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Cyclists' eye movements and crossing judgments at uncontrolled intersections: An eye-tracking study using animated video clips

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ABSTRACT

Research indicates that crashes between a cyclist and a car often occur even when the cyclist must have seen the approaching car, suggesting the importance of hazard anticipation skills. This study aimed to analyze cyclists' eye movements and crossing judgments while approaching an intersection at different speeds. Thirty-six participants watched animated video clips with a car approaching an uncontrolled four-way intersection and continuously indicated whether they would cross the intersection first. We varied (1) car approach scenario (passing, colliding, stopping), (2) traffic complexity (one or two approaching cars), and (3) cyclist's approach speed (15, 25, or 35 km/h). Results showed that participants looked at the approaching car when it was relevant to the task of crossing the intersection and posed an imminent hazard, and they directed less attention to the car after it had stopped or passed the intersection. Traffic complexity resulted in divided attention between the two cars, but participants retained most visual attention to the car that came from the right and had right of way. Effects of cycling speed on cyclists' gaze behavior and crossing judgments were small to moderate. In conclusion, cyclists' visual focus and crossing judgments are governed by situational factors (i.e., objects with priority and future collision potential), whereas cycling speed does not have substantial effects on eye movements and crossing judgments.

1. Introduction

Naturalistic cycling studies and accident data analyses indicate that cyclists are particularly at risk when encountering a car at an intersection (Akhtar et al., 2010; Dozza et al., 2016; Schepers et al., 2011; Summala et al., 1996). Contributory factors to bicycle-car collisions at intersections include the driver's failure in perceiving the cyclist and the cyclist's incorrect anticipation of the driver's intentions (Räsänen and Summala, 1998). Similarly, analyses of car-car and motorcycle-car intersection crashes have found that not only perceptual errors, but also false assumptions about the other's future actions are frequent causes of crashes (Choi, 2010; Najm et al., 1994; Pai, 2011).

The importance of 'knowing what is going on' in the environment can be captured by the construct of situation awareness, comprising three levels (Endsley, 1995). Level 1 is the perception of individual elements of the scene, Level 2 involves the comprehension of their meaning and importance, and at Level 3 the road user anticipates future events, such as a car driver's intentions. Researchers have identified

several factors that are associated with perceptual errors at intersections, such as information processing limitations and perceptual filtering (e.g., Crundall et al., 2008; Herslund and Jørgensen, 2003; Scott et al., 2013; Werneke and Vollrath, 2012). However, less empirical evidence exists concerning the mechanisms responsible for road users' failures in comprehension and anticipation of other road users' intentions.

Several studies have used time-to-arrival judgments tasks to examine participants' anticipation of the future location of other road users (e.g., Caird and Hancock, 1994; Hancock and Manster, 1997; Van Loon et al., 2010), gap acceptance or interception tasks to investigate under which conditions individuals cross an intersection (e.g., Chihak et al., 2010; Grechkin et al., 2013; Lobjois et al., 2013; Louveton et al., 2012; Simpson et al., 2003), and judgment tasks to examine the perceived risk associated with crossing the intersection in front of an approaching car (e.g., Ebbesen et al., 1977). Stimuli for these tasks included cars approaching intersections at constant speeds while the participant was either stationary or moving toward the intersection.

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Chihak et al. (2010) used a bicycle simulator to investigate how children and adult cyclists adjust their approach speed to successfully pass through a gap in crossing traffic. Their results indicated that instead of cycling with a constant speed, cyclists used a two-stage interception strategy where they slowed down first, and accelerated when being close to the intersection (approximately 4–6 s). A possible reason why cyclists adjust their approach speed is that it allows them to improve the timing of the entry into the gap while minimizing the amount of time spent in the path of the oncoming traffic. Traditionally, the emphasis has been on how accurately people make judgments about potential collisions and on the probability/timing of crossing the intersection, whereas relatively little attention has been paid to what sources of visual information humans use in such tasks.

Early work on fixation allocation using pictures has indicated that viewers do not look randomly at the scene but gaze predominantly to informative areas of the picture (Buswell, 1935; Mackworth and Morandi, 1967). In a traffic environment, informative areas are those where hazards can arise from as well as objects in the visual field relevant to the performed task (e.g., a vehicle having priority). In an eye-tracking experiment by Van Loon et al. (2010), observers watched animated video clips while making relative timing judgments about approaching vehicle at a T-junction. Results showed that drivers made saccadic movements between the road ahead and the approaching car while spending the most viewing time (37%) on the approaching car. Eye-tracking studies conducted among car drivers have shown that hazardous events reduce saccadic activity (i.e., reduced spread of search) and increase fixation durations on the hazardous object, which may reflect in-depth information processing (Crundall et al., 1999, 2002; Chapman and Underwood, 1998; Velichkovsky et al., 2002). Perceptual narrowing in traffic may be similar to the ‘weapon focus’ phenomenon whereby observers fixate more often and for a longer duration on a threatening object than on a neutral object (Loftus et al., 1987; Underwood et al., 2003). At intersections, it can be expected that road users shift their attention between potentially hazardous objects while allocating most visual attention to high-value information sources (Werneke and Vollrath, 2012; Wickens et al., 2001).

Humans have evolved to perform ambulatory tasks up to 10 km/h, whereas driving and cycling occur at considerably higher speeds, posing challenges for safety and human information processing (Rumar, 1985). Driving simulator studies have shown that drivers reduce their horizontal gaze variance as driving speed increases (Rogers et al., 2005; Van Leeuwen et al., 2015). When driving at a low speed, road users have more time for perceptual and cognitive processing, whereas at higher speeds they look farther ahead and become more selective in their attention allocation (Summala and Räsänen, 2000).

Formal traffic rules (e.g., the right-hand rule) help road users act in a safe manner (Åberg, 1998). However, road users’ behavior is not only governed by formal traffic rules (Özkan and Lajunen, 2005). For example, a driver may let a cyclist cross first, even when the driver has right of way. One explanation for bicycle-car collisions when a cyclist must have seen the car is that the cyclist anticipates that the driver will yield if slowing down, while in fact, that driver is preparing to make a turn and has not seen the cyclist (Summala and Räsänen, 2000). Thus, it is important that cyclists detect relevant information that can be used for confirming or updating preliminary decisions (Näätänen and Summala, 1974).

In the present study, participants were asked to watch animated video clips from the viewpoint of a cyclist. In these video clips, the cyclist encountered different types of car approach scenarios while cycling towards an uncontrolled four-way intersection. We recorded participants’ eye movements while participants were tasked to indicate continuously whether they believed they or the car(s) would cross the intersection first, by respectively pressing or releasing the spacebar. The aim of this paper is to investigate how cyclist’s eye movements and ‘I will cross the intersection first’ judgments differ as a function of car approach scenario (passing, collision, stopping), traffic complexity (one

vs. two approaching cars), and cycling speed (15, 25, or 35 km/h). The questions addressed in this study are as follows:

1. *How do cyclists’ eye movements and their crossing judgments differ between car approach scenarios at the same four-way intersection?*

Based on previous research (e.g., Chapman and Underwood, 1998; Loftus et al., 1987), we hypothesized that when approaching the intersection, participants focus on a car if the car is relevant to their task of crossing the intersection, while gazing less to the car if it is irrelevant and does not pose an imminent hazard. Further, we expected that crossing judgment continuously changes while approaching an intersection based on traffic rules (i.e., the initial appearance of the car) and visual information (i.e., particular approach scenario). To address this research question, three approach scenarios with one car were created: (a) a car coming from the right and passing in front of the cyclist, (b) impending collision with a car coming from the right, (c) a car coming from the right and stopping.

2. *How do cyclists’ eye movements and their crossing judgments change when traffic complexity increases?*

Based on Werneke and Vollrath (2012) and Wickens et al. (2001), we hypothesized that if traffic complexity increases (i.e., more cars approach the intersection), participants divide their attention between the cars relevant to their task. To investigate this research question, a scenario with two cars was added: a car coming from the right and stopping (same as in approach scenario c) together with a car coming from the left that is also stopping. We hypothesized that crossing judgment is done based on the car that has higher task relevance (in this case the car from the right) and, thus, there will be no difference in crossing judgments between scenarios with one or two cars.

3. *How do cyclists’ eye movements and their crossing judgments differ between three cycling speeds?*

We expected visual tunneling whereby cyclists are more likely to glance at the task-relevant sources of information (i.e., an approaching car) if the cycling speed is higher (Summala and Räsänen, 2000; Rogers et al., 2005; Van Leeuwen et al., 2015). Cycling speeds (15, 25, and 35 km/h) were chosen based on previous experiments showing that conventional, electric, and racing bicycles users differ in their speed choice (Hendriksen et al., 2008; Methorst et al., 2011; Schleinitz et al., 2017).

2. Methods

2.1. Participants

Thirty-seven cyclists (6 females, 31 males) recruited from the Delft University of Technology took part in this study. The age range was 18–27 years ($M = 21.0$, $SD = 2.0$). All participants reported normal or corrected-to-normal vision. Thirty-four participants possessed a driving license ($M = 3.0$ years; $SD = 1.6$). The participants had started cycling at the age of 3–6 years and 32 of them cycled frequently (i.e., at least 3 days per week). The research was approved by the Human Research Ethics Committee of the Delft University of Technology (Ethics application no. 34, 2016), and all participants provided written informed consent. Participants were financially compensated for their time.

2.2. Apparatus

Participants sat approximately 95 cm in front of a 24-inch monitor and rested their head on an adjustable head support. The horizontal field of view (i.e., the size of the screen from the participant’s perspective) was approximately 31 degrees. The eye tracker was placed at 60 cm in front of the participants with the lens centered at the right eye. Viewing was binocular, but only the right eye movements were tracked, at a sampling rate of 2000 Hz using the EyeLink 1000 Plus Eye Tracker (SR Research, Canada). Participants used a keyboard to provide input about whether or not they would cross the intersection first. No sounds were provided during the experiment.

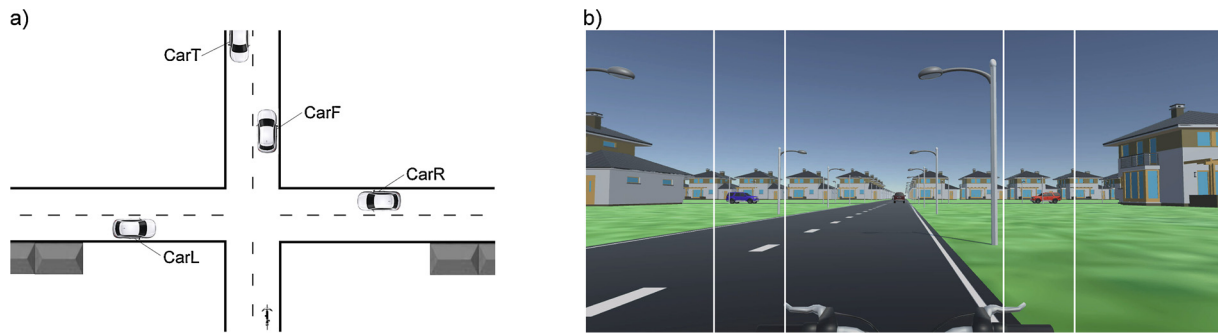


Fig. 1. A four-way uncontrolled intersection shown in the video clips: (a) Schematic top-view of the intersection; (b) Screenshot of scenario R&L stop at 25 km/h. The white vertical lines indicate the areas of interest of CarL and CarR.

2.3. Stimuli

Non-interactive animated video clips were designed, in which a cyclist approached an uncontrolled four-way intersection with 4 m wide two-lane roads in a suburban environment. A car approached the intersection from the right (CarR) or the left (CarL) (Fig. 1). Two more cars were added to the traffic environment in each scenario. One car (CarF) started 40 m in front of the bicycle and drove 20 km/h faster than the cyclist. This car drove away from the cyclist and passed the intersection before CarR and CarL arrived at the intersection. The other car (CarT) drove at a relative velocity of 55 km/h towards the cyclist and did not arrive at the intersection before the video ended.

There were no priority signs and no stop lines, meaning that a vehicle approaching from the right had right of way. The roads were perpendicular to each other, and along each road, there were street lamps.

The cyclist always started at a distance of 100 m in front of the intersection. All videos ended when the cyclist was about 5 m in front of the intersection. Accordingly, the cyclist never crossed the intersection or collided with a car.

Buildings were positioned approximately 30 m from the road (Fig. 1). Participants watched the animated video clips from a first-person perspective. A handlebar was shown at the bottom of the screen to create an impression of cycling. The stimulus materials were built in Unity, a gaming engine. Videos had a frame rate of 30 fps and a resolution of 1920×908 pixels.

Three independent variables were manipulated:

- (1) *Car approach scenario*. The car's motion was manipulated to create the three car approach scenarios:
 - (a) *R passes*. A car came from the right and slowed down. It crossed the intersection while driving at 20 km/h in front of the cyclist.
 - (b) *R collision*. A car came from the right, slowed down to 10 km/h, and continued driving at that speed. It entered the intersection while driving at 10 km/h so that it was on a collision course with the cyclist.
 - (c) *R stops*. A car came from the right and stopped in front of the intersection.
- (2) *Traffic complexity*. The traffic complexity was manipulated by the number of approaching cars.
 - (a) *R stops*. Only one car approached the intersection and stopped in front of the intersection.
 - (b) *R&L stop*. In the 'R stops' scenario, a car from the left was added. Thus, a car came from the right and another car came from the left. Both cars stopped in front of the intersection (see Fig. 1 for a screenshot) but CarL stopped approximately 1.5 s earlier than CarR. Thus, four different intersection scenarios were used in the present experiment: three with one approaching car (i.e., CarR) and one scenario with two approaching cars (i.e., CarR and

CarL).

- (3) *Cycling speed*. The participant could approach the intersection at three different speeds. These speeds were combined with the four intersection scenarios, yielding 12 conditions (i.e., video clips). The three levels of cycling speed variable were:

- (a) 15 km/h (video duration of 22.67 s; CarR appeared in view between 12.87 s and 12.93 s after the start of the video),
- (b) 25 km/h (13.50 s; CarR appeared in view between 3.60 s and 3.77 s after the start of the video),
- (c) 35 km/h (9.70 s; CarR appeared in view between 1.13 s and 1.20 s after the start of the video).

To make sure that the desired scenario occurred at all three cycling speeds, the start of CarR and CarL was triggered when the cyclist was at a certain distance to the intersection. This trigger distance was 60, 100, and 100 m, and the starting distance of CarR and CarL to the intersection was 80, 80, and 50 m, for cycling speeds 15, 25, and 35 km/h, respectively. Both cars were triggered at an initial speed of 40 km/h and decelerated to 20 km/h in 'R passes' (deceleration rate was 2.31 m/s^2), 10 km/h in 'R collision' (2.89 m/s^2), and to 0 km/h in 'R stops' (1.37 m/s^2) and in 'R&L stop' (1.37 m/s^2 and 2.47 m/s^2 for CarR and CarL, respectively).

Three training video clips were shown prior to the experimental video clips, to let the participants familiarize themselves with the task and the virtual environment. The first one contained only CarF. In the second video clip, there was only CarR which behaved the same as it did during the scenario 'R passes'. In the third clip, there was only CarL which behaved the same as CarR in scenario 'R passes' but from the left. During the training clips, the cyclist had a speed of 25 km/h. Additionally, six decoy video clips were played during the experiment to minimize the impression that there was always a car from the right. In the first decoy scenario, there was only CarL; CarL came to a full stop, just as CarL in scenario 'R&L stop'. In the second decoy scenario, neither CarR nor CarL appeared. These decoy scenarios were also combined with the three different cycling speeds. These six decoy scenarios were not included in the present analyses.

Each of the 12 experimental video clips was shown three times, and two decoy scenarios were shown once for each speed. Accordingly, participants viewed 45 videos (i.e., three training, thirty-six experimental, and six decoy video clips).

2.4. Procedure

First, the participants signed the consent form and read a form describing the task instructions and experimental procedures. The form stated that participants had to imagine themselves cycling in a simulated environment. Participants were instructed to indicate whether they would cross the intersection first or whether they would not cross the intersection first by pressing or releasing the spacebar during the video clip, respectively. The form clarified that the animation was not

interactive. That is, participants' input did not influence the behavior of the bicycle. Furthermore, participants were informed that they had to press the spacebar at the beginning of the video (i.e., they *would cross the intersection first*) and that they could press/release the spacebar at any time and for as many times as they would need during the video clip. Finally, the form stated that participants would encounter three different cycling speeds '*slow: cycling speed on a conventional bicycle*', '*medium: cycling speed on a racing bicycle in an urban area*' and '*high: cycling speed on a racing bicycle in a rural area*' for 15, 25, and 35 km/h, respectively. Participants were not informed about the intersection scenarios.

At the beginning of the experiment, the eye tracker was calibrated using a nine-point calibration. All participants were initially shown three training clips. If necessary, instructions regarding the spacebar input were provided again. The experiment was divided into three sets of 14 animations, containing each of the 12 experimental clips and two of the six decoy clips. The 14 video clips were randomized per set using a pseudorandom generator.

Before each video clip, a screen was shown containing the task instructions and the speed of the cyclist in the upcoming animation. The following instructions were given: "Press 'Space-bar' = 'I will cross the intersection first'; Release 'Space-bar' = 'I will not cross the intersection first'; Your velocity will be: Medium". This screen was visible until the participant pressed the spacebar. First, a black screen with a fixation point located in the middle was shown for approximately 1 s, and then the video clip automatically started. No feedback was provided during the experiment.

Following the presentation of the last animated video clip, participants completed a questionnaire containing questions about their background information and yielding behavior in four hypothetical scenarios (Section 2.5.3). The whole experiment lasted about 30 min.

2.5. Measures

2.5.1. Crossing judgments

Mean number of crossing judgment changes. This measure describes how many times the participants changed their crossing judgment when approaching the intersection. The mean number of crossing judgment changes was based on 108 trials (i.e., 36 participants x 3 repetitions) for each of the 12 conditions. The initial judgment was always 'I will cross the intersection first' (i.e., spacebar pressed). Note that the time between the video frame where CarR became visible until the end of the video clip was similar between the three cycling speeds (these durations ranged between 8.50 s and 9.90 s for the 12 videos depending on the intersection scenario and cycling speed).

2.5.2. Eye movements

The following measures were calculated as an average across 108 trials for each of the 12 conditions. The measures were calculated from the first video clip frame where part of CarR became visible till the frame where part of CarR disappeared from view or when the video clip ended (durations ranged between 7.80 s and 9.90 s depending on the intersection scenario and cycling speed). Dynamic areas of interest (AOIs) were used to determine whether the participants were looking at CarR or CarL. The AOIs were defined using vertical lines with a 70-pixel margin on the front of the car, and a 35-pixel margin on the rear of the car (Fig. 1 right).

Dwell time percentage (% of time). This measure represents the percentage of time spent looking at the AOI.

Frequency of entry fixations (Hz). This measure describes the frequency at which the participants' eyes entered and fixated on the AOI.

Mean fixation duration (s). This measure is the average of durations of all fixations on the AOI.

2.5.3. Self-reported yielding behavior

Four yielding behavior items were developed, based on Houtenbos

(2008), who studied driver behavior at intersections that are not regulated by traffic signs. Participants were asked whether they would take priority in four scenarios (see Table 1), and marked their responses by ticking one of the three options: yes, no, unsure.

2.6. Analyses

2.6.1. Processing of crossing judgment and eye-tracking data

One male participant was excluded from the analysis due to a misunderstanding of the crossing judgment task. Data checks further revealed that participants in 14.5% of the 'R passes' trials (out of 324) indicated that they would cross the intersection first at the end of the video clip, even though the car in this scenario had crossed the intersection first. This could mean that these participants interpreted the spacebar task as 'I want to cross the intersection now' rather than 'I would cross the intersection first'. Because such potential misinterpretation does not invalidate the results before entering the intersection, these trials were retained in the analysis.

The eye tracker provided the participants' gaze coordinates on the screen. First, eye blinks were removed through linear interpolation. Extraneous noise in horizontal (x) and vertical (y) directions was filtered using a median filter with a frame size of 100 ms. Second, eye movements were classified into fixations and saccades. A saccade was defined as an interval in which the eye movement speed exceeded 2000 pixels/s (after smoothing of the gaze speed using a 2nd order Savitzky-Golay filter with a 20 ms frame size, i.e., 41 samples at 2000 Hz). Fixations shorter than 40 ms (see also Nyström and Holmqvist, 2010) and fixations longer than 5.0 s (indicating prolonged staring towards one point in the scene) were removed from the analysis.

2.6.2. Analyses and statistical tests

Because the videos featured a dynamic chain of events, we first visualized participants' crossing judgments and eye movements as a function of elapsed time in the video clip to gain an insight into participants' aggregate hazard anticipation. Next, we proceeded with an analysis of averages calculated across the time windows when CarR was visible. Differences between the 12 conditions were analyzed with two-way repeated measures analyses of variance (ANOVA). First, an ANOVA was performed with the car approach scenario ('R passes' vs. 'R collision' vs. 'R stops') and the cycling speed (15 km/h vs. 25 km/h vs. 35 km/h), as independent variables. Second, an ANOVA was performed with traffic complexity (CarR in 'R stops' vs. CarR in 'R&L stop') and cycling speed (15 km/h vs. 25 km/h vs. 35 km/h) as independent variables. The effect size was reported as partial eta squared, η^2 (Cohen, 1988).

3. Results

3.1. Self-reported yielding behavior

The results for the yielding behavior questionnaire (Table 1) showed that none of the participants would take priority if a car from the right does not slow down, whereas 11% of the participants reported taking priority if the car from the right does slow down. The percentage of participants who reported taking priority was higher when the car would approach from the left as compared to when the car would approach from the right (8% vs. 0% and 92% vs. 11% for the car does not slow down and the car slows down, respectively).

3.2. Crossing judgments

As can be seen in Fig. 2, participants changed their initial 'I will cross first' judgment to 'I will not cross first' judgment within 2 s after CarR appeared from behind the building in approximately two-thirds of the trials, for each of the 12 conditions. The crossing judgments had a similar pattern for the three cycling speeds, but there were clear

Table 1Self-reported yielding behavior ($n = 36$) in four scenarios. Dashed lines indicate that the car slows down and the solid lines indicate that the car does not slow down.

Would you take priority?				
Yes	0%	11%	8%	92%
No	97%	58%	72%	3%
Unsure	3%	31%	20%	5%

differences between the four scenarios (Fig. 2).

In the 'R passes' scenario, the 'I will cross first' judgment showed a decreasing trend from 100% to about 10%. In the 'R stops' and 'R&L stop' scenarios, the majority of the participants changed their initial 'I will cross first' judgment to 'I will not cross first' judgment, and changed back to 'I will cross first' after CarR had come to a stop (Fig. 2). In the 'R collision' scenario, participants were more likely to indicate 'I will cross first' judgment while CarR was approaching the intersection compared to the other three scenarios. This can be explained by the strong deceleration from 40 km/h to 10 km/h after which CarR continued moving slowly at 10 km/h (see the rise after the pink vertical line in Fig. 2). When CarR got closer to the intersection, participants gradually changed their judgment to 'I will not cross first', as it became clear that CarR would enter the intersection before the cyclist.

On average (Table 2), participants changed their judgments the lowest number of times in the 'R passes' scenarios (mean = 1.24, $SD = 0.33$), followed by 'R stops' (mean = 1.69, $SD = 0.52$), 'R&L stop' (mean = 1.72, $SD = 0.57$), and 'R collision' (mean = 1.76, $SD = 0.69$). The number of crossing judgment changes significantly differed between three car approach scenarios ($F(2,70) = 13.638$, $p < 0.001$, $\eta^2 = 0.280$). Furthermore, participants changed their crossing judgment more times when watching video clips at 15 km/h compared to other two speeds ($F(2,70) = 5.009$, $p = 0.009$, $\eta^2 = 0.125$). The interaction 'car approach scenario x cycling speed' was not significant ($p = 0.663$).

There was no significant effect of traffic complexity ($F(1,35) = 0.680$, $p = 0.415$, $\eta^2 = 0.019$) nor of cycling speed ($F(2,70) = 2.823$, $p = 0.066$, $\eta^2 = 0.075$) on the number of crossing judgment changes in the two stop scenarios. The interaction 'traffic complexity x cycling speed' was not significant either ($p = 0.959$).

3.3. Eye movements

3.3.1. Gaze distribution

Fig. 3 shows the aggregate distributions of the 12 conditions of participants' horizontal eye movements. In all 12 conditions, participants looked mostly straight ahead and sampled both crossroads before CarR appeared. Gaze was directed primarily (about 80% in all 12 conditions) at CarR right after the car appeared in view. The participants spent more time looking at CarR than at the road ahead or at the left crossroad during the time interval when CarR was approaching the intersection.

Differences in gaze distribution between the scenarios occurred when the car was close to the intersection. In 'R passes', the dwell time percentage on CarR was about 95% when the car entered the intersection, and dropped quickly after the car had crossed the intersection. In 'R stops', a maximum dwell time of 95% was reached just before the car came to a standstill, and dropped quickly afterward. In 'R collision', the dwell time percentage on CarR increased to nearly 100% when CarR entered the intersection.

Participants distributed their gaze comparably between CarR and CarL when both cars were moving (Fig. 3). Similar to 'R stops', participants in 'R&L stop' reduced glancing at CarL directly after it came to a standstill. A maximum dwell time percentage of around 40% on CarL was reached prior to when the car came to a full stop, after which participants primarily directed their gaze to the moving CarR. Overall, the dwell time percentage was higher on CarR than on CarL.

Figs. 4 and 5 show that participants' dwell time percentage on CarR was higher in 'R collision' (mean = 77.28%, $SD = 8.40$) than in 'R passes' (mean = 66.83%, $SD = 7.66$), 'R stops' (mean = 64.76%, $SD = 10.12$), and 'R&L stop' (mean = 46.62%, $SD = 9.00$). The dwell

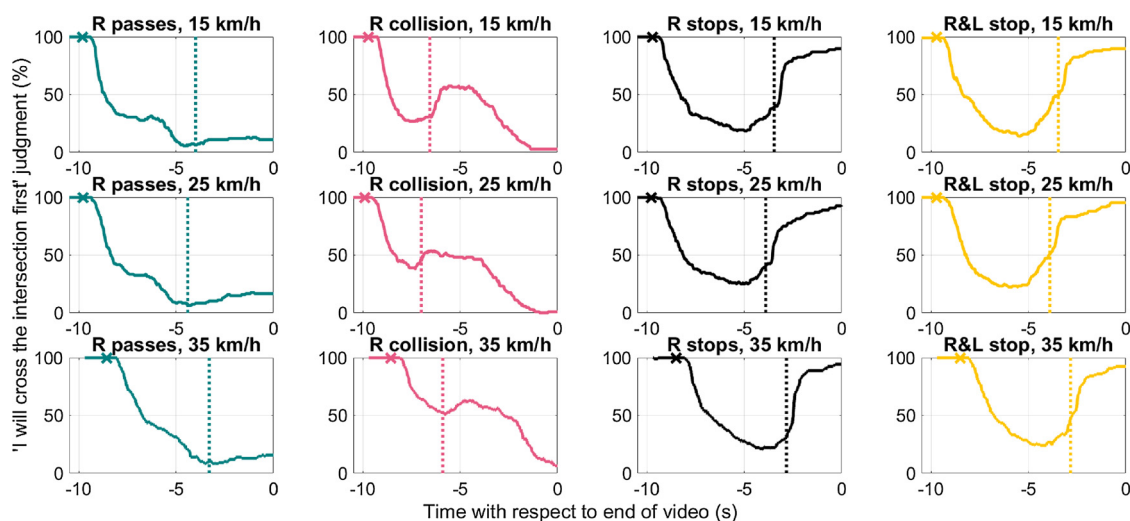


Fig. 2. Percentage of 'I will cross first' judgments for the four intersection scenarios at three cycling speeds. The 'x' symbols at the left top indicate when CarR became visible. The vertical lines indicate the moment when CarR entered the intersection ('R passes' scenario), stopped decelerating and continued moving at a constant speed of 10 km/h ('R collision' scenario), or came to a full stop ('R stops' and 'R&L stop' scenarios).

Table 2

Number of trials in which participants' judgment changed (from 'I will cross first' to 'I will not cross first', or from 'I will not cross first' to 'I will cross first') ($n = 108$ trials for each row), and mean and standard deviation of the mean number of judgment changes at the level of the participants ($n = 36$).

	0 changes <i>I will cross first</i>	1 change <i>I will not cross first</i>	2 changes <i>I will cross first</i>	3 changes <i>I will not cross first</i>	4 changes <i>I will cross first</i>	5 or 7 changes <i>I will not cross first</i>	Number of judgment changes Mean (SD)
R passes 15 km/h	0	88	10*	8	2*	0	1.30 (0.52)
R passes 25 km/h	4*	87	13*	3	1*	0	1.17 (0.35)
R passes 35 km/h	3*	84	14*	5	0	2	1.27 (0.49)
R collision 15 km/h	1	60	2	40	0	5	1.94 (0.89)
R collision 25 km/h	0	73	1	32	0	2	1.68 (0.80)
R collision 35 km/h	2	74	3	23	2	4	1.66 (0.87)
R stops 15 km/h	13	11	78	0	6	0	1.77 (0.62)
R stops 25 km/h	19	8	79	1	1	0	1.60 (0.60)
R stops 35 km/h	18	6	80	0	4	0	1.69 (0.65)
R&L stop 15 km/h	11	11	81	1	4	0	1.81 (0.61)
R&L stop 25 km/h	18	5	83	0	2	0	1.66 (0.64)
R&L stop 35 km/h	17	8	78	0	5	0	1.70 (0.67)

Notes. The final judgment for each spacebar change is indicated in Italics.

* The opposite judgment from what would be expected (i.e., the participant did not cross the intersection first in the animated video clip).

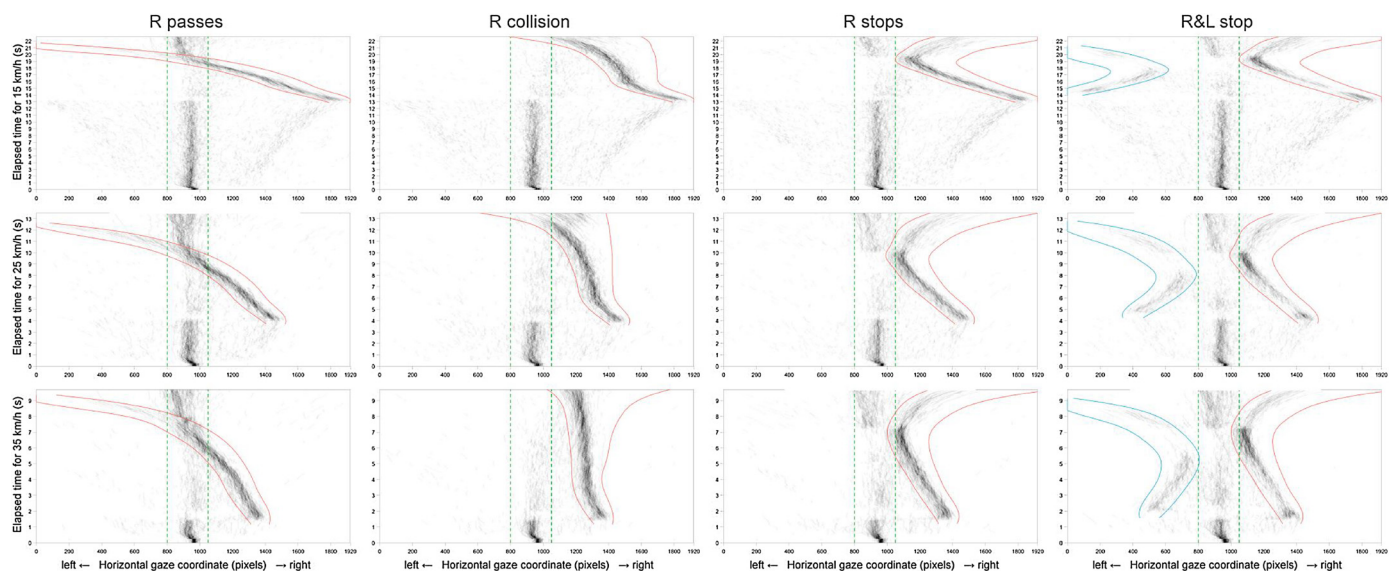


Fig. 3. Distribution of the horizontal gaze coordinate for the four intersection scenarios at three cycling speeds. The grayscale runs from 0 (no sampling at that coordinate) to 1 (maximum value). The red and blue lines represent the AOIs of CarR and CarL, respectively. The dashed vertical lines represent the approximate boundaries of the road. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

time percentage strongly and significantly differed between three car approach scenarios ($F(2,70) = 73.384$, $p < 0.001$, $\eta^2 = 0.677$) but it did not significantly differ between three cycling speeds ($F(2,70) = 1.683$, $p = 0.193$, $\eta^2 = 0.046$). The interaction effect 'car approach scenario x cycling speed' was small yet statistically significant ($F(4,140) = 2.768$, $p = 0.030$, $\eta^2 = 0.073$). In 'R stops', dwell time percentage on CarR decreased with increasing speed, whereas speed did not clearly affect dwell time percentage in 'R passes' and 'R collision' (Fig. 4 top).

Concerning traffic complexity, the dwell time percentage on CarR was lower in 'R&L stop' compared to 'R stops' (Fig. 5, top). This was supported by an ANOVA, indicating a strong and significant effect of traffic complexity ($F(1,35) = 271.555$, $p < 0.001$, $\eta^2 = 0.886$) and a moderate effect of cycling speed ($F(2,70) = 10.901$, $p < 0.001$, $\eta^2 = 0.237$), whereas the interaction effect 'traffic complexity x speed' was not significant ($p = 0.910$).

3.3.2. Entry fixations

As shown in Fig. 4 (middle), participants fixated on CarR at similar frequencies in 'R passes' (mean = 0.47, $SD = 0.11$), 'R collision' (mean = 0.46, $SD = 0.13$), and 'R stops' (mean = 0.49, $SD = 0.13$).

Further, participants fixated on CarR at slightly higher frequency in 'R&L stop' (mean = 0.53, $SD = 0.11$) compared to 'R stops' indicating that traffic complexity resulted in higher eye-movement activity (Fig. 5 middle). In addition, participants fixated at lower frequency CarL compared to CarR in 'R&L stop'.

There were no statistically significant differences in the frequency of entry fixations on CarR between three car approach scenarios ($F(2,70) = 1.943$, $p = 0.151$, $\eta^2 = 0.053$) and neither between the three cycling speeds ($F(2,70) = 0.854$, $p = 0.430$, $\eta^2 = 0.024$). The interaction effect 'car approach scenario x cycling speed' was not significant ($p = 0.117$).

An ANOVA showed a significant effect of traffic complexity ($F(1,35) = 9.833$, $p = 0.003$, $\eta^2 = 0.219$) and no significant effect of speed ($F(2,70) = 0.216$, $p = 0.806$, $\eta^2 = 0.006$) on the frequency of entry fixations to CarR in the two stop scenarios. The interaction effect 'traffic complexity x cycling speed' was not significant ($p = 0.163$).

3.3.3. Fixation duration

The mean fixation duration on CarR varied as a function of elapsed time in the video clips (Fig. 6). In 'R passes', participants showed relatively long fixations on CarR when the car was approaching the

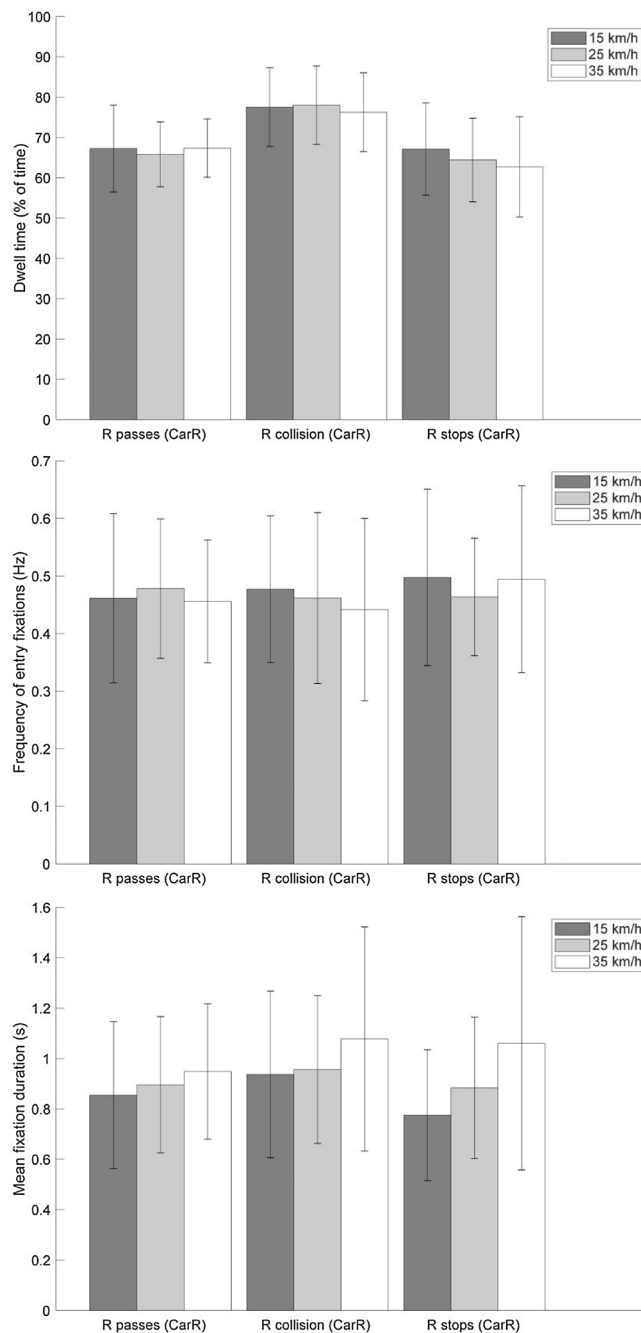


Fig. 4. Dwell time (top), frequency of entry fixations (middle), and mean fixation duration (bottom) for three car approach scenarios at three cycling speeds. The corresponding AOI is mentioned in parentheses. The error bars represent the mean $\pm$ 1 standard deviation across the 36 participants.

intersection, and fixation durations decreased after CarR had entered the intersection. In 'R stops', participants showed elevated fixation durations on CarR just before CarR came to a standstill at the intersection. In 'R collision', fixation durations on CarR were high during the entire period when CarR was approaching the intersection. Finally, in 'R&L stop', participants showed short fixations on CarR when CarR was approaching the intersection (presumably because attention had to be shared with CarL, which was approaching at the same time), but long fixations just before CarR came to a standstill (as in 'R stops' scenario).

Compared to 'R stops', participants in 'R&L stop' showed shorter fixation durations on CarR (Fig. 5 bottom), but the mean fixation durations followed the same pattern. Fig. 5 (bottom) shows that mean

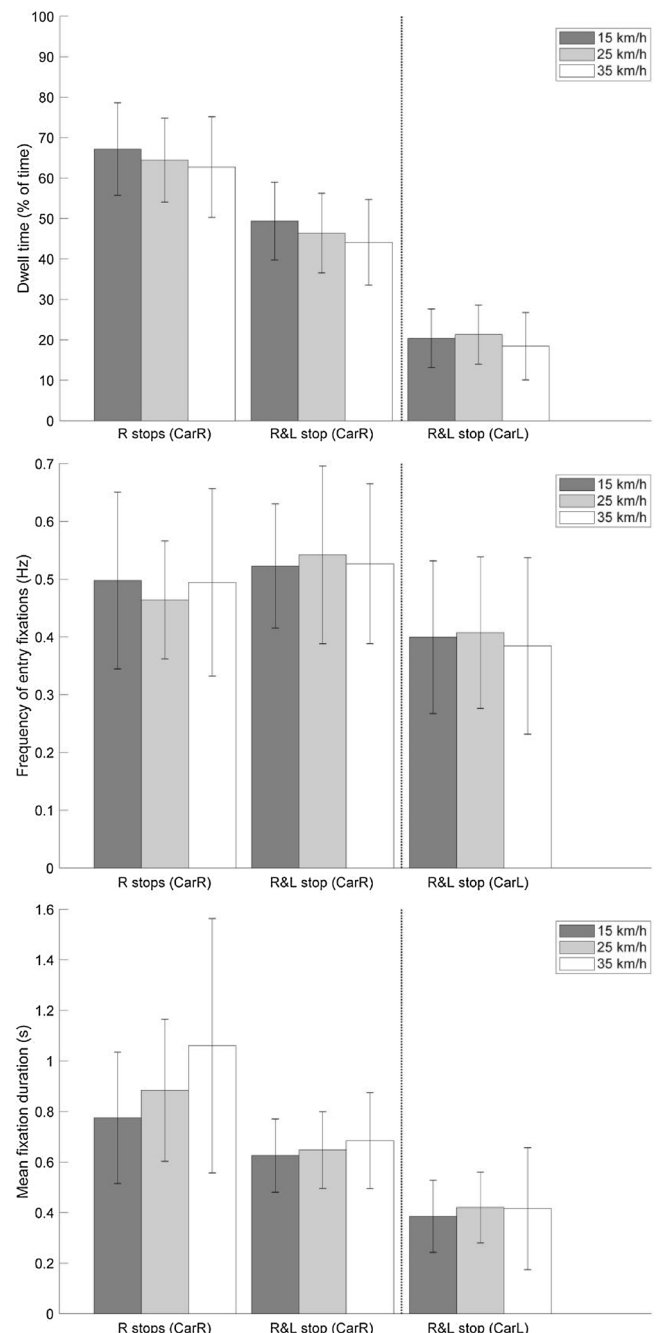


Fig. 5. Dwell time (top), frequency of entry fixations (middle), and mean fixation duration (bottom) for two traffic complexity conditions at three cycling speeds. The corresponding AOI is mentioned in parentheses. The error bars represent the mean $\pm$ 1 standard deviation across the 36 participants.

fixation durations on CarL were lower than mean fixation durations on CarR.

Fixation durations on CarR were higher in 'R collision' (mean = 0.99, SD = 0.30) compared to 'R passes' (mean = 0.90, SD = 0.22) and 'R stops' (mean = 0.91, SD = 0.28). In 'R&L stop', participants' fixation durations on CarR were the shortest (mean = 0.65, SD = 0.13). Mean fixation durations on CarR (Fig. 4 bottom) significantly differ between the three car approach scenarios ($F(2,70) = 3.800$, $p = 0.027$, $\eta^2 = 0.098$). The fixation durations were significantly longer when cycling speed was higher ($F(2,70) = 11.795$, $p < 0.001$, $\eta^2 = 0.252$). The interaction effect 'car approach scenario $\times$ cycling speed' was not significant ($p = 0.171$).

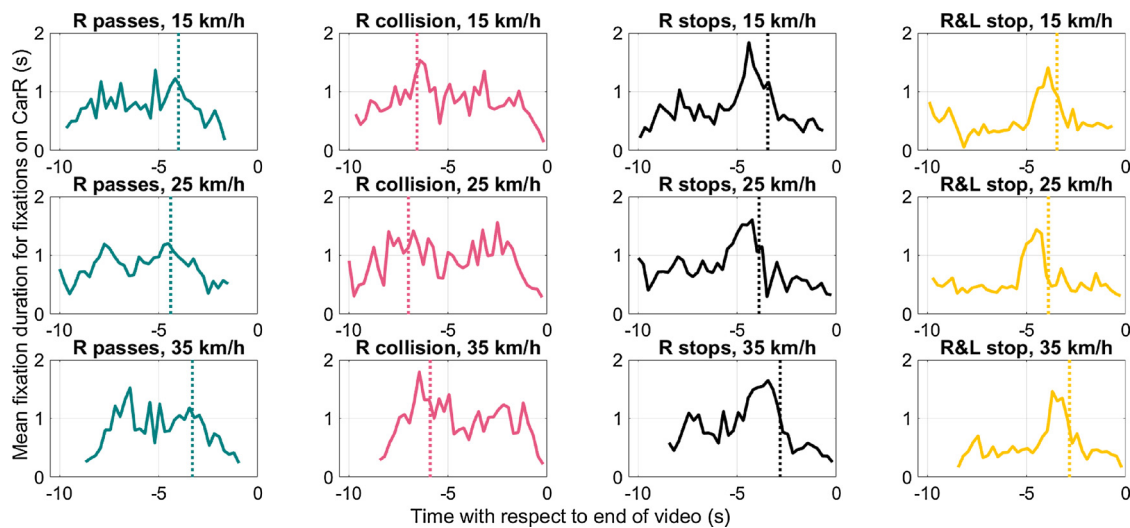


Fig. 6. Mean fixation duration on CarR as a function of elapsed video time for the four intersection scenarios at three cycling speeds. The vertical lines indicate the moment when CarR entered the intersection ('R passes' scenario), stopped decelerating and continued moving at a constant speed of 10 km/h ('R collision' scenario), or came to a full stop ('R stops' and 'R&L stop' scenarios). Data are shown from when CarR became visible from behind the building until the car disappeared from the view, or when the video clip stopped. Mean fixation durations are calculated per bin of 250 ms.

Traffic complexity (i.e., 'R stops' vs. 'R&L stop') resulted in shorter fixation durations on CarR (Fig. 5 bottom). The ANOVA showed a significant effect of traffic complexity ($F(1,35) = 61.016$, $p < 0.001$, $\eta^2 = 0.635$) and speed ($F(2,70) = 9.671$, $p < 0.001$, $\eta^2 = 0.216$) on the mean fixation duration in the two stop scenarios. The interaction effect 'traffic complexity x cycling speed' was significant ($F(2,70) = 5.901$, $p = 0.004$, $\eta^2 = 0.144$). This interaction effect is because the fixation duration on CarR increased with increasing speed in 'R stops', yet was relatively similar for the three speeds in 'R&L stop' (Fig. 5).

3.4. Combined analysis of eye movements and crossing judgments

Above, we analyzed whether participants looked at CarR (dwell time in Figs. 4 and 5, heat maps in Fig. 3) and whether participants indicated to cross the intersection first or not as the situation evolved (Fig. 2). In this section, we provide a more in-depth analysis of the interaction between gaze behavior and crossing judgments. More specifically, Fig. 7 shows whether (green lines) or not (black lines) participants were looking at CarR while indicating 'I will cross first' (solid lines) or 'I will not cross first' (dotted lines) as a function of elapsed time.

In 'R passes', participants were likely to look at CarR and indicate 'I will not cross first' judgment before CarR crossed the intersection (i.e., a high value of the green dotted line). After CarR passed the intersection, participants often did not look at CarR anymore while still indicating 'I will not cross first' judgment (i.e., a high value of the black dotted line).

In 'R stops' scenario, participants looked at CarR and indicated 'I will not cross first' judgment before CarR stopped (i.e., a high value of the green dotted line). After CarR had stopped, participants looked considerably less at the car and indicated they would cross first (i.e., a relatively high value of the black solid line). Participants were looking less at CarR in 'R&L stop' than in 'R stops' while indicating their crossing judgment (i.e., a relatively high value of black dotted line). The results for the 'R&L stop' scenario were similar to the 'R stops' scenario after CarL had come to a stop.

Regarding 'R collision', it can be seen that participants were looking at CarR in a high percentage of trials regardless of their judgment input (i.e., high values of both green lines). To illustrate, between -7 s and -4.5 s, approximately half of the participants were indicating the 'I will cross first' judgment whereas the other half indicated 'I will not cross first' judgment (Fig. 7), suggesting that participants kept looking at

CarR because they were uncertain about whether CarR would cross first. Near the end of the video clip, nearly all participants looked at CarR and made 'I will not cross first' judgment (i.e., a high value of the green dotted line).

4. Discussion

Accident statistics indicate that crashes between cyclists and car drivers at intersections occur even when the cyclist must have seen the approaching car, suggesting the importance of hazard anticipation issues and expectancy (Räsänen and Summala, 1998). To understand how cyclists anticipate potential hazards at intersections, we examined how the motion of an approaching car (culminating in safe and collision scenarios between the cyclist and the car) and traffic complexity (i.e., one versus two approaching cars) are associated with cyclists' eye movements and crossing judgments. Further, we investigated the effect of the cyclist's approach speed on visual patterns and crossing judgments.

In line with Van Loon et al. (2010), participants spent more time looking at the approaching car(s) than to the rest of the visual scene. Participants looked at the approaching car when the car was still relevant to the task of crossing the intersection and focused on the road ahead when the car did not pose an imminent hazard anymore. Once the car had stopped (as shown in 'R stops' and 'R&L stop' scenarios) or once the car had passed the intersection (as shown in 'R passes') participants paid considerably less attention to it. In 'R collision', participants kept looking at the car until the end of the video clip even when they already indicated they would not cross the intersection first. We conclude that cyclists ignore the car and direct their attention to the road ahead only when they can be certain that the car does not pose a threat.

Fixation durations were elevated right before the car came to a full stop or entered the intersection. This may reflect in-depth processing (Crundall et al., 1999, 2002; Chapman and Underwood, 1998; Velichkovsky et al., 2002) whereby the cyclist tries to ascertain whether the car stops or not. In addition, significantly longer fixations were observed in the collision scenario compared to the two safe scenarios, suggesting a narrowing focus to the threatening object (Underwood et al., 2003).

As expected, traffic complexity resulted in divided attention between two approaching cars and gazing to the right car at a higher frequency. After the car approaching the intersection from the left had

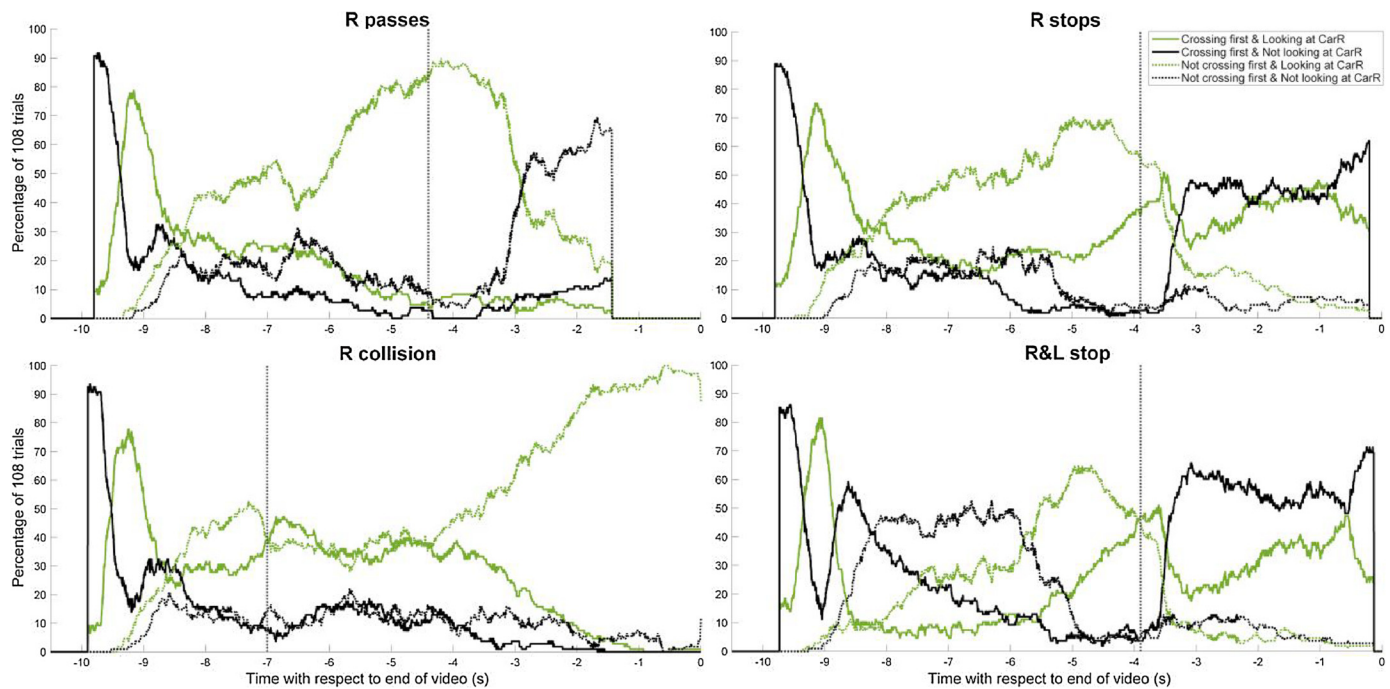


Fig. 7. Percentage of trials in which participants looked (green lines) or did not look (black lines) at CarR while indication ‘I will cross first’ (solid lines) or ‘I will not cross first’ (dotted lines) judgments as a function of elapsed video time for four intersection scenarios for cycling speed of 25 km/h. The vertical lines indicate the moment when CarR entered the intersection (‘R passes’ scenario), stopped decelerating and continued moving at a constant speed of 10 km/h (‘R collision’ scenario), or came to a full stop (‘R stops’ and ‘R&L stop’ scenarios). The four reported percentages add up to 100%. Results follow a similar pattern for the other two cycling speeds (see [Appendix A](#)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

stopped, participants focused their attention predominantly to the right car, which still posed a hazard and had higher relevance to the crossing task. Even though participants spent less time looking at the car from the right and also fixated it with shorter durations at higher traffic complexity, there were no significant differences in crossing judgments between the two traffic complexities. This suggests that participants made their judgments based on the car that had a higher relevance to the task (in this case the right car). This finding is consistent with the self-reports, in which participants were more likely to yield to a car approaching from the right than to a car from the left.

Participants changed their initial “I will cross the intersection first” judgment once the car from the right appeared in view and updated this judgment based on how the traffic situation unfolded. These findings indicate that both visual information (i.e., bottom-up cues) and expectancies (i.e., top-down cues) guide cyclists’ crossing judgments (see also [Underwood, 2007](#)). In approximately two-thirds of the trials, participants indicated that they would not cross the intersection first once the right car had appeared from behind the building (see [Fig. 2](#)), which is consistent with the self-reported yielding behavior (see [Table 1](#)) which showed that participants are likely to yield to a car having right of way (i.e., a car from the right). The participants updated their crossing judgments when relevant discrete events (i.e., car stopping, car passing the intersection) occurred in the environment. These results can be interpreted using gap acceptance research (e.g., [Chihak et al., 2010](#); [Louveton et al., 2012](#)) which showed that when road users approach an intersection, they first slow down (a period where they can be assumed to gaze at the approaching vehicle) and accelerate to cross the gap at the right time. Similarly, directly after the discrete event, participants in our study stopped looking at the approaching car and indicated that they would like to cross.

The results from the present study indicate that cyclists are responsive to discrete events. However, a clear perceptual event did not occur in the collision scenario, which involved ongoing uncertainty about whether the car would stop or not. Cyclists might expect that a car having right of way is yielding when it has slowed down, while in

fact, the driver might not slow down because of the cyclist ([Summala and Räsänen, 2000](#)). Our results of the ‘Collision R’ scenario are representative of this problem, as participants were likely to provide “I will cross the intersection first” judgments while the vehicle was slowing down yet not yielding to the cyclist. More research should be conducted to understand which visual cues cyclists should pick up to be able to predict hazardous outcomes at intersections.

Overall, participants spent a similar amount of time looking at the car even though the cycling speeds were vastly different (15, 25, and 35 km/h). The results showed moderate but statistically significant effects of cycling speed on the fixation duration, with higher speeds corresponding to longer fixation durations. One plausible explanation for the lack of strong effects of cycling speed on cyclists’ eye movements is that cycling speeds are considerably lower than typical driving speeds; in driving tasks it has been found that drivers reduce their horizontal gaze variability as driving speeds increase ([Rogers et al., 2005](#); [Van Leeuwen et al., 2015](#)). Another explanation is that participants did not have to control the bicycle, and so could safely direct their visual attention away from the road. Small differences in the number of crossing judgment changes were found between the three speeds. However, the same pattern of crossing judgment changes was observed across all three cycling speeds suggesting that participants’ crossing judgments were governed by the motion of the car rather than by cycling speed.

Several limitations have to be taken into account when interpreting the results of this study. First, we asked participants to indicate their crossing judgment by means of the spacebar. This task may have been confusing because video clips were non-interactive. In reality, it may be more intuitive to brake prior to entering the intersection than to indicate who will cross the intersection first. Second, the participants were watching the videos on a computer screen with a limited field of view and a simple virtual environment. A large field of view and being involved in a physical cycling task may enhance situation awareness compared to passive observation. This limitation could be addressed by using an immersive cycling simulator (e.g., [Chihak et al., 2010](#);

Grechkin et al., 2013). Third, in this study, we manipulated only the car's motion, whereas in reality a cyclist can extract various visual cues that are indicative of a driver's intentions, such as arm motion, lighting the high beams, eye contact, and head movement (e.g., Renge, 2000). Fourth, participants watched video clips while not controlling the bicycle. The actual control of a bicycle may place additional demands on a person's gaze behavior, as the road ahead might be more relevant to scan for active cyclists than for passive viewers (Zeuwts et al., 2016). Mackenzie and Harris (2015) found that scan patterns were wider for participants who we asked to observe the road as compared to participants were asked to drive themselves. Thus, it is possible that the passive viewing of the video clips allowed our participants to gaze longer on the right and left roads where the approaching cars were located than it would be possible when controlling a bicycle. Finally, the role of traffic complexity and traffic rules deserves further investigation. In this study, CarR always had right of way and CarL always stopped. In reality, intersections can be busier and a car driver without right of way can violate traffic rules.

5. Conclusions and recommendations

In conclusion, visual behavior and crossing judgments of cyclists approaching uncontrolled intersections differ between situational aspects of safe and collision outcomes, locations of cars at the intersection, and traffic complexity. Cyclists are more inclined to look at a car that is on a collision course (i.e., a car approaching an intersection) than at a car that has already passed an intersection or a car that has stopped in front of the intersection. The effect of cycling speed on dwell time, fixation durations, and crossing judgments is small to moderate.

It remains to be investigated which cues guide cyclists anticipation and whether cyclist can perform a satisfactory braking maneuver in collision scenarios where the driver has not seen the approaching cyclist. Knowledge of cyclists' gaze and crossing behavior in safe and collision scenarios could prove useful in the development of training programs for cyclists, as well as in the design of intersection warning systems and vehicle-to-vehicle communication technologies.

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Appendix A. Supplementary material

Supplementary data, scripts, and video clips are available at: <https://doi.org/10.4121/uuid:1d8ddcd0-5139-4ada-81a1-9f34c9f70c88>.

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