

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

3 Lola Tran Van^{a,b*}, Catherine Berthelon^b, Jordan Navarro^c, Cédric Goulon^a and
4 Gilles Montagne^a

5 ^aAix-Marseille Université, CNRS, ISM, 13228 Marseille, France ; ^bUniversité Gustave Eiffel,
6 TS2-LMA, F-13300 Salon de Provence, France ; ^cUniversité Lumière Lyon 2, Laboratoire
7 d'Étude des Mécanismes Cognitifs, Lyon, France

8

9 **Acknowledgements** : This research was funded by a doctoral fellowship obtained by Lola Tran
10 Van from Gustave Eiffel University and the regional council ('Région Sud').

11

12 Corresponding author

13 Lola Tran Van

14 Université Gustave Eiffel

15 Campus Méditerranée / Salon-de-Provence

16 304, chemin de la Croix Blanche

17 F-13300 Salon-de-Provence • France

18 Email address : lola.tran-van@univ-eiffel.fr

19

20

21

22

23

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

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

41

42

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

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

74 The present study is part of a long-term research program which aims at developing a driver
75 assistance system (ADAS) designed to compensate for the limited (perceptual-motor)
76 capacities of older drivers so that they can drive safely when intercepting a moving interval.
77 The idea is to provide an ADAS that is consistent with their specific needs (Vrkljan & Miller-
78 Polgar, 2005). Indeed, a number of studies have shown if used appropriately, ADAS have the
79 potential to help drivers cope with the complex demands of driving (Vrkljan & Miller-Polgar,
80 2005; Young, 2016). They could reduce the occurrence of ~~intersection~~ accidents by
81 compensating for age-related perceptual, cognitive and physical declines (Caird, 2004; Davidse
82 et al., 2009) and therefore delay the cessation of driving, which is synonymous with loss of
83 independence and sociability (Koppel et al., 2009; Koppel & Charlton, 2013).

84 To date, very few studies have been designed to characterize the regulation behavior produced
85 by older drivers when intercepting a moving interval. Otherwise, previous work by our group
86 (Louveton, Bootsma, et al., 2012; Louveton, Montagne et al., 2012; Louveton et al., 2018;
87 Mathieu et al., 2017a, 2017b) provides a good understanding of these regulations when younger
88 drivers are faced with this type of task. In these studies, driving simulators were used,
89 interactively coupling a driving interface to a screen on which the driving environment was
90 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

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

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

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

141 ~~(2018) was designed to describe age-related differences in the perceptual-motor skills~~
142 ~~underlying locomotor pointing behavior.~~ In the study by Van Andel et al. (2018) participants
143 were asked to approach and step onto a curb-like platform. Several variables including the time
144 at which participants (younger vs., older) begin to adjust their steps, the strategy used to regulate
145 the steps and the strength of perceptual-motor coupling have been analyzed. Not only older
146 participants have been showed to produce functional step lengths adjustments allowing the
147 experimental task to be performed equally well in comparison with the control group, but it has
148 also been shown that the strength of the information-movement coupling increases with age.
149 More precisely the step lengths produced in the last steps was strongly related to the step lengths
150 required to perform the task successfully among older participants. This increased coupling
151 reflects the fact that given the well-documented decline in action capabilities with age, older
152 people prefer distributing the modulations of the step lengths over a large number of steps which
153 supposes a close and continuous dialogue between information and movement.

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

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

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

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

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

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

199 **Method**

200 *Participants*

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

211 *Apparatus and Visual Environment*

212 *Apparatus*

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

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

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

222 The virtual environment was generated using ICE© software. This home-made
223 software allows creating virtual reality environments offering both visual and auditory content,
224 as well as programming scenarios, synchronizing the driving interface and the virtual reality
225 headset as well as making the data acquisition (e.g., Marti et al., 2015; Coutton-Jean et al.,
226 2009). The virtual environment was projected through a virtual reality headset (HTC Vive®
227 Pro Eye) which had a screen offering a resolution of 2880x1600 pixels and 615 PPP and an eye
228 tracking system. In our experience, this system made it possible to follow the movement of the
229 eyes at 100 Hz.

230 ***Visual Environment***

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

235

236 [Figure 1 near here]

237

238 ***Experimental design***

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

245 ~~[Figure 2 near here]~~

246 ***Task and Experimental Design***

247 ***Calibration Phase***

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

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

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

265 [Figure 2 near here]

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

276 *Experimental Phase (Moving gap interception)*

277 **Task**

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

286 [Figure 3 near here]

287 **Procedure**

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

302 **Independent variables**

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

305 Offset

306 The initial distance between the participants and the intersection was manipulated according to
307 5 modalities to create an Offset between the participant's arrival time at the intersection (in the
308 case the initial speed was held constant) and the arrival time of the center of the gap to be
309 crossed (see Mathieu et al., 2017b for a similar procedure). Our aim was to manipulate the task

310 constraints to induce distinct regulations. In the "no offset" condition (Offset 0), the initial
311 distance (150 m) was set so that the participant could cross the intersection at the center of the
312 inter-vehicular interval while keeping his/her initial speed (i.e., 16 m/s or 57.6 km/h)
313 unchanged. In the other 4 conditions (Offset +2, +1, -1 and -2, seconds) the distances (118, 134,
314 166 and 182 meters) were set to induce specific regulations. When the participant encountered
315 either a positive or negative offset, he/she was required to decelerate or accelerate in order to
316 safely pass through the intersection. For example, in the Offset-2 condition, if the participant
317 did not change his/her speed, he would pass through the intersection two seconds after the center
318 of the inter-vehicular space had passed the intersection, resulting in a collision with the vehicle
319 located at the end of the gap. Thus, to succeed at the task, a change of speed was mandatory
320 (i.e., speed increase for negative offsets and speed decrease for positive offsets).

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

324 ***Dependent variables***

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

329 *Driving Behavior*

330 *Gap crossing position.* The most macroscopic variable was the gap crossing position defined
331 relative to the time of arrival of the center of the inter-vehicular gap at the intersection. This
332 value was calculated for each trial of each condition and allowed us to calculate the constant
333 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 (t₀). 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

358 would allow the participant to cross the intersection at the center of the inter-vehicular space.
359 In the other Offset conditions (i.e., -2, -1, +1 and +2 seconds) the initial current deviation was
360 -2, -1, +1 and +2 seconds respectively at the start of the trial. Only speed changes would allow
361 participants to cross the intersection near the center of the inter-vehicle window. The aim of the
362 analysis was precisely to describe the dynamics of changes in current deviation. We used the
363 same procedure as the one used for the speed profiles for current deviation profiles (i.e., first,
364 trial synchronizations, followed by trial discretizations). We calculated for each participant and
365 for each time step the average current deviation as well as the inter-trial variability of the current
366 deviation.

367 *Ocular Behavior*

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

376

377 [Figure 4 near here]

378 *Statistics*

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

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

389

390 **Results**

391 *Driving Behaviors*

392 *Success Rate*

393 During the experiment, the participants crossed the intersection 800 times. There were no
394 crashes for younger drivers (100% success rate), while there were 11 crashes for older drivers
395 (98.6% success rate). These trials were excluded from further analyses.

396

397 *Gap crossing position*

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

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

405 comparison with younger participants. A posteriori comparisons performed on Offset revealed
406 that gap crossing position differed for each Offset condition (all $p < 0.05$) except between Offset
407 0 and -1 ($p > 0.05$).

408 [Figure 5 near here]

410 *Gap crossing position variability*

411 The analysis of variance performed on the gap crossing position variability revealed a
412 significant main effect of Offset ($F(4, 152) = 9.896, p < 0.001, \eta^2 = 0.140$). The main effect of
413 Population failed to reach significance ($F(1, 38) = 3.846, p < 0.057, \eta^2 = 0.029$). Older drivers
414 tend to be more variable than younger drivers (Offset -2: 0.28 s older vs., 0.26 s younger; Offset
415 -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
416 older vs., 0.17 s younger; Offset 2: 0.21 s older vs., 0.17 s younger)(figure 6).

417
418 Post-hoc comparisons on Offset revealed higher gap crossing position variability in Offset -1
419 (0.28 s) and Offset-2 (0.27 s) in comparison with Offset +1 (0.19 s) and Offset +2 (0.12 s) (all
420 $p < 0.001$)(figure 6).

422 [Figure 6 near here]

424 *Speed Profiles*

425 The analysis of variance on speed revealed a significant main effect of Offset ($F(4, 2667.639)$
426 $= 1630.063, p < 0.001, \eta^2 = 0.884$) and Time ($F(7, 417.501) = 283.786, p < 0.001, \eta^2 = 0.141$).
427 The first-order interactions Offset*Population ($F(4, 7.684) = 4.536, p < 0.002, \eta^2 = 0.002$) and
428 Offset*Time ($F(28, 198.880) = 537.255, p < 0.001, \eta^2 = 0.268$) are significant.

429 A posteriori comparisons carried out on the Offset*Time interaction indicate that from 5
430 seconds before the crossing, the evolution of the speed differs according to the offset condition.
431 The most representative example is the comparison between Offset -2 and Offset 2. For Offset
432 2, there is a decrease in speed between 5 and 2 seconds before the crossing from 14 m/s to 11
433 m/s followed by an increase in speed from 2 seconds until the crossing from 11 m/s to 14 m/s.
434 While for the -2 Offset condition, there is an increase in speed from 5 seconds before the
435 crossing until the moment of crossing from 16 m/s to 25 m/s (figure 7). A posteriori comparison
436 carried out on the Offset*Population interaction indicate that the displacement speed produced
437 by younger and older people are not significantly different except in the Offset -2 condition. In
438 Offset -2 older people vehicle speed (20.09 m/s) was lower than the younger drivers (20.64
439 m/s)($p < 0.05$)(figure 7).

440 [Figure 7 near here]

441 *Current Deviation Profiles*

442 The analysis of variance on the current deviation reveals significant main effects of Offset (F
443 (4,152) = 846.092, $p < 0.001$, $\eta^2 = 0.536$) and Population ($F(1,38) = 4.532$, $p < 0.040$ $\eta^2 = 0.003$).
444 The first-order interactions Offset*Population ($F(4,152) = 5.255$, $p < 0.001$, $\eta^2 = 0.003$) and
445 Offset*Time ($F(28,266) = 813.681$, $p < 0.001$, $\eta^2 = 0.354$) are significant. The second-order
446 interaction Offset*Population*Time ($F(28,266) = 3.847$, $p < 0.001$, $\eta^2 = 0.002$) is also
447 significant.

448 Post-hoc comparisons performed on the Offset*Population*Time interaction reveal a
449 significant difference between younger and older people in the Offset -2 condition from 5 s to
450 2 s before crossing the intersection. Indeed, the current deviation is lower for older than for
451 younger drivers (5s before crossing : -1.87 s older vs., -1.46 s younger; 4s: -1.38 s older vs., -
452 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

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

[Figure 8 near here]

456 *Speed Variability*

457 The analysis of variance on the inter-trial speed variability revealed significant main effects of
458 the factors Offset ($F(4,152) = 23.930, p < 0.001, \eta^2 = 0.051$), Population ($F(1,38) = 6.336,$
459 $p < 0.016, \eta^2 = 0.010$) and Time ($F(7,266) = 392.113, p < 0.001, \eta^2 = 0.545$). The first-order
460 interactions Time*Population ($F(7,266) = 7.790, p < 0.001, \eta^2 = 0.011$) and
461 Offset*Time ($F(28,266) = 17.598, p < 0.001, \eta^2 = 0.057$) were also significant.

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

[Figure 9 and 10 near here]

469 *Current Deviation Variability*

470 The analysis of variance of the current deviation variability revealed significant main effects of
471 Offset ($F(4, 152) = 12.169, p < 0.001, \eta^2 = 0.036$) and Time ($F(7, 266) = 251.133, p < 0.001,$
472 $\eta^2 = 0.525$) conditions. The analysis also revealed that the first-order interaction Offset*Time
473 ($F(28, 266) = 5.802, p < 0.001, \eta^2 = 0.020$) was significant.

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

476 [Figure 11 near here]

477 ***Ocular Behavior***

478 *Percentage of Time Spent within in Each Area of Interest*

479 Taking into account the percentage of time spent in the 4 AOIs allowed us to account for
480 approximately 90% of the overall ocular behavior of the participants. An analysis of variance
481 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.

484 Post hoc comparisons performed on the Offset*AOI interaction revealed that participants spent
485 more time fixating AOI2 in Offset-2, Offset-1 and Offset0 conditions in comparison with Offset
486 +1 and Offset +2 ($p < .05$) (figure 13). The reverse was true for AOI3 ($p < .05$) (figure 12).

487 [Figure 12 near here]

488 *Number of Fixations in Each Area of Interest*

489 An analysis of variance on the number of fixations revealed significant main effects of Offset
490 ($F(4, 152) = 38.521, p < 0.001, \eta^2 = 0.046$) and AOI ($F(3, 114) = 92.939, p < 0.001, \eta^2 = 0.418$).
491 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).

493 Post-hoc comparisons performed on the Offset*AOI interaction revealed that Offset conditions
494 0, +1 and +2 gave rise to less fixations of AOI1 than the other two Offset conditions (i.e., Offset-
495 1 and Offset-2). They also revealed that the number of visits to AOI2 and AOI3 is influenced
496 by the Offset. Offset-2 was the condition with the most visits for AOI2 and AOI3 (figure 13).

497 [Figure 13 near here]

498 *Mean Fixation Durations of Each Area of Interest*

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

503 Post-hoc comparisons performed on the Offset*AOI interaction revealed that the number of
504 AOI3 visits is influenced by the Offset conditions. The average duration of an AOI3 visit
505 decreases as the initial distance from the intersection increases (from Offset 2 to Offset -2).
506 Offset 2 is the condition where the average AOI3 visit duration is the longest; conversely Offset
507 -2 condition gives rise to the shortest average visit durations (figure 14).

508 [Figure 14 near here]

509

510 **Discussion**

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

518

519 *Analysis of the Regulations Produced*

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

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

526 *Control Population*

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

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

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

554

555 *Older drivers*

556 The speed regulations observed among older drivers are to some extent comparable to those
557 observed among younger drivers in our study but also to those described in our previous work
558 (Louveton, Bootsma, et al., 2012; Louveton, Montagne et al., 2012; Louveton et al., 2018;
559 Mathieu et al., 2017a, 2017b). Indeed, these regulations implemented allow to cross the
560 intersection just before the center of the inter-vehicular interval except for offset -2. These
561 regulations usually occur early and are followed by a final acceleration when crossing the
562 intersection. Moreover, these changes in speed induce a gradual convergence of the current
563 deviation towards the first half of the interval. Finally, a compensatory variability pattern
564 appears when comparing the evolution of the variability of the reference speed with the
565 evolution of the variability of the current deviation. All these results confirm the presence of
566 control based on information-movement coupling for older drivers in an intersection crossing
567 task, despite advancing age. Comparable results have been described in studies on the control
568 of goal-directed locomotor displacements. Van Andel et al (2018) described the step length
569 regulations implemented by two populations of subjects (i.e., younger and older) when they
570 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,

596 the driver has to decelerate or accelerate respectively to cross the gap at the right place at the
597 right time (cf., Bastin et al., 2006b; Morice et al., 2010). As a reminder, in our experiment, the
598 initial speed of the participants was always the same and the 5 Offset conditions were obtained
599 by manipulating the initial distance between the driver and the intersection at the moment the
600 intersection appeared. Simulations were carried out to determine how the bearing angle varies
601 in the positive and negative Offset conditions when the travel speed is held constant (Figure
602 16). These simulations indicate that the greater the distance between the driver and the
603 intersection, the smaller the bearing angle changes. It is worthnoting that the bearing angle
604 changes are the weakest in the Offset -2 condition. Studies have shown that the thresholds for
605 detecting movement are lower for older people than for younger people (Andersen & Enriquez,
606 2006; Tran et al., 1998 ; Warren et al., 1989; François et al., 2011). It would seem therefore,
607 that the specific regulation behavior exhibited by the older drivers in our study with negative
608 Offset conditions may be related to the difficulties encountered by the older drivers in detecting
609 changes in bearing angle that inform them of the need to produce appropriate speed changes.
610 Bearing angle changes would become available later on during the approach and would allow
611 the production of functional regulations, although it would not be possible to fully compensate
612 the delay in the initiation of regulation.

613

614 [Figure 16 near here]

615

616 *Analysis of Visual Information Pick-Up Strategies*

617

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

621 crossing (Chihak et al., 2010; Chihak et al., 2014; Louveton, Bootsma, et al., 2012; Louveton,
622 Montagne et al., 2012; Louveton et al., 2018; Mathieu et al., 2017a, 2017b ; Plumert & Kearney,
623 2014) and could be particularly useful when designing driver assistance systems that could
624 come to the aid of drivers attempting to cross an intersection. As a reminder, four areas of
625 interest (AOI) were defined in our analysis corresponding to the vehicle train located behind
626 (AOI1) or in front (AOI3) of the inter-vehicular interval, the inter-vehicular interval (AOI2)
627 and the junction of the two roads (AOI4).

628
629 Given that no differences were found according to the population tested the overall results will
630 be presented. As a reminder the analysis focused on the average percentage of time spent in
631 each AOI during a trial, the average number of visits as well as the average durations of these
632 visits in each AOI (Navarro et al., 2019). The results indicate that the AOI3 is the area of interest
633 looked at the longest during a trial (60% of the overall time spent in the AOIs), but also the one
634 with the longest visits. This result seems logical; as drivers target the first part of the inter-
635 vehicle interval, the location of the vehicle train preceding the interval is of great importance
636 when controlling the approach speed. In contrast, the number of AOI visits is much more evenly
637 distributed over the 4 areas of interest. The average visit duration of some AOIs are therefore
638 much shorter (AOI 1 and AOI 4 in particular) so that the function of these fixations is probably
639 different. For example, fixing the intersection zone would allow an estimation of the time
640 remaining before the crossing.

641
642 Our analysis also revealed differences in the information gathering strategies implemented
643 according to the Offset conditions. For negative offset conditions, the vehicle train before the
644 inter-vehicle interval (AOI3) remains the information gathering zone targeted by drivers, but
645 the inter-vehicle interval (AOI2) is also favored. As a reminder, our results have shown that the

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

655

656 **Conclusion**

657 Our ambition was to characterize as precisely as possible the product regulation behavior and
658 the information taking strategies of our population. Our results reveal similarities in the
659 behavior of older people in comparison with that of younger drivers. The regulations produced
660 are based on a close coupling between information and movement, giving rise to functional
661 speed adjustments throughout the approach. They also reveal specific difficulties linked to the
662 perceptual constraints induced by particular situations (i.e., negative Offsets). The analysis of
663 the eye-tracking data also enabled the identification of areas containing information relevant to
664 travel controls and the impact of task constraints on the nature of the favor areas. This dataset
665 will be particularly useful in future work on the design of driver assistance systems (ADAS)
666 for older drivers. As an example, the difficulties encountered by the older participants for
667 negative Offsets could be solved by providing older drivers concurrent feedback representing
668 at any time their current deviation relative to the inter-vehicular gap to be intercepted, allowing
669 them not only to identify very early the regulations to be produced but also to guide them until
670 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.

674

675

676

677 **References**

- 678 Andersen, G. J., & Enriquez, A. (2006). Aging and the detection of observer and moving object
679 collisions. *Psychology and aging*, (21)1,74-85. [https://doi.org/10.1037/0882-](https://doi.org/10.1037/0882-7974.21.1.74)
680 [7974.21.1.74](https://doi.org/10.1037/0882-7974.21.1.74)
- 681 Ball, K., Owsley, C., Stalvey, B., Roenker, D.L., Sloane, M.E., & Graves, M. (1998). Driving
682 avoidance and functional impairment in older drivers. *Accident Analysis & Prevention*,
683 30, 313–322. [https://doi.org/10.1016/s0001-4575\(97\)00102-4](https://doi.org/10.1016/s0001-4575(97)00102-4)
- 684 Bardy, B. G., & Laurent, M. (1998). How is body orientation controlled during somersaulting?
685 *Journal of Experimental Psychology: Human Perception and Performance*, 24, 963–977.
686 <https://doi.org/10.1037//0096-1523.24.3.963>
- 687 Bastin, J., Calvin, S., & Montagne, G. (2006a). Muscular proprioception contributes to the
688 control of interceptive actions. *Journal of experimental psychology: human perception*
689 *and performance*, 32(4), 964-972. <https://doi.org/10.1037/0096-1523.32.4.964>
- 690 Bastin, J., Craig, C., & Montagne, G. (2006). Prospective strategies underlie the control of
691 interceptive action. *Human Movement Science*, 25, 718-732.
- 692 Caird, J. K., & Hancock, P. A. (1994). The perception of arrival time for different oncoming
693 vehicles at an intersection. *Ecological Psychology*, 6(2), 83–109.
- 694 Case, H. W., Hulbert, S. & Beers, J. (1970). Driving abilities as affected by age. Final report
695 70-18. Institute of Transportation and Traffic Engineering, University of California, Los
696 Angeles.
- 697 Bootsma, R. J. (1998). Ecological movement principles and how much information matters. In
698 A. A. Post, J. R. Pijpers, P Bosch, & M. S. J. Boschker (Eds.), *Models in human movement*
699 *science* (pp 51– 63). Enschede, The Netherlands: PrintPartners Ipskamp.

700 Bootsma, R. J., & Van Wieringen, P. C. W. (1990). Timing an attacking forehand drive in table
701 tennis. *Journal of Experimental Psychology: Human Perception and Performance*, 16,
702 21–29. <https://doi.org/10.1037/0096-1523.16.1.21>

703 Caird, J. (2004). In-vehicle intelligent transportation systems. *Transportation in an Aging*
704 *Society*, 236.

705 Caird, J. K., & Hancock, P. A. (1994). The perception of arrival time for different oncoming
706 vehicles at an intersection. *Ecological Psychology*, 6(2), 83–109.

707 Camachon, C., Buekers, M. J., & Montagne, G. (2004). Is the learning of goal-directed
708 displacement effector independent? *Human Movement Science*, 23, 239–255.
709 <https://doi.org/10.1016/j.humov.2004.08.006>

710 Chardenon, A., Montagne, G., Buekers, M. J., & Laurent, M. (2002). The visual control of ball
711 interception during human locomotion. *Neuroscience Letters*, 334, 13–16.
712 [https://doi.org/10.1016/S0304-3940\(02\)01000-5](https://doi.org/10.1016/S0304-3940(02)01000-5)

713 Chardenon, A., Montagne, G., Laurent, M., & Bootsma, R. J. (2004). The perceptual control of
714 goal-directed locomotion : a common architecture for interception and navigation ?
715 *Experimental Brain Research*, 158, 100-108.

716 Chihak, B. J., Grechkin, T. Y., Kearney, J. K., Cremer, J. F., & Plumert, J. M. (2014). How
717 children and adults learn to intercept moving gaps. *Journal of Experimental Child*
718 *Psychology*, 122, 134–152. <https://doi.org/10.1016/j.jecp.2013.12.006>

719 Chihak, B. J., Plumert, J. M., Ziemer, C. J., Babu, S., Grechkin, T., Cremer, J. F., & Kearney,
720 J. K. (2010). Synchronizing self and object movement: How child and adult cyclists
721 intercept moving gaps in a virtual environment. *Journal of Experimental Psychology :*
722 *Human Perception and Performance*, 36,1535–1552. <https://doi.org/10.1037/a0020560>

723 Coutton-Jean, C., Mestre, D. R., Goulon, C., & Bootsma, R. J. (2009). The role of edge lines
724 in curve driving. *Transportation Research Part F: Traffic Psychology and Behavior*,
725 12, 483–493. <https://doi.org/10.1016/j.trf.2009.04.006>

726 Davidse, R. J., Hagenzieker, M. P., van Wolffelaar, P. C., & Brouwer, W. H. (2009). Effects of
727 in-car support on mental workload and driving performance of older drivers. *Human*
728 *Factors*, 51, 463–476. <https://doi.org/10.1177/0018720809344977>

729 Davis, G. A., & Swenson, T. (2004). Field Study of Gap Acceptance by Left-Turning Drivers.

730 Douissembekov, E., Michael, G.A., Rogé, J., Bonhoure, P., Gabaude, C., & Navarro, J. (2015).
731 Effects of shrinkage of the visual field through ageing on parking performance: a
732 parametric manipulation of salience and relevance of contextual components.
733 *Ergonomics*, 58(5), 698-711. <https://doi.org/10.1080/00140139.2014.987699>

734 Douissembekov, E., Navarro, J., Michael, G. A., Bonhoure, P., Gabaude, C., & Rogé, J. (2015).
735 Parking Manoeuvres Differ among Drivers with Narrower and Wider Field of View in
736 the Presence of a Spatial Reference. *Applied Cognitive Psychology*, 29(2), 309–313.
737 <https://doi.org/10.1002/acp.3110>

738 François, M., Morice, A. H. P., Blouin, J., & Montagne, G. (2011). Age-related decline in
739 sensory processing for locomotion and interception. *Neuroscience*, 172, 366–378.
740 <https://doi.org/10.1016/j.neuroscience.2010.09.020>

741 Gibson, J. J. (1979). The theory of affordances. The ecological approach to visual perception.
742 In *The People, Place and, Space Reader* (pp. 56-60). Routledge New York and London.

743 Koppel, S. N., & Charlton, J. L. (2013). Behavioural adaptation and older drivers. In C. M.
744 Rudin-Brown & S. L. Jamson (Eds.), *Behaviorial Adaptation and Road Safety: Theory,*
745 *Evidence and Action* (pp. 303-322). CRC Press.

- 746 Koppel, S. N., Charlton, J.L., & Fildes, B. (2009). Distraction and the older driver. In Regan,
747 M. A. Regan, J. D. Lee, & K. L. Young (Eds.), *Driver Distraction: Theory, Effects and*
748 *Mitigation* (pp. 353–382). CRC Press.
- 749 Lappi, O., Lehtonen, E., Pekkanen, J., & Itkonen, T. (2013). Beyond the tangent point: gaze
750 targets in naturalistic driving. *Journal of vision*, 13(13),11,1-18.
751 <https://doi.org/10.1167/13.13.11>
- 752 Lee, D. N., Lishman, J. R., & Thomson, J. A. (1982). Regulation of gait in long jumping.
753 *Journal of Experimental Psychology: Human Perception and Performance*, 8, 448–458.
754 <https://doi.org/10.1037/0096-1523.8.3.448>
- 755 Lenoir, M., Savelsbergh, G. J., Musch, E., Thiery, E., Uyttenhove, J., & Janssens, M. (1999a).
756 Intercepting moving objects during self-motion: effects of environmental changes.
757 *Research Quarterly for Exercise and Sport*, 70, 349–360.
758 <https://doi.org/10.1080/02701367.1999.10608055>
- 759 Lenoir, M., Musch, E., Janssens, M., Thiery, E., Uyttenhove, J. (1999b). Intercepting moving
760 objects during self-motion. *Journal of Motor Behavior*, 31, 55–67.
- 761 Louveton, N., Bootsma, R. J., Guerrin, P., Berthelon, C., & Montagne, G. (2012). Intersection
762 crossing considered as intercepting a moving traffic gap: Effects of task and
763 environmental constraints. *Acta Psychologica*, 141, 287–294. [https://doi.org](https://doi.org/10.1016/j.actpsy.2012.08.003)
764 [/10.1016/j.actpsy.2012.08.003](https://doi.org/10.1016/j.actpsy.2012.08.003)
- 765 Louveton, N., Montagne, G., Berthelon, C., & Bootsma, R. J. (2012). Intercepting a moving
766 traffic gap while avoiding collision with lead and trail vehicles: Gap-related and
767 boundary-related influences on drivers' speed regulations during approach to an
768 intersection. *Human Movement Science*, 31, 1500–1516. [https://doi.org](https://doi.org/10.1016/j.humov.2012.07.010)
769 [/10.1016/j.humov.2012.07.010](https://doi.org/10.1016/j.humov.2012.07.010)

770 Louveton, N., Montagne, G., Berthelon, C. (2018). Synchronising self-displacement with a
771 cross-traffic gap: How does the size of traffic vehicles impact continuous speed
772 regulations? *Transportation research part F Traffic Psychology and Behaviour*, 58,80-
773 92. <https://doi.org/10.1016/j.trf.2018.05.030>

774 Mathieu, J., Bootsma, R. J., Berthelon, C., & Montagne, G. (2017a). Judging arrival times of
775 incoming traffic vehicles is not a prerequisite for safely crossing an intersection:
776 Differential effects of vehicle size and type in passive judgment and active driving tasks.
777 *Acta Psychologica*, 173, 1–12. <https://doi.org/10.1016/j.actpsy.2016.11.014>

778 Mathieu, J., Bootsma, R. J., Berthelon, C., & Montagne, G. (2017b). Information-movement
779 coupling in the control of driver approach to an intersection. *Ecological psychology*,
780 29,317-341. <https://doi.org/10.1080/10407413.2017.1369853>

781 McLeod, P., & Dienes, Z. (1993). Running to catch the ball. *Nature*, 362(6415), 23.
782 <https://doi.org/10.1038/362023a0>

783 Marti, G., Morice, A. H. P., & Montagne, G. (2015). Drivers' decision-making when attempting
784 to cross an intersection results from choice between affordances. *Frontiers in Human*
785 *Neuroscience*, 9 (8),1026. <https://doi.org/10.3389/fnhum.2014.01026>

786 Michaels, C. F., & Oudejans, R. R. D. (1992). The optics and actions of catching fly balls:
787 zeroing out optical acceleration. *Ecological Psychology*, 4, 199-222.

788 Montagne, G., Cornus, S., Glize, D., Quaine, F., & Laurent, M. (2000). A perception–action
789 coupling type of control in long-jumping. *Journal of Motor Behavior*, 32,37–44.
790 <https://doi.org/10.1080/00222890009601358>

791 Montagne, G., Laurent, M., Durey, A., & Bootsma, R. J. (1999). Movement reversals in ball
792 catching. *Experimental Brain Research*, 129,87–92.
793 <https://doi.org/10.1007/s002210050939>

794 Montagne, G. (2005). Prospective control in sport. *International Journal of Sport Psychology*,
795 36, 127-150.

796 Morice, A. H. P., François, M., Jacobs, D. M., & Montagne, G. (2010). Environmental
797 constraints modify the way an interceptive action is controlled. *Experimental brain*
798 *research*, 202(2),397-411. <https://doi.org/10.1007/s00221-009-2147-0>

799 Navarro, J., Osiurak, F., Ovigue, M., Charrier, L., & Reynaud, E. (2019). Highly Automated
800 Driving Impact on Drivers' Gaze Behaviors during a Car-Following Task. *International*
801 *Journal of Human-Computer Interaction*, 35(11), 1008–1017.
802 <https://doi.org/10.1080/10447318.2018.1561788>

803 ONISR (2020). La sécurité routière en France : bilan de l'année. Rapport technique, ONISR.
804 Paris, France.

805 Peper, C. E., Bootsma, R. J., Mestre, D. R., Bakker, F. C. (1994). Catching balls: how to get
806 the hand to the right place at the right time. *Journal of Experimental Psychology: Human*
807 *Perception and Performance*, 20, 591–612.

808 Plumert, J. M., & Kearney, J. K. (2014). How do children perceive and act on dynamic
809 affordances in crossing traffic-filled road? *Child development perspectives*, 8(4),207–
810 212. <https://doi.org/10.1111/cdep.12089>

811 Schmidt, R. A., & Lee, T. D. (2005). Motor control and learning: A behavioral emphasis (4th
812 ed.). *Human Kinetics*

813 Tran, D.B., Silverman, S. E., Zimmerman, K., & Feldon, S. E. (1998). Age-related deterioration
814 of motion perception and detection. *Graefes Arch Clin Exp Ophthalmol*, 236(4),269-273.
815 <https://doi.org/10.1007/s004170050076>

816 Van Andel, S., Cole, M. H., & Pepping, G. J. (2018). Regulation of locomotor pointing across
817 the lifespan: Investigating age-related influences on perceptual-motor coupling. *PLoS*
818 *ONE* 13(7), e0200244. <https://doi.org/10.1371/journal.pone.0200244>

819 Vrkljan, B. H., & Miller-Polgar, J. (2005). Advancements in vehicular technology: potential
820 implications for the older driver. *International Journal of Vehicle Information and*
821 *Communication Systems*, 1(1-2),88-105. <https://doi.org/10.1504/JVICS.2005.007587>

822 Warren, W. H. (1988). Action mode and laws of control for the visual guidance of action. In O.
823 Meijer & K. Roth (Eds.), *Complex movement behavior: 'The' motor-action controversy*
824 (pp. 339–380). Amsterdam, The Netherlands: North-Holland.

825 Warren, W. H. (2006). The dynamics of perception and action. *Psychological Review*, 113,
826 358–389. <https://doi.org/10.1037/0033-295X.113.2.358>

827 Warren, W. H., & Yaffe, D. M. (1989). Dynamics of step length adjustment during running: a
828 comment on Patla, Robinson, Samways, and Armstrong. *Journal of Experimental*
829 *Psychology Human Perception and Performance*, (15)3,618 -
830 623. <https://doi.org/10.1037/0096-1523.15.3.618>

831 Young, K. L., Koppel, S., & Charlton, J. L. (2016). Toward best practice in Human Machine
832 Interface design for older drivers: A review of current design guidelines. *Accident*
833 *analysis and prevention*, 106, 460 - 467. <https://doi.org/10.1016/j.aap.2016.06.010>

834

835

836

837

838

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 tasks 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.

869

870

871

872

873

Figure 1



874

875

876

877

878

879

880

881

882

883

884

885

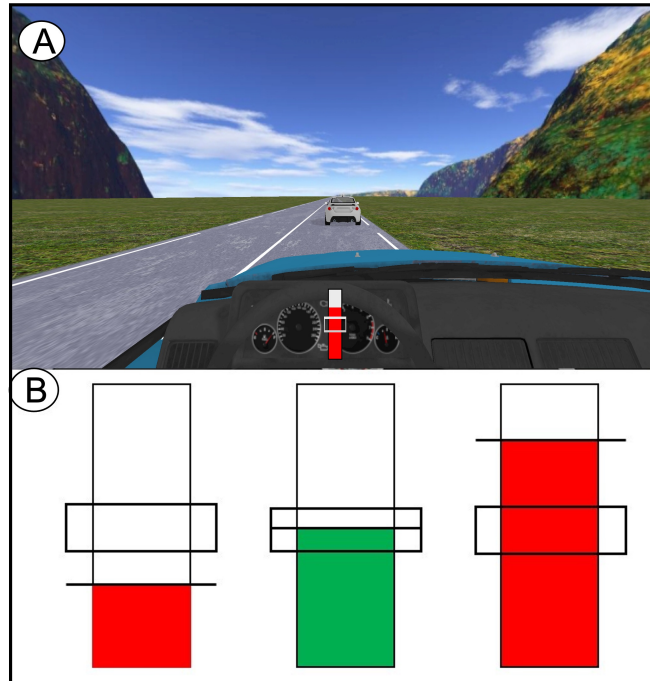
886

887

888

889

Figure 2



890

891

892

893

894

895

896

897

898

899

Figure 3



900

901

902

903

904

905

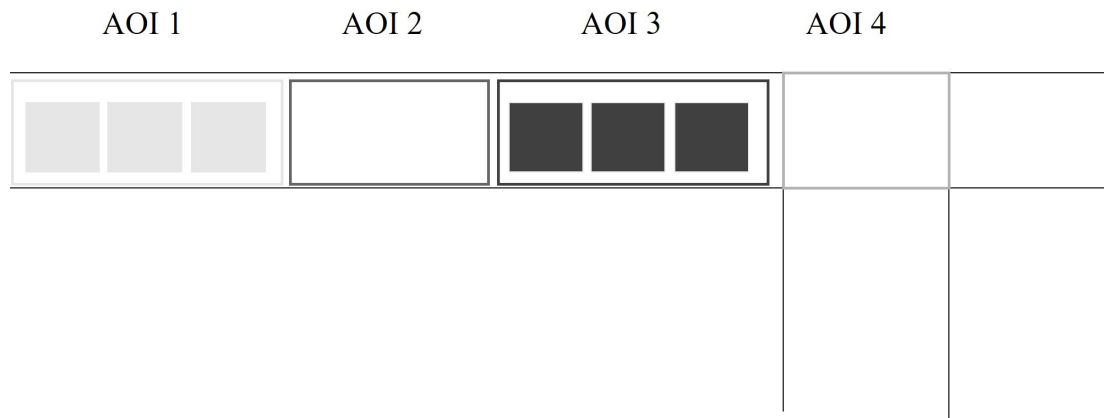
906

907

908

909

Figure 4



910

911

912

913

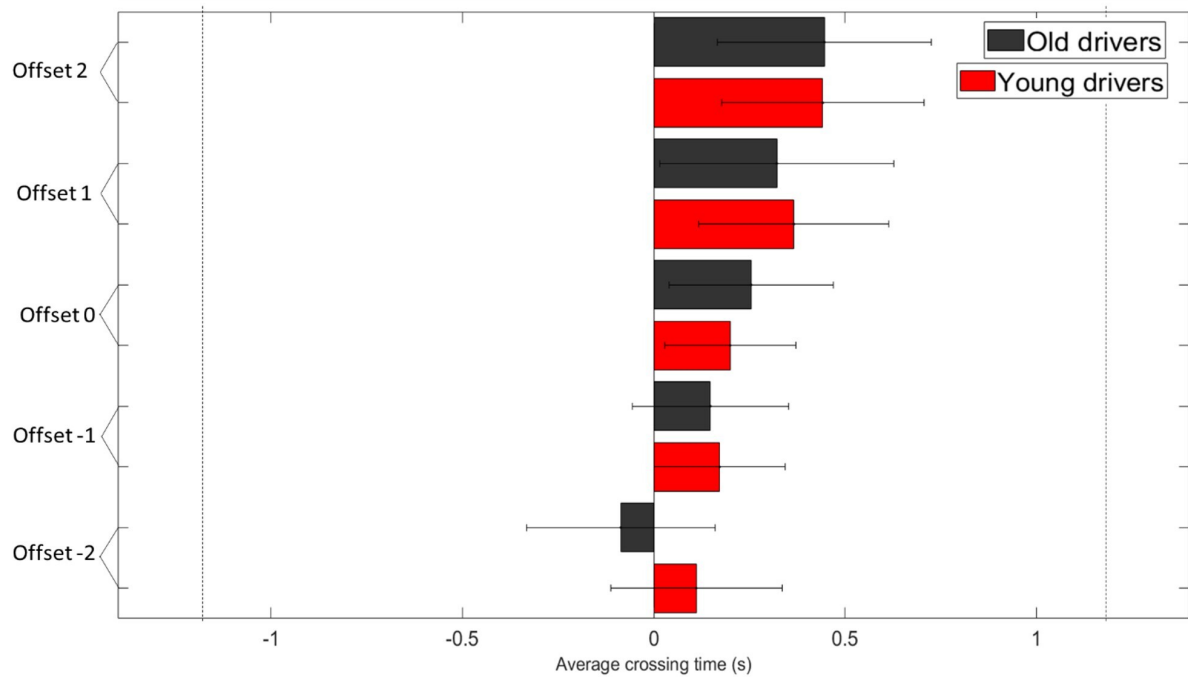
914

915

916

917

Figure 5



918

919

920

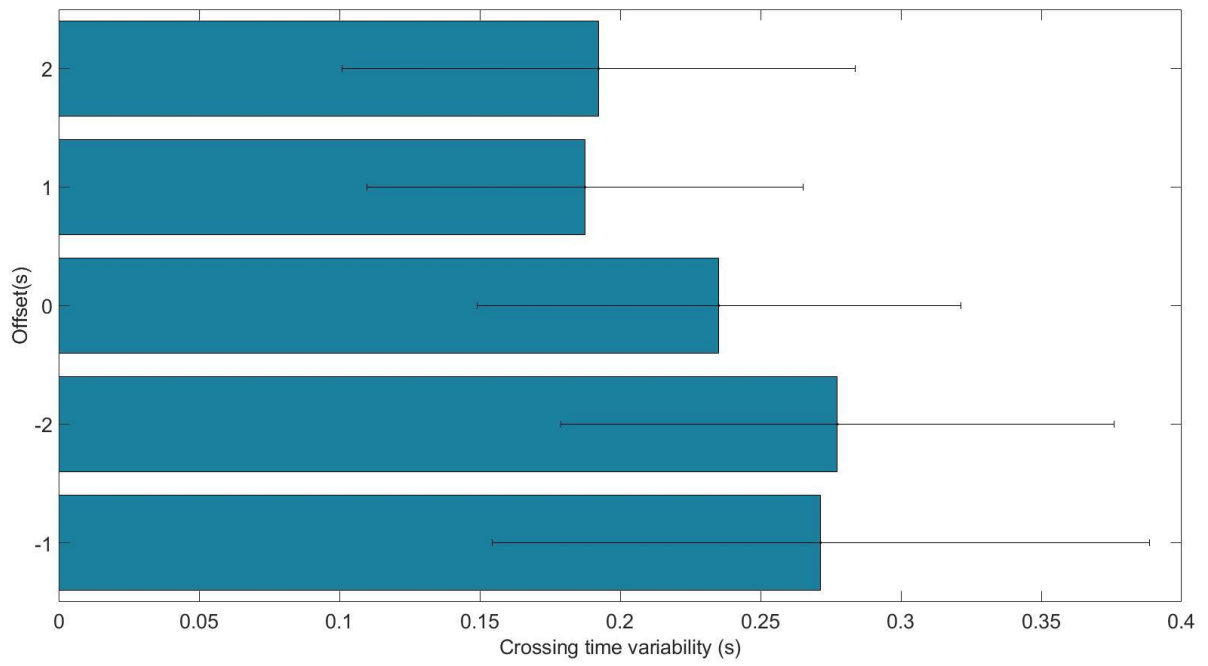
921

922

923

924

Figure 6



925

926

927

928

929

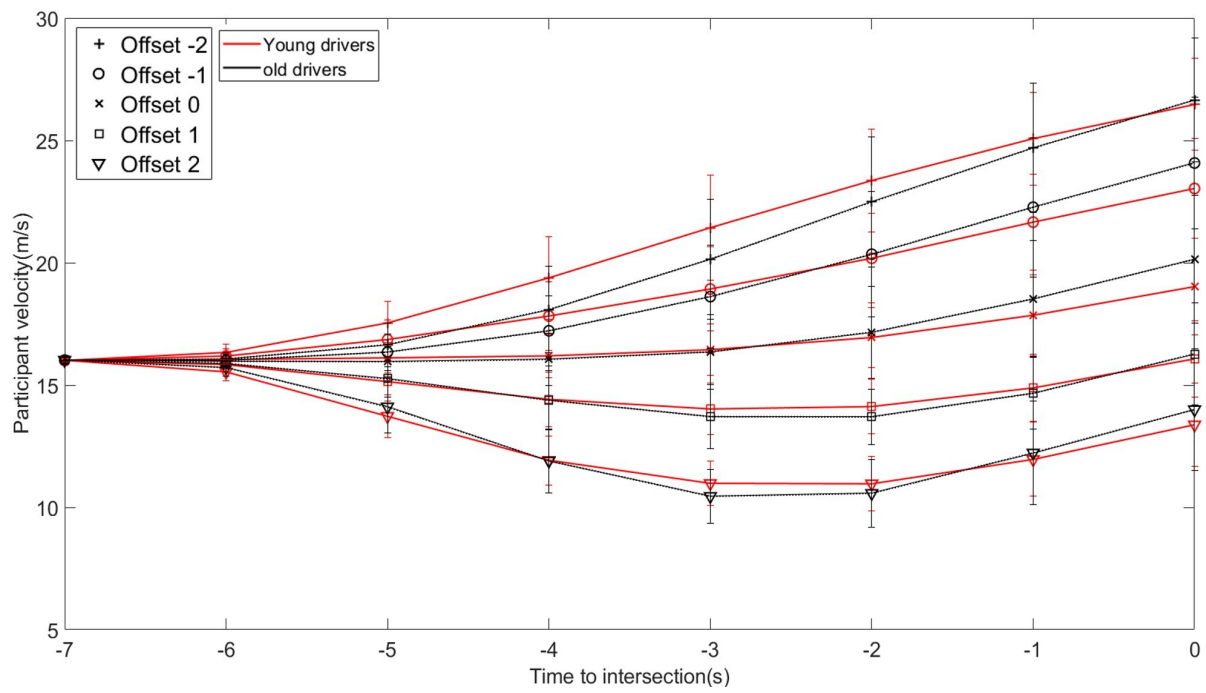
930

931

932

933

Figure 7



934

935

936

937

938

939

940

941

942

943

944

945

946

947

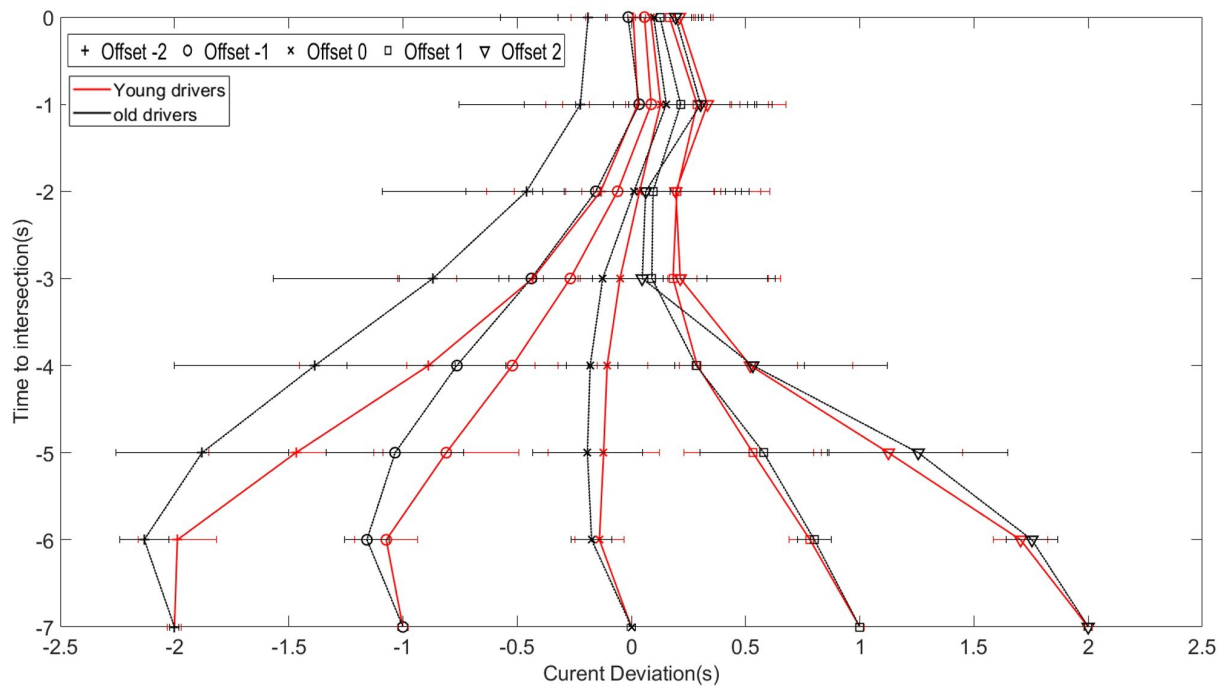
948

949

950

951

Figure 8



952

953

954

955

956

957

958

959

960

961

962

963

964

965

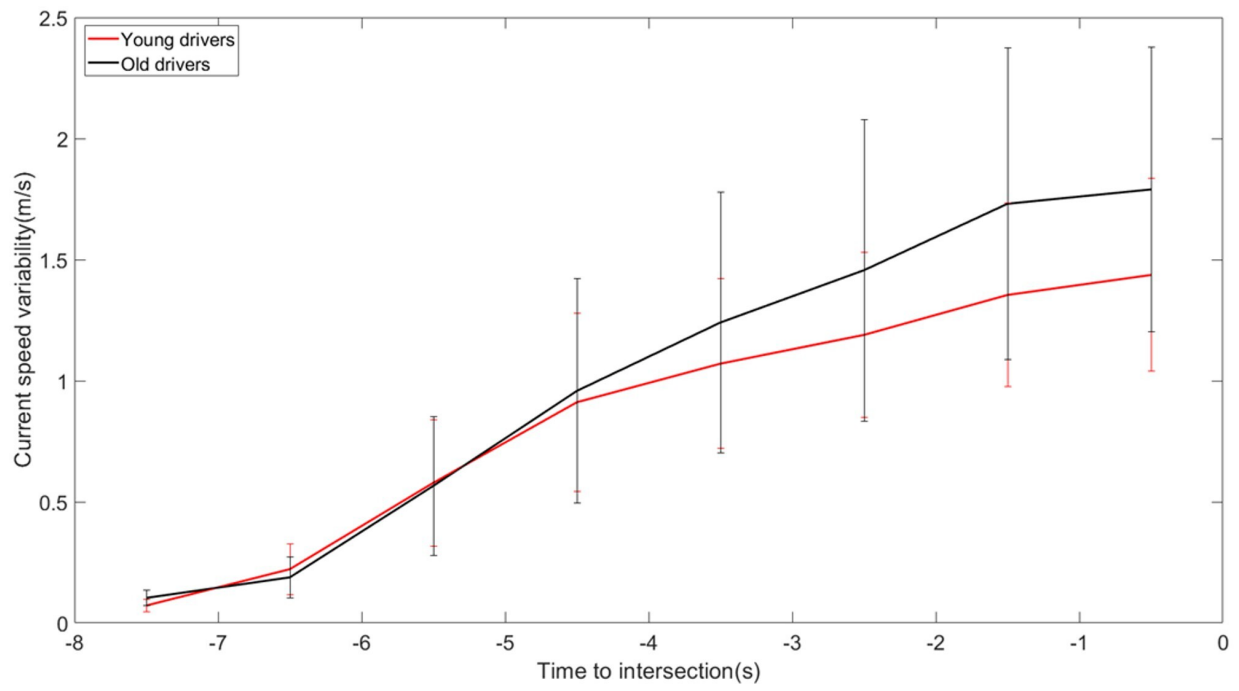
966

967

968

969

Figure 9



970

971

972

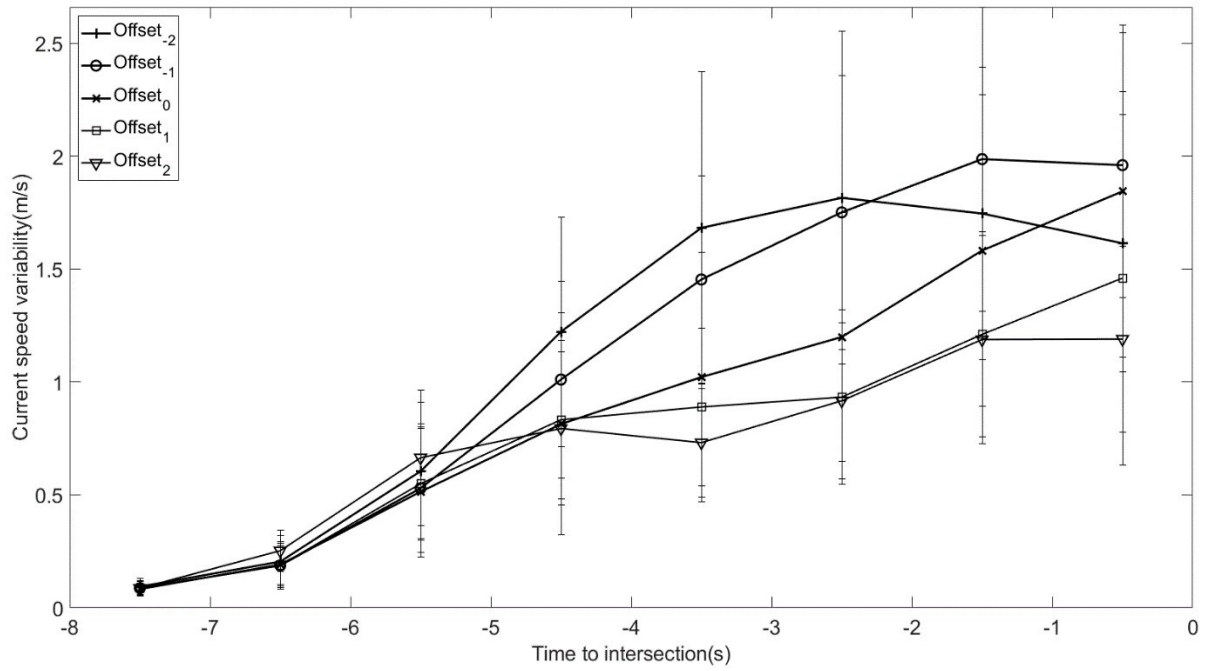
973

974

975

976

Figure 10



977

978

979

980

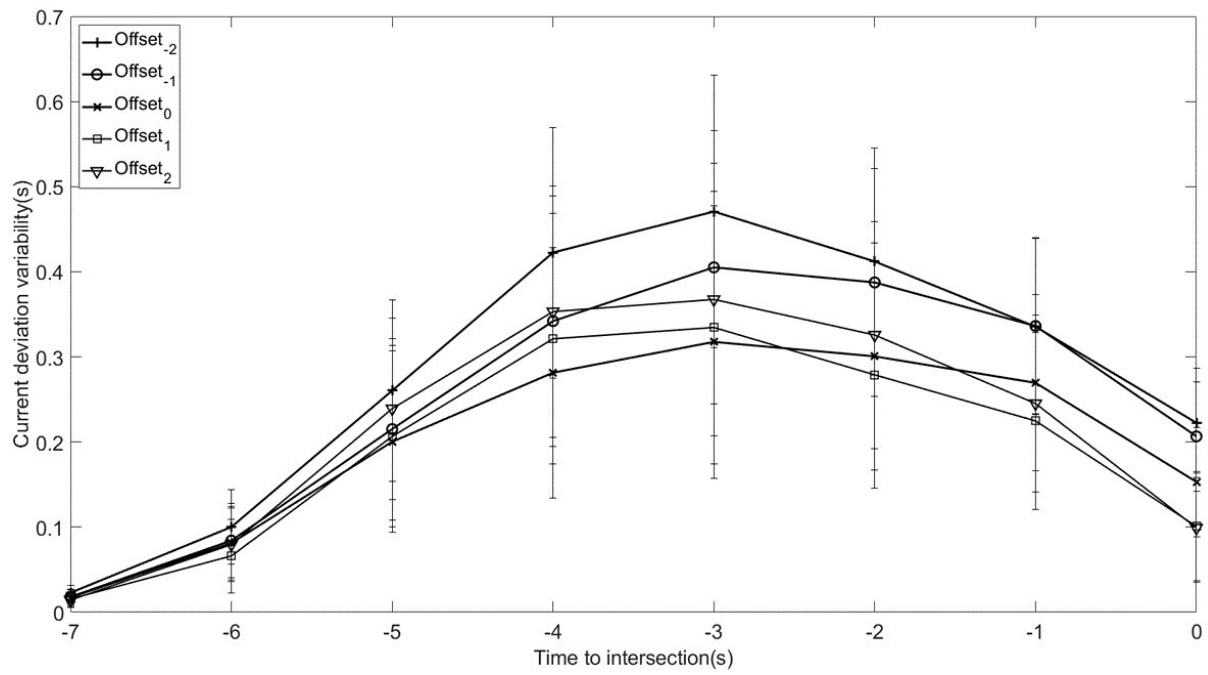
981

982

983

984

Figure 11



985

986

987

988

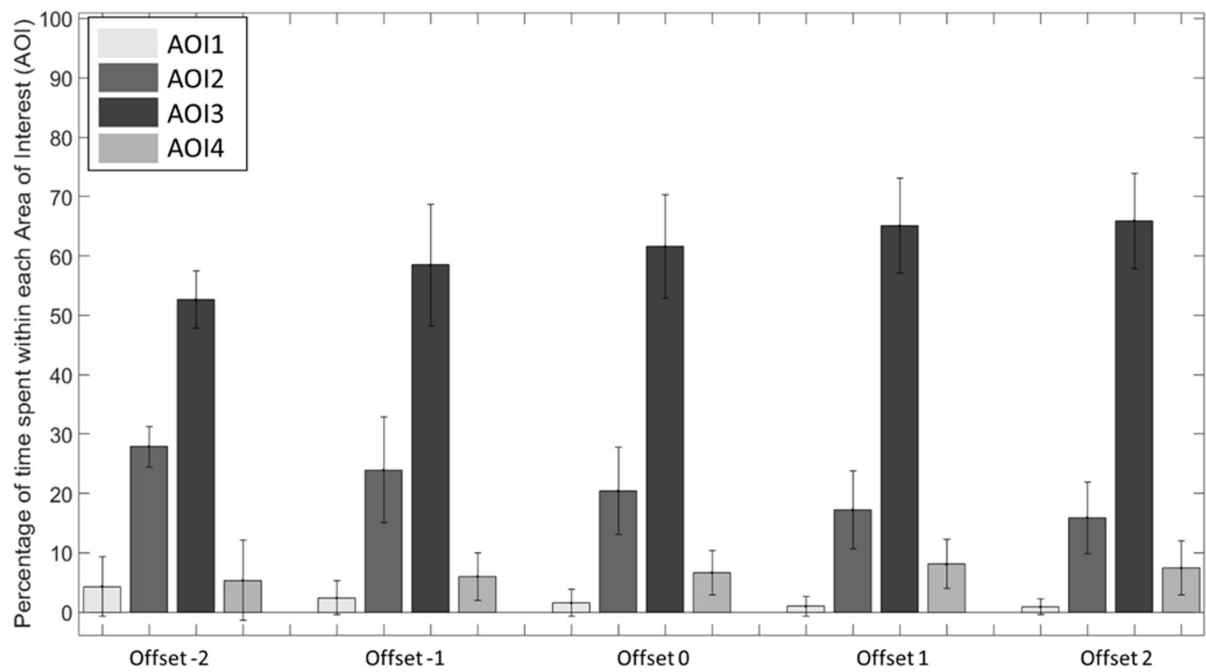
989

990

991

992

Figure 12



993

994

995

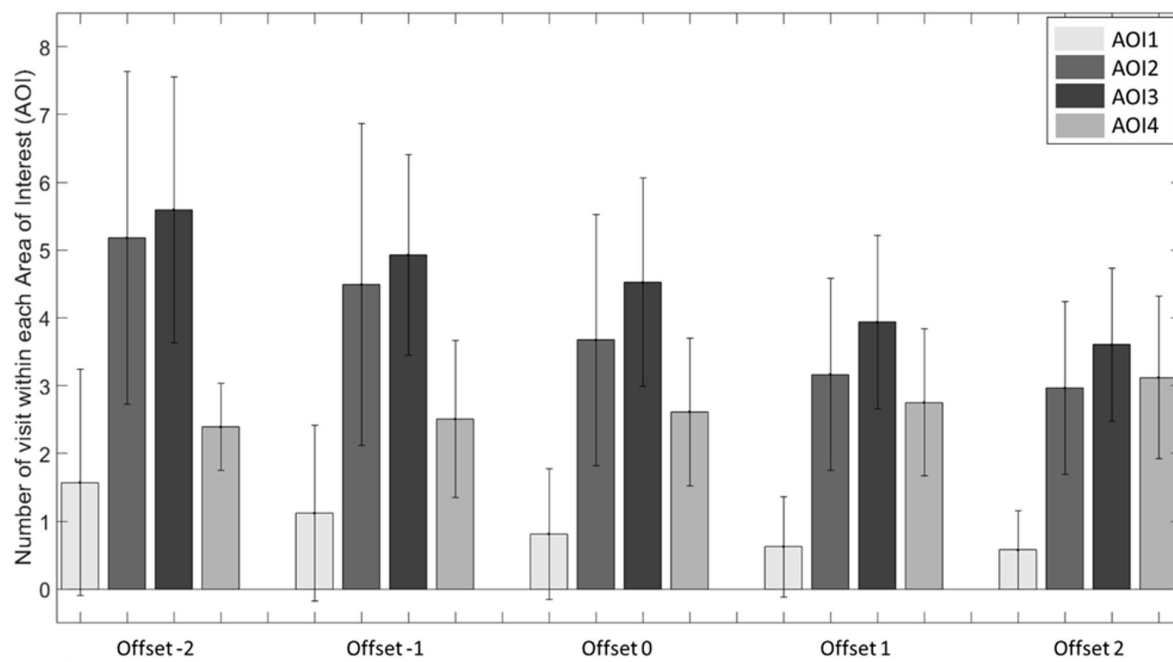
996

997

998

999

Figure 13



1000

1001

1002

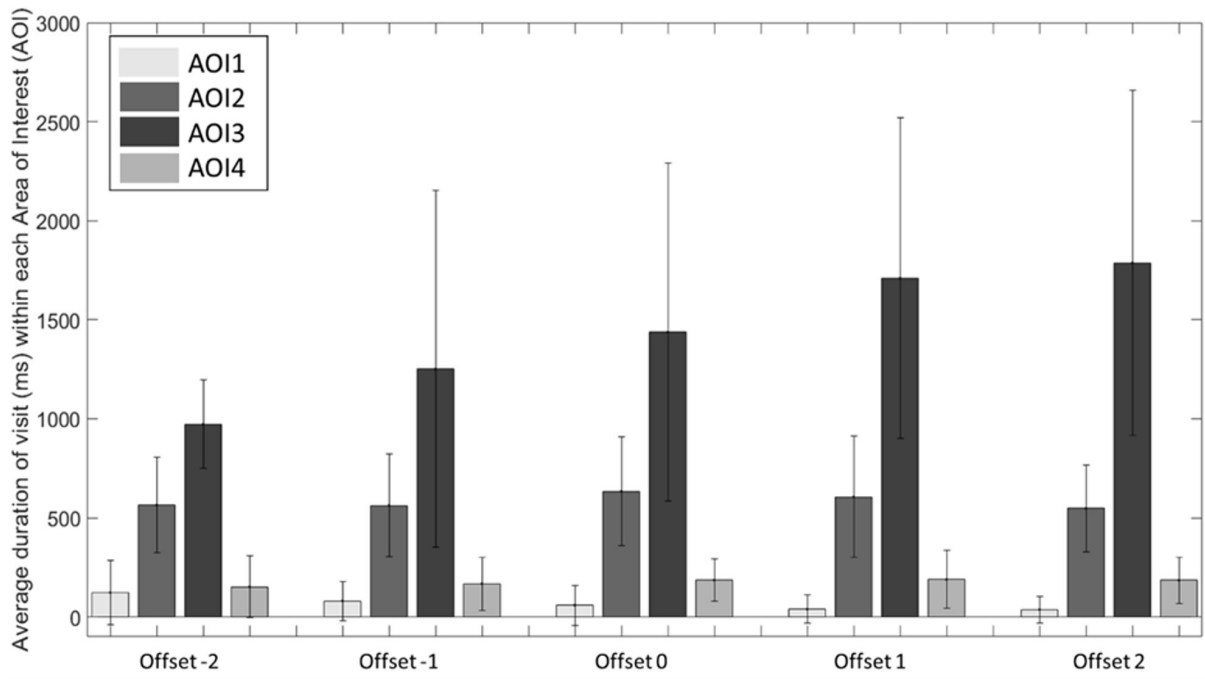
1003

1004

1005

1006

Figure 14



1007

1008

1009

1010

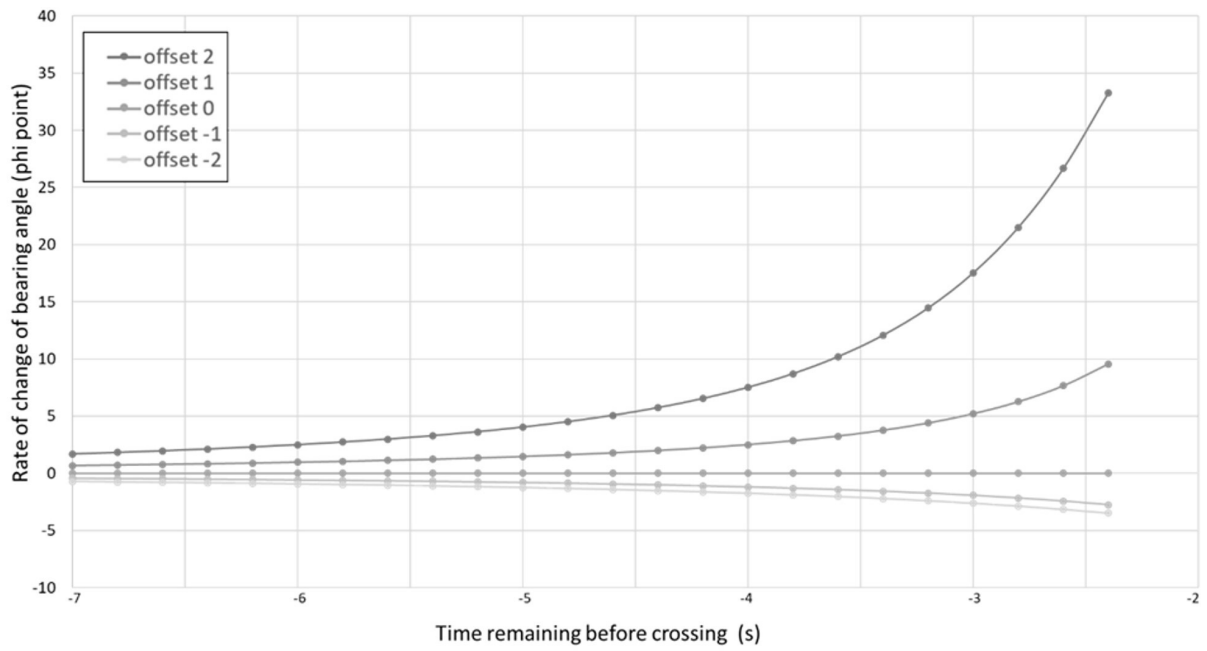
1011

1012

1013

1014

Figure 15



1015

1016

1017

1018

1019

1020

1021