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Drivers' eye movements as a function of collision avoidance warning conditions in red light running scenarios

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ABSTRACT

The intersection collision avoidance warning systems (ICAWSs) have substantial potentials in improving driving performance and reducing the number and severity of intersection collisions, through helping drivers timely detect hazardous conflicting vehicles in precrash scenarios. However, the influences of ICAWS on drivers' visual performance have barely been discussed. This study focuses on exploring the patterns in drivers' eye movements as a function of ICAWS's warning conditions in red light running scenarios based on a driving simulation experiment. Two types of speech warning conditions including warning timings (varied form 2.5 s to 5.5 s) and directional information (with or without) are examined, and the no-warning condition is the baseline. The results revealed that more subjects would be likely to benefit from the ICWAS under the earlier warning timings. The warning condition of 4.5 s ahead of a collision had the best effectiveness in terms of visual performances. Under such a warning timing, drivers had shorter fixation duration and higher frequency of searching for the red light running (RLR) vehicles. Compared to the warning condition without directional information, the directional warning information could capture drivers' attention more efficiently, help driver direct fixations toward the RLR vehicles more quickly and lead to more scanning activities. Compared to female drivers, male drivers had more scanning activities when approaching intersections, detected the RLR vehicles more quickly and were more likely to avoid the RLR collisions. Besides, the experiment results indicated that the female drivers were more inclined to trust the warning information and got more benefits from the RLR-ICAWS in terms of the crash risk reduction rate than male drivers. Finally, the conclusions lead the way toward warning condition design recommendations for improving the effectiveness of the RLR-ICAWSs.

1. Introduction

The statistical data from both developed and developing countries showed that red light violation behavior is the most important reason of traffic accidents at intersections and red light running (RLR) crashes are more severe than other types of crashes (e.g., Yousif et al., 2014; Aeron-Thomas and Hess, 2005). In the US, red light running resulted in 714 fatalities and an estimated 144,000 injuries in 2011 (IIHS, 2013a,b). In China, 4227 severe injury crashes and 789 fatalities were attributable to RLR in 2012 between January and October (MPS, 2012).

The intersection-related areas usually have more complex traffic environments with traffic control devices, pavement markings, traffic signs, pedestrians and vehicles from different directions, etc. Once legal drivers who approaching intersections during the green phase encounter red light running vehicles, better visual searching abilities are required to judge traffic situations and identify the conflicting vehicles. If they failed to detect the violating vehicles, the chance of collisions would be highly increased (Graab et al., 2008). In order to enhance drivers' crash response capability in hazardous situations, the intersection collision avoidance warning systems (ICAWS) have been widely explored to help drivers identify the conflicting vehicles at intersections through estimating specific collision points based on the geometric positions, directions, speed and other parameters of vehicles (Yang et al., 2011). Corresponding to red light running violation scenarios, RLR-ICAWSs are especially developed to timely provide drivers warning information in order to avoid the potential collisions with the RLR vehicles (King and Refai, 2011; Atev et al., 2004).

Some evidence has been identified to support that RLR-ICAWS could help drivers deal with urgent situations in the critical inter-

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section and enhance drivers' RLR collision avoidance performances (e.g., Yan et al., 2015; Werneke and Vollrath, 2013). The RLR-ICAWS could assist drivers in detecting the RLR vehicles more quickly, leading to the shorter reaction times in response to potential collisions with RLR vehicles at intersections, and thereby reducing the intersection-crash involvement rate (Yan et al., 2014). Moreover, when and how to release the warning information could significantly influence the effectiveness of ICAWS (e.g., Tang and Yip, 2010; Ho and Spence, 2009; Janssen and Nilsson, 1993). The previous studies have shown that an earlier delivery of warning message results in the shorter reaction time and lower deceleration rate, which would lead to well-prepared performances to an imminent collision (Werneke and Vollrath, 2013; Abe and Richardson, 2004; Lee et al., 2002). Additionally, the warning messages with or without directional information have different effects on crash avoidance driving performances (Yan et al., 2014).

When approaching to the signalized intersections, drivers heavily rely upon the visual behavior to detect, integrate and act upon changing information from traffic elements and environments (Caird et al., 2008). Thus, the abilities of visual search for judging and identifying potential risk are the most important factors to ensure driving safety at intersections. Essentially, the RLR-ICAWS would not take any measures to directly intervene drivers' vehicle maneuver process but direct drivers' visual attention to the traffic hazards and the conflicting RLR vehicles as effectively as possible. Hence, it is crucial to uncover the drivers' visual performance patterns during the process of collision avoidance as a function of the different RLR-ICAWS conditions, which would be useful for guiding the technologies' development and optimizing the systems' application effectiveness. Nevertheless, how the varying warning conditions affect the driver's visual performances has not been discussed in previous research yet.

A typical method for measuring visual performance is to use eye tracking techniques (Pradhan et al., 2005), though video recording is often used as well. In the field of traffic research, many studies on drivers' eye movements under different driving situations have already been conducted, such as drivers' characteristics of different experience or age (e.g., Dukic and Broberg, 2012; Crundall et al., 2004; Crundall and Underwood, 1998), different weather conditions (e.g., Konstantopoulos et al., 2010), drowsy and distracted driving (e.g., Zeng et al., 2010; Hu and Zheng, 2009; Miyaji et al., 2009; Hong et al., 2007; Liang et al., 2007; Hayami et al., 2002), etc. In the ISO 15007-1 and 15007-2 standards, the eye movement behavior can be analyzed based on either by the glance-based measures or fixations-based measures when supported by an eye-tracker with sufficient accuracy and precision. The glance-based measures are a little different from fixations-based measures that are widely used to investigate more detailed visual performance, such as fixation durations, number of fixations, and saccadic movements. The fixation analyses are commonly associated with cognitive processing and are applied to evaluate the mental effort. The length of fixation duration has been found to be connected with the degree of the complexity of the visual scene (e.g., Niezgoda et al., 2015), and the shorter but more frequent fixations could reduce processing time (e.g., Konstantopoulos et al., 2010). The individual fixations indicate how drivers guide actions and to recognize objects and events (e.g., Land and Hayhoe, 2001). The auditory in-vehicle information systems have also been found to affect drivers' fixation behaviors (e.g., Victor et al., 2005). Additionally, several studies have proposed that the saccades have relationship with visual inspection (e.g., Spotorno and Masson, 2016). Visual performance analyses have been conducted in a naturalistic study for evaluating the effectiveness of the forward collision warning systems (FCWS) in rear-end precrash scenarios (e.g., Wege et al., 2013). Therefore, it is interesting to know the fixation patterns in the drivers' visual process when encountering the RLR vehicles, which may represent how the RLR-ICAWS guide drivers to detect and recognize hazards, judge the emergent traffic event, and guide further actions for crash avoidance. Meanwhile, saccades may redirect the drivers' fixations toward the hazardous objects according to the warning information (for example, giving the RLR vehicle's coming directions), which can reflect the effect of RLR-ICAWS on drivers' abilities of visual inspection and scanning.

The objective of this study is to investigate the patterns in drivers' eye movements as a function of collision avoidance warning conditions in red light running scenarios based on a driving simulation experiment, which is appropriate to simulate the RLR precrash event and precisely control various warning conditions at signalized intersections. Specifically, seven levels of warning timings (gradually increasing from 2.5 s to 5.5 s by 0.5 s) and two levels of warning directional information (with or without directional information) were designed, resulting in 14 warning conditions. The analyses of experiment results focused on examining the relationship between warning conditions and drivers' visual performances to the RLR vehicles through eye movements, including saccades and fixations in the area of interests. In this study, the following hypotheses were established:

- Auditory warning could help reduce collision rate through improving drivers' crash avoidance performance.
- Auditory warning could contribute to drivers' detecting the RLR vehicle more quickly through priming drivers' expectation of RLR vehicle and thus allow drivers to have adequate time for collision avoidance.
- A proper timing of auditory warning could optimize the warning effect, such as contributing to a lower crash rate and shifting drivers' visual attention from the forward roadway to the RLR vehicles more effectively.
- The auditory warning with direction information of the conflicting vehicle could help drivers detect the conflicting vehicle more quickly.

This study provides a reference for identifying the optimal range of warning conditions through using an eye-tracking system combined with a driving simulator.

2. Method

2.1. Subjects

A total of 24 paid subjects (11 male drivers and 13 female drivers) were tested for this research. Subjects' average age was 34.7, ranging from 31 to 39 years old, with a standard deviation of 2.9 years. The average age of males was 35.2 with a standard deviation of 2.8 years and 34.4 with a standard deviation of 2.9 years for females. This experiment intentionally recruited drivers within a narrow age range in order to focus on examining the influence of RLR warning on drivers' visual performances. Each subject held a valid Beijing's driver's license with at least three years of driving experience and at least twenty thousand kilometers of driving mileage per year. The experiment lasted for about 30 min in total and each participant was compensated 1000 Chinese RMB (about 154 U.S. dollars).

2.2. Apparatus

The Beijing Jiaotong University (BJTU) driving simulator is used to conduct the experiment and collect data, which is able to simulate various road traffic environments and driving scenes, as shown in Fig. 1a. The high-performance, high-fidelity simulator has a full-size vehicle cabin with brake pedal, throttle and steering wheel,