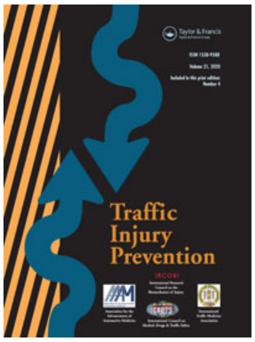

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Drivers' visual attention during the onset of the circular yellow indication at high-speed signalized intersections

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ABSTRACT

Objective: Drivers have difficulty deciding whether to stop at the stop line or proceed through the intersection at the onset of the circular yellow (CY) indication. The purpose of this study was to understand how drivers distribute their visual attention when the traffic signal turns to the CY indication at high-speed signalized intersections, and whether factors such as time to stop line, headway or following vehicle type, influence overt visual attention.

Method: Data included eye-tracking metrics from 45 participants during a 24-scenario driving simulator experiment. Three areas of interest (AOIs) were defined (traffic signal, rear view mirror, and side view mirrors).

Results: Results showed that while the CY indication was displayed, total fixation durations (TFDs) were highest on the traffic signal (626 s), lower for the rear view mirror (50 s), and lowest for the side view mirrors (3 s). Repeated-measures ANOVAs indicated that the type of following vehicle influenced TFDs. Being followed by a heavy vehicle resulted in drivers shifting their fixations away from the traffic signal. Drivers fixated on the traffic signal more when followed by a passenger car than they did when followed by a heavy vehicle. Additionally, higher time to stop lines resulted in greater TFDs on the traffic signal.

Conclusions: This study highlights the importance of understanding the fixation behavior of drivers and the factors that influence drivers' visual attention. These findings could guide future efforts by the transportation community to involve drivers in training programs to emphasize the risks associated with ignoring rear view mirrors during their response to CY indications.

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Eye tracking; visual attention; dilemma zone

Introduction

Driving behavior contributes significantly to signalized intersection safety. The circular yellow (CY) indication cautions drivers that the green indication has terminated and the red indication is imminent. However, the inconsistency between state yellow laws and driver training manual guidance may contribute to variability of driver comprehension and decision making in response to CY indications (Mohammed et al. 2018). When a CY indication is displayed, the driver has two choices: decelerate and stop or clear the intersection (Noble 2015).

Two dilemma zone situations may occur when a driver faces a CY indication. In the Type I dilemma zone, the length of yellow change and red clearance intervals are insufficient, such that the driver cannot stop without braking uncomfortably but cannot clear the intersection without accelerating (Gates et al. 2007). In the Type II dilemma zone (indecision zone), the driver has difficulty making the correct decision at the onset of the CY. The driver may incorrectly decide to go when the safer decision is to stop or vice versa, resulting in an increased frequency of rear-end collisions, severe right-angle crashes, and left-turn head-on collisions (Hurwitz et al. 2012). Driver decisions to proceed or not in response to the onset of the CY indication have been most directly associated with time to stop line (TTSL) (Xiong et al. 2016). TTSL is the number of seconds it takes for a vehicle traveling at a certain speed to reach the stop line following the yellow onset. The difficulty of driver decision making may also increase with the presence of a following vehicle with short headway. Headway is the difference in time (seconds) between the same position of a lead and a following vehicle arriving at a specific point on a roadway (Koonce and Rodegerdts 2008). Finally, the type of following vehicle might also influence driver behavior, with drivers being more attentive to heavy vehicles versus passenger cars behind them.

A high percentage of vehicular crashes can be attributed to failures of attention and information processing rather than the lack of skill in response to this information (Recarte and Nunes 2000). In many cases, inattention is indicated by the disruption of visual focus while driving. Visual inattention for a few seconds or even a fraction of a second while driving can lead to crash contributing driving errors. One common approach used to infer what information drivers attend to is eye-tracking (Wilkie et al. 2010). Eye-movement recordings provide timestamped information

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about where users look, how long they look at something, and the path that their eyes follow (Castro 2008).

The objective of this study was to understand how drivers distribute their visual attention at the onset of the CY indication at high-speed signalized intersections, and which variables influence visual attention. The study was conducted in the Oregon State University (OSU) Driving Simulator, using total fixation duration (TFD) on the three defined AOIs: traffic signal, rear view mirror, and side view mirrors as the dependent variable and TTSL, headway, and following vehicle type as independent variables.

Background

Several studies have quantified indecision zone boundaries. Zegeer and Deen (1978) suggested that the upstream boundary of the dilemma zone occurs where 90% of drivers stopped and the downstream boundary of the dilemma zone occurs where only 10% of the drivers stopped. The time to stop line (TTSL) has been used to define these boundaries. For example, Bonneson et al. (2002) suggested that the indecision zone typically occurs between a TTSL of 2.5 and 5.5 s. This boundary definition has been widely adopted (Hurwitz et al. 2012).

Eye-tracking measures are often used to infer important sources of visual information in driving. Underwood et al. (2002) found that novice drivers were more dependent than experienced drivers on their rearview mirrors, even when a lane-changing maneuver required information about traffic in the adjacent lane. Use of the side view mirror by novices increased in response to increased driving needs, suggesting that they had an awareness of situations that required interweaving with traffic. Knodler and Noyce (2005) used a driving simulator equipped with eye-tracking equipment to identify sources of information used by left-turning drivers. The drivers looked at least once at the protected/permissive left-turn (PPLT) signal display and the opposing traffic stream before entering the intersection. Hurwitz et al. (2014) examined drivers' visual fixations on three- and four-section flashing yellow arrow (FYA) signal configurations at high speed signalized intersections in a driving simulator with an eye tracker. Little difference in the visual search tasks of drivers was observed in the vertical position of the FYA display, and there were no significant differences in the average driver fixation duration between any of the independent control variables studied, between the three- and four-section FYA displays.

Pastor et al. (2006) studied the relationship between the frequency of rearview mirror uses and time variations in attention while subjects drove in a real environment on a highway and on local roads. The findings indicated a direct link between the attention level and the mirror use while driving on a highway but did not show this connection on local roads. Zhang et al. (2016) examined convenient visual search patterns during overtaking maneuvers on freeways in a driving simulator. Drivers tended to search for decisive traffic information by more frequently shifting their fixations between the initial lane and destination lane.

Despite extensive research on the Type II dilemma zone and various aspects of eye movements, there are still knowledge gaps related to driver behavior and safety at signalized intersections. This study investigated drivers' visual attention during interactions with the CY indication in the situation of a closely following vehicle.

Research questions

No literature to date has specifically examined the visual attention of drivers while being closely followed in the dilemma zone. The potential influence of experimental factors on drivers' eye movements provides context for the research questions in this study.

1. How do drivers distribute their visual attention (traffic signal, rear view mirror, and side view mirrors) at the onset of the circular yellow indication (CY)?
2. Is the visual attention of the driver influenced by the TTSL, headway, and/or following vehicle type at the onset of the CY?

Methods

Design

A partially randomized, counterbalanced, factorial experimental design was employed. Three independent variables were used: time to stop line (TTSL) (2.5, 3.5, 4.5, or 5.5 s), headway (0.5, 1, or 2 s), and following vehicle type (passenger car or heavy vehicle). Participants were presented 24 scenarios across six experimental routes. Three areas of interest (AOIs) were studied: traffic signal, rear view mirror, and side view mirrors. Fixations on each AOI were recorded. The dependent variable was eye movement (i.e., total fixation duration (TFD) on each AOI) during dilemma zone situations. This study was approved by the OSU Institutional Review Board #8080.

Participants

Fifty-four drivers were recruited using flyers posted and distributed around the OSU campus and the city of Corvallis for the experiment. Nine participants were excluded from analysis due to technical issues in eye-tracking calibration. Data from the remaining 45 participants were used in the final analysis. Remaining participants included 17 women (Mage = 31 years, SDage = 12.78 years) and 28 men (Mage = 31.29 years, SDage = 14.01 years), aged 18 to 70 years. Participants had normal or corrected-to-normal vision.

Stimuli

Participants drove six predetermined routes in the OSU Driving Simulator. Routes included a two-lane suburban road with moderate traffic and four signalized intersections. Participants encountered scenarios including different TTSLs, headways, and following vehicle types. Duration of the yellow change interval was 4.5 s, and the speed limit was 45 miles per hour (mph). Researchers did not add any additional driving hazards to focus on the independent variables of interest.

Figure 1. OSU researcher demonstrating the Mobile Eye XG Glasses.

Laboratory equipment

The OSU driving simulator consists of a fully functional full-size 2009 Ford Fusion cab mounted on an electric pitch motion system. The cab is surrounded by screens where the simulated environment is projected. The vehicle cab instruments are fully functional and include a steering control loading system to accurately represent steering torques based on vehicle speed and steering angle.

An Applied Science Laboratories (ASL) Mobile Eye-XG eye tracker was used to record eye movements (Figure 1). A 30-Hz sampling rate was used, with an accuracy of 0.5–1.0. The ASL Mobile Eye-XG system records a fixation when the subject's eyes pause for >100 ms.

Eye-tracking data reduction

Fixations were analyzed by coding area of interest (AOI) polygons in ETAnalysis. Researchers drew AOI polygons on individual video frames in single frame intervals. Once the researcher manually situated each AOI, an "anchor" was created in the software. Distance and size differences of AOIs between anchors were interpolated by the software, to ensure that all fixations on AOIs were captured. Researchers analyzed drivers' eye-tracking data from the moment the CY indication was displayed until the traffic signal turned to circular red or the participant crossed the intersection.

Figure 2 presents example video frames that have been coded with one AOI. In this example, the participant was fixating on the rearview mirror. This figure includes heatmaps (green-red patterns, with red indicating higher fixation duration at that location within the AOI).

After AOIs were coded for each individual video file, output spreadsheets of all fixations for each AOI were produced. Fixations outside of the coded AOIs were not analyzed.

Data analysis

Initially, data were analyzed with IBM SPSS Statistics software version 24. As each participant was exposed to all possible combinations of independent variables, repeated-measures analysis of variance (ANOVA) tests were performed with TTSL, headway, and following vehicle type as within-subject factors. Mean (M) and standard deviation (SD) were calculated. Mauchly's sphericity test was used to confirm sphericity assumptions. An alpha level of 0.05 was used as the criterion for statistical significance. Partial eta-

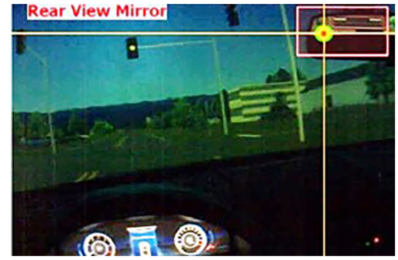

Figure 2. Example of a participant fixating on the rearview mirror.

squared was computed as an effect size statistic. Bonferroni corrected for pairwise comparisons of estimated marginal means ($\alpha = 0.05$) were used to determine differences between TTSL, headway, and following vehicle type levels.

Results

Repeated-measures ANOVA

The mean TFDs of three areas of interest (AOIs) were analyzed: traffic signal ($N = 1{,}069$, $M = 0.59$ s, $SD = 0.86$ s), rear view mirror ($N = 277$, $M = 0.18$ s, $SD = 0.35$ s), and side view mirrors ($N = 17$, $M = 0.15$ s, $SD = 0.35$ s). The summation of TFDs on each AOI was applied. As a comparison between the three AOIs, the highest summation of total fixation duration (TFD) was located on the traffic signal (626 s), followed by the rearview mirror (50 s) and side view mirrors (3 s). Additionally, the summation of TFDs outside of three AOIs was 5,354 s. TFD measurements help to infer whether a driver might have identified critical elements in the visual scene. Table 1 shows the descriptive statistics for TTSL, headway, and following vehicle type. For the traffic signal AOI which was influenced by TTSL, the highest mean TFD was 0.70 s when TTSL was 4.5 s. For the rear view mirror AOI which was influenced by headway, the highest mean TFD was 0.07 s when the headway was 0.5 s.

Data were visualized as boxplots of TFD for the three AOIs, disaggregated by different levels of headway in Figure 3. For the passenger car, higher median TFDs ranged from 0.09 to 0.37 s, with the traffic signal having the highest value when the headway was 2 s. For the heavy vehicle, median TFDs ranged from 0 to 0.30 s, with the traffic signal having the highest value when the headway was 1 s.

Repeated-measures ANOVA was conducted to determine whether TFD differed between factors for each AOI. When a significant effect was observed, pairwise comparisons were conducted to find the origin of the difference. Mauchly's test of sphericity was also performed, with sphericity assumed for $p > 0.05$. For the traffic signal AOI, Mauchly's test for the headway and the interaction between the following vehicle type and headway was not significant ($p > 0.05$); therefore, sphericity was assumed. Mauchly's test for all remaining variables was significant ($p < 0.001$); thus, sphericity was not assumed, and the Greenhouse-Geisser adjustment was used.

As shown in Table 2, the following vehicle type ($F(1, 44) = 6.348$, $p = 0.015$) and time to stop line (TTSL) ($F(2.495, 109.764) = 4.916$, $p = 0.005$) both had significant effects on the traffic signal TFD. Overall, the traffic signal TFD was significantly higher when a passenger car was following. Pairwise comparisons showed that the TFD was significantly higher

Table 1. Mean and standard error of TFD (s) at levels of TTSL, headway, and following vehicle type. PC = passenger car and HV = heavy vehicle.

Factor	Level	Traffic signal (M)	Traffic signal (SE)	Rear view mirror (M)	Rear view mirror (SE)
TTSL (s)	2.5	0.51	0.07	0.04	0.09
	3.5	0.45	0.07	0.04	0.10
	4.5	0.70	0.11	0.06	0.02
	5.5	0.61	0.08	0.06	0.02
Headway (s)	0.5	0.61	0.09	0.07	0.02
	1.0	0.55	0.06	0.04	0.01
	2.0	0.55	0.08	0.03	0.01
Following vehicle type	PC	0.63	0.08	0.04	0.01
	HV	0.50	0.07	0.06	0.01

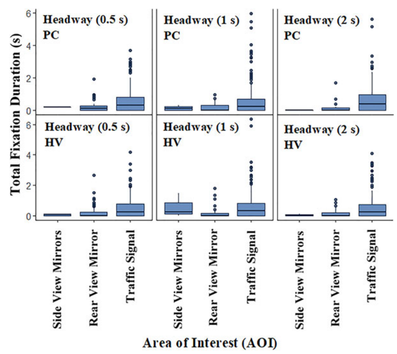

Figure 3. Boxplot of TFD for following passenger car and heavy vehicle for the three different headways.

Table 2. Repeated-measures ANOVA results for within-subject factors on the traffic signal AOI.

Source	$F(v_1,v_2)$	p-value	η_p^2
Following vehicle type	6.348 (1, 44)*	0.015	0.126
Headway	0.649 (2, 88)	0.525	0.015
TTSL	4.916 (2.495, 109.764)*	0.005	0.100
Following vehicle type × Headway	3.314 (2, 88)*	0.041	0.070
Following vehicle type × TTSL	0.324 (2.3, 101.187)	0.754	0.007
Headway × TTSL	2.886 (4.357, 191.697)*	0.020	0.062
Following vehicle type × Headway × TTSL	1.023 (4.522, 198.951)	0.402	0.023

Note: F denotes F statistic; v_1 and v_2 denote degrees of freedom; η_p^2 denotes partial eta squared. *Statistically significant at 95% confidence interval (CI).

overall for the 4.5 s TTSL than for the 3.5 s TTSL ($p = 0.027$). Based on results in Table 2, a change in the following vehicle type (passenger car or heavy vehicle) had the greatest effect on the traffic signal TFD, accounting for about 12.6% of the within-subject variance.

As shown in Table 2, only the traffic signal AOI had significant two-way interactions. There was an interaction between the combined effects of following vehicle type and headway on traffic signal TFD ($F(2, 88) = 3.314$, $p = 0.041$). There was also a significant interaction between the combined effects of headway and TTSL on the traffic signal TFD ($F(4.357, 191.697) = 2.886$, $p = 0.020$).

Additionally presented in Table 3, the rearview mirror AOI was influenced by following vehicle type and headway. The following vehicle type ($F(1, 44) = 4.392$, $p = 0.042$) and headway ($F(1.538, 67.661) = 3.450$, $p = 0.049$) both had significant effects on rear view mirror TFD. The rear view TFD was significantly higher when a heavy vehicle was following. Pairwise comparison showed that TFD was not statistically different between levels of headway. The effect size finding indicated that the change in following vehicle type

Table 3. Repeated-measures ANOVA results for within-subject factors on the rearview mirror AOI.

Source	$F(v_1,v_2)$	p-value	η_p^2
Following vehicle type	4.392 (1, 44)*	0.042	0.091
Headway	3.450 (1.538, 67.661)*	0.049	0.073
TTSL	1.519 (2.423, 106.634)	0.220	0.033
Following vehicle type × Headway	0.7333 (1.519, 66.85)	0.449	0.016
Following vehicle type × TTSL	2.689 (1.854, 84.579)	0.078	0.058
Headway × TTSL	1.117 (3.914, 172.23)	0.350	0.025
Following vehicle type × Headway × TTSL	0.558 (2.999, 131.977)	0.644	0.013

Note: F denotes F statistic; v_1 and v_2 denote degrees of freedom; η_p^2 denotes partial eta squared. *Statistically significant at 95% confidence interval (CI).

had the highest effect on TFD, accounting for about 9% of within-subject variance. None of the factors significantly influenced TFD for the side view mirrors.

Discussion

This study was conducted at high-speed signalized intersections, where the potential for serious crashes and greater variability in vehicle speeds makes driver attention essential. Drivers had limited time to respond, as the yellow change interval was only 4.5 seconds. We evaluated how drivers distributed their visual attention between different critical elements in their forward and rear view and found that most of the drivers' fixations (626 s) were on the traffic signal itself as compared with other two AOIs during the circular yellow (CY) indication. The drivers only periodically fixated (50 s) at the rearview mirror to monitor the following vehicle and almost never fixated (3 s) at the side view mirrors. Time spent looking at regions outside of the three AOIs was 5,354 s. Underwood et al. (2005) suggested that a reduction in mirror-fixation frequency is probably related to an increase in looking straight ahead. In addition, existing literature reports that drivers spend more time looking straight ahead neglecting side and rear view mirrors when workload increases (Harbluk et al. 2007; Recarte and Nunes 2000).

Drivers spent significant time looking at the traffic signal and comparatively much less time inspecting the vehicles behind them during the CY indication. From a safety perspective, when drivers are not looking at the vehicle behind them during the CY indication and suddenly decide to stop, rear-end crashes could occur. Thus, drivers need to be aware to the following vehicle when they respond to the CY indication. During the CY indication, drivers have to distribute their attention between looking at the traffic signal to avoid potential right-angle crashes and looking at the following vehicle to avoid potential rear-end crashes.

Brief glances away from the forward roadway for the purpose of scanning the driving environment are safe and actually decrease crash risk. Glances away from the forward roadway of two seconds or more can create a significantly greater risk of a crash (Klauer et al. 2006). Results showed that the mean glance length on the rearview mirror was 0.18 s which may not be long enough to correctly detect and identify hazards to the rear of the vehicle. Thus, increasing TFDs on the rear view may be necessary to avoid rear-end crash risk. In general, drivers look at their side view mirrors to find visual information about possible changes in traffic situations. In this study, the low frequency of side view mirror fixations during the CY indication was possibly due to the fact that the suburban road had just a single lane in each direction, which reduces the need to use side view mirrors. Consistent with this, Underwood et al. (2003) found fewer mirror inspections on a suburban road and a rural, single-lane carriageway.

The results showed that the fixation frequencies on the traffic signal and on the rearview mirror were significantly different depending on whether the type of following vehicle was a passenger car or a heavy vehicle. Greater risk is indeed involved when a driver is being followed by a heavy vehicle versus a passenger car, due to the physical characteristics of the following vehicle (i.e., mass). Thus, it makes sense for drivers to fixate on their rearview mirrors more in this situation. Time to stop line (TTSL) also had an influence on drivers' visual attention during the approach to a signalized intersection. In fact, when the driver was far enough away from the stop line and the CY indication was displayed, the driver typically increased the frequency of traffic signal fixations to monitor the status of traffic signal and make the appropriate decision. However, at the onset of the CY indication on the approach to a high speed signalized intersection drivers were required to perform their visual search task in less time and allocate more visual attention to the potential conflicts, such as following vehicles, because the speeds of vehicles were high and any incorrect decision could lead to dramatic consequences.

This study has two limitations associated with demographic characteristics. First, 84% of the drivers were between 18-37 yrs, so the results of these findings might not generalize to older adult drivers. In addition, the gender of drivers was not perfectly balanced, as 62% of the drivers were men and 38% were women. However, the findings indicated not statistically differences between a mean TFD for men and women in their performance. For example, mean TFD for men and women was the same (0.18 s) when they fixated on the rear view mirror and only slightly different when fixating on the traffic signal with a mean TFD of 0.57 s for men and 0.62 s for women but it was not significant ($p = 0.48$).

These findings could guide future efforts to educate drivers to properly attend to rear hazards at high speed signalized intersections. From a safety perspective, rear-end crashes can occur when the driver is not attentive to a closely following vehicle and decides to stop suddenly during the onset of the CY indication. There is an opportunity to involve drivers in training programs to emphasize the risks associated with ignoring rear view mirrors during their response to CY indications. Moreover, advanced vehicle technology could alert the driver if there is a closely following vehicle during the CY indication.

Disclosure statemnt

The authors do not have a conflict of interest related to the work documented in this journal article.

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Data availability statement

The data that support the findings of this study are available from the corresponding author, DSH, upon reasonable request.

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