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Right-Hook Crash Scenario: Effects of Environmental Factors on Driver's Visual Attention and Crash-Risk

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ABSTRACT

A right-hook (RH) crash is a common type of bicycle-motor vehicle crash that occurs between a right-turning vehicle and through-moving bicycle at an intersection in right hand driving countries. Despite the frequency and severity of this crash type, no significant driver-performance based evidence of the causes of RH crashes at signalized intersections was found in the literature. This study examined the driver's visual attention in a right-turning scenario at signalized intersections with bicycle lanes but no exclusive right-turning lanes while interacting with a bicyclist to develop an understanding of RH crash causality. Fifty-one participants in 21 simulated road scenarios performed a right-turning maneuver at a signalized intersection while conflicting with traffic, pedestrians and bicyclists. Overall, a total of 820 (41*20) observable right-turn maneuvers with visual attention data were analyzed. The results show that in the presence of conflicting oncoming left-turning vehicular traffic, drivers spent less visual attention on the approaching bicyclist, thus, making them less likely to be detected by the driver. The presence of oncoming left-turning traffic and the, bicyclist's speed and relative position, and conflicting pedestrians were found to likely increase the risk of RH crashes. The results of the

current study will help to identify effective crash mitigation strategies which may include improving the vehicle-human interface or the implementation of design treatments in the road environment to improve driver and bicyclist performance.

Keywords: Bicycle-motor vehicle Crash, Right hook crash, Bicyclist, Road safety, Driving simulator, Driver behavior

BACKGROUND

Most bicycle-motor vehicle (BMV) crashes occur at intersections in urban areas—with crashes involving right-turning vehicles and through moving bicycles, which are commonly termed as “right-hook (RH) crashes” (see Fig. **1**). According to the Oregon (OR) Bicycle Manual, “A RH crash occurs when a right-turning driver crosses the path of a through bicyclist at an intersection” (Oregon Department of Transportation (ODOT) 2016). The United States National Highway Traffic Safety Administration (NHTSA) categorized this crash type as “parallel path*”* crash under “driver turn/merge into path of bicyclist” subgroup in NHTSA Manual Accident Typing (MAT) for Bicyclist Accidents Coder's Handbook (Karsch et al. 2012; Hunter et al. 1995), when the driver was making a right-turn and the bicyclist was riding in the same or opposite direction of traffic. RH crashes at intersections can occur as the result of several scenarios of traffic control and lane geometries at the intersection. This study examined the specific case of RH crashes after the start-up period at a signalized intersection with no dedicated turning lane. In this scenario (sometimes referred to as “stale” green) both conflicting vehicles (the bicyclist and the car) are moving. A RH crash in this condition can occur when a bicyclist overtakes a slow-moving vehicle on the right and the vehicle unexpectedly makes a right-turn, or when a fast-moving vehicle overtakes the bicyclist and then tries to make a right-turn directly in front of the bicyclist.

NHTSA reports that there were 840 fatal bicycle-related crashes in 2016, which accounted for 2.2% of transportation-related fatalities. NHTSA reported that 71% of fatal bicycle crashes occurred in urban areas in 2016, with 30% of them at intersections. The literature identifies intersections as hot-spots for bicycle-motor vehicle-related crashes (Korve and Niemeier 2002; Wachtel et al. 1994; Wang and Nihan 2004; Weigand 2008).

To safely accomplish the dynamic and multifaceted driving task, drivers need to perceive, identify, and correctly interpret the elements of the current traffic situation including immediately adjacent traffic, road signs, route direction, and other inputs, while being vigilant for obstacles and making predictions of near future traffic conditions to maintain control, guidance, and navigation of the vehicle (Baumann et al. 2007).

Improper allocation of visual attention has been recognized for some time as a causal factor in vehicular crashes (Treat et al. 1979). A NHTSA study confirmed that 55.7% of intersection-related crashes occurred due to drivers' recognition errors such as inattention, internal and external distractions, or inadequate surveillance (NHTSA 2010). The most frequently assigned critical reason was found to be inadequate surveillance, which constituted 44.1% of all intersection-related crashes. Inadequate surveillance occurs when the driver is in a situation where they need to scan a certain location to safely complete a maneuver and they either fail to look in the appropriate place or looks but does not see. This failure can occur at an intersection when the driver looks in the required direction before making a turn but fails to see the approaching traffic (Dingus et al. 2006); or when the driver fails to identify the visual cue on time, since the visual cue is in an unexpected location or incompatible with the driver's schemes (Borowsky et al. 2008).

Driver’s visual attention was also found to be a factor in the case of motor-bicycle crashes. One of the major contributing factors to this crash type is the improper allocation of driver’s visual attention while making turns at an intersection. Before making a right turn, drivers focus their visual attention on the cars coming from the left and fail to detect the bicyclist coming from their right early enough to respond safely, even when the bicyclist could be easily detected (Summala et al. 1996; Wachtel et al. 1994). In the case of a bicyclist coming from an unexpected direction, prior research found that even if drivers looked in the relevant direction and noticed the bicyclist, often the identification was too late to effectively stop or yield (Räsänen and Summala 1998).

It is worth noting that although the topic of right-turning vehicle crashes with bicycles appears in the literature with some frequency (Summala 1988; Wachtel et al. 1994; Weigand 2008), comparably little substantive research has been conducted on this topic. Improper allocation of drivers’ visual attention and inadequate surveillance methods were demonstrated as factors contributing to crashes between a driver turning right and a bicyclist from previous studies. A safe right-turning maneuver requires that the driver will look and detect the bicyclist, so their decision to make the right turn will be based on that information and corresponding conditions at the intersection. It was the goal of this study to measure the driver’s visual attention in these cases to identify the scenarios that increase the risk of a RH crash. The study hypothesis was that right-turning driver’s visual attention would be influenced by the relative position of bicyclists and other visual cues in the driving environment; thereby bicyclists’ relative position and speed would increase the crash risk. The primary failure mechanism would be drivers who fail to detect the bicyclist when approaching from behind in the driver’s blind spot as compared to when the bicyclist is riding in front of the driver in her focal vision.

RESEARCH METHODOLOGY

Participants

A total of 67 individuals, primarily from the community surrounding Corvallis, OR, participated in the driving simulator study. The responses recorded from 16 participants who exhibited simulator sickness, were excluded from the original data set. As such, the results of 51 participants (30 males, 21 females) aged 19-69 (mean=30.24) were included in the analysis. All participants had a valid driving license with at least one year driving experience and were required to declare that they were still mentally and physically fit to drive at the time of the experiment. Participants were given $20 compensation in cash for participating in the experiment.

Apparatus

The driving simulator

The Oregon State University (OSU) Driving Simulator is a high-fidelity, motion-based simulator, consisting of a full 2009 Ford Fusion cab mounted above an electric pitch motion system capable of rotating ±4 degrees (see Fig. **1.** Schematic description of a right-hook crash.

Fig. 2). The vehicle cab is mounted on the pitch motion system with the driver's located at the center of the viewing volume. The pitch motion system allows for the accurate representation of acceleration or deceleration (Oregon State University 2011). Three projectors with a resolution of 1,400 by 1,050 are used to project a front view of 180 degrees by 40 degrees on three adjacent screens, measure 3.4 meters by 2.3 meters each. A digital light-processing projector is used to display a rear image for the driver’s center mirror and the two side mirrors have embedded liquid crystal displays (LCD). The simulator is equipped with a surround sound system that produces ambient and driving sounds. The simulator software is capable of capturing and outputting highly accurate values for performance measures such as speed, position, brake, and acceleration. The virtual environment was developed using Simcreator simulator software package by Realtime technologies (RTI), Internet Scene Assembler (ISA) and Google Sketchup.

Eye-tracking

Eye-tracking data were collected with the Mobile Eye-XG platform from Applied Science Laboratories (ASL) as displayed in Fig. **3**. This platform allows the user to have both unconstrained eye and head movement. A sampling rate of 30 Hz was used, with an accuracy of 0.5-1.0 degrees (Oregon State University 2011). The participant's gaze was calculated based on the correlation between the participant's pupil position and the reflection of three infrared lights on the eyeball. The system records a fixation when the participant's eyes pause in a certain position for more than 100 milliseconds.

Eye-Fixation Data Reduction

The eye fixation data analysis process was performed on 25 second video clips capturing each participant's approach to an intersection preparing to and completing a right turn. Each video clip started from the point when the participant approached the intersection and ended when the participant completed the right-turn maneuver. The participant's eye movement data was analyzed with ASL Results Plus software. For this process, researchers watched each collected approach video (20 per participant) and drew AOI (area of interest) polygons on individual video frames in a sequence separated by intervals of approximately 5-10 frames. Once the researcher manually situated each AOI, the Results Plus software automatically identified the fixations inside each AOI (i.e., traffic signals (overhead and post-mounted), pedestrians, bicyclists, mirrors (rear and driver's right side), and oncoming left turning vehicles) (See Fig. **4**). At the end of the process a data set was exported from the Results Plus software that summarizes the fixations data during a single 25-second intersection approach video for further statistical analysis. The data included: the number of fixations, total fixation durations (secs), average fixation durations (secs), and time of the first fixation within each AOI created during an intersection approach and right-turn maneuver. Fixations outside of coded AOIs were universally defined as OUTSIDE and were not analyzed further.

Driving scenarios

Twenty-one different right-turning road scenarios within seven different driving tracks were constructed in a typical suburban-like virtual environment where shops and housing buildings are placed along the sides of the road. In each, a cross section of the roadway included three 3.6 meters traffic lanes with 1.7 meters bicycle lanes in each direction was presented. In the driver's direction of travel, the intersection approach was a single shared through and turning lane. In the opposing direction, there were two lanes. No exclusive left-turn or right-turn bay was provided at the intersection. The receiving roadway for the right turn had a single receiving lane. The intersection approaches had a posted speed limit of 15.65 meter/second (m/s) (35 miles/hour (mph)) (see Fig. **5**). The scenarios introduced a combination of four independent variables resulted in 20 right-turning scenarios that were presented to the participant. The scenarios introduced a variation of on-coming traffic, crossing pedestrian, and traveling bicyclist's position and speed (see study design). The movements of the other dynamic actors in the scene were initiated with proximity sensors coded in the simulation in response to the position and speed of the subject vehicle. The oncoming left-turning vehicles start their movement on the green light, while the driver is waiting at the red light at the intersection. As the driver approached the signalized intersection, the pedestrian entered the conflicting crosswalk to cross the road. The movement of the bicycle ahead was synced with the movement of the vehicle, so, when the driver was approaching the intersection the bicyclist ahead of him was also moving toward the intersection. The bicyclists from behind condition was designed in a way that they were visible in drivers' rear view or side mirror while the drivers were approaching the intersection. The simulated environment was designed in a way that drivers could not see the bicyclists pulling onto the bike lane from the adjacent lane behind them (though they would have passed other bicyclists in the tangent sections so were aware bicycles were present in the simulation).

The design and sequencing of the 20 scenarios was influenced by a need to minimize the occurrence of simulator sickness. Therefore, the experimental driving was divided into seven individual driving tracks of intersections and each included 2-4 right-turning scenarios. Each scenario was assigned a position on a grid based on the assignment of random number generation. The order of presentation of driving tracks 1 to 6 was partly counterbalanced (i.e. there were four possible sequences of presentation to the driving tracks) to minimize the practice effect on driver performance and made it more difficult for participants to predict when the simulation would stop. Each participant was randomly assigned to drive the tracks in one of those orders. To provide more variability in the sequence of right turning scenario presentations, the start and finish locations of these driving tracks were not consistent. Also, the scenarios were interrupted by through movements at intersections that were not experimental scenarios to prevent participants anticipating the motivation for the study and to reduce simulator sickness. Participants were given the instruction to turn right at an intersection through an automated voice command saying: "Turn Right at the Next Intersection", 100 meters upstream of the intersection. This voice command was automatically generated on the vehicle approach to the intersection. Fig. **6** shows an example driving track layout of three right-turning scenarios (e.g., tracks 1, 2 and 7). The “Path” in the figure indicates the sequence of maneuvers participants were asked to perform.

Experimental procedure

Upon arrival, the participant was presented with an informed consent document that provided a general description of the entire experiment and the opportunity to ask clarifying questions. Participants were informed that they could stop the experiment at any time for any reason and still receive full compensation. Participants were not told of the specific research objective or the associated hypotheses. Participants completed a prescreening demographic survey, including questions related to: age, gender, driving experience, highest level of education, use of corrective glasses or contact lenses, as well as their prior experience with both driving simulators and motion sickness.

At this stage, participants were required to perform a 3- to 5-minute practice drive to acclimate to the operational characteristics of the driving simulator, and to confirm if they experienced simulator sickness at any point during the practice drive. Once seated in the vehicle, participants were allowed to adjust the seat, rear-view mirror, and steering wheel to maximize comfort and performance while driving in the experiment. Participants were also instructed to drive and follow all traffic laws as they normally would. The calibration drive was conducted in a generic city environment, as previously described, and drivers were required to make several right turns. If a participant reported simulation sickness during or after the calibration drive, their experimental work was stopped, they were fully compensated, and any recorded data was excluded from further analysis.

Before starting the experimental drive, participants were instrumented with a head-mounted eye tracker and performed a short calibration process. After that, participants received a brief instruction about the test environment and the tasks they were required to perform. Participants were asked to perform right-turning maneuvers at signalized intersections. As noted in the introduction, all participants approaching the intersection were presented a green signal and were in motion. Participant's eye movements were collected while driving through 20 typical right-turning intersections in the simulated environment. As previously stated, the entire experiment was divided into seven driving tracks that were presented in a random order and random starting and ending points within each track. The virtual driving course took participants 20 to 30 minutes to complete. The entire experiment, including the consent process, eye tracker calibration and post-drive questionnaire, lasted approximately 50 minutes.

Study design

To measure participant's visual attention during the course of the right-turn maneuver, the average total (summed) fixation duration (ATFD) was documented for each predefined dynamic area of interest (AOI) in each scenario. Fig. **7** shows examples of different AOIs that drivers fixated on during the experiment.

Analysis of fixations was conducted to investigate the percentage of drivers who fixated on the bicyclist before turning right at the intersection. The determination of the fixation on a bicyclist was limited to when a driver fixated directly on the bicyclist AOI. For example, a driver who fixated on the rear view or side mirror, but did not fixate directly on the bicyclist coming from behind and then turned-right without yielding to the bicyclist - these cases indicated that driver failed to detect the bicyclist and were coded as "not fixated" in the analysis.

Independent variables

The relative position and speed of bicyclist, presence of oncoming left-turning vehicular traffic, and conflicting pedestrian in the crosswalk may influence drivers' visual attention while turning right. Therefore, all these factors were included as independent variables.

The first independent variable "relative position of bicyclist" had three levels – 1) no bicyclist, 2) bicyclist approaching from behind the driver, and 3) bicyclist riding ahead of the driver. The second independent variable, bicyclist's speed had two levels – 1) lower (5.36 m/s (12 mph)), and 2) high (7.15 m/s (16 mph)). The third independent variable was the "presence of oncoming left-turning vehicular traffic", which had two levels – 1) no oncoming (zero) vehicles and 2) three oncoming vehicles. The last independent variable was the "presence of a conflicting pedestrian in the crosswalk, which also had two levels – 1) no (zero) pedestrian and 2) one conflicting pedestrian walking towards the participant.

Research Hypotheses

One of the common features of BMV crashes at intersections includes drivers' learned routine of failing to account for an adjacent bicyclist before turning (Räsänen & Summala, 1998). It was hypothesized that right-turning driver's visual search would be influenced by the relative position of bicyclists. It was inferred that the driver would fail to detect the bicyclist when approaching from behind in the driver's blind spot as compared to when the bicyclist is riding in front of the driver in his/her/their focal vision. Two hypotheses were formulated to address this:

$H_{0\ (VSP1)}$: Relative positions of adjacent bicyclists' have no effect on the right-turning drivers' mean total fixation duration on areas of interest in the driving environment.

$H_{0\ (VSP2)}$: There is no difference in the proportion of drivers who fixate on an adjacent bicyclist during the right-turn maneuver at signalized intersections as the relative position of the bicyclist changes.

It has also been suggested that before turning right, drivers tend to focus their attention on the cars coming from the left and fail to notice bicycles coming from their right early enough to respond safely (Summala, Pasanen, Räsänen, & Sievänen, 1996). Therefore, it was hypothesized that driver's visual attention will be influenced when an oncoming car turns left in front of the driver. Also, a study on bike boxes in Portland, Oregon suggested that the speed of bicyclists overtaking the right-turning vehicle was a contributing factor to the occurrence RH crash (Dill, Monsere, & McNeil, 2012). It was inferred that bicyclist's speed would have an effect on the visual attention of drivers while turning right during the latter portion of the green phase. Again, the Institute of Transportation Engineers (ITE) Transportation Planning Handbook states that one of the most common pedestrian crashes is the vehicle turn/merge conflict type (Meyer, 2009). This conflict type occurs when a pedestrian and vehicle collide while the vehicle is conducting, preparing, or has just completed a turning movement (Hurwitz & Monsere, 2013). Considering this finding, it was also hypothesized that the presence of a pedestrian in the conflicting crosswalk might influence the visual attention of a right-turning driver.

$H_{0\ (VSP3)}$: The speed of adjacent bicyclists have no effect on right-turning drivers' mean total fixation duration on areas of interest in the driving environment.

$H_{0\ (VSP4)}$: The presence of oncoming left-turning vehicular traffic has no effect on the right-turning drivers' mean total fixation duration on areas of interest in the driving environment.

$H_{0\ (VSP5)}$: The presence of pedestrian in the conflicting crosswalk have no effect on the right-turning drivers' mean total fixation duration on areas of interest in the driving environment.

Data Analysis

Fifty-one participants successfully completed the driving simulator experiment. However, due to eye-tracker calibration issues, completely usable data was only collected from 41 participants representing a total of 820 (41*20) observable right-turn maneuvers with visual attention data.

To test the five hypotheses stated above, for each of the four independent variables (bicyclist's position, bicyclist's speed, oncoming vehicle presence, and pedestrian's presence) an analysis of variance test (ANOVA) was conducted to statistically determine if there was any difference in the ATFDs. However, when the variances were not equal (determined by Levene's test) indicating the violation of the assumption of homogeneity of variance, the Welch's Robust test or Omnibus F were used to interpret the F-statistic. Finally, pairwise comparisons were calculated with Tukey's Honest Significant Difference (HSD) test.

RESULTS

Forty-one participants (in total of 820 observable right-turn maneuvers with visual attention data). To detect crashes, the driving task in the simulated environment was observed continuously from the simulator's operator station and records were taken at the moment a crash occurred. Drivers were also asked at the end of the experiment if they were involved in any crashes during the experiment. The recorded crash data was further validated by checking the locations of the subject vehicle and bicycle centroid, recorded as a dynamic variable data in the driving simulator. In most cases, drivers could not notice when a crash occurred due to their inadequate surveillance behavior and overloaded working memory during turning maneuver. A Chi-square test was conducted for each of the independent variables to reveal significant differences in the risk of a crash.

Fig. **8** shows the ATFD values and 95% CIs for four AOIs at an intersection scenario where the driver was presented with no pedestrians, no oncoming vehicles, and no bicyclists.

This particular intersection is the most basic of all intersections shown to the participants. This scenario presented the simplest driving scenario to the driver.

Fig. **9** shows the ATFDs from all participants at an intersection where the bicyclist was approaching from behind the driver at 7.15 m/s, oncoming vehicles were present, and a pedestrian was present in the conflicting crosswalk. This case includes the greatest number of experimental variables, and is one of the most visually complex scenario.

Bicyclist's relative position

Three possible conditions existed for the bicyclist's position, the bicyclist was either riding ahead of the driver, approaching from behind the driver, or there was no bicyclist. The first two conditions were included in eight experimental scenarios each and the third level (no bicyclist) resulted in four experimental scenarios. The dataset was aggregated this way to isolate the impact of individual variable levels. Fig. **10** shows boxplots of ATFDs on each AOI for the bicyclist conditions. The boxplots display the distribution of ATFD in quartiles and indicat the mean and median of those distributions. The results of the ANOVA and pairwise comparisons presented in Table 1 shows that ATFDs on the bicyclist, pedestrian, right-side mirror, and oncoming vehicles had statistically significant differences. A two-sided Welch's two sample t-test indicated a statistically significant difference in ATFDs on bicyclists with respect to bicyclists' position. Drivers spent more time fixating on bicyclists when they were riding ahead as compared to when bicyclists were approaching from behind. The ATFD for the pedestrian AOIs was different when the bicyclist was riding in front vs when the bicyclist was approaching from behind with statistical significance. This finding revealed that in the presence of a bicyclist in the forward field of view, drivers spent less time fixating on the pedestrian compared to when the bicyclist was approaching from the behind. Similar findings were observed in the case of the oncoming vehicle AOI. However, a statistically significant difference in the ATFDs on the right-side mirror and corresponding pairwise comparison showed that drivers spent more time fixation on the right-side mirror when a bicyclist was approaching from behind compared to when there was no bicyclist present at the intersection. No other significant differences were found with 95% confidence.

Thirteen crashes occurred when the bicyclist approached from behind and in the remaining two crash incidents the bicyclist was riding ahead of the driver. A Chi-square test revealed a statistically significant difference between these two bicyclist positions ($p<0.01$) with respect to the occurrence of a crash.

Detecting the bicyclist

As summarized in Table 2 there were 328 (41 participants*8 turns) right-turns scenarios for each bicyclist position. When the bicyclist was riding ahead of the driver in the forward field of view, in 87% of the cases the drivers fixated on the bicyclist, i.e. actively scanned for the bicyclist before turning right. However, when a bicyclist was approaching from behind, in only 44% of the scenarios did a driver fixate on the bicyclist before turning right. A Chi-square test revealed a statistically significant difference (p-value < 0.001) between the frequencies of driver fixation on the bicyclist with different bicyclist positions.

Speed of Approaching Bicyclist

A comparison of ATFDs with respect to the bicyclist's speed was also conducted. Bicyclists traveled at either 7.15 m/s or 5.36 m/s. These two conditions consisted of eight experimental scenarios each. The boxplot of ATFDs on AOIs by bicyclists speed is presented in Fig. **11**.

Table 3 presents the results of two-sample, two-sided t-tests that were conducted to determine the difference in the ATFDs with respect to bicyclist's speed. A statistically significant difference was found only in the ATFDs on the rear-view mirror with changes in the bicyclist's speed. When bicyclist's speed was lower (5.36 m/s), drivers spent more time scanning the rear-view mirror compared to higher (7.15 m/s) speed scenarios. This was likely because the bicyclist required more time to travel the same distance before reaching the intersection in the lower speed condition compared to the higher speed condition, while the driver yielded for the bicyclist to pass.

In 12 out of the 15 crashes occurred when the bicyclist approached at 7.15 m/s speed and in the remaining three crashes had bicyclists approaching at 5.36 m/s speed. A Chi-square test revealed a statistically significant difference between bicyclist speeds ($p\text{-value}<0.05$).

Presence of oncoming left turning vehicle

There were two levels of oncoming left turn vehicular traffic in the experiment (No vehicles and 3 vehicles). These two conditions consisted of 10 experimental scenarios each. Fig. **12** shows the boxplot of ATFDs on AOIs by the presence of oncoming left turn vehicular traffic. Table 4 presents the results of two-sample, two-sided t-tests that were conducted to determine the difference in the ATFDs with respect to presence of oncoming vehicle. Statistically significant differences indicated that drivers spent less time fixating on pedestrians, bicyclists riding ahead of the driver, and the side signal when there were oncoming left-turn vehicles as compared to when there was no oncoming left-turn vehicle present.

Eight crashes occurred when oncoming left-turning vehicles were present, and seven crashes occurred when no oncoming vehicle was present. No statistically significant difference was found for the presence of oncoming vehicles with respect to crash outcome.

Presence of pedestrian

Ten experimental scenarios presented a single pedestrian in the crosswalk and ten experimental scenarios had no pedestrian present on the crosswalk. Fig. **13** shows the boxplot of ATFDs on AOIs by the presence of a conflicting pedestrian.

From the result of two-sample, two-sided Students or Welch's t-tests, the only statistical significant different in ATFD was found in the bicyclist behind AOI with the presence of a pedestrian (Table 5). Results indicated that drivers spent more time fixating on the bicyclist approaching from behind when a conflicting pedestrian was present in the crosswalk as compared to when no pedestrian present. No statistically significant difference was found for the presence of pedestrian with respect to crash outcomes.

DISCUSSION

This study investigated driver's visual attention and the risk of crash in a simulated virtual environment while performing a right turn at a signalized intersection when a bicyclist is present and in different circumstances (i.e. a pedestrian in the conflicting crosswalk and oncoming left turn vehicles) that might affect the driver's visual attention. The aim of this study was to identify scenarios in the driver's visual search that increase the risk of a RH crash with the bicyclist. The ATFD within a prescribed AOI was used to measure driver's visual attention on different targets. Findings related to each research question on driver's visual attention are summarized below.

Aligned with the study hypothesis, a statistically significant difference (p-value < 0.001) was found in the ATFDs on adjacent bicyclist between when a bicyclist was approaching from behind and when a bicyclist was riding ahead of the driver. This circumstance also increases the crash risk. This finding is consistent with the finding of Falzetta (Falzetta, M. (2004). A Comparison of driving performance for individuals with and without Attention-Deficit-Hyperactivity Disorder. Unpublished Masters Thesis, Clemson University, Psychology

Department, Clemson, SC.), where it was found that participants detected forward events more successfully than rear events, and the location effect was consistent with an attention allocation strategy that gave higher priority to the road ahead. A statistically significant difference (p-value < 0.001) was observed between the frequencies of driver fixations on the bicyclist when the bicyclist was approaching from behind (44%) vs. when bicyclist was riding ahead (87%). Such scanning behavior places bicyclists approaching from behind in a more vulnerable situation where they are not detected by a driver at an intersection, contributing to the occurrence of RH crashes.

Statistically significant differences were also observed in the visual attention allocated to conflicting pedestrians and oncoming left turn vehicles with respect to bicyclist's position. This finding might suggest that when a bicyclist was riding ahead in the driver's visual field, drivers anticipated a potential risk of collision with them more so than when they were approaching from behind. However, when the bicyclist was approaching from behind, drivers spent more time fixating on other traffic elements immediately relevant to the safe operation of the vehicle. Another statistically significant finding was observed in the ATFDs on the right-side mirror when the bicyclist was approaching from the behind compared to when there was no bicyclist. This suggests that when drivers detected a bicyclist approaching from behind in the right-side mirror, they spent more time fixating on the right-side mirror while waiting for the bicyclist to pass through the intersection compared to when there was no bicyclist present. Bicyclist's speed when approaching from behind had a statistically significant effect only on the visual attention allocated to the rear-view mirror. A bicyclist that was detected in the rear-view mirror would require more time to travel the same distance before reaching the intersection at the lower speed.

Therefore, it can be assumed that the total fixation duration on checking the rear-view mirror in search of the bicyclist was higher when the bicyclist traveled at a lower speed.

Oncoming left-turning traffic had a meaningful effect on the driver's visual attention spread, demonstrated in the ATFDs on the side traffic signal, crossing pedestrian, and a bicyclist riding ahead. Results suggest that in the presence of oncoming traffic, drivers spent less time checking on other traffic elements in their focal vision, such as scanning for the pedestrian, checking for the traffic signal status, or fixating on the bicyclist ahead. In the presence of oncoming vehicular traffic, drivers spent a significant part of their time fixating on the oncoming traffic, to the expense of the other traffic elements. The preferential visual attention oncoming traffic gets from the driver over other road users and elements was observed in other circumstances. In previous laboratory experiment it was observed that drivers' visual attention was drawn to the oncoming traffic on the expense of pedestrians (Hurwitz & Monsere, 2013), and left turning drivers at signalized intersections were less likely to seek out for additional cues from the road environment in the presence of opposing traffic (Knodler and Noyce 2005). In the analysis of bicycle-car collisions at non-signalized intersections in the Helsinki City area, Finland, by assessing the visual scanning behavior of drivers, researchers had found that drivers develop a visual scanning strategy which concentrates on detection of more frequent and major dangers, such as conflicting vehicles but ignores and may even mask visual information on less frequent dangers, such as bicyclists (Summala et al. 1996). The driver possesses only a limited capacity for visual attention, and so in accordance with the results from the current and previous studies (Hurwitz S and Monsere 2013; Knodler and Noyce 2005; Summala et al. 1996) the presence of oncoming vehicles perceived by the driver as posing more of a collision risk as compared to other objects in the road environment (like the bicyclists), and as a result of that the driver consistently spends more time fixating on the oncoming vehicles.

The presence of pedestrians also affected the driver's visual attention to the bicyclist approaching behind him, yet not the risk of a crash. Results were suggestive that when drivers were waiting for the conflicting pedestrian to pass through the intersection, they spent more time on fixating on the bicyclists approaching from behind compared to when there was no pedestrian, but not on the bicyclist that ride ahead from the driver. This was likely because while drivers were waiting for the pedestrian to pass through the intersection, they had more time to fixate on the bicyclist approaching from behind compared to when there was no crossing pedestrian.

Overall, this research provides valuable insights on the causal factors of RH crashes after the start-up period at a signalized intersection with no dedicated turning lane. These findings can help roadway engineers and planners while designing roadway sections and locations where bicycles are likely to be routinely overtaking motor vehicles on the right, especially at higher speeds. This can occur either in congested vehicle traffic or when bicycles have the advantage of a downgrade, as found in earlier studies. Findings from this study emphasizes the need for other design considerations to reduce RH crashes, for example additional pavement markings or signs may increase driver awareness. Other designs, such bending out the bicycle lane at the intersection or separating the bicycle movement with a separate signal phase may be feasible options. In bicycle-lane markings or minor speed humps may be effective at slowing bicycle speeds if other solutions are not feasible. To some degree, interactions at closely spaced signalized intersections in urban areas can be managed with careful thought of the bicycle and vehicle progression in platoons from upstream signals. This could be accomplished with a leading bicycle interval at the upstream signal that allows the majority of the bicycle platoon to arrive ahead of vehicles (Kothuri et al. 2018).

CONCLUSIONS

The results indicate that bicyclist approaching from behind the driver in the blind spot is the most vulnerable situation for a right-turning driver to fail to detect the bicyclist, potentially leading to a RH crash. The presence of oncoming left-turning traffic and pedestrian at the crosswalk are likely to increase the risk of RH crash, as they draw the driver's visual attention away from other objects (e.g. the bicyclist). Results also indicate that higher speed bicyclists are likely to contribute to the risk of RH crash.

As with any driving simulator experiment, while the various driver performance metrics are measured robustly, it is not yet clear how to map the magnitudes of the differences to expected crash outcomes. More work is needed to connect visual attention metrics and crash outcomes. Additional variables could be included in the experiment to determine their effects on the occurrence of right-hook crashes, for example the conspicuity of bicyclist, and time of day. The assumption of constant speed of the approaching bicyclist is also limiting; in reality some people on bicycles would slow down to avoid a collision or near collision. A study that included dynamic bicycle approach speeds would be an improvement. Finally, one of the fundamental limitations of within-subject design is fatigue effects that can cause participant's performance to decline over time during the experiment. To mitigate this a larger sample of shorter drives might reduce the risk of fatigue effect and simulator sickness, the experiment could be conducted in two trials on two different days. Finally, the design of the experiment could be modified with navigation tasks or other workloads enhancements so that the driver workload is more representative of actual conditions.

DATA AVAILABILITY

Some or all data, models, and code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions (e.g. anonymized data). Specifically, driver's visual attention data (number of fixations and durations) for each scenario aggregated by area of interest is available.

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Table 1. ANOVA analysis of difference in ATFDs by bicyclist position.

Area of Interest	Relative position of bicyclist			ANOVA	Tukey's HSD for pairwise comparisons of means w.r.t bicyclist positions								
	Ahead	Behind	None	All	Ahead vs Behind			Ahead vs None			Behind vs None		
		ATFD		p-value	p-value	Sig	Diff	p-value	Sig	Diff	p-value	Sig	Diff
Bicyclist	1.40	0.25	N/A	N/A	<0.001 +	Yes	1.15	N/A			N/A		
Pedestrian	3.28	4.02	3.85	0.03 *	0.039	Yes	-0.74	0.28	No	-0.57	0.89	No	0.17
Signal (overhead)	0.13	0.16	0.18	0.16 *	0.4	No	-0.03	0.17	No	-0.06	0.74	No	-0.02
Signal (side)	0.14	0.13	0.14	0.83	0.82	No	0.014	0.99	No	0	0.95	No	-0.01
Rear view mirror	0.43	0.40	0.43	0.82	0.83	No	0.03	0.99	No	0	0.9	No	-0.03
Side mirror	0.39	0.45	0.29	0.03 *	0.53	No	-0.06	0.302	No	0.1	0.049	Yes	0.16
Oncoming veh	1.42	2.01	1.48	0.002 *	0.002	Yes	-0.59	0.95	No	-0.06	0.53	No	-0.03

+ No multiple comparisons required. P-value reflects a two-sided Welch's two sample t-test.

* P-value reflects a Welch F test.

Table 2. Detecting of a bicyclist.

Frequency of fixation	Bicyclist position	
	Ahead	*Behind*
Total (n)	328	328
Fixated	284	145
%	87%	44%

Table 3. Two-sample *t*-test of ATFDs by bicyclist speed.

Areas of Interest	Speed of Bicyclist		Two sample two tail *t*-test	
	7.15 m/s	5.36 m/s	*7.15 m/s vs* 5.36 m/s	
	ATFD (sec)		p-value	Significant
Pedestrian	3.61	3.68	0.83	No
Bicyclist ahead	1.43	1.38	0.78	No
Bicyclist behind	0.20	0.30	0.98	No
Signal (overhead)	0.14	0.14	1.00	No
Signal (side)	0.14	0.13	0.91	No
Rear view mirror	0.36	0.47	0.03 +	Yes
Side view mirror	0.39	0.46	0.23 +	No
Oncoming veh	1.89	1.54	0.06	No/Suggestive

+ P-value reflects a two-sided Welch's two sample *t*-test

Table 4. Two-sample t-test of ATFDs comparing AOIs by oncoming left turn vehicles condition.

Areas of Interest	Oncoming Vehicle		Two sample two tail t-test	
	3 Veh	No Veh	3 Veh vs No Veh	
	ATFD (sec)		p-value	Significant
Pedestrian	3.11	4.26	<0.001 +	Yes
Bicyclist ahead	1.20	1.61	0.01 +	Yes
Bicyclist behind	0.21	0.29	0.09 +	No
Signal (overhead)	0.16	0.14	0.57	No
Signal (Side)	0.11	0.16	0.02 +	Yes
Rear view mirror	0.38	0.46	0.11 +	No
Side view mirror	0.39	0.40	0.87	No
Oncoming veh	1.67	N/A	N/A	N/A

+ P-value reflects a two-sided Welch's two sample t-test

Table 5. Two-sample t-test of ATFDs comparing AOIs by Conflicting Pedestrian.

Areas of Interest	Pedestrian		Two sample two tail *t*-test	
	Ped	No Ped	*Ped vs No Ped*	
	ATFD (sec)		p-value	Significant
Pedestrian	3.69	N/A	N/A	N/A
Bicyclist Ahead	1.39	1.42	0.88	No
Bicyclist Behind	0.38	0.12	<0.001 +	Yes
Signal_Overhead	0.14	0.16	0.35	No
Signal_Side	0.17	0.10	0.72	No
RV_Mirror	0.47	0.38	0.06 +	Suggestive
Side_Mirror	0.40	0.39	0.76	No
Oncoming veh	1.67	1.66	0.99	No

+ P-value reflects a two-sided Welch's two sample *t*-test

Captions and Notes for Figures

Fig. 1. Schematic description of a right-hook crash.

Fig. 2. The OSU Driving Simulator from inside (a) and outside (b) the vehicle.

Fig. 3. OSU researcher demonstrating the Mobile Eye XG recording unit (image by David S. Hurwitz).

Fig. 4. The ASL Results Plus software. In this frame the driver was fixating on a bicyclist before turning right. This figure also includes heat maps (shaded circular patterns) for the conflicting pedestrian AOI crossing the intersection and the side traffic signal AOI with green indication in driver's field of view.

Fig. 5. Screen capture of intersection approach in the simulated environment, this scenario includes the presence of oncoming left-turning vehicles waiting in the queue, and a bicyclist riding ahead of the right-turning driver at the latter portion of green phase.

Fig. 6. Example driving track layout for tracks 1, 2 and 7 with three right-turning scenarios – path Start-Thru-Right-Thru-Right-Thru-Right-Finish.

Fig. 7. Examples of Different AOIs Drivers Fixated On During the Experiment

Fig. 8. ATFDs with 95% CIs for Control Case (No Bicyclists, No Vehicles, No Pedestrians)

Fig. 9. ATFD with 95% CIs for One of the Most Visually Complex Scenario (Bicyclist Approaching From Behind at 7.15 m/s, Three Vehicles, One Conflicting Pedestrian)

Fig. 10. Box plot of ATFDs at all intersections by bicyclist position.

Fig. 11. Box plot of ATFDs at all intersections, according to bicyclist's speed.

Fig. 12. Box plot of ATFDs at all intersections, according to the presence of oncoming left turn vehicle.

Fig. 13. Box Plot of ATFDs at all Intersections by the Presence of Pedestrians.