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Behavioral and workload measures in real and simulated driving:

Do they tell us the same thing about the validity of driving simulation?

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76 **Behavioral and workload measures in real and simulated driving:**
77 **Do they tell us the same thing about the validity of driving simulation?**

78 **1. Introduction**

79 For the sake of controllability, repeatability, and safety, driving simulators are
80 extensively used for driver behavior research. However, they must have appropriate validity
81 to be useful human factor research tools. Since Blaauw (1982), few studies have compared
82 on-road and simulator driver behavior. While such comparative studies are not easy to carry
83 out (Carsten & Jamson, 2011; Carsten et al., 2013), they remain the most appropriate means
84 to evaluate and improve driving simulator validity. Most of them relied on behavioral
85 measures to capture the differences between on-road and simulated driving (Blana, 1996;
86 Mullen et al., 2011; Shechtman, 2010). More recently, few studies assessed the level of
87 mental workload when driving in a real vehicle or in a simulator and showed contradictory
88 results (e.g., Diels et al., 2011; Johnson et al., 2011; Milleville-Pennel & Charron, 2015). On
89 another note, it has been found that mental workload measures were more sensitive to task
90 demands than behavioral measures (Mehler et al., 2009, 2012; Yang et al., 2013). Therefore
91 the present study was aimed at assessing behavioral and mental workload measures to better
92 understand the differences between real and simulated driving.

93 Blaauw (1982) proposed to assess driving simulator validity based on physical and
94 behavioral criteria. Physical validity corresponds to the extent to which software and
95 hardware components of the simulator reproduce the physical reality of driving. Behavioral
96 validity has been defined as the correspondence between driver behavior in a simulator and on
97 the road. While some studies have paid attention to hardware components of the simulator to
98 improve physical fidelity (e.g., Chatziastros et al., 1999; Jamson & Jamson, 2010; Kappé et
99 al., 1999; Klüver et al., 2016), it is relatively well established that behavioral validity is a
100 more important criterion than physical validity. This can be explained by the fact that the

101 strict duplication of reality is impossible to obtain in simulated driving (Pinto et al., 2008). In
102 addition, a high level of physical fidelity is not always required to achieve good levels of
103 behavioral validity (Blana, 1996; Klüver et al., 2016; Pinto et al., 2008). Blaauw (1982) also
104 made a distinction between relative and absolute behavioral validity. Absolute validity is
105 established with the sameness of numerical values in the behavioral measures in the two
106 different environments. Relative validity is concluded when the differences due to the
107 experimental manipulation are of the same order and direction and have a similar or identical
108 magnitude in real and simulated driving conditions (for a discussion, see Klüver et al., 2016).

109 Longitudinal and lateral control have been mainly used to assess the behavioral validity
110 of driving simulators, with speed being undoubtedly the most widely used (see
111 Supplementary Table 1 for an overview of results obtained in studies that have compared real
112 and simulated driving under free driving conditions. For a recent review of driving simulator
113 validation studies, see Wynne et al., 2019). For lateral position, strong absolute differences
114 between simulated and real driving have been found in the mean and standard deviation of
115 lateral position. Relative validity of simulated driving is however relatively well preserved
116 (see Supplementary Table 1). For speed, 11 out of the 20 studies which examined vehicle
117 speed when driving freely concluded absolute validity while 7 concluded relative validity
118 (two studies showed significant differences between the two systems). When relative validity
119 of the experimental treatment ~~is was~~ found, driving speed ~~is was~~ higher in simulators than on
120 roads (see Supplementary Table 1). Whether for lateral control or speed measures, these
121 results greatly depended on the type of simulator (for a recent review, see Klüver et al., 2016)
122 and driving context, such as the type of road, road geometry (Bella, 2008; Bittner et al., 2002;
123 Branzi et al., 2017), presence of oncoming traffic (Alm, 1995) or traffic in the lane (Wang et
124 al., 2010), and both posted and traffic speed (Wang et al., 2010).

125 While most of the studies evaluated behavioral validity, Blaauw (1982) initially
126 proposed not only to assess behavioral measures but also mental workload measures. For
127 Malaterre and Fréchaux (2001), this corresponds to the psychological validity of driving
128 simulators defined as the sameness of the psychological processes underlying the driving
129 activity, including mental workload. Focusing specifically on mental workload, which is the
130 result of the interaction between task demands and the attentional resource capacity of the
131 operator (Borghini et al., 2014; O'Donnell & Eggemeier, 1986), this distinction finds model-
132 based and empirical evidence. De Waard (1996) offered a model which relates the operator's
133 performance and workload to task demands. When the task demands are low, the operator is
134 weakly engaged in the task and the level of mental workload is high while performance is
135 low. When the task demands outmatch the operator's attentional resources, the latter is
136 overloaded and performance is dramatically low. In-between these two extrema, two states
137 are of interest here: i) when task demands are high enough to engage the operator whose
138 attentional resources meet the task requirements, performance is high while mental workload
139 level is low; ii) when the task demands increase, the operator has to engage more resources to
140 maintain his performance and mental workload level is consequently high. This last state has
141 been highlighted in studies showing that when task demands increased, physiological or
142 visual attention measures of mental workload were sensitive to these changes while driving
143 performance measures were not (e.g., Mehler et al., 2009, 2012; Yang et al., 2013).

144 Based on these considerations, when driving performance, namely vehicle handling, is
145 maintained in a simulator compared to on-road driving, the mental workload level may then
146 be either the same in both environments or different. If the mental workload level is the same,
147 then the simulator does not place more demands on vehicle handling. The control of the
148 vehicle, which belongs to the operational level of driving activity and requires little
149 attentional resources, is not hampered when driving a simulator. If the mental workload level

150 is higher in the simulator, this suggests that more attentional resources have to be allocated to
151 maintain driving performance. This increase in task demands could come from the lack of
152 vestibular and proprioceptive cues (e.g., Bittner et al., 2002; Boer et al., 2000; Klee et al.,
153 1999). Lastly, if the mental workload is higher when driving on a road, the difference could
154 be due to a higher perception of risk and consequences of collisions that are not present in the
155 simulator (Bella, 2008; Deniaud et al., 2015; Engström et al., 2005; Mueller, 2015).

156 Surprisingly, the assessment of mental workload when driving on a road and ~~on~~ in a
157 simulator has given rise to a small pool of studies and to contradictory findings. Alm (1995)
158 and Blaauw (1982) first showed that, while longitudinal control was well preserved whether
159 the simulator was static or dynamic, driving in a simulator was quoted as being more difficult
160 and more effort-demanding than driving for real. Similarly, Diels et al. (2011) found a very
161 close correspondence in speed between the car and the simulator but subjective ratings of
162 mental workload tended to be moderately higher in the driving simulator. Engström et al.
163 (2005) compared vehicle-handling measures and physiological measures of mental workload
164 (heart rate and skin conductance) in a static simulator, a dynamic simulator and an
165 instrumented vehicle. Driving measures in the simulators were consistent with those obtained
166 in real driving conditions. However, physiological measures of workload were higher in the
167 field, suggesting an increased effort due to higher actual risk in real traffic. Other studies
168 confirmed that physiological signals of mental workload were higher when driving on the
169 road than driving in a simulator; however, no speed or lateral-control measures were reported
170 (Johnson et al., 2011; Milleville-Pennel & Charron, 2015; Reimer & Mehler, 2011). At the
171 very least, Milleville-Pennel and Charron (2015) reported that the self-rated driving
172 performance was judged to be lower when driving in the simulator than in the field. Using a
173 cognitive secondary task, Reimer and Mehler (2011) and Mehler et al. (2009) showed in two
174 different studies sharing the same manipulation that when the secondary task difficulty

175 increased, the performance decreased by a greater amount in the simulator (Mehler et al.,
176 2009) than in real driving conditions (Reimer & Mehler, 2011). This is in keeping with the
177 idea that mental demand coming from simulated driving is higher. A similar result was found
178 by Chen et al. (2015). In this study, participants had to perform a reaching task to virtual and
179 real targets while verbally responding to an auditory tone. Results showed that the response
180 time to the auditory stimulus was significantly longer for the virtual than for the real target
181 condition, confirming that a VR-based task was more attention-demanding than its
182 conventional real-world counterpart.

183 In sum, it appears that measures of behavioral validity may return only a partial view of
184 the correspondence between driving for real and driving in a simulator. As suggested by
185 model-based and empirical evidence, attentional resources required by the driving task during
186 real and simulated driving might differ, while behavioral measures may not (De Waard, 1996;
187 Mehler et al., 2009, 2012; Yang et al., 2013). This would lead to wrongfully inferring
188 (behavioral) absolute validity while validity on other dimensions would not be established.

189 The objective of this study was therefore to assess driving simulation validity by
190 confronting measures of behavioral (speed) and psychological (mental workload) validity. In
191 this purpose, we selected a route where participants could drive freely and were likely to
192 adopt a similar speed in real and simulated conditions. This made it possible to examine
193 whether mental workload level differed between real and simulated driving while speed
194 measures had a good correspondence in both driving conditions. It also appears that workload
195 level in virtual environments has received little attention and results are controversial. One
196 reason could be the use of a variety of measures in isolation, which are known to dissociate
197 (e.g., Brookhuis & de Waard, 2002; Faure et al., 2016; Yeh & Wickens, 1988). We therefore
198 used a multiple measurement approach of workload, with subjective, physiological (eye-blink
199 rate) and secondary task performance measures.

200 **2. Method**

201 **2.1. Participants**

202 Twenty-four participants (8 females) took part in the experiment. They had a mean age
203 of 43.5 ± 8.9 years, ranging from 27 to 56 years old. All participants had their driver's license
204 for a minimum of two years. The self-reported experience ranged from 9 to 36 years (mean =
205 23 ± 9.6 years) and the self-reported total mileage ranged from 20,000 to 420,000 km (mean =
206 $300,000 \pm 196,000$ km). All participants had normal or corrected-to-normal vision, and were
207 naïve as to the aims of the experiment. Before they took part in the study, all gave their
208 informed consent which was approved by the local Ethics Committee. The ethical
209 considerations and principles of the World Medical Association Declaration of Helsinki
210 regarding experimentation were respected.

211 **2.2. Experimental set-up**

212 **2.2.1. Real vehicle**

213 The field experiment was run using a Renault Clio III with manual transmission. It was
214 equipped with a GPS sensor (GlobalSat Technology BR-355, Taiwan), a Controller Area
215 Network (CAN) interface (PEAK System PCAN-USB, Germany), and three cameras (4Kam
216 Wideboy Sport, United-Kingdom). GPS data were logged with 1 Hz, and vehicle-related data
217 were logged between 10 and 50 Hz depending on the data. All data sources were
218 synchronized on a computer (Toshiba Satellite Pro A300, Japan) running a data acquisition
219 and synchronization software (Intempora RTMaps, France).

220 **2.2.2. Fixed-base simulator**

221 The experiment in the virtual environment was run using a fixed-base driving simulator
222 composed of a force-feedback steering wheel, foot pedals, gearbox (Logitech G25), and a
223 Renault Clio driving seat (Figure 1). The simulated environment was displayed on three
224 screens 0.53 m wide and 0.30 m high (resolution: 1,280 x 1,024 pixels; refresh rate: 30 Hz).

225 The distance between the participant's head and the center of each screen was 1 m. The visual
226 angle subtended by this configuration was 97° horizontally and 30° vertically. The images
227 were calculated and projected at the participant's eye height, with the simulated viewing angle
228 aimed at the vanishing point of the simulated scenario. Engine sounds and environmental
229 noises were generated by five speakers. The speedometer was displayed in the lower part of
230 the central screen. The central mirror was superimposed on the visual environment in the
231 upper part of the central screen. Data were collected at a sampling rate of 30 Hz.



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Figure 1. Illustration of the fixed-base driving simulator.

234 2.2.3. Eye-tracker

235 Two identical Pertech head-mounted eye-trackers were used to record eye measures in
236 the instrumented vehicle and the driving simulator, respectively. This monocular eye-tracker
237 uses a pupil tracking technology with an image processing algorithm to define the ocular
238 direction (50 Hz sampling rate) and has 0.25° of accuracy (according to the manufacturer
239 specification). A seven-point calibration was performed at the beginning of each real and
240 simulated experimental trial. Eye measures data were synchronized with simulated and real
241 car data so that they could be analyzed relative to the road geometry and any driving
242 measures.

243 2.2.4. Driving environment

244 The experimental route (Figure 2) was a 7.5 km long section of the D786 road near
245 Saint-Brieuc (France) between Plérin (GPS coordinates: 48.549687, -2.796007) and Binic
246 (GPS coordinates: 48.6014398, -2.8356539) and consisted of three different road sections.

247 The first road section was a circa 4.2 km long dual 2-lane carriageway road including a
248 roundabout. The posted speed limit was 110 km/h and then 70 km/h before entering the
249 roundabout (limited to 50 km/h). ~~except at the approach to the roundabout where it was set at~~
250 ~~70 km/h~~. After the roundabout, the posted speed limit was set again at 110 km/h and then
251 90 km/h at the end of the section (hereafter labeled highway environment). The roundabout
252 was excluded from the analysis as the corresponding speed limit (50 km/h) was not in line
253 with high-speed environment and free driving conditions. This initial decision was reinforced
254 by the fact that in real driving conditions all participants had to stop due to the presence of
255 other vehicles on the roundabout. The second road section was a circa 1.8 km undivided two-
256 lane rural road. The posted speed limit was 90 km/h in the first section and 70 km/h in the last
257 winding section (hereafter labeled rural environment). The third road section was a circa
258 1.5 km urban single carriageway road passing through the town of Binic. The posted speed
259 limit was 50 km/h (hereafter labeled urban environment).

260 With the objective of minimizing the impact of traffic uncertainties and congestion on
261 the driving task, we selected based on traffic surveys carried out on several sections of the
262 experimental road two periods of time (9:30 am to 11 am and 2:30 pm to 4 pm) during which
263 traffic density was the lowest. Furthermore, in case of particular events during the driving
264 sessions in the real environment that could not be reproduced in the simulated driving session
265 (e.g., red traffic light, pedestrians, vehicle overtaking), the corresponding sequences were
266 excluded from data analyses. These sequences represented less than 5% of the data.

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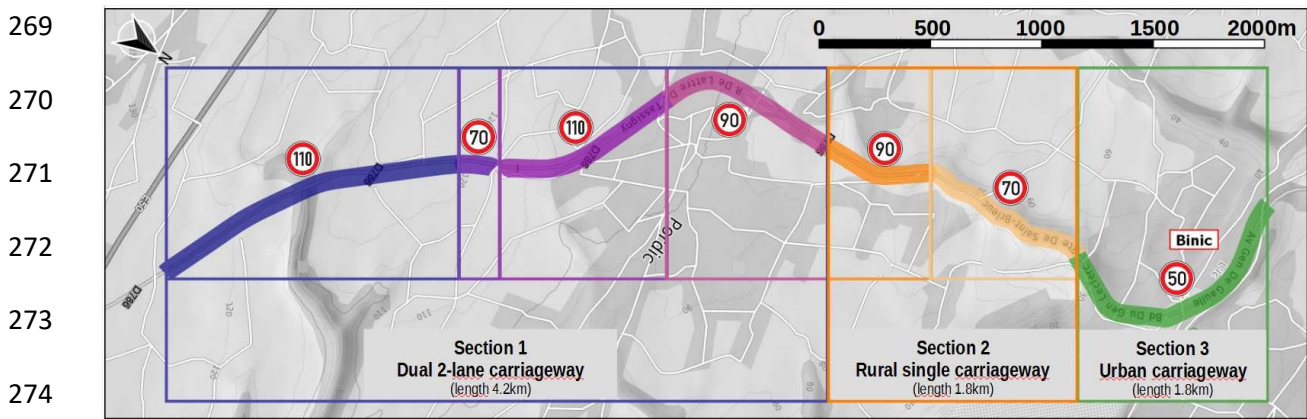


Figure 2. Overview of the experimental route and its different subsections.

All the important features of the real-world environment were replicated in a simulated 3D virtual world (see Figure 3). This included the three different driving environments (dual 2-lane carriageways and single carriageways in rural and urban contexts, respectively), roundabout, road signs, and buildings especially in the urban section. The road signs were positioned in the visual database at their corresponding locations in the real road. The traffic light in the actual traffic conditions was turned to green in the simulated scenario. In addition, traffic running in the opposite direction to that of the participant's car was introduced in the virtual environment. The traffic density corresponded to that surveyed during the two periods of time chosen for the on-road session. The simulated vehicles were of several types (passenger vehicles, commercial vehicles, trucks) and colors and obeyed the speed limit proper to the speed sections in the three driving environments.

Based on the classification of the effects of driving task demands on mental workload level (see Patten et al., 2004, 2006) and previous empirical results showing that drivers' mental workload is differently affected depending on the driving contexts (e.g., Faure et al., 2016; Mackenzie & Harris, 2017; Michaels et al., 2017; Patten et al., 2006), these three different driving environments were selected with the aim of triggering different levels of mental workload. The highway environment consisted of a straight carriageway located in the countryside with monotonous surrounding conditions, so that drivers would be undistracted



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299 Figure 3. Illustration of the three different driving environments (top: highway environment in
300 the first section at 110 km/h; middle: two-lane rural road in the section at 90 km/h; bottom:
301 urban environment) in the simulator and in real situation. Views in the real situation were
302 taken from Street View database (Google).

303

304 by the roadside environment and could control their vehicle in a consistent manner. This
305 environment was therefore supposed to trigger a low level of mental workload. The rural
306 environment represented a winding single carriageway lined with trees. In this scenario, an
307 intermediate level of workload was expected as it required a greater degree of steering control
308 than the highway environment. Lastly, the urban environment represented a visually rich
309 neighborhood (street furniture, buildings, signs, traffic lights and intersections). Drivers had
310 to adjust their trajectory and their speed and had to pay attention to their surrounding
311 environment as they progressed through the environment. The urban section was therefore
312 assumed to impose a high level of mental workload. The rationale for selecting these road
313 sections was to examine whether the effects of the driving environment on drivers' mental
314 workload varied in an absolute (i.e., sameness of numerical values between the two systems)
315 or relative (i.e., same order and direction and similar or identical magnitude in the two
316 systems) manner during real and simulated driving.

317 **2.3. Experimental design and task**

318 The experimental route was driven twice by all participants, one with the instrumented
319 vehicle in real condition and one with the simulator in the 3D world. As the driving
320 environment is known to affect drivers' mental workload level, we used a within-subject
321 design with two driving conditions (real road and driving simulator) and three driving
322 environments (highway environment, rural environment and urban environment). In the real
323 driving condition, participants were asked to drive in the way that they were used to. In the
324 driving simulator condition, they were asked to drive as if they were in a real car on a real
325 road, while obeying the traffic regulations and speed limits.

326 While participants were performing the primary driving task, they also had to perform a
327 tone reaction time task. This subsidiary secondary task consisted of responding verbally
328 ("top") to an auditory stimulus (100 ms duration, 1.5 kHz amplitude) as quickly as possible.

329 To prevent any anticipation, the inter-stimulus interval varied between 7 and 10 s. It was
330 adapted from the standard subsidiary secondary task (motor response to visual stimulus) as
331 one of its drawbacks is the occurrence of manual and visual interference with the driving task
332 (see Cantin et al., 2009; Jahn et al., 2005). Auditory stimuli were pre-recorded. In the real
333 vehicle, sounds were played by an independent speaker. In the simulator, they were embedded
334 into the engine sound. The participants' responses were recorded by the eye-tracker
335 microphone. Compliant with the subsidiary task paradigm (Cain, 2007), participants were
336 instructed to prioritize the primary driving task while responding to the auditory stimuli as
337 rapidly as possible.

338 **2.4. Procedure**

339 On their arrival, the nature and requirements of the experiment were explained to the
340 participants. They signed an informed consent form and demographic data were collected.
341 They drove the real and simulated condition in a counterbalanced order.

342 For the field test, participants sat in the instrumented vehicle and were invited to adjust
343 the position of the seat, steering wheel and mirrors. They were then equipped with the eye-
344 tracker before it was calibrated. Two experimenters also sat in the vehicle. The first one was
345 seated at the front of the vehicle to record traffic events. The second was at the back to
346 supervise data recording. When necessary due to the counterbalanced order of presentation of
347 the two driving conditions, participants were trained with the audio-vocal reaction time task.
348 Then, they drove the vehicle from the lab to a parking lot at the entrance to the course, located
349 15 km away, which gave them time to get accustomed to the experimental vehicle. Once the
350 quality of the ocular tracking had been checked, the experimenter seated in front reminded the
351 participant of the instructions of the driving session. The participants then drove on the
352 experimental course and performed the audio-vocal reaction time task concurrently. Once the
353 total experimental route had been completed, they stopped in a parking lot and completed the

354 mental workload assessment questionnaire (NASA-TLX scale from Hart & Staveland, 1988)
355 before removing the eye-tracker. Finally, one of the experimenters brought the vehicle back to
356 its starting point.

357 For the simulator test, a similar procedure was used. Participants first made sure they
358 were comfortable when sat in the simulator. One of the experimenters then fitted and
359 calibrated the eye-tracker. When necessary (i.e., when they drove in the simulator condition
360 first), participants familiarized themselves with the subsidiary secondary task. Then, they
361 underwent a training period with the simulator which consisted of driving on a winding rural
362 road with bends varying in length, curvature and direction (13 km long without any other
363 traffic). Finally, a reminder of the instructions for the driving and the reaction time task was
364 given. At the end of the driving session, participants completed the NASA-TLX questionnaire
365 before removing the eye-tracker. The experiment lasted approximately 1 hr. 30.

366 **2.5. Dependent Variables**

367 **2.5.1. Speed**

368 The participant-determined speed was used to compute the mean speed (km/h) over the
369 entire experimental route. As the speed limit varied within and between driving environments,
370 the mean speed was also calculated for each speed section ($n = 7$) for each environment. Since
371 most comparative studies were run in a unique driving environment, this made it possible to
372 examine the potential differences between real and simulated driving for different posted
373 speed limits and sections.

374 **2.5.2. Blink rate**

375 Eye blinking has proven to be a useful and reliable signature of drivers' mental
376 workload variations (e.g., Lohani et al., 2019), with a downward trend in the eye blink rate
377 when the primary task difficulty increased (e.g., Faure et al., 2016; Hancock et al., 1990;
378 Veltman & Gaillard, 1996; Wiberg et al., 2015). Capitalizing on previous research,

379 endogenous blinks corresponded to eye closures lasting between 80 (Benedetto et al., 2011,
380 2014; Faure et al., 2016; McIntire et al., 2014) and 500 ms (Stern et al., 1984). Blink events
381 were captured according to a modified version of the algorithm developed by Pedrotti et al.
382 (2011) for low-speed eye-trackers, and the blink rate (number of blinks per minute) was
383 computed in each driving environment and condition.

384 **2.5.3. Audio-vocal reaction time**

385 Reaction time to the secondary task was defined as the time lag between tone onset and
386 voice onset. Before the mean response time (ms) was computed for each participant, outlier
387 data were removed following a procedure similar to Cantin et al. (2009). Outliers
388 corresponded to reaction times shorter than 150 ms or slower than each participant's mean
389 reaction time plus two standard deviations. The mean response time was computed for each
390 driving environment and condition.

391 **2.5.4. Subjective workload**

392 The NASA-TLX was used to assess the operator's perceived workload according to six
393 dimensions: mental demand, physical demand, temporal demand, performance, effort, and
394 frustration. The mean ratings on each dimension and the global score were computed for each
395 driving condition (following the unweighted procedure).

396 **2.6. Statistical Analysis**

397 All statistical analyses were done with p set at .05. Speed differences between real and
398 simulated driving were examined for the entire experimental route and each speed section
399 ($n = 7$). Speed results were first checked for distribution normality using Shapiro-Wilk tests
400 for small samples. Pairwise comparisons were conducted using paired t tests when the data
401 sets were normally distributed or Wilcoxon signed-rank tests when one of the distributions
402 was not normally distributed. Effect sizes were reported as Cohen's d . Because of technical
403 problems during real driving conditions, these analyses were performed with 21 participants.

404 The possible effects of the driving condition and the driving environment on blink rate
405 and reaction time to the secondary task were assessed using 2 (driving conditions: real
406 driving, simulated driving) \times 3 (driving environment: highway, rural, urban) repeated
407 measures analyses of variance (ANOVAs). Mauchly's test of sphericity was run to determine
408 whether the sphericity assumption was violated. When necessary, the degrees of freedom
409 were adjusted with the Greenhouse-Geisser correction. Tukey's honestly significant
410 difference (HSD) procedure was run to follow up on significant effects. For each significant
411 effect, partial eta-squared (η_p^2) was computed to determine the proportion of total variability
412 accounting for the effect. Note that the reaction time analysis was performed with 21
413 participants because of technical problems during real driving condition.

414 Subjective workload ratings were analyzed following similar procedures as described
415 above. Differences between real and simulated driving were first compared on global demand.
416 To explore the origin of global demand differences, a repeated-measure ANOVA was run on
417 mean ratings, with driving conditions and NASA-TLX subscales as within-participant factors.

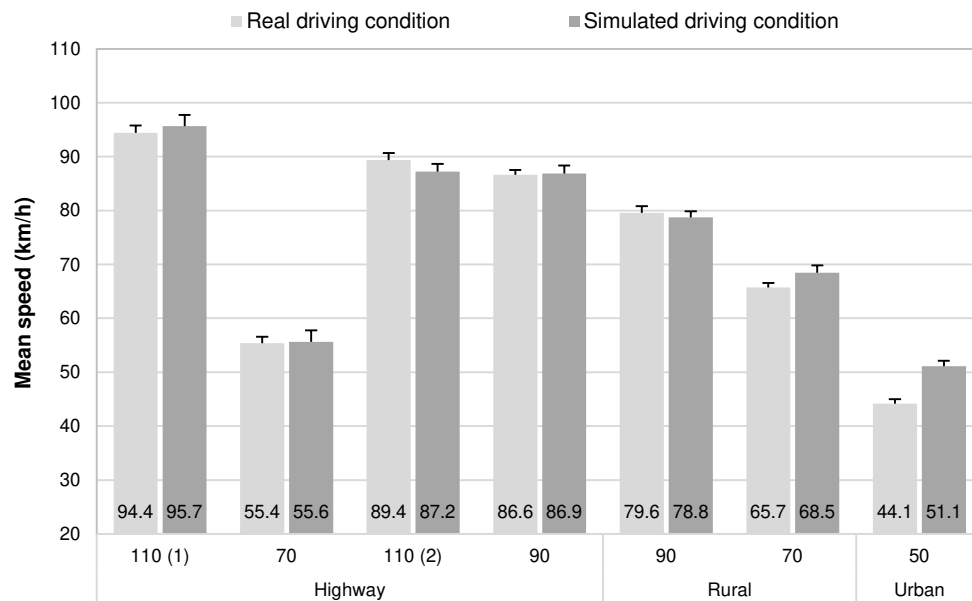
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419 **3. Results**

420 **3.1. Speed**

421 Statistical comparison of the mean driving speed computed for the entire route revealed
422 that speed did not differ between real (73.6 ± 3.4 km/h) and simulated (74.8 ± 5.4 km/h)
423 conditions ($t(20) = -1.18, p = .25$). Analyses comparing speed between the two driving
424 conditions in each speed section showed that speed did not differ in the highway environment
425 (110 km/h: $Z = 1.02, p = .30$; 70 km/h: $Z = .08, p = .93$; 90 km/h: $t(20) = 1.93, p = .07$; 90
426 km/h: $t(20) = -.21, p = .83$) nor in the rural environment (90 km/h: $t(20) = .81, p = .43$;
427 70 km/h: $Z = 1.69, p = .09$). However, in the urban environment, speed was significantly

428 higher in simulated than real condition ($Z = 4.01, p < .001, d = -1.74$). Mean speed in each
 429 driving condition, driving environment and speed section is provided in Figure 4.



430 **Driving environment and speed section (km/h)**

430

431 Figure 4. Mean speeds as a function of driving condition (real and simulated) for each driving
 432 environment and speed section. Bars represent standard error of the mean.

433

434

435 3.2. Eye blink rate

436 The repeated measures ANOVA on eye blink rate revealed a significant main effect of

437 the driving condition ($F(1,23) = 17.54, p < .001, \eta_p^2 = .43$), due to more frequent blinks

438 during real driving (11 ± 9.7 blinks/min) than simulated driving (4.1 ± 4 blinks/min), a

439 significant main effect of the driving environment ($F(2,46) = 5.86, p < .01, \eta_p^2 = .20$), and a

440 significant interaction between the two factors ($F(1.28,29.37) = 7.81, p < .01, \eta_p^2 = .25$).

441 Pairwise comparisons for the main effect of the driving environment showed that more blinks

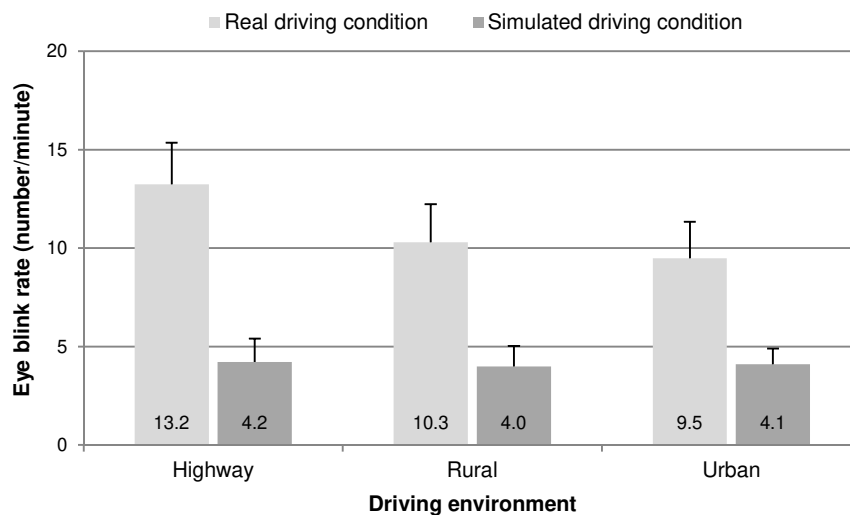
442 were made when driving on highway ($M = 8.7 \pm 9.5$ blinks/min) than when driving in rural

443 ($M = 7.1 \pm 8.2$ blinks/min) and urban settings ($M = 6.8 \pm 7.5$ blinks/min), which did not

444 differ. The interaction between driving condition and driving environment (see Figure 5)

445 revealed the same effect of the driving environment as above in the real driving condition. In

446 the simulated driving condition, however, the blink rate did not vary significantly with the
 447 driving environment. Note that the difference between real and simulated driving conditions
 448 was significant in the three driving environments. It should also be mentioned that the eye
 449 blink frequency decreased in the simulated as compared to the real driving condition in 21 out
 450 of 24 participants.



451

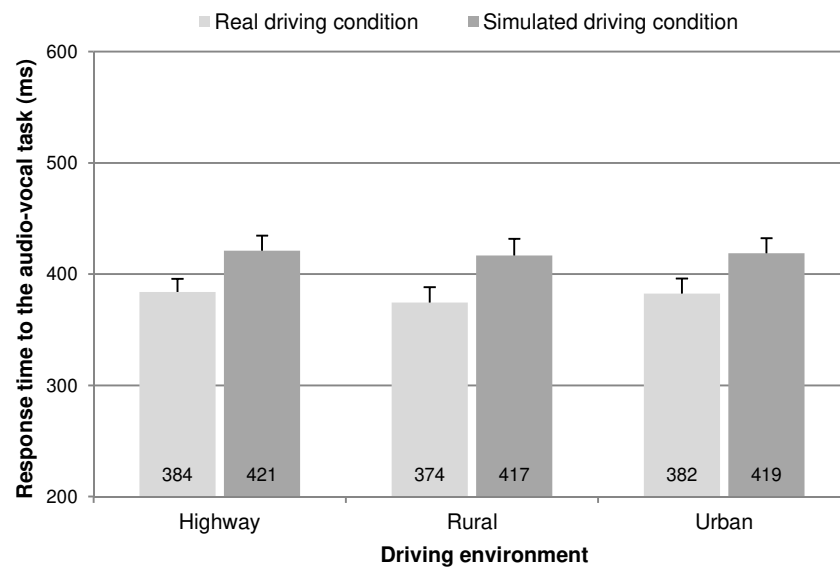
452 Figure 5. Interaction between driving condition (real and simulated) and driving environment
 453 on eye blink rate. Bars represent standard error of the mean.

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455

456 3.3. Response time to the audio-vocal task

457 The repeated measures ANOVA on the response time to the audio-vocal task, with
 458 driving condition and driving environment as within-participant variables, yielded a
 459 significant main effect of the driving condition ($F(1,20) = 13.18, p < .01, \eta_p^2 = .40$). No other
 460 main effect or interaction was observed. The response time was higher when driving the
 461 simulator (419 ± 65 ms) than when driving for real (380 ± 60 ms). Note that the mean
 462 response time increased in the simulated as compared to the real driving condition in 18 out of
 463 21 participants. The mean response time as a function of driving condition and driving
 464 environment is given for information in Figure 6.



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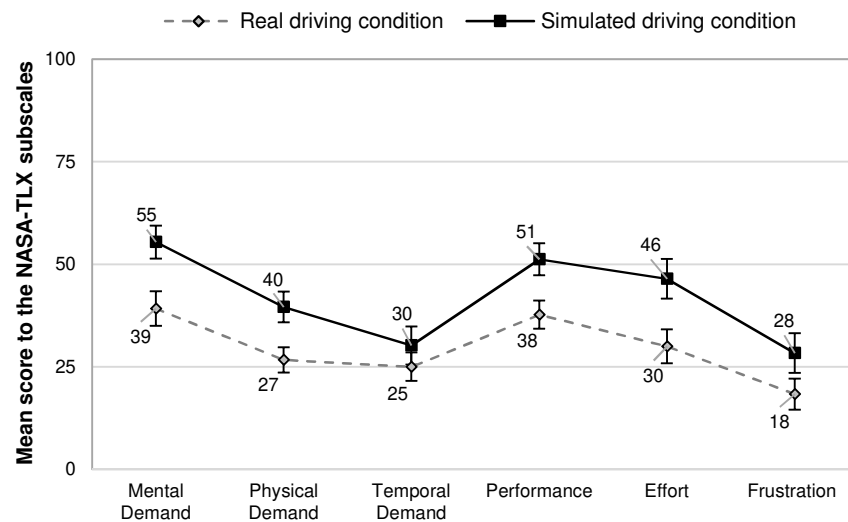
466 Figure 6. Mean response time (ms) to the audio-vocal task as a function of driving condition
 467 (real and simulated) and driving environment. Bars represent standard error of the mean.

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470 3.4. Subjective workload (NASA-TLX)

471 A first *t*-test was run to compare the global score of subjective workload (unweighted
 472 mean of all six subscales) between real and simulated driving. This analysis revealed a
 473 statistically significant difference ($t(23) = -3.75, p < .01, d = -.75$), with perceived workload
 474 higher in simulated ($M = 41.9$) than in real conditions ($M = 29.5$). Global score in the
 475 simulated condition outmatched the one in the real driving condition in 18 out of 24
 476 participants (two participants had the same score in the two conditions). To examine the
 477 workload profile and determine whether it changed with driving conditions, a 2 (driving
 478 conditions: real, simulated) \times 6 (subscales: mental demand, physical demand, temporal
 479 demand, performance, effort, and frustration) repeated measures ANOVA was performed on
 480 the ratings. Results revealed a significant main subscale effect ($F(5,115) = 15.20, p < .001,$
 481 $\eta_p^2 = .40$). Pairwise comparisons indicated that the effect was due to significantly higher
 482 ratings of mental demand and performance (inverted scale: the higher the score, the worse the
 483 performance) compared to physical demand, temporal demand and frustration, and to higher
 484 ratings of effort compared to temporal demand and frustration (see Figure 7).



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486 Figure 7. Workload profile (mean rating for each subscale) as a function of driving condition
 487 (real and simulated). Bars represent standard error of the mean.

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490 4. Discussion

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To date, few studies have tracked driving simulator validity using mental workload measures and they have found contradictory findings (e.g., Diels et al., 2011; Johnson et al., 2011; Milleville-Pennel & Charron, 2015). In this context, the present study aimed at determining whether mental workload varied between on-road and simulated driving while behavioral measures (speed) did not. To achieve this, we selected a free driving condition expected to induce a good correspondence in speed behavior. If the mental workload level differed according to the driving condition, the objective was to examine whether the effect of driving environment on mental workload was similar (relative validity) or not between simulated and real driving.

The findings confirmed previous studies (e.g., Ahlström et al., 2012), showing that the mean speed over the entire route had a very good correspondence between simulated (74.8 km/h) and on-road driving (73.6 km/h). However, mental workload level was higher in the simulator as revealed by scores to the NASA-TLX, response times to the subsidiary task and eye blink rate.

505 The similar speed but increased mental workload results in the simulator are consistent
506 with the predictions we made from De Waard's model (1996). In real world driving,
507 controlling the vehicle in free driving conditions is automated and requires few attentional
508 resources. In driving simulation, on the other hand, vehicle handling is not automated. This
509 could be explained by the low physical validity of the simulator (e.g., lack of inertial cues)
510 which disrupts the naturalness of the perceptual-motor loop. This disruption may then call for
511 an increase in the attentional resources allocated to vehicle handling to preserve driving
512 performance. In this vein, Sahami and Sayed (2013) argued that when participants start to
513 drive a simulator, they have to adapt their skills to the simulator outputs. Consequently, they
514 need time to transfer their already existing driving-related perceptual-motor skills to operate
515 the simulator appropriately (Ronen & Yair, 2013; Sahami & Sayed, 2010). However, this
516 period imposes a mental effort, which lasts until driving becomes automatic (Sahami &
517 Sayed, 2013). As an example, Benedetto et al. (2014) examined mental workload level during
518 the first periods of exposition to a simulator and showed that mental workload level decreased
519 with repetitions. In the present study, the non-significant effect of the driving environment on
520 mental workload measures in the simulator suggests that mental workload level did not
521 decrease with time on task; however, this may be confounded with the order of presentation
522 of the environments, the urban one, which was encountered last, being known to increase task
523 demands (Faure et al., 2016; Michaels et al., 2017). One way forward on this topic would be
524 to examine together the adaptation period and mental workload to explore whether or not
525 workload level decreases with the adaptation of the perceptual-motor loop to the simulator.
526 This has significance as the allocation of additional mental resources to a level of driving
527 activity known to be automated may interfere with the allocation of attention toward other
528 driving tasks (e.g., Mackenzie & Harris, 2017; see also Wynne et al., 2019).

529 To broaden these results, the validity of driving simulators and VR systems for studying
530 human behavior has been assessed through different user-centered dimensions (Malaterre &
531 Fréchaux, 2001; Morice et al., 2008; Pinto et al., 2008). However, some studies have pointed
532 out that these dimensions might be differently affected by the properties of a VR system.

533 Morice et al. (2008) argued that behavioral validity may be deteriorated by the system
534 properties, while subjective validity (i.e., the extent to which the simulated experience is
535 subjectively close to the real situation) remains good. Using a virtual ball-bouncing task, they
536 found that bouncing performance deteriorated for small delays while participants reported a
537 conscious perception of system latency for relatively high ones. In riding simulation, Lobjois
538 et al. (2016) showed that visual roll used to elicit the leaning sensation when driving round a
539 bend was preferred to no roll, although large visual roll hindered steering behavior. On the
540 other hand, the combined evaluation of behavioral and psychological dimensions of validity
541 also suggests a discrepancy between these two dimensions. As reported earlier, some studies
542 showed that subjective workload ratings may be higher even when vehicle handling is well
543 preserved in a simulator (Alm, 1995; Blaauw, 1982; Diels et al., 2011). Here, we showed that
544 behavioral validity showed a good correspondence between on-road and simulated driving,
545 but mental workload was higher in the simulator. These results thus support the idea that for
546 in-depth evaluation of a VR system, user-centered effects are also to be examined at the level
547 of psychological validity, i.e., at the level of the underlying processes.

548 Results also revealed that speed behavior was similar in 6 out of 7 speed sections. In the
549 highway and rural environments, mean speed in each section did not vary between simulated
550 and real driving. In the urban environment, however, participants drove faster in the simulator
551 than in real driving conditions. In other words, speed was similar between both driving
552 conditions in the less demanding environments, but it was higher when driving the simulator
553 in the more demanding environment. This pattern of results is not consistent with previous

554 findings showing that participants drive faster in the simulator for the easiest driving
555 situations (Bella, 2008; Bham et al., 2014; Bittner et al., 2002; Branzi et al., 2017). Nor is it
556 consistent with other models which predict that reducing speed is a way to cope with task
557 difficulty (e.g., Fuller, 2005). A potential perspective that could account for these results is a
558 combined effect of increased workload and range of speed. Regarding the workload effect, it
559 is well known that an increase in cognitive workload leads to visual tunneling and reduces
560 glances to dashboard information and mirrors (Engström et al., 2005; Recarte & Nunes, 2000,
561 2003; Reimer, 2009; Reimer et al., 2012; Tsai et al., 2007; Victor et al., 2005). It may then be
562 that increased workload induced by driving a simulator leads to fewer fixations on the
563 speedometer. Regarding the speed range effect, Wu et al. (2017) proposed that the perception
564 of speed might be biased differently according to the range of speed. They showed that
565 participants who passively observed video footage from a driver's perspective overestimated
566 low speeds (range from 8 to 40 km/h) but underestimated high speeds (range from 64 to 96
567 km/h). In a recent study by Hussain et al. (2019), participants had to actively drive a simulator
568 and drive in the field and estimate when they reached the required speed (50, 70, 80, or 100
569 km/h). Without having access to the speedometer, participants, in both driving conditions,
570 underestimated their own speed and so drove faster than the 50 km/h requested speed;
571 however, they drove slower than the 100 km/h requested speed. Interestingly, when they had
572 access to the speedometer, participants drove slower than the 50 km/h requested speed in the
573 field (48 km/h); in the simulator, however, they underestimated their own speed and drove
574 faster than the requested speed (51 km/h). For higher speeds, participants overestimated their
575 own speed in both conditions similarly. Taken together, these results suggest that the possible
576 visual tunneling due to increased workload in the simulator may have led participants to rely
577 on speed estimation to select their own speed. As low speeds are underestimated while

578 actively driving (Hussain et al., 2019), this could explain why participants drove the simulator
579 faster than the real car in the urban environment.

580 Regarding mental workload and the issue of relative validity of driving simulators,
581 different effects of the driving environment were found depending on the mental workload
582 measures. First, the effect of the driving environment on blink frequency was significant in
583 the field. As expected, the blink rate decreased when the complexity of the driving context
584 increased. However, on the simulator, the driving environment was not found to have any
585 effect on the blink frequency. This pattern of results does not support relative validity. With
586 regard to subsidiary task performance, no difference was found deriving from the driving
587 environment either in real or simulated driving. Unlike eye blink frequency, this result
588 supports relative validity. Alternatively, the non-significant effect of the driving environment
589 in real driving conditions may suggest that variations in task demands from one environment
590 to another were not sufficient to elicit differences on this variable. This stems from the
591 sensitivity of subsidiary tasks to mental workload variations. These tasks are sensitive to short
592 peaks in mental workload (Jahn et al., 2005), unlike other measures that need to integrate raw
593 data over longer intervals. Given free driving conditions with no particular scenario (such as
594 pedestrians stepping out into the road), driving for real in the urban environment may have
595 been carried out without compromising the reaction time task. Beyond this potential limit, the
596 fact that the effects of driving environment on eye blink frequency and response time do not
597 converge in both settings reflects previous studies that concluded that there was (e.g., Reimer
598 & Mehler, 2011) or was not (e.g., Santos et al., 2005) relative validity depending on the
599 mental workload measures. Finally, scores on the NASA-TLX questionnaire may contribute
600 to the issue of relative validity. Galy et al. (2018) highlighted the value of distinguishing
601 between the different subscales of the NASA-TLX rather than using only the global score. In
602 addition, scores greater than the midpoint of a subscale (50) indicates substantial workload

603 levels and can be seen as “drivers” of task workload (Greenlee et al., 2018). The analysis
604 revealed that the global score was mainly driven by scores on the mental demand,
605 performance and effort subscales. While these scores were above or approached the subscale
606 midpoint in the simulator, the workload profile was similar in the real and simulated
607 conditions. Although subjective workload ratings were not collected for each environment,
608 the similar workload profile in both settings is a reasonable case for overall relative validity of
609 driving simulation.

610 **5. Limitations and conclusion**

611 It is important to note several limitations to the present study. While we concluded that
612 a low-cost driving simulator has behavioral validity, lateral control measures were not
613 collected. However, these measures are sensitive to the difference between real and simulated
614 driving (see Supplementary Table 1; but see also the recent review by Wynne et al., 2019) and
615 are also known to be correlated with mental workload level (e.g., Jamson & Merat, 2005;
616 Faure et al., 2016). If behavioral validity is supported by the present speed behavior data, the
617 same may not be true with lateral control measures. The question also arises whether a similar
618 dissociation between behavioral and psychological validity would be observed with a high-
619 fidelity driving simulator. Alm (1995) and Klüver et al. (2016) concluded absolute behavioral
620 validity of high-fidelity driving simulators based on lateral control measures, as compared to
621 fixed-base counterparts (but see Hallvig et al., 2013; Harms, 1996). This suggests better
622 attunement of the perceptual-motor loop in high fidelity simulators and it cannot be excluded
623 that mental workload level may be similar in high-fidelity driving simulators and on-road
624 driving. Although Alm (1995) showed that subjective workload ratings were higher in a
625 moving-base simulator than when driving in the field, this topic needs further research.

626 To conclude, the present study renews evidence that in free driving conditions, speed
627 behavior in simulated driving closely matches that in real driving. Nevertheless, workload

628 level, as measured by blink frequency, response time to a subsidiary task and subjective
629 ratings, was consistently higher in the simulator. These results thus suggest that while
630 behavioral validity can be concluded for speed measures, no similar conclusion can be drawn
631 when attentional resources allocated to vehicle handling come into consideration. The
632 allocation of more attentional resources to a level of driving known to be automated may
633 however interfere with other driving tasks. This fact should therefore be taken into account
634 when driving simulators are used to study tactical or strategic aspects of the driving task
635 which require attentional resources, or to study drivers interacting with in-vehicle information
636 or assistance systems. **A potential follow-up of this study would be to explore whether
637 workload level can be mitigated with the adaptation of the perceptual-motor loop to the
638 simulator.**

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