



HAL
open science

Impact of interface design on drivers' behavior in partially automated cars: An on-road study

Noé Monsaingeon, Loïc Caroux, Axelle Mouginé, Sabine Langlois, Céline Lemerrier

► To cite this version:

Noé Monsaingeon, Loïc Caroux, Axelle Mouginé, Sabine Langlois, Céline Lemerrier. Impact of interface design on drivers' behavior in partially automated cars: An on-road study. *Transportation Research Part F: Traffic Psychology and Behaviour*, 2021, 81, pp.508-521. 10.1016/j.trf.2021.06.019 . hal-03322187

HAL Id: hal-03322187

<https://hal.science/hal-03322187v1>

Submitted on 2 Aug 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.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

23 the test were also transcribed and coded. Results revealed shorter response times for
24 questions on speed with the exocentric and multimodal HMI. The duration and number of
25 fixations on the speedometer were also greater with the driving-centered HMI. The
26 exocentric and multimodal HMI helped drivers understand the functioning of the system, but
27 was more visually distracting than the traditional HMI. Both HMIs caused mode confusions.
28 The use of a multimodal HMI can be beneficial and should be prioritized by designers. The
29 use of auditory feedback to provide information about the level of automation needs to be
30 explored in longitudinal studies.

31

32 KEYWORDS

33 automated vehicles, human-machine interface, multimodal interface, mode transition,
34 verbatim, eye tracking

35

36

37

38 1. INTRODUCTION

39 The scientific literature identifies inattention while driving as the main cause of road
40 accidents, with more than 70% of car crashes involving inattention or fatigue (Dingus, Neale,
41 Klauer, Petersen, & Carroll, 2006; Lemercier, Pêcher, Berthié, et al., 2014; Victor, Dozza,
42 Bärghman, et al. 2015; Wang, Knipling, & Goodman, 1996). In a society where the priority is
43 to substantially increase road safety, automated cars appear to be the solution for reducing
44 the human factor in road accidents. However, as vehicles become more automated, the
45 collaboration between the driver and the system also becomes more complex. Partially

46 automated vehicles can take charge of some parts of the driving activity. The driver and the
47 system therefore have to work as a team, as they share control of the vehicle. For this team
48 to be efficient, its two members need to communicate via a human-machine interface
49 (HMI). Communication can take place via auditory, haptic and visual displays, as well as via
50 controls. The term *HMI* is used here to encompass all the explicit and implicit forms of
51 communication between the driver and the system. In automated vehicles, the precise role
52 of the driver depends on the state of the automated system. An increasing level of
53 automation means an increasing amount of information to be displayed. Drivers therefore
54 have to be capable of finding the right information, in order to know which role they need to
55 play in the team. The present study investigated how the design of the HMI in partially
56 automated vehicles influences drivers' understanding of the level of automation and the
57 functioning of the system. In the present exploratory study, two vehicles were driven on
58 road to evaluate the impact of two different HMIs in an ecological setting.

59

60 **1.1. Automated driving**

61 Highly automated cars are expected to arrive on the market within the next few decades.
62 The idea behind automation is that the system replaces the driver in the operational,
63 tactical, and strategic control of the vehicle (Michon, 1985), allowing the driver to devote
64 attentional resources to other activities (e.g., reading, working, or talking to other
65 passengers). Six levels of automation have been established, based on the driver's and
66 system's respective degrees of control (SAE, 2018). The present study focused on vehicles
67 equipped with Level 1 and Level 2 systems. At Level 1, the driver is responsible for the
68 operational, tactical and strategic control of the vehicle. Level 2 vehicles are classified as
69 *partially automated* vehicles, as the car can partially perform the driving activity. Relying on

70 adaptive cruise control (ACC) and lane centering assist (LCA), the system controls the
71 vehicle's longitudinal and lateral movements. However, even if the vehicle drives itself,
72 drivers are not passive, as they must monitor the vehicle's environment and behavior.
73 Operational control is therefore carried out by the system, but the driver is in charge of
74 strategic and tactical control.

75 Humans do not perform well in prolonged monitoring activities. According to Bainbridge
76 (1985), it is very hard for them to maintain their visual attention on tasks in which very little
77 happens for more than 30 minutes. In highly automated vehicles, this can lead to
78 disengagement in the monitoring activity and engagement in secondary tasks (Carsten, Lai,
79 Barnard, Jamson, & Merat, 2012). The problem is that the system requires specific
80 conditions to operate properly. For LCA, the main condition is to have clear lane markings,
81 so if these markings cease to be visible, the LCA may switch itself off. In this scenario, drivers
82 must realize that the automated system has switched itself off and that they therefore have
83 to take over control of the vehicle.

84

85 **1.2. Issues with existing Level 2 vehicles**

86 Existing partially automated vehicles appear to have difficulty communicating the correct
87 information to the driver. Drivers have been found to be less inclined to look at the road
88 when using the Tesla Model S with Level 2 systems activated than they are when using a
89 Level 1 or Level 0 (Gaspar & Carney, 2019). These authors found that drivers potentially
90 over-relied on the system and were not fully aware of the role they still had to play. In a
91 naturalistic study featuring the Tesla Model S, Banks, Eriksson, O'Donoghue, and Stanton
92 (2018) observed confusion between the levels of automation. Participants were filmed and
93 recorded as they drove on the road for 40 minutes. The recorded behaviors were then

94 analyzed. At some point, several drivers let go of the steering wheel, in the mistaken belief
95 that they had activated the Level 2 automation. They only realized that they were confusing
96 modes of automation when they consulted the HMI display. Mode confusions can lead to
97 very hazardous situations, if the driver expects the vehicle to behave in a specific way and it
98 does not (Sarter & Woods, 1995). For example, if drivers think that the vehicle is in charge of
99 lateral control, they will not move the steering wheel in a bend, meaning that the vehicle
100 ploughs straight into the side of the road. Banks, Eriksson, O'Donoghue, and Stanton (2018)
101 suggested that one possible reason for these mode confusions is that drivers place too much
102 faith in the system, but hypothesized that the HMI's lack of transparency is the most likely
103 cause.

104

105 **1.3. Mental model**

106 As the relation between the driver and the system changes according to the degree of
107 automatization, so the HMI has to change too. Carsten and Martens (2019) recently
108 established goals that need to be achieved when designing HMIs for automated vehicles.
109 The first goal is to ensure that the driver understands the capabilities of the vehicle and the
110 level of automation that has been activated. To achieve this goal, HMIs need to adapt to the
111 new constraints that automation places on the driving activity. In the present study, we
112 compared two HMIs to evaluate which one came closer to meeting Carsten and Martens
113 (2019)'s first goal. HMIs need to foster accurate mental models and avoid mode confusions.
114 *Mental models* are the representations that humans have of a system's purpose, form,
115 functioning, state, and structure (see Seppelt & Victor, 2020, for a more detailed definition).
116 In the context of automated driving, drivers with an accurate mental model know when the

117 automated system has been activated or deactivated. They also understand which situations
118 are appropriate for using the system. Driving-related mental models are influenced by three
119 main factors: experience, training, and HMI transparency (Endsley, 2017). Experience came
120 into play in Forster et al. (2019)'s study, as the more situations the participants encountered,
121 the more accurate their mental models became. These findings were supported by Strand et
122 al. (2018)'s study, where three purchasers of Level 2 vehicles were interviewed as they
123 familiarized themselves with the system. Results revealed that although they refined their
124 mental models, their primary representations of the system influenced the subsequent
125 formation of their mental models. Blömacher et al. (2020) reached the same conclusion.
126 They gave correct or incorrect information to drivers regarding the functioning of the system
127 before they used a Level 3 vehicle. Results revealed that the veracity of the information
128 given at the beginning influenced the formation of mental models and reaction time at take-
129 overs. However, although experience with an automated system allows individuals to form
130 accurate mental models, it can sometimes lead them to disengage from the monitoring task
131 (Solís-Marcos & Kircher, 2019). These results highlight the influence of training and
132 experience on the formation of mental models. Moreover, they support the idea that the
133 driver's first impression of the system is crucial. The information displayed by the HMI needs
134 to clearly be understood, so that the driver forms an accurate mental model at the very
135 beginning of the interaction. To be understood, the HMI must be tailored to the human's
136 cognitive limits and to the specificity of driving an automated vehicle. Several cognitive
137 models have been built to inform design in transportation and are discussed in the next
138 section.

139

140 **1.4. Models of driving activity**

141 Michon (1985) proposed a very classic hierarchical categorization of the driving task
142 (operational level, tactical level, and strategic level). Stanton et al. (2001) used this
143 categorization to develop a model of the driving task that focused on the interaction of the
144 driver with the automated system. This model is composed of three subtasks: navigation
145 (choosing the itinerary), control (whether to turn right or left at the next intersection), and
146 hazard identification (avoiding pedestrians, trees, buildings, respecting speed limits).
147 Automated driving consists in supporting or replacing the human in one or more of those
148 tasks. ACC, for example, replaces the driver in the longitudinal control of the car. Mental
149 workload is supposed to decrease as the human has fewer tasks to perform, but appears to
150 stay stable with automation (Stanton et al., 2001). This is because although automation
151 replaces the driver, reducing the number of driving-related tasks, it increases the number of
152 tasks related to monitoring the system's activity, meaning that the mental workload remains
153 the same. This issue could be addressed through the design of HMIs, which are not
154 necessarily adapted to the changes in the driving activity. Interfaces designed to help drivers
155 perform their tasks and which take their cognitive limits into account might be more
156 effective.

157

158 **1.5. Design solution to improve interaction with the automated system**

159 When driving, humans have to process a large amount of visual information from both the
160 cockpit and the external environment. One model that is relevant to HMI design because it
161 takes account of humans' cognitive limitations is the multiple resource model developed by

162 Wickens (2008). Currently used in the design of interfaces for complex environments that
163 require simultaneous information processing, this model can predict the allocation of
164 attentional resources to tasks performed simultaneously according to their qualitative
165 characteristics. For the same amount of information, tasks in different sensory modalities
166 (e.g., visual and auditory) are performed better than tasks in a single sensory modality.
167 Accordingly, HMIs that use multiple sensory modalities to communicate should elicit a more
168 effective distribution of attentional resources. Zhang et al. (2019)'s meta-analysis showed
169 that HMIs providing a combination of visual and auditory or tactile information allow take-
170 over time to be reduced in Level 3 vehicles. HMIs using two or more sensory channels to
171 inform the driver on the state of automation help the latter understand which actions have
172 to be performed. Use of a similar HMI in Level 2 vehicles could also improve interaction
173 between the automated system and the driver.

174

175 **1.6. Research question and hypotheses**

176 The number of studies carried out on open roads with Level 2 vehicles is increasing (Banks,
177 Eriksson, O'Donoghue, & Stanton, 2018; Endsley, 2017; Solís-Marcos & Kircher, 2019). So far,
178 studies have investigated the impact on the driver of driving an automated vehicle at a
179 subjective or cognitive level. However, none of them have compared different HMI designs,
180 even though some HMIs may be safer than others. According to the multiple resource model
181 and previous studies of Level 3 vehicles (Wickens, 2008; Zhang et al., 2019), a driving-
182 centered HMI that takes the limitations of the human cognitive system into account by
183 providing information via multiple resource channels (i.e., visual and auditory) should be
184 more easily understood and elicit more accurate mental models, compared with a classic
185 visual-only vehicle-centered HMI. We therefore asked whether a multimodal HMI centered

186 on the driving activity and the limitations of the human cognitive system is more efficient
187 than a visual HMI centered on the state of the advanced driver-assistance system (ADAS). By
188 comparing the on-road usage of two existing vehicle HMIs, we sought to identify which HMI
189 characteristics help drivers to understand the capabilities and automation status of their
190 vehicle. We hypothesized that compared with the classic visual vehicle-centered HMI, an
191 exocentric and multimodal driving-centered HMI allows the driver to have a better
192 understanding of how the vehicle operates when the automated system is activated. This
193 translates as better retrieval of information about the system, fewer visual fixations on the
194 cluster, and fewer mode confusions. To test this hypothesis, participants drove one of two
195 vehicles equipped with HMIs that fitted our description (i.e., driving-centered HMI vs.
196 vehicle-centered HMI) on an open road while using automated systems.

197

198 2. MATERIAL & METHOD

199 2.1. Participants

200 We recruited 20 volunteers (19 men) aged 27-59 years ($M = 40.80$, $SD = 8.53$). They had held
201 a driving license for a mean period of 21 years. The volunteers had no visual, even corrected
202 (myopia, astigmatism, presbyopia), or auditory impairment. They were recruited among
203 employees at Renault Group's Technocentre site in France. They were not paid, and they all
204 signed an informed consent form. These volunteers were randomly assigned to one of the
205 two vehicles (10 participants for each vehicle). The main criterion for recruitment was to
206 have never driven the vehicle to which they were assigned. Seven participants had already
207 driven a Level 1 vehicle before the experiment: two in the vehicle-centered HMI group, and

208 five in the driving-centered HMI group. None of the participants had driven Level 2 vehicles
209 before. All participants were familiar with an automatic gearbox and cruise control.

210



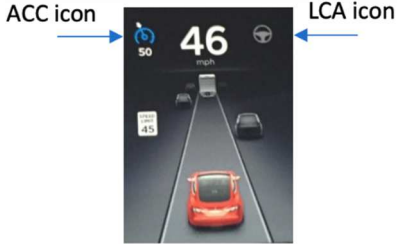

211 2.2. HMIs and embedded systems

212 We selected two vehicles with similar types of driving assistance (ACC and LCA) but different
213 HMIs. The HMI in the first car provided an exocentric representation of the road scene and a
214 multimodal display interface. It displayed relevant information for driving a partially-
215 automated vehicle and took the limitations of the human cognitive system into account
216 (Blömacher et al., 2020; Forster et al., 2019; Strand et al., 2018). This HMI is therefore
217 referred to hereafter as the *driving-centered HMI*. The HMI in the second car only provided
218 visual information about the state of the ADAS, and is therefore referred to hereafter as the
219 *vehicle-centered HMI*. These HMIs differed on three major points: 1) the representation of
220 the information regarding driving assistance; 2) the location of this information; and 3) the
221 modalities used. The driving-centered HMI represented information in an exocentric form
222 (Tesla Model S, software version 8.0). The detection of road markings and other vehicles was
223 indicated on the cluster. Icons representing the activation of Level 1 or Level 2 automation
224 were displayed at the top of the cluster. The visual feedback was supplemented with
225 auditory signals. When the Level 2 automated system (ACC + LCA) was activated or
226 deactivated, a sound was emitted. The sound of activation was a two-note rising tone. The
227 sound of deactivation was a two-note falling tone. By contrast, the vehicle-centered HMI
228 only provided visual feedback (Volvo XC60). Pictograms representing the activation of
229 automation were located on the cluster and the head-up display (HUD). The steering wheel
230 was slightly stiffer at Level 2 than at Level 1 for both vehicles, but the strength needed to
231 override the lateral control was slightly greater for the driving-centered HMI than for the

232 **vehicle-centered HMI**. A description of the technical features of the two HMIs is provided in
 233 Table 1. Both vehicles required specific conditions to activate their automated system. Two
 234 clear road markings were necessary for the activation of Level 2. The driving-centered HMI
 235 indicated the availability of the automation by highlighting the road marking representation
 236 in gray on the cluster. If the system could no longer detect one of the road markings, it
 237 switched itself off. The main reason for deactivation was failure to detect a road marking.
 238 The one major difference between the two types of automation was that the Tesla was able
 239 to perform automatic lane changes. When Level 2 was activated, activation of the turn
 240 signals automatically resulted in a lane change.

241

242 Table 1: Display of onboard system activation by the driving-centered HMI and vehicle-
 243 centered HMI. The HUD of the vehicle-centered HMI is shown on the righthand side.

		Driving-centered HMI	Vehicle-centered HMI
No assisted systems			
Display of activated systems	ACC (Level 1)		

	ACC + LCA (Level 2)	
Activation commands	ACC (Level 1)	<p>ACC steering-wheel button</p>
	ACC + LCA (Level 2)	<p>LCA steering-wheel button</p>

244

245



246

247 Figure 1: Photos showing the instrument panel and forward views of each vehicle with either
 248 the driving-centered HMI (left) or vehicle-centered HMI (right). The letter A indicates the icon
 249 displayed when LCA and ACC are activated.

250 **2.3. Task**

251 Participants had to drive the vehicle they were assigned on a pre-established circuit. They
252 were instructed to drive normally, as though they were driving their own car. They were
253 encouraged to use the automated system whenever they wanted and whenever they felt
254 safe. They were instructed to respect the speed limits and traffic laws. A satnav system
255 indicated the directions both visually (on the central multimedia screen) and verbally in each
256 vehicle. During the drive, the experimenter asked the driver questions. The questions were
257 asked when the driver was cognitively available (e.g., while driving along a straight road), so
258 as not to increase cognitive load. Drivers had to respond as spontaneously and sincerely as
259 possible. These questions were designed to evaluate the drivers' understanding of the
260 vehicle's status and functioning.

261

262 **2.4. Road circuit**

263 The road circuit was a 45-minute round trip along public roads and highways, at an average
264 speed of 75.75 km/hr. First, participants drove along a divided highway for 4 km. Then came
265 a 9-km stretch of motorway (four lanes of traffic travelling in each direction for 4 km, then
266 three lanes in each direction for 5 km), followed by a further 11 km on a divided highway.
267 They then turned round at a roundabout, and followed the same itinerary in the opposite
268 direction until they reached their starting point. For the entire round trip, the two sides of
269 the road were separated from each other by a central reservation, and the road was mostly
270 straight or slightly curved.

271

272 **2.5. On-road questioning**

273 Participants were asked on-road questions to assess their awareness of the functioning and
274 level of automation of the vehicle they were driving. To answer the questions, drivers either
275 had to look for the requested information in their environment or else retrieve it from
276 memory. The questions covered four topics. The first type of question (*system questions*)
277 was system-oriented and concerned the status and functioning of the vehicle (e.g. “What is
278 your current speed?” or “Is the ACC activated?”). The second type of question (*personal*
279 *questions*) covered personal information about the driver (e.g. “Do you have children?”). The
280 third type of question (*interior questions*) covered information accessible inside the car (e.g.
281 “What radio station are we listening to?”). The last type of question (*exterior questions*)
282 covered information accessible outside the car (e.g. “Is the car behind us black?”) (see
283 Appendix 1 for the list of questions). The system questions were mixed with the other types
284 of questions, so that participants were not able to prepare their answers. The order of the
285 questions was randomized. The answers to the questions were recorded. The start and end
286 times of each question and each answer were extracted with Audacity software for the
287 vehicle-centered HMI group, and BeGaze software for the driving-centered HMI group.

288

289 **2.6. Eye tracker**

290 Our choice of eye-tracking technique took into consideration the areas fixated by drivers
291 during the experiment while answering the questions. This measure allowed us to ensure
292 that drivers knew where to find the required information. We used SensoMotoric
293 Instruments (SMI) Eye Tracking Glasses, which are equipped with infrared sensors to
294 monitor eye movements (saccades, fixations and blinks) and a front camera to record the
295 field of vision. The eye-tracking data were recorded at a sampling frequency of 60 Hz. The

296 glasses were connected to a mobile phone (Samsung Galaxy Note 4) that allowed us to
297 power the glasses, calibrate the gaze measures, monitor the visual behavior in real time, and
298 store the video and audio recordings. Eye-tracking data were extracted and processed using
299 BeGaze 3.7 software. We also used this software to map the fixations. This mapping
300 consisted in associating each recorded fixation with an area of interest (AOI). BeGaze
301 software then calculated the gaze count and duration for each AOI. There is no explicit
302 definition of a gaze in the BeGaze software, but we worked on the principle that a gaze is a
303 fixation on an AOI if it remains within a 100-pixel area for around 20 ms.

304

305 **2.7. Drivers' comments**

306 During the tests, participants were free to comment on their driving experience. The
307 comments made during the entire experiment were recorded with the eye-tracker's
308 microphone. As the microphone was placed on the bridge of the glasses not far from the
309 mouth, the audio recording was good enough to hear the participant's comments. These
310 comments were transcribed and classified. This method served to complement the eye-
311 tracking and on-road questioning measures. The goal of the analysis was to identify mode
312 confusions, which was not possible with the quantitative data. It also served to collect
313 information about which aspects of the HMI allowed drivers to understand the automated
314 systems.

315

316 **2.8. Procedure**

317 Participants began the experiment by filling out a questionnaire. The training phase then
318 began. During this phase, the basic controls were explained to the participants, as were

319 specific aspects of the activation and deactivation of the automated system. The driver's
320 responsibilities regarding the use of each assistive device were explained to participants.
321 Afterwards, the participants were equipped with the eye-tracking glasses. The volunteers
322 then drove the vehicle for about 10 minutes on a straight road. Once the experimenter was
323 sure that the volunteers were able to control the car and its features, the experimental
324 phase began. Participants drove for about 45 minutes, following the pre-established circuit
325 on the satnav. The experimenter sat in the front passenger seat and asked the participant
326 questions without disturbing him or her. Finally, the experiment ended with a questionnaire
327 and an interview.

328

329 **2.9. Experimental design**

330 A 2 (between-participants) x 4 (within-participants) experimental mixed design was used.
331 The first factor we manipulated was the driven vehicle, and it had two modalities (driving-
332 centered HMI vs. vehicle-centered HMI). The second manipulated factor was type of
333 question, and it had four modalities (system questions vs. personal questions vs. interior
334 questions vs. exterior questions).

335

336 **2.10. Measures & analysis**

337 **2.10.1. Response times to on-road questions**

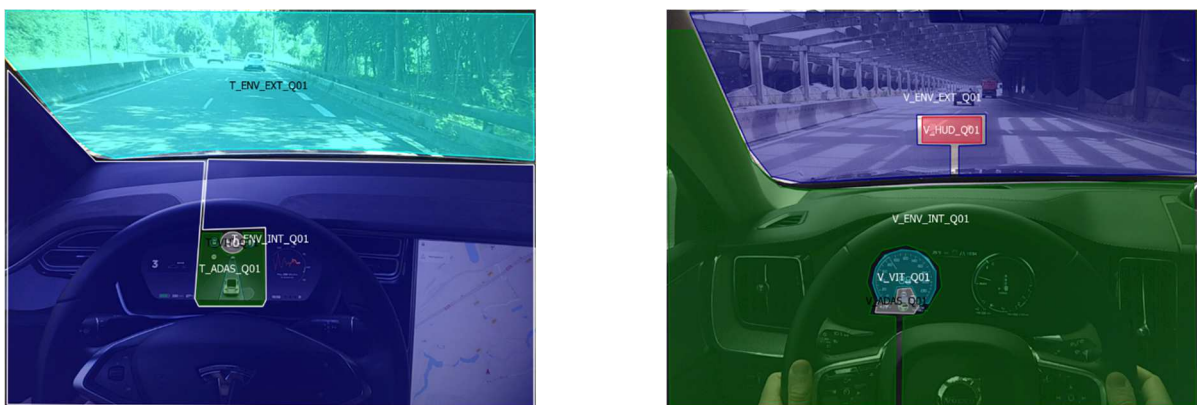
338 For the audio recordings of the drivers answering the on-road questions, we began by
339 extracting the start and end times of each question and each answer. To measure the time
340 needed by participants to access the information and verbalize it, we calculated the interval
341 between the end of the question and the end of the answer. The assumption of normality of

342 residuals for mean response times was not met for the driving-centered HMI group. We ran
343 a mixed variance analysis on means of median response times, with type of questions as a
344 within-participants factor, and HMI type as a between-participants factor. To investigate
345 HMI use in greater depth, the questions were analyzed separately for each system. Given
346 the small sample, we ran a two-tailed Mann-Whitney U test for each system question, with
347 HMI type as a between-participants factor. The Mann-Whitney U test is a nonparametric
348 test that allows two small independent samples to be compared, in order to decide whether
349 they are equally distributed or not (Mann & Whitney, 1947).

350

351 **2.10.2. Fixation count and duration**

352 Gaze positions were coded on a reference image featuring all the AOIs. We used four or five
353 AOIs for each vehicle. For the driving-centered HMI group, the AOIs were the external
354 environment, the interior environment, the speed display, and the ADAS. The vehicle-
355 centered HMI had the same AOIs, plus the HUD (see Fig. 2). For each AOI, we extracted the
356 mean fixation duration and number of fixations during an 8-second window, extending from
357 4 s before to 4 s after the end of the question. This window allowed us to consider the
358 processing time (i.e. listening to the question, finding the answer, and verbalizing it). The
359 analyses compared the driving-centered HMI group and the vehicle-centered HMI group on
360 the mean duration and number of fixations. Owing to the small sample and the non-respect
361 of the normality of residuals for the driving-centered HMI group, we ran nonparametric
362 analyses. Nonparametric Wilcoxon rank-sum tests were carried out, with group as a
363 between-participants factor for both measures. The same analyses were carried out
364 separately for each system question on each AOI, except for the HUD. **No participants were**
365 **excluded from the analysis** ($N = 20$).



366 Figure 2: AOIs used in the driving-centered HMI (left) and vehicle-centered HMI (right).

367

368 The HUD displayed the vehicle's speed and information about the automated system (see
369 Table 1). The HUD AOI was too small for us to know for certain whether the fixations were
370 on the speed information or on the automation information. We therefore did not include
371 the HUD in the comparison between the two HMIs. We can, however, assume that during
372 the questions about speed or the automated system, drivers looked at the HUD to obtain
373 the relevant information. To consider the fixations on the HUD, we calculated descriptive
374 statistics. For the vehicle-centered HMI group, we calculated the means and standard errors
375 of fixation count and duration on the HUD, speed display, and ADAS AOIs. The same
376 operation was repeated for the driving-centered HMI group, minus the HUD. We then
377 calculated the mean fixation count and duration for each AOI for the questions on speed.
378 We repeated the same operation for the questions on the automated system.

379

380 **2.10.3. Classification of drivers' comments**

381 The drivers' comments about the HMI in relation to the automated system were transcribed
382 and categorized, using a bottom-up approach. Three categories and 15 subcategories
383 emerged. The three categories were (1) activation of ACC (Level 1) or ACC combined with
384 LCA (Level 2), (2) deactivation of ACC (Level 1) or ACC combined with LCA (Level 2), and 3)
385 mode confusions. Each category contained five subcategories. These subcategories
386 corresponded to the communication medium between driver and system: (1) visual
387 information display on the cluster; (2) auditory signals; (3) haptic feedback; (4) kinesthetic
388 sensations; (5) commands; and (6) HUD (only for the vehicle-centered HMI group). The
389 analysis consisted in counting the number of comments in each category and subcategory.

390

391 **4. RESULTS**

392 After indicating the response times for each type of question and each vehicle, we compare
393 the vehicles on the system questions. Next, we describe the analysis of the eye-tracking
394 data, comparing the two groups on fixation count and duration for the system questions.
395 Finally, we describe the classification of the drivers' comments for each vehicle.

396

397 **4.1. Response times**

398 We found a difference in the means of median response times between the groups and
399 types of question (see Table 2). The ANOVA revealed an effect of type of question on
400 response times, $F(3, 16) = 7.01, p < .001$, indicating that participants needed different
401 amounts of time to answer the system questions, personal questions, interior questions, and
402 exterior questions. Less time was needed to answer the system questions than either the
403 personal questions, interior questions, or exterior questions. Regarding the effect of type of
404 HMI on response times for each type of question, the mixed ANOVA revealed no significant
405 effect, $F(3, 16) = 3.53, p = .077, d = .67$. This means that participants took more or less the
406 same time to answer each type of question regardless of which group they belonged to (see
407 Fig. 3). No interaction effect was observed between type of question and group ($p > .1$). For
408 the system questions, groups differed slightly on the means of median response times (see
409 Table 2). However, this difference was not significant ($p > .1$). Regarding the personal
410 questions, we found a slight difference between the groups, but tests indicated that it was
411 not significant ($p > .1$). This suggests that personal questions were not influenced by type of
412 HMI. For the interior questions, there was a small difference in mean response times, as well
413 as in standard deviations. However, tests indicated that these differences were not
414 significant ($p > .1$). For the exterior questions, we found a substantial difference. Driving-

415 centered HMI drivers seemed to answer questions about the external environment quicker
416 than vehicle-centered HMI drivers did. Again, however, tests indicated that this difference
417 was not significant ($p > .1$). We then compared the two groups on response times for each
418 system question.

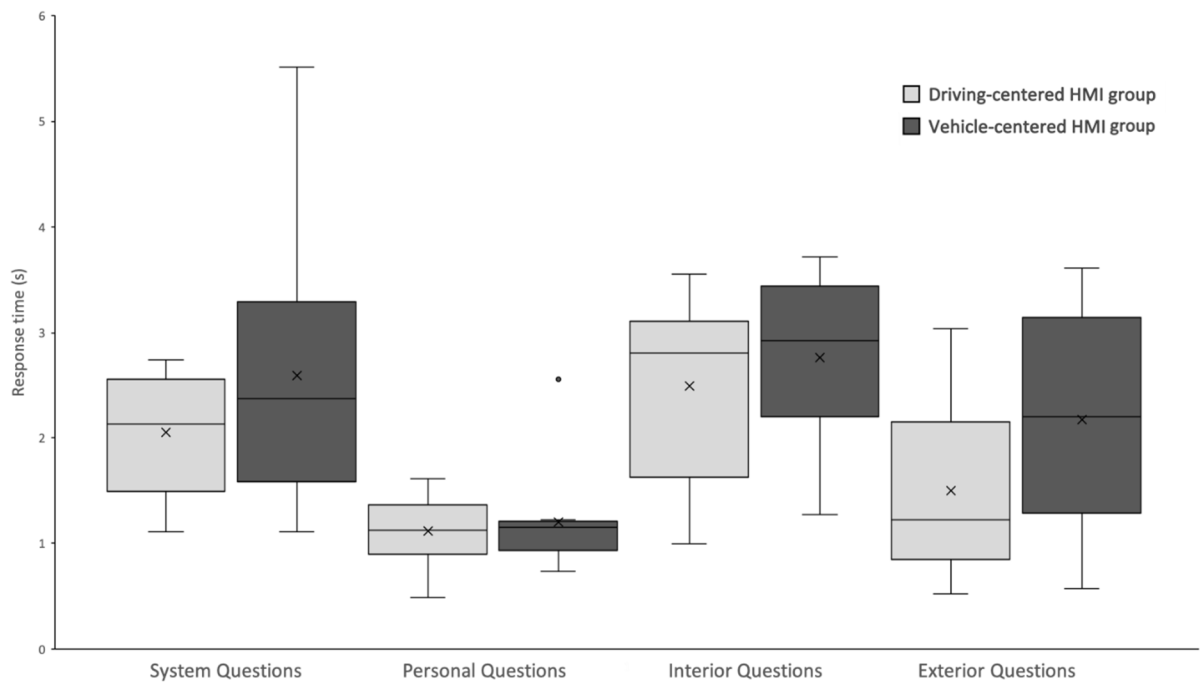
419

420

421 Table 2: Mean (standard deviation) response times depending on HMI and question type.

	System Questions	Personal Questions	Interior Questions	Exterior Questions
Driving-centered HMI group	1.61 s (0.46)	1.17 s (1.08)	2.27 s (0.84)	1.50 s (0.86)
Vehicle-centered HMI group	2.16 s (1.50)	1.13 s (0.41)	2.55 s (1.04)	2.17 s (0.74)

422



423

424 Figure 3: Boxplot of response times depending on type of question and HMI group.

425

426 **4.2. System questions**

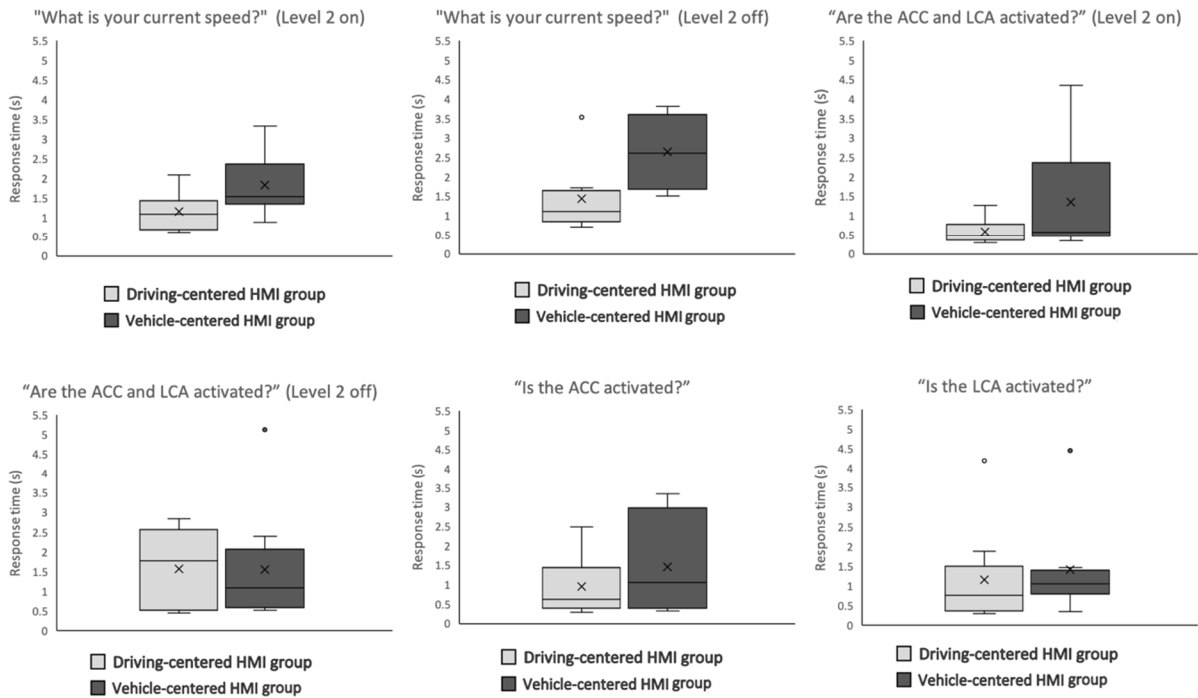
427 The Mann-Whitney tests on each system question revealed significant differences between
 428 the two groups (see Fig. 4). For the question "What is your current speed?" when the
 429 automated system was active, analysis revealed a significant difference between the groups,
 430 $U = 14, p = .02, r = -0.55$. On average, driving-centered HMI users gave their speeds faster
 431 ($Mdn = 1.15$) than vehicle-centered HMI users did ($Mdn = 1.82$). For the question "What is
 432 your current speed?" when the automated system was inactive, analysis revealed no
 433 significant effect, $U = 6, p = .07, r = -0.51$. Driving-centered HMI users responded slightly
 434 faster ($Mdn = 1.43$) than vehicle-centered HMI users did ($Mdn = 2.64$). Analysis of responses
 435 to the other system questions failed to reveal any significant differences ($p > .1$; see Table 3).
 436

437 Table 3: Sample sizes and median (interquartile range) response times depending on the
 438 question and the HMI. * $p < .05$.

System questions	Driving-centered HMI group	Vehicle-centered HMI group	Test results
"What is your current speed?" (Level 2 on)	$(n = 10)$ 1.08 s (0.74)	$(n = 8)$ 1.53 s (1.01) *	$U = 14, p =$.02, $r = -.55$
"What is your current speed?" (Level 2 off)	$(n = 9)$ 1.11 s (0.08)	$(n = 4)$ 2.61 s (1.91)	$U = 6, p = .07,$ $r = -.51$

“Are the ACC and LCA activated?” (Level 2 on)	(n = 10) 0.49 s (0.41)	(n = 9) 0.56 s (1.90)	$U = 30, p = .24, r = -.28$
“Are the ACC and LCA activated?” (Level 2 off)	(n = 9) 1.78 s (2.05)	(n = 9) 1.09 s (1.49)	$U = 43, p = .86, r = -.05$
“Is the ACC activated?”	(n = 10) 0.62 s (1.05)	(n = 10) 1.06 s (2.59)	$U = 36, p = .32, r = -.24$
“Is the LCA activated?”	(n = 9) 0.76 s (1.14)	(n = 8) 1.05 s (0.60)	$U = 25, p = .32, r = -.26$

439



440

441

442 Figure 4: Boxplot of response times depending on system question and HMI group.

443

444 4.3. Eye tracking

445 The subsequent analyses served to compare the two groups on each measure, each AOI, and
446 each system question. Because of the large number of analyses (more than 50), only the
447 significant effects and those tending toward significance are reported here. For the question
448 "What is your current speed?" when the ACC and LCA were active, no significant difference
449 was observed between the groups on the mean fixation time on the speedometer, $U = 17$, p
450 $= .06$, $r = -0.449$ (see Table 4). Driving-centered HMI users made slightly longer fixations on
451 the speedometer ($Mdn = 294$ ms) than vehicle-centered HMI users did ($Mdn = 75$ ms; see
452 Fig. 5). For the question "What is your current speed?" when in manual driving mode,
453 analysis revealed an effect of group on the number of fixations on the speedometer, $U = 3$, p
454 $= .02$, $r = -0.656$. Driving-centered HMI users looked at the speedometer more often ($Mdn =$
455 2) than vehicle-centered HMI users did ($Mdn = 0$). Groups did not differ significantly on
456 mean fixation time for this question, $U = 5.5$, $p = .07$, $r = -0.524$. On average, driving-centered
457 HMI users made slightly longer fixations ($Mdn = 523$ ms) on the speedometer than vehicle-
458 centered HMI users did ($Mdn = 0$ ms). For the question "Is the ACC activated?" when it was
459 activated, the test revealed no significant effect on the number of fixations on the ADAS AOI,
460 $U = 20.5$, $p = .07$, $r = -0.422$. Driving-centered HMI users tended to look slightly more often
461 ($Mdn = 6$) at the ADAS than vehicle-centered HMI users did ($Mdn = 0$). A significant
462 difference was observed for the number of fixations on the interior of the vehicle for the
463 same question, $U = 17$, $p = .03$, $r = -0.422$. Vehicle-centered HMI users ($Mdn = 1$) made more
464 fixations on the interior of the vehicle than driving-centered HMI users did ($Mdn = 0$). In

465 addition, there was a significant difference between the groups on mean fixation duration
 466 outside the vehicle for the same question, $U = 11$, $p = .009$, $r = -0.614$. Vehicle-centered HMI
 467 users ($Mdn = 5793$ ms) looked outside the vehicle for significantly longer time periods than
 468 the driving-centered HMI users did ($Mdn = 4066$ ms).

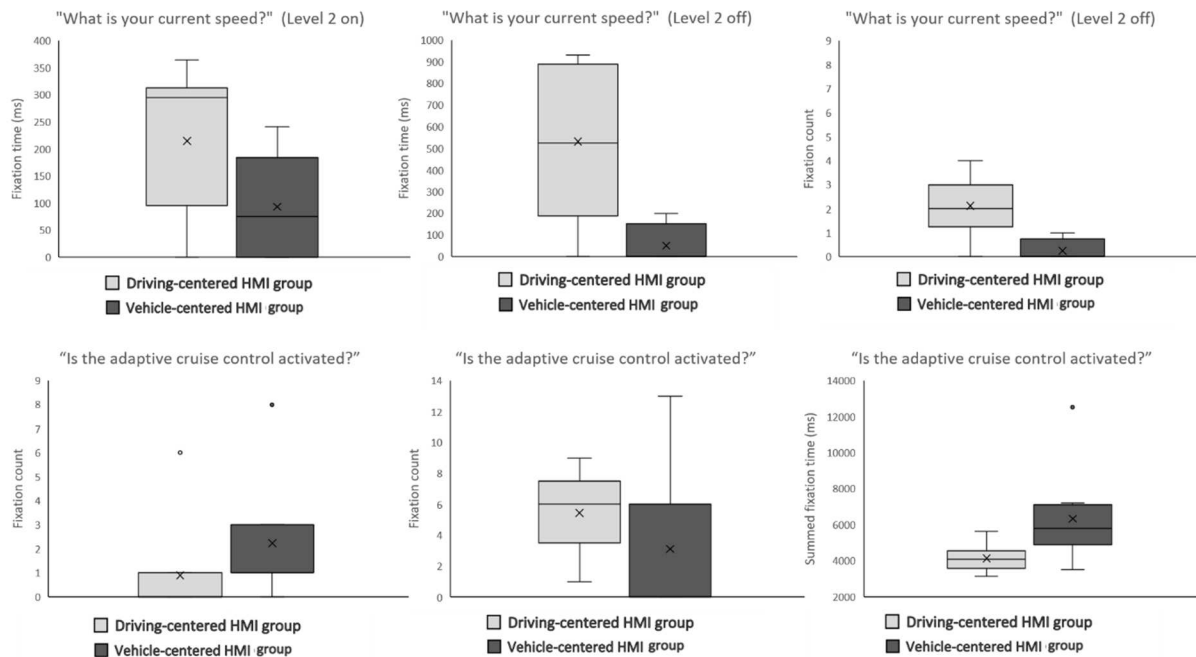
469

470 Table 4: Sample sizes, median (interquartile range) numbers and mean durations of fixations
 471 depending on the vehicle, and results of nonparametric analysis. Significant differences are
 472 in italics. * $p < .05$. ** $p < .01$.

Question	AOI	Measure	Driving-centered HMI	Vehicle-centered HMI	Test results
"What is your current speed?" (Level 2 on)	Speedometer	Fixation duration	<i>(n = 9)</i> 294 ms (194)	<i>(n = 8)</i> 75 ms (171)	<i>U = 17</i> <i>p = .06</i> <i>r = -0.45</i>
		Number of fixations	<i>(n = 8)</i> 2 (2.5)	<i>(n = 4)</i> 0 (1.25)	<i>U = 3</i> <i>p = .02</i> <i>r = -0.66</i>
"What is your current speed?" (Level 2 off)	Speedometer	Fixation duration	<i>(n = 8)</i> 211.6 ms (150)	<i>(n = 4)</i> 0 ms (171)	<i>U = 5.5</i> <i>p = .07</i> <i>r = -0.52</i>
		Number of fixations	<i>(n = 8)</i> 2 (2.5)	<i>(n = 4)</i> 0 (1.25)	<i>U = 3</i> <i>p = .02</i> <i>r = -0.66</i>

“Is the adaptive cruise control activated?”	ADAS	Number of fixations	(n = 9) 6 (3)	(n = 9) 0 (4)	$U = 20.5$ $p = .07$ $r = -0.42$
	Interior of the vehicle	Number of fixations	(n = 9) 0 (3)	(n = 9) 1 (4)	$U = 17$ $p = .03$ $r = -0.42$
	External environment	Summed fixation duration	(n = 9) 4066 ms (63)	(n = 9) 5793 ms (114)	$U = 11$ $p = .009$ $r = -0.61$

473



474

475 Figure 5: Boxplots of fixation counts and durations depending on the question and the HMI
476 group.

477

478 For the vehicle-centered HMI group, the number of fixations on the HUD and their mean
 479 duration were non-negligible (see Table 5). The number and duration of fixations on the
 480 HUD were the same as for the speedometer (for speed questions) and the ADAS (for
 481 automated system questions). This suggests that the HUD was used just as much as the
 482 speedometer and the ADAS to answer system questions.

483

484 Table 5: Mean (standard deviation) fixation count and duration on the HUD, speedometer
 485 and ADAS AOIs of the vehicle-centered HMI and driving-centered HMI groups for each type
 486 of question.

		Vehicle-centered HMI		Driving-centered HMI	
Question	AOI	Fixation count	Mean fixation duration	Fixation count	Mean fixation duration
Speed questions	Speedometer	3.20 (2.95)	146 ms (71)	2.40 (1.06)	227 ms (118)
	HUD	4.25 (2.25)	280 ms (117)		
System questions	ADAS	4.91 (3.61)	201 ms (124)	2.36 (1.47)	183 ms (103)
	HUD	3.20 (1.67)	336 ms (289)		

487

488 **4.4. Drivers' comments**

489 Every participant made spontaneous comments about the driving experience, HMI, and
490 functioning of the automated system. These comments are described separately for each
491 vehicle. We divided them into three categories: (1) activation of automated system, (2)
492 deactivation of automated system, and (3) mode confusions. We counted the number of
493 comments in each category. Most of the vehicle-centered HMI users referred to the cluster
494 to comment on the activation of the automated system (See Table 6). Four of the 10 vehicle-
495 centered HMI users referred to the HUD. One vehicle-centered HMI user referred to the
496 commands, and four to the haptic feedback. Finally, four participants in the vehicle-centered
497 HMI group reported relying on kinesthetic sensations. For the deactivation of the automated
498 system, three of the 10 vehicle-centered HMI users mentioned the commands. Only one
499 vehicle-centered HMI user reported using the cluster. The most frequently encountered
500 mode confusions for the vehicle-centered HMI drivers were between Levels 1 and 2. Three
501 vehicle-centered HMI users became confused because of unclear information on the cluster.
502 One vehicle-centered HMI user reported uncertainty or mode confusion between manual
503 driving and ACC (Level 1) when consulting the visual information on the cluster. Another
504 user reported mode confusion between manual driving and the ACC (Level 1) when using
505 the commands.

506

507 Table 6: Number of participants in the vehicle-centered HMI group (total number of
508 participants in the group) who commented about a specific modality of the HMI regarding
509 activation, deactivation, or mode confusions.

	Activation of	Deactivation of	Mode	Mode
--	---------------	-----------------	------	------

	automated system	automated system	confusion between manual driving and Level 1 systems	confusion between Level 1 and Level 2 systems
Visual	8 (10)	1 (10)	1 (10)	3 (10)
Commands	1 (10)	3 (10)	1 (10)	0
Haptic feedback	4 (10)	0	0	0
Kinesthetic sensations	4 (10)	0	0	0
HUD	4 (10)	0	0	0

510

511 Five of the 10 users of the driving-centered HMI reported relying on the visual modality of
512 the cluster to know if the automation was activated. Only one participant reported using the
513 auditory feedback. Two participants referred to the commands. One participant referred to
514 the haptic feedback, while another referred to kinesthetic sensations. As for deactivation of
515 the automated system, two of the 10 driving-centered HMI users relied on visual
516 information displayed on the cluster, two referred to the commands, two to the auditory
517 feedback, and one to the haptic feedback. Three participants experienced confusion
518 between Level 2 (ACC + LCA) and either Level 1 (ACC) or manual driving when consulting the
519 visual information. The same kind of confusion was reported by three participants when
520 listening to the auditory feedback. Confusion between Level 1 and either the Level 2 or

521 manual driving was experienced by one driving-centered HMI user when consulting the
 522 visual information on the cluster. Confusion between Level 1 and Level 2 was experienced by
 523 one participant in the driving-centered HMI group when consulting the visual information.
 524 The same kind of confusion was reported by one riving-centered HMI user who relied on
 525 kinesthetic sensations.

526

527 Table 7: **Number of participants in the driving-centered HMI group (total number of**
 528 **participants in the group)** who commented about a specific modality of the HMI regarding
 529 activation, deactivation, or mode confusions.

	Activation of automated systems	Deactivation of automated systems	Mode confusion between Level 2 and Level 1 or manual driving	Mode confusion between Level 1 and Level 2 or manual driving	Mode confusion between Levels 1 and 2
Visual	5 (10)	2 (10)	3 (10)	1 (10)	1 (10)
Auditory	1 (10)	2 (10)	3 (10)	0	0
Commands	2 (10)	2 (10)	0	0	0
Haptic feedback	2 (10)	1 (10)	0	0	0
Kinesthetic	1 (10)	0	0	0	1 (10)

sensations					
------------	--	--	--	--	--

530

531 **5. DISCUSSION**

532 Our study was designed to explore the impact of HMI design on the detection of information
533 about the status and functioning of two partially automated vehicles. We compared two
534 HMIs: a driving-centered HMI and a vehicle-centered HMI. The driving-centered HMI used an
535 exocentric representation of the road scene and multimodal information to inform drivers
536 about the level of automation. The vehicle-centered HMI used a traditional display with
537 visual information only. During a 45-minute on-road driving session, response times and eye
538 movements were recorded while participants answered questions. Spontaneous comments
539 were also recorded, and subsequently classified according to whether they were related to
540 the HMI or the status of the automated systems. In this section, we discuss the extent to
541 which our results answer the question of whether the exocentric and multimodal driving-
542 centered HMI allows drivers to have a better understanding of the functioning of the vehicle
543 when using an automated system than a classic visual vehicle-centered HMI.

544 Overall, response times for system questions were shorter for the driving-centered HMI
545 group than for the vehicle-centered HMI group. More specifically, the two groups differed
546 on response times for questions about vehicle speed. When the automation was on, driving-
547 centered HMI users responded faster than vehicle-centered HMI users. These results suggest
548 that vehicle speed information is more accessible in the driving-centered HMI than in the
549 vehicle-centered HMI. However, we failed to find any differences in response times to
550 questions about the activation of ACC (Level 1) or ACC + LCA (Level 2). Compared with the
551 classic HMI, the multimodal and realistic driving-centered HMI seemed to inform drivers

552 more efficiently about the functioning of the vehicle, though not about the level of
553 automation. Regarding the eye-tracking data, for the speed questions, the driving-centered
554 HMI group made more/longer fixations than the vehicle-centered HMI group on the
555 speedometer. At first glance, our results suggest that the exocentric HMI captured the
556 drivers' visual resources more than the classic HMI did when it came to vehicle speed. This
557 suggests that it may have been difficult to extract visual information (Jacob & Karn, 2003).
558 However, we observed a high fixation count and duration on the HUD, such that the vehicle-
559 centered HMI drivers fixated the HUD at least as many times and for at least as long as they
560 did either the speedometer or the ADAS. The fact that participants looked at both the
561 speedometer and the HUD when answering the speed question suggests that they double-
562 checked. They may have seen the information on the HUD and verified it on the
563 speedometer. The time needed to perform this double checking may explain why it took the
564 vehicle-centered HMI users longer to answer questions about vehicle speed. The use of the
565 HUD in this situation may have been more demanding than that of the driving-centered
566 HMI. One way to measure the benefit of the HUD would be to compare the answers of
567 vehicle-centered HMI drivers to speed questions in two HUD conditions: activated versus
568 deactivated. This would make it possible to evaluate the HUD's impact on response times.
569 Regarding ACC activation (Level 1), results diverged. Driving-centered HMI users looked
570 more often at the ADAS, where the information was displayed. By contrast, vehicle-centered
571 HMI users looked more often at the interior of the vehicle, suggesting that they were looking
572 for the information in the wrong places. However, they also looked at the external
573 environment for longer periods than the driving-centered HMI users, which suggests better
574 situational awareness. We had expected driving-centered HMI users to make shorter and
575 fewer fixations on the cluster than the vehicle-centered HMI users when answering

576 questions on automation. The multimodal driving-centered HMI provided auditory feedback
577 about the level of automation, meaning that users could access the information without
578 having to look at the cluster. However, we found no significant differences in fixations
579 compared with the classic HMI. This suggests that the multimodal HMI did not correctly
580 inform drivers about the status and functioning of the vehicle. This result was confirmed by
581 the mode confusions encountered by the driving-centered HMI group.

582 We observed a wider range of mode confusion situations for the driving-centered HMI group
583 than for the vehicle-centered HMI group (see Tables 6 and 7). For the driving-centered HMI
584 users, most of the confusions were related to Level 2 (ACC + LCA), and involved both visual
585 and auditory information. Thus, instead of helping drivers to distinguish between the modes,
586 the multimodal HMI actually induced confusion in some of them. This may be an indication
587 that the auditory information was not correctly perceived or understood by users. In the
588 vehicle-centered HMI group, most of the mode confusions concerned Levels 1 (ACC) and 2
589 (ACC + LCA). There was only a subtle distinction between these two levels on the cluster,
590 which may explain these confusions. Fewer confusions related to the ACC were observed for
591 the driving-centered HMI. The use of a realistic representation of the vehicle being followed
592 may be an efficient clue, helping drivers to understand the activation status of the ACC
593 (Level 1).

594 According to the multiple resources model, using different sensory channels to convey
595 information is more efficient than using a single one (Wickens, 2008). According to the
596 automated driving model, an HMI that informs drivers about the tasks undertaken by the
597 automated systems is more efficient (Stanton et al., 2001). On the basis of these two
598 models, we had assumed that the multimodal and exocentric driving-centered HMI would
599 allow drivers to understand the vehicle's status and capabilities more efficiently than the

600 vehicle-centered HMI would. Despite the presence of an HUD in the vehicle-centered HMI,
601 the driving-centered HMI allowed drivers to respond faster to questions about the vehicle's
602 level of automation. Interestingly, however, the driving-centered HMI captured more visual
603 attention overall than the vehicle-centered HMI did. This result is consistent with the results
604 of Gaspar and Carney (2019). In their study, participants used a Tesla Model S (driving-
605 centered HMI) to do daily drives, and their eye movements were recorded. The authors
606 found that users looked at the external environment less frequently when Level 2 was
607 activated. Our results corroborate these findings, suggesting that an exocentric
608 representation tends to be visually distracting. Regarding mental models, the exocentric and
609 multimodal driving-centered HMI seemed to induce mode confusions. Banks et al. (2018)
610 observed similar results with participants using a Tesla Model S with an HMI similar to the
611 one we used in our study. These authors reported mode confusions with the activation of
612 Level 2 automation. Mode confusion with the activation of Level 2, specifically relating to
613 visual information, was also reported in the present study. Interestingly, however, we
614 observed more mode confusion with the deactivation of Level 2. This confusion was related
615 to the auditory feedback intended to inform drivers about the activation or deactivation of
616 the automated system. Participants' verbal comments indicate that some of these sounds
617 were not understood. Carsten and Martens (2019) suggested that an efficient automated
618 vehicle HMI design implies that the functioning of the vehicle can be understood. If the
619 meaning of signals from the HMI is not understood, an accurate mental model cannot be
620 forged. This is particularly important when the signal serves to inform the driver of a return
621 to manual control. Many sounds are emitted nowadays in cars. Most of them are meant to
622 alert drivers of an emergency. Designers should focus on sounds that efficiently inform them
623 about the activation level of the automated system.

624

625 **5.1. Conclusion**

626 The purpose of our study was to compare the characteristics and on-road use of two HMIs.
627 More specifically, our protocol was intended to determine which of the two designs best
628 helped drivers understand the status and functioning of their vehicle. The first HMI was
629 multimodal and featured an exocentric representation of the road scene. The second HMI
630 was more traditional and used codes that are widely used in the automobile industry. The
631 two designs gave rise to similar performances on questions about the status and functioning
632 of the vehicle. However, the driving-centered HMI was more efficient when it came to
633 informing drivers about current speed. Eye movements suggested that its multimodal and
634 realistic representation was more visually demanding. Finally, the driving-centered HMI
635 induced mode confusions related to Level 2, whereas the classic HMI induced mode
636 confusions related to Level 1. Taken together, results indicate that the multimodal driving-
637 centered HMI did not help participants driving the vehicle for the first time to gain a better
638 understanding of the functionalities and activation level of the automated system. The mode
639 confusions and failure to use the auditory information suggest that the sounds indicating
640 activation and deactivation of automation could be improved. Future experiments should
641 measure HMI use over an extended period of time.

642

643 **5.2. Limitations**

644 On-road studies have just as many disadvantages as they do advantages. In ecological
645 situations, some factors cannot be controlled. Variables dependent on the surrounding
646 environment can interfere with the protocol. For example, the experiments with the vehicle-

647 centered HMI took place during vacation periods. The participants who drove with this HMI
648 were therefore more likely to encounter traffic jams. When in a traffic jam, the vehicle's
649 speed is often too low to activate the automation. The vehicle-centered HMI participants
650 therefore used the automated system for shorter periods of time than the driving-centered
651 HMI users did. Another limitation arising from the ecological situation concerns the intrinsic
652 differences between the vehicles. The main difference between the vehicles here was the
653 presence of an HUD in the vehicle-centered HMI but not in the driving-centered HMI. Drivers
654 could obtain several types of information from the HUD, as it centralized information about
655 automation status and speed. Given the broad range of information and the relatively small
656 surface area, we were not able to compare eye-tracking data for this AOI with that of the
657 other AOIs. However, analysis of participants' comments suggested that the HUD was an
658 important source of information on automation status.

659 Another limitation was the small sample size. With only 10 participants per group, caution
660 needs to be exercised when considering the conclusions we drew. Except for one ANOVA,
661 we only carried out nonparametric tests. Several differences were significant, but a larger
662 sample size would have allowed us to increase the statistical power and strengthen the
663 possible effects. This is one reason why we considered the drivers' comments. These
664 supplemented the quantitative data by explaining what the participants experienced. Mode
665 confusions are difficult to reproduce and observe in simulators. They can be accessible if
666 drivers are interviewed, but this is generally done after the experiment, and only rarely while
667 they are driving. Recording and transcribing drivers' comments allowed us to access mode
668 confusions and explain the quantitative data. This exploratory study yielded relevant
669 information about the impact an interface may have on drivers' awareness about mode
670 status. However, it is important to note that this experiment only told us about what

671 happens while drivers are familiarizing themselves with a vehicle. A 1-hour drive is not long
672 enough for them to understand every feature of the HMI, and familiarity with automated
673 systems can have an impact on their utilization (Solís-Marcos & Kircher, 2019).

674

675 **5.3. Future research**

676 As well as emphasizing the need for the functioning of the vehicle to be understood, Carsten
677 and Martens (2019) underscored the need to carefully calibrate trust. Too much trust leads
678 to disengagement, while too little trust discourages drivers from using the automated
679 system. These authors argued that the exocentric representation of the driving-centered
680 HMI may simply serve to promote trust in the system. It may be esthetically appealing, but
681 possibly not that useful in helping drivers take back control when necessary. It may be more
682 suited to Level 3 vehicles, where the automated system gives drivers more time to take back
683 control. In Level 2 vehicles, drivers need to be ready to do so at all times. The calibration of
684 trust is therefore crucial. Future research should focus on looking for HMIs that foster the
685 right degree of trust. One idea would be to indicate the vehicle's limitations. Beller, Heesen,
686 and Vollrath (2013) explored the idea of warning drivers about the automation's uncertainty
687 in order to bring them back into the loop. In highly automated vehicles, the display features
688 an icon representing uncertainty in situations where the automation may fail. In this
689 condition, drivers are faster at taking back control and have greater trust in the automation.
690 This kind of display could be included in Level 2 vehicles.

691 Another point to consider in future studies is familiarity with the system. Our study focused
692 on the first driving session that participants had with the vehicle. A driver who is used to a
693 Level 2 vehicle should know when the system is able to function properly or not. However,
694 Solís-Marcos and Kircher (2019) observed a potential effect of familiarity with automation

695 on eye movements. More specifically, the more experienced participants performed more
696 secondary tasks, potentially leading to a loss of situational awareness. Future research
697 should take experience with the system into account by featuring longitudinal experiments.

698

699 **ACKNOWLEDGMENTS**

700 The first author of this study is funded by Renault Group and the French National Association
701 for Research and Technology (ANRT). The authors thank Pierre-Vincent Paubel for his
702 technical assistance with the eye-tracking data collection and analysis, Majide Burlet-
703 Parendel for the illustrations, and Xavier Chalandon and Jean-François Forzy for their writing
704 assistance.

705

706 **BIBLIOGRAPHY**

- 707 Bainbridge, L. (1983). Ironies of automation. In *Analysis, design and evaluation of man-*
708 *machine systems* (pp. 129-135). Pergamon.
- 709 Banks, V. A., Eriksson, A., O'Donoghue, J., & Stanton, N. A. (2018). Is partially automated
710 driving a bad idea? Observations from an on-road study. *Applied Ergonomics*, 68,
711 138–145. <https://doi.org/10.1016/j.apergo.2017.11.010>
- 712 Beller, J., Heesen, M., & Vollrath, M. (2013). Improving the driver–automation interaction:
713 An
714 approach using automation uncertainty. *Human Factors*, 55(6), 1130-1141.
- 715 Blömacher, K., Nöcker, G., & Huff, M. (2020). The evolution of mental models in relation to
716 initial information while driving automated. *Transportation Research Part F: Traffic*
717 *Psychology and Behaviour*, 68, 198–217. <https://doi.org/10.1016/j.trf.2019.11.003>
- 718 Carsten, O., Lai, F. C. H., Barnard, Y., Jamson, A. H., & Merat, N. (2012). Control task

719 substitution in semiautomated driving: Does it matter what aspects are automated?
720 Human Factors, 54(5), 747– 761. <https://doi.org/10.1177/0018720812460246>

721 Carsten, O., & Martens, M. H. (2019). How can humans understand their automated cars?
722 HMI principles, problems and solutions. *Cognition, Technology & Work*, 21(1), 3–20.
723 <https://doi.org/10.1007/s10111-018-0484-0>

724 Dingus, T. A., Neale, V. L., Klauer, S. G., Petersen, A. D., & Carroll, R. J. (2006). The
725 development
726 of a naturalistic data collection system to perform critical incident analysis: An
727 investigation of safety and fatigue issues in long-haul trucking. *Accident Analysis &*
728 *Prevention*, 38(6), 1127–1136. <https://doi.org/10.1016/j.aap.2006.05.001>

729 Endsley, M. R. (2017). Autonomous driving systems: A preliminary naturalistic study of the
730 Tesla Model S. *Journal of Cognitive Engineering and Decision Making*, 11(3), 225–238.
731 <https://doi.org/10.1177/1555343417695197>

732 Forster, Y., Hergeth, S., Naujoks, F., Beggiato, M., Krems, J. F., & Keinath, A. (2019). Learning
733 and Development of Mental Models during Interactions with Driving Automation: A
734 Simulator Study. *Proceedings of the 10th International Driving Symposium on Human*
735 *Factors in Driver Assessment, Training and Vehicle Design: Driving Assessment 2019*,
736 398–404. <https://doi.org/10.17077/drivingassessment.1724>

737 Gaspar, J., & Carney, C. (2019). The effect of partial automation on driver attention: a
738 naturalistic driving study. *Human factors*, 61(8), 1261-1276.
739 <https://doi.org/10.1177/0018720819836310>

740 Jacob, R. J. K., & Karn, K. S. (2003). Commentary on Section 4 - Eye tracking in human-
741 computer interaction and usability research: Ready to deliver the promises. In J.

742 Hyönä, R. Radach, & H. Deubel (Eds.), *The Mind's Eye* (pp. 573–605). North-Holland.
743 <https://doi.org/10.1016/B978-044451020-4/50031-1>

744 Lemercier, C., Pêcher, C., Berthié, G., Valéry, B., Vidal, V., Paubel, P.-V., ... Maury, B. (2014).
745 Inattention behind the wheel: How factual internal thoughts impact attentional
746 control while driving. *Safety Science*, 62, 279–285.
747 <https://doi.org/10.1016/j.ssci.2013.08.011>

748 Mann, H. B., & Whitney, D. R. (1947). On a test of whether one of two random variables is
749 stochastically larger than the other. *Annals of Mathematical Statistics*, 18(1), 50–60.
750 <https://doi.org/10.1214/aoms/1177730491>

751 Michon, J. A. (1985). A critical view of driver behavior models: What do we know, what
752 should we do? In L. Evans & R. C. Schwing (Eds.), *Human behavior and traffic safety*
753 (pp. 485–524). https://doi.org/10.1007/978-1-4613-2173-6_19

754 SAE Levels of Driving Automation. (2018). </blog/2013/12/sae-levels-driving-automation>

755 Sarter, N. B., & Woods, D. D. (1995). How in the world did we ever get into that mode?
756 Mode error and awareness in supervisory control. *Human Factors*, 37(1), 5–19.
757 <https://doi.org/10.1518/001872095779049516>

758 Seppelt, B., & Victor, T. (2020). Driver's mental model of vehicle automation. In **Handbook of**
759 **Human Factors for Automated, Connected, and Intelligent Vehicles, 55-66.** (pp. 55-
760 66).
761 CRC Press.

762 Solís-Marcos, I., & Kircher, K. (2019). Event-related potentials as indices of mental workload
763 while using an in-vehicle information system. *Cognition, Technology & Work*, 21(1),
764 55–67. <https://doi.org/10.1007/s10111-018-0485-z>

765 Stanton, N. A., Young, M. S., Walker, G. H., Turner, H., & Randle, S. (2001). Automating the
766 driver's control tasks. *International Journal of Cognitive Ergonomics*, 5(3), 221–236.
767 https://doi.org/10.1207/S15327566IJCE0503_5

768 Strand, N., Stave, C., & Ihlström, J. (2018). A case-study on drivers' mental model of partial
769 driving automation. In 25th ITS World Congress, Copenhagen, Denmark, 17-21
770 September 2018.

771 Victor, T., Dozza, M., Bärghman, J., Boda, C.-N., Engström, J., Flannagan, C., ... Markkula, G.
772 (2015). Analysis of naturalistic driving study data: Safer glances, driver inattention,
773 and crash risk. SHRP 2 Report, (Report S2-S08A-RW-1). Retrieved from
774 <https://trid.trb.org/view/1323585>

775 Wang, J.-S., Knipling, R. R., & Goodman, M. J. (1996). The role of driver inattention in
776 crashes:
777 New statistics from the 1995 Crashworthiness Data System: (533322008-001) [Data
778 set]. <https://doi.org/10.1037/e533322008-001>

779 Wickens, C. D. (2008). Multiple resources and mental workload. *Human Factors*, 50(3), 449–
780 455. <https://doi.org/10.1518/001872008X288394>

781 Zhang, B., de Winter, J., Varotto, S., Happee, R., & Martens, M. (2019). Determinants of take-
782 over time from automated driving: A meta-analysis of 129 studies. *Transportation
783 Research Part F: Traffic Psychology and Behaviour*, 64, 285–307.
784 <https://doi.org/10.1016/j.trf.2019.04.020>
785

Target questions
What is your current speed? (Level 2 on)
What is your current speed? (Level 2 off)
Is the Auto Pilot activated? (Level 2 on)
Is the Auto Pilot activated? (Level 2 off)
Is the adaptive cruise control activated?
Is the lane centering assist activated?
Personal questions
Do you have any children/grandchildren?
Do you have any pets?
What are their names?
Do you play sports?
Interior questions
What color is the pen I'm writing with?
What radio station are we listening to?
What color are my clothes?
Exterior questions
Do you think it will rain today?
Is the vehicle on our right green?
Is the car behind us black?

787

788

Elizabeth Wiles Portier
La Crique
Lieu-dit Le Buisson
50480 Audouville la Hubert

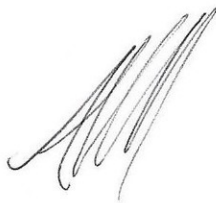
Tél. 09.62.59.17.64
e-mail : e-portier@wanadoo.fr

Noé Monsaingeon
Renault Technocentre
1, avenue du Golf
78280 Guyancourt

21 April 2021

DECLARATION

As a professional translator for the English language, I hereby declare that I carried out the language editing of the article entitled *Impact of interface design on drivers' behavior in partially automated cars: an on-road study* (N. Monsaingeon et al.).



Elizabeth Wiles Portier
BA (Cantab)
DESS (Ecole Supérieure d'Interprètes et de Traducteurs)