaction and coordination of all these factors is essential for a successful performance (Kröling et al., 2021) and depends on higher cognitive functions, called executive functions, that continue to develop into early adulthood (Uhr, 2015).

Especially road crossing can lead to potentially dangerous situations since it requires many different competencies. Krause (2018) in describes the following five steps to cross a road: (1) Resolution to cross the road, (2) Approaching the curb, (3) Monitor traffic situation, (4) Decision to cross the road and (5) Crossing the road. Each step requires different skills, all of which must be brought together to cross a street safely. The decision to cross is also influenced by external factors, e.g., behavioural, dynamical and contextual factors (Dey, Martens, Eggen, & Terken, 2019; Ezzati Amini, Katrakazas, & Antoniou, 2019; Nuñez Velasco et al., 2021). This includes vehicle's movement and speed or distance to the pedestrian. Thus, the detection of a deceleration can also impact the crossing decision, which could be facilitated by an FBL (Petzoldt et al., 2018). However, children behave differently than adults in road traffic due to their lack of experience and their developmental stage. Therefore, research results obtained with adults cannot be generalized to children and need to be further investigated, including possible negative effects, to draw conclusions about the impact of an FBL on children's road safety. This requires conceptual replication with a child sample to allow comparison with adults.

1.2 Research questions

The potentially different effects of an FBL on adults and children and the current lack of studies investigating the effect of an FBL on children, motivated the present study. In addition to the presence of an FBL, the braking onset and the distance from the pedestrian were varied. Children's willingness to cross the road was assessed. Situations in which deceleration occurred (i.e., FBL is active if it is present) and situations in which deceleration did not occur (i.e., FBL is not active if it is present) were included. The aim was to investigate the effect of an FBL on children's willingness to cross a road. The following research questions (RQ) were examined: RQ1: Does an FBL influence children's willingness to cross the road? RQ2: Do other factors that have been shown to influence willingness to cross (braking onset, distance from pedestrian) still play a role in the presence of an FBL? RQ3: Are the effects similar to those of adults? RQ4: How is an FBL assessed by children?

2 Materials and method

2.1. Participants

A total of 46 children participated in the study (20 female, 26 male). The age ranged from six to twelve years ($M = 9.9$, $SD = 2.1$). Twenty-four children were recruited from a German primary school and 22 from a German comprehensive school. All children were assigned to an experimental condition (EC) or a control condition (CC) by block randomization, balanced in group size (23 children in each condition) and age ($M_{EC} = 9.8$, $SD_{EC} = 2.1$, $M_{CC} = 9.9$, $SD_{CC} = 1.9$). The study design and materials were reviewed and ethically approved by the Ethics committee of the Department of Psychology of the Rheinische-Friedrich-Wilhelms-University Bonn. Written parental consent and verbal child consent were obtained prior to each child's participation.

2.2. Design

In order to investigate the influence of an FBL on children's willingness to cross the road and to compare the results with those of adult pedestrians the study of Eisele and Petzoldt (unpublished results) was replicated, but adapted for children. Eisele and Petzoldt (unpublished results) conducted an online study, where participants watched videos of an approaching vehicle on a straight one-lane street. The perspective was that of a pedestrian standing at the curb (see Fig. 1).

Following these authors, a mixed design with two conditions, an EC and a CC, was employed. Within the EC, the vehicles were equipped with an FBL, whereas in the CC no vehicle had an FBL. As within factor the vehicle's behaviour was varied: either the vehicle yielded (yielding) or maintained its speed (non-yielding). In addition, the braking onset was varied. In the non-yielding trials, there



Fig. 1. Screenshot of a decelerating vehicle (left: equipped with an FBL; right: not equipped with an FBL).

was no braking onset – therefore coded as 0 m. In the yielding trials the vehicle started to decelerate either at 55 m or at 32 m and stopped close to observer's position. These differences in vehicle behaviour were introduced due to theoretical interest but also to reduce predictability of vehicle's behaviour. In the study by Eisele and Petzoldt (unpublished results), the initial approach speed of the vehicle was manipulated (30 km/h and 50 km/h). The videos stopped automatically at five different distances to the point of the observer: 45, 30, 15, 5 or 1.5 m, which has been demonstrated to be suitable in a previous study (Dey et al., 2019). This resulted in a 2 (condition) $\times$ 2 (speed) $\times$ 5 (distance from pedestrian) $\times$ 3 (braking onset)-mixed design. However, since the vehicle did not yet decelerate at a distance of 45 m when the braking onset was 32 m, this stimulus combination was identical to a non-yielding vehicle at a distance of 45 m (at both possible speeds). This unnecessary doubling was avoided so that every participant experienced 28 stimulus combinations. All 28 possible combinations were shown twice, so 56 videos resulted per participant. This would have taken too much time in the present study for two reasons. First, the ability to sustain attention over a longer time is not yet fully developed in younger children (Kröling et al., 2021). Second, the study was conducted during class, so the time needed to be kept as short as possible. Therefore, in this study vehicles only approached with an initial speed of 30 km/h and each combination of approach speed and the five distances was only shown once. This initial speed was chosen because a speed limit of 30 km/h is usually applied in Germany in front of facilities where children are present, e.g., kindergarten and schools (Verwaltungsvorschrift, 2021). The two different braking onsets were kept as they made the vehicle's behaviour less predictable. This resulted in 14 videos (2 (condition) $\times$ 5 (distance from pedestrian) $\times$ 3 (braking onset)-mixed design minus the combination of 45 m distance from the pedestrian and 32 m braking onset), which were presented in a randomised order. In the study of Eisele and Petzoldt (unpublished results) the participants' task was to indicate their willingness to cross on a ten-point Likert scale, i.e., they indicated which number best suited their willingness to cross ranging from 1 (very low) to 10 (very high) at the moment the video ended. For the purpose of this study, the response format was changed to a two-step response format, which is easier for young children (Fritzsche, 2012). First, children were asked if they would cross the road in front of the car. They could choose between *rather yes*, *I do not know* and *rather no*. The *rather yes* and *rather no* response was also illustrated with a green picture of a walking person and a red figure of a stationary person, respectively, which are commonly used as signals for pedestrians in Germany. In case children indicated *rather yes*, they were further asked whether they would cross the road *for sure* or *probably* in front of the car. In case children indicated *rather no* in the first step, they were asked whether they would cross the road *probably not* or *for sure not* in front of the car. If they indicated *I do not know*, no second specified question followed. This allowed to code the answers on a five-point Likert scale. In addition, children in the EC indicated afterwards their agreement to the following short statements about the FBL on a five-point Likert scale: *The FBL is a good idea*, *the FBL makes me feel safe*, *the FBL should be present on all vehicles* and *the FBL is difficult to understand*.

2.3. Material

The material created by Eisele and Petzoldt (unpublished results) was used. In their study, the VICOM Editor Software (TÜV | DEKRA arge tp21 GbR, 2021) was used to create the videos from the perspective of a pedestrian. At the beginning of the videos, the vehicles were approaching 100 m away from the pedestrian and either maintained their speed or decelerated evenly until they stopped close to observer's position, but there was still enough space, so the observer had the impression to be able to cross in front of the

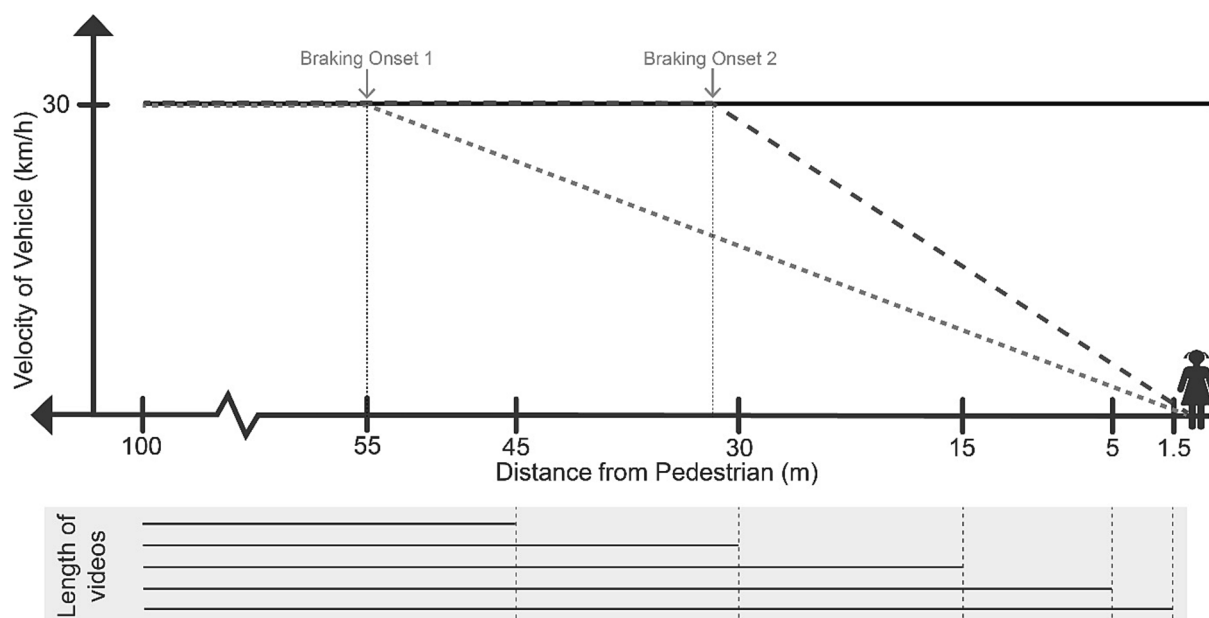


Fig. 2. Different vehicle behaviours (top) and end of video segments at different distances from pedestrian's position (bottom).

vehicle. This resulted in smooth deceleration rates of 0.6 m/s^2 at the 55 m braking onset and 1.1 m/s^2 at the 32 m braking onset (see Fig. 2). The FBL, a single light on the radiator grille of the vehicle, in the EC was added with the video editing software DaVinci Resolve (Blackmagicdesign, 2021). The chosen colour of the FBL by Eisele and Petzoldt (unpublished results) was magenta (RGB 225, 0, 225), since it is not already used in traffic in Germany and thus does not compete with other meanings and it is well (peripheral) visible (Werner, 2018). Furthermore, this simple design seemed to be suitable for children since it does not contain any text (Tabone et al., 2021), which could be especially difficult for younger children. Within the experiment, no audio was present. This experiment was programmed and presented in Labvanced (Scicoverly GmbH, 2021), which is a platform to build and run experiments. The material was presented to the participants on a 27" Quad HD monitor, the resolution of the videos was $2048 \times 1152 \text{ px}$ at 24 fps.

2.4. Procedure

The study was conducted in a room of the primary or comprehensive school. After arriving, the child was welcomed and introduced to the purpose and procedure of the study. Since there were no FBL in the control condition, all children were told that the objective of the study is to investigate the children's willingness to cross the road, but there was no mention of the FBL at this point. After their verbal consent, they were introduced to the anticipated situation by a screenshot. They should imagine that they are a pedestrian waiting at the curb of a one-way street and intend to cross the street in order to go to school, but they are not in a hurry. The procedure of participants in the EC was then as follows: An example video of a yielding vehicle with an FBL was shown. Then, children were informed about the FBL with the help of pictures of the experimental vehicle from the front and back. One set of pictures showed a yielding vehicle with activated frontal and rear brake lights. The other set showed a non-yielding vehicle with deactivated frontal and rear brake lights. The experimenter taught the children that the FBL works exactly like the rear brake lights. After that, their task, to indicate whether they would cross the street in front of the car or not, and the two-step response format was explained. Two practice trials followed with the possibility of repetition, before the experiment with 14 trials started. After finishing the experimental trials, children should indicate their agreement to short statements about the FBL (e.g., *the FBL is a good idea*, *the FBL is difficult to understand*) on a five-point Likert scale. After that, children indicated their age, grade and gender. In the end, the complete purpose of the study and the two conditions were clarified. Participants of the CC went through a similar procedure. As an example video, they were shown a yielding vehicle without an FBL, followed by the instruction of the task by the experimenter. After two practice trials, also with the possibility of repetition, the experiment started with 14 trials. Subsequently, the children also indicated their age, grade, and gender. After clarifying the overall purpose of the study and the two conditions, the function and mechanism of an FBL was explained to the children who participated in the CC. On average, each child took ten minutes to complete the experiment. After participating, each child was allowed to take a sticker. This study complied with the tenets of the Declaration of Helsinki.

3. Results

3.1. Analysis

A separate analysis of the yielding and non-yielding trials was conducted. No participants were excluded from the analysis. An inspection of outliers using Boxplots for each condition showed that there were none in the yielding trials. In the non-yielding trials, there were some outliers at the distances 1.5 m, 5 m, and 15 m. Some participants rated their willingness to cross in non-yielding conditions surprisingly high. However, these outliers were retained in the analysis, since removing these datapoints could have led to an underestimation of potentially dangerous crossing decisions by children.

A mixed repeated measures ANOVA (Analysis of Variance) was performed for both the yielding and non-yielding trials. This kind of statistical test allowed to test whether the different manipulated factors significantly impacted the willingness to cross. The equipment of the vehicle with or without FBL functioned as between-subjects factor. The braking onset and distance from the pedestrian at end of video were within-subject factors. The dependent variable was the willingness to cross. As vehicles with a braking onset at 32 m did not decelerate at 45 m, this trial was not included in the analysis of yielding trials but used in the analysis of the non-yielding trials. As the age of the participants covered a large part of childhood and therefore covers different developmental stages, age was additionally introduced as a covariate. However, age did not explain any of the observed variance in willingness to cross. Therefore, age was dropped from the analysis.

Mauchly's test of sphericity disclosed some violations of the assumption of sphericity. In such cases, the Huynh-Feldt corrected F-statistics were reported, since ϵ was above 0.75 (Field, 2017). Also, Levene's test for equality of variances showed significant differences in variances of the dependent variable between the control and experimental conditions in two terms. Due to ANOVA's robustness of such minor violations of its assumptions in sufficiently large ($n > 10$) and equally sized samples, this was not considered to be an issue (Bortz, 2005). At <https://osf.io/3nk2p/> a download of the dataset is possible.

3.2. Yielding trials

The calculation of the ANOVA indicated significant main effects of braking onset, $F(1, 44) = 30.53, p < .001, \eta_p^2 = 0.41$, distance from pedestrian, $F(2.43, 106.70) = 6.52, p = .001, \eta_p^2 = 0.13$, and condition, $F(1, 44) = 6.51, p = .014, \eta_p^2 = 0.13$. As expected, the vehicle's motion dynamics influenced children's willingness to cross. It was significantly higher at the early braking onset (i.e., when the vehicle started to decelerate at 55 m distance to pedestrian compared to 32 m) with a large effect size. In addition, when the vehicle was still comparatively far away (at 30 m) the willingness to cross was higher than at the smaller distances. It increased again at the

smallest distance (at 1.5 m). Furthermore, there was a significant difference between the conditions. Those participants who interacted with vehicles equipped with FBL indicated a higher willingness to cross than those in the control condition. Fig. 3 shows willingness to cross as a function of the distance from the pedestrian, whereby the two conditions are depicted separately. The difference of willingness to cross between these two conditions was higher at mid-range distances (5 m and 15 m) than at close and further distances (1.5 m and 30 m). Simple main effects showed that the condition differences at the distance of 5 m and 15 m were significant ($p = .002$ and $p = .016$, respectively), whereas the others were not.

There was also a significant interaction between braking onset and condition, $F(1, 44) = 6.96$, $p = .011$, $\eta_p^2 = 0.14$. This suggests that the differences between the conditions are affected by the braking onset of the vehicle. The effect of the FBL on the willingness to cross was higher at early braking onset than at late braking onset. In Fig. 4 it can be seen that the willingness to cross did not differ much between both conditions at the late braking onset. No gender differences were observed. Table 1 depicts descriptive values of willingness to cross as a function of braking onset, distance and condition. Children's willingness to cross appeared relatively conservative regardless of condition.

3.3. Non-yielding trials

The calculation of the ANOVA indicated significant main effects of distance from the pedestrian, $F(3.10, 136.49) = 35.89$, $p < .001$, $\eta_p^2 = 0.45$, and condition, $F(1, 44) = 4.65$, $p < .037$, $\eta_p^2 = 0.10$. No interaction effect was found. As expected, distance significantly affected willingness to cross with a very large effect size. The higher the distance, the higher the willingness to cross. Bonferroni-corrected post-hoc tests showed significant stepwise differences between 45 m and 15 m (every $p < .001$ except for the difference between 45 m and 30 m, $p = .016$). Differences between 15 m, 5 m and 1.5 m were not significant.

Again, significant condition differences were found. However, there was an opposite effect to the yielding trials. Willingness to cross was higher in the CC (i.e., where no vehicle was equipped with an FBL) than in the EC (where the FBL was not activated in the non-yielding trials), see Fig. 5. Examining the simple main effects, it was revealed that the differences between the conditions were only significant at 15 m ($p = .014$). No gender differences were found. Table 2 depicts descriptive values of willingness to cross divided by distance and condition. Children's willingness to cross was low across all conditions when the vehicle did not decelerate.

3.4. Subjective ratings of the FBL

Children in the EC were asked about their subjective assessment of the FBL (see Fig. 6). Overall, they had a positive impression of the FBL. They could imagine that the FBL can increase safety. Most children also indicated that it is a good idea, and every vehicle should be equipped with an FBL. For most of the participants, the FBL was not difficult to understand, whereby one child indicated that the FBL was hard to understand.

4. Discussion

In this study, the effect of an FBL, the vehicle braking onset, and distance from the pedestrian were assessed to study children's willingness to cross the road. Referring to RQ1, the results imply that an FBL affects children's willingness to cross a road in front of a vehicle. The willingness to cross the road was higher in front of yielding vehicles equipped with an FBL than vehicles without an FBL. The participants of the control condition, who did not know about the concept of an FBL and only saw vehicles without an FBL, indicated a lower willingness to cross in front of yielding vehicles. The effect size of the condition (i.e., presence/absence of FBL) in front of yielding vehicles were remarkably similar to the one observed in an adult sample by Eisele and Petzoldt (unpublished results). This means that the FBL had an equal impact on children and adults in this regard (see RQ3). However, these differences between

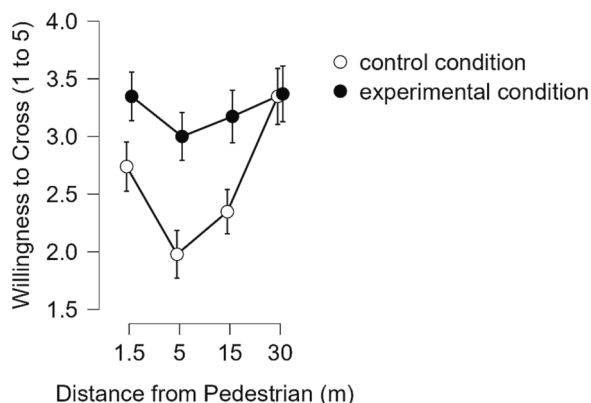


Fig. 3. Willingness to cross in yielding trials in dependence of the distance from the pedestrian split by conditions. Error bars display the standard error of the mean.

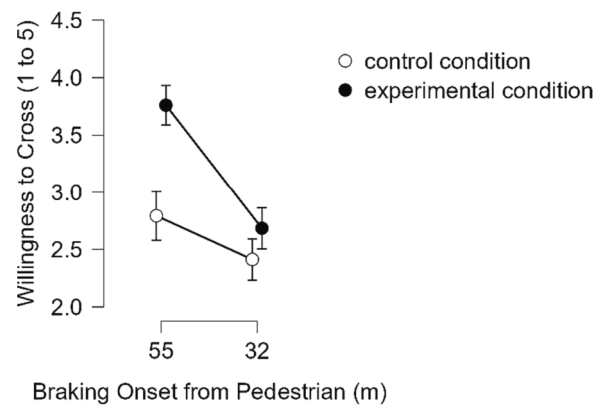


Fig. 4. Willingness to cross in yielding trials in dependence of braking onset split by conditions. Error bars display the standard error of the mean.

Table 1

Descriptive values of willingness to cross in yielding trials at different distances divided by braking onset and condition. EC = experimental condition, CC = control condition.

Distance	32 m					-	55 m					
	EC		-	CC			-	EC		-	CC	
	M	SD		M	SD			M	SD		M	SD
1.5 m	2.9	1.6		2.4	1.6		3.8	1.3		3.0	1.8	
5 m	2.4	1.3		2.0	1.5		3.6	1.3		2.0	1.5	
15 m	2.5	1.2		2.0	1.3		3.8	1.4		2.7	1.8	
30 m	2.9	1.5		3.2	1.3		3.8	1.4		3.5	1.5	

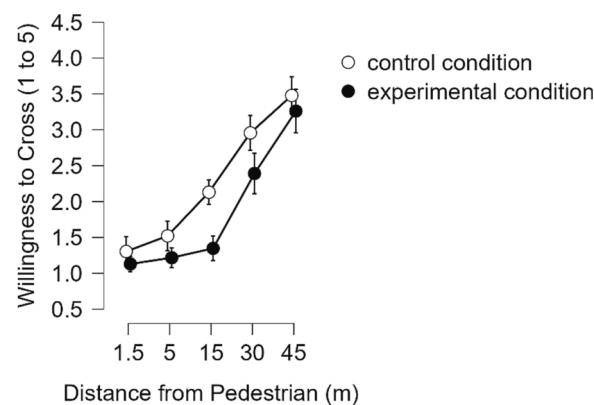


Fig. 5. Willingness to cross in non-yielding trials in dependence of the distance from the pedestrian split by conditions. Error bars display the standard error of the mean.

Table 2

Descriptive values of willingness to cross in non-yielding trials at different distances divided by condition. EC = experimental condition, CC = control condition.

Distance	EC		-	CC	
	M	SD		M	SD
1.5 m	1.1	0.5		1.3	0.8
5 m	1.2	0.7		1.5	1.0
15 m	1.3	0.7		2.1	1.3
30 m	2.4	1.4		3.0	1.6
45 m	3.3	1.5		3.5	1.3

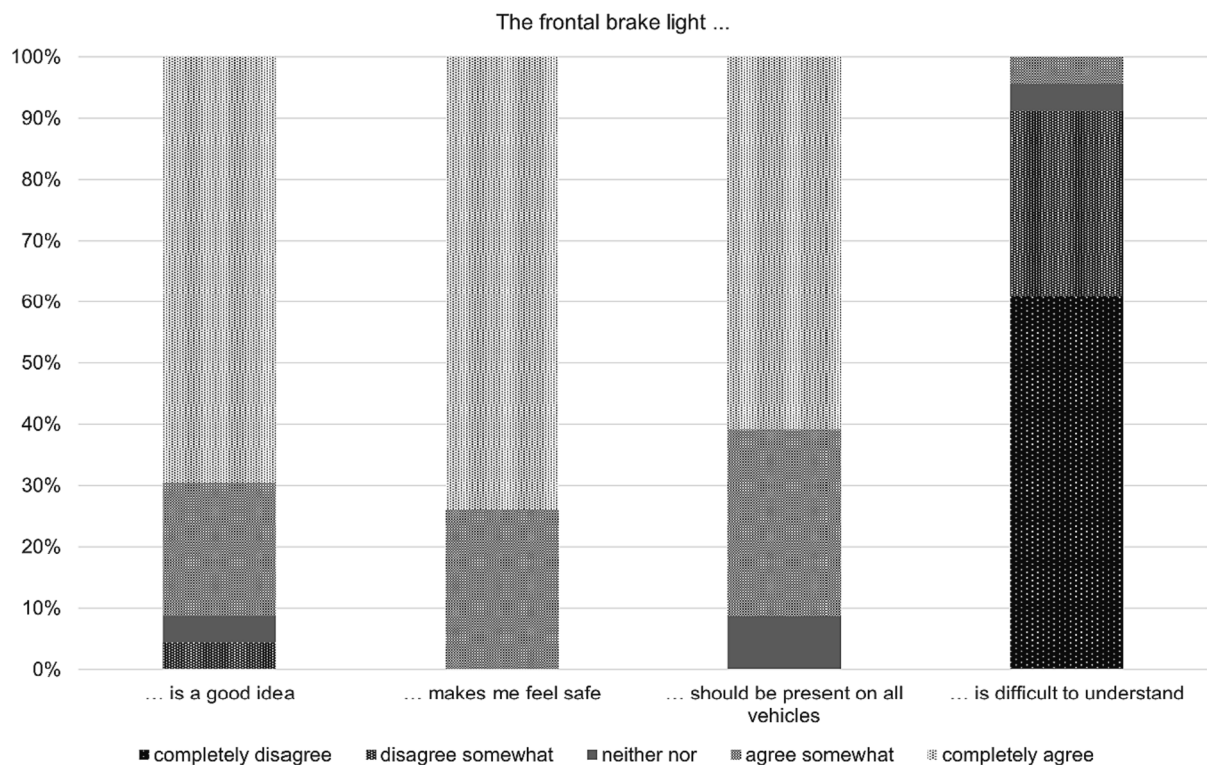


Fig. 6. Participants' ratings of the FBL, relative frequencies in %.

willingness to cross were only significant at medium distances (5 m and 15 m), not at a comparatively far (30 m) and close distance (1.5 m, i.e., when the vehicle was not far away anymore and was braking but not close to standstill). Even though in the latter case the average willingness to cross was descriptively lower in CC, it did not differ significantly. In line with prior research, this implies that the FBL might influence children to cross the road especially at medium distances, where there is the greatest uncertainty regarding safe crossing due to an ambiguous situation (Dey et al., 2019). At a far distance, there was no difference between the two conditions (i.e., there was a higher willingness to cross the road in both conditions), which is in contrast to the findings in the adult sample reported in Eisele and Petzoldt (unpublished results), where a significant difference was found at each distance. This could be due to the fact that children generally pay much attention to distance information when making crossing decisions (Connelly et al., 1998; Wang et al., 2020) and possibly less to information gained by an FBL than adults. At a very close distance, there was also no significant difference between conditions which suggests that more attention was paid to vehicle dynamics here, which also contrasts with the results of the adult sample by Eisele and Petzoldt (unpublished results). At this distance, the vehicle had nearly decelerated to standstill. Consequently, it was apparent that the vehicle will yield without the help of an FBL, which also emphasizes the preferential consideration of distance information by children when making crossing decisions (Connelly et al., 1998; Wang et al., 2020). Generally, children's willingness to cross was highest at the furthest distance, decreased as the vehicle came closer and increased again at closest distance, which is in line with previous research (Dey et al., 2019; Ezzati Amini et al., 2019). In addition, the impact of an FBL on willingness to cross the road was greatly affected by braking onset. At early braking onset, the willingness to cross was higher than at late braking onset. So, the braking onset interacts with the occurrence of an FBL. At early braking onset, an FBL increases the willingness to cross, whereas there was no difference at late braking onset in our study. In case of a late onset, scepticism might prevail as to whether the vehicle really stops. The willingness to cross was generally rather low at late braking onset, in contrast to early braking onset, where the willingness was higher independently of the occurrence of an FBL. This interaction was not observed in adults (Eisele & Petzoldt, unpublished results). Adults may take into account information gained by FBL more than children. It further emphasizes the influence of vehicle dynamics in crossing decisions (in line with prior research, e.g., Dey et al., 2019; Eisele & Petzoldt, unpublished results; Ezzati Amini et al., 2019). These results suggest that children do not understand an activation of the FBL as a call to action but use it only as an additional information. These findings imply that they still take motion dynamics like distance and deceleration rate into account when deciding whether to cross the road (see RQ2) – to a conspicuously similar extent as adults. In line with previous research, these findings call for simple eHMIs that only indicate a change in status and do not request a specific action from the pedestrian (Tabone et al., 2021).

Overall, the willingness to cross was noticeably low, suggesting that the participants behaved conservative regarding their willingness to cross in front of a decelerating vehicle. Notably, the variance in willingness to cross the road in yielding trials was smaller in the subjects who were confronted with an FBL than in those who were not confronted with an FBL, except for the late braking onset at

the 30 m distance. This corroborates the prior observation that the FBL can not only influence willingness to cross but could also lead to more homogeneous pedestrian behaviour (Eisele & Petzoldt, unpublished results), which may increase road safety, both by reducing children's unsafe behaviours through more consistent judgments (Connelly et al., 1998) and by making children's behaviours more predictable for drivers.

Notably, not only the direct interaction with an FBL, i.e., active FBL when vehicle decelerates, but also an indirect interaction, i.e., inactive FBL when vehicle does not decelerate, affected the willingness to cross. When the vehicles did not decelerate, the willingness of cross of those participants who knew about the FBL was significantly lower than those who did not know about the concept of an FBL. Therefore, knowing about an FBL and its absence might lead to more conservative crossing decisions. This effect has also been observed in an adult sample, see RQ3 (Eisele & Petzoldt, unpublished results; Petzoldt et al., 2018). This effect occurred at the ambiguous distance of 15 m. Furthermore, the willingness to cross in front of non-yielding vehicles decreased the closer the vehicle was, regardless of FBL, which is in line with intuition and literature (Nuñez Velasco et al., 2021). Nevertheless, the willingness to cross in front of a non-yielding vehicle was relatively low overall, regardless of condition. This could be due to the fact that children are taught to cross a road behind an approaching car, especially on a single-lane road with only one approaching vehicle. Interestingly, any age effects within this sample were identified although the age of the participants covered a large chunk of childhood and different developmental phases.

Regarding the subjective ratings (see RQ4), participants rated the FBL positively, as has previously been reported for adults (Eisele & Petzoldt, unpublished results; Monzel et al., 2021; Petzoldt et al., 2018). Most participants indicated that it is a good idea, and it can increase their perception of safety. Most would like every vehicle to be equipped with an FBL. Moreover, the concept was not difficult to understand for most of them, whereby one child indicated that the FBL was difficult to understand. However, it seems plausible that knowledge of the function of an FBL influenced children's understanding and ratings. Taken together, these findings suggest that children would willingly interact with an FBL in real traffic, as it appears to be suitable and comprehensible for children. However, possible ramifications need to be further investigated.

4.1 Limitations and future research

This experiment was designed as a video-based study using rendered stimuli in order to enable an accurate manipulation of parameters and controllability of experimental conditions as well as due to safety concerns. The children were in a safe environment and not exposed to any risks. Nevertheless, there are some limitations regarding the used method. The viewing perspective was always the same and was not dependent on the actual size of the child. Considering the age range in our participants, actual eye-height differed considerably. Also, there were no acoustic cues, which could have an impact on the willingness to cross. However, the controllability of parameters was essential in order to investigate the research questions. Therefore, the used method seems to be practicable for this purpose.

Furthermore, a relatively simple setting with only one road lane and one approaching vehicle was employed. Children only had to interact with one vehicle at a time, so their conservative willingness to cross the road may have been caused by knowing they could safely cross the road behind that vehicle. This seems like a reasonable crossing strategy taught by parents and educational staff. Still, our experimental manipulations were apt to answer the research question at hand. The simple setting does also not reflect the complexity of real traffic, where children have to interact with many more road users and are confronted with distractible stimuli, which affect children's crossing decision (Dunbar et al., 2001; Tapiro et al., 2020). The broad spectrum of possible factors was not considered in this experiment.

In the future, possible desirable and undesirable effects of an FBL on children's willingness to cross in more complex scenarios should be investigated. A key question is when and under what conditions an FBL can be beneficial and when it could result in misunderstandings and potentially unwanted calls to action. The consideration of more and different road users, a more complex road infrastructure or a variation of vehicle characteristics are conceivable. Moreover, the effect of an FBL in mixed traffic, e.g., some vehicles are equipped with an FBL and some vehicles are not, should also be considered in future research. This implies the interaction with conventional motorized participants as well as automated vehicles, which should be further investigated with children. Since participants in the EC were informed about the function of an FBL, future research should examine potential effects of an FBL in cases where children do not receive any information about it. The design of an FBL and its effects should also be addressed in future studies, as this was not the focus of the present study, but there are several possible designs of an FBL that need to be considered, e.g., a green light (e.g., Monzel et al., 2021; Petzoldt et al., 2018). Within the scope of this study effects on children and adults were compared. An exploratory analysis of age effects within the children was further conducted but found none. Although this is a statistically sound finding within the scope of this study, it should be interpreted with caution, as it is likely that differences exist between children of different ages, especially outside the age range of participants used in this study. However, a more detailed investigation of this issue was beyond the scope of this study and should be addressed in future research. It may also be interesting to investigate additional age groups like young adults or elderly pedestrians due to their different developmental stages.

5. Conclusion

In this study, the effect of an FBL on children's willingness to cross the road was examined. To that goal, the independent variables presence of an FBL (EC and CC), braking onset and distance from the pedestrian were varied. Children's willingness to cross the road functioned as dependent variable. The results suggest that an FBL affects the willingness to cross a road in children in a similar way as in adults. Willingness to cross increases in the case of FBL activation when a vehicle yields and decreases in the case of FBL inactivation

when the vehicle does not yield. However, there were no significant differences in willingness to cross in front of a yielding vehicle between EC and CC at far and close distances as well as to the FBL, like distance and deceleration, when waging whether to cross the road. This appeared to be even more prominent in children than in the adult sample (Eisele & Petzoldt, unpublished results). Adults may focus more on information gained by an FBL than children. Therefore, this suggests that the FBL would not be understood by children as a call to action (i.e., to cross the road) in a simple setting but rather as an additional information to assess whether it is safe to cross the road. This study provides first insights on the effects of an FBL on children's street-crossing. Nevertheless, further research is needed to assess potential undesirable side effects of FBL in more complex and potentially confusing scenarios. This is required to draw more global conclusions about the impact of an FBL on road safety for pedestrians of all age groups.

Glossary

Frontal Brake Light – A light on the front of a vehicle that indicates the deceleration of the vehicle in the same manner as the rear brake lights.

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CRediT authorship contribution statement

Luka-Franziska Bluhm: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. **Daniel Eisele:** Conceptualization, Methodology, Software, Formal analysis, Writing – review & editing, Visualization. **Wolfgang Schubert:** Conceptualization, Supervision, Writing – review & editing. **Rainer Banse:** Conceptualization, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Rainer Banse, Wolfgang Schubert reports a relationship with LUMACO INNOVATIONS AG Sihleggstrasse 23 8832 Wollerau Schweiz that includes: funding grants.

References

- Allgemeine Verwaltungsvorschrift zur Straßenverkehrs-Ordnung (VwV-StVO), zu Zeichen 274, XI (2021). Retrieved July 07, 2023, from https://www.verwaltungsvorschriften-im-internet.de/bsvwvbund_26012001_S3236420014.htm.
- Blackmagicdesign. (2021). *DaVinci Resolve (Version 18) [Computer software]*. Blackmagicdesign. Retrieved from <https://www.blackmagicdesign.com/de/products/davinciresolve>.
- Bortz, J. (2005). *Statistik für Human- und Sozialwissenschaftler* ((6th edition). Springer-Lehrbuch.). Heidelberg: Springer Medizin Verlag.
- Bundesministerium für Verkehr und digitale Infrastruktur (BMVI) (June 2021). *Verkehrssicherheitsprogramm der Bundesregierung 2021 bis 2030*. Berlin.
- Connelly, M. L., Conaglen, H. M., Parsonson, B. S., & Isler, R. B. (1998). Child Pedestrians' Crossing Gap Thresholds. *Accident, Analysis & Prevention*, 30, 443–453. [https://doi.org/10.1016/S0001-4575\(97\)00109-7](https://doi.org/10.1016/S0001-4575(97)00109-7)
- Dey, D., Habibovic, A., Löcken, A., Wintersberger, P., Pflieger, B., Riener, A., & Terken, J. (2020). Taming the eHMI jungle: A classification taxonomy to guide, compare, and assess the design principles of automated vehicles' external human-machine interfaces. *Transportation Research Interdisciplinary Perspectives*, 7, Article 100174. <https://doi.org/10.1016/j.trip.2020.100174>
- Dey, D., Martens, M., Eggen, B., & Terken, J. (2019). Pedestrian road-crossing willingness as a function of vehicle automation, external appearance, and driving behaviour. *Transportation Research Part F: Traffic Psychology and Behaviour*, 65, 191–205. <https://doi.org/10.1016/j.trf.2019.07.027>
- DGVP Verkehrspsychologie. (2017). Nichtmotorisierte Verkehrsteilnehmer / Vulnerable Road User (VRU). Retrieved February 03, 2023, from <https://www.dgvp-verkehrspsychologie.de/unsere-arbeitsbereiche/strasse/fahrzeug-und-verkehrsraum/nichtmotorisierte-verkehrsteilnehmer-vulnerable-road-user-vru/>.
- Dommes, A., Le Lay, T., Vienne, F., Dang, N.-T., Beaudoin, A. P., & Do, M. C. (2015). Towards an explanation of age-related difficulties in crossing a two-way street. *Accident, Analysis and Prevention*, 85, 229–238. <https://doi.org/10.1016/j.aap.2015.09.022>
- Douglass, S. F. (1924) U.S. Patent No 1,519,980, United States Patent Office, Washington, D.C.
- Dunbar, G., Hill, R., & Lewis, V. (2001). Children's attentional skills and road behavior. *Journal of Experimental Psychology: Applied*, 7(3), 227–234. <https://doi.org/10.1037/1076-898X.7.3.227>
- Eisele, D., & Petzoldt, T. (2022). Effects of traffic context on eHMI icon comprehension. *Transportation Research Part F: Traffic Psychology and Behaviour*, 85, 1–12. <https://doi.org/10.1016/j.trf.2021.12.014>
- Eisele, D., & Petzoldt, T. (unpublished results). Effects of a Frontal Brake Light on Pedestrians' Willingness to Cross the Street.
- Ezzati Amini, R., Katrakazas, C., & Antoniou, C. (2019). Negotiation and Decision-Making for a Pedestrian Roadway Crossing: A Literature Review. *Sustainability*, 11 (23), 6713. <https://doi.org/10.3390/su11236713>
- Field, A. (2017). *Discovering statistics using IBM SPSS statistics* ((5th edition).). SAGE Publications.
- Foot, H. C., Thomson, J. A., Tolmie, A. K., Whelan, K. M., Morrison, S., & Sarvary, P. (2006). Children's understanding of drivers' intentions. *British Journal of Developmental Psychology*, 24(4), 681–700. <https://doi.org/10.1348/026151005X62417>
- Fritzsche, E. S. (2012). *Antwortssicherheit von Grundschulkindern: Ein Maß für das Selbstkonzept? (Dissertation)*. Erlangen-Nürnberg: Friedrich-Alexander-Universität.
- Horswill, M. S., & McKenna, F. P. (2004). Drivers' hazard perception ability: Situation awareness on the road. In S. Banbury, & S. Tremblay (Eds.), *A Cognitive Approach to Situation Awareness* (pp. 155–175). Aldershot, UK: Ashgate.
- Kavsek, M., & Granrud, C. E. (2012). Children's and adults' size estimates at near and far distances: A test of the perceptual learning theory of size constancy development. *I-Perception*, 3(7), 459–466. <https://doi.org/10.1068/i0530>
- Krause, A. (2018). Freie Querung einer Straße. In B. Schlag, S. Richter, K. Buchholz, & T. Gehlert (Eds.), *Ganzheitliche Verkehrserziehung für Kinder und Jugendliche: Teil 1: Wissenschaftliche Grundlagen (Forschungsbericht, No. 50 pp. 69–95)*. Berlin: Gesamtverband der Deutschen Versicherungswirtschaft e.V.
- Kröling, S., Schlag, B., Richter, S., & Gehlert, T. (2021). *Ganzheitliche Verkehrserziehung für Kinder und Jugendliche: Teil 1: Entwicklung verkehrsrelevanter Kompetenzen im Alter von 0 bis 14 Jahren Band 1: Übersicht Kompetenzentwicklung (Forschungsbericht No. 77)*. Berlin: Gesamtverband der Deutschen Versicherungswirtschaft e.V. Unfallforschung der Versicherer.

- Limbou, M. (1997). Gefahrenkognition und Präventionsverständnis von 3- bis 15jährigen Kindern. In *Sicher Leben, Kindersicherheit: Was wirkt?*, Essen.
- Limbou, M. (2010). *Kinder unterwegs im Straßenverkehr (Prävention in NRW, No. 12)*. Düsseldorf: Unfallkasse Nordrhein-Westfalen.
- Matsuda, F. (2001). Development of concepts of interrelationships among duration, distance, and speed. *International Journal of Behavioral Development*, 25(5), 466–480. <https://doi.org/10.1080/016502501316934905>
- Monzel, M., Keidel, K., Schubert, W., & Banse, R. (2021). A field study investigating road safety effects of a front brake light. *IET Intelligent Transport Systems*, 15(8), 1043–1052. <https://doi.org/10.1049/itr2.12080>
- Núñez Velasco, J. P., Mun Lee, Y., Uttley, J., Solernou, A., Farah, H., van Arem, B., & Merat, N. (2021). Will pedestrians cross the road before an automated vehicle? The effect of drivers' attentiveness and presence on pedestrians' road crossing behavior. *Transportation Research Interdisciplinary Perspectives*, 12, Article 100466. <https://doi.org/10.1016/j.trip.2021.100466>
- O'Neal, E. E., Jiang, Y., Franzen, L. J., Rahimian, P., Yon, J. P., Kearney, J. K., & Plumert, J. M. (2018). Changes in perception-action tuning over long time scales: How children and adults perceive and act on dynamic affordances when crossing roads. *Journal of Experimental Psychology. Human Perception and Performance*, 44(1), 18–26. <https://doi.org/10.1037/xhp0000378>
- Petzoldt, T., Schleinitz, K., & Banse, R. (2018). Potential safety effects of a frontal brake light for motor vehicles. *IET Intelligent Transport Systems*, 12(6), 449–453. <https://doi.org/10.1049/iet-its.2017.0321>
- Pirkey, O. S. (1925) U.S. Patent No. 1,553,959. United States Patent Office, Washington, D.C.
- Post, D. V., & Mortimer, R. G. (1971). *Subjective Evaluation of the Front-Mounted Braking Signal*. Michigan.
- Schlag, B., Richter, S., Buchholz, K., & Gehlert, T. (2018). *Ganzheitliche Verkehrserziehung für Kinder und Jugendliche: Teil 1: Wissenschaftliche Grundlagen (Forschungsbericht, No. 50)*. Berlin: Gesamtverband der Deutschen Versicherungswirtschaft e.V. Unfallforschung der Versicherer.
- Schmid, M. (2018). Situation: Linksabbiegen mit dem Fahrrad an ungeregelten Kreuzungen. In B. Schlag, S. Richter, K. Buchholz, & T. Gehlert (Eds.), *Ganzheitliche Verkehrserziehung für Kinder und Jugendliche: Teil 1: Wissenschaftliche Grundlagen (Forschungsbericht, No. 50 pp. 142–158)*. Berlin: Gesamtverband der Deutschen Versicherungswirtschaft e.V.
- Schubert, W., & Kirschbaum, B. (10/2018). *The Front Brake Light: Its conception and theoretical and experimental evidence for increasing traffic safety*. Bonn. Retrieved from https://www.frontbrakelights.com/wp-content/uploads/2019/01/BIRVp_the_Front_Brake_light_final.pdf.
- Schwebel, D. C., Gaines, J., & Severson, J. (2008). Validation of virtual reality as a tool to understand and prevent child pedestrian injury. *Accident Analysis & Prevention*, 40(4), 1394–1400. <https://doi.org/10.1016/j.aap.2008.03.005>
- Scicover GmbH. (2021). *Labvanced [Computer software]*. Scicover GmbH: Scicover GmbH. Retrieved from <https://www.labvanced.com>.
- Selman, R. L. (1984). *Die Entwicklung des sozialen Verstehens: Entwicklungspsychologische und klinische Untersuchungen. (Beiträge zur Soziogenese der Handlungsfähigkeit)*. Frankfurt a.M: Suhrkamp.
- Simpson, G., Johnston, L., & Richardson, M. (2003). An investigation of road crossing in a virtual environment. *Accident Analysis & Prevention*, 35(5), 787–796. [https://doi.org/10.1016/S0001-4575\(02\)00081-7](https://doi.org/10.1016/S0001-4575(02)00081-7)
- Sperandio, I. (2021). Developmental Trajectories of Size Constancy as Implicitly Examined by Simple Reaction Times. *Vision (Basel, Switzerland)*, 5(4). <https://doi.org/10.3390/vision5040050>
- Tabone, W., de Winter, J., Ackermann, C., Bärghman, J., Baumann, M., Deb, S., ... Stanton, N. A. (2021). Vulnerable road users and the coming wave of automated vehicles: Expert perspectives. *Transportation Research Interdisciplinary Perspectives*, 9, Article 100293. <https://doi.org/10.1016/j.trip.2020.100293>
- Tapiro, H., Oron-Gilad, T., & Parmet, Y. (2020). Pedestrian distraction: The effects of road environment complexity and age on pedestrian's visual attention and crossing behavior. *Journal of Safety Research*, 72, 101–109. <https://doi.org/10.1016/j.jsr.2019.12.003>
- TÜV | DEKRA arge tp21 GbR (2021). VICOM Editor (Version 1.11) [Computer software]. TÜV | DEKRA arge tp21 GbR: TÜV | DEKRA arge tp21 GbR. Retrieved from www.vicomeditor.de.
- Uhr, A. (2015). *Entwicklungspsychologische Grundlagen: Überblick und Bedeutung für die Verkehrssicherheit (bfu-Grundlagen)*. Bern: BFU, Beratungsstelle für Unfallverhütung.
- Wang, H., Gao, Z., Shen, T., Li, F., Xu, J., & Schwebel, D. C. (2020). Roles of individual differences and traffic environment factors on children's street-crossing behaviour in a VR environment. *Injury Prevention*, 26, 417–423. <https://doi.org/10.1136/injuryprev-2019-043>
- Werner, A. (2018). New colors for autonomous driving: An evaluation of chromaticities for the external lighting equipment of autonomous vehicles. *Colour Turn - An Interdisciplinary and International Journal, IV Colour & Technology*, 1–15. <https://doi.org/10.25538/tct.v0i1.692>