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Changes of drivers’ visual performances when approaching a signalized intersection under different collision avoidance warning conditions

Yuting Zhang¹, a, Xuedong Yan¹, b, Xiaomeng Li¹, c, Jiawei Wu², d

¹MOE Key Laboratory for Urban Transportation Complex Systems Theory and Technology, School of Traffic and Transportation, Beijing Jiaotong University, Beijing, 100044, P. R. China
²Center for Advanced Transportation System Simulation, Department of Civil Environment Construction, Engineering, University of Central Florida, Orlando, Florida, USA

*15114233@bjtu.edu.cn, bxdyan@bjtu.edu.cn (corresponding author), c13114249@bjtu.edu.cn, dwjw345178371@knights.ucf.edu

Abstract: Intersections have been recognized as hazard locations with lots of visual information that drivers need to process. Although the collision avoidance systems (CASs) have been proved to effectively reduce the crash rate and much research on the effectiveness of CASs has been conducted with regard to the driving behaviors, drivers’ visual performances under the effects of different collision avoidance warning conditions that were closely related to the effectiveness of CAS have been neglected. In this study, a driving simulator experiment was conducted to evaluate the relationships among drivers’ visual performances, drivers’ different warning conditions (warning timings × warning content) and driver’s gender when they crossed the intersections involved with red-light running (RLR) vehicles. The experimental results showed that warning timings had significant effects on the detection stage and reaction stage. Specifically, drivers could detect the conflicting RLR vehicle most quickly in the warning timings of 4.5 s ahead of a collision. When the warning was released earlier than 5.0 s ahead of a collision, driver tended to take brake action earlier than paying a fixation on a conflicting RLR vehicle. Warning content only had significant effects on drivers’ detection stage. Compared to the non-directional warning, the specific directional information could shorten the time spent in detecting the conflicting RLR vehicle. Besides, directional information could increase drivers’ average blink duration during the process of collision avoidance. Additionally, the results showed that female drivers were more likely to be involved with RLR collisions, and male drivers could detect the conflicting RLR vehicle more quickly than female drivers. Also, it had been found that later warning timings tended to increase female drivers’ blink rate, and non-directional warning tended to increase female drivers’ blink rate. These findings could direct warning condition design to improve the effectiveness of collision avoidance systems.

Keywords: Collision avoidance system; Warning timings; Warning content; Visual performances; Driving simulator; Red-light running
1. Introduction

Intersections have been recognized as a complicated and hazardous roadway environment to drivers (Tay, 2015). Driving crossing an intersection is a complex task with the presence of signals, guide signs for street names, indications of upcoming turn lanes, conflict traffic, exclusive left turn and right turn lanes, and other ancillary facilities associated with intersections create a high degree of conflict, which heavily relies upon the visual element (Dong et al., 2014). Drivers need to perceive, identify and anticipate road elements and other road users’ behaviors while maintaining an appropriate control of steering and speed. Once emergency events or suspected targets occur, drivers have to pay and shift attention to process a large amount of visual and spatial information quickly, and to respond properly in order to cross the intersection successfully in order to avoid crashes.

Recently, the collision avoidance system (CAS) are designed to direct a driver’s attention to an impending crash and to initiate an avoidance maneuver appropriately. The increasing developments of CAS have potential in reducing the number and severity of collisions (e.g., Wu et al., 2014; Becic et al., 2013; Fort et al., 2013; Tanaka et al., 2010; Chang et al., 2009). Many studies have researched on the effects of different warning conditions of CAS on driving behaviors (e.g., Winkler et al., 2016; Xiang et al., 2015; McGehee et al., 2002). For the modality of warning, visual warning, tactile warning and auditory warning were widely discussed in past research. Compared to visual warning and tactile warning, auditory warning can provide omnibearing sound signals to ensure that drivers could receive the warning no matter where they were focused on, and it would not damage visual attention (Haas and Edworthy, 2006). Besides, the auditory warning form is more applicable than the other forms because it can be easily embedded into GPS that are equipped in the majority of vehicles (Regan et al., 2006). For the warning timings, drivers could avoid most collisions if the warning messages were delivered in advance of the potential accidents with sufficient amount of time. The later warning condition was also able to reduce collisions, but it was less effective than the earlier warning condition (Lee et al., 2002). In the earlier warning condition, drivers had significantly shorter accelerator release reaction times, fewer crashes, and less severe crashes (e.g., Werneke and Vollrath, 2013; Abe and Richardson, 2004; McGehee et al., 2002). For the warning content, compared to the simple beep sound, speech messages were suggested because they could lead to a significant reduction of perception-reaction time of drivers (Chang et al., 2008). The verbal auditory warning could provide the drivers time-critical information which aimed at avoiding impending disaster calmly, rather than the nonverbal warning in high-pitched, high-rate tones that is likely to startle the listener (e.g., Edworthy et al., 2003).

Among the different types of warning conditions, the directional information of warning content would be one of the important factors. It could inform drivers with the orientation of potential collisions at intersections. Such information is supposed to reduce drivers’ mental workload by narrowing their vision of attentions and therefore it might help drivers take timely crash avoidance actions. However, Yan et al. (2014) concluded that a directional warning may delay the mental processing of the warning information and cause insufficient decelerations under a late warning timing (3 second). Thus, the interaction effects of directional information and warning timings might result in various crash avoidance performances, which would be inspected in this study.
Previous studies have shown that collisions related with intersections are mostly caused by poor visibility of intersection control devices or illegal vehicle who fails to observe traffic regulations (e.g., Yan et al, 2007). For example, the red-light running (RLR) crash could be made by vertical visibility blockage of larger size vehicles when passing an intersection (e.g., Harb et al, 2007). Hence, ignoring influence of different warning conditions based on eye movements on RLR related crash occurrence will miss an opportunity to reveal any true underlying association between warning conditions and effectiveness of CASs. Besides, people’s eyes collect the information to keep the drivers driving safely, and the eye movements are essential to carry the visual attention and then to collect vital visual information to be processed by the brain. Thus, a better understanding of the effects of the warning conditions on drivers’ changes of eye movements is required, which would help the design of CAS to fit well with drivers’ expectations.

Of all the eye-related measures, eye blinking is often used as a potential indicator to provide a useful and reliable signal of drivers’ mental workload variations (e.g., Faure et al., 2016; Savage et al., 2013). Blink frequency has association with mental workload depending on whether it comes from the primary task difficulty or from the presence of a concurrent secondary task (e.g., Lehtonen et al., 2012; Konstantopoulos et al., 2010), and blink inhibition could be regarded as a mechanism to cope with the increased task demands by reducing the risk of missing incoming information (e.g., Fogarty and Stern, 1989; Recarte et al., 2008). Besides, pupil diameter has also been used in the past studies, especially in the dual-tasking driving (e.g., Demberg et al., 2013; Palinko et al., 2010), which reported that pupils dilate in response to the task demand, and the pattern of an increasing pupil diameter is consistent across different mental tasks. Indeed, the eye-movement recording methodologies are very popular in driving research (e.g., Shinar, 2008).

The objective of this study is to investigate the effects of different warning conditions of CAS and gender on drivers’ collision avoidance performances considering drivers’ eye movement data when encountering conflicting RLR vehicles at signalized intersections. Specifically, a conceptual relationship between dependent variables and independent variables during the process of collision avoidance was shown in Figure 1. As Figure 1 shown, the factors considered in this study included different warning conditions of CAS (warning timings × warning content) and drivers’ gender. The process of collision avoidance could be divided into two stages in this study: detection stage and reaction stage. The two stages might result in drivers’ successfully avoiding a collision from the conflicting RLR vehicle. The dependent variables of first fixation time on the RLR vehicle (FFT) and perception-reaction time (PRT) represented these two stages, respectively. Thus, the influences of different warning conditions and gender for these two stages of collision avoidance and collision results were explored in this study. Besides, drivers’ eye movements such as blink and pupil diameter during the process of collision avoidance were also analyzed. Additionally, the simulated driving is conducted, which are usually safer than naturalistic driving research and are relatively easy to collect data.
In this study, several hypotheses were established as following.

- Collision avoidance warning could help reduce RLR collision rate through improving drivers’ abilities to detect and respond RLR collisions quickly.
- Collision avoidance warning could direct their fixations to the conflicting RLR vehicles, which allow drivers to have adequate time for proper response.
- The proper collision avoidance warning timings could shorten drivers’ detection time to the RLR vehicles.
- The collision avoidance warning with detailed direction of conflicting RLR vehicles could help drivers collect critical information and reduce the workload in information processing.
- Combined with the different warning timings, the specific directional information would lead to different visual performances. Compared to the earlier warnings, the specific directional information would play a more important role in helping narrow drivers’ scanning and locate the potential threat quickly in the later warning timings.

The results of this study could provide a reference for the optimal range of warning timing and recommend warning condition for collision at intersections.

2. Methodology

2.1 Participants. Twenty-four participants (11 male drivers and 13 female drivers) who had no long-term or short-term health problems according to their self-reports were recruited, and they were all young mature drivers aging from 31 to 39 (Mean =35 years old). A valid Beijing’s driver license with at least three years driving experience was required for each participant, and the participants who suffered from motion sickness in a test driving were excluded from the formal experiment. The experiment lasted 40 minutes approximately in total and each participant was paid for 500 Chinese RMB (equivalent to USD80 approximately).

2.2 Apparatus. Figure 2 shows the Beijing Jiaotong University (BJTU) driving simulator, which
was used to conduct the experiment and collect the data. The BJTU simulator has a full-size vehicle cabin with the brake pedal, throttle, steering wheel and gear, which are completely identical to a real vehicle (a Ford Focus). The high-performance, high-fidelity simulator is also equipped with a real operational interface, environmental noise and shaking simulation system, digital video replay system and vehicle dynamic simulation system. This simulator has one degree of freedom motion platform to imitate the feeling of motion. A 300-degree front/peripheral view of display system and simulated left, middle, and right back mirrors are used to project the simulated environment. Besides, the glasses eye tracking system (SMI ETGTM) is used to record drivers’ eye movements during the driving. The recorded data includes a video file and several text files, which contains the position of drivers’ eye fixation, blink and pupil diameter, etc.

![Figure 2 The BJTU driving simulator](image)

**2.3 Scenario design.** The experiment was designed as a 7 (warning timing) × 2 (directional information) within-subjects repeated measures. The seven kinds of advance warning releasing timing varied from 2.5 s to 5.5 s with 0.5 s interval. The two levels of directional information were: auditory warning “please watch out for the red light running vehicle on the right” with directional information and “please watch out for the red light running vehicle” without directional information, respectively. In addition, no-warning condition was regarded as a baseline. Finally, 15 different types (7 timings x 2 direction) and 1 no-warning) of experimental scenarios were performed in this study.

As shown in Figure 3-a, the right-angle collisions caused by RLR vehicle were focused in this study. A conflicting RLR vehicle would be triggered by a Time-to-collision (TTC) sensor to cross the intersection with a velocity of 72 km/h, which attempts to run a red light at a signalized intersection while the signal light is on green phase for the simulator (test vehicle). The approaching time of the RLR vehicle to the conflict point is designed as 7 s and the RLR vehicle is initiated at the 140 m upstream of the conflict point. Once the approaching time of the simulator to the conflict point satisfies a predefined warning time value (varied from 2.5 s to 5.5 s), the audio warning will be released to alert the driver to the RLR vehicle. These scenarios are carefully designed so that the simulator will collide with the conflicting vehicle unless the simulator accelerates or decelerates when it approaches intersections. Additionally, the top of Figure 3-a showed the splayed front visibility of driving simulator, and figure 3-b showed a screenshot of the...
driver’s view.

In this study, five sets of experimental driving routes were designed to test participants’ visual performances during the process of collision avoidance from the RLR vehicle. Each route was composed of six identical signalized intersections, which was connected by 600 m straight road segments with two-way two lanes that were 3.5 m wide and had 80 km/h speed limits. Each signalized intersection was clear without any distractions to participant drivers, and no obstacle was set for each signalized intersection to avoid the influences of limited field view. Among the six intersections in each set of experimental driving route, three of them would be randomly selected as the test intersections where participants encountered the RLR conflicting vehicles to counterbalance the effects of time order. Besides, in order to discourage participants from speculating about the experiment’s purpose and to minimize their adaptability to repeated RLR collision avoidance tests, at least 10 minutes of normal driving in a typical rural traffic environment were inserted between each two sets of formal experiments.

(a) Design of RLR collision at the test intersection;
2.4 Experiment procedure. Upon arrival, requirements of the experiment were briefly introduced to the participants and an informed consent form was asked to sign. All the participants were then advised to drive and behave as they normally would and to adhere to traffic laws as in real-life situations. Before the formal experiment, the drivers were trained for at least 10 minutes to familiarize with the driving simulator operation. Additionally, a break of at least 5 minutes was allowed between tests and the participants could quit the experiment at any time in case of any kind of discomfort.

2.5 Dependent measures. During the experiment, the simulator data were sampled at 60 Hz and the eye movement data were 30 Hz. In the simulator experiments, the measured parameters include collision or not (CON), first fixation time on the RLR vehicle (FFT), perception-reaction time (PRT), blink rate during the 7 s process of collision avoidance (BR), average blink duration during the 7 s process of collision avoidance (ABD) and drivers’ average pupil diameter during the 7 s process of collision avoidance (APD). These dependent measures are explained as follows:

- **Collision or Not (CON):** The variable of CON represented whether the driver collided with the conflicting RLR vehicle or not. It was an index for traffic safety evaluation.
- **First Fixation Time on the RLR Vehicle (FFT):** The variable of FFT (in second) was defined as the duration from the moment when the RLR vehicle was trigged (7 s to the intersection’s conflicting point) to the moment when a driver’s fixation allocated on the RLR vehicle for the first time. The variable could indicate the degree of timeliness that drivers detect the RLR vehicles.
- **Perception-reaction time (PRT):** The variable of PRT (in second) in this study was defined from the time that drivers’ first fixation located on the RLR vehicles to the time that drivers took brake actions, which could indicate the drivers’ responding abilities of potential collision.
- **Average Blink Duration (ABD):** The variable of ABD (in millisecond) in this study represented drivers’ average blink duration during the 7 s process of collision avoidance.
- **Blink Rate (BR):** The variable of BR (per second) in this study represented the number of blinks per second during the 7 s process of collision avoidance.
- **Average Pupil Diameter (APD):** The variable of APD (in millimeter) in this study represented drivers’ average pupil diameter during the 7 s process of collision avoidance.

2.6 Data analysis. In this study, due to a small sample size, the random parameter modeling in the logistic regression analysis was used to analyze the classified variable of CON, which could neutralize the heterogeneity effects of individuals. Similarly, the mixed model with consideration of fixed and random effects was used to analyze the continuous dependent variables (FFT, PRT, ABD, BR and APD). The hypothesis testing in the following analyses was based on a significance level of 0.05.

3 Experiment results
The basic statistical descriptions of the collision results and factors are listed in Table 1 and Table 2, respectively. In the subsequent statistical analyses, mixed models were used to investigate the differences of drivers’ performances between factors (see Table 3).

Table 1 Descriptive statistical result for CON

| Factors          | Parameter | Collision       |        |        |
|------------------|-----------|-----------------|--------|--------|
|                  |           | Non-collision   | Collision | Total   |
| Warning timings  | No-warning| N               | 15     | 9      | 24    |
|                  |           | %               | 62.50 % | 37.50 % | 100.00 % |
|                  | 2.5 s     | N               | 42     | 6      | 48    |
|                  |           | %               | 87.50 % | 12.50 % | 100.00 % |
|                  | 3.0 s     | N               | 48     | 0      | 48    |
|                  |           | %               | 100.00 % | 0.00 % | 100.00 % |
|                  | 3.5 s     | N               | 42     | 6      | 48    |
|                  |           | %               | 87.50 % | 12.50 % | 100.00 % |
|                  | 4.0 s     | N               | 48     | 0      | 48    |
|                  |           | %               | 100.00 % | 0.00 % | 100.00 % |
|                  | 4.5 s     | N               | 47     | 1      | 48    |
|                  |           | %               | 97.90 % | 2.10 % | 100.00 % |
|                  | 5.0 s     | N               | 47     | 1      | 48    |
|                  |           | %               | 97.90 % | 2.10 % | 100.00 % |
|                  | 5.5 s     | N               | 48     | 0      | 48    |
|                  |           | %               | 100.00 % | 0.00 % | 100.00 % |
| Total            |           | N               | 337    | 23     | 360   |
|                  |           | %               | 93.60 % | 6.40 % | 100.00 % |
| Warning content  | No-warning| N               | 15     | 9      | 24    |
|                  |           | %               | 62.50 % | 37.50 % | 100.00 % |
|                  | Non-directional | N         | 158    | 10     | 168   |
|                  |           | %               | 94.00 % | 6.00 % | 100.00 % |
|                  | Directional| N              | 164    | 4      | 168   |
|                  |           | %               | 97.60 % | 2.40 % | 100.00 % |
| Total            |           | N               | 337    | 23     | 360   |
|                  |           | %               | 93.60 % | 6.40 % | 100.00 % |
| Gender           | Male      | No-warning      | N      | 8      | 3     | 11    |
|                  |           | %               | 72.70 % | 27.30 % | 100.00 % |
|                  | With warning | N          | 152    | 2      | 154   |
|                  |           | %               | 98.70 % | 1.30 % | 100.00 % |
|                | Parameter | FFT (s) | PRT (s) | ABD (ms) | BR (/s) | APD (mm) |
|----------------|-----------|---------|---------|----------|---------|----------|
| **No-warning** | Mean      | 3.19    | -0.42   | 300.93   | 0.488   | 4.04     |
|                | S.D.      | 2.17    | 3.03    | 219.69   | 0.422   | 1.31     |
| 2.5 s          | Mean      | 3.64    | 0.54    | 312.33   | 0.560   | 3.87     |
|                | S.D.      | 2.16    | 2.46    | 188.12   | 0.420   | 1.13     |
| 3.0 s          | Mean      | 2.98    | -0.03   | 313.70   | 0.536   | 3.71     |
|                | S.D.      | 1.96    | 2.84    | 209.40   | 0.393   | 1.46     |
| 3.5 s          | Mean      | 3.06    | 1.39    | 369.42   | 0.614   | 4.01     |
|                | S.D.      | 1.86    | 1.68    | 204.21   | 0.457   | 0.86     |
| 4.0 s          | Mean      | 2.75    | 0.75    | 336.81   | 0.616   | 3.82     |
|                | S.D.      | 1.79    | 2.08    | 225.97   | 0.516   | 1.08     |
| 4.5 s          | Mean      | 2.33    | 0.55    | 350.08   | 0.658   | 3.76     |
|                | S.D.      | 1.70    | 1.85    | 182.78   | 0.391   | 1.29     |
| 5.0 s          | Mean      | 3.37    | -1.10   | 339.76   | 0.562   | 3.73     |
|                | S.D.      | 1.70    | 2.22    | 180.57   | 0.411   | 1.69     |
| 5.5 s          | Mean      | 3.49    | -1.40   | 299.70   | 0.563   | 3.55     |
|                | S.D.      | 1.58    | 2.09    | 214.29   | 0.529   | 1.66     |
| **Total**      | Mean      | 3.10    | 0.06    | 329.63   | 0.581   | 3.80     |
|                | S.D.      | 1.87    | 2.42    | 202.00   | 0.445   | 1.33     |

### Warning content

|                | Parameter | FFT (s) | PRT (s) | ABD (ms) | BR (/s) | APD (mm) |
|----------------|-----------|---------|---------|----------|---------|----------|
| **No-warning** | Mean      | 3.19    | -0.42   | 300.93   | 0.488   | 4.04     |
|                | S.D.      | 2.17    | 3.03    | 219.69   | 0.422   | 1.31     |
| **Non-directional** | Mean | 3.35    | 0.08    | 349.53   | 0.614   | 3.73     |
|                | S.D.      | 1.91    | 2.47    | 200.77   | 0.431   | 1.31     |
| **Directional** | Mean     | 2.84    | 0.10    | 313.84   | 0.560   | 3.73     |
|                | S.D.      | 1.78    | 2.30    | 199.97   | 0.461   | 1.36     |
| **Total**      | Mean      | 3.10    | 0.06    | 329.63   | 0.581   | 3.80     |
|                | S.D.      | 1.87    | 2.42    | 202.00   | 0.445   | 1.33     |

### Gender

|                | Parameter | FFT (s) | PRT (s) | ABD (ms) | BR (/s) | APD (mm) |
|----------------|-----------|---------|---------|----------|---------|----------|
| **Male**       | Mean      | 2.86    | 0.01    | 331.49   | 0.587   | 3.83     |
|                | S.D.      | 1.87    | 2.42    | 202.00   | 0.445   | 1.33     |

Table 2 Descriptive statistical result for dependent variables
Table 3 Results of mixed model for dependent measures

| Source                          | d.f. | F-ratio       |
|---------------------------------|------|---------------|
|                                 |      | FFT (s) | PRT (s) | ABD (ms) | BR (/s) | APD (mm) |
| Warning timings                 | 6    | 2.275** | 9.372** | 0.627    | 0.501   | 0.670    |
| Warning content                 | 1    | 4.457** | 0.001   | 3.088*   | 1.538   | 0.410    |
| Gender                          | 1    | 2.950*  | 0.358   | 0.116    | 0.005   | 0.288    |
| Warning timings*Warning content | 6    | 0.969   | 0.741   | 0.742    | 1.010   | 0.742    |
| Warning timings*Gender          | 1    | 0.762   | 1.768   | 1.467    | 1.930*  | 0.209    |
| Warning content*Gender          | 1    | 1.303   | 0.910   | 2.533    | 2.763*  | 0.006    |

** Significant at the 0.05 level.
* Marginally significant at the 0.1 level.

3.1 Correlation analyses for Dependent variables

Table 4 Correlation analysis results among dependent variables

| Variables | CON | FFT (s) | PRT (s) | ABD (ms) | BR (/s) | APD (mm) |
|-----------|-----|---------|---------|----------|---------|----------|
| CON       | 1   | 0.242** | 0.015   | 0.017    | -0.042  | 0.097    |
| FFT (s)   | 0.242** | 1       | -0.625** | 0.047    | -0.007  | 0.064    |
| PRT (s)   | 0.015 | -0.625** | 1       | -0.028   | -0.020  | 0.046    |
| ABD (ms)  | 0.017 | 0.047   | -0.028  | 1        | 0.311** | 0.025    |
| BR (/s)   | -0.042 | -0.007  | -0.020  | 0.311**  | 1       | 0.036    |
| APD (mm)  | 0.097* | 0.064   | 0.046   | 0.025    | 0.036   | 1        |

** Significant at the 0.05 level.
* Marginally significant at the 0.1 level.

Table 4 shows correlation analysis among the dependent variables. For collision or not, the results showed that drivers’ FFT showed significant positive correlation with collision or not (R= 0.242, p< 0.001). As Figure 4-a shown, the drivers who had involved with RLR collisions (M= 4.91 s, S.D. = 2.05 s) spent more time to locate in the conflicting RLR vehicle than those who avoid RLR collisions successfully (M= 2.99 s, S.D. = 1.81 s). It was also found that there was a marginally significant positive correlation between the pupil diameter and collision results (R= 0.097, p= 0.066< 0.1). As Figure 4-b shown, compared to the non-collision group (M= 3.76 s, S.D. = 1.35 s), drivers had larger APDs when encountering a RLR collision (M= 4.29 s, S.D. = 0.93 s). For drivers’ PRT, the results showed that drivers’ FFT had significant negative correlation with drivers’ PRT (R= -0.625, p< 0.001), indicating a negative correlation between drivers’ detection stage and
reaction stage during the process of collision avoidance. Intuitively, for the two stages, if drivers spent less time in detecting RLR vehicle, they would have more time to respond to the conflicting RLR vehicle. Additionally, it was found that drivers’ BR had a significant positive correlation with ABD (R= 0.311, p< 0.001).

![Diagram](image1)

(a) Drivers’ FFT for the non-collision group and collision group;

![Diagram](image2)

(b) Drivers’ APD for the non-collision group and collision group;

**Figure 4** Drivers’ FFT and APD for the non-collision group and collision group (Error bar: 95 % CI)

### 3.2 Collision or Not (CON)

Table 5 Logistics regression result for CON
In this experiment, 360 completed tests (24 subjects × 15 experimental intersection) were carried out, and the overall collision rate was 6.4 %. Among the 6.4 % crash test (23 crashes), 39.1 % of the crashes happened under the no-warning condition. In the logistic regression model, the variable of warning timings was considered as a continuous variable, which were coded with the actual time (2.5, 3.0, … , 5.5). For the no-warning condition, it could be expressed as 0. The variable of warning content was considered as categorical variable, which included no-warning condition, non-directional condition and directional condition. Specifically, no-warning condition was coded as 0 and was regarded as the reference. The non-directional condition was coded as 1 and directional condition was coded as 2. Drivers’ gender was also considered as categorical variable, which included male driver and female driver. Male group was coded as 1 and was regarded as the reference, and female group was coded as 2 in the model. The results of logistic regression were shown in Table 5, and it was found that warning timing (p<0.001) and gender (p=0.041<0.05) had significant influences on the collision rate. Specifically, the collision rate would be decreased by 63.0 % when warning timing was one second earlier (Exp (B) = 0.370), indicating the benefits got from the earlier warning timings. For the gender effect, the collision involvement rate for female drivers is 4.745 times of that for male drivers (Exp (B) = 4.745). It indicated that female drivers were more likely to get involved in RLR collisions than male drivers. Additionally, in the no-warning condition, the collision rate for female driver was 46.2 % (6 collisions of 13 tests) and that for male driver was 27.3 % (3 collisions of 11 tests), which demonstrated that female drivers might be more likely to involve a RLR collision than male drivers under no-warning condition. When a CAS warning was released, the decreased collision rates for female drivers and male drivers were 39.6 % (from 46.2 % to 6.60 %) and 26 % (from 27.3 % to 1.30 %), respectively. In term of RLR collision risk reduction, the result indicated that female drivers tended to get more benefits from the CAS than male drivers.

### 3.3 First Fixation Time on the RLR Vehicle (FFT)

Sample tests of which drivers had failed to detect the RLR vehicle during the 7 s collision avoidance processes were removed from the entire dataset in this study, since in these scenarios the FFTs were larger than 7 s or smaller than 0 s. Thus, 270 observations were used to conduct differences of drivers’ FFT between factors. Table 2 lists the statistic description results of drivers’ FFT and Table 3 lists the mixed model results of FFT. Significant effects of warning content (F= 4.457, p= 0.036) and warning timings (F= 2.275, p= 0.048) were shown on drivers’ FFT. As Figure 5-a shown, drivers could detect the conflicting RLR vehicle most quickly under the warning with directional information (M= 2.84 s, S.D. = 1.78 s), and then followed by the no-warning condition (M= 3.19 s, S.D. = 2.17 s), and warning condition without directional information (M= 3.35 s, S.D. 0.765, S.E, 0.361, P-value 0.682).
= 1.91 s). Considering the different warning timings, drivers under the warning timing of 4.5 s had the shortest time to detect the RLR vehicles (see Figure 5-b). Although no significant interaction effects of warning content and warning timings were shown in the ANOVA results, Figure 5-c indicated that compared to the earlier warning timings, the differences of drivers’ FFT caused by directional information were larger in the later warning timings, especially under the warning timings of 2.5 s and 3.0 s. It implied that the warnings could help drivers detect the conflicting RLR vehicle more quickly when directional information was contained, especially under later warning timings. For gender effect, the result listed in Table 3 showed a marginally effect on drivers’ FFT (F= 2.950, p= 0.099< 0.1). Male drivers (M= 2.86 s, S.D. = 1.74 s) had shorter FFT than female drivers (M= 3.35 s, S.D. = 1.98 s), which indicated that male drivers tended to detect the conflicting RLR vehicle more quickly than female drivers (see Figure 5-d).

(a) FFT under the different warning content;

(b) FFT under the different warning timings (s)
(b) FFT under the different warning timings;

(c) FFT under the interaction conditions of warning timings and warning content;

(d) FFT for male and female drivers;

**Figure 5 Drivers’ FFT under the different conditions (Error bar: 95% CI)**

3.4 Perception-reaction time (PRT)

Sample tests of which drivers had no fixation on the RLR vehicle and taken no brake actions during the 7 s collision avoidance processes were removed from the entire dataset in this study, since in these scenarios the FFTs were larger than 7 s or smaller than -7 s. Thus, 287 observations were used to conduct differences of drivers’ PRT between factors. The result listed in Table 3 had found that significant main effect of warning timings (F= 9.372, p< 0.001) was shown on the drivers’ PRT. As Figure 6 shown, the interesting finding is that when the warning was released earlier than 5.0 s ahead of a collision, driver tended to take brake action earlier than paying a fixation on the
conflicting RLR vehicle. In the moderate warning timings (between 3.5 s and 4.5 s ahead of a collision), drivers’ PRT showed a decreased trend as the warning timings became earlier.

![Figure 6 Drivers’ PRT under the different warning timings (Error bar: 95 % CI)](image)

**3.5 Average Blink Duration (ABD) and Blink Rate (BR)**

The 360 observations were used to conduct differences of drivers’ ABD and BR during the 7 s process of collision avoidance between factors. As the results listed in Table 3, it was found that warning content had a marginally significant effect on drivers’ ABD ($F= 3.088$, $p= 0.08< 0.1$). Compared to the no-warning condition ($M= 300.93$ ms, S.D. = 219.69 ms), the ABD under the warning condition without directional information was highest ($M= 349.53$ ms, S.D. = 200.77 ms), followed by the warning condition with directional information ($M= 313.84$ ms, S.D. = 199.97 ms), as shown in Figure 7-a. For drivers’ BR, marginally interaction effects of warning timings and gender ($F= 1.930$, $p= 0.087< 0.1$) were shown on BR, as well as interaction effects of warning content and gender ($F= 2.763$, $p= 0.098< 0.1$). As Figure 7-b shown, the male drivers’ BRs were higher than those of female driver in the no-warning condition. When the warning was released later than 3.5 s ahead of a collision, the BRs for female drivers became increased and was larger than male drivers. For the interaction effects of warning content and gender, it had been found that an auditory warning had association with an increase of BRs for both female and male driver (see Figure 7-c). For male drivers, they had higher BRs under the warning condition without directional information compared to warning condition with directional information. For female drivers, the BR for warning condition without directional information and warning condition with directional information was nearly same.
(a) ABD under the different warning content;

(b) BR under the interaction conditions of warning timings and gender;
Figure 7 Drivers’ ABD and BR under the different conditions (Error bar: 95% CI)

3.6 Average Pupil Diameter (APD)
The 360 observations were used to conduct differences of drivers’ APD during the 7 s process of collision avoidance between factors. No significant main effects of warning timing (F = 0.670, p = 0.674 > 0.1), warning content (F = 0.410, p = 0.522 > 0.1), or gender (F = 0.288, p = 0.594 > 0.1) were found for drivers’ pupil diameter, as well as the interaction effect of warning timings × warning content (F = 0.742, p = 0.618 > 0.1), warning timings × gender (F = 0.209, p = 0.973 > 0.1) or warning content × gender (F = 0.006, p = 0.940 > 0.1).

4 Discussions
This study mainly identified drivers’ ability of detecting, perceiving potential dangers and the ability of information processing when approaching signalized intersection under different warning conditions by recording their eye movements. Furthermore, this study investigated how different warning conditions combined warning content with warning timings influenced drivers’ visual performances, and assessed the effects of different warning conditions on the effectiveness of CASs.

When the driver approaches a signalized intersection with potential RLR vehicle, the first stage of collision avoidance was to detect the conflicting RLR vehicle. Generally, drivers had no expectations or experience in encountering a conflicting RLR vehicle, and they had a strong uncertainty in detecting the conflicting RLR vehicle (Koustanai et al., 2008). In this study, the release of collision warning was found to help alert drivers to the conflicting RLR vehicle, and prompt them to perceive the conflicting vehicle earlier with enough time taking moderate collision avoidance measures, which was consistent with the studies of Lenné et al. (2008) and Xiang et al. (2015). For the different warning timings, the experimental results showed that drivers detected the conflicting vehicle most quickly in the warning condition of 4.5 s ahead of a collision, which
indicated that drivers could get most benefit in detecting when the warning was released around 4.5 s ahead of a collision. Considering warning content, especially when the directional information was included, the drivers focused their attention more quickly on the conflicting RLR vehicle in the complex dynamic driving situations, and thus had a larger chance in making possible ready responses in the collision avoidance. The similar results were obtained by a study of Koyuncu and Amado (2008). However, the benefit of directional information did not cover all warning timings. Compared to the earlier warning timings, the differences of drivers’ FFT caused by directional information were larger in the later warning timings, especially in the warning conditions of 2.5 s and 3.0 s ahead of a collision. The possible reason is that in an emergent situation in the later warning timings, drivers would seek the potential conflicting RLR vehicle in the direction obtained from warning information immediately, and pay attention to the conflicting RLR vehicle more quickly.

Once the conflicting RLR vehicle is detected, drivers need to decide when to take collision avoidance measures depending on their relative speed and location. The stage of perception-reaction would be the second stage of collision avoidance, which started from the moments that drivers’ first fixation located on the conflicting RLR vehicle and ended to the moment that drivers took brake actions. The result of correlation analysis showed a significant negative correlation between drivers’ FFT and PRT, which indicated that if drivers had shorter time to detect, they might be had longer time to react to the conflicting RLR vehicle. In the present study, it was found that only warning timings had significant effects on drivers’ PRT. Compared to no-warning condition, drivers were more likely to take brake actions before paying fixations to the conflicting RLR vehicle in the earlier warning timings (earlier than 5.0 s ahead of a collision). For the moderate warning timings (between 3.5 s to 4.5 s ahead of a collision), drivers’ PRT showed a decreased trend as warning timing was earlier. Aforesaid results showed the different effects of warning condition on drivers’ detection stage and reaction stage. Few related studies divided drivers’ response time into two stages of detecting and reaction to investigate the effects of directional information combined with warning timings deeply, and the findings obtained in this study could provide theoretical support for the optimization of the warning conditions.

During the process of RLR collision avoidance in this study, the results showed that CAS warning increased drivers’ BR and ABD. Previous studies had found that blink can provide information about the processes involved in attention and response programming and execution (Recarte et al., 2008; Ahlstrom and Friedman-Berg, 2006), and the suppression of blinks demonstrated that drivers paid more attention to the target stimuli (Bauer et al., 1985; Veltman and Gaillard et al., 1996). The results indicated that driver paid less attention in scanning surrounding environment and detecting potential hazards when collision warning was provided. First, the decrease concentration on the visual task may be due to the presented auditory warning, and hence the reducing visual concentration may cause the increased number of blinks (Tsai et al., 2007). Another possible reason of the increased number of blinks is that the warning could help drivers collect critical information and narrow the range of drivers’ threat information processing, and hence reduce the workload in information processing. Considering the directional information, a downward trend of drivers’ blink rate was found when the directional warning was released, since more attention was needed to
process the spatial auditory warning, and similar downward trend in the eye blink rate was shown in a study of visuo-spatial tasks (Van Orden et al, 2001).

Additionally, no significant effects were found on drivers’ pupil diameter between factors in this study. The low sampling rate of the eye-tracker equipment (30 Hz) might be one of the reasons, which was also the limitation of this study. Lower sampling rate might result in a less sensitive measure of pupil diameter. Moreover, drivers’ eye movements might be different in the simulator and realistic road driving, and research on drivers’ eye movements in the realistic road driving with regard to the effectiveness of collision warning system should be considered in the future.

In term of gender effects, the results in this study showed that female drivers were more likely to involve RLR collisions than male drivers. The possible reason is that male drivers may be more vigilant to potential hazards owing to more often encounter dangerous driving situations than female (Son et al., 2015) and female drivers may be more prone to small driving errors and slips, especially in situations requiring increased attention and perception (Özkan and Lajunen, 2006). For the reduction of collision risks, the results indicated that female drivers tended to benefit more from CAS warning than male drivers. Similar results related to other in-vehicle warning systems were also found in previous studies. For instance, compared to male driver, it had been found that females with auditory warning tend to have quicker first fixation on the targets (Lerner et al., 2015). For the detection stage and reaction stage, marginally gender effects were shown on drivers’ detection stage. The results indicated that male drivers tended to detect conflicting RLR vehicle earlier than female drivers, and hence they had adequate time to take brake actions to avoid a RLR collision. These findings might explain in part why male drivers had a lower crash rate than female drivers, and the similar gender difference pattern in crash involvement was identified in the other previous studies (Classen et al., 2012; D’Ambrosio et al., 2008). Besides, marginally interaction effects of gender and warning conditions on drivers’ BR were also found during the process of collision avoidance. In the no-warning condition, male drivers had higher BRs than female drivers. When the warning was released later than 3.5 s ahead of a collision, the BRs for female drivers was larger than those of male drivers. Female drivers might decrease more visual concentration than male drivers in the later warning timings. When the warning was released with directional information, male driver had smaller BR than female drivers, which indicated that male drivers seemed to pay more attention to deal with directional warning information than female drivers. Due to the limitation of a small sample size for the two categories of gender, further studies are needed to explore the gender differences of the different warning conditions of CASs.

5 Conclusions
With the driving simulation experiment, the study had proved that collisions with RLR vehicle were dramatically reduced when the driver was assisted by a CAS. For drivers’ detect stage of collision avoidance, warning timings and warning content showed significant effects on drivers’ FFT. The results showed that drivers were more likely to detect conflicting RLR vehicle most quickly in the warning timing of 4.5 s ahead of collision. Besides, compared to no-warning condition, drivers spent less time in detecting the conflicting RLR vehicle with specific directional warning. For drivers’ reaction stage of collision avoidance, experimental results showed that in the earlier
warning conditions (earlier than 5.0 s ahead of a collision), drivers might take brake actions before paying a fixation on the conflicting RLR vehicle. For the whole process of collision avoidance, the later warning timings (later than 3.5 s ahead of a collision) tended to increase female drivers’ BR compared to no-warning conditions and earlier warning timings. In the warning conditions with directional information, male drivers tended to have shorter BR than female drivers. Besides, male drivers tended to spend less time in detecting the conflicting RLR vehicle, and were less likely to get involved in a RLR collision. All these findings of the study pointed out the significant change of visual performances under different warning conditions, which could provide important guidance to improve the development of CASs in the future.

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