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**Perceptual-Motor Regulations and Visual Exploration Strategies Allowing
Older Drivers to Intercept a Moving Inter-Vehicular Gap**

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Perceptual-Motor Regulations and Visual Exploration Strategies Allowing Older Drivers to Intercept a Moving Inter-Vehicular Gap

The aim of this study was to characterize the behavior of older people when intercepting a moving gap, with reference to that produced by younger people. Participants were asked to intercept a moving inter-vehicular space within a train of vehicles, by modulating their speed if necessary. Five initial distances to the interception location have been manipulated (Offset), without the knowledge of the participants, requiring distinct speed regulations. The analyses focused on displacements kinematics as well as on the associated visual information taking strategies. The results indicate several similarities in the behaviors produced by two populations. Functional speed regulations are initiated early and persist until the interception. These regulations allow for safe interception. The visual strategies deployed by the older participants are also relatively close to those of the younger participants, with the main areas of interest located on the vehicles located upstream of the interval. The results also reveal differences between the two populations. The regulations produced by older drivers are initiated late in negative Offset giving rise to some extent to unsafe behavior. These results are discussed in relation to the decrease in motion detection thresholds with age. Our dataset could be particularly useful in view of the design of driver assistance systems for older drivers.

43 **Introduction**

44 In France, the National Inter-ministerial Observatory for Road Safety (ONISR, 2020) has
45 produced an accident report for the year 2020, which reveals that maneuvers performed when
46 approaching an intersection are particularly prone to accidents. In fact, in 2020, 15,973 bodily
47 injury accidents occurred at intersections (472 deaths), representing 19% of all road deaths.
48 These epidemiological data highlight the danger of these maneuvers and the complexity of the
49 associated tasks. The driver approaching the intersection must first identify the type of
50 intersection he/she is about to cross (number of branches, priority regime, ...), choose the
51 appropriate action (e.g., to cross or not to cross), and finally control the selected action taking
52 into consideration a number of parameters, including the displacement of other vehicles in
53 relation to his/her own displacement.

54 Older drivers are particularly prone to road accidents. In 2020, 643 older drivers died on the
55 road, which represents 25.3% of the people killed, while they constitute 21% of the population
56 and 11% of all accident victims. These data reveal the severity of injuries caused by accidents
57 among older drivers: 12 older drivers are killed for every 100 injured, which is three times more
58 than for those under 65 years old. Older drivers might be more prone to crashes due to well-
59 documented general decreases in motor, cognitive and perceptual capacities with age (Ball et
60 al., 1998, Case et al., 1970). Such a perceptual-attentional decrease has been observed for
61 instance during parking maneuvers (Douissembekov, Michael, et al., 2015; Douissembekov,
62 Navarro, et al., 2015). In line with driving research devoted to investigating drivers' perception
63 of other vehicles arrival time at an intersection or to a given location (e.g., Caird & Hancock,
64 1994; Davis & Swenson, 2004), the present study has been designed to investigate the ability
65 of elderly people to intercept a moving interval while driving. Even if the experimental task is

relatively far from real driving tasks, we believe that it is likely to provide results that will allow to better understand the perceptual-motor problems encountered by older drivers during driving tasks that require precise timing such as this is the case in many tasks as crossing intersections. ~~It is thus legitimate to characterize as precisely as possible the perceptual-motor behavior of older drivers during this specific maneuver, i.e., approaching and crossing an intersection. The combined study of the behavior of older drivers confronted with more or less constrained intersection crossing tasks and the associated information gathering strategies, should allow us to better understand the effect of age on the underlying perceptual-motor processes.~~

The present study is part of a long-term research program which aims at developing a driver assistance system (ADAS) designed to compensate for the limited (perceptual-motor) capacities of older drivers so that they can drive safely when intercepting a moving interval. The idea is to provide an ADAS that is consistent with their specific needs (Vrkljan & Miller-Polgar, 2005). Indeed, a number of studies have shown if used appropriately, ADAS have the potential to help drivers cope with the complex demands of driving (Vrkljan & Miller-Polgar, 2005; Young, 2016). They could reduce the occurrence of ~~intersection~~ accidents by compensating for age-related perceptual, cognitive and physical declines (Caird, 2004; Davidse et al., 2009) and therefore delay the cessation of driving, which is synonymous with loss of independence and sociability (Koppel et al., 2009; Koppel & Charlton, 2013).

To date, very few studies have been designed to characterize the regulation behavior produced by older drivers when intercepting a moving interval. Otherwise, previous work by our group (Louveton, Bootsma, et al., 2012; Louveton, Montagne et al., 2012; Louveton et al., 2018; Mathieu et al., 2017a, 2017b) provides a good understanding of these regulations when younger drivers are faced with this type of task. In these studies, driving simulators were used, interactively coupling a driving interface to a screen on which the driving environment was projected. Participants moved through a virtual rural environment in which an intersection

91 could appear at specific locations, while a train of vehicles was coming from the left. The
92 participants were asked to cross the intersection safely by targeting a specific inter-vehicular
93 space. The influence of several variables on the regulation behavior of the drivers has been
94 investigated including the size of the inter-vehicle gaps and the geometry of the intersection
95 (Louveton, Bootsma, et al., 2012; Louveton, Montagne et al., 2012), the speed of the vehicles
96 (Louveton, Bootsma, et al., 2012; Louveton, Montagne et al., 2012), the size and type of
97 vehicles that make up the traffic stream (Mathieu et al., 2017a, 2017b). The results showed that
98 these variables systematically affect the evolution of driving speed when approaching the
99 intersection. However, irrespective of the task constraints, not only the crossing location
100 remained circumscribed to an area slightly ahead of the center of the gap, but also the speed
101 regulations of the drivers were initiated extremely early during the approach and evenly
102 distributed throughout the approach. The analyzes carried out also revealed the functional
103 nature of these regulations, that is to say they allow for greater precision throughout the process
104 (Louveton, Bootsma, et al., 2012; Louveton, Montagne et al., 2012). Interestingly equivalent
105 results have been found when crossing an intersection by bicycle (Chihak et al., 2010; Chihak,
106 et al., 2014). The information-movement coupling involved when approaching and crossing an
107 intersection are of the same nature regardless of the interface used (i.e., either bike or car). Now,
108 identifying the information used to control goal-directed displacement while intercepting a
109 moving interval is not easy given the large number of crossing locations compatible with the
110 success of the task. The studies which have aimed to identify optical variables likely to be used
111 in order to control goal-directed displacements mainly focused on ball-interception tasks (e.g.,
112 Michaels & Oudejans, 1992; Lenoir et al., 1999a&b). High order variables have been identified,
113 e.g., the rate of change in bearing angle (Chardenon et al., 2002) or the optical acceleration
114 (McLeod & Dienes, 1993), allowing participants to intercept moving balls by implementing
115 parsimonious prospective control mechanisms (see Montagne, 2005 for a review) which makes

it possible to succeed in the task without the need to predict the place and time of interception (e.g., Peper et al., 1994; Chardenon et al., 2004). The only thing an agent has to do, provided he/she is attuned to the relevant high order variable, is to cancel continuously any change, say in the bearing angle, by an appropriate displacement, to make sure to intercept the ball (Bastin et al., 2006a). The problem drivers have to solve when intercepting a moving gap is slightly different insofar as the bearing angle can be referred to an almost infinite number of unmaterialized locations within the interval. Another related strategy could consist in modifying (if necessary) displacement speed to ensure that the bearing angle referred to the vehicle opening the gap to be intercepted decreases (Louveton et al., 2012 a&b).

In any case, although the high order variable used by younger drivers to make speed adjustments to intercept a gap has not been clearly identified in the previous studies yet, all the results obtained are compatible with the notion of information-movement coupling proposed in the context of the ecological approach to perception and action (Bootsma & van Wieringen, 1990 ; Gibson, 1979; Montagne et al., 1999). An information-movement coupling type of control has been showed to be implemented in a number of goal-directed tasks including take-off board pointing in a long jump (Lee et al., 1982 ; Montagne et al., 2000), controlling the body rotation in a back flip in gymnastics (Bardy & Laurent, 1998) or controlling whole body displacement when intercepting a fly ball in base-ball (McLeod & Dienes, 1993). The implementation of this coupling supposes the establishment of circular relations between a high order variable which specifies the state of the agent-environment system and a movement parameter (Bootsma, 1998; Gibson, 1979; Warren, 1988, 2006). This conceptual framework is particularly suitable for driving since the guidance of displacement is mainly based on perceptual-motor skills (Navarro et al., 2018).

Studies in other domains have also investigated the effect of aging on perceptual-motor skills underlying goal-directed behavior (e.g., Van Andel et al., 2018). ~~The study by Van Andel et al.~~

~~(2018) was designed to describe age-related differences in the perceptual-motor skills~~
~~underlying locomotor pointing behavior.~~ In the study by Van Andel et al. (2018) participants
were asked to approach and step onto a curb-like platform. Several variables including the time
at which participants (younger vs., older) begin to adjust their steps, the strategy used to regulate
the steps and the strength of perceptual-motor coupling have been analyzed. Not only older
participants have been showed to produce functional step lengths adjustments allowing the
experimental task to be performed equally well in comparison with the control group, but it has
also been shown that the strength of the information-movement coupling increases with age.
More precisely the step lengths produced in the last steps was strongly related to the step lengths
required to perform the task successfully among older participants. This increased coupling
reflects the fact that given the well-documented decline in action capabilities with age, older
people prefer distributing the modulations of the step lengths over a large number of steps which
supposes a close and continuous dialogue between information and movement.

If we turn back now to intercepting a moving gap while driving, our objective is to provide a
better understanding of the effect of age on the perceptual-motor skills involved and on the
information-gathering strategies implemented. A driving simulator coupling a virtual
environment available *via* a virtual reality head-mounted display system (HTC Vive® Pro Eye),
including an eye tracking device, and a driving interface have been developed. A specific
methodology already used in previous experiments allowed us to study the regulation behavior
produced by the participants, while the type (either increase or decrease in speed) and the
magnitude (either greater or lesser increase or decrease in speed) of the regulations required to
fulfil the task were manipulated.

There is no reason to believe that the regulation behavior exhibited by younger drivers should
be different in comparison with the one described in previous studies (Louveton, Bootsma, et
al., 2012; Louveton, Montagne et al., 2012; Louveton et al., 2018; Mathieu et al., 2017a, 2017b).

Based on the study by Van Andel et al. (2018) older people should also implement an information-movement type of control. Now although our task and the one used by Van Andel et al. (2018) have similarities (both involve goal-directed displacements), they also have specificities which are worth considering when trying to make predictions about what the regulation behavior should look like in the older group.

For example, action capabilities are a limiting factor for older participants in the study by Van Andel et al. (2018), in the sense that they do not have the ability to modulate step lengths in significant proportion in comparison with the control group. In the present experiment the driving task used allows the participants to benefit from the same action capabilities, i.e., the acceleration and the deceleration capabilities allowed by the vehicle. From this respect there is no reason to anticipate a difference in the way the action should be regulated when comparing the two groups. Conversely, the driving task under consideration in the present study is a very demanding task from a perceptual point of view, as the driver has to extract from a complex optic flow combining global (displacement of the self) and local (displacement of other vehicles) components, the information he/she needs to regulate, if necessary, displacement speed.

It is reasonable to anticipate that given the difficulties encountered by older people to detect movement (e.g., Andersen & Enriquez, 2006; Tran et al., 1998; Warren & Yaffe, 1989), older people should produce a specific regulation behavior in comparison with the control group when the perceptual constraints they have to deal with are high. For example, as mentioned previously, we plan in the present experiment to manipulate the starting distances from the intersection (Offset manipulations). It is important to notice that the greater the starting distance, the smaller the optical displacements caused by approaching vehicles. In the case drivers would rely on the rate of change in bearing angle, related for example to the middle of the interval, to adjust displacement speeds, these changes would more or less easily accessible

depending on the characteristics of the population. Given the fact that motion detection thresholds are lower in older people, these experimental conditions should give rise to specific behaviors with reference to the control population. We could anticipate for example delayed speed regulations for older people when the starting distance is high (i.e., negative Offsets). In order to identify and compare the type of information used by older and younger people when crossing intersections, an eye-tracking analysis was also performed. Indeed, the eye-tracking data ~~eye-tracking data~~ should indicate to what extent older people implement particular strategies to compensate for the motion detection problem they face.

Method

Participants

Twenty younger drivers (23 years \pm 3 years) and twenty older drivers (73 years \pm 5 years) with normal or corrected to normal vision, volunteered for participating in experiment. Drivers were also required to have a minimum of two years driving experience and drive at least 20 kilometers per week. The older participants were chosen from a cohort that underwent a series of tests including the Mini-Mental State Examination (MMSE). Participants had to present a score higher than 24 to participate in the experiment. The participants retained had a mean score of 27.2 (SD 1.8). The study was conducted in accordance with the ethical guidelines of the Ethics committee for research in science and technology of physical and sports activities (CERSTAPS: IRB00012476-2021-05-02-86) as well as in accordance with the declaration of Helsinki for human research and international principles governing research involving humans.

Apparatus and Visual Environment

Apparatus

A fixed base driving simulator was used. The driving simulator couples a high-resolution steering wheel and a set of pedals (*Extreme Competition Control*, Minneapolis,

United States) to a virtual reality application developed in our laboratory (software ICE©) running on PC (Microsoft Windows 10 Pro, intel Core i99900 processors (8 curs, 3.15.0 Ghz Turbo, 16 Mo cache, graphic card NVIDIA Geforce RTX2080 Super). The virtual environment was projected in a virtual reality headset (HCT vive® Pro Eye).

The position of the seat and the pedals was adjustable on the piloting interface. The participants did not have to change gears manually, as an automatic gearbox was used. Therefore, the participant had to use only the accelerator and brake pedals.

The virtual environment was generated using ICE© software. This home-made software allows creating virtual reality environments offering both visual and auditory content, as well as programming scenarios, synchronizing the driving interface and the virtual reality headset as well as making the data acquisition (e.g., Marti et al., 2015; Coutton-Jean et al., 2009). The virtual environment was projected through a virtual reality headset (HTC Vive® Pro Eye) which had a screen offering a resolution of 2880x1600 pixels and 615 PPP and an eye tracking system. In our experience, this system made it possible to follow the movement of the eyes at 100 Hz.

Visual Environment

The simulated environment consisted of a straight road, with two lanes separated by a white continuous line and delimited by broken shore lines. A second road with the same characteristics crossed the first one at a variable distance thus forming an intersection at right angles. A train of vehicles could approach the intersection from the left.

[Figure 1 near here]

Experimental design

Participants had to approach and cross an intersection while targeting a specific inter-vehicle interval. A protocol has been used so that drivers can take ownership of the driving interface before carrying out the actual experiment (~~Figure 2~~). The participants first carried out a calibration task which was intended to allow them to calibrate the acceleration and deceleration capabilities of the vehicle being driven. Then they carried out the actual experimental task following a short familiarization phase.

[~~Figure 2 near here~~]

Task and Experimental Design

Calibration Phase

The calibration phase involved asking participants to drive along a straight road maintaining a constant distance behind a car moving in front of them at varying speed. At the beginning of each calibration session, the participant was stationary 18 meters behind the reference car. The test started when the reference car started. This reference car changed speed regularly every 15 seconds within a window ranging from 40 km/h to 100 km/h. Each speed plateau was followed and preceded by acceleration or deceleration phases of different durations depending on the speed to be achieved.

The calibration phase consisted of 3 sessions of 2 minutes each. In the first minute of each session, the participant was provided with concurrent feedback in the form of a vertical gauge located slightly on the left of the steering wheel (Mathieu et al., 2017b, Figure 2a). This gauge contained a cursor that moved along the gauge and indicated the current inter-vehicular distance. The horizontal rectangular area in the center of the gauge represented the inter-vehicle distance that had to be kept constant. When the cursor was positioned in this rectangular area, the gauge turned green (Figure 2b). When the cursor was in the upper or lower part of the gauge (i.e., the actual distance was greater or less than the prescribed distance), the gauge turned red.

In the second minute of each session, the calibration task was performed without concurrent feedback.

[Figure 2 near here]

When concurrent feedback was no longer available, the percentage of time during which the gauge if it had been visible would have remained positioned in the prescribed zone was calculated. This calculation was only performed during the last 5 seconds of each plateau (i.e., from 10 to 15 seconds) as the task was too complex during the transition phases (i.e., when the speed of the vehicle to be followed varied). After obtaining a percentage for each speed plateau, an average was calculated to have a single value per session. When a score of 80% was obtained in at least 2 of the 3 calibration sessions, the participant was considered "calibrated". If not, a calibration session was added and the percentage was again calculated from the last 3 sessions performed. Once the participant was calibrated, he/she had 5 minutes to rest before starting the experimental phase.

Experimental Phase (Moving gap interception)

Task

The task used in this experimental phase was similar to the one used in the studies by Louveton, Bootsma, et al. (2012), Louveton, Montagne et al.(2012), Louveton et al. (2018) and Mathieu et al. (2017a, 2017b). The participants had to cross an intersection where a train of vehicles was coming from the left. They had to cross in the inter-vehicular space delimited by the two purple cars belonging to the vehicle train, by changing displacement speed if necessary. This train of vehicles, consisting of a total of 6 sport utility vehicle (SUV) (length: 4.205 m, width: 1.80 m, height: 1.70 m), was moving at a speed of 10 m/s (36 km/h). The inter-vehicular interval offered a window of either 27 m or 2.7 s depending on the metric used (Figure 3).

[Figure 3 near here]

Procedure

At the beginning of each trial, the participant was stationary in his/her lane. The environment was composed of a straight dual carriageway in a rural setting. First, the participant had to start, accelerate and follow this route at a stabilized speed of 16 m/s (57.6 km/h). No numerical information was available, but the participant was given concurrent feedback about the difference between the current speed and the required speed. The feedback was available as a vertical gauge based on the same principle as the one used in the calibration phase (see Figure 2). When the cursor was in the horizontal rectangle in the center of the gauge (i.e., when the current speed corresponded to the required speed), the gauge was green. Conversely, when the cursor was at the top or bottom, the gauge turned red indicating to the participant that he or she was moving either too fast or too slow. When the speed was stabilized in the target zone for at least 10 seconds, the gauge disappeared. The disappearance of the gauge initiated the beginning of the crossing scenario. The intersection and the approaching train of vehicles were displayed. This procedure made it possible to standardize the initial conditions for carrying out the task (i.e., the initial speed of the participants) for each experimental condition.

Independent variables

In addition to the characteristics of the participants (see ‘Participants’ section) the initial distance of the participant’s car with respect to the intersection (Offset) was also manipulated.

Offset

The initial distance between the participants and the intersection was manipulated according to 5 modalities to create an Offset between the participant's arrival time at the intersection (in the case the initial speed was held constant) and the arrival time of the center of the gap to be crossed (see Mathieu et al., 2017b for a similar procedure). Our aim was to manipulate the task

constraints to induce distinct regulations. In the "no offset" condition (Offset 0), the initial distance (150 m) was set so that the participant could cross the intersection at the center of the inter-vehicular interval while keeping his/her initial speed (i.e., 16 m/s or 57.6 km/h) unchanged. In the other 4 conditions (Offset +2, +1, -1 and -2, seconds) the distances (118, 134, 166 and 182 meters) were set to induce specific regulations. When the participant encountered either a positive or negative offset, he/she was required to decelerate or accelerate in order to safely pass through the intersection. For example, in the Offset-2 condition, if the participant did not change his/her speed, he would pass through the intersection two seconds after the center of the inter-vehicular space had passed the intersection, resulting in a collision with the vehicle located at the end of the gap. Thus, to succeed at the task, a change of speed was mandatory (i.e., speed increase for negative offsets and speed decrease for positive offsets).

In summary, each participant was exposed to 5 different Offset (+2, +1, 0, -1, -2). Each experimental condition was repeated 8 times. The 40 trials were randomly distributed in 4 blocks of 10 trials, while the order of passage of the blocks was counterbalanced.

Dependent variables

The analysis carried out in this study first focused on driving behavior through different variables including the gap crossing position, the time course of both speed and current deviation profiles, and their associated variability. In a second step, our analyzes also focused on pour participants' ocular behavior.

Driving Behavior

Gap crossing position. The most macroscopic variable was the gap crossing position defined relative to the time of arrival of the center of the inter-vehicular gap at the intersection. This value was calculated for each trial of each condition and allowed us to calculate the constant and variable error (Schmidt & Lee, 2005).

334 The constant error (CE) was an indicator of a ‘bias’ when crossing the inter-vehicular interval,
335 given the fact that it takes into account the sign of the error. Taking the center of the inter-
336 vehicular space as the origin, a positive value meant that participants crossed the intersection
337 before the center of the inter-vehicular space (i.e., closer to the gap opening vehicle).
338 Conversely, a negative value meant that participants crossed the intersection after the center of
339 the inter-vehicular space (i.e., closer to the vehicle closing the gap). In our experiment we will
340 call this variable gap crossing position.

341 The variable error (VE) was an indicator of the homogeneity of performance. It corresponds to
342 the standard deviation of the error ($n=8$) produced in each Offset condition. In our experiment
343 we will call it gap crossing position variability.

344 *Displacement speed and displacement speed variability.* In order to examine the nature of
345 speed adjustments made during the approach to the intersection, we first analyzed the time
346 course of speed. All trials were first synchronized using the time of the gap crossing as a
347 common reference (t_0). For each trial the speed profile was then discretized backwards from
348 the time of crossing the intersection to 7 time steps (i.e., 7-6 s, 6-5 s, 5-4 s, 4-3 s, 3-2 s, 2-1 s,
349 1-0 s). Once this division done, we calculated for each participant and for each time step an
350 average displacement speed as well as the inter-trial variability of the displacement speed.

351 *Current deviation and current deviation variability.* Our analysis then focused on the current
352 deviation (Louveton, Bootsma, et al., 2012; Louveton, Montagne et al., 2012). Current
353 deviation can be defined for each time step as the moment of crossing of the participant in the
354 inter-vehicular space if the current speed was kept constant. This variable can be calculated at
355 any time and changes as the participants' speed changes, indicating the extent to which the speed
356 changes produced are functional. In the Offset 0 condition, the current deviation is by definition
357 zero at the start of the trial so that maintaining the initial speed constant throughout the trial

would allow the participant to cross the intersection at the center of the inter-vehicular space. In the other Offset conditions (i.e., -2, -1, +1 and +2 seconds) the initial current deviation was -2, -1, +1 and +2 seconds respectively at the start of the trial. Only speed changes would allow participants to cross the intersection near the center of the inter-vehicle window. The aim of the analysis was precisely to describe the dynamics of changes in current deviation. We used the same procedure as the one used for the speed profiles for current deviation profiles (i.e., first, trial synchronizations, followed by trial discretizations). We calculated for each participant and for each time step the average current deviation as well as the inter-trial variability of the current deviation.

Ocular Behavior

In a second step, an analysis of the visual exploration strategies used by the participants was carried out. For this purpose, four Areas Of Interest (AOI) were defined (Figure 4) corresponding to the vehicle train behind (AOI1) or ahead (AOI3) the interval, the inter-vehicle interval (AOI2) and the junction of the two roads (AOI4). The successive locations of the gaze were recorded between the moment of appearance of the intersection and its crossing. From these data the average percentage of time spent in each area of interest (AOI) during a trial was computed, as well as the average number of visits for each AOI and the average duration of these visits (see Navarro et al., 2019, for a similar procedure).

[Figure 4 near here]

Statistics

Statistical analyses were performed using repeated measures ANOVA. For the gap crossing position and its variability, Population (Younger, Older) was used as a between subject factor and Offset (-2,-1,0,1,2) as a within subject factor. For the time course of both speed and current

deviation and their variabilities, Population (Younger, Older) was used as a between subject factor and Offset (-2,-1,0,1,2) and Time (from 7s from gap interception to interception in intervals of 1s gap crossing, i.e., 7 bins) as within subject factors. Finally, for the average percentage of time, the average number of visits and the average duration of these visits Population (Younger, Older) was used as a between subject factor and Offset (-2,-1,0,1,2) and AOI as within subject factors. In case the results were significant, post-hoc analyses were performed using Holm's test.

Results

Driving Behaviors

Success Rate

During the experiment, the participants crossed the intersection 800 times. There were no crashes for younger drivers (100% success rate), while there were 11 crashes for older drivers (98.6% success rate). These trials were excluded from further analyses.

Gap crossing position

The analysis of variance on gap crossing position revealed a significant main effect of Offset ($F(4,152) = 44.745, p < 0.001, \eta^2 = 0.296$). Furthermore, the first-order interaction Offset*Population ($F(4,152) = 3.640, p < 0.007, \eta^2 = 0.024$) was also significant.

Post-hoc comparisons on the Offset*Population interaction did not reveal any significant differences. Participants regardless of their age, crossed the intersection slightly before the center of the inter-vehicular space (i.e., closer to the lead vehicle) in most Offset conditions (Figure 5). However, older people tended to cross the interval later in the offset -2 condition in

comparison with younger participants. A posteriori comparisons performed on Offset revealed that gap crossing position differed for each Offset condition (all $p < 0.05$) except between Offset 0 and -1 ($p > 0.05$).

[Figure 5 near here]

Gap crossing position variability

The analysis of variance performed on the gap crossing position variability revealed a significant main effect of Offset ($F(4, 152) = 9.896, p < 0.001, \eta^2 = 0.140$). The main effect of Population failed to reach significance ($F(1, 38) = 3.846, p < 0.057, \eta^2 = 0.029$). Older drivers tend to be more variable than younger drivers (Offset -2: 0.28 s older vs., 0.26 s younger; Offset -1: 0.30 s older vs., 0.25 s younger; Offset 0: 0.25 s older vs., 0.22 s younger; Offset 1: 0.20 s older vs., 0.17 s younger; Offset 2: 0.21 s older vs., 0.17 s younger)(figure 6).

Post-hoc comparisons on Offset revealed higher gap crossing position variability in Offset -1 (0.28 s) and Offset-2 (0.27 s) in comparison with Offset +1 (0.19 s) and Offset +2 (0.12 s) (all $p < 0.001$)(figure 6).

[Figure 6 near here]

Speed Profiles

The analysis of variance on speed revealed a significant main effect of Offset ($F(4, 2667.639) = 1630.063, p < 0.001, \eta^2 = 0.884$) and Time ($F(7, 417.501) = 283.786, p < 0.001, \eta^2 = 0.141$). The first-order interactions Offset*Population ($F(4, 7.684) = 4.536, p < 0.002, \eta^2 = 0.002$) and Offset*Time ($F(28, 198.880) = 537.255, p < 0.001, \eta^2 = 0.268$) are significant.

A posteriori comparisons carried out on the Offset*Time interaction indicate that from 5 seconds before the crossing, the evolution of the speed differs according to the offset condition. The most representative example is the comparison between Offset -2 and Offset 2. For Offset 2, there is a decrease in speed between 5 and 2 seconds before the crossing from 14 m/s to 11 m/s followed by an increase in speed from 2 seconds until the crossing from 11 m/s to 14 m/s. While for the -2 Offset condition, there is an increase in speed from 5 seconds before the crossing until the moment of crossing from 16 m/s to 25 m/s (figure 7). A posteriori comparison carried out on the Offset*Population interaction indicate that the displacement speed produced by younger and older people are not significantly different except in the Offset -2 condition. In Offset -2 older people vehicle speed (20.09 m/s) was lower than the younger drivers (20.64 m/s)($p < 0.05$)(figure 7).

[Figure 7 near here]

Current Deviation Profiles

The analysis of variance on the current deviation reveals significant main effects of Offset ($F(4,152) = 846.092$, $p < 0.001$, $\eta^2 = 0.536$) and Population ($F(1,38) = 4.532$, $p < 0.040$, $\eta^2 = 0.003$). The first-order interactions Offset*Population ($F(4,152) = 5.255$, $p < 0.001$, $\eta^2 = 0.003$) and Offset*Time ($F(28,266) = 813.681$, $p < 0.001$, $\eta^2 = 0.354$) are significant. The second-order interaction Offset*Population*Time ($F(28,266) = 3.847$, $p < 0.001$, $\eta^2 = 0.002$) is also significant.

Post-hoc comparisons performed on the Offset*Population*Time interaction reveal a significant difference between younger and older people in the Offset -2 condition from 5 s to 2 s before crossing the intersection. Indeed, the current deviation is lower for older than for younger drivers (5s before crossing : -1.87 s older vs., -1.46 s younger; 4s: -1.38 s older vs., -0.88 s younger ; 3s : -0.86 s older vs., -0.43 s younger; 2s: -0.46 s older vs., -0.13 s younger). We

can see a much more gradual convergence of the current deviation towards the inter-vehicle gap crossing location for older drivers.

[Figure 8 near here]

Speed Variability

The analysis of variance on the inter-trial speed variability revealed significant main effects of the factors Offset ($F(4,152) = 23.930$, $p < 0.001$, $\eta^2 = 0.051$), Population ($F(1,38) = 6.336$, $p < 0.016$, $\eta^2 = 0.010$) and Time ($F(7,266) = 392.113$, $p < 0.001$, $\eta^2 = 0.545$). The first-order interactions Time*Population ($F(7,266) = 7.790$, $p < 0.001$, $\eta^2 = 0.011$) and Offset*Time ($F(28,266) = 17.598$, $p < 0.001$, $\eta^2 = 0.057$) were also significant.

A posteriori comparisons performed on the Time*Population interaction (Figure 9) revealed a higher increase in speed variability for older drivers than for younger drivers in the last 3 seconds before crossing ($p < 0.05$). A posteriori comparisons performed on the Offset*Time interaction (Figure 10) reveal in the last 4 seconds before crossing a more pronounced increase in speed variability in the two negative Offset conditions (-1 and -2) in comparison with the positive Offset conditions (+1 and +2).

[Figure 9 and 10 near here]

Current Deviation Variability

The analysis of variance of the current deviation variability revealed significant main effects of Offset ($F(4, 152) = 12.169$, $p < 0.001$, $\eta^2 = 0.036$) and Time ($F(7, 266) = 251.133$, $p < 0.001$, $\eta^2 = 0.525$) conditions. The analysis also revealed that the first-order interaction Offset*Time ($F(28, 266) = 5.802$, $p < 0.001$, $\eta^2 = 0.020$) was significant.

Post-hoc comparisons performed on the Offset*Time interaction revealed greater variability 2 and 3 seconds before crossing for the -2 offset condition than for the 1 and 2 offset conditions.

[Figure 11 near here]

Ocular Behavior

Percentage of Time Spent within in Each Area of Interest

Taking into account the percentage of time spent in the 4 AOIs allowed us to account for approximately 90% of the overall ocular behavior of the participants. An analysis of variance on the percentage of time spent in each area revealed a significant main effect of AOI ($F(3, 114) = 668.581, p < 0.001, \eta^2 = 0.905$). The first-order Offset*AOI interaction ($F(12, 456) = 35,094,094, p < .001, \eta^2 = .019$) was also significant.

Post hoc comparisons performed on the Offset*AOI interaction revealed that participants spent more time fixating AOI2 in Offset-2, Offset-1 and Offset0 conditions in comparison with Offset +1 and Offset +2 ($p < .05$) (figure 13). The reverse was true for AOI3 ($p < .05$) (figure 12).

[Figure 12 near here]

Number of Fixations in Each Area of Interest

An analysis of variance on the number of fixations revealed significant main effects of Offset ($F(4, 152) = 38.521, p < 0.001, \eta^2 = 0.046$) and AOI ($F(3, 114) = 92.939, p < 0.001, \eta^2 = 0.418$). The analysis had also revealed that the first-order interaction Offset*AOI ($F(12, 456) = 29.511, p < 0.001, \eta^2 = .045$) was significant (figure 13).

Post-hoc comparisons performed on the Offset*AOI interaction revealed that Offset conditions 0, +1 and +2 gave rise to less fixations of AOI1 than the other two Offset conditions (i.e., Offset-1 and Offset-2). They also revealed that the number of visits to AOI2 and AOI3 is influenced by the Offset. Offset-2 was the condition with the most visits for AOI2 and AOI3 (figure 13).

[Figure 13 near here]

Mean Fixation Durations of Each Area of Interest

An analysis of variance on the mean fixation duration revealed significant main effects of Offset ($F(4, 152) = 19.612, p < 0.001, \eta^2 = 0.012$) and AOI ($F(3, 114) = 133.355, p < 0.001, \eta^2 = 0.617$) conditions. The first-order Offset*AOI interaction ($F(12, 456) = 20.921, p < .001, \eta^2 = .037$) was also significant.

Post-hoc comparisons performed on the Offset*AOI interaction revealed that the number of AOI3 visits is influenced by the Offset conditions. The average duration of an AOI3 visit decreases as the initial distance from the intersection increases (from Offset 2 to Offset -2). Offset 2 is the condition where the average AOI3 visit duration is the longest; conversely Offset -2 condition gives rise to the shortest average visit durations (figure 14).

[Figure 14 near here]

Discussion

Our experiment aimed to provide a better understanding of the regulation and information-taking strategies underlying an intersection crossing task in older people with reference to a control population (younger drivers). The results revealed behavioral regulations that allowed both younger and older participants to cross an intersection safely. However, specificities in the behavior of older drivers have emerged with delayed regulations and less safe behavior in negative Offset conditions. Finally, the eye-tracking analyses didn't reveal different strategies according to age but several adaptations according to task constraints (i.e., Offset conditions).

Analysis of the Regulations Produced

As a reminder, in this experiment, the initial distance between the participants and the intersection was manipulated to induce distinct speed regulations (+2, +1, 0, -1 and -2 s). When

the participant encountered a positive or negative offset, he/she had to decelerate or accelerate appropriately in order to cross the intersection at the center of the inter-vehicular space, otherwise he/she would cross the intersection 1 or 2 seconds before the center of the interval (Offset+1 and Offset+2) or 1 or 2 seconds after (Offset-1 and Offset-2)

Control Population

The results revealed that the speed regulations produced by younger drivers systematically resulted in a crossing position slightly before the center of the inter-vehicular interval. This type of behavior was already observed in our previous studies. It is likely to reflect the use of a safe crossing strategy, allowing participants not only to avoid a collision, but also to benefit from an optimal time window to cross the intersection (Louveton, Bootsma, et al., 2012; Louveton, Montagne et al., 2012; Chihak et al., 2010, 2014). In all Offset conditions we observed early and gradual speed regulation to compensate for initial Offsets, followed by acceleration on the approach to the crossing to minimize the time taken to cross the intersection, as already observed by Chihak et al. (2010, 2014) in an intersection crossing task on a bicycle. These changes in speed result in a progressive reduction and convergence of the current deflection towards the first half of the center of the inter-vehicular interval. In line with these initial results, the comparative analysis of the patterns of variability (intra-participant inter-trials) of speed and current deviation reveals patterns of compensatory variabilities (Camachon et al., 2004; Chardenon et al., 2002). The increase in speed variability when approaching the intersection is accompanied by a decrease in the variability of the current deviation. The speed changes that occur during the approach have the function of minimizing the fluctuations of the current deviation.

These results obtained in this study are consistent with those reported in previous work (Louveton, Bootsma, et al., 2012; Louveton, Montagne et al., 2012; Louveton et al., 2018; Mathieu et al., 2017a, 2017b) but also with those described in other tasks requiring the

production of goal-directed movements (e.g., Bardy & Laurent, 1998; Camachon et al., 2004; Chardenon et al., 2002; Lee et al., 1982). These results confirm the presence of a control based on a close information-movement coupling. This coupling is flexible because it allows to have regulations adapted to task constraints in all conditions. In addition to showing consistent results with previous studies, our study also extends these observations to the two extreme Offset conditions (-2 and 2 seconds) that were added with the objective of inducing more important regulations.

Older drivers

The speed regulations observed among older drivers are to some extent comparable to those observed among younger drivers in our study but also to those described in our previous work (Louveton, Bootsma, et al., 2012; Louveton, Montagne et al., 2012; Louveton et al., 2018; Mathieu et al., 2017a, 2017b). Indeed, these regulations implemented allow to cross the intersection just before the center of the inter-vehicular interval except for offset -2. These regulations usually occur early and are followed by a final acceleration when crossing the intersection. Moreover, these changes in speed induce a gradual convergence of the current deviation towards the first half of the interval. Finally, a compensatory variability pattern appears when comparing the evolution of the variability of the reference speed with the evolution of the variability of the current deviation. All these results confirm the presence of control based on information-movement coupling for older drivers in an intersection crossing task, despite advancing age. Comparable results have been described in studies on the control of goal-directed locomotor displacements. Van Andel et al (2018) described the step length regulations implemented by two populations of subjects (i.e., younger and older) when they were asked to approach and step onto a curb-like platform. The results reveal that the regulation

571 patterns produced by the two populations of subjects show great similarities and reflect the
572 implementation of a close coupling between information and movement.

573 Our study also reveals specificities in the regulation patterns produced by the older drivers that
574 deserve to be highlighted and analyzed. Thus, in certain Offset conditions the regulation
575 behavior of the older drivers differs from that produced by the control population. It's the case
576 in the negative Offset conditions, i.e., Offset -2 and to a lesser extent Offset -1. As an example,
577 in the Offset -2 condition, the speed adjustments made by the older drivers are initiated later
578 than in the control population. Once initiated, the speed adjustments do result in a reduction of
579 the current deviation, but the older drivers cross the intersection in the second half of the interval
580 without benefiting from the usual safety margin that results from crossing the interval in its first
581 half. ~~The inability of older drivers to initiate regulation early in this condition does not allow~~
582 ~~them to produce the safety behavior observed in this same population in the zero and positive~~
583 ~~offset conditions.~~ Although the effects are less pronounced in the -1 Offset condition, older
584 drivers also appear to have difficulty initiating regulation early in this condition.

585 The late initiation of regulations in this type of task is problematic because not only will these
586 regulations be necessarily less gradual in reference to regulations initiated early, but they give
587 rise to less safe behavior when crossing the interval. Given the road safety issues associated
588 with this behavior, it seemed appropriate to try to understand the origin of this type of behavior.
589 This led us to analyze the perceptual constraints induced by the different Offset conditions. One
590 higher order information the driver can use to regulate his/her speed of travel when approaching
591 the intersection is the rate of change of the bearing angle (Lenoir et al., 1999; Chardenon et al.,
592 2002; Louveton, Bootsma, et al., 2012; Louveton, Montagne et al., 2012). The bearing angle is
593 the angle subtended between, for example, the direction of travel and the position of the center
594 of the inter-vehicle interval. If the driver wants to cross the intersection at the center of the
595 interval, he/she just need to keep the bearing angle constant. If the angle increases or decreases,

the driver has to decelerate or accelerate respectively to cross the gap at the right place at the right time (cf., Bastin et al., 2006b; Morice et al., 2010). As a reminder, in our experiment, the initial speed of the participants was always the same and the 5 Offset conditions were obtained by manipulating the initial distance between the driver and the intersection at the moment the intersection appeared. Simulations were carried out to determine how the bearing angle varies in the positive and negative Offset conditions when the travel speed is held constant (Figure 16). These simulations indicate that the greater the distance between the driver and the intersection, the smaller the bearing angle changes. It is worth noting that the bearing angle changes are the weakest in the Offset -2 condition. Studies have shown that the thresholds for detecting movement are lower for older people than for younger people (Andersen & Enriquez, 2006; Tran et al., 1998 ; Warren et al., 1989; François et al., 2011). It would seem therefore, that the specific regulation behavior exhibited by the older drivers in our study with negative Offset conditions may be related to the difficulties encountered by the older drivers in detecting changes in bearing angle that inform them of the need to produce appropriate speed changes. Bearing angle changes would become available later on during the approach and would allow the production of functional regulations, although it would not be possible to fully compensate the delay in the initiation of regulation.

[Figure 16 near here]

Analysis of Visual Information Pick-Up Strategies

In this experiment, an analysis of visual prospecting patterns was carried out in an attempt to identify the strategies implemented during intersection crossing. This type of analysis has never been performed in previous studies focusing on the control of intersection approach and

crossing (Chihak et al., 2010; Chihak et al., 2014; Louveton, Bootsma, et al., 2012; Louveton, Montagne et al., 2012; Louveton et al., 2018; Mathieu et al., 2017a, 2017b ; Plumert & Kearney, 2014) and could be particularly useful when designing driver assistance systems that could come to the aid of drivers attempting to cross an intersection. As a reminder, four areas of interest (AOI) were defined in our analysis corresponding to the vehicle train located behind (AOI1) or in front (AOI3) of the inter-vehicular interval, the inter-vehicular interval (AOI2) and the junction of the two roads (AOI4).

Given that no differences were found according to the population tested the overall results will be presented. As a reminder the analysis focused on the average percentage of time spent in each AOI during a trial, the average number of visits as well as the average durations of these visits in each AOI (Navarro et al., 2019). The results indicate that the AOI3 is the area of interest looked at the longest during a trial (60% of the overall time spent in the AOIs), but also the one with the longest visits. This result seems logical; as drivers target the first part of the inter-vehicle interval, the location of the vehicle train preceding the interval is of great importance when controlling the approach speed. In contrast, the number of AOI visits is much more evenly distributed over the 4 areas of interest. The average visit duration of some AOIs are therefore much shorter (AOI 1 and AOI 4 in particular) so that the function of these fixations is probably different. For example, fixing the intersection zone would allow an estimation of the time remaining before the crossing.

Our analysis also revealed differences in the information gathering strategies implemented according to the Offset conditions. For negative offset conditions, the vehicle train before the inter-vehicle interval (AOI3) remains the information gathering zone targeted by drivers, but the inter-vehicle interval (AOI2) is also favored. As a reminder, our results have shown that the

location of the interval crossing differs according to the offset conditions. The crossing location is closer to the center of the interval for negative offsets. In this context, it is relatively logical that drivers also prioritize the inter-vehicular area (AOI2) in their search for information. This double prioritization (AOI2 and AOI3) mechanically translates into a reduction in the time spent scanning these two zones. These results illustrate the extent to which the constraints of the task (in this case the imposed Offset) have an impact on the information-gathering strategies implemented by the drivers. It should be noted that the lack of difference between younger and older drivers indicates that older drivers continue to look at areas of interest relevant to regulation.

Conclusion

Our ambition was to characterize as precisely as possible the product regulation behavior and the information taking strategies of our population. Our results reveal similarities in the behavior of older people in comparison with that of younger drivers. The regulations produced are based on a close coupling between information and movement, giving rise to functional speed adjustments throughout the approach. They also reveal specific difficulties linked to the perceptual constraints induced by particular situations (i.e., negative Offsets). The analysis of the eye-tracking data also enabled the identification of areas containing information relevant to travel controls and the impact of task constraints on the nature of the favor areas. This dataset will be particularly useful in future work on the design of driver assistance systems (ADAS) for older drivers. As an example, the difficulties encountered by the older participants for negative Offsets could be solved by providing older drivers concurrent feedback representing at any time their current deviation relative to the inter-vehicular gap to be intercepted, allowing them not only to identify very early the regulations to be produced but also to guide them until crossing. This perceptual aid would be intended to be used if the driver deems it necessary but

671 does not have the function of prescribing driving behavior. We plan to test in the future these
672 assistance systems in the case concurrent feedbacks are located either on the dashboard of the
673 vehicle or integrated into the traffic flow.

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Figure captions

839 Figure 1: Illustration of the virtual environment projected in the virtual reality headset during
840 the calibration task.

841 ~~Figure 2 : Chronological rise representing the different stages of the experiment~~

842 Figure 2: Representation of the gauge used in the calibration phase. A) Location of the gauge
843 representing the concurrent feedback during the experiment. The gauge was located slightly on
844 the left of the steering wheel on the windscreen. B) Description

845 Figure 3: Illustration of the virtual environment during the task completion

846 Figure 4: Schematic representation of the four Areas of Interest (AOI) used in the experiment
847 as part of the eye-tracking analysis: AOI1: Last part of the vehicle train; AOI2: Inter-vehicular
848 space; AOI3: First part of the train; AOI4: Intersection

849 Figure 5: Average gap crossing position (constant error) as a function of the Offset. The vertical
850 dotted black line shows the space available to cross the intersection

851 Figure 6: Gap crossing position variability as a function of Offset

852 Figure 7: Time course of the participants' average speed in the different Offset conditions for
853 the two populations (Younger and Older drivers).

854 Figure 8: Time course of the current deviation for each Offset condition (from Offset -2 to
855 Offset 2) and for each population (Younger in red and Older in black).

856 Figure 9: Average intra-participant speed variability as a function of time to intersection for
857 each population (Younger drivers in red and Older drivers in black).

858 Figure 10: Average intra-participant speed variability as a function of time to intersection and
859 Offset (from Offset -2 to Offset 2)).

860 Figure 11: Average variability of intra-participant current deviation as a function of time to
861 intersection and offset.

862 Figure 12: Percentage of time spent in each Area of Interest (AOI) for each Offset (from Offset
863 -2 to Offset 2).

864 Figure 13: Number of visits in each AOI according to the different Offset conditions.

865 Figure 14: Average duration of a visit in each area of interest (AOI) according to the different
866 Offset conditions.

867 Figure 15: Simulation of the time course of the bearing angle changes during the approach in
868 the different Offset conditions, when the displacement speed is kept constant.

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Figure 1



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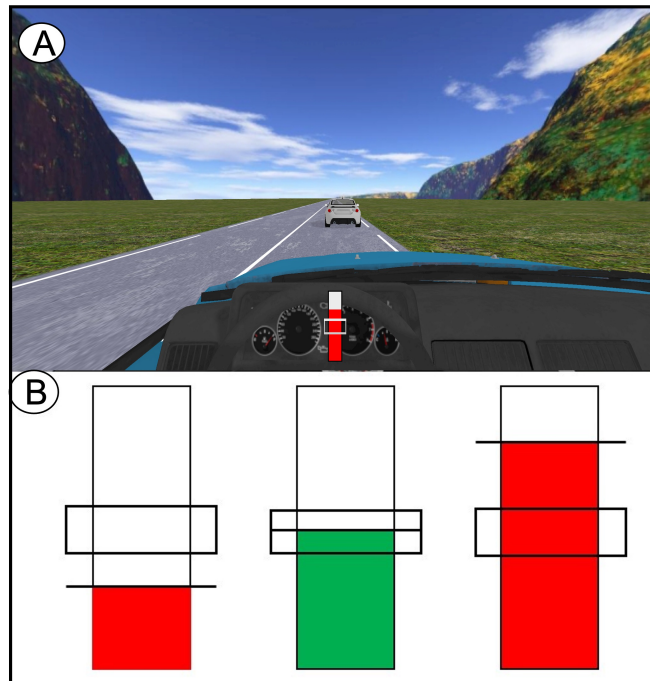
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Figure 2



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Figure 3



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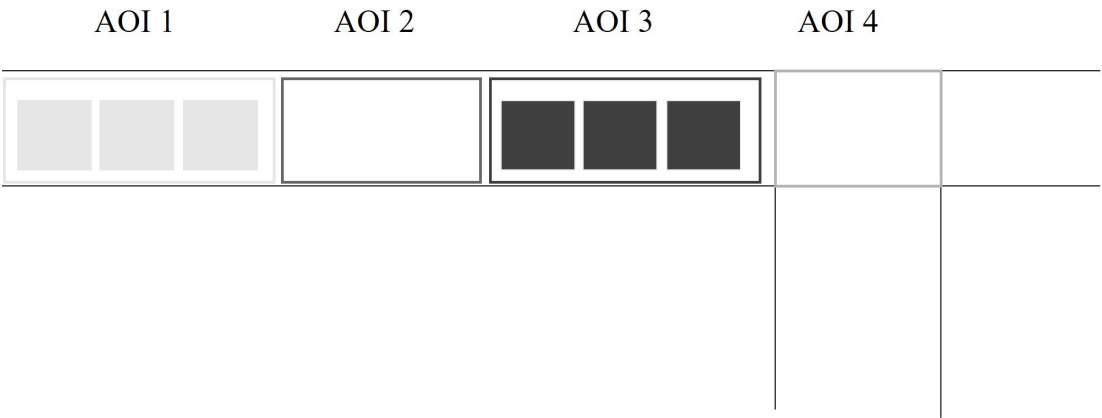
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Figure 4



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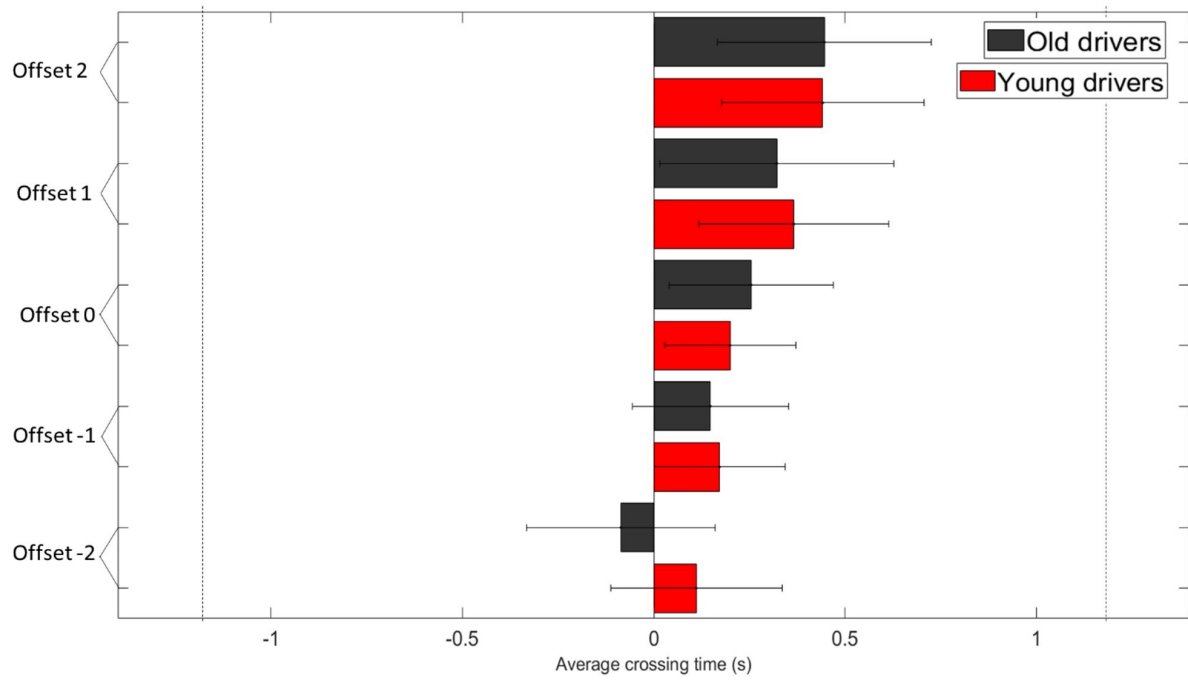
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Figure 5

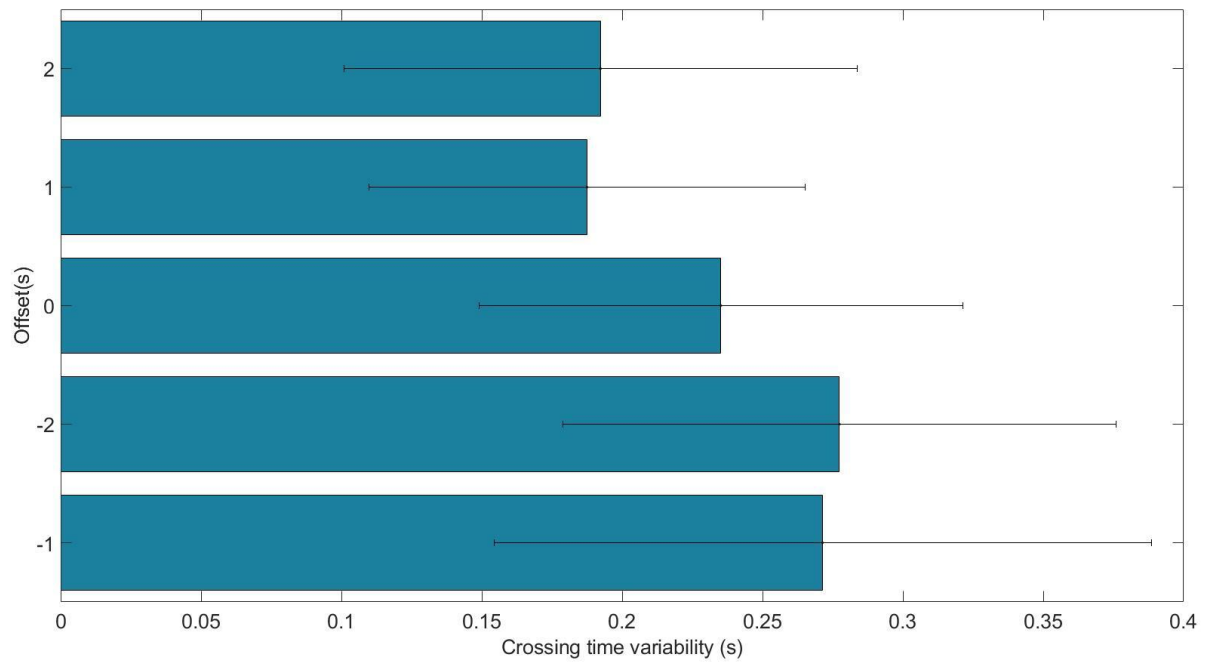


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Figure 6



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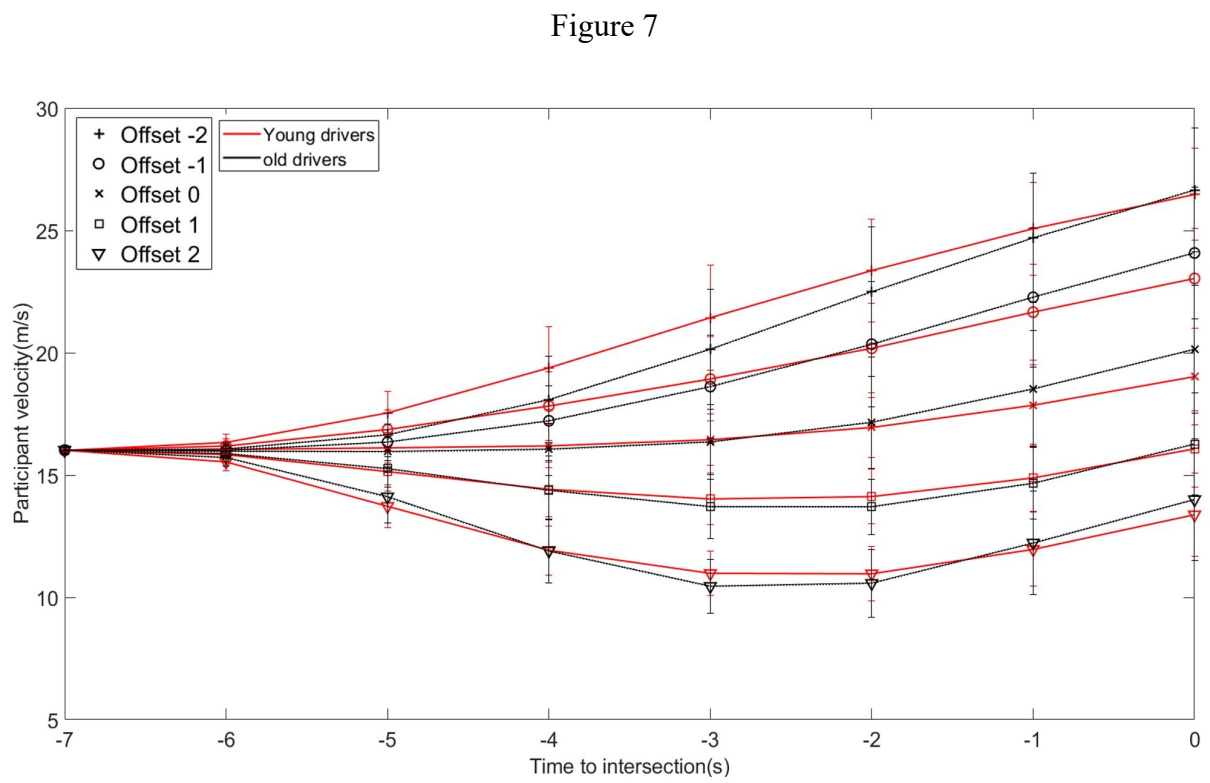
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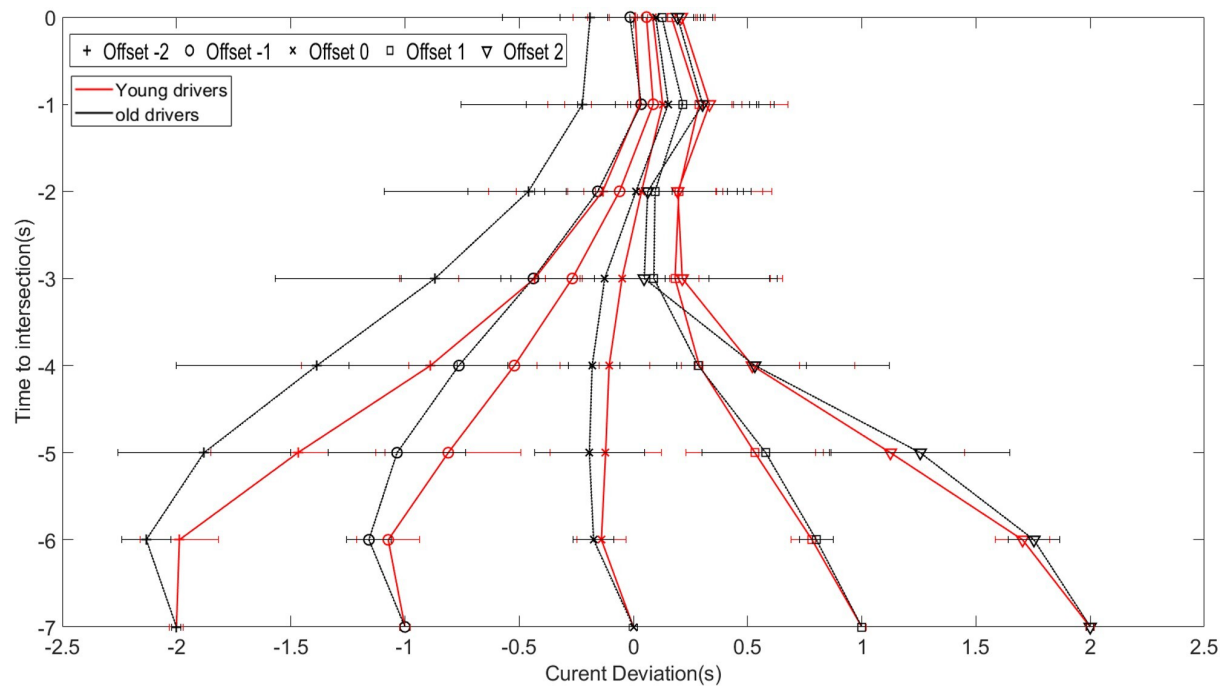
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Figure 8



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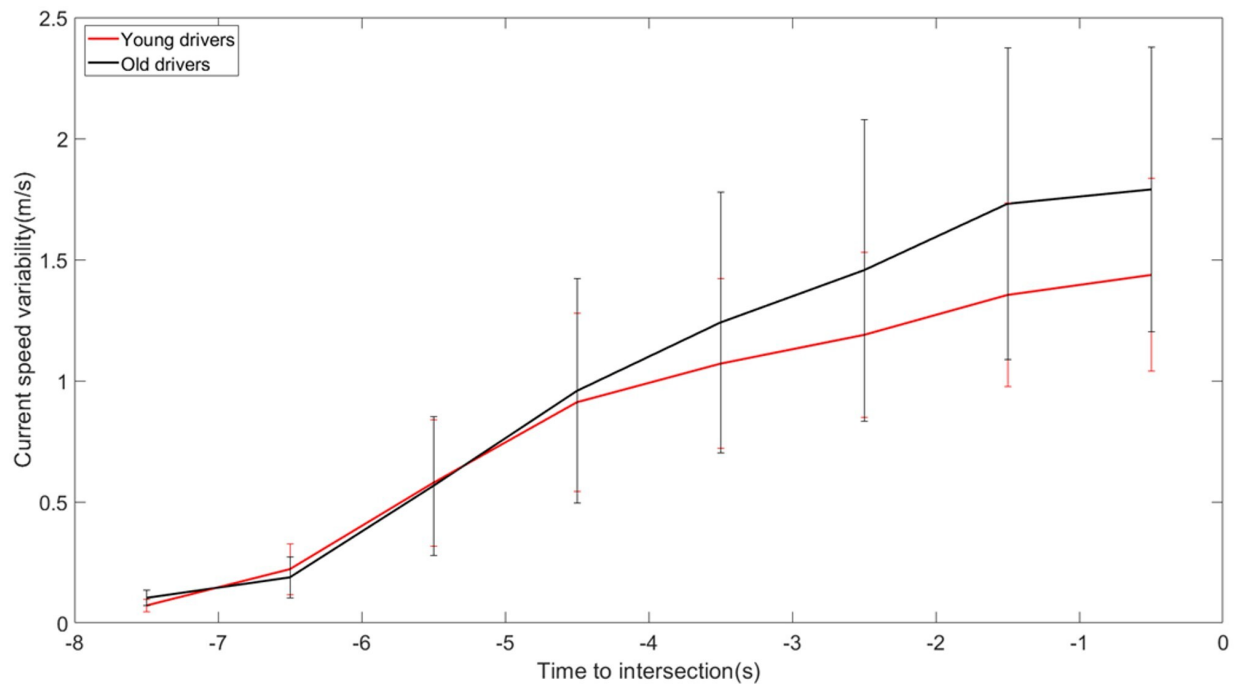
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Figure 9



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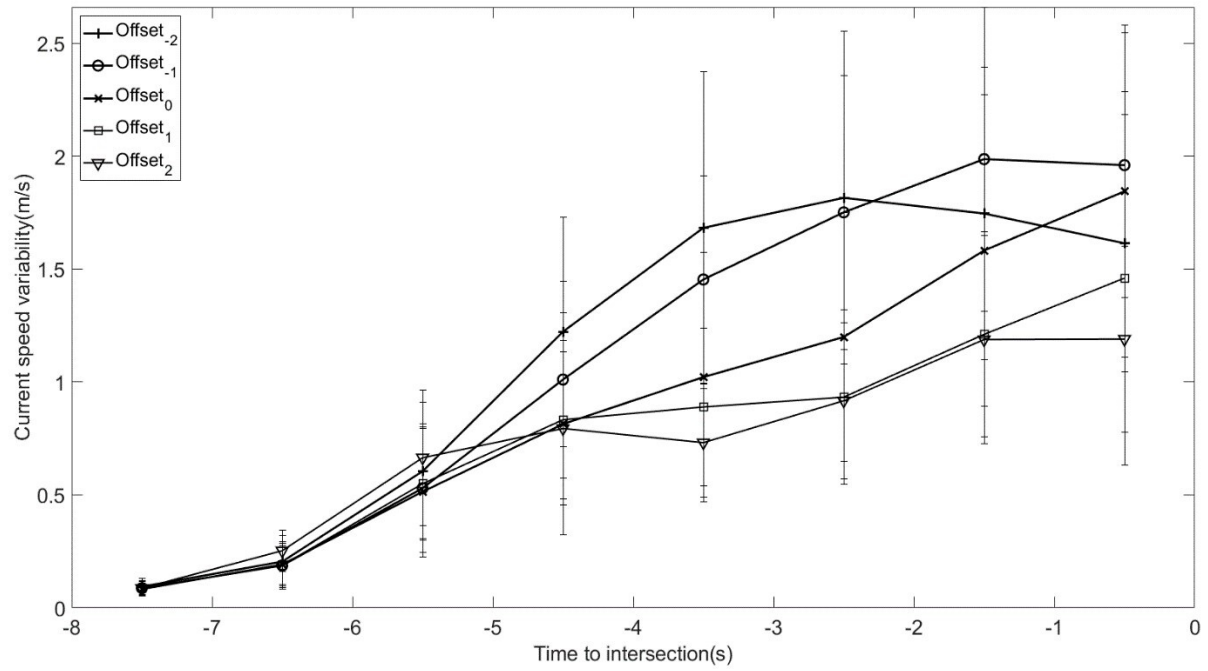
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Figure 10



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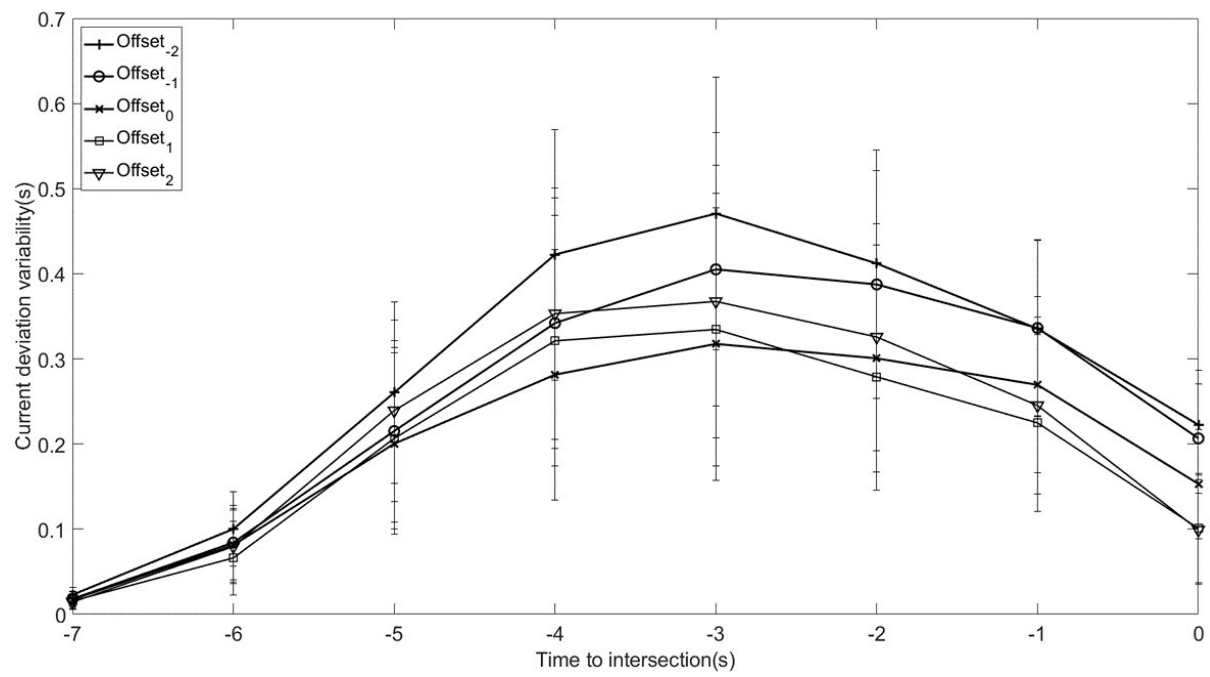
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Figure 11



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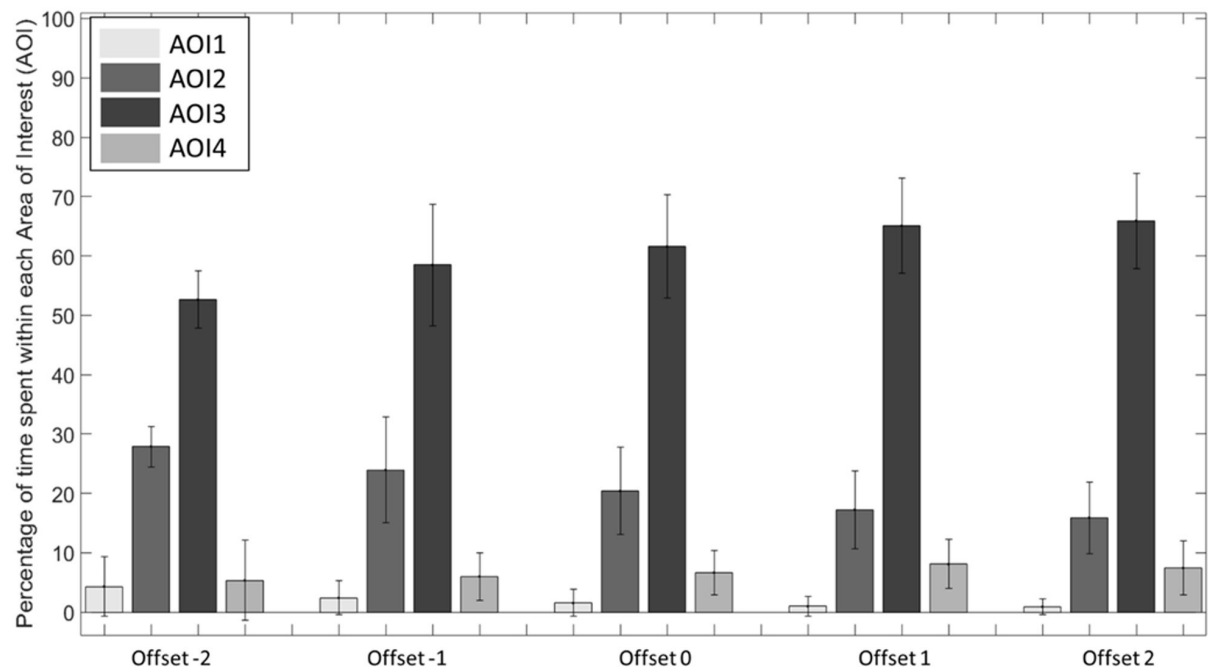
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Figure 12



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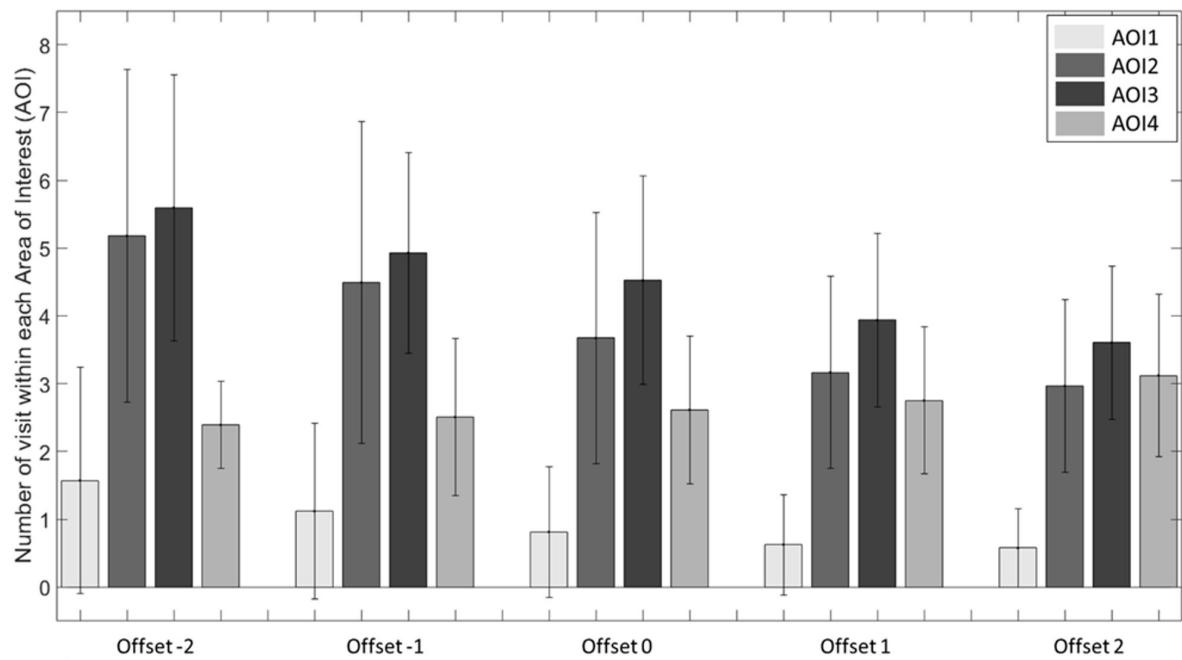
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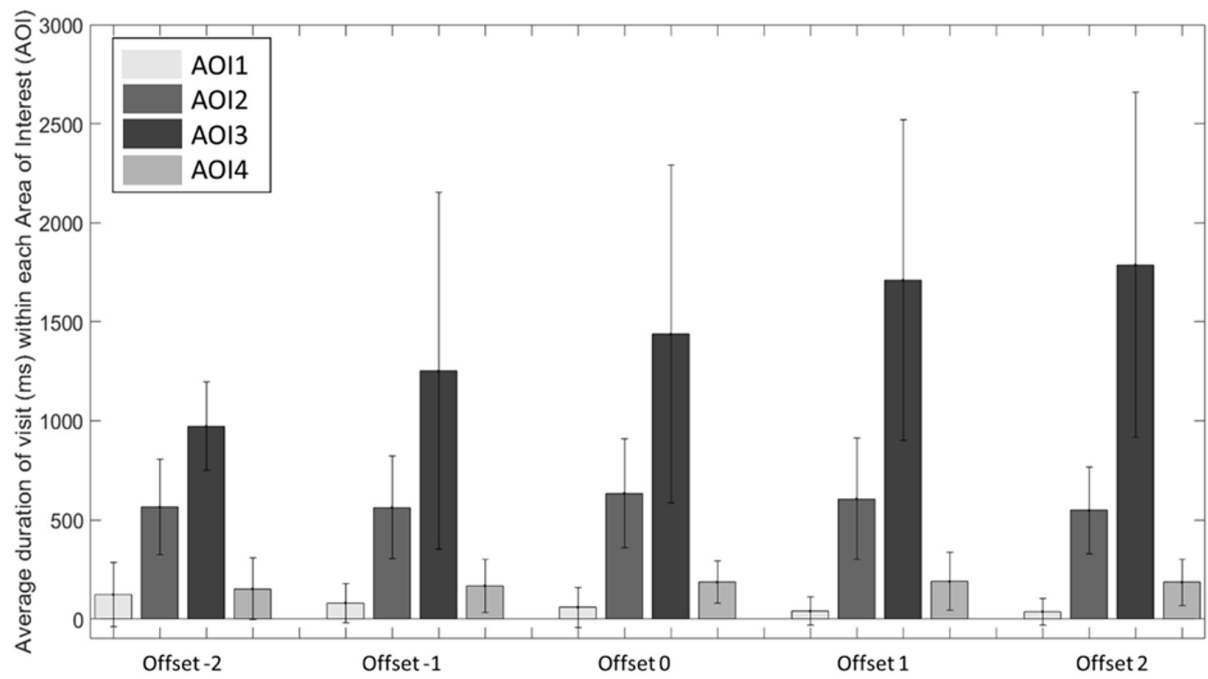
Figure 13



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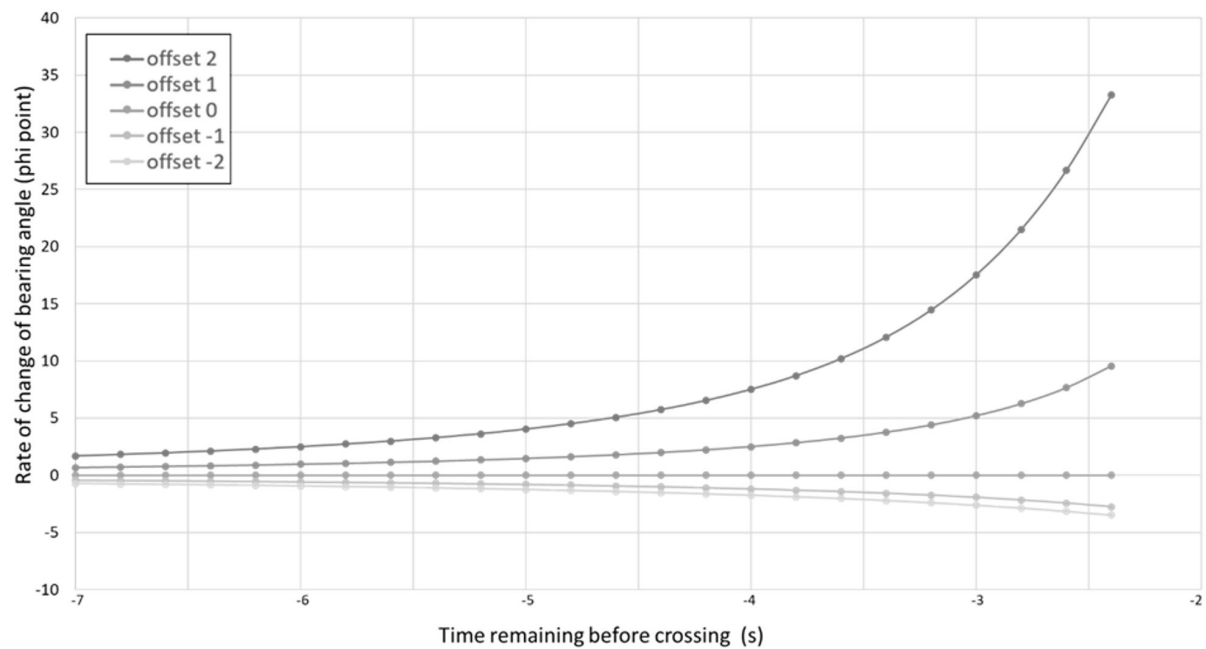
Figure 14



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Figure 15



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