Visual Attention Failures during Turns at Intersections: An On-road Study

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Abstract

Crash data indicate that misallocation of attention is a major source of vehicle crashes with vulnerable road users (pedestrians and cyclists) at intersections. Video recordings from outside and inside the vehicle indicate that drivers allocate their attention based on their expectations but the extent that drivers fail to scan for vulnerable road users at intersections is not known. In this paper, we examine failures to check for vulnerable road users during right turns at intersections. Eye-tracking data was analyzed from 19 drivers between the ages of 35 and 54 who participated in an on-road instrumented vehicle study conducted in downtown Toronto. Each participant made two right turns from a major arterial road. In addition to attention allocation failures, we assessed whether the objective data was correlated with experience driving in the area as well as with drivers' subjective responses about their intersection-related errors collected through the Driver Behaviour Questionnaire (DBQ). Eleven of the 19 participants had a failure in at least one of the intersections; all failures related to checking for cyclists. At a marginally significant level, attentional failures were more likely for those who drove more frequently in downtown Toronto and for those who had larger error scores on intersection-related questions of DBQ. The prevalence of attentional failures observed is alarming, especially given that our participants represented the lowest crash-risk age group. It appeared that drivers less familiar with an area were more cautious when it comes to negotiating an intersection. Additionally, drivers appeared to be aware of their intersection-related errors as indicated by their DBQ responses. Further research with an increased sample size and on a variety of intersections is needed to generalize these findings.

Résumé

Les données sur les accidents indiquent que l’inattention est une source majeure des accidents de véhicules avec les usagers vulnérables (piétons, cyclistes et motocyclistes) au niveau des intersections. Les enregistrements vidéo provenant de l'extérieur et de l'intérieur des véhicules indiquent que les conducteurs accordent leur attention en fonction de leurs attentes. Toutefois, nous ne savons pas à quel point les conducteurs échouent dans la vérification des usagers vulnérables aux niveaux des intersections. Dans cet article, nous examinons l’échec de la vérification des usagers vulnérables lorsqu’ils tournent à droite aux niveaux des intersections. Les données de suivi du regard ont été analysées chez 19 conducteurs âgés de 35 à 54 ans. Ces derniers ont participé à une étude sur les véhicules instrumentés dans de situations réelles menées au centre-ville de Toronto. Chaque participant à tourner deux fois à droite à partir d'une route artérielle majeure. En plus de l’inattention, nous avons vérifié si les données objectives étaient corrélées avec l'expérience de conduire dans la zone et avec les réponses subjectives des conducteurs. Ces dernières concernent leurs erreurs liées aux intersections recueillies via le Driver Behaviour Questionnaire (DBQ). Onze des 19 participants ont eu un échec dans au moins une des intersections; tous les échecs ont été liés à la vérification des cyclistes. À un niveau marginalement significatif, les échecs attentionnels étaient plus probables chez ceux qui conduisaient plus fréquemment au centre-ville de Toronto et chez ceux qui avaient des scores d'erreur plus élevés dans les questions liées aux intersections du DBQ. La prévalence des échecs attentionnels observée est alarmante, notamment que les participants représentaient le groupe d'âge le plus faible au risque d'accident. Il semble que les conducteurs moins familiers avec une zone sont plus prudents lorsqu'il s'agit d’a border une intersection. De plus, les conducteurs semblent connaître leurs erreurs liées aux intersections, comme il est indiqué dans leurs réponses aux DBQ. Des recherches supplémentaires avec une taille d'échantillon plus grande et sur une variété d'intersections sont nécessaires pour généraliser ces résultats.

INTRODUCTION

Drivers experience increased visual and mental demands while driving through or making turns at intersections [1–3], as intersections require drivers to divide their attention in several directions and toward a variety of traffic participants (e.g., other vehicles, pedestrians, cyclists) and control devices (e.g. road signs, traffic signals) [4]. With increased demands, traffic safety at intersections becomes of concern. These safety concerns are also substantiated by crash statistics. For example, among the U.S. crashes recorded in 2015, 47% were at an intersection or were intersection-related [5]. A similar rate was observed for Ontario, Canada in 2014, with 42% of crashes occurring at an intersection or being intersection-related [6].

Intersection-crashes are of particular concern when it comes to vulnerable road users, such as pedestrians and cyclists [7], as these users interact with vehicles at intersections in close proximity. Toronto Public Health reported that between 2008 and 2012, 69% of motor vehicle collisions with vulnerable road users occurred at intersections [8]. Given the minimal personal protection of vulnerable road users, the severity of these collisions tends to be high. More complex intersections, for instance, those found on arterial roads in Toronto, are expected to generate higher driving demands [3]. These intersections also handle large volumes of traffic, hence requiring attention particularly when it comes to vulnerable road user safety. It was reported that 70% of pedestrian major-injury/fatalities recorded in Toronto between 2008 and 2012 happened as a result of a vehicular crash on a major arterial road [8]; for cyclists, this statistic was 64%. The City of Toronto defines “major arterial roads” as highly trafficked roads that accommodate more than 20,000 vehicles per day in both directions [9]. These widely used roads have sidewalks on both sides and several intersections; there are 128 such roads in Toronto.

Although vulnerable user behaviour can play a role in intersection crashes, driver error appears to play a larger role. Between 2000 and 2009, 40% of Canadian pedestrian fatalities/injuries occurred when a pedestrian had the right of way, whereas only 20% occurred when a pedestrian crossed without right of way [10]. For the city of Toronto, a larger difference is reported: between 2008 and 2012, 67% of pedestrians were identified to have had the right of way when they were struck as opposed to 19% who did not (with 14% unknown) [8]. An in-depth analysis conducted in Finland found that cyclist-car crashes occurred most commonly when the driver was turning right. Only 11% of these drivers noticed the cyclist before impact, whereas 68% of the cyclists noticed the driver and most of them thought that the driver would give way as required by law [11]. The drivers were identified to be misallocating their attention because they were looking left for vehicle traffic.

Parker et al. [12] introduced three categories of behaviours within the context of the Driver Behaviour Questionnaire (DBQ) [13], a widely used method for assessing aberrant driving behaviours: lapses, errors, and violations. Lapses are attention and memory failures that are unlikely to have an impact on safety (e.g., missing an exit). Errors are failures of planned actions that can result in safety consequences (e.g., failure to notice pedestrian when turning). Violations are deliberate deviations from practices that are believed necessary for safety (e.g., speeding). Canadian police-reports from 1999 to 2008 list “failing to yield the right-of-way” and “distraction and inattention” as the top two most common driver errors leading to pedestrian crashes [10]. It appears that driver actions most relevant to pedestrian crashes fall under the error category within this taxonomy. The same can be said for cyclist crashes based on Räsänen& Summala [11] who found “misallocation of attention such that others are not detected” to be a common mechanism underlying this type of crash. In fact, the two vulnerable-user related items of the DBQ are grouped under the error category [14]: (1) fail to notice pedestrians crossing when turning onto a side street, and (2) when making a right turn, you almost hit a cyclist or pedestrian who has come up on your right side. Both items are also related to making turns at an intersection. The DBQ has one more error item that is related to making turns at an intersection: (3) when preparing to turn from a side road onto a main road, you pay too much attention to the traffic on the main road so that you nearly hit the car in front of you.

Although crash data indicate that misallocation of attention is a major source of vulnerable road user crashes on intersections, to the best of our knowledge, no study to date used eye-tracking equipment to accurately assess where drivers are looking at when they are turning at an intersection. Video recordings from outside [11] and inside [15] the vehicle indicate that drivers allocate their attention based on their expectations but the extent that drivers fail to properly scan for vulnerable road users at intersections is not known. In this paper, we examine attention allocation failures toward vulnerable road users during right turns at intersections based on data obtained in an instrumented vehicle study. Nineteen drivers participated in this study, which focused on driving demands associated with urban driving (e.g., intersection maneuvers, parking search), and their gaze patterns were recorded with a head-mounted eye tracker. During the study, each participant made two right turns on a major arterial road in downtown Toronto. In addition to attention allocation failures toward vulnerable road users based on eye tracking data, we also assessed whether the objective data recorded correlates with drivers' subjective responses about their intersection-related errors (three listed above) collected through the Driver Behaviour Questionnaire [14].

METHODS

In the instrumented vehicle study, each participant drove through the same pre-determined routes in downtown Toronto following turn-by-turn directions provided by the experimenter. Within the two routes, participants made a right turn at two intersections (same across participants) from a major arterial road with a dedicated bike lane to a side street. Data from these turns was used in the following analysis. The experiment was approved by the University of Toronto Research Ethics Board.

Participants

Participants were recruited mainly through notices posted on online public forums. Due to insurance constraints, they were required to be between 35-54 years old and to have held a full driver's license for over 3 years. Thus, they represent the lowest crash-risk age group [16, 17]. In addition, participants were required to drive without glasses to improve eye tracking accuracy; contact lenses were allowed. In this analysis, we report data from 19 participants (9 males, 10 females), who had a complete dataset (several participants' eye-tracking data were lost due to equipment failures). Participants' mean age was 42 (SD = 5.9, Min = 36, Max = 54) and they self-reported to be safe drivers with an average response of 8.7 (SD=1.06) on a scale of 1: very unsafe to 10: very safe. Nine out of the 19 drivers self-reported to drive at least a few times a week in downtown Toronto. The experiment took approximately 3 hours and participants were reimbursed at a rate of C$15/hr.

Apparatus

The instrumented vehicle was a Toyota RAV4. A vehicle-mounted camera recorded the front view of the vehicle. Visual attention was recorded using head-mounted Dikablis Eye Tracking Glasses by Ergoneers at 50 Hz (Figure 1). The gaze position is calculated automatically using two cameras pointed at the pupils, then overlaid on video captured by the front-facing camera of the eye tracker. Although electrocardiogram and galvanic skin response sensors were also utilized, only data collected by the eye-tracking system was considered in the current analysis. The D-Lab software by Ergoneers was used to collect and sync data from all devices. A computer and display in the back seat allowed for real-time monitoring of data collected.

Figure 1 Driver outfitted with eye-tracking glasses

Procedure

Experiments began only on weekends at either 10:30 AM or 1:30 PM, in order to maintain experimental control for density of traffic and parked cars, and to avoid interruptions by roadwork or delivery/garbage trucks. The study ran from July to October 2017, mostly on dry days but with one participant experiencing light rain during the experiment. Before driving the vehicle, participants completed a set of questionnaires including one on demographics, general driving history, and experience driving in downtown Toronto. They also completed the U.S. version of the Driver Behaviour Questionnaire (DBQ) [14], which consists of 24 questions asking participants how often they exhibit certain driving behaviours. The responses are collected on a six-point scale ranging from “never” (coded as 0 for analysis) to “nearly all the time” (coded as 5).

Participants were then asked to drive in a mixed retail/residential area of downtown Toronto (see Figure 2) with the head investigator seated in the passenger seat and another researcher in the back operating the computer and monitoring data collection, and they were instructed to “keep talking to a minimum unless necessary”. Participants first completed a 5 to 10-minute familiarity drive to get accustomed to the instrumented vehicle and its controls. After, participants were equipped with the head-mounted eye tracking device, as well as the ECG and GSR sensors. Following the initial set-up, participants drove through the designated routes, where, among other tasks, they were asked to make a right turn at two intersections (details provided below). Their total driving time after the practice drive was approximately 35 minutes.

Intersections

The same major arterial road (Bloor St.) was used for both turns: the first turn was toward a collector road (Palmerston Ave.) on a signalized 4-way cross intersection, and the second was toward a local road (Major St.) on a non-signalized T-intersection (Figure 2). Bloor St., the major arterial road, has a single lane in each direction separated by a yellow line, with a semi-protected bike lane. It also contains a street parking lane on the right side, when approaching the second turn, separating the bike lane from vehicle traffic; 10 m before the intersection the bike lane and vehicle traffic are separated by a traversable median and a bollard. There are no dedicated bike lanes on the collector and local roads.

(a)

(b)

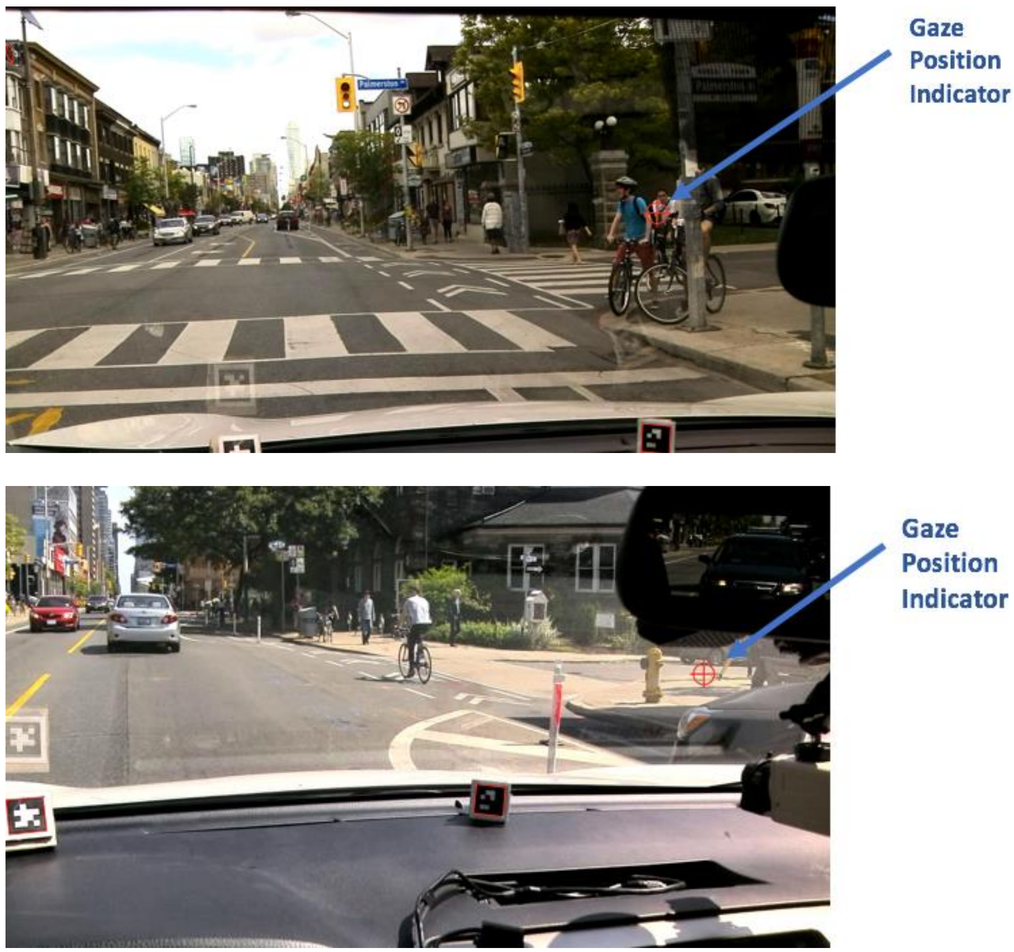
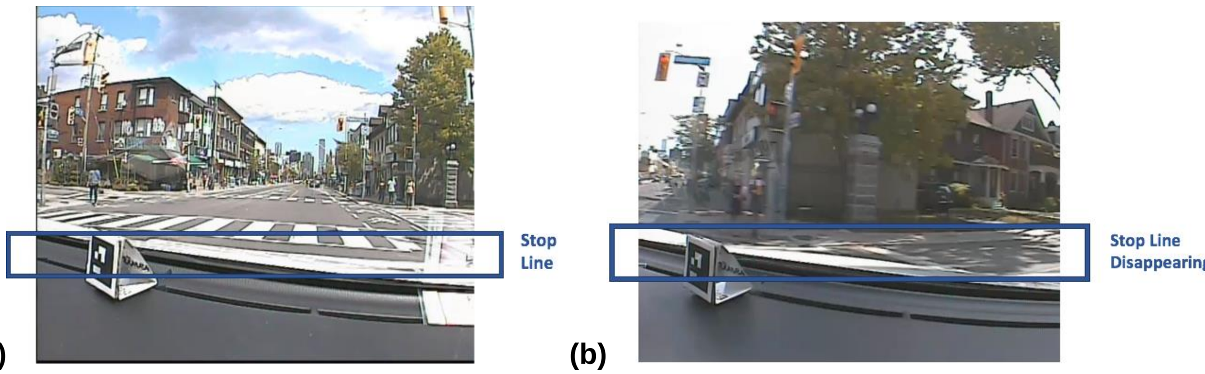


Figure 2 The two intersections where the drivers made right turns. The snapshots are from the video data recorded by the eye tracking system, where the red crosshair indicates gaze position. (a) Turn toward a collector road (from Bloor St. to Palmerston Ave.). (b) Turn toward a local road (from Bloor St. to Major St.).

Attention Failure Coding

As mentioned previously, the gaze position data calculated by the eye-tracking system was overlaid automatically on video captured by the front-facing camera of the eye tracker. Figure 2 provides example snapshots of the video data recorded by the eye tracking system. The red crosshairs indicate gaze position. Eye-tracking videos along with the videos captured through the dashboard-mounted camera (see Figure 3 for example snapshots) were used in determining whether the participants had visual attention allocation failures during a turn.



(a) **(b)**

Figure 3 Example snapshot of the video data recorded by the dashboard-mounted camera. (a) Stop line approaching the intersection is visible at the bottom of the windshield indicating the start of a turn. (b) Stop line of the target road about to disappear from camera vision, indicating the end of a turn.

A turn was defined to start when the stop line of the intersection was at the bottom of the windshield in the dashboard-mounted camera view; the turn ended when the stop line of the target road disappeared from the same camera view (Figure 3). Given that drivers start preparing for a turn before they arrive at an intersection, we coded whether our participants had attentional failures starting from 15 seconds prior to the beginning of the turn. We ended the coding at the end of the turn. Three coders watched the videos independently and identified if the drivers performed necessary checks for vulnerable road-users. A failure was defined to occur when a participant failed to gaze at a certain area of importance (e.g., bike lane on the right) with enough frequency (“enough” subjectively determined based on traffic conditions and duration of a turn). To assess drivers’ attention to cyclists, the coders looked for failures to check the bike lane on the right through over-the-shoulder and/or mirror checks, and for failures to check for potential bikes coming from the left (on the collector road with no dedicated bike lane). Participants were not expected to perform an over-the-shoulder check for cyclists in all circumstances. For example, when the street parking lane was empty on the second turn, participants could properly see the dedicated bike lane through their right mirror. However, when there were parked cars, an over-the-shoulder check had to be performed for this turn. To assess attention to pedestrians, the coders looked for failures to check the sidewalks and crosswalks. The overall agreement between the three coders was 85%. Given that coders had to make a decision for each turn, the fixed-marginal kappa was calculated to assess interrater reliability [18]. Kappa was calculated to be 0.67, considered to represent a substantial level of agreement [19]. After independently coding the videos, the coders discussed their ratings in person and came to a consensus on whether there was a failure or not for each turn.

RESULTS

Driver Behaviour Questionnaire (DBQ)

As mentioned earlier, participants completed the DBQ before they started driving [14] and the responses were collected on a six-point scale ranging from "never" (coded as 0 for analysis) to "nearly all the time" (coded as 5). Overall, participants had an average lapse score of 0.92 (SD=0.42), error score of 0.88 (SD=0.42), and violation score of 1.07 (SD=0.46). These statistics were in line with the findings of [14] that were obtained on a sample with an age range comparable to our sample. The three error items related to attentional failures during turns at intersections are presented in Table 1. For rest of the DBQ questions, the reader is referred to [14]. Overall, participants reported exhibiting these intersection-related failures either "never" (coded as 0), "hardly ever" (coded as 1), or "occasionally" (coded as 2). As shown in Table 1, the average scores fell between "never" and "hardly ever", again in line with the findings of [14].

DBQ item on intersection-related errors	Average	SD
Question: How often do you do each of the following?		
(1) fail to notice pedestrians crossing when turning onto a side street	0.89	0.57
(2) when making a right turn, you almost hit a cyclist or pedestrian who has come up on your right side.	0.74	0.65
(3) when preparing to turn from a side road onto a main road, you pay too much attention to the traffic on the main road so that you nearly hit the car in front of you.	0.74	0.65

Table 1 DBQ Scores on Intersection-related Error Items

Attention Failures

Out of the 19 participants, 6 were found to exhibit an attentional failure during Turn 1, whereas this number increased to 10 participants for the second turn. Five of the participants failed in both turns, 6 failed in one of the turns (5 failed in Turn 2), and 8 did not fail in either turn. All failures were related to checking for cyclists. In Turn 1, four out of the six failures were due to participants entirely failing to check the dedicated bike lane for cyclists behind. Two had made a check but not frequent enough for the duration of their turn. As mentioned earlier, when Turn 2 had parked cars separating the bike lane from vehicle traffic, the participants had to do an over-the-shoulder check to be able to see the dedicated bike lane. For 7 of the 10 failures recorded for this turn, participants checked their right mirror but failed to perform an over-the-shoulder check once they cleared the parked cars. Two participants failed entirely to check the dedicated bike lane and one participant was too late in the turn when they made a check.

The likelihood of exhibiting an attentional failure was investigated through an ordered logit model. The outcome variable was the number of turns where a failure was observed for a participant (0, 1, or 2); Table 2. The predictor variables were DBQ score on intersection-related errors (lower vs. higher; Table 2) and frequency of driving in downtown Toronto (frequent, non-frequent; Table 3). We did not have enough statistical power to assess interaction effects. Both DBQ score and frequency of driving in downtown Toronto were grouped into two categories based on the distribution of the data. Drivers who had an average score of 1 or more (in the three DBQ items related to intersection errors) were categorized into the higher error score group (n=10), the rest were categorized into the lower error score group (n=9). As for frequency of driving in downtown Toronto, drivers who reported to driving a few times a week or more in downtown Toronto were categorized to be frequent downtown Toronto drivers (n=9), the rest were categorized to be non-frequent downtown Toronto drivers (n=10). No multicollinearity was found between these two predictor variables (Table 4) based on a Fisher's exact test, $\chi^2(1) = 1.35$, $p = .37$.

	DBQ intersection-related error score		*Total # of participants*
Attentional failures	Higher Error	Lower Error	
No failure	2	6	8
Failed at 1 turn	4	2	6
Failed at both turns	4	1	5
Total # of participants	10	9	19

Table 2 Number of Participants by Frequency of Attentional Failures and DBQ Intersection-Related Error Score

	Downtown Toronto driving		*Total # of participants*
Attentional failures	Frequent	Non-Frequent	
No failure	1	7	8
Failed at 1 turn	5	1	6
Failed at both turns	3	2	5
Total # of participants	9	10	19

Table 3 Number of Participants by Frequency of Attentional Failures and Frequency of Driving in Downtown Toronto

	DBQ intersection-related error score		*Total # of participants*
Downtown Toronto driving	Higher Error	Lower Error	
Frequent	6	3	9
Non-Frequent	4	6	10
Total # of participants	10	9	19

Table 4 Number of Participants by Frequency of Downtown Toronto Driving and DBQ Intersection-related Error Scores

The statistical model was built in SAS University Edition using the GENMOD procedure with the cumulative logit link function and the multinomial distribution specifications. Both DBQ error scores and downtown Toronto driving frequency were found to be significant at a marginal level. Higher intersection-related DBQ error scores were associated with an increase in the likelihood of attentional failures, Odds Ratio (OR) = 6.04, 95% Confidence Interval (95% CI) = 0.84, 43.73, p=.07. Further, the likelihood of attentional failures was higher for those who drive at least a few times a week in downtown Toronto compared to those who drive a few times a month or less, OR = 6.04, 95% CI = 0.84, 43.73, p=.07.

DISCUSSION

In an instrumented vehicle study conducted in downtown Toronto, ON, we examined drivers' attention allocation failures regarding checks for vulnerable road users while they made right turns at intersections. The focus was on high traffic areas; we investigated right turns at two intersections on a major arterial road. Our study is the first to utilize eye-tracking to investigate the extent that drivers fail to properly scan for vulnerable road users at intersections. Glance data collected via an eye tracker from 19 drivers, aged 35 and 54, were analysed. Eleven participants (58%) had an attentional failure in at least one of the turns (5 in both turns; 6 in one turn). The prevalence of failures observed in our study is concerning especially given that our participants represented the lowest crash-risk age group [16, 17]. Our results provide support for findings from crash data indicating that misallocation of attention is a major source of vulnerable road user crashes on intersections [11]. In addition to attention allocation failures, we assessed whether the objective data we collected was correlated with experience driving in the area as well as with drivers' subjective responses about their intersection-related errors collected through the DBQ [14]. At a marginally significant level, attentional failures were more likely for those who drove more frequently in downtown Toronto and for those who had larger error scores on intersection-related questions of the DBQ.

All failures we identified were related to cyclist safety. It appeared that participants were better at attending to areas of importance for pedestrians (i.e., crosswalks and sidewalks) than they were to areas of importance for cyclists (i.e., bike lane). One potential reason is the difference in effort: It is more effortful for drivers to check for cyclists given that over-the-shoulder-checks require head movements [20]. Another reason is the difference in how long a vulnerable road user stays within the drivers' field of view: In mixed traffic intersections, where there are pedestrians and cyclists, pedestrians are in the drivers' view for longer durations of time and hence drivers' attention may be captured by pedestrians more than cyclists. We have observed this phenomenon in our data; when a pedestrian was detected, participants tended to follow the pedestrian's movement, allocating most of their attention to the areas of importance for pedestrians. Further, although we did not observe any failures of attention toward pedestrians, it should be noted that we defined a failure of attention as not looking toward an area of importance. Directing gaze toward a location is a pre-requisite for perception but it does not guarantee perception [21]. Thus, even when the drivers were scanning areas of importance for pedestrian traffic, there is a chance that they may not have been noticing pedestrians.

As for the two intersections used in data collection, we found more failures on the turn toward the local road (Turn 2) than the one toward the collector road (Turn 1). There were many structural differences between the two intersections (e.g., signalized 4-way cross vs. non-signalized T); however, it appeared that the major driving factor for the difference in failures observed was the parking lane that separated the bike lane from vehicle traffic leading up to the intersection (the parking lane ended 10 m before the intersection). In Turn 2, the parked vehicles blocked drivers' view of the cyclists as the drivers approached the intersection, necessitating an over-the-shoulder check after the parking lane ended. The effects of different structural elements should be examined further in future research. For example, there are differences in the prevalence of crashes at intersections with different traffic control devices: Among the intersection or intersection-related crashes recorded in the U.S. in 2015, 26% had no traffic control device, 54% had a traffic signal, and 14% had a stop sign [5]. An on-road study with a higher level of experimental control can tease apart the effects of these different control devices on drivers' attention allocation at intersections.

Both intersections utilized in data collection were on the same major arterial road, which had a dedicated bike lane surrounding these intersections. The dedicated bike lane was introduced in May 2016, thus some of the participants may not have been as familiar with the new design as others. However, we found that, at a statistically marginally significant level, those who drove in downtown Toronto more frequently (i.e., a few times a week of more) had more attentional failures than those who drove in downtown less frequently. Thus, drivers who drove in the area less often appeared to be more cautious of vulnerable road users. Less familiarity seems to have created a positive effect here.

Another point of interest for the study was to assess the relation between attentional failures observed on the road and participants' subjective responses on intersection-related error items of the DBQ [14]. The DBQ is widely used in driving research to assess aberrant driving behaviours and has been validated using self-reported crash data [22, 23] as well as on-road studies [24, 25]. However, to the best of our knowledge, no study to date focused on the validity of the intersection-related error items of the DBQ. In their validation, Zhao et al. [24] collected on-road data on a highway and Amado et al. [25] excluded DBQ items related to vulnerable road users. Our statistical model showed that, at a marginally significant level, drivers who self-reported making more intersection-related errors did have more attentional failures. Thus, our data provides support to the validity of the intersection-related error items of the DBQ. However, we only had marginal statistical significance likely due to our relatively small sample size.

In general, sample size is a limitation of our study. Collecting on-road data is costly and time intensive, and on-road studies lack the level of experimental control that can be introduced in a simulator thus requiring even larger sample sizes. There were variations in signal status and traffic flow that likely introduced variability to drivers' behaviours. However, compared to a simulator study, our study has a higher level of ecological validity. Still, it was an experiment with two researchers present in the vehicle, which may have also influenced the drivers' behaviours. Although the participants were instructed to keep talking to a minimum, the mere fact that they were being observed could have affected their behaviour [26]. Further, our participants were between the ages of 35 and 54 and were not novice drivers. Intersection-related behaviours of drivers from different age and experience groups, and on various types of intersections (signal-controlled, roundabouts, stop-controlled) should be studied in future research.

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