



HAL
open science

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

Lola Tran Van, Catherine Berthelon, Jordan Navarro, Cédric Goulon, Gilles Montagne

► **To cite this version:**

Lola Tran Van, Catherine Berthelon, Jordan Navarro, Cédric Goulon, Gilles Montagne. Perceptual-Motor Regulations and Visual Exploration Strategies Allowing Older Drivers to Intercept a Moving Inter-Vehicular Gap. *Ecological Psychology*, 2022, 34 (4), pp.157-182. 10.1080/10407413.2022.2125393 . hal-04008158v2

HAL Id: hal-04008158

<https://amu.hal.science/hal-04008158v2>

Submitted on 15 Mar 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

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 were manipulated (Offset), without
30 the knowledge of the participants, requiring distinct speed regulations. The analyses focused on
31 displacements kinematics as well as on the associated visual information taking strategies. The
32 results indicate several similarities in the behaviors produced by two populations. Functional
33 speed regulations are initiated early and persist until the interception. These regulations allow
34 for safe interception. The visual strategies deployed by the older participants are also relatively
35 close to those of the younger participants, with the main areas of interest located on the vehicles
36 located upstream of the interval. The results also reveal differences between the two
37 populations. The regulations produced by older drivers are initiated late in negative Offset
38 giving rise to some extent to unsafe behavior. These results are discussed in relation to the
39 decrease in motion detection thresholds with age. Our dataset could be particularly useful in
40 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, right of way...), 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 older people to intercept a moving interval while driving. Even if the experimental task is

66 not identical to 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 The present study is part of a long-term research program which aims at developing a driver
70 assistance system (ADAS) designed to compensate for the reduced (perceptual-motor)
71 capacities of older drivers so that they can drive safely when intercepting a moving interval.
72 The idea is to provide an ADAS that is consistent with their specific needs (Vrkljan & Miller-
73 Polgar, 2005). Indeed, a number of studies have shown if used appropriately, ADAS have the
74 potential to help drivers cope with the complex demands of driving (Vrkljan & Miller-Polgar,
75 2005; Young, 2016). They could reduce the occurrence of accidents by compensating for age-
76 related perceptual, cognitive and physical declines (Caird, 2004; Davidse et al., 2009) and
77 therefore delay the cessation of driving, which is synonymous with loss of independence and
78 sociability (Koppel et al., 2009; Koppel & Charlton, 2013).

79 To date, very few studies have been designed to characterize the regulation behavior produced
80 by older drivers when crossing a moving gap. Otherwise, previous work by our group
81 (Louveton, Bootsma, et al., 2012; Louveton, Montagne et al., 2012; Louveton et al., 2018;
82 Mathieu et al., 2017a, 2017b) provides a good understanding of these regulations when younger
83 drivers are faced with this type of task. In these studies, driving simulators were used,
84 interactively coupling a driving interface to a screen on which the driving environment was
85 projected. Participants moved through a virtual rural environment in which an intersection
86 could appear at specific locations, while a train of vehicles was coming from the left. The
87 participants were asked to cross the intersection safely by targeting a specific inter-vehicular
88 space. The influence of several variables on the regulation behavior of the drivers has been
89 investigated including the size of the inter-vehicle gaps and the geometry of the intersection
90 (Louveton, Bootsma, et al., 2012; Louveton, Montagne et al., 2012), the speed of the vehicles

91 (Louveton, Bootsma, et al., 2012; Louveton, Montagne et al., 2012), the size and type of
92 vehicles that make up the traffic stream (Mathieu et al., 2017a, 2017b). The results showed that
93 these variables systematically affect the changes in driving speed when approaching the
94 intersection. However, whatever the task constraints were, the crossing location remained
95 circumscribed to the area ahead the gap's center. Additionally, driver's speed regulation started
96 in the very early phase of the approach and then uniformed meanwhile. The analyzes carried
97 out also revealed the functional nature of these regulations, that is to say they allow for greater
98 precision throughout the process (Louveton, Bootsma, et al., 2012; Louveton, Montagne et al.,
99 2012). Interestingly equivalent results have been found when crossing an intersection by bicycle
100 (Chihak et al., 2010; Chihak, et al., 2014). The information-movement coupling involved when
101 approaching and crossing an intersection are of the same nature regardless of the interface used
102 (i.e., either bike or car). Now, identifying the information used to control goal-directed
103 displacement while intercepting a moving interval is not easy given the large number of
104 crossing locations compatible with the success of the task. The studies which have aimed to
105 identify optical variables likely to be used in order to control goal-directed displacements
106 mainly focused on ball-interception tasks (e.g., Michaels & Oudejans, 1992; Lenoir et al.,
107 1999a&b). Higher order variables have been identified, e.g., the rate of change in bearing angle
108 (Chardenon et al., 2002) or the optical acceleration (McLeod & Dienes, 1993), allowing
109 participants to intercept moving balls by implementing parsimonious prospective control
110 mechanisms (see Montagne, 2005 for a review) which makes it possible to succeed in the task
111 without the need to predict the place and time of interception (e.g., Peper et al., 1994; Chardenon
112 et al., 2004). The only thing an agent has to do, provided he/she is attuned to the relevant higher
113 order variables, is to cancel continuously any change, say in the bearing angle, by an appropriate
114 displacement, to make sure to intercept the ball (Bastin et al., 2006a). The problem drivers have
115 to solve when intercepting a moving gap is slightly different insofar as the bearing angle can be

116 referred to an almost infinite number of unmaterialized locations within the interval. Another
117 related strategy could consist in modifying (if necessary) displacement speed to ensure that the
118 bearing angle referred to the vehicle opening the gap to be intercepted decreases (Louveton et
119 al., 2012 a&b).

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

134 Studies in other domains have also investigated the effect of aging on perceptual-motor skills
135 underlying goal-directed behavior (e.g., Van Andel et al., 2018). In Van Andel et al. (2018)
136 study, participants were asked to approach and step on a platform that represented a sidewalk.
137 Time at which participants (younger vs., older) started to adjust their steps, the strategy used to
138 regulate the steps, and the strength of perceptual-motor coupling were analyzed. Results
139 reported that adjusting step length performance in the experimental group was not different
140 from the same variable measured in the control group. However, information-movement

141 coupling strength was higher in older participants, meaning that it increases with age. More
142 precisely the step lengths produced in the last steps was strongly related to the step lengths
143 required to perform the task successfully among older participants. This increased coupling
144 strength reflects that older people distribute step lengths modulation over a large number of
145 steps. This is in accordance with literature about age-related decline in action capabilities, and
146 it suggests that a close information-movement coupling nevertheless makes it possible to
147 preserve the adaptive capacities of older people.

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

157 There is no reason to believe that the regulation behavior exhibited by younger drivers should
158 be different in comparison with the one described in previous studies (Louveton, Bootsma, et
159 al., 2012; Louveton, Montagne et al., 2012; Louveton et al., 2018; Mathieu et al., 2017a, 2017b).
160 Based on the study by Van Andel et al. (2018) older people should also implement an
161 information-movement type of control. Now although our task and the one used by Van Andel
162 et al. (2018) have similarities (both involve goal-directed displacements), they also have
163 specificities which are worth considering when trying to make predictions about what the
164 regulation behavior should look like in the older group.

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

176 It is reasonable to anticipate that given the difficulties encountered by older people to detect
177 movement (e.g., Andersen & Enriquez, 2006; Tran et al., 1998; Warren & Yaffe, 1989), older
178 people should produce a specific regulation behavior in comparison with the control group
179 when the perceptual constraints they have to deal with are high. For example, as mentioned
180 previously, we plan in the present experiment to manipulate the starting distances from the
181 intersection (Offset manipulations). It is important to notice that the greater the starting
182 distance, the smaller the optical displacements caused by approaching vehicles. In the case
183 drivers would rely on the rate of change in bearing angle, related for example to the middle of
184 the interval, to adjust displacement speeds, these changes would more or less easily accessible
185 depending on the characteristics of the population. Given the fact that motion detection
186 thresholds are lower in older people, these experimental conditions should give rise to specific
187 behaviors with reference to the control population. We could anticipate for example delayed
188 speed regulations for older people when the starting distance is high (i.e., negative Offsets). In
189 order to identify and compare the type of information used by older and younger people when

190 crossing intersections, an eye-tracking analysis was also performed. Since motion detection is
191 harder for older people, this analysis would allow to understand the strategies they used to
192 compensate and accomplish the task.

193 **Method**

194 *Participants*

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

205 *Apparatus*

206 A fixed base driving simulator was used. The driving simulator couples a high-
207 resolution steering wheel and a set of pedals (*Extreme Competition Control, Minneapolis,*
208 *United States*) to a virtual reality application developed in our laboratory (*software ICE*©)
209 running on PC (*Microsoft Windows 10 Pro, intel Core i99900 processors (8 curs, 3.15.0 Ghz*
210 *Turbo, 16 Mo cache, graphic card NVIDIA Geforce RTX2080 Super*). The virtual environment
211 was projected in a virtual reality headset (*HCT vive*® *Pro Eye*).

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

215 The virtual environment was generated using ICE© software. This custom-made
216 software allows creating virtual reality environments offering both visual and auditory content,
217 as well as programming scenarios, synchronizing the driving interface and the virtual reality
218 headset as well as making the data acquisition (e.g., Marti et al., 2015; Coutton-Jean et al.,
219 2009). The virtual environment was projected through a virtual reality headset (HTC Vive®
220 Pro Eye) which had a screen offering a resolution of 2880x1600 pixels and 615 PPP and an eye
221 tracking system. In our experience, this system made it possible to follow the movement of the
222 eyes at 100 Hz.

223 *Visual Environment*

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

228

229 [Figure 1 near here]

230

231 **Experimental design**

232 Participants had to approach and cross an intersection while targeting a specific inter-vehicle
233 interval. A protocol has been used so that drivers can become accustomed to using of the driving
234 interface before performing the actual experiment. The participants first performed a calibration
235 task which was intended to allow them to calibrate the acceleration and deceleration capabilities

236 of the vehicle being driven. Then they carried out the actual experimental task following a short
237 familiarization phase.

238 *Calibration Phase*

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

246 The calibration phase consisted of 3 sessions of 2 minutes each. In the first minute of each
247 session, the participant was provided with concurrent feedback in the form of a vertical gauge
248 located slightly on the left of the steering wheel (Mathieu et al., 2017b, Figure 2a). This gauge
249 contained a cursor that moved along the gauge and indicated the current inter-vehicular
250 distance. The horizontal rectangular area in the center of the gauge represented the inter-vehicle
251 distance that had to be kept constant. When the cursor was positioned in this rectangular area,
252 the gauge turned green (Figure 2b). When the cursor was in the upper or lower part of the gauge
253 (i.e., the actual distance was greater or less than the prescribed distance), the gauge turned red.
254 In the second minute of each session, the calibration task was performed without concurrent
255 feedback.

256 [Figure 2 near here]

257 When concurrent feedback was no longer available, the percentage of time during which the
258 gauge if it had been visible would have remained positioned in the prescribed zone was
259 calculated. This calculation was only performed during the last 5 seconds of each plateau (i.e.,

260 from 10 to 15 seconds) as the task was too complex during the transition phases (i.e., when the
261 speed of the vehicle to be followed varied). After obtaining a percentage for each speed plateau,
262 an average was calculated to have a single value per session. When a score of 80% was obtained
263 in at least 2 of the 3 calibration sessions, the participant was considered "calibrated". If not, a
264 calibration session was added and the percentage was again calculated from the last 3 sessions
265 performed. Once the participant was calibrated, he/she had 5 minutes to rest before starting the
266 experimental phase.

267 *Experimental Phase (Moving gap interception)*

268 *Task*

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

277 [Figure 3 near here]

278 *Procedure*

279 At the beginning of each trial, the participant was stationary in his/her lane. The environment
280 was composed of a straight dual carriageway in a rural setting. First, the participant had to start,
281 accelerate and follow this route at a stabilized speed of 16 m/s (57.6 km/h). Not numerical
282 information about speed, but the participant was given concurrent feedback about the difference
283 between the current speed and the required speed. The feedback was available as a vertical

284 gauge based on the same principle as the one used in the calibration phase (see Figure 2). When
285 the cursor was in the horizontal rectangle in the center of the gauge (i.e., when the current speed
286 corresponded to the required speed), the gauge was green. Conversely, when the cursor was at
287 the top or bottom, the gauge turned red indicating to the participant that he or she was moving
288 either too fast or too slow. When the speed was stabilized in the target zone for at least 10
289 seconds, the gauge disappeared. The disappearance of the gauge initiated the beginning of the
290 crossing scenario. The intersection and the approaching train of vehicles were displayed. This
291 procedure made it possible to standardize the initial conditions for carrying out the task (i.e.,
292 the initial speed of the participants) for each experimental condition.

293 *Independent variables*

294 Participant's baseline characteristics (see 'Participants' section), and the initial distance of
295 participant's car with respect to the intersection (Offset) varied.

296 *Offset*

297 The initial distance between the participants and the intersection was manipulated according to
298 5 modalities to create an Offset between the participant's arrival time at the intersection (in the
299 case the initial speed was held constant) and the arrival time of the center of the gap to be
300 crossed (see Mathieu et al., 2017b for a similar procedure). Our aim was to manipulate the task
301 constraints to induce distinct regulations. In the "no offset" condition (Offset 0), the initial
302 distance (150 m) was set so that the participant could cross the intersection at the center of the
303 inter-vehicular interval while keeping his/her initial speed (i.e., 16 m/s or 57.6 km/h)
304 unchanged. In the other 4 conditions (Offset +2, +1, -1 and -2, seconds) the distances (118, 134,
305 166 and 182 meters) were set to induce specific regulations. When the participant encountered
306 either a positive or negative offset, he/she was required to decelerate or accelerate in order to
307 safely pass through the intersection. For example, in the Offset-2 condition, if the participant

308 did not change his/her speed, he would pass through the intersection two seconds after the center
309 of the inter-vehicular space had passed the intersection, resulting in a collision with the vehicle
310 located at the end of the gap. Thus, to succeed at the task, a change of speed was mandatory
311 (i.e., speed increase for negative offsets and speed decrease for positive offsets).

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

315 *Dependent variables*

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

320 *Driving Behavior*

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

325 The constant error (CE) was an indicator of a 'bias' when crossing the inter-vehicular interval,
326 given the fact that it takes into account the sign of the error. Taking the center of the inter-
327 vehicular space as the origin, a positive value meant that participants crossed the intersection
328 before the center of the inter-vehicular space (i.e., closer to the gap opening vehicle).
329 Conversely, a negative value meant that participants crossed the intersection after the center of

330 the inter-vehicular space (i.e., closer to the vehicle closing the gap). In our experiment we will
331 call this variable gap crossing position.

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

335 *Displacement speed and displacement speed variability.* In order to examine the nature of speed
336 adjustments made during the approach to the intersection, we first analyzed the time course of
337 speed. All trials were first synchronized using the time of the gap crossing as a common
338 reference (t₀). For each trial the speed profile was then discretized backwards from the time of
339 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, 1-0 s). Once
340 this division done, we calculated for each participant and for each time step an average
341 displacement speed as well as the inter-trial variability of the displacement speed.

342 *Current deviation and current deviation variability.* Our analysis then focused on the current
343 deviation (Louveton, Bootsma, et al., 2012; Louveton, Montagne et al., 2012). Current
344 deviation can be defined for each time step as the moment of crossing of the participant in the
345 inter-vehicular space if the current speed was kept constant. This variable can be calculated at
346 any time and changes as the participants' speed changes, indicating the extent to which the speed
347 changes produced are functional. In the Offset 0 condition, the current deviation is by definition
348 zero at the start of the trial so that maintaining the initial speed constant throughout the trial
349 would allow the participant to cross the intersection at the center of the inter-vehicular space.
350 In the other Offset conditions (i.e., -2, -1, +1 and +2 seconds) the initial current deviation was
351 -2, -1, +1 and +2 seconds respectively at the start of the trial. Only speed changes would allow
352 participants to cross the intersection near the center of the inter-vehicle window. The aim of the
353 analysis was precisely to describe the dynamics of changes in current deviation. We used the

354 same procedure as the one used for the speed profiles for current deviation profiles (i.e., first,
355 trial synchronizations, followed by trial discretizations). We calculated for each participant and
356 for each time step the average current deviation as well as the inter-trial variability of the current
357 deviation.

358 *Ocular Behavior*

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

367

368 [Figure 4 near here]

369 *Statistics*

370 Statistical analyses were performed using repeated measures ANOVA. For the gap crossing
371 position and its variability, Population (Younger, Older) was used as a between subject factor
372 and Offset (-2,-1,0,1,2) as a within subject factor. For the time course of both speed and current
373 deviation and their variabilities, Population (Younger, Older) was used as a between subject
374 factor and Offset (-2,-1,0,1,2) and Time (from 7s from gap interception to interception in
375 intervals of 1s gap crossing, i.e., 7 bins) as within subject factors. Finally, for the average
376 percentage of time, the average number of visits and the average duration of these visits
377 Population (Younger, Older) was used as a between subject factor and Offset (-2,-1,0,1,2) and

378 AOI as within subject factors. In case the results were significant, post-hoc analyses were
379 performed using Holm's test.

380

381 **Results**

382 *Driving Behaviors*

383 *Success Rate*

384 During the experiment, the participants crossed the intersection 800 times. There were no
385 crashes for younger drivers (100% success rate), while there were 11 crashes for older drivers
386 (98.6% success rate). These trials were excluded from further analyses.

387

388 *Gap crossing position*

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

392 Post-hoc comparisons on the Offset*Population interaction did not reveal any significant
393 differences. Participants regardless of their age, crossed the intersection slightly before the
394 center of the inter-vehicular space (i.e., closer to the lead vehicle) in most Offset conditions
395 (Figure 5). However, older people tended to cross the interval later in the offset -2 condition in
396 comparison with younger participants. A posteriori comparisons performed on Offset revealed
397 that gap crossing position differed for each Offset condition (all $p < 0.05$) except between Offset
398 0 and -1 ($p > 0.05$).

399

[Figure 5 near here]

400

401 *Gap crossing position variability*

402 The analysis of variance performed on the gap crossing position variability revealed a
403 significant main effect of Offset ($F(4, 152) = 9.896, p < 0.001, \eta^2 = 0.140$). The main effect of
404 Population failed to reach significance ($F(1, 38) = 3.846, p < 0.057, \eta^2 = 0.029$). Older drivers
405 tend to be more variable than younger drivers (Offset -2: 0.28 s older vs., 0.26 s younger; Offset
406 -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
407 older vs., 0.17 s younger; Offset 2: 0.21 s older vs., 0.17 s younger).

408

409 Post-hoc comparisons on Offset revealed higher gap crossing position variability in Offset -1
410 (0.28 s) and Offset-2 (0.27 s) in comparison with Offset +1 (0.19 s) and Offset +2 (0.12 s) (all
411 $p < 0.001$) (figure 6).

412

413 [Figure 6 near here]

414

415 *Speed Profiles*

416 The analysis of variance on speed revealed a significant main effect of Offset ($F(4, 2667.639)$
417 $= 1630.063, p < 0.001, \eta^2 = 0.884$) and Time ($F(7, 417.501) = 283.786, p < 0.001, \eta^2 = 0.141$).
418 The first-order interactions Offset*Population ($F(4, 7.684) = 4.536, p < 0.002, \eta^2 = 0.002$) and
419 Offset*Time ($F(28, 198.880) = 537.255, p < 0.001, \eta^2 = 0.268$) are significant.

420 A posteriori comparisons carried out on the Offset*Time interaction indicate that from 5
421 seconds before the crossing, the evolution of the speed differs according to the offset condition.

422 The most representative example is the comparison between Offset -2 and Offset 2. For Offset
423 2, there is a decrease in speed between 5 and 2 seconds before the crossing from 14 m/s to 11
424 m/s followed by an increase in speed from 2 seconds until the crossing from 11 m/s to 14 m/s.

425 While for the -2 Offset condition, there is an increase in speed from 5 seconds before the
426 crossing until the moment of crossing from 16 m/s to 25 m/s (figure 7). A posteriori comparison
427 carried out on the Offset*Population interaction indicate that the displacement speed produced
428 by younger and older people are not significantly different except in the Offset -2 condition. In
429 Offset -2 older people vehicle speed (20.09 m/s) was lower than the younger drivers (20.64
430 m/s)($p < 0.05$)(figure 7).

431 [Figure 7 near here]

432 *Current Deviation Profiles*

433 The analysis of variance on the current deviation reveals significant main effects of Offset (F
434 (4,152) = 846.092, $p < 0.001$, $\eta^2 = 0.536$) and Population (F (1,38) = 4.532, $p < 0.040$ $\eta^2 = 0.003$).
435 The first-order interactions Offset*Population (F (4,152) = 5.255, $p < 0.001$, $\eta^2 = 0.003$) and
436 Offset*Time (F (28,266) = 813.681, $p < 0.001$, $\eta^2 = 0.354$) are significant. The second-order
437 interaction Offset*Population*Time (F (28,266) = 3.847, $p < 0.001$, $\eta^2 = 0.002$) is also
438 significant.

439 Post-hoc comparisons performed on the Offset*Population*Time interaction reveal a
440 significant difference between younger and older people in the Offset -2 condition from 5 s to
441 2 s before crossing the intersection. Indeed, the current deviation is lower for older than for
442 younger drivers (5s before crossing: -1.87 s older vs., -1.46 s younger; 4s: -1.38 s older vs., -
443 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
444 can see a much more gradual convergence of the current deviation towards the inter-vehicle
445 gap crossing location for older drivers.

446 [Figure 8 near here]

447 *Speed Variability*

448 The analysis of variance on the inter-trial speed variability revealed significant main effects of
449 the factors Offset ($F(4,152) = 23.930, p < 0.001, \eta^2 = 0.051$), Population ($F(1,38) = 6.336,$
450 $p < 0.016, \eta^2 = 0.010$) and Time ($F(7,266) = 392.113, p < 0.001, \eta^2 = 0.545$). The first-order
451 interactions Time*Population ($F(7,266) = 7.790, p < 0.001, \eta^2 = 0.011$) and Offset*Time (F
452 $(28,266) = 17.598, p < 0.001, \eta^2 = 0.057$) were also significant.

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

459 [Figure 9 and 10 near here]

460 *Current Deviation Variability*

461 The analysis of variance of the current deviation variability revealed significant main effects of
462 Offset ($F(4, 152) = 12.169, p < 0.001, \eta^2 = 0.036$) and Time ($F(7, 266) = 251.133, p < 0.001,$
463 $\eta^2 = 0.525$) conditions. The analysis also revealed that the first-order interaction Offset*Time
464 ($F(28, 266) = 5.802, p < 0.001, \eta^2 = 0.020$) was significant.

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

467 [Figure 11 near here]

468 *Ocular Behavior*

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

470 Taking into account the percentage of time spent in the 4 AOIs allowed us to account for
471 approximately 90% of the overall ocular behavior of the participants. An analysis of variance
472 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.

475 Post hoc comparisons performed on the Offset*AOI interaction revealed that participants spent
476 more time fixating AOI2 in Offset-2, Offset-1 and Offset0 conditions in comparison with Offset
477 +1 and Offset +2 ($p < .05$) (figure 13). The reverse was true for AOI3 ($p < .05$) (figure 12).

478 [Figure 12 near here]

479 *Number of Fixations in Each Area of Interest*

480 An analysis of variance on the number of fixations revealed significant main effects of Offset
481 ($F(4, 152) = 38.521, p < 0.001, \eta^2 = 0.046$) 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).

484 Post-hoc comparisons performed on the Offset*AOI interaction revealed that Offset conditions
485 0, +1 and +2 gave rise to less fixations of AOI1 than the other two Offset conditions (i.e., Offset-
486 1 and Offset-2). They also revealed that the number of visits to AOI2 and AOI3 is influenced
487 by the Offset. Offset-2 was the condition with the most visits for AOI2 and AOI3 (figure 13).

488 [Figure 13 near here]

489 *Mean Fixation Durations of Each Area of Interest*

490 An analysis of variance on the mean fixation duration revealed significant main effects of Offset
491 ($F(4, 152) = 19.612, p < 0.001, \eta^2 = 0.012$) 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.

494 Post-hoc comparisons performed on the Offset*AOI interaction revealed that the number of
495 AOI3 visits is influenced by the Offset conditions. The average duration of an AOI3 visit
496 decreases as the initial distance from the intersection increases (from Offset 2 to Offset -2).
497 Offset 2 is the condition where the average AOI3 visit duration is the longest; conversely Offset
498 -2 condition gives rise to the shortest average visit durations (figure 14).

499 [Figure 14 near here]

500

501 **Discussion**

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

509

510 *Analysis of the Regulations Produced*

511 As a reminder, in this experiment, the initial distance between the participants and the
512 intersection was manipulated to induce distinct speed regulations (+2, +1, 0, -1 and -2 s). When
513 the participant encountered a positive or negative offset, he/she had to decelerate or accelerate
514 appropriately in order to cross the intersection at the center of the inter-vehicular space,
515 otherwise he/she would cross the intersection 1 or 2 seconds before the center of the interval
516 (Offset+1 and Offset+2) or 1 or 2 seconds after (Offset-1 and Offset-2)

517 *Control Population*

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

535 These results obtained in this study are consistent with those reported in previous work
536 (Louveton, Bootsma, et al., 2012; Louveton, Montagne et al., 2012; Louveton et al., 2018;
537 Mathieu et al., 2017a, 2017b) but also with those described in other tasks requiring the
538 production of goal-directed movements (e.g., Bardy & Laurent, 1998; Camachon et al., 2004;
539 Chardenon et al., 2002; Lee et al., 1982). These results confirm the presence of a control based
540 on a close information-movement coupling. This coupling is flexible because it allows to have
541 regulations adapted to task constraints in all conditions. In addition to showing consistent results

542 with previous studies, our study also extends these observations to the two extreme Offset
543 conditions (-2 and 2 seconds) that were added with the objective of inducing more important
544 regulations.

545

546 *Older drivers*

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

564 Our study also reveals specificities in the regulation patterns produced by the older drivers that
565 deserve to be highlighted and analyzed. Thus, in certain Offset conditions the regulation
566 behavior of the older drivers differs from that produced by the control population. It's the case

567 in the negative Offset conditions, i.e., Offset -2 and to a lesser extent Offset -1. As an example,
568 in the Offset -2 condition, the speed adjustments made by the older drivers are initiated later
569 than in the control population. Once initiated, the speed adjustments do result in a reduction of
570 the current deviation, but the older drivers cross the intersection in the second half of the interval
571 without benefiting from the usual safety margin that results from crossing the interval in its first
572 half. Although the effects are less pronounced in the -1 Offset condition, older drivers also
573 appear to have difficulty initiating regulation early in this condition.

574 The late initiation of regulations in this type of task is problematic because not only will these
575 regulations be necessarily less gradual in reference to regulations initiated early, but they give
576 rise to less safe behavior when crossing the interval. Given the road safety issues associated
577 with this behavior, it seemed appropriate to try to understand the origin of this type of behavior.
578 This led us to analyze the perceptual constraints induced by the different Offset conditions. One
579 higher order variable the driver can use to regulate his/her speed of travel when approaching
580 the intersection is the rate of change of the bearing angle (Lenoir et al., 1999; Chardenon et al.,
581 2002; Louveton, Bootsma, et al., 2012; Louveton, Montagne et al., 2012). The bearing angle is
582 the angle subtended between, for example, the direction of travel and the position of the center
583 of the inter-vehicle interval. If the driver wants to cross the intersection at the center of the
584 interval, he/she just need to keep the bearing angle constant. If the angle increases or decreases,
585 the driver has to decelerate or accelerate respectively to cross the gap at the right place at the
586 right time (cf., Bastin et al., 2006b; Morice et al., 2010). As a reminder, in our experiment, the
587 initial speed of the participants was always the same and the 5 Offset conditions were obtained
588 by manipulating the initial distance between the driver and the intersection at the moment the
589 intersection appeared. Simulations were carried out to determine how the bearing angle varies
590 in the positive and negative Offset conditions when the travel speed is held constant (Figure
591 16). These simulations indicate that the greater the distance between the driver and the

592 intersection, the smaller the bearing angle changes. It is worthnoting that the bearing angle
593 changes are the weakest in the Offset -2 condition. Studies have shown that the thresholds for
594 detecting movement are lower for older people than for younger people (Andersen & Enriquez,
595 2006; Tran et al., 1998; Warren et al., 1989; François et al., 2011). It would seem therefore, that
596 the specific regulation behavior exhibited by the older drivers in our study with negative Offset
597 conditions may be related to the difficulties encountered by the older drivers in detecting
598 changes in bearing angle that inform them of the need to produce appropriate speed changes.
599 Bearing angle changes would become available later on during the approach and would allow
600 the production of functional regulations, although it would not be possible to fully compensate
601 the delay in the initiation of regulation.

602

603 [Figure 16 near here]

604

605 *Analysis of Visual Information Pick-Up Strategies*

606

607 In this experiment, an analysis of visual prospecting patterns was carried out in an attempt to
608 identify the strategies implemented during intersection crossing. This type of analysis has never
609 been performed in previous studies focusing on the control of intersection approach and
610 crossing (Chihak et al., 2010; Chihak et al., 2014; Louveton, Bootsma, et al., 2012; Louveton,
611 Montagne et al., 2012; Louveton et al., 2018; Mathieu et al., 2017a, 2017b ; Plumert & Kearney,
612 2014) and could be particularly useful when designing driver assistance systems that could
613 come to the aid of drivers attempting to cross an intersection. As a reminder, four areas of
614 interest (AOI) were defined in our analysis corresponding to the vehicle train located behind
615 (AOI1) or in front (AOI3) of the inter-vehicular interval, the inter-vehicular interval (AOI2)
616 and the junction of the two roads (AOI4).

617

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

630

631 Our analysis also revealed differences in the information detection strategies implemented
632 according to the Offset conditions. For negative offset conditions, the vehicle train before the
633 inter-vehicle interval (AOI3) remains the information detection zone targeted by drivers, but
634 the inter-vehicle interval (AOI2) is also favored. As a reminder, our results have shown that the
635 location of the interval crossing differs according to the offset conditions. The crossing location
636 is closer to the center of the interval for negative offsets. In this context, it is relatively logical
637 that drivers also prioritize the inter-vehicular area (AOI2) in their search for information. This
638 double prioritization (AOI2 and AOI3) mechanically translates into a reduction in the time
639 spent scanning these two zones. These results illustrate the extent to which the constraints of
640 the task (in this case the imposed Offset) have an impact on the information detection strategies
641 implemented by the drivers. It should be noted that the lack of difference between younger and

642 older drivers indicates that older drivers continue to look at areas of interest relevant to
643 regulation.

644

645 **Conclusion**

646 Our ambition was to characterize as precisely as possible the product regulation behavior and
647 the information taking strategies of our population. Our results reveal similarities in the
648 behavior of older people in comparison with that of younger drivers. The regulations produced
649 are based on a close coupling between information and movement, giving rise to functional
650 speed adjustments throughout the approach. They also reveal specific difficulties linked to the
651 perceptual constraints induced by particular situations (i.e., negative Offsets). The analysis of
652 the eye-tracking data also enabled the identification of areas containing information relevant to
653 travel controls and the impact of task constraints on the nature of the favor areas. This dataset
654 will be particularly useful in future work on the design of driver assistance systems (ADAS)
655 for older drivers. As an example, the difficulties encountered by the older participants for
656 negative Offsets could be solved by providing older drivers concurrent feedback representing
657 at any time their current deviation relative to the inter-vehicular gap to be intercepted, allowing
658 them not only to identify very early the regulations to be produced but also to guide them until
659 crossing. This perceptual aid would be intended to be used if the driver deems it necessary but
660 does not have the function of prescribing driving behavior. We plan to test in the future these
661 assistance systems in the case concurrent feedbacks are located either on the dashboard of the
662 vehicle or integrated into the traffic flow.

663

664

665

666 **References**

667 Andersen, G. J., & Enriquez, A. (2006). Aging and the detection of observer and moving object
668 collisions. *Psychology and aging*, (21)1,74-85. [https://doi.org/10.1037/0882-](https://doi.org/10.1037/0882-7974.21.1.74)
669 7974.21.1.74

670 Ball, K., Owsley, C., Stalvey, B., Roenker, D.L., Sloane, M.E., & Graves, M. (1998). Driving
671 avoidance and functional impairment in older drivers. *Accident Analysis & Prevention*,
672 30, 313–322. [https://doi.org/10.1016/s0001-4575\(97\)00102-4](https://doi.org/10.1016/s0001-4575(97)00102-4)

673 Bardy, B. G., & Laurent, M. (1998). How is body orientation controlled during somersaulting?
674 *Journal of Experimental Psychology: Human Perception and Performance*, 24, 963–977.
675 <https://doi.org/10.1037//0096-1523.24.3.963>

676 Bastin, J., Calvin, S., & Montagne, G. (2006a). Muscular proprioception contributes to the
677 control of interceptive actions. *Journal of experimental psychology: human perception*
678 *and performance*, 32(4), 964-972. <https://doi.org/10.1037/0096-1523.32.4.964>

679 Bastin, J., Craig, C., & Montagne, G. (2006). Prospective strategies underlie the control of
680 interceptive action. *Human Movement Science*, 25, 718-732.

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

683 Case, H. W., Hulbert, S. & Beers, J. (1970). Driving abilities as affected by age. Final report
684 70-18. Institute of Transportation and Traffic Engineering, University of California, Los
685 Angeles.

686 Bootsma, R. J. (1998). Ecological movement principles and how much information matters. In
687 A. A. Post, J. R. Pijpers, P Bosch, & M. S. J. Boschker (Eds.), *Models in human movement*
688 *science* (pp 51– 63). Enschede, The Netherlands: PrintPartners Ipskamp.

689 Bootsma, R. J., & Van Wieringen, P. C. W. (1990). Timing an attacking forehand drive in table
690 tennis. *Journal of Experimental Psychology: Human Perception and Performance*, 16,
691 21–29. <https://doi.org/10.1037/0096-1523.16.1.21>

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

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

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

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

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

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

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

- 712 Coutton-Jean, C., Mestre, D. R., Goulon, C., & Bootsma, R. J. (2009). The role of edge lines
713 in curve driving. *Transportation Research Part F: Traffic Psychology and Behavior*,
714 12, 483–493. <https://doi.org/10.1016/j.trf.2009.04.006>
- 715 Davidse, R. J., Hagenzieker, M. P., van Wolffelaar, P. C., & Brouwer, W. H. (2009). Effects of
716 in-car support on mental workload and driving performance of older drivers. *Human*
717 *Factors*, 51, 463–476. <https://doi.org/10.1177/0018720809344977>
- 718 Davis, G. A., & Swenson, T. (2004). Field Study of Gap Acceptance by Left-Turning Drivers.
719 *Transportation Research Record*, 1899(1), 71–75. <https://doi.org/10.3141/1899-09>
- 720 Douissembekov, E., Michael, G.A., Rogé, J., Bonhoure, P., Gabaude, C., & Navarro, J. (2015).
721 Effects of shrinkage of the visual field through ageing on parking performance: a
722 parametric manipulation of salience and relevance of contextual components.
723 *Ergonomics*, 58(5), 698-711. <https://doi.org/10.1080/00140139.2014.987699>
- 724 Douissembekov, E., Navarro, J., Michael, G. A., Bonhoure, P., Gabaude, C., & Rogé, J. (2015).
725 Parking Manoeuvres Differ among Drivers with Narrower and Wider Field of View in
726 the Presence of a Spatial Reference. *Applied Cognitive Psychology*, 29(2), 309–313.
727 <https://doi.org/10.1002/acp.3110>
- 728 François, M., Morice, A. H. P., Blouin, J., & Montagne, G. (2011). Age-related decline in
729 sensory processing for locomotion and interception. *Neuroscience*, 172, 366–378.
730 <https://doi.org/10.1016/j.neuroscience.2010.09.020>
- 731 Gibson, J. J. (1979). The theory of affordances. The ecological approach to visual perception.
732 In *The People, Place and, Space Reader* (pp. 56-60). Routledge New York and London.

- 733 Koppel, S. N., & Charlton, J. L. (2013). Behavioural adaptation and older drivers. In C. M.
734 Rudin-Brown & S. L. Jamson (Eds.), *Behavioral Adaptation and Road Safety: Theory,*
735 *Evidence and Action* (pp. 303-322). CRC Press.
- 736 Koppel, S. N., Charlton, J.L., & Fildes, B. (2009). Distraction and the older driver. In Regan,
737 M. A. Regan, J. D. Lee, & K. L. Young (Eds.), *Driver Distraction: Theory, Effects and*
738 *Mitigation* (pp. 353–382). CRC Press.
- 739 Lappi, O., Lehtonen, E., Pekkanen, J., & Itkonen, T. (2013). Beyond the tangent point: gaze
740 targets in naturalistic driving. *Journal of vision*, 13(13),11,1-18.
741 <https://doi.org/10.1167/13.13.11>
- 742 Lee, D. N., Lishman, J. R., & Thomson, J. A. (1982). Regulation of gait in long jumping.
743 *Journal of Experimental Psychology: Human Perception and Performance*, 8, 448–458.
744 <https://doi.org/10.1037/0096-1523.8.3.448>
- 745 Lenoir, M., Savelsbergh, G. J., Musch, E., Thiery, E., Uyttenhove, J., & Janssens, M. (1999a).
746 Intercepting moving objects during self-motion: effects of environmental changes.
747 *Research Quarterly for Exercise and Sport*, 70, 349–360.
748 <https://doi.org/10.1080/02701367.1999.10608055>
- 749 Lenoir, M., Musch, E., Janssens, M., Thiery, E., Uyttenhove, J. (1999b). Intercepting moving
750 objects during self-motion. *Journal of Motor Behavior*, 31, 55–67.
- 751 Louveton, N., Bootsma, R. J., Guerrin, P., Berthelon, C., & Montagne, G. (2012). Intersection
752 crossing considered as intercepting a moving traffic gap: Effects of task and
753 environmental constraints. *Acta Psychologica*, 141, 287–294. [https://doi.org](https://doi.org/10.1016/j.actpsy.2012.08.003)
754 [/10.1016/j.actpsy.2012.08.003](https://doi.org/10.1016/j.actpsy.2012.08.003)

755 Louveton, N., Montagne, G., Berthelon, C., & Bootsma, R. J. (2012). Intercepting a moving
756 traffic gap while avoiding collision with lead and trail vehicles: Gap-related and
757 boundary-related influences on drivers' speed regulations during approach to an
758 intersection. *Human Movement Science*, 31, 1500–1516. <https://doi.org/10.1016/j.humov.2012.07.010>
759

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

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

768 Mathieu, J., Bootsma, R. J., Berthelon, C., & Montagne, G. (2017b). Information-movement
769 coupling in the control of driver approach to an intersection. *Ecological psychology*,
770 29,317-341. <https://doi.org/10.1080/10407413.2017.1369853>

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

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

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

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

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

784 Montagne, G. (2005). Prospective control in sport. *International Journal of Sport Psychology*,
785 36, 127-150.

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

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

793 ONISR (2020). La sécurité routière en France : bilan de l’année. Rapport technique, ONISR.
794 Paris, France.

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

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

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

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

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

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

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

815 Warren, W. H. (2006). The dynamics of perception and action. *Psychological Review*, 113,
816 358–389. <https://doi.org/10.1037/0033-295X.113.2.358>

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

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

824

825

826

Figure captions

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

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

832 Figure 3: Illustration of the virtual environment during the tasks completion

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

836 Figure 5: Average gap crossing position (constant error) as a function of the Offset. The vertical
837 dotted black line shows the space available to cross the intersection. Error bars represents
838 Standard Deviation (SD).

839 Figure 6: Gap crossing position variability as a function of Offset. Error bars represents
840 Standard Deviation (SD).

841 Figure 7: Time course of the participants' average speed in the different Offset conditions for
842 the two populations (Younger and Older drivers). Error bars represents Standard Deviation
843 (SD).

844 Figure 8: Time course of the current deviation for each Offset condition (from Offset -2 to
845 Offset 2) and for each population (Younger in red and Older in black). Error bars represents
846 Standard Deviation (SD).

847 Figure 9: Average intra-participant speed variability as a function of time to intersection for
848 each population (Younger drivers in red and Older drivers in black). Error bars represents
849 Standard Deviation (SD).

850 Figure 10: Average intra-participant speed variability as a function of time to intersection and
851 Offset (from Offset -2 to Offset 2)). Error bars represents Standard Deviation (SD).

852 Figure 11: Average variability of intra-participant current deviation as a function of time to
853 intersection and offset. Error bars represents Standard Deviation (SD).

854 Figure 12: Percentage of time spent in each Area of Interest (AOI) for each Offset (from Offset
855 -2 to Offset 2). Error bars represents Standard Deviation (SD).

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

857 Figure 14: Average duration of a visit in each area of interest (AOI) according to the different
858 Offset conditions. Error bars represents Standard Deviation (SD).

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

861

862

863

864

865

Figure 1



866

867

868

869

870

871

872

873

874

875

876

877

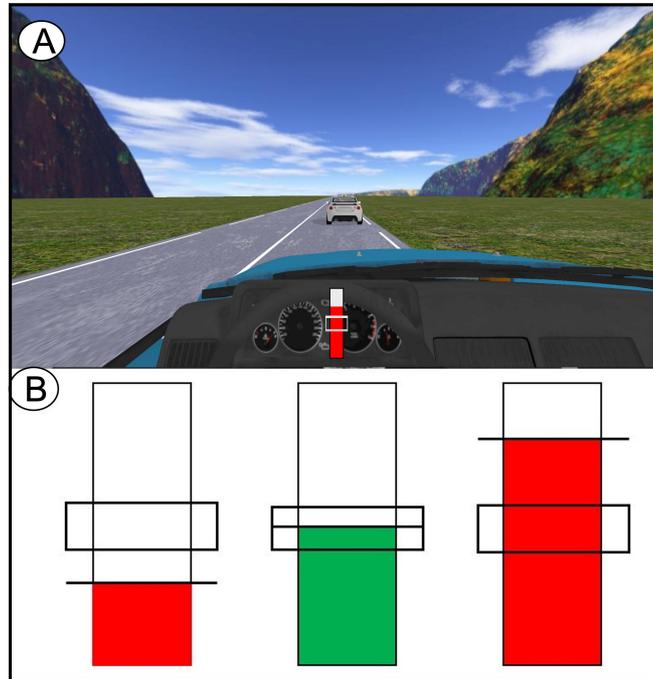
878

879

880

881

Figure 2



882

883

884

885

886

887

888

889

890

891

Figure 3



892

893

894

895

896

897

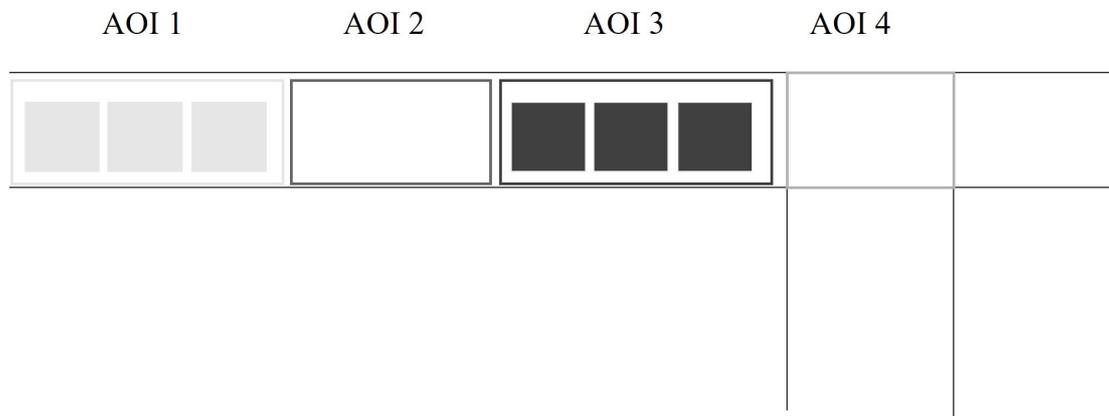
898

899

900

901

Figure 4



902

903

904

905

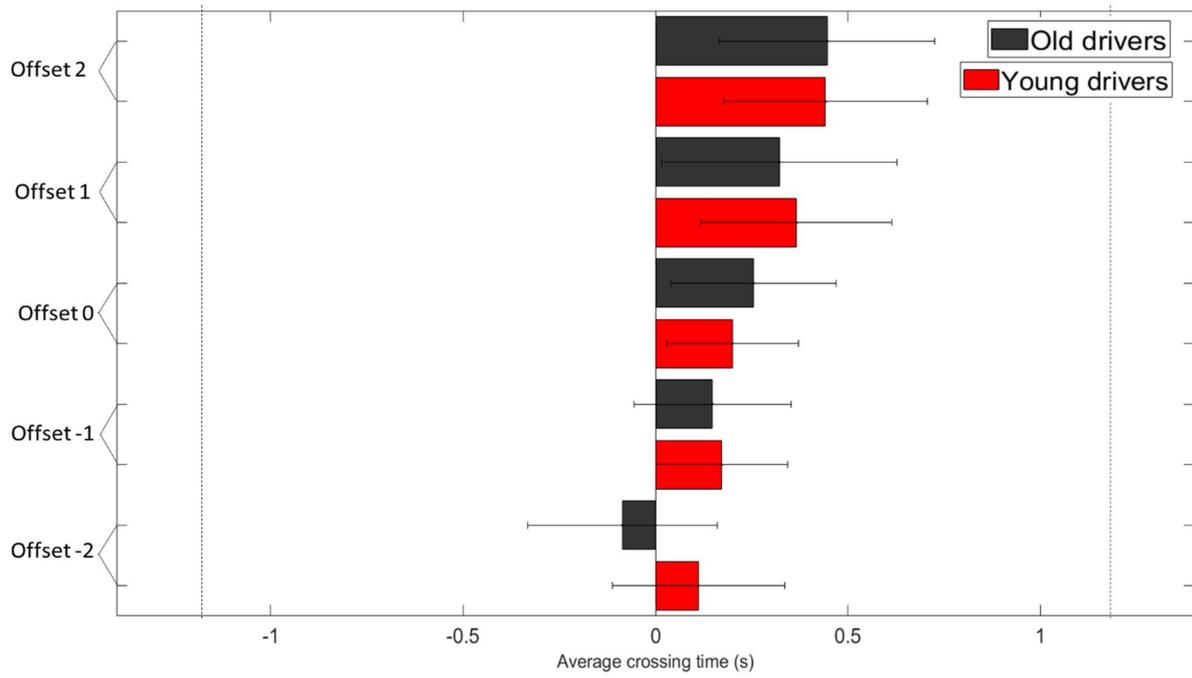
906

907

908

909

Figure 5



910

911

912

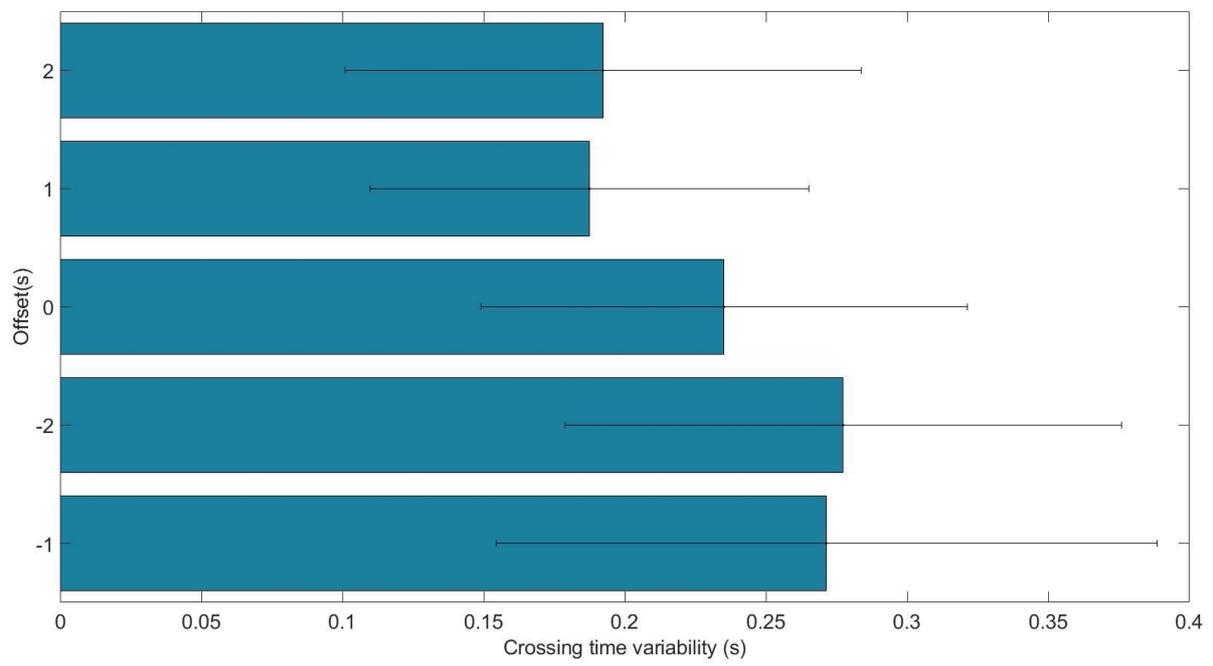
913

914

915

916

Figure 6



917

918

919

920

921

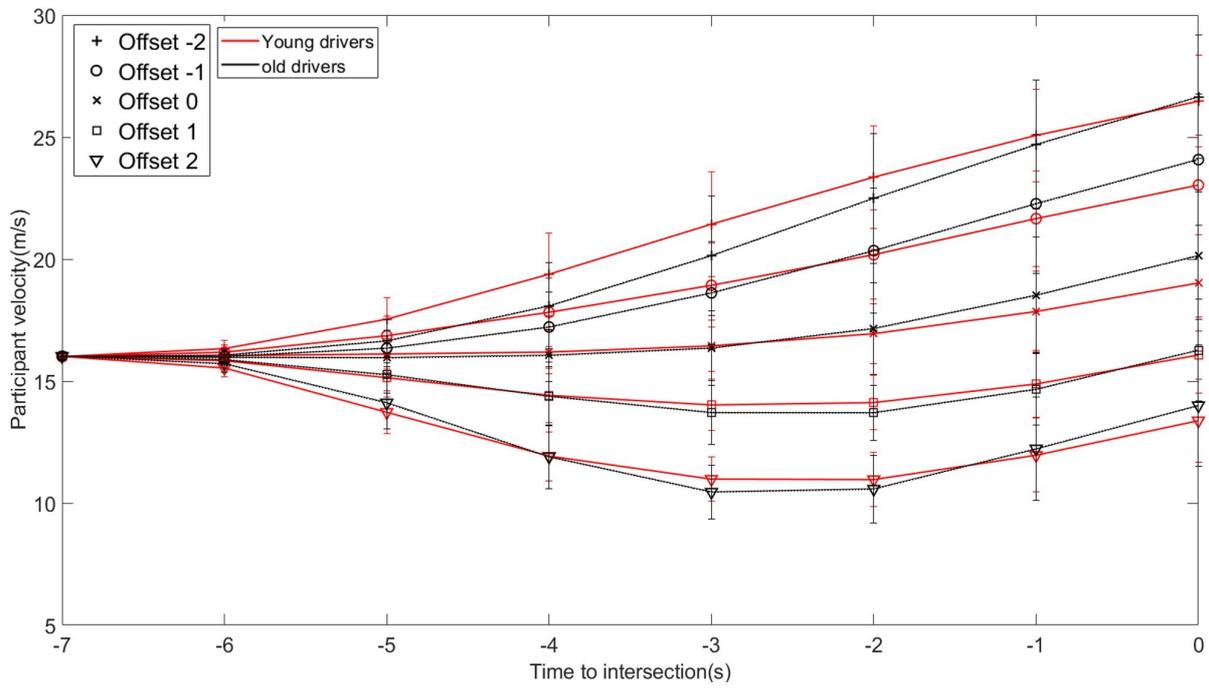
922

923

924

925

Figure 7



926

927

928

929

930

931

932

933

934

935

936

937

938

939

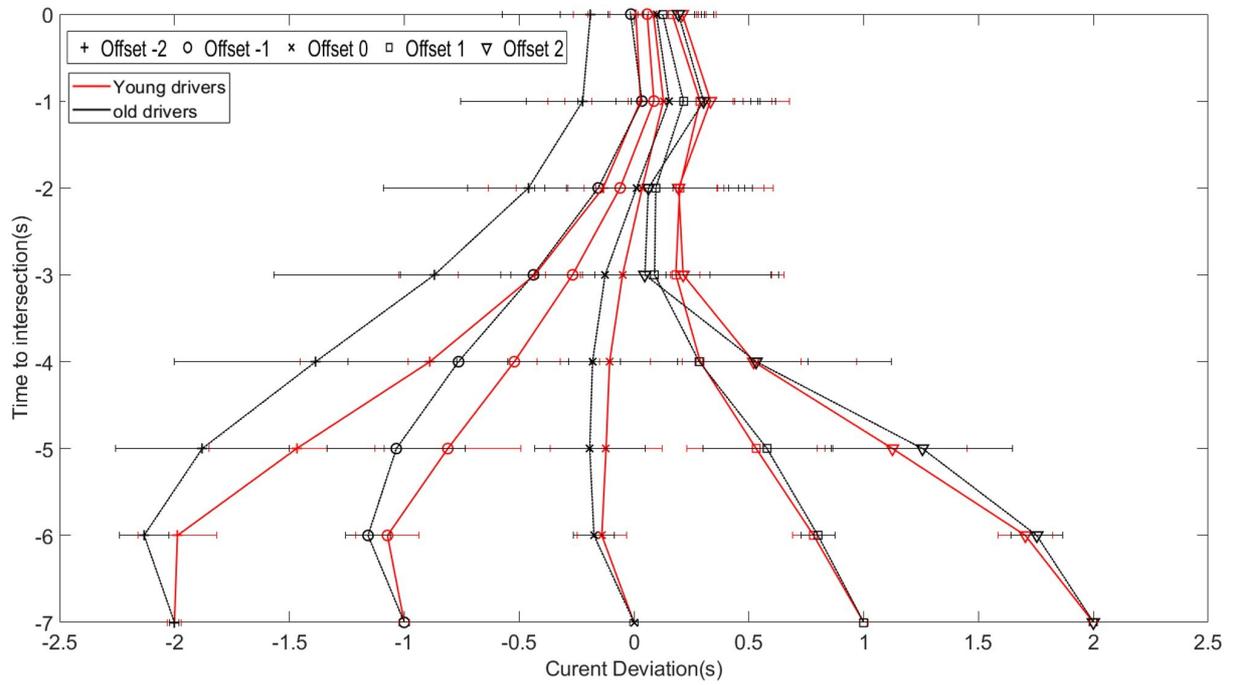
940

941

942

943

Figure 8



944

945

946

947

948

949

950

951

952

953

954

955

956

957

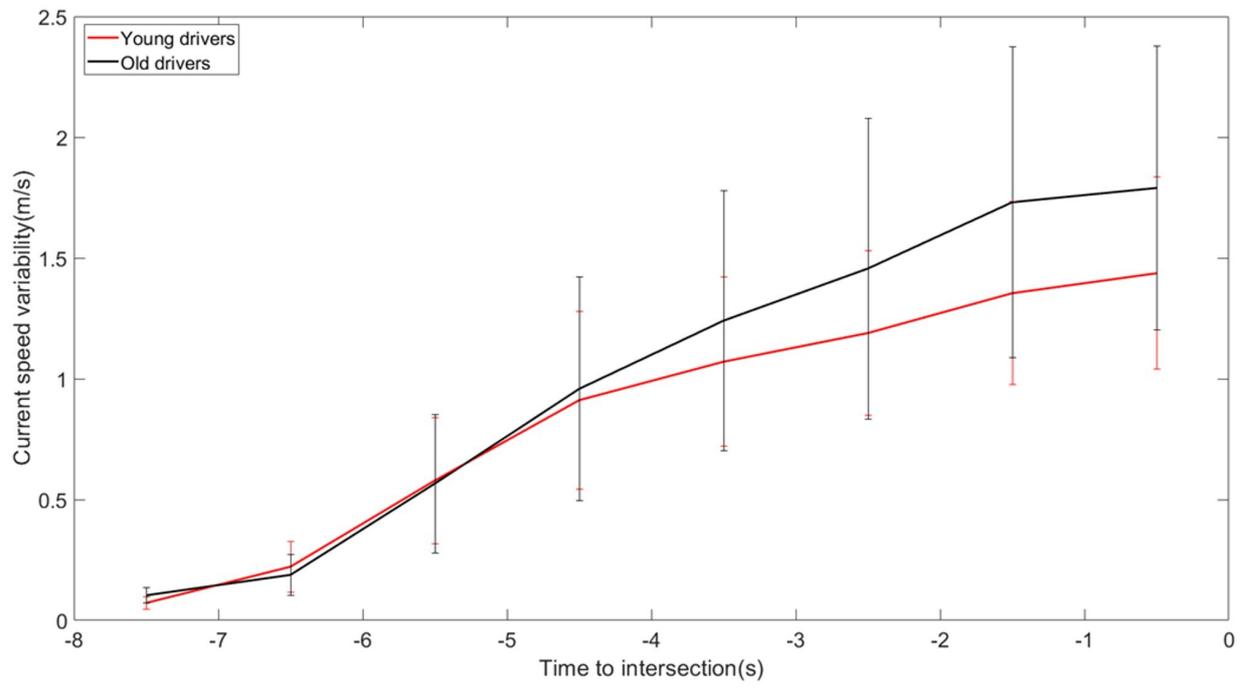
958

959

960

961

Figure 9



962

963

964

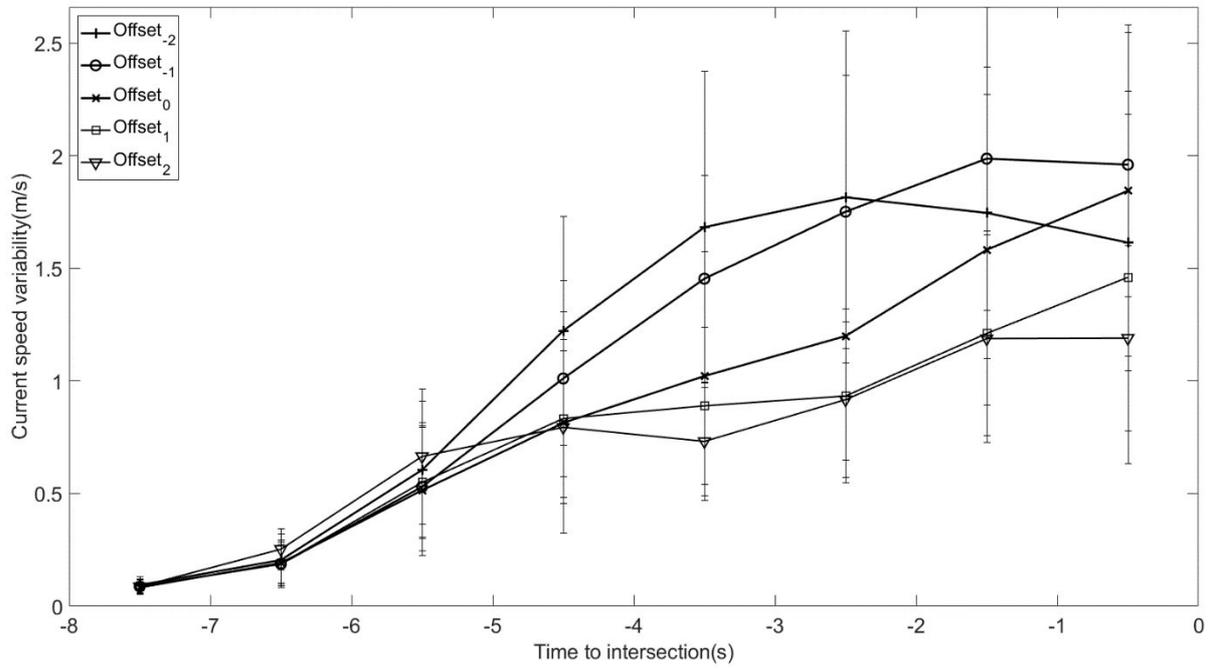
965

966

967

968

Figure 10



969

970

971

972

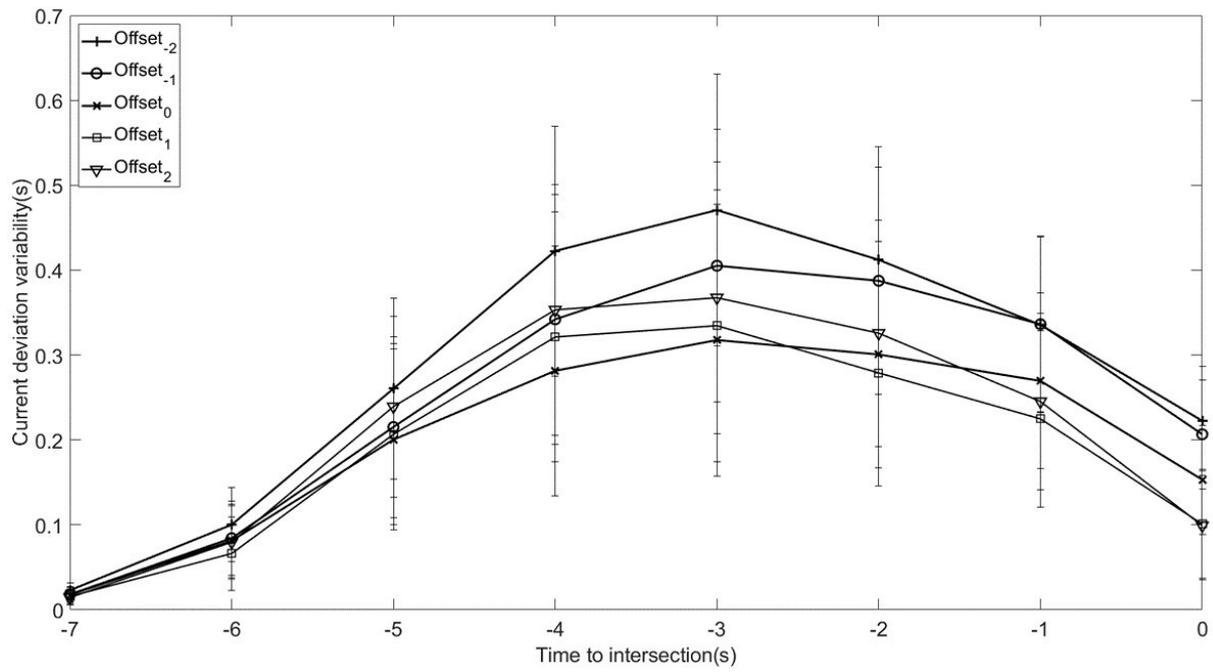
973

974

975

976

Figure 11



977

978

979

980

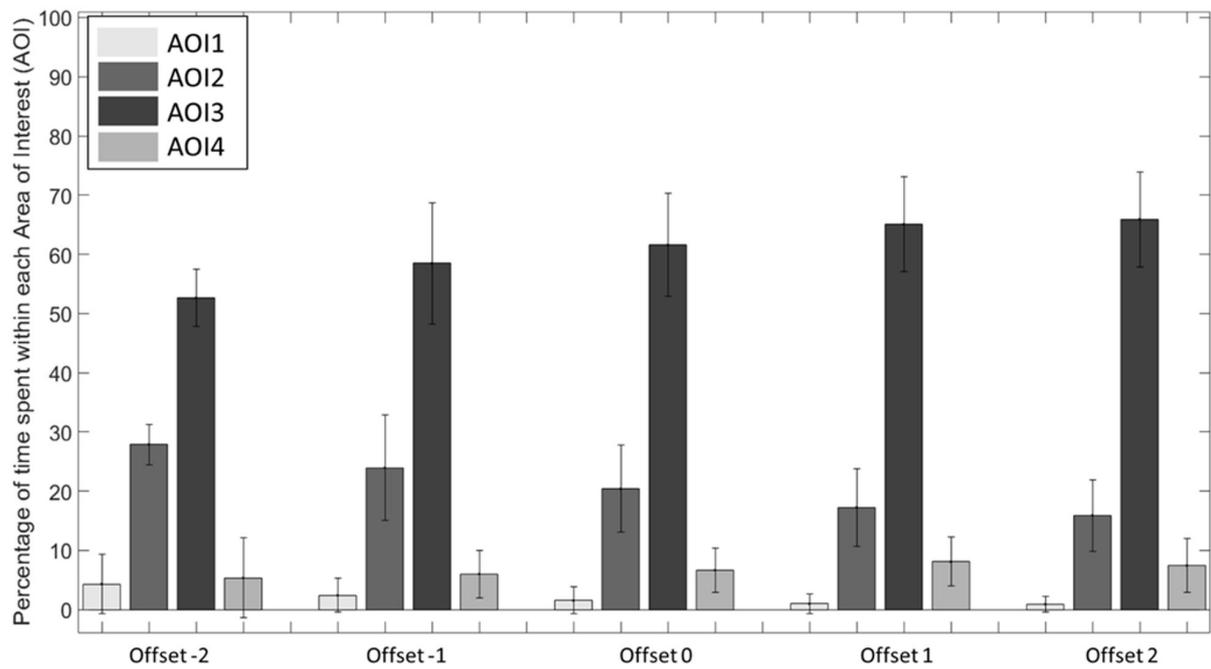
981

982

983

984

Figure 12



985

986

987

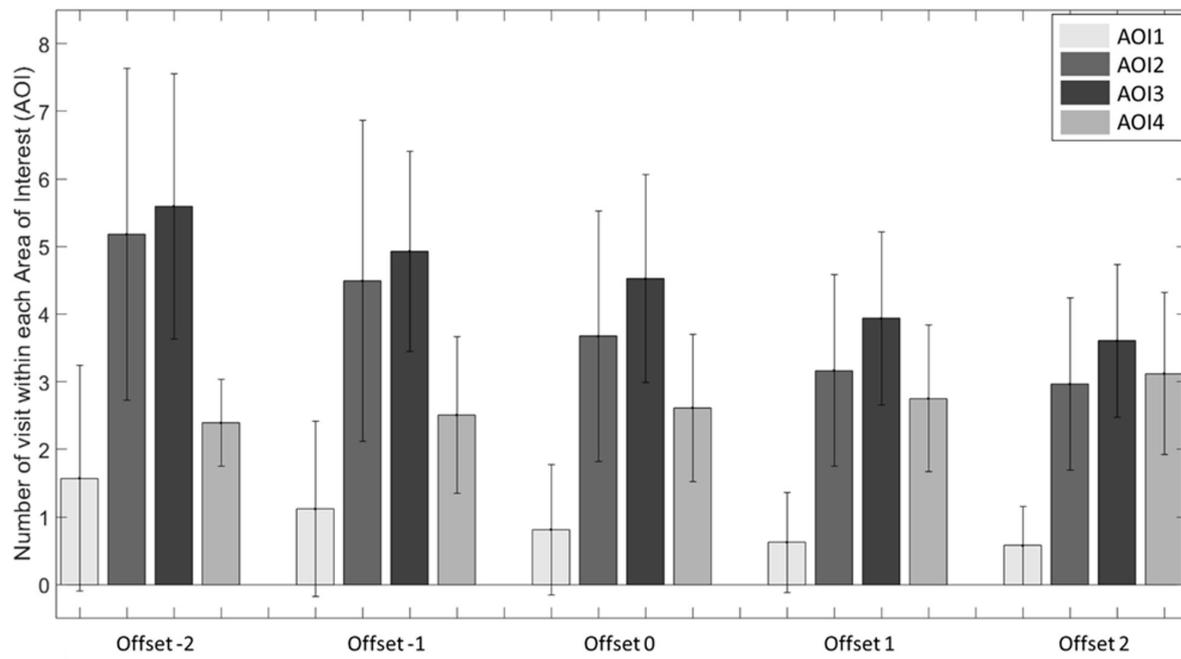
988

989

990

991

Figure 13



992

993

994

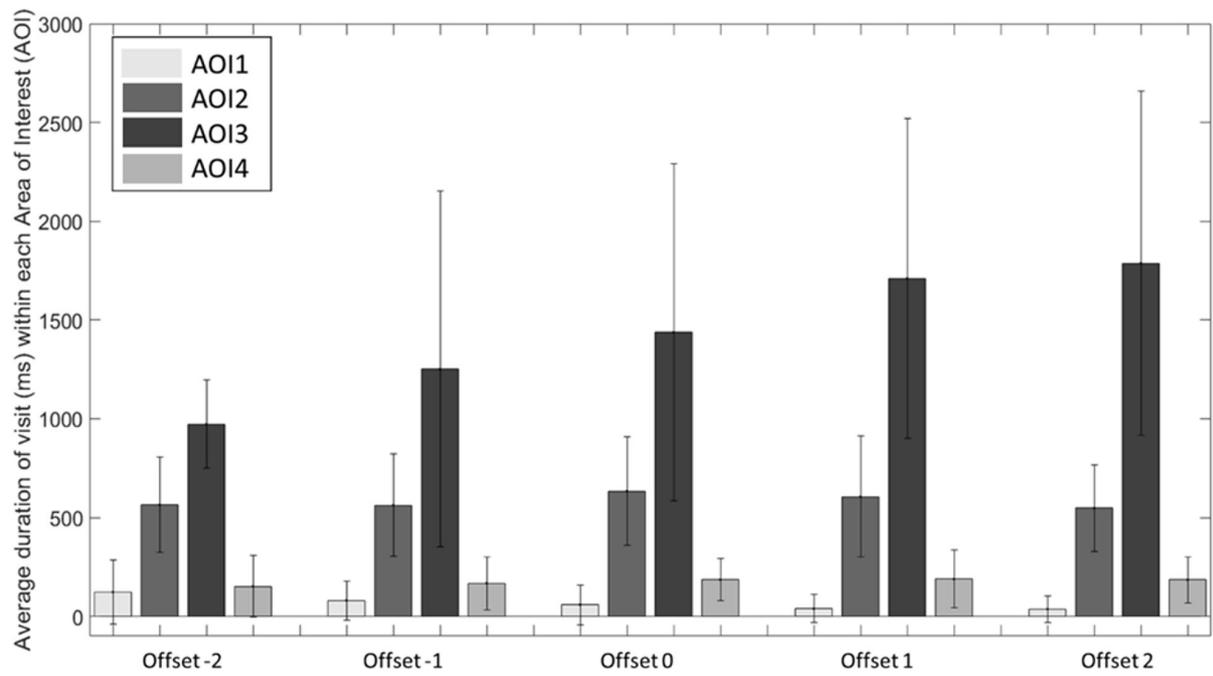
995

996

997

998

Figure 14



999

1000

1001

1002

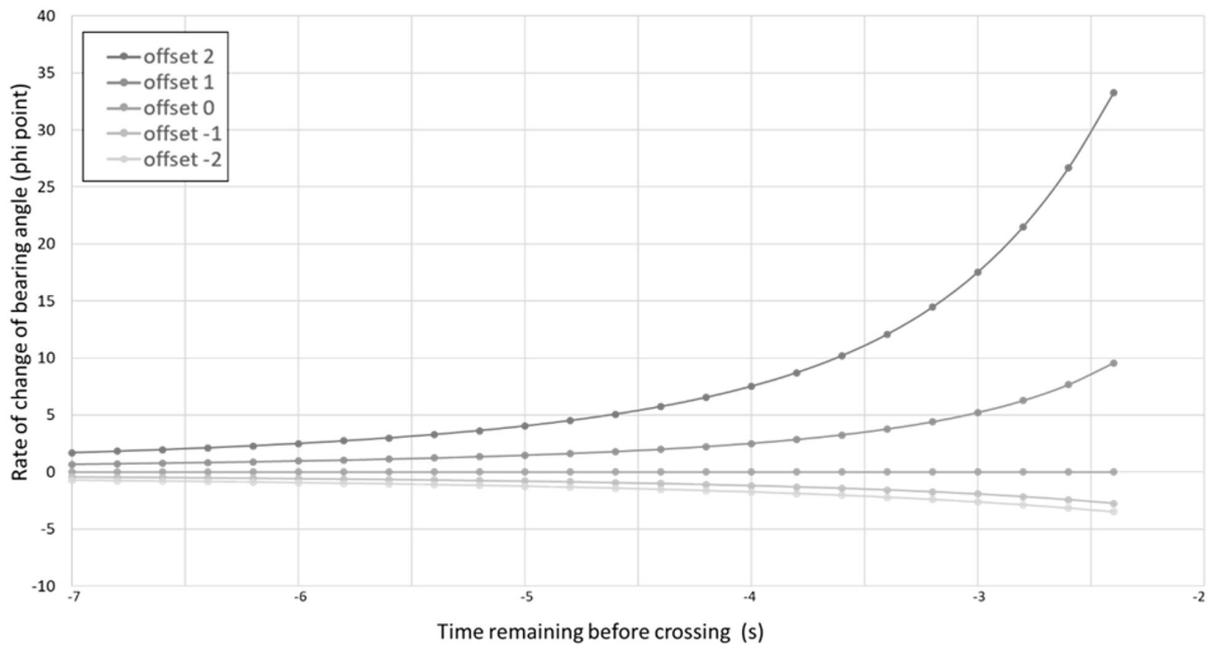
1003

1004

1005

1006

Figure 15



1007

1008

1009

1010

1011

1012

1013