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The Detection of Vulnerable Road Users by Younger and Older Drivers

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Highlights

- The aim was to investigate the effect of aging on the detection, under time constraints, of vulnerable road users
- The detection of vulnerable road users decreased with aging, even in the younger-old group
- Older-old adults compensated for their visual-field decline by doing more visual exploration than the other two groups did to correctly detect vulnerable road users
- Further studies should investigate the detection of vulnerable road users, including those on personal mobility devices and using different exploration times.

Abstract

The detection of vulnerable road users (VRUs), especially under time constraints, may be impaired in elderly drivers, due to their visual and cognitive decline. This represents a major concern for road safety. The objective of the present study was to investigate the effect of aging on the detection of VRUs. A further aim was to investigate the impact of external factors on VRU detection. Twenty-two young adults, 20 younger-old adults, and 32 older-old adults were included in the study. A series of photographs were displayed for 500 ms. Participants were asked to detect the VRU, which could be a motorcyclist, a cyclist, or a pedestrian. The VRU was located at one of two distances (near/far), one of two locations (off-centered/centered), and in two car-DRL (daytime running lights) environments (on/off). The ability to correctly detect a VRU was measured. An eye-tracker was used to record eye movements. The main findings showed that VRU-detection performance decreased with aging, even in the younger-old group (ages 55 to 68). The ability to correctly detect a VRU by older-old adults was poorer particularly when the VRU was a motorcyclist or a cyclist. As a whole, the older-old adults made more fixations to correctly detect the VRU than the other two age groups did. Moreover, the visual angle between the gaze of the participant's last fixation and the target in the older-old group was lower than in the other two groups, particularly when the VRU was off-centered. This finding suggests that older-old adults compensated for their visual-field decline by doing more visual exploration than the other two groups did to correctly detect the VRU. The results are discussed with regards to age-related cognitive and visual deficits.

Word count: 279

Keywords: older drivers; vulnerable road users; detection performance; visual exploration

1 **1. Introduction**

2 The safety of vulnerable road users (VRUs), including pedestrians, cyclists, and
3 motorcyclists, is a major concern in many countries (WHO, 2018) where they have a
4 significantly higher risk of being killed or seriously injured than do car drivers. VRU
5 fatalities currently represent 42.5% of all fatalities in France (ONISR, 2019), 46.5% in
6 Europe (ERSO, 2018), and 56% in the world (WHO, 2018). With the COVID-19
7 pandemic situation, daily mobility of individuals has considerably changed (Li et al.,
8 2022): the number of VRUs, especially in the big cities is constantly growing. A further
9 increase in the number of VRUs can be expected due to a rise in petrol prices but
10 also due to ecological and health considerations.

11 Main factors that could explain poor VRU detection

12 In order to safely interact with vulnerable road users, the drivers of motorized vehicles
13 must detect them quickly. In fact, late detection is the basic driver error that leads to
14 collisions (Rumar, 1990). Besides expectation errors (i.e., failure to scan for a specific
15 class of road users), Rumar et al. (1990) mentioned perceptual difficulties, especially
16 when low-contrast conditions and/or the peripheral visual field of the observer are
17 involved. VRUs are often more difficult to detect than cars because of their smaller
18 size and irregular contours (Cavallo & Pinto, 2012). The fact that they are not very
19 conspicuous visually and fail to be perceived by other vehicle drivers are frequent
20 causes of accidents (Van Elslande et al., 2012). A previous study showed that drivers
21 detect pedestrians less often when they appear in urban areas and more often when
22 they appear in residential areas (Borowsky et al., 2012). In urban areas, drivers are
23 not necessarily attuned to pedestrians, whereas in residential areas, their mindset is
24 such that they expect and search for pedestrians. Furthermore, findings have

25 demonstrated that driving experience is also a dominant factor that affects the
26 identification of pedestrians. Regarding motorcycle accidents, for instance, it has
27 been shown that poor motorcycle detectability is one of the main risk factors and
28 leads to right-of-way violations (ACEM, 2009; Hurt et al., 1981). While motorcycle
29 conspicuity has improved since the use of daytime running lights (DRLs, which
30 became compulsory in the seventies in many countries), this conspicuity advantage
31 has been jeopardized by the increasing use of DRLs on cars, which became
32 compulsory in Europe in 2011. Previous experimental studies have shown that car
33 DRLs, which act as a kind of visual noise, hamper motorcycle detection (Brendicke
34 et al., 1994; Cavallo & Pinto, 2012), and also have a detrimental effect on the
35 detection of bicyclists and pedestrians (Cavallo & Pinto, 2012). Although rarely
36 studied, VRU detectability, especially in a car-DRL environment, represents a major
37 concern for road safety.

38 The impact of age-related declines on VRU detection

39 Perceptual difficulties in detecting VRUs can also be caused by factors internal to
40 drivers who are visually impaired and/or exhibit age-related declines. It has been
41 shown that elderly drivers are over-represented in accidents involving pedestrians
42 (Bromberg et al., 2012) and motorcyclists (Pai et al., 2009). While speed/distance
43 judgment errors are often mentioned (e.g., Hancock & Caird, 1993; Oxley et al., 2006;
44 Pai, 2011), detection failures in elderly drivers, together with longer perception and
45 reaction times at intersections, have also been observed (e.g., Staplin, 1995). Using
46 a video observation technique, the Bromberg et al. study (2012) showed that elderly
47 drivers had longer response times on hazard detection, especially for pedestrian-
48 related hazardous events.

49 Late detection and failure to detect among elderly people are classically explained in
50 terms of an age-related deterioration of visual capacities, as reflected by declines in
51 visuo-attentional abilities, and also in terms of less effective visual exploration
52 strategies.

53 Among the age-related sensory changes, we find impaired visual acuity in both
54 central and peripheral vision (Collins et al., 1989; Derefeldt et al., 1979; Harwood,
55 2001; Ivers et al., 1998; Owsley et al., 1983), low motion sensitivity (Sekuler et al.,
56 2000; Snowden & Kavanagh, 2006), and poor adaptation to the dark (McMurdo &
57 Gaskell, 1991). The visual field, as measured in optometry, is also subject to an age
58 effect (Coleman et al., 2007; Freeman et al., 2007; Jaffe et al., 1986), with a greater
59 decrease in peripheral than in central vision. Contrast sensitivity also deteriorates
60 with age (Elliott, 1987), particularly at high spatial frequencies, i.e., the ability to see
61 details.

62 The useful field of view test (Ball et al., 1988) refers to the ability, in one glance, to
63 detect a peripheral visual target and to identify a central visual target. Findings from
64 a computer-screen task (UFOV^R), have consistently shown that the ability to detect
65 peripheral targets in this dual task deteriorates with age, and that the difference
66 between younger and older people becomes greater as the eccentricity of the
67 peripheral target increases (Ball et al., 1988; Scialfa et al., 1987; Sekuler & Ball,
68 1986). This is partly due to the lowering of processing speed with ageing, as
69 demonstrated by Salthouse (Salthouse, 1996).

70 Similar age effects have also been observed when participants performed a task of
71 detecting visual targets in a road scene while driving on a simulator (Rogé et al., 2003,
72 2004; Rogé & Pébayle, 2009). It has been shown that the accident risk was much

73 higher for elderly drivers when their useful field of view was reduced by 40% or more
74 (Ball & Owsley, 1993; Owsley, 1994; Sims et al., 2000). The poor UFOV performance
75 of participants referred for fitness-to-drive assessment was found to be associated
76 with a large number of driving errors during real-world driving (Myers et al., 2000).
77 Similar results have been found on a driving simulator (Henderson et al., 2013). With
78 respect to the detection of VRUs, Rogé and Pébayle's (2009) simulator study showed
79 that drivers with a limited useful field of view detected fewer motorcycles in the road
80 scene, especially in the distant periphery, than those who had a more extensive useful
81 field of view. Although that study only involved younger drivers, it can be assumed
82 that such motorcycle-detection difficulties are more pronounced for older drivers,
83 whose UFOV performance is generally impaired.

84 It is also well known in vision science that age impacts eye movements. While age
85 does not seem to affect eye-movement accuracy (Moschner & Baloh, 1994), it has
86 been shown to impact saccadic speed (Abel et al., 1983), saccadic latency, and
87 saccadic reaction time (SRT) (Moschner & Baloh, 1994; Munoz et al., 1998). More
88 specifically, an effect of age on SRT has been observed for persons over 40.

89 Objectives

90 The number of older drivers is increasing and their age-related declines may
91 negatively impact the detection of VRUs, which may represent a major concern for
92 road safety. It is surprising to notice that the detection of VRUs by older drivers has
93 been very little investigated (Borowsky et al., 2012; Bromberg et al., 2012). The first
94 objective of the present study was therefore to investigate the effect of aging on the
95 detection of VRUs. Three age groups (young adults, younger-old adults, older-old
96 adults) participated in the study. We expected an age-related decrease in the

97 detection of VRUs. We also hypothesized that a limited useful field of view, as
98 measured by the UFOV test, would be associated with poor detection of VRUs.

99 Another objective was to investigate the extent to which the detection of VRUs is
100 affected by external factors such as the presence/absence of daytime running lights
101 on cars, the kind of VRU to be detected (pedestrian, cyclist, motorcyclist), their
102 distance from the observer, and their location in the visual scene. The exploratory
103 aim was to better understand the visual strategies used by older drivers to correctly
104 detect a VRU.

105 **2. Method**

106 *2.1 Participants*

107 A total of 74 participants were included in the study. In the group of young adults
108 (N=22), there were 10 males and 12 females. Their median age was 29 years (range
109 25-46) and their median number of years of driving experience was 5 (range 1-25).
110 In the group of younger-old adults (N=20), there were 16 males and 4 females. Their
111 median age was 61.5 years (range 55-68) and their median number of years of driving
112 experience was 42 (age 15-50). As cognitive decline often occurs at older ages (70
113 or more) (Aartsen et al., 2002), we added a third group of older-old adults (N = 32)
114 whose median age was 73 years (range 70-87) and whose median number of years
115 of driving experience was 51 (range 4-70). There were 19 males and 13 females.

116 The inclusion criteria were: (1) having normal or corrected-to-normal vision (at least
117 6/10), (2) being a driving-license holder, (3) being an active driver (driving more than
118 2500 km/year), and (4) not declaring any neurological disorders.

119 None of the participants were professional drivers. Participants were recruited by
120 flyers or social networks. Written informed consent was obtained from all participants
121 before the experiment.

122 *2.2 Task and experimental design*

123 A series of photographs were displayed for 500 ms (for an example, see Figure 1).
124 The participants had to detect the presence of a VRU and determine whether it was
125 a motorcyclist, bicyclist, or pedestrian. They had to choose between four response
126 types displayed on the screen: bicyclists, motorcyclists, pedestrians, or none of the
127 above. They indicated their response to the experimenter orally. Practice trials were
128 performed before the experiment. A mixed experimental design was employed, with
129 *group (young, younger-old, older-old)* as a between-subject variable. There were four
130 within-subject variables: the targeted *VRU* (motorcyclist, bicyclist, or pedestrian), the
131 *distance* of the VRU in the scene (far vs. near), the DRL environment of the cars
132 (DRLs on vs. off), the VRU's *location* (centered vs. off-centered). Each experimental
133 condition was repeated three times (VRU (3) × Distance (2) × Car-DRL (2) × Location
134 (2)), making for a total of 72 experimental trials. Eighteen distractors containing a
135 VRU (located at different distances from those used in the experimental trials) were
136 added. In order to obtain a balanced design, 90 distractors with no target were added,
137 making a total of 180 trials. The stimuli were presented in four blocks of 45 trials each.

138



139 Figure 1. Example of a trial involving a motorcyclist (a scooter) centered at a near
140 distance, among cars with their daytime running lights off

141

142 *2.3 Apparatus and stimuli*

143 The stimuli were photographs of urban traffic at intersections in overcast weather.
144 The photographs were presented on a 47" flat-panel LCD display (width: 1.02 m;
145 height: 0.57 m). Participants were seated 1.60 m from the screen (angular size of the
146 screen: $32.5^\circ \times 19.6^\circ$). The eye-tracking system was SMI (SensoMotoric
147 Instruments), and the sampling rate was 60 Hz. The data was processed using
148 BeGaze (SMI software). Participants performed Part 3 of the UFOV test, considered
149 to be a measure of selective attention (Ball et al., 1993). In this part of the test, an
150 object (truck or car) was presented in the center of the screen. At the same time,
151 another object (truck or car) was presented in the periphery among 47 distractor
152 triangles of the same size, contrast, and luminance. Following the identification of the
153 central target object, participants had to indicate at which location the peripheral
154 object was displayed.

155

156 *2.4 Procedure*

157 All participants first took a visual acuity test (Ergovision) and Part 3 of the UFOV test.
158 Then the participants read the instructions of the experiment. The order of the four
159 blocks was counterbalanced across participants. Each trial included the display of a
160 fixation cross for 1500 ms, followed by the photographs for 500 ms. The screen turned
161 gray at the end of the trial. Then the participants had to choose between four response
162 types displayed on the screen. No feedback on response accuracy was given.
163 Participants were allowed breaks during the blocks and between the blocks. The
164 experimental session lasted approximately one hour and 30 minutes.

165 *2.5 Dependent variables and statistical analyses*

166 *2.5.1 Dependent variables*

167 For each experimental trial, we determined the number of correct detections,
168 identification errors, and misses. A correct detection was counted when the right VRU
169 category was recognized. An identification error was counted when a VRU was
170 detected but not correctly identified, and a miss was counted when the VRU was not
171 detected at all. Performance on distractor items was not analyzed. The number of
172 fixations, known to be an indicator of visual exploration, was analyzed. Given that
173 visual-field size decreases and peripheral vision declines with aging, the visual angle
174 between the gaze of the last fixation and the target was also analyzed. To better
175 understand the visual strategies used by older drivers to correctly detect a VRU, the
176 number of fixations and the visual angle were analyzed specifically on correct
177 detections. However, differences in visual strategies between correct detections and
178 no detections (including misses and identification errors) were also explored for all

179 participants and for each age group. For the UFOV test, the presentation time in
180 milliseconds (ms), necessary for correct identification, was measured.

181 *2.5.2 Statistical analyses*

182 A binary logistic regression was performed on the ability to correctly detect a VRU.
183 This was done in the framework of the generalized linear mixed model (GLMM) in
184 order to take into account the individual random effect, using the SPSS v.26s
185 Genlinmixed procedure (see Agresti, 2013, for more details). The binary response on
186 each trial (yes = 1, no = 0, 0 being the reference category), indicating the ability to
187 correctly detect a VRU, was chosen as the dependent variable. A binomial distribution
188 and a logit link function were assumed.

189 The number of fixations during a trial, as well as the visual angle between the gaze
190 (of the last fixation) and the target, were analyzed for correct detections. To analyze
191 the number of fixations on correct detections, a Poisson regression in the framework
192 of the GLMM model was conducted. To analyze the visual angle between the gaze
193 (of the last fixation) and the target on correct detections, a linear regression was
194 performed in the framework of the GLMM model.

195 All of these models (binary logistic regression, Poisson regression, and linear
196 regression) included five predictors that were categorical variables. The four within-
197 subject variables were VRU type (pedestrian, motorcyclist, cyclist), VRU distance (far,
198 near), car-DRL environment (on, off), and VRU location (centered, off-centered). The
199 single between-subject variable was age group. For the purpose of this study, only
200 the interactions between age group and VRU type, age group and distance, age
201 group and location, and age group and car-DRL environment were examined. Post-
202 hoc comparisons for the GLMMs were performed using t-tests. Significance levels

203 were adjusted for multiple comparisons using the sequential Bonferroni correction (or
204 Holm's sequential Bonferroni procedure; Holm, 1979). Successive models were
205 tested by removing non-significant terms one by one until the best fit was found using
206 the corrected Akaike Information Criterion (cAIC), which decreases with increasing
207 model fit. Given the small number of identification errors and misses, we did not
208 examine the effect of within-subject variables on errors and misses. However, paired
209 t-tests for all participants and for each group were performed between correct
210 detections and no detections for the number of fixations and the degree of visual
211 angle to determine whether there are any significant differences in visual strategies
212 between correct detections and no detections.

213 For identification errors, misses, and UFOV performance, the data were not normally
214 distributed. Values are expressed as medians (Q1-Q3). Between-group differences
215 were examined using Kruskal-Wallis tests (KW). Post-hoc analyses used Wilcoxon
216 rank-sum tests, with Holm's correction for multiple comparisons (Holm, 1979).

217 Pearson correlations between UFOV performance and VRU detection performance
218 were conducted for all participants.

219 All statistical analyses were performed using SPSS, version 26.0.

220 **3. Results**

221 *3.1 Detection task*

222 *3.1.1 Ability to correctly detect a VRU*

223 Table 1 presents the findings for the GLMM. A significant main group effect was found
224 on the ability to correctly detect a VRU. Post hoc tests showed that the older-old
225 participants detected the VRUs significantly less well than both the younger-old and

226 young groups did ($p < 0.001$), and the younger-old adults detected the VRUs
 227 significantly less well than the young adults did ($p < 0.001$). The mean (\pm standard
 228 deviation) proportion of correct detections was 0.55 ± 0.01 for the older-old adults,
 229 0.67 ± 0.01 for the younger-old adults, and 0.82 ± 0.01 for the young adults.

230 For all within-group variables, significant main effects on the ability to correctly detect
 231 a VRU were also found (Table 1). Post-hoc comparisons showed that the mean
 232 proportion of correct detections was significantly lower in the far condition ($0.57 \pm$
 233 0.01) than in near conditions (0.79 ± 0.001). The proportion of correct detections was
 234 also significantly lower in off-centered than in centered conditions. For location, the
 235 values were 0.78 ± 0.001 for centered VRUs and 0.59 ± 0.01 for off-centered VRUs.
 236 The proportion of correct detections was also lower for the DRLs-on than for the
 237 DRLs-off condition, but this difference was not significant. For the car-DRL
 238 environment, the values were 0.71 ± 0.01 for DRLs off and 0.67 ± 0.01 for DRLs on.

239 Table 1. Fixed effects using GLMM

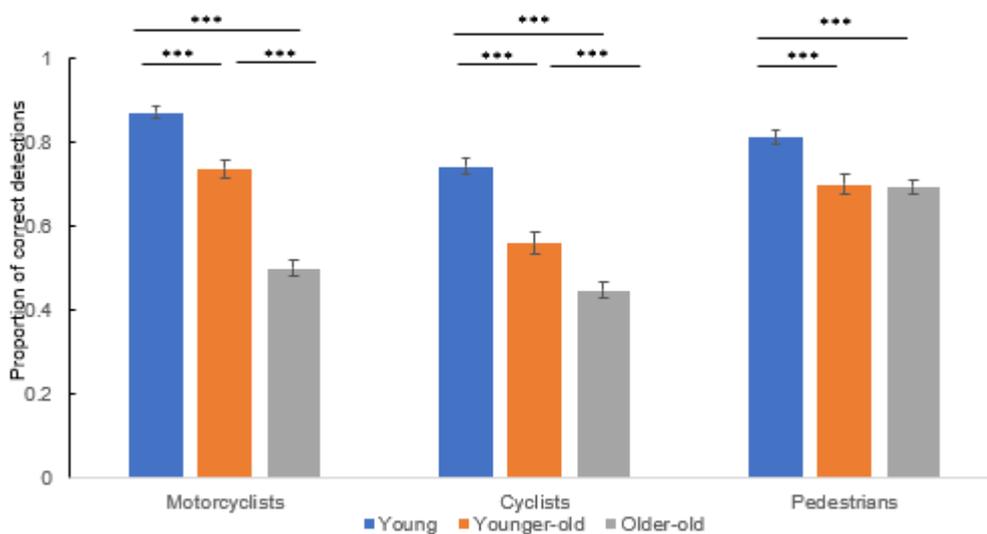
<i>Between-group variable</i>	
<i>Age group</i>	$F_{2,4842} = 115.17, p < 0.001$
<i>Within-group variables</i>	
<i>Type of VRU</i>	$F_{2,4842} = 43.02, p < 0.001$
<i>VRU distance</i>	$F_{1,4842} = 219.28, p < 0.001$
<i>VRU location</i>	$F_{1, 4842} = 172.98, p < 0.001$
<i>Car-DRL environment</i>	$F_{1, 4842} = 5.00, p = 0.02$
<i>Interactions</i>	

240

241 Figure 2 shows the estimated mean proportion of correct detections per age group
242 for each VRU type. The older-old adults detected significantly fewer pedestrians,
243 motorcyclists, and cyclists than the young adults did ($p < 0.001$); the older-old adults
244 detected significantly fewer motorcyclists and cyclists than the younger-old adults did
245 ($p < 0.001$); and the younger-old adults detected significantly fewer motorcyclists,
246 cyclists, and pedestrians than the young adults did ($p < 0.001$). Pairwise comparisons
247 also revealed that older-old adults detected significantly more pedestrians than
248 cyclists and motorcyclists ($p < 0.001$). Younger-old adults detected significantly more
249 pedestrians and motorcyclists than cyclists ($p < 0.001$). Young adults detected more
250 motorcyclists than cyclists and pedestrians ($p < 0.001$). They also detected more
251 pedestrians than cyclists ($p < 0.001$).

252 No significant interactions between age group and VRU distance, age group and VRU
253 location, or age group and car-DRL environment were found.

254



255 *** $p < 0.001$

256 Figure 2. Estimated proportion of correct detections as a function of age group and VRU type. Only
257 significant between-group differences are shown in this figure. Error bars represent the standard
258 error.

259

260 3.1.2 Identification errors and misses

261 Older-old adults made more identification errors than young adults ($p < 0.01$). The
262 median percentage of identification errors for older-old adults was 5.59 (4.17 – 10.14)
263 and for young adults, it was 2.78 (1.41 – 4.17). Both older-old adults and younger-old
264 adults missed more VRUs than young adults did ($p < 0.01$). The median percentage
265 of misses for older-old adults was 37.50 (29.13 – 42.85). For younger-old adults, this
266 value was 30.07 (22.22 – 36.11), and for young adults, it was 19.44 (11.94 – 23.61).

267 3.2 Eye-related variables for correct detections

268 For the number of fixations, the final model included the significant main effects of
269 distance ($F_{1,3157} = 18.47$, $p < 0.001$), location ($F_{1,3157} = 8.28$, $p = 0.004$), and age group
270 ($F_{2,3157} = 204.93$, $p < 0.001$). For the visual angle, the final model included the
271 significant main effects of distance ($F_{1,3153} = 8.78$, $p = 0.003$), location ($F_{2,3153} =$
272 2507.81 , $p < 0.001$), age group ($F_{2,3153} = 16.09$, $p < 0.001$), and a significant distance
273 by age group interaction ($F_{2,3153} = 3.86$, $p = 0.02$) as well as a significant location by
274 age group interaction ($F_{2,3153} = 59.64$, $p < 0.001$).

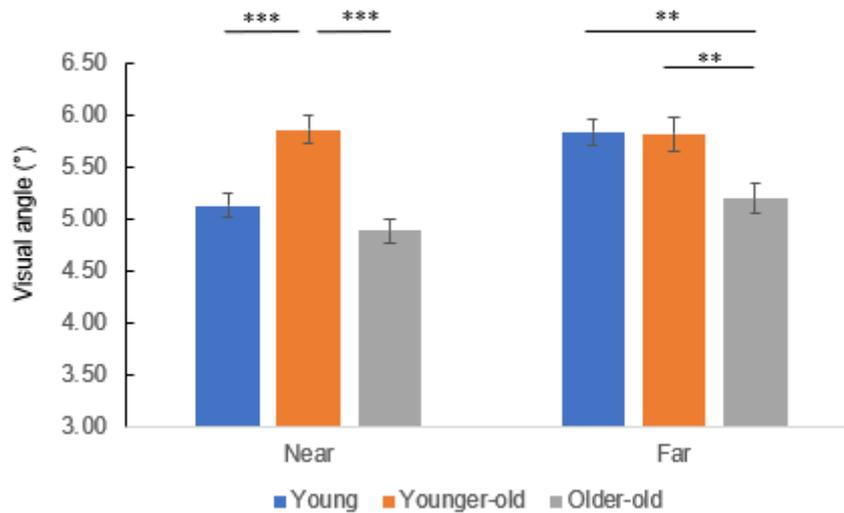
275 There were a greater number of fixations in far VRU locations than in near ones. The
276 mean number of fixations in a far location ($M \pm SD$) was 1.77 ± 0.02 ; in a near location,
277 it was 1.68 ± 0.02 , $p < 0.001$.

278 The findings also revealed a significant main effect of location, with a significantly
279 higher average number of fixations in the off-centered condition than in centered
280 conditions. The mean number of fixations ($M \pm SD$) in off-centered condition was 1.76
281 ± 0.02 . In the centered condition, it was 1.69 ± 0.02 , $p = 0.004$.

282 There was a significant main effect of age group on the number of fixations for correct
283 detections, and on the visual angle between the gaze and the target. Post-hoc tests
284 showed that the older-old group had a significantly higher number of fixations than
285 either younger groups. The mean number of fixations for the older-old adults was
286 2.05 ± 0.02 . For the younger-old adults, it was 1.51 ± 0.02 , and for the young adults,
287 it was 1.61 ± 0.02 ($p < 0.001$ on all pairwise comparisons). The older-old group had
288 smaller visual angle than the younger-old group ($p < 0.001$) and the young group (p
289 $= 0.001$). The visual angle in degrees for the older-old adults was 5.05 ± 0.09 . For the
290 younger-old adults, it was 5.85 ± 0.11 , and for the young adults, it was 5.49 ± 0.09 (p
291 ≤ 0.01 on all pairwise comparisons).

292 *Interaction between age group and distance*

293 The older-old adults had a significantly smaller visual angle than younger-old group
294 did in both the near and far locations ($p < 0.001$, $p = 0.009$, respectively). In the far
295 location, the older-old adults had smaller visual angle than did the young group ($p =$
296 0.003) (Figure 3). Only the younger group had a visual angle greater in the far location
297 than in the near location ($p < 0.001$).



299 **p<0.01

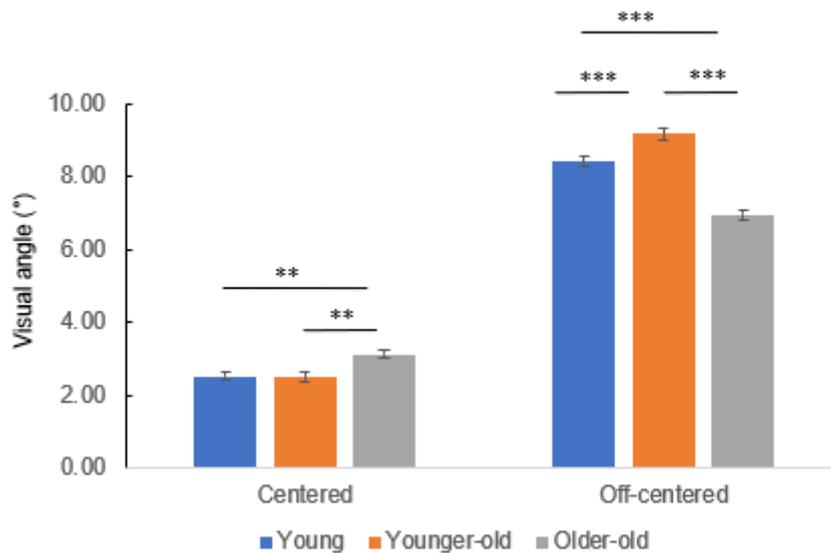
300 ***p<0.001

301 Figure 3. Visual angle by age group, for each distance. This represents the estimated values from the
 302 final model. Only significant between-group differences are shown in this figure. Error bars represent
 303 the standard error.

304

305 *Interaction between age group and location*

306 The older-old group had a significantly smaller visual angle than did the younger-old
 307 group and the young group in the off-centered condition ($p < 0.001$ on all pairwise
 308 comparisons) (Figure 4). The younger-old group also had a greater visual angle than
 309 the young group did ($p < 0.001$) in the off-centered condition. In the centered
 310 condition, the older-old group had a greater visual angle than the younger groups did
 311 ($p = 0.001$ on all pairwise comparisons). For all age groups, the visual angle was
 312 greater when the VRU was off-centered than when it was centered ($p < 0.001$).



314 **p<0.01

315 ***p<0.001

316 Figure 4. Visual angle by age group, for each location. This represents the estimated values from the
 317 final model. Only significant between-group differences are shown in this figure. Error bars represent
 318 the standard error.

319 3.3 Differences in visual strategies between correct detections and no detections

320 For the number of fixations, there was no significant difference between correct
 321 detections and no detections (correct detections = 1.76 ± 0.30 versus no detections
 322 = 1.77 ± 0.29 , $t = 0.99$, $p = 0.33$). Furthermore, no significant differences between
 323 correct detections and no detections were found for each age group ($P > 0.05$).
 324 However, a significant difference was found between correct detections and no
 325 detections for the visual angle (Visual angle for correct detections = $4.96^\circ \pm 0.98$
 326 versus Visual angle for no detections = $8.24^\circ \pm 1.48$, $t = 0.99$, $p < 0.001$). These
 327 differences remain significant for each age group (Younger adults: Visual angle for
 328 correct detections = $5.21^\circ \pm 0.67$ versus Visual angle for no detections = $7.31^\circ \pm 1.32$,
 329 $t = 6.66$, $p < 0.001$; younger-old adults: Visual angle for correct detections = $5.25^\circ \pm$
 330 0.59 versus Visual angle for no detections = $7.93^\circ \pm 1.17$, $t = 8.04$, $p < 0.001$; Older-

331 old adults: Visual angle for correct detections = $4.64^\circ \pm 1.23$ versus Visual angle for
332 no detections = 9.05 ± 1.32 , $t = 14.29$, $p < 0.001$).

333

334 *3.3 UFOV test*

335 The younger-old and older-old groups performed significantly less well on Part 3 of
336 the UFOV test than the young group did ($p < 0.001$). The young adults had a median
337 (Q1 - Q3) of 103 ms (80 - 140). The younger-old adults' median (Q1 - Q3) was 300
338 ms (257 - 407) and the older-old adults' median (Q1 - Q3) was 335 ms (253 - 500).

339 *3.4 Correlation between Part 3 of the UFOV test and detection performance*

340 For all participants, poor performance on Part 3 of the UFOV test was strongly
341 correlated with poor VRU detection ($r = - 0.67$, $p < 0.001$).

342 **4. Discussion**

343 The aim of this study was to investigate the effects of aging on the detection of VRUs.
344 The VRU could be a pedestrian, a motorcyclist, or a cyclist, positioned in two different
345 locations and at two different distances in urban traffic. The cars could have their
346 DRLs turned on or off. The contribution of this study is that VRU detection
347 performance decreased with age, even in the younger-old group (ages 55 to 68).
348 Furthermore, older-old adults performed poorly, particularly when the VRU was a
349 motorcyclist or a cyclist. Finally, this study suggests that older participants used
350 compensatory mechanisms for their poorer visual field by increasing visual
351 exploration, without reaching the detection performance of the younger group.

352 As a whole, the older-old adults made more fixations to correctly detect the VRU than
353 the other two age groups did. As expected, there were a greater number of fixations

354 to far VRU locations than to near ones. The mean number of fixations to detect the
355 VRU in a far location was 1.77 whereas in a near location, it was 1.68, meaning that
356 more individuals needed 2 fixations to detect far VRUs as compared to near VRUs.
357 Moreover, the visual angle between the detected VRU and the last fixation was
358 smaller in the older-old group than in the younger-old group, whether the VRU was in
359 the far or near location. The visual angle of the older-old group was also smaller than
360 that of the other two groups when the VRU was off-centered.

361 Importantly, detection performance decreased with aging, not only in the older-old
362 participants (ages 70 to 87) but even in the younger-old group (ages 55 to 68). These
363 findings are consistent with previous driving studies showing that age has an impact
364 on the ability to detect visual signals (Rogé et al., 2003, 2004). Poor detection
365 performance may be explained by a deterioration of selective attention with aging. In
366 the present study, lower detection performance was strongly associated with a poorer
367 measure of selective attention (Part 3 of the UFOV). Previous findings have shown
368 that a decrease in selective attention appears early in the course of aging, between
369 the ages of 40 and 50 (Sekuler et al., 2000). Another explanation could be the slowing
370 of processing speed with aging (Owsley, 2011; Salthouse, 1996). In our study,
371 participants were under time constraints when detecting a VRU since the
372 photographs were displayed for only 500 ms. This could explain why even the
373 younger-old adults could not compensate for their slowing in processing speed and
374 exhibited a decrease in VRU detection performance. Older-old adults made more
375 identification errors and both older groups (older-old and younger-old) missed more
376 VRUs than young adults did, suggesting that they did not have time to see and identify
377 the VRU.

378 Unexpectedly, the interaction between age group and centeredness on the ability to
379 detect a VRU was not significant. Yet, for correct detections, the visual angle between
380 the gaze and a VRU located in the periphery was narrower for older-old adults than
381 for younger-old and young adults. This finding indicates that older-old adults' eyes
382 need to land closer to the target to correctly detect a VRU in the periphery. It suggests
383 that the older-old adults used mechanisms that compensate for visual-field decline by
384 doing more visual exploration than the other two groups to correctly detect the VRU
385 (Coeckelbergh et al., 2004). Our findings on the detection of VRUs located in the
386 periphery differ from those of previous studies (Rogé et al., 2003, 2004; Rogé &
387 Pébayle, 2009), which showed that older drivers detected fewer signals than younger
388 drivers, particularly when the signal was farther away from the fixation point.
389 Discrepancies across studies may be due to differences in methodology (screen size)
390 or the type of task (observation versus driving). Interestingly, the number of fixations
391 did not differ between correct detections and no detections whereas the degree of
392 visual angle was larger for no detections, for all age groups. This result suggests that
393 visual strategies of participants differ between correct detections and no detections:
394 all participants (regardless of the age) need to land closer to the target to correctly
395 detect a VRU.

396 Similarly, no age-related deterioration in the ability to detect a VRU among cars with
397 their DRLs on was found in our study. Yet, the use of DRLs had a negative impact on
398 detection performance in all three age groups. Previous studies have shown that the
399 use of DRLs by cars may create "visual noise" that hinders the perception of other
400 VRUs, such as pedestrians, cyclists, or motorcyclists (Cavallo & Pinto, 2012), which
401 makes them less conspicuous and less noticeable (Brouwer et al., 2004). Our results

402 thus suggest that the use of DRLs by cars affects the detection of VRUs for all
403 individuals, irrespective of their age.

404 Another interesting finding is that older-old adults and younger-old adults detected
405 pedestrians better than they did motorcyclists and/or cyclists, which was not the case
406 for our young adults. One explanation could be that older adults identified more with
407 pedestrians than with motorcyclists and cyclists.

408 **5. Limitations and future research avenues**

409 Methodological considerations include the use of static images, i.e., photographs of
410 urban traffic instead of dynamic images in videos or during simulated driving. The
411 decision to use static images in the present study allowed us to investigate attentional
412 aspects of road-user behavior. Photographs were displayed for 500 ms, which is quite
413 short. In real life, drivers need to quickly detect relevant information in the road scene,
414 and detection failures are more likely to occur under time pressure and when visual
415 exploration time is short. Also, the age gap between our younger-old and older-old
416 groups was quite close (65-68 vs. 70-87). However, our findings indicated some
417 significant differences in VRU detection performance and visual exploration.
418 Furthermore, the age gap between the older groups and the younger group was
419 relatively large, which can explain significant differences between these two groups.
420 Additional studies that include an intermediate age group with a mean age around 50
421 should be conducted to better understand the time course of visual and attentional
422 aging in VRU detection. Time constraints play a major role in detection performance
423 in older adults. In the present study, photographs were displayed for 500 ms, which
424 may be not enough to correctly detect the VRU, especially for older adults. Future

425 research should vary presentation times of photographs in order to determine the role
426 of exploration times in relation with compensation strategies in older adults.

427 It would be interesting in future studies on older adults to investigate VRU detection
428 using a driving simulator. The use of a driving simulator enables one to assess VRU
429 detection during driving, and to better understand the compensatory strategies of
430 older adults. A previous simulator study showed that elderly drivers drove about 20%
431 slower than experienced non-elderly drivers (Bromberg et al., 2020), which suggests
432 that as a whole, elderly drivers are aware of their deficiencies in detecting hazards.

433 A valuable contribution for improving road safety would be to investigate different
434 types of interventions aimed at helping older drivers better detect VRUs, particularly
435 motorcyclists and cyclists. Based on the results of this study, we can contend that
436 older individuals detect fewer motorcyclists and cyclists than pedestrians. There are
437 several ways to improve VRU detection performance. A variety of training methods
438 have been employed to improve VRU detection by car drivers. One such method is
439 useful-visual-field training which could improve elderly car drivers' VRU-detection
440 (Rogé et al., 2014). It has been shown that drivers who had undergone training for
441 perceiving motorcycles were better able to identify motorcyclists than ones who had
442 not been trained (Crundall et al., 2017). Also, safety messages have been developed
443 to improve the perception of VRU vulnerability during driving (Rogé et al., 2015).

444 Additional research needs to be conducted to explore the benefits of automated
445 vehicles for detecting VRUs, particularly among older adults. The introduction of
446 automated vehicles with external human-machine interfaces, and the use of
447 augmented reality in automated vehicles, could help drivers to better detect VRUs
448 and may also enhance future interaction between VRUs and autonomous vehicles

449 (Tabone et al., 2021). Several safety systems such as pedestrian alerts could inform
450 drivers of a potential hazard (Large et al., 2019). However, the additional cognitive
451 load induced by these systems should be considered with caution in future studies,
452 especially for older adults.

453 As a complement to studies investigating VRU detection by drivers, eye-tracking
454 studies should also explore the interactions between drivers and pedestrians from the
455 pedestrian's point of view (Lévêque et al., 2020).

456 Further research should also help improve the visibility of VRUs. Previous studies
457 have shown that the use of specific conspicuous clothes (for example,
458 retroreflective and yellow clothes) by cyclists, or having specific headlights on
459 motorcycles could improve their detection (e.g., Olson et al., 1981; Pinto et al.,
460 2014; Ranchet et al., 2016).

461 **6. Conclusion**

462 The main findings of this study are that VRU detection performance decreased with
463 aging, even in the group of younger-old adults (after age 55). This may be partly due
464 to age-related deficits in selective attention and visual exploration. With the increasing
465 number of personal mobility devices (PMD) (e.g., electric scooters, unicycles,
466 segways, hoverboards), particularly in cities, the number of accidents involving both
467 PMD riders and other road users is increasing (Ang et al., 2021). The detectability of
468 VRUs on PMDs by drivers or other road users, particularly older adults, has become
469 a major challenge for road safety. Further studies should investigate the detection of
470 VRUs - including those on PMDs - by other road users (e.g., drivers, pedestrians,
471 cyclists).

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477

478 References

- 479 Aartsen, M. J., Smits, C. H. M., van Tilburg, T., Knipscheer, K. C. P. M., & Deeg, D.
480 J. H. (2002). Activity in older adults : Cause or consequence of cognitive
481 functioning? A longitudinal study on everyday activities and cognitive performance
482 in older adults. *The Journals of Gerontology. Series B, Psychological Sciences and*
483 *Social Sciences*, 57(2), P153-162. <https://doi.org/10.1093/geronb/57.2.p153>
- 484 Abel, L. A., Troost, B. T., & Dell'Osso, L. F. (1983). The effects of age on normal
485 saccadic characteristics and their variability. *Vision Research*, 23(1), 33-37.
486 [https://doi.org/10.1016/0042-6989\(83\)90038-X](https://doi.org/10.1016/0042-6989(83)90038-X)
- 487 ACEM. (2009). *Maids—In-Depth investigation of motorcycle accidents*.
488 <http://www.maids-study.eu/>
- 489 Agresti, A. (2013). *Categorical Data Analysis* (3rd éd.). Wiley.
- 490 Ang, K. X. M., Chandrakumara, S. D., Kon Kam King, C., & Loh, S. Y. J. (2021).
491 The Orthopedic Injury Burden of Personal Mobility Devices in Singapore – Our
492 Experience in the East Coast. *Journal of Clinical Orthopaedics and Trauma*, 13,
493 66-69. <https://doi.org/10.1016/j.jcot.2020.08.015>
- 494 Ball, K., Beard, B. L., Roenker, D. L., Miller, R. L., & Griggs, D. S. (1988). Age and
495 visual search : Expanding the useful field of view. *Journal of the Optical Society of*
496 *America. A, Optics and Image Science*, 5(12), 2210-2219.
497 <https://doi.org/10.1364/josaa.5.002210>
- 498 Ball, K., & Owsley, C. (1993). The useful field of view test : A new technique for
499 evaluating age-related declines in visual function. *Journal of the American*
500 *Optometric Association*, 64(1), 71-79.
- 501 Borowsky, A., Oron-Gilad, T., Meir, A., & Parmet, Y. (2012). Drivers' perception of
502 vulnerable road users : A hazard perception approach. *Accident Analysis &*
503 *Prevention*, 44(1), 160-166. <https://doi.org/10.1016/j.aap.2010.11.029>
- 504 Brendicke, R., Forke, E., & Schaefer, D. (1994). Auswirkungen einer allgemeinen
505 tageslichtpflicht auf die sicherheit motorisierter zweiraeder. *VDI-Berichte*, 1159.
506 <https://trid.trb.org/view/1000302>
- 507 Bromberg, S., Oron-Gilad, T., Ronen, A., Borowsky, A., & Parmet, Y. (2012). The
508 perception of pedestrians from the perspective of elderly experienced and
509 experienced drivers. *Accident Analysis & Prevention*, 44(1), 48-55.
510 <https://doi.org/10.1016/j.aap.2010.12.028>
- 511 Brouwer, R. F. T., Jansen, W. H., Theeuwes, J., Duistermaat, M., & Alferdinck, J.
512 W. A. M. (2004). Do other road users suffer from the presence of cars that have
513 their daytime running lights on ? *TNO*.

514 Cavallo, V., & Pinto, M. (2012). Are car daytime running lights detrimental to
515 motorcycle conspicuity? *Accident; Analysis and Prevention*, 49, 78-85.
516 <https://doi.org/10.1016/j.aap.2011.09.013>

517 Coeckelbergh, T. R. M., Cornelissen, F. W., Brouwer, W. H., & Kooijman, A. C.
518 (2004). Age-Related Changes in the Functional Visual Field : Further Evidence for
519 an Inverse Age x Eccentricity Effect. *The Journals of Gerontology: Series B*, 59(1),
520 P11-P18. <https://doi.org/10.1093/geronb/59.1.P11>

521 Coleman, A. L., Cummings, S. R., Yu, F., Kodjebacheva, G., Ensrud, K. E.,
522 Gutierrez, P., Stone, K. L., Cauley, J. A., Pedula, K. L., Hochberg, M. C., Mangione,
523 C. M., & Study Group of Osteoporotic Fractures. (2007). Binocular visual-field loss
524 increases the risk of future falls in older white women. *Journal of the American*
525 *Geriatrics Society*, 55(3), 357-364. [https://doi.org/10.1111/j.1532-](https://doi.org/10.1111/j.1532-5415.2007.01094.x)
526 [5415.2007.01094.x](https://doi.org/10.1111/j.1532-5415.2007.01094.x)

527 Collins, M. J., Brown, B., & Bowman, K. J. (1989). Peripheral visual acuity and age.
528 *Ophthalmic & Physiological Optics: The Journal of the British College of Ophthalmic*
529 *Opticians (Optometrists)*, 9(3), 314-316. [https://doi.org/10.1111/j.1475-](https://doi.org/10.1111/j.1475-1313.1989.tb00914.x)
530 [1313.1989.tb00914.x](https://doi.org/10.1111/j.1475-1313.1989.tb00914.x)

531 Crundall, D., Howard, A., & Young, A. (2017). Perceptual training to increase
532 drivers' ability to spot motorcycles at T-junctions. *Transportation Research Part F:*
533 *Traffic Psychology and Behaviour*, 48, 1-12. <https://doi.org/10.1016/j.trf.2017.05.003>

534 Derefeldt, G., Lennerstrand, G., & Lundh, B. (1979). Age variations in normal
535 human contrast sensitivity. *Acta Ophthalmologica*, 57(4), 679-690.
536 <https://doi.org/10.1111/j.1755-3768.1979.tb00517.x>

537 Elliott, D. B. (1987). Contrast sensitivity decline with ageing : A neural or optical
538 phenomenon? *Ophthalmic and Physiological Optics*, 7(4), 415-419.
539 <https://doi.org/10.1111/j.1475-1313.1987.tb00771.x>

540 ERSO. (2018). *Annual Accident Report 2018* (European Road Safety Observatory).

541 Freeman, E. E., Muñoz, B., Rubin, G., & West, S. K. (2007). Visual field loss
542 increases the risk of falls in older adults : The Salisbury eye evaluation. *Investigative*
543 *Ophthalmology & Visual Science*, 48(10), 4445-4450.
544 <https://doi.org/10.1167/iovs.07-0326>

545 Hancock, P. A., & Caird, J. K. (1993). Experimental evaluation of a model of mental
546 workload. *Human Factors*, 35(3), 413-429.
547 <https://doi.org/10.1177/001872089303500303>

548 Harwood, R. H. (2001). Visual problems and falls. *Age and Ageing*, 30 Suppl 4,
549 13-18. https://doi.org/10.1093/ageing/30.suppl_4.13

550 Henderson, S., Gagnon, S., Collin, C., Tabone, R., & Stinchcombe, A. (2013). Near
551 peripheral motion contrast threshold predicts older drivers' simulator performance.

552 *Accident; Analysis and Prevention*, 50, 103-109.
553 <https://doi.org/10.1016/j.aap.2012.03.035>

554 Holm, S. (1979). A Simple Sequentially Rejective Multiple Test Procedure.
555 *Scandinavian Journal of Statistics*, 6(2), 65-70.

556 Hurt, H. H. J., Ouellet, J. V., & Thom, D. R. (1981). *Motorcycle accident cause*
557 *factors and identification of countermeasures* (NHTSA report N° 81-1-VOL-1 Final
558 Rpt.). Department of Transportation. <https://trid.trb.org/view/170348>

559 Ivers, R. Q., Cumming, R. G., Mitchell, P., & Attebo, K. (1998). Visual impairment
560 and falls in older adults : The Blue Mountains Eye Study. *Journal of the American*
561 *Geriatrics Society*, 46(1), 58-64. <https://doi.org/10.1111/j.1532-5415.1998.tb01014.x>

562 Jaffe, G. J., Alvarado, J. A., & Juster, R. P. (1986). Age-Related Changes of the
563 Normal Visual Field. *Archives of Ophthalmology*, 104(7), 1021-1025.
564 <https://doi.org/10.1001/archopht.1986.01050190079043>

565 Large, D. R., Kim, H., Merenda, C., Leong, S., Harvey, C., Burnett, G., & Gabbard,
566 J. (2019). Investigating the effect of urgency and modality of pedestrian alert
567 warnings on driver acceptance and performance. *Transportation Research Part F:*
568 *Traffic Psychology and Behaviour*, 60, 11-24.
569 <https://doi.org/10.1016/j.trf.2018.09.028>

570 Li, X., Farrukh, M., Lee, C., Khreis, H., Sarda, S., Sohrabi, S., Zhang, Z., &
571 Dadashova, B. (2022). COVID-19 impacts on mobility, environment, and health of
572 active transportation users. *Cities*, 103886.
573 <https://doi.org/10.1016/j.cities.2022.103886>

574 McMurdo, M. E., & Gaskell, A. (1991). Dark adaptation and falls in the elderly.
575 *Gerontology*, 37(4), 221-224. <https://doi.org/10.1159/000213264>

576 Moschner, C., & Baloh, R. W. (1994). Age-Related Changes in Visual Tracking.
577 *Journal of Gerontology*, 49(5), M235-M238.
578 <https://doi.org/10.1093/geronj/49.5.M235>

579 Munoz, D. P., Broughton, J. R., Goldring, J. E., & Armstrong, I. T. (1998). Age-
580 related performance of human subjects on saccadic eye movement tasks.
581 *Experimental Brain Research*.

582 Myers, R. S., Ball, K. K., Kalina, T. D., Roth, D. L., & Goode, K. T. (2000). Relation
583 of Useful Field of View and other Screening Tests to on-Road Driving Performance.
584 *Perceptual and Motor Skills*, 91(1), 279-290.
585 <https://doi.org/10.2466/pms.2000.91.1.279>

586 ONISR. (2019). *Bilan 2019 de la sécurité routière | Observatoire national*
587 *interministériel de la sécurité routière*. [https://www.onisr.securite-](https://www.onisr.securite-routiere.gouv.fr/etat-de-l-insecurite-routiere/bilans-annuels-de-la-securite-routiere/bilan-2019-de-la-securite-routiere)
588 [routiere.gouv.fr/etat-de-l-insecurite-routiere/bilans-annuels-de-la-securite-](https://www.onisr.securite-routiere.gouv.fr/etat-de-l-insecurite-routiere/bilans-annuels-de-la-securite-routiere/bilan-2019-de-la-securite-routiere)
589 [routiere/bilan-2019-de-la-securite-routiere](https://www.onisr.securite-routiere.gouv.fr/etat-de-l-insecurite-routiere/bilans-annuels-de-la-securite-routiere/bilan-2019-de-la-securite-routiere)

590 Owsley, C. (1994). Vision and driving in the elderly. *Optometry and Vision Science: Official Publication of the American Academy of Optometry*, 71(12), 727-735.
591 <https://doi.org/10.1097/00006324-199412000-00002>
592

593 Owsley, C. (2011). Aging and vision. *Vision Research*, 51(13), 1610-1622.
594 <https://doi.org/10.1016/j.visres.2010.10.020>

595 Owsley, C., Sekuler, R., & Siemsen, D. (1983). Contrast sensitivity throughout
596 adulthood. *Vision Research*, 23(7), 689-699. [https://doi.org/10.1016/0042-](https://doi.org/10.1016/0042-6989(83)90210-9)
597 6989(83)90210-9

598 Oxley, J., Fildes, B., Corben, B., & Langford, J. (2006). Intersection design for older
599 drivers. *Transportation Research Part F: Traffic Psychology and Behaviour*, 9(5),
600 335-346. <https://doi.org/10.1016/j.trf.2006.06.005>

601 Pai, C.-W. (2011). Motorcycle right-of-way accidents—A literature review. *Accident*
602 *Analysis & Prevention*, 43(3), 971-982. <https://doi.org/10.1016/j.aap.2010.11.024>

603 Pai, C.-W., Hwang, K. P., & Saleh, W. (2009). A mixed logit analysis of motorists'
604 right-of-way violation in motorcycle accidents at priority T-junctions. *Accident;*
605 *Analysis and Prevention*, 41(3), 565-573. <https://doi.org/10.1016/j.aap.2009.02.007>

606 Ranchet, M., Cavallo, V., Dang, N.-T., & Vienne, F. (2016). Improving motorcycle
607 conspicuity through innovative headlight configurations. *Accident; Analysis and*
608 *Prevention*, 94, 119-126. <https://doi.org/10.1016/j.aap.2016.05.011>

609 Roenker, D. L., Cissell, G. M., Ball, K. K., Wadley, V. G., & Edwards, J. D. (2003).
610 Speed-of-processing and driving simulator training result in improved driving
611 performance. *Human Factors*, 45(2), 218-233.
612 <https://doi.org/10.1518/hfes.45.2.218.27241>

613 Rogé, J., El Zufari, V., Vienne, F., & Ndiaye, D. (2015). Safety messages and
614 visibility of vulnerable road users for drivers. *Safety Science*, 79, 29-38.
615 <https://doi.org/10.1016/j.ssci.2015.05.002>

616 Rogé, J., Ndiaye, D., & Vienne, F. (2014). Useful visual field training : A way to
617 improve elderly car drivers' ability to detect vulnerable road users. *Transportation*
618 *Research Part F: Traffic Psychology and Behaviour*, 26, 246-257.
619 <https://doi.org/10.1016/j.trf.2014.08.005>

620 Rogé, J., & Pébayle, T. (2009). Deterioration of the useful visual field with ageing
621 during simulated driving in traffic and its possible consequences for road safety.
622 *Safety Science*, 47(9), 1271-1276. <https://doi.org/10.1016/j.ssci.2009.03.012>

623 Rogé, J., Pébayle, T., El Hannachi, S., & Muzet, A. (2003). Effect of sleep
624 deprivation and driving duration on the useful visual field in younger and older
625 subjects during simulator driving. *Vision Research*, 43(13), 1465-1472.
626 [https://doi.org/10.1016/s0042-6989\(03\)00143-3](https://doi.org/10.1016/s0042-6989(03)00143-3)

627 Rogé, J., Pébayle, T., Lambilliotte, E., Spitzenstetter, F., Giselbrecht, D., & Muzet,
628 A. (2004). Influence of age, speed and duration of monotonous driving task in traffic

629 on the driver's useful visual field. *Vision Research*, 44(23), 2737-2744.
630 <https://doi.org/10.1016/j.visres.2004.05.026>

631 Rumar, K. (1990). The basic driver error : Late detection. *Ergonomics*, 33(10-11),
632 1281-1290. <https://doi.org/10.1080/00140139008925332>

633 Salthouse, T. A. (1996). The processing-speed theory of adult age differences in
634 cognition. *Psychological Review*, 103(3), 403-428. <https://doi.org/10.1037/0033-295X.103.3.403>

636 Scialfa, C. T., Kline, D. W., & Lyman, B. J. (1987). Age differences in target
637 identification as a function of retinal location and noise level : Examination of the
638 useful field of view. *Psychology and Aging*, 2(1), 14-19.
639 <https://doi.org/10.1037//0882-7974.2.1.14>

640 Sekuler, A. B., Bennett, P. J., & Mamelak, M. (2000). Effects of aging on the useful
641 field of view. *Experimental Aging Research*, 26(2), 103-120.
642 <https://doi.org/10.1080/036107300243588>

643 Sekuler, R., & Ball, K. (1986). Visual localization : Age and practice. *Journal of the*
644 *Optical Society of America. A, Optics and Image Science*, 3(6), 864-867.
645 <https://doi.org/10.1364/josaa.3.000864>

646 Sims, R. V., McGwin, G., Allman, R. M., Ball, K., & Owsley, C. (2000). Exploratory
647 study of incident vehicle crashes among older drivers. *The Journals of Gerontology.*
648 *Series A, Biological Sciences and Medical Sciences*, 55(1), M22-27.
649 <https://doi.org/10.1093/gerona/55.1.m22>

650 Snowden, R. J., & Kavanagh, E. (2006). Motion perception in the ageing visual
651 system : Minimum motion, motion coherence, and speed discrimination thresholds.
652 *Perception*, 35(1), 9-24. <https://doi.org/10.1068/p5399>

653 Staplin, L. (1995). Simulator and field measures of driver age differences in left-turn
654 gap judgments. *Transportation Research Record*, 1485.
655 <https://trid.trb.org/view/451819>

656 Tabone, W., de Winter, J., Ackermann, C., Bärghman, J., Baumann, M., Deb, S.,
657 Emmenegger, C., Habibovic, A., Hagenzieker, M., Hancock, P. A., Happee, R.,
658 Krems, J., Lee, J. D., Martens, M., Merat, N., Norman, D., Sheridan, T. B., &
659 Stanton, N. A. (2021). Vulnerable road users and the coming wave of automated
660 vehicles : Expert perspectives. *Transportation Research Interdisciplinary*
661 *Perspectives*, 9, 100293. <https://doi.org/10.1016/j.trip.2020.100293>

662 Van Elslande, P., Fournier, J.-Y., & Jaffard, M. (2012). In-depth analysis of road
663 crashes involving powered two-wheelers vehicles : Typical human functional failures
664 and conditions of their production. *Work (Reading, Mass.)*, 41 Suppl 1, 5871-5873.
665 <https://doi.org/10.3233/WOR-2012-0978-5871>

666 WHO. (2018). *Global status report on road safety 2018 : Summary* (World Health
667 Organization).

