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1 Title: Do distinct mind wandering differently disrupt drivers? Interpretation of physiological
2 and behavioral pattern with a data triangulation method

3

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14 behavior, Neuroergonomics

15 1. INTRODUCTION

16 In absence of a specific task demand, it is extremely difficult to prevent our minds to wander
17 (Corballis, 2013). Even during our daily living activities, our minds commonly escape from the
18 here and now (Killingsworth & Gilbert, 2010). Mind-wandering, also known as off-task
19 thoughts, is a remarkable evolutionary achievement allowing to plan self-relevant events or
20 remember memorable contents. But although this state can be beneficial, it can also be
21 detrimental by impairing current task performance (McVay & Kane, 2009). For this reason, it
22 is damaging for tasks requiring sustained and divided attention, as can be the driving activity.
23 Recent findings seemed to be indicating that all mind wandering may not be equal (Burdett,
24 Charlton, & Starkey, 2016; Galera et al., 2012; Golchert et al., 2017). The present paper intends
25 to delve into characteristics of off-task thoughts to assess their respective detrimental impacts
26 on driving.

27 1.1 Attention and driving

28 Since a decade now, epidemiological studies have indicated that drivers' inattention and
29 distraction accounted for 25 to 50% of road accidents (Mosedale, Purdy, & Clarkson, 2004).
30 Inattention and distraction have been described as states with different impacts on drivers while
31 they would be responsible for an equivalent part of accidents (Galera et al., 2012). Although
32 different taxonomies have been proposed to better understand and distinguish these states and
33 their respective impacts on drivers, they are still inconsistently defined. Indeed, the relationship
34 between them remains unclear, generating serious difficulties for researchers to study and
35 measure same phenomenon. In the present study, despite the taxonomy of (Regan & Strayer,
36 2014), inattention is defined as a state in which attention have endogenously slid from the main
37 activity to thoughts and feelings. However, inattention does not really exist per se; our mind is
38 always focused on something but not necessarily on the main activity and people are not all
39 time aware of where their thoughts are focused. Considering the constant fluctuations of
40 people's mind and conscious, it could be hard to spot the different moments when they are no
41 longer focused on the main activity. These fluctuations go from being fully on-task to being in
42 a mind-blanking state (Ward & Wegner, 2013) by going through a wide range of inattentive
43 states. This is why inattention is not a homogeneous state and can be differently critical for safe
44 driving.

45 Inattention gathers several states including Mind-Wandering (MW) which corresponds to a
46 shift in the content of thoughts away from an ongoing task to self-generated thoughts and
47 feelings (Smallwood & Schooler, 2015). But even with a specific definition of MW, it remains
48 difficult to unbendingly categorize driver's thoughts and, more broadly, driver's states. Indeed,
49 MW is by nature an unprompted, constantly fluctuating state, which presence varies
50 spontaneously over time (Chaparro, 2015). MW does not correspond to all off-task thoughts
51 but to self-generated and stimulus-independent thoughts (SITUTs). For example, thinking to
52 the next step of our trip is not considered as MW because it is related to the driving task. But in
53 a different context, it could be considered as MW showing the difficulty to categorize driver's
54 thoughts. Assessing the presence of MW is even more essential since it represents between 30
55 to 50% of our daily life thoughts and this phenomenon occurs frequently in all forms of activity

56 (Berthié et al., 2015; Bixler & D’Mello, 2014; Killingsworth & Gilbert, 2010). It is also a
57 recurring phenomenon in driving: four drivers out of five declare having being aware of their
58 wandering thoughts during their last journey and felt being in this state for more than a third of
59 the time (Berthié et al., 2015). The occurrence of MW is also negatively correlated with task
60 demand (Braboszcz & Delorme, 2011; He, Becic, Lee, & McCarley, 2011). As an ubiquitous
61 state whether in driving or in everyday life, MW can have serious consequences.

62 1.2 Consequences of MW behind the wheel

63 MW, as defined across studies, has adaptive and useful roles in our life such as autobiographical
64 planning, creative thinking or self-reflection (Baird, Smallwood, & Schooler, 2011;
65 Mooneyham & Schooler, 2013; Smallwood et al., 2011). But it is a detrimental state in driving
66 since it interferes with the driving activity. MW with high disrupting content multiplies by 2.12
67 the risk to be responsible for a road accident (i.e., 1.98 for sleep deprivation, 1.76 for
68 psychotropic drug use and 1.06 for MW with little disrupting content; (Galera et al., 2012). This
69 higher crash risk could be explained by the perceptual decoupling (Smallwood, McSpadden, &
70 Schooler, 2008) which could underlie the looked-but-failed-to-see phenomenon (Brown, 2005).
71 Perceptual decoupling corresponds to the capacity for the mind to flexibly disengage attentional
72 processes from perception (Smallwood & Schooler, 2015). Besides, changes in the brain during
73 MW (Christoff, Gordon, Smallwood, Smith, & Schooler, 2009; Greicius, Krasnow, Reiss, &
74 Menon, 2003; Raichle et al., 2001) will affect driver behavior.

75 MW might degrade the driver’s control of the vehicle, with a decrease of speed micro-
76 regulations and larger lane departures (Lemercier et al., 2014). In addition, it seems to increase
77 the reaction time variability and decreases safety distances (Yanko & Spalek, 2014). MW also
78 might cause a failure to scan the environment because of a visual attention focused narrowly
79 on the road ahead (He et al., 2011). Although people control the location of where they are
80 looking, it is physically impossible for drivers to control or manipulate fixations and saccades
81 (Rayner, 1998). Such lack of control suggests that gaze behavior might provide a relevant
82 behavioral marker of directed attention and seems responsive to MW (He et al., 2011). In sum,
83 perceptual decoupling leads to changes in driver’s behavior leading to higher frequency of
84 errors, which may explain the important role of MW on the occurrence of accidents. MW also
85 leads to changes in drivers’ physiological functions. It increases heart rate (Smallwood et al.,
86 2004) and leads to changes in several cardiac markers (Ottaviani et al., 2014). It seems therefore
87 appropriate to investigate MW by using behavioral and physiological measurements.

88 But, in the light of previous results (Galera et al., 2012), it seems that all kind of mind-
89 wandering are not equal and could generate different level of risk for drivers. Consequently, it
90 seems appropriate to investigate factors involved in the dangerousness of MW. Indeed, a
91 wandering mind can suffer from a higher crash risk because of a highly disrupting content or
92 not. In the driving context, to further improve road safety, it is therefore relevant to investigate
93 how our attention is drawn from the main activity and how the kind of thought would differently
94 affect drivers and potentially increase their level crash risk.

96 As already said, inattention is difficult to assess regarding its spontaneous fluctuation. And this
97 state seems even more complicated to study since it is not uniform. Indeed, inattention
98 corresponds to Task-Unrelated Thoughts (TUTs) gathering all the kinds of inattentive thoughts
99 such as Task-Related Interferences (TRIs) or Stimulus-Independent Task-Unrelated Thoughts
100 (SITUTs) (Lemercier et al., 2014; Stawarczyk, Majerus, Maj, Van der Linden, &
101 D'Argembeau, 2011). SITUTs correspond to the typical MW experience. In the past decade,
102 MW has been popularized and drawn scientists' attention to better understand the stream of
103 thoughts and consciousness. Research on this topic has seen a substantial increase boosted by
104 many studies (for a review, see Smallwood & Schooler, 2015). Mind-wandering is generally
105 conceptualized as a two steps state. The onset phase represents the initial moment when the
106 mind drifted away from task focus to off-task focus. The maintenance phase represents the
107 cognitive experience and duration of the off-task episode (Smallwood, 2013). This last phase
108 could be maintained due to failures in attentional disengagement which might be due to the
109 attentional tunneling phenomenon (Dehais, Causse, & Tremblay, 2011). During the onset phase
110 of MW, a first self-generated drift of attention toward an off-task focus occurs. Then, cognitive
111 resources are drawn to sustain the MW state. Different kinds of thought can be generated from
112 these resources.

113 It appears that each thought owns specific features considering its willfulness (intentional vs.
114 self-generated), awareness (aware vs. unaware), content: temporality (past, present or future),
115 emotional valence (positive vs. negative) etc... Internal mental task as well as mentally solving
116 problems can not be considered as MW at once; thoughts features should be dug deeper to
117 classify the kind of thought although all inattentive thoughts belong to the TUTs category. For
118 example, intentional TUTs such as Problem Solving Thoughts (PSTs) (Golchert et al., 2017),
119 and unintentional TUTs such as MW are different states and are characterized by distinctive
120 neural networks (Smith et al., 2006). Moreover, at a brain level, what researchers call MW
121 (unaware and unintentional) arise with an activation of the default mode network (DMN) alone
122 while intentional off-task thoughts such as PSTs arise from an activation of the DMN with a
123 region of grey matter associated with intentional off-task thoughts (Golchert et al., 2017). For
124 this reason, the impact of intentionality of TUTs has to be assessed to explain the disruptiveness
125 of MW (Seli, Ralph, Konishi, Smilek, & Schacter, 2017). Moreover, MW experience are
126 unaware (during the onset phase) and self-generated (not primed by an external element) while
127 PSTs are aware and intentional. Those features shape the kind of thought (Spronken, Holland,
128 Figner, & Dijksterhuis, 2016) and the intentionality of MW seems promising to explain
129 different impacts of TUTs (Kopp, D'Mello, & Mills, 2015) on drivers' behavior and
130 physiological signals, and more broadly on their respective dangerousness. Indeed, intentional
131 and unintentional off-task thoughts are underpinned by distinct neural networks which could
132 explain different level of dangerousness (Smith et al., 2006). Considering links between MW
133 and oculometric indicators (He et al., 2011) and the fact that intentional processes are often
134 regulated by executive control allowing operators to regulate their state, it could then generate
135 a higher level of gaze fixity or larger lane departures for MW than for PSTs. More gaze fixity
136 or lane departures might reflect a higher level of dangerousness for the driver. But, when

137 investigating MW or off-task thoughts in general, studies can suffer from a too low
138 experimental control because of the multiplicity of features, thoughts and experiences lived by
139 participants. It is therefore necessary to be cautious on this particular regard and improve the
140 experimental control to avoid biases (Smallwood & Schooler, 2015).

141 1.4 The neuroergonomics approach

142 In 2003, Parasuraman introduced a new interdisciplinary field called "neuroergonomics," which
143 aspires to be the best methodological approach for studying the "brain at work". The interaction
144 between ergonomics and neurosciences would improve our understanding of the brain in action
145 and our ability to study internal states. Using objective and direct data drawn from neurosciences
146 or related to it (Parasuraman, 2003) would allow to enhance knowledge about internal mental
147 states. By highlighting behavioral and/or physiological patterns of MW, the first stone of a
148 detection model of MW would be laid. Indeed, it is already possible to use datamining
149 methodology on objective data to detect an internal mental state (Liang, Reyes, & Lee, 2007;
150 Liang & Lee, 2014). Previous authors managed to build and prove the worth of a detection
151 model of distraction. In the same vein, a detection model could be proposed to detect MW while
152 driving. Considering that notable behaviors such as eyes-off the road are not sensitive enough
153 to spot inattention, the search of MW indicators should focus on physiological data and on
154 leaner behavior, almost impossible to control. To achieve this goal, a data triangulation
155 methodology has been set up, whereby we use the confluence of behavioral, physiological and
156 self-report data (J. W. Schooler & Schreiber, 2004) to improve the experimental control,
157 essential to study MW (Smallwood & Schooler, 2015). Such methods allow validating each
158 dimension as measures of "what they say they measure" (Seth, Dienes, Cleeremans, Overgaard,
159 & Pessoa, 2008).

160 Given a detection model of disruptive MW as a long-term objective, we need to expand our
161 understanding of MW, delving the characteristics underlying this state. More specifically, we
162 need to understand if the intentionality of TUTs will affect the disruptiveness of MW. To do
163 so, it is relevant to investigate how the kind of thought differentially disrupts driver's behavior
164 (speed, lane departure) and impact physiological signatures. Subjective data on the other hand
165 allow classifying drivers' state and then make comparisons between on-task and off-task
166 moments using physiological and behavioral metrics. It could therefore be possible to better
167 understand the most deleterious aspect of MW in order to detect it during risk situations while
168 permitting the mind to wander when the driving demand is low.

169 1.5 Aim of the paper

170 There are three main objectives for the present study. First, it intends to assess the physiological
171 and behavioral correlates of Task-Unrelated Thoughts (TUTs) in driving. Second, it intends to
172 explain the differences between intentional (PSTs) and unintentional (MW) off-task thoughts
173 by making a clear distinction between these kinds of thought to better describe their respective
174 impacts on drivers. Third, with the use of a data triangulation methodology, it aims at
175 highlighting different physiological and behavioral signatures for Problem-Solving Thoughts
176 (PSTs) and (MW) while driving.

177 2. MATERIALS AND METHODS

178 2.1 Participants

179 Twenty healthy volunteers (10 males; age 34.15 ± 11.93) consented to participate in the present
180 study. Before starting the experiment, participants were asked about their health status and none
181 declared cardiovascular disease, attentional or sensorial deficit or any comprehension difficulty
182 were included. All of them reported normal or corrected to normal visual acuity and had been
183 holders of a valid driving license for at least 3 years. All participants gave written consent and
184 received 30 euros for their participation. No participant declared having consumed coffee,
185 alcohol or drug the day of experiment.

186 2.2 Experimental design

187 One repeated measure (temporal-windows: [-5.5s; +5.5s]) and one within-subject factor (the
188 kinds of thought: MW and PSTs) were studied.

189 In order to evaluate the impact of the kind of thought on behavioral and physiological
190 measurement, two tasks were proposed. For the first one, participants were told to keep their
191 attention on the driving task as much as possible and to indicate whenever they realized that
192 their attention had drifted away to MW. For that they had to push the headlights close to self-
193 report (SR) their MW episodes. MW was defined for participants as “when you are thinking
194 about something that has nothing to do with driving. For example, something you were doing
195 before the experiment, something you will do later or thinking about people or a particular
196 person” (Burdett et al., 2016). Each time they pushed the headlights, participants declared
197 unintentional off-task thoughts. Participants then had to focus on the driving activity. The
198 second task consisted in asking participants to find innovations on specific topics while driving
199 (for instance: “how to improve mobility for disabled or older persons”). Innovations should not
200 exist yet and had to be as sophisticated as possible. Participants had to say “Stop” when they
201 considered their ideas were elaborated enough. Such task allowed generating Problem Solving
202 Thoughts (PSTs) whose characteristics are close to MW except that thoughts are intentional.
203 Moreover, participants were not asked to think about a personal goal or issue to control the
204 content of thought (temporal orientation and distance, emotional valence...). By saying “Stop”
205 at the end of each PSTs phase, participants declared having intentional off-task thoughts.

206 In each PST phase, participants were given instructions about a specific area (e.g., educational
207 system, sport etc.). They then had to elaborate one innovation. In each scenario, 3 topics were
208 proposed and all participants were asked to reflect upon 6 different innovations during the
209 whole experiment. Instructions about each innovation were previously recorded and
210 broadcasted in the simulator cabin at the beginning of each PST phase. The end of each PST
211 phase was also announced by instructions broadcasted in the cabin. Then, a new MW phase
212 started and participants were reminded they had to push the headlights whenever they realized
213 that their mind wandered. Each MW phase lasted 1 min and a half and each PST phase lasted
214 2 minutes. All participants had the same order of conditions presentation which was MW-PST-
215 MW-PST-MW-PST-MW for both scenarios. Considering the changing aspect of MW,
216 alternating tasks appeared to be the more realistic way to create an enabling environment for

217 the emergence of MW. For this reason four phases of self-reported MW were alternated with
218 three phases of reflections on innovations (PSTs). Each scenario began and ended with a MW
219 phase.

220 The really nature of the two tasks that participants were asked to perform would lead to a
221 different number of events for each kind of thought. During MW phases, participants were able
222 to self-report several MW episodes while they had to think about one innovation during the
223 PST phase.

224 Moments when participants self-reported their wandering thoughts or said “stop” after
225 reflecting upon innovations were considered as “events”. Physiological and behavioral data
226 were compared before and after self-report events and before and after participants said “stop”
227 after thinking on innovations. Therefore, it was possible to compare temporal window
228 designated as inattention interval (before) and temporal window designated as an attentive
229 interval (after) (He et al., 2011).

230 2.3 Material & Apparatus

231 2.3.1 Driving simulator

232 The driving simulator used in this experiment was a Peugeot 308 cabin (length = 4.27 m;
233 width = 1.81 m) surrounded by seven video projection screens (covering a total angular space
234 of 270° and vertical angular size of 47.5°). Participants drove in a straight line interrupted by
235 right and left curves in an urban residential zone. It was a two-way country road with only few
236 vehicles coming from the opposite direction of the participant vehicle so as to enable the
237 emergence of MW (He et al., 2011). To remain coherent with Braboszcz & Delorme, 2011 and
238 He et al., (2011), the driving environment was purposely refined to encourage MW. The road
239 contained long straight lines interrupted by right and left curves. Participants completed 2
240 scenarios of 12 min using the same visual base. They had a break between the two scenarios to
241 avoid any fatigue effect.

242 2.3.2 Physiological and behavioral measurements and pre-processing

243 2.3.2.1 *Cardiac measurement*

244 Heart rate was measured using 3 electrodes (Biopac, MP150 using Bionomadix transmitters)
245 during the whole experiment. The positive electrode was placed under the last left rib, the
246 negative electrode on the manubrium of the sternum, and the ground electrode on the right side,
247 just on top of the hip. In a test phase, it has been checked that this positioning satisfies the main
248 conditions to collect correct cardiac signal during driving: compromising with the length of the
249 wires and avoiding a noisy signal due to muscular activity.

250 Heart Rate (HR) values were computed using equations provided by Roy, (2015) and illustrated
251 by Pepin et al., (2017). From the cardiac signal, several time-domain indices bringing
252 information about heart rate variability have been calculated from IBI such as the Root Mean
253 Square Successive Differences of NN intervals (RMSSD) and proportion of the number of
254 interval differences of successive NN intervals greater than 50 ms (pNN50).

255

2.3.2.2 *Oculometric measurement*

256 Eye movements were sampled at 30 Hz with an eye-tracking device (Tobii Glasses v1). To
257 analyze the visual information gathering while driving, a gaze fixity rate indicator has been
258 designed. The gaze fixity was present if at least 90% of eye absolute positions were contained
259 in a visual angle area of 2° for more than 1 s. So, the gaze fixity is a binary indicator and then
260 can take only 2 values (1 when there is gaze fixity and 0 when there is not). An algorithm has
261 been set up to transform the absolute position towards gaze fixity for each time step. In order
262 to convert the absolute gaze position into the gaze fixity, such process has been carried out for
263 each time step for each participant throughout a sliding window conversion. This algorithm,
264 coded 1 if 90% of the 29 next gaze absolute positions (corresponding to 1 sec) were contained
265 in a 2° of visual angle area. The gaze fixity rate is the mean of gaze fixity across all events of
266 each condition.

267

2.3.2.3 *Driving data*

268 The driving simulator provided several driving measures such as the speed (in kilometer per
269 hour), the lateral position compared to the center of the lane (in meter) and the steering wheel
270 angle (in degree). Measures of driving performance were sampled at a mean rate of 60 Hz and
271 were synchronized with cardiac data through the BioPac MP150 and with the Tobii Glasses 1.

272

2.3.2.4 *Questionnaire*

273 Participants had to fill in a questionnaire about personal details (age, gender, driving habits,
274 driving experience, attentional and auditory disorder, drug consumption etc...).

275 After each scenario participants had to fill a survey about the content of MW and PSTs. Items
276 enlighten the temporal focus of MW (past, present or future), its emotional valence and its
277 subjective impact on driving performance. For each proposal, participants had to indicate the
278 number of wandering thoughts they remembered having for each dimension.

279

2.4 Procedure

280 Prior to the experiment, participants were informed about the content of the experiment and
281 asked to give their informed consent. They were also aware that they could stop the experiment
282 at any time. Cardiac electrodes were affixed. Then, participants sat in the simulator cabin and a
283 5 min baseline measurement of HR was recorded. A short training session on the driving
284 simulator was performed to familiarize him/herself with the simulator and the driving
285 environment. Then, participants were equipped with the eye-tracker glasses and the calibration
286 phase started. Prior to the beginning of the first scenario, participants were instructed about
287 PSTs and MW conditions. Participants were asked to maintain the car speed at 70 Km/h and
288 stay in the center of the lane. After the first scenario, they completed the « Mind Wandering »
289 questionnaire about their attentional focus and the content of their thoughts. After a break, they
290 performed the second scenario. Then, they completed the MW questionnaire once again and
291 the survey about personal information. Finally, at the very end of the experiment, a debriefing
292 session was performed to explain the purpose of the study and answer participants' questions.

293 2.5 Statistical analyses

294 Physiological and behavioral data were compared before and after MW moments and before
295 and after PST moments. Such comparisons allow to make within-subject comparisons. It
296 assumes that participants were in a MW state or were reflecting upon innovation before
297 participants SR their wandering thoughts or said stop after reflecting upon innovation.
298 Moreover, it assumes that they were refocused on the main activity (i.e., driving) after it.
299 Considering temporal windows used in a previous study(He et al., 2011), [-5.5s; 0s] and
300 [0s; +5.5s] temporal windows were chosen here to study and compare respectively off-task
301 (PSTs or MW) and on-task thoughts. This decision is based on assumptions that in the 5.5
302 seconds prior to the event participants were in MW or focus on their PSTs while theirattention
303 in the 5.5 seconds following the event was redirected towards driving. These assumptions seem
304 more likely to be verified than with the use of temporal windows used in other studies (He et
305 al., 2011).

306 Statistical analyses were conducted to address two experimental questions in particular:

- 307 1) What are the behavioral and physiological correlates of inattentive thoughts
308 towards driving?
- 309 2) Is it possible to distinguish problem solving thoughts and stimulus-independent
310 and task-unrelated thoughts (MW)?

311 The first step was to check distributions normality using the Kolmogorov–Smirnov test.
312 Depending on this result, ANOVAs, Wilcoxon were conducted to compare 1) changes between
313 before and after, 2) changes between before and after according to the kind of thought and t-
314 tests were conducted to compare 3) differences during before and after according to the kind of
315 thought.

316 3. RESULTS

317 Overall, 285 events were collected across all conditions and through all participants. Grand
 318 mean responses have been computed by averaging data over all events. Different numbers of
 319 events from cardiac and oculometric metrics have been removed resulting in different numbers
 320 of event suitable for analysis. It appears that 13.68% of eye-tracking data, 7.37% of cardiac data
 321 and 0% of driving data have been removed. Events were removed from analyses either because
 322 temporal windows were overlapping other events or because data were unsuitable for analysis.
 323 It is also possible that participants did not said “stop” because did not complete their innovation
 324 within the allocated time. The number of each event for each variable is presented in Table 1.

325 *Table 1: Number of usable events, mean, standard deviation and p-value of the difference for each variable. MW*
 326 *= Mind-wandering; PST = Problem-Solving Thought*

	MW									PST								
	Number of participant with usable data	Mean of usable events by participant	SD of usable events by participant	Sum of usable events	Mean for [-5,5; 0] time-window	SD for [-5,5; 0] time-window	Mean for [0; +5,5] time-window	SD for [0; +5,5] time-window	p-value	Number of participant with usable data	Mean of usable events by participant	SD of usable events by participant	Sum of usable events	Mean for [-5,5; 0] time-window	SD for [-5,5; 0] time-window	Mean for [0; +5,5] time-window	SD for [0; +5,5] time-window	p-value
Gaze Fixity	20	10,00	4,68	200	0,52	0,15	0,41	0,19	< .001	15	2,40	1,82	48	0,46	0,24	0,41	0,22	> .05
Heart Rate	20	9,55	4,02	191	72,51	13,72	73,51	14,40	< .001	17	2,35	1,57	47	73,25	15,00	74,13	15,74	< .01
Speed	20	11,1	5,17	222	70,72	2,26	71,46	2,65	< .05	19	2,70	1,45	54	72,52	4,14	72,27	4,38	> .05

327 3.1 Questionnaires

328 Participants declared having more future-oriented (47.64%) than past-oriented (13.19%)
 329 thoughts ($T = 56, z = 3.89, p < .0001$). Considering thoughts emotional valence, participants
 330 declared having less negative thoughts (15%) than neutral (44.47%) ($T = 74, z = 3.69, p < .001$)
 331 or positive thoughts (40.53%) ($T = 88, z = 3.29, p < .001$).

332 3.2 Comparisons Before/After for TUTs

333 Cardiac data

334 The only significant result among cardiac measurement concerned Heart Rate (HR) which was
 335 higher after ($m = 73.34, SD = 13.29$) TUTs than before ($m = 72.33, SD = 12.53$)
 336 ($F(1, 19) = 11.57, p < .01$). RMSSD and pNN50 metrics appeared non-significant with
 337 Wilcoxon tests ($p > .05$).

338 Eye-tracking data

339 The difference in gaze fixity rate between before ($m = 0.495, SD = 0.25$) and after
 340 ($m = 0.511, SD = 0.17$) gave rise to a significant effect in the [-5.5s; +5.5s] temporal window
 341 ($F(1, 19) = 10.15, p < .01$).

342 3.2.3 Driving data

343 A trend appeared for the vehicle speed is different between before ($m = 71.07, SD = 2.36$) and
 344 after ($m = 71.83, SD = 3.14$) and it gave rise to a significant effect in the [-5.5s; +5.5s] temporal
 345 window ($F(1, 19) = 3.84, p = .065$).

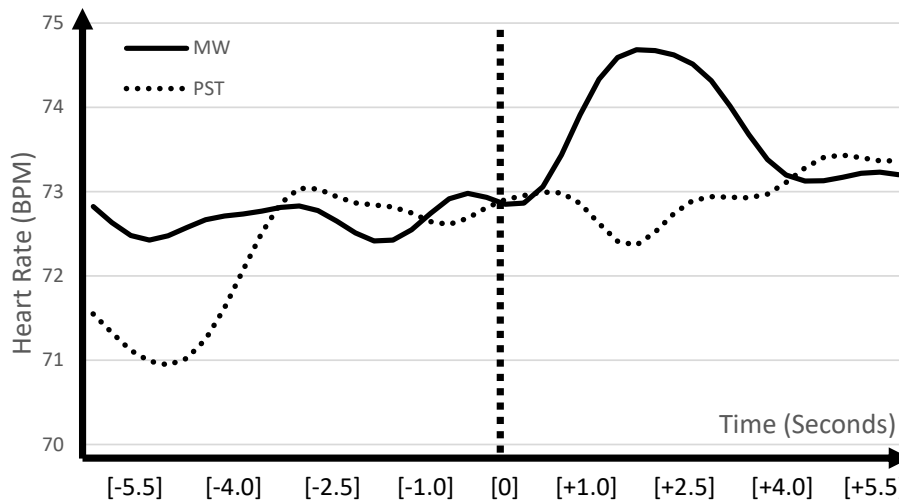
346 The lateral position and the steering wheel angle comparisons appeared both non-significant
347 ($p > .05$).

348 3.3 Comparisons Before/After for MW and PST

349 3.3.1 Cardiac data

350 HR appeared significantly different between before ($m = 72.51$, $SD = 13.72$) and after
351 ($m = 73.51$, $SD = 14.40$) for the MW condition: $F(1, 19) = 10.85$, $p < .01$.

352 HR averaged across all participants in the $[-5.5s; +5.5s]$ temporal window according to the kind
353 of thought is presented in Figure 1.



354

355 *Figure 1: Evolution of grand mean heart rate (obtained from raw data) within 11 seconds*
356 *surrounding the event, data depict MW and PST conditions.*

357 For PST, a trend appeared for HR between the inattentive phase ($m = 73.25$, $SD = 15.00$) and
358 the attentive phase ($m = 74.13$, $SD = 15.74$), for the PST thoughts ($F(1, 19) = 3.109$, $p = .093$).

359 3.3.2 Eye-tracking data

360 The gaze fixity rate was higher during MW ($m = 0.522$, $SD = 0.15$) than during attentive
361 moments ($m = 0.413$, $SD = 0.19$) in the $[-5.5s; +5.5s]$ temporal window
362 ($F(1, 19) = 10.95$, $p < .01$).

363 Conversely, the difference in the gaze fixity rate for the PST condition in the $[-5.5s; +5.5s]$
364 temporal window was not significant ($F < 1$).

365 Gaze fixity rates according to the type of tasks are presented in Figure 2 and Figure 3.

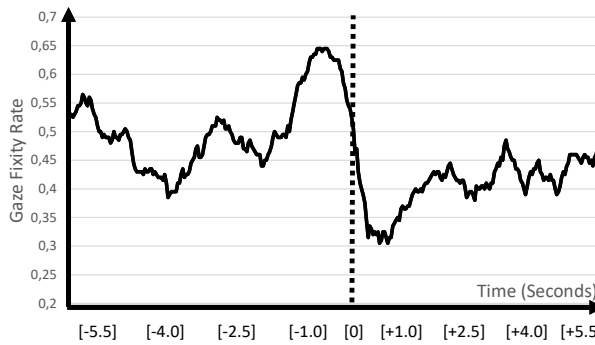


Figure 2: Grand mean of gaze fixity in the 11 seconds surrounding a MW self-report. Data averaged over 200 events

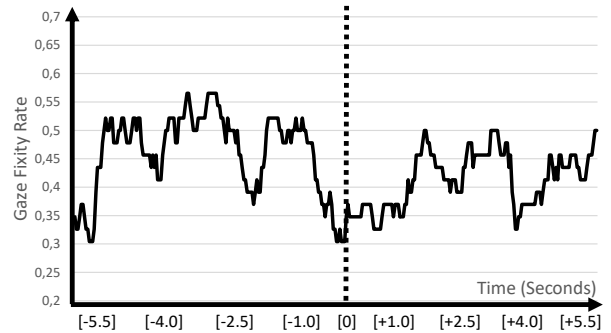


Figure 3: Grand mean of gaze fixity in the 11 seconds surrounding a PST event. Data averaged over 46 event

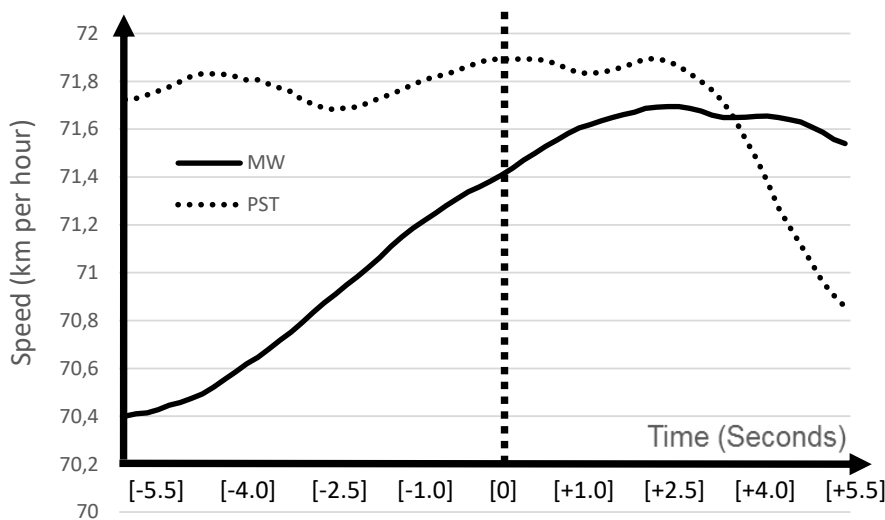
366 3.3.3 Driving data

367 Concerning MW results, differences concerning lateral position as well as the steering wheel
 368 angle appeared non-significant ($p > .05$) between before and after MW.

369 A trend appeared for the car speed between before ($m = 70.72$, $SD = 2.56$) and after for the MW
 370 condition ($m = 71.46$, $SD = 2.65$) in the $[-5.5s; +5.5s]$ temporal window
 371 ($F(1, 19) = 4.01$, $p = .060$).

372 Concerning PST, neither the lateral position, nor the steering wheel angle, nor the vehicle speed
 373 was significantly different between before and after moments.

374 Car speeds according to the kind of task are presented in Figure 4.



375
 376 Figure 4: Grand mean of vehicle speed in the 11 seconds surrounding events, data depict MW
 377 and PST conditions.

378

379 4. DISCUSSION

380 The objectives of the present study was to (1) make a clear distinction between intentional
381 (Problem Solving Thoughts = PSTs) and unintentional (MW) off-task thoughts, (2) assess the
382 physiological and behavioral signatures of TUTs (both MW and PSTs) and (3) compare MW
383 and PST. Participants had to 1) Self-Report (SR) their wanderings thoughts when they realized
384 their mind drifted away from driving and 2) intentionally generate PST. For this, one repeated
385 measure (temporal-windows: [-5.5s; +5.5s]) and one within-subject factor (the kinds of
386 thought: MW and PSTs) were studied.

387 4.1 MW features

388 Concerning the features of thoughts that participants declared (MW condition), the prospective
389 bias showed in previous studies has been replicated: 48% of SR thoughts were future-oriented
390 while only 13% were past-oriented. These findings support the view of an important role of
391 MW to enable anticipation and planning of personally relevant future goals (Baird et al., 2011;
392 Stawarczyk, Cassol, & D'Argembeau, 2013). Proportion of interfering thoughts related to the
393 task (39% in the present study) is also consistent with prior findings (Gonçalves et al., 2017;
394 Stawarczyk et al., 2011). Moreover, considering links between temporality and valence, the
395 high proportion of neutral or positive thoughts (85%) is also consistent with the prospective
396 bias highlighted here. Results obtained from questionnaires indicate that 1) MW own a useful
397 planning role in our lives and 2) that participants generated ecological off-task thoughts
398 comparable to MW generated during other studies.

399 4.2 TUTs signatures

400 Physiological data analysis showed that Heart Rate (HR) was significantly lower during Task-
401 Unrelated Thoughts (TUTs) than in the following seconds, during attentive driving. It means
402 that TUTs could have an impact on HR even on a 11s time-window. No difference has been
403 found for heart rate variability indicators (RMSSD and pNN50). This result is not in line with
404 Smallwood et al., (2004) since HR was found to be higher during TUTs. Such different results
405 could be explained by differences in the dynamic of the tasks the participants had to achieve
406 (computer task vs. driving). TUTs moments could consequently be distinguished from attentive
407 moment (on-task thoughts) using heart rate. This potential distinction would be more effective
408 by taking the kind of thoughts into account (see next section).

409 Behavioral data analysis showed that the gaze fixity was higher during TUTs than during
410 attentive driving for on 11s time-window. As drivers' gaze is focused narrowly on the road
411 ahead during TUTs, gaze fixity seems to be a sensitive indicator of TUTs. Our results, in line
412 with He et al., (2011), showed that drivers' visual scanning is reduced their during TUTs.
413 Moreover, it means that TUTs damage their road sides scanning leading to impaired
414 information collection and processing coming from there. This could explain the part of the
415 higher crash risk associated to TUTs and particularly to MW. Considering driving data, the
416 vehicle speed appeared to be lower during TUTs episodes than after strengthening the impact
417 of TUTs on drivers' behavior. So, in line with previous findings, TUTs should have an impact
418 on drivers' behavior and physiological signals (Baird et al., 2011; He et al., 2011; Lemercier et

419 al., 2014; Smallwood et al., 2004). In order to better understand such impact, it is necessary to
420 categorize the kind of thought drivers are involved in. In the next part, the relative impact of
421 each kind of thought is described by comparing the Stimulus Independent and Task-Unrelated
422 Thoughts (SITUTs = MW) and Problem Solving Thoughts (PSTs).

423 4.3 Comparisons between MW and PSTs signatures

424 4.3.1 Cardiac data

425 Considering cardiac measurement, it appears that heart rate is significantly lower during MW
426 than after being aware of it in the [-5.5s; +5.5s] temporal window. Such significance, which has
427 not been highlighted in previous study, is due to a specific pattern in HR in seconds following
428 participant's SR (Figure 1). This special pattern could be explained by the dynamic of the task
429 in which drivers were involved. Indeed, participants were asked to be focus on the driving task
430 and self-report their MW episodes. This means that in the seconds prior to self-reports, drivers
431 were focused on their personal thoughts rather than driving. Thus, when they became aware of
432 their inattentive state, corresponding to a gain in meta-consciousness (Schooler, 2002)
433 participants declared their thought and were instructed to focus back on the driving task.
434 However, MW impairs the working memory update (Kam, Nagamatsu, & Handy, 2014) by
435 drawing attentional resources from it to feed thoughts (Levinson, Smallwood, & Davidson,
436 2012). This means that drivers could no longer be able to refresh their situational awareness,
437 which corresponds to the state of knowledge about the elements in a dynamic environment
438 (Endsley, 1995). Hence, as soon as they became aware of a wandering thought, drivers seemed
439 to seek information (their speeds, the location of others vehicles etc...), processed it and
440 integrated it to quickly recover a clear and accurate situational awareness. If they did so, they
441 had to spend cognitive resources to shift between the default and the attentional mode (Yanko
442 & Spalek, 2014). This switchover could have a cost in terms of attentional resources. Yet, a
443 recent study has showed the feasibility of detecting the cognitive effort generating by a
444 cognitive demand of a task through heart rate measurement (Pepin et al., 2017). It appears that
445 the specific pattern found here after participants self-reported their MW episodes could
446 correspond to a cognitive effort pattern. Time-windows used for this experiment and in Pepin
447 et al., (2017) are similar. As previously explained, it seems likely that this increase in HR is
448 responsible for the statistical significance highlighted here. The difference is therefore due to
449 an increase in HR, which could come from a cognitive cost. This cognitive cost could have be
450 necessary to shift from a wandering mode underlain by the default mode network (Christoff et
451 al., 2009) to an attentive mode (Mason et al., 2007) underlain by the dorsal attentional network
452 (Vincent et al., 2006) generating the special pattern in [+1s; +4s] following the SR.

453 The special pattern spelt out here is not present for the PST condition in the same time-window.
454 Nevertheless, different fluctuations in HR have been highlighted between PSTs and attentive
455 driving meaning that PSTs could have a cardiac signature while the only difference for the MW
456 conditions have been found during the attentive driving period (Figure 1). Even if the difference
457 for MW and PSTs is not significant regardless time-window (before and after), this cardiac
458 pattern could be discussed regarding results outlined above. Indeed, the need to reorient our
459 attention to driving could have generated a small cognitive effort, insufficient to reach

460 significance. With a less refine environment and more vehicles, the reorientation of attention
461 could have been more expensive in cognitive resources inducing a larger HR acceleration. The
462 present study has not been able to highlight a cardiac signature of MW or PSTs but found that
463 the reorientation of drivers' attention after a MW episode gets a cognitive cost that could be
464 detectable by averaging heart rate values.

465 4.3.2 Ocular behavior

466 Considering oculometric measurement, the gaze fixity rate was higher during MW episodes
467 than after. The difference is significant in the [-5.5s; +5.5s] time-window. Conversely, no
468 difference has been found for PST conditions. Such results support the previous hypothesis in
469 which the specific cardiac pattern is due to a need for drivers to reorient attention towards
470 driving after a MW episodes. Indeed, drivers' gaze appeared to be fixed during MW episodes
471 meaning that the amplitude of their visual scanning is reduced. Drivers do not seem to be as
472 efficient to collect and process information as they were when focusing on driving. Hence, to
473 update their situational awareness, drivers scanned the environment in a broader way after
474 having self-reported their MW episodes (Figure 2). It has already been proven that MW leads
475 to a reduction in drivers horizontal visual scanning (He et al., 2011) but an increase in drivers
476 gaze fixity during MW means that drivers' gaze get stuck straight ahead. A parallel could be
477 made with failure in attentional disengagement among aircraft pilots (Dehais et al., 2011).
478 Indeed, MW could prevent attentional disengagement from drivers' thoughts to driving. This
479 failure in attentional disengagement would lead to a staring gaze and then increase the risk of
480 an accident.

481 Now, considering PST, no difference has been found for the gaze fixity rate. Such result might
482 be the fact that 200 events were averaged to analyze MW while only 46 events have been
483 averaged for PST (Figure 3). Still, it appears that there are substantial differences between MW
484 and PST. Indeed, the gaze is more fixed during MW than during PST. More than 60% of drivers
485 gaze during MW events were fixed in the second before the SR while it barely raise 45% for
486 PSTs (it has to be noted that the gaze fixity baseline reaches 37%). MW impact gaze behavior
487 by reducing the visual scanning and generating an impaired visual attention while the gaze
488 fixity seems to be non-sensitive to PSTs under current experimental conditions.

489 4.3.3 Driving behavior

490 Considering driving behavior, the vehicle speed tends to be lower during TUTs than during
491 attentive driving moments. However, in the present study, vehicles' speed gradually increase
492 while it has been shown to decrease while having off-task thoughts (Yanko & Spalek, 2014).
493 When having a closer look and taking into account the kind of thought, it appears that the
494 vehicle speed is lower during MW than during attentive driving but tends to gradually increase
495 up to approximately 1 second after drivers self-reported their wandering thoughts (Figure 4). It
496 could correspond to the necessary time for drivers to reorient their attention towards driving,
497 update information and rectify their speed. While drivers were asked to maintain the speed of
498 their vehicle as close as possible to 70km per hour, it seems that they did not have enough
499 cognitive resources to be focus on their thoughts and control lateral and longitudinal positions
500 of their vehicle. Drivers seemed to experience a failure in their executive control leading to

501 higher speeds, which could partly explain the higher crash risk imputable to MW (Galera et al.,
502 2012). Some reservations should be made with the present interpretation since only a trending
503 effect have been highlighted.

504 Conversely, no statistical significance has been found for the vehicle speed between PSTs and
505 attentive driving moments and between PST and MW for the vehicle lateral position, steering
506 wheel angle or speed. Similarly, no statistical significance has been found after having TUTs,
507 during attentive driving moments, for MW and PST conditions, meaning that the driving
508 behavior seems to be affected by TUTs but globally unaffected by the intentionality of TUTs.
509 Drivers were aware that they were having off-task thoughts during PSTs so they could have
510 been able to set up strategies. Those strategies could have been absent for MW explaining that
511 speed gradually increased at that time. The absence of statistical significance for the lateral
512 position of the vehicle and the steering wheel angle could be partially explained by the presence
513 of curves during driving sessions. Indeed, several events (self-report mind wandering and
514 reflection upon innovation) happened during curves leading to high steering wheel angle values
515 and high variation in the lateral positions values of the vehicle. These alterations of data
516 occurred sometimes during TUTs and sometimes during attentive driving moments. To be able
517 to conclude about the impact of the kind of thoughts on the lateral position of the vehicle and
518 the steering wheel angle, the use of a different task with straight lines and no curve should have
519 been used. To conclude about speed, it is also likely that the vehicle speed management is
520 affected by MW while the lateral position and the steering wheel angle are not. Indeed,
521 managing speed requires drivers a constant cognitive resources allocation management. To do
522 so, drivers have to periodically check the speedometer, keep in mind the information and then
523 adapt their behavior. Nevertheless, with an increase in the gaze fixity and an impossibility to
524 update their working memory, drivers fail to process such information generating a
525 perseverative behavior and a gradual speed increase. In conclusion, MW seems to impair
526 drivers' executive control leading to a persistent behavior. During MW, drivers are no longer
527 able to keep watch their speed. This could be problematic, especially under real driving
528 conditions with strong time pressure (Merat, Jamson, Lai, Daly, & Carsten, 2014).

529 4.4 Conclusion

530 The question of how various off-task thoughts might impact drivers is a topic of increasing
531 concern not only for road safety but also for human performance and comprehension. The
532 present study intended to make a distinction between intentional (PSTs) and unintentional
533 (MW) thoughts. Being more specific about the features of thought allow to better understand
534 inattention and to take effective countermeasures to ensure drivers' safety. The present study
535 highlighted behavioral and physiological signatures of Task-Unrelated Thoughts (TUTs).
536 During TUTs, the gaze fixity is higher and the speed of the vehicle is lower than during attentive
537 driving moments. When taking the kind of thought into consideration, it appeared that heart
538 rate and speed are affected by both MW and PSTs while the gaze fixity is only sensitive to MW.
539 For this reason, the gaze fixity appeared as a sensitive indicator of MW. Indeed, MW draws on
540 working memory resources (Kam et al., 2014) to trigger and feed self-generated thoughts
541 (Levinson et al., 2012). MW and PSTs seem to have different oculometric signatures
542 strengthening the need to distinguish the kind of thought when studying off-task thoughts. The

543 following perseverative behavior and staring gaze prevent drivers to properly scan the
544 environment. And even if they collect a part of available information, evidences coming from
545 neurosciences have showed that sensory cortices are less active and information are less well-
546 processed during MW (Smallwood, Beach, Schooler, & Handy, 2008). Oculometric
547 measurements should therefore be considered more closely when researchers study MW.
548 Consistent with previous findings (McVay & Kane, 2009; Smallwood, 2010), behavioral
549 outcomes showing that gaze fixity and speed increase during TUTs unveil a failure in executive
550 control and in resources allocation management. This leads to incapacity to both maintain TUTs
551 and manage speed. Nevertheless, and this is the first limitation of the present study, changing
552 the response mode between MW and PSTs add some variability in data which could explain
553 this difference. Indeed, flashing headlights and say “stop” are two different output modes,
554 which could have influence the gaze fixity. Secondly, MW and PST conditions were not
555 averaged over the same number of events leading to more accurate interpretations and
556 conclusions for MW than for PSTs. Moreover, when participants were asked to self-report their
557 wandering thoughts we assume that we can only study MW that became, at a certain moment,
558 conscious. Participants cannot report an unconscious wandering thought and can only wait for
559 this thought to become conscious before being able to report it. This is why the present study
560 only considered unintentional and, in the first place, unaware thoughts that became, at one time
561 aware. Such off-task thoughts might be different from thoughts that would never become aware.

562 This study has not been capable to demonstrate strong differences between PST and MW. But
563 recent findings seemed to direct research towards more specific thoughts features (Golchert et
564 al., 2017) such as awareness (Smith et al., 2006), temporal focus (Smallwood & Schooler,
565 2015), temporal distance (Spronken et al., 2016), emotional valence (Killingsworth & Gilbert,
566 2010), relevance of the thought to the individual (Andrews-Hanna et al., 2013) and task demand
567 (He et al., 2011). A better understanding of the respective impact of these features could be
568 very useful to identify detrimental thoughts responsible for the “disruptive mind-wandering”
569 state doubling the risk to be responsible for a car accident (Galera et al., 2012). But the
570 importance of each factor is difficult to measure considering strong and winding links between
571 them (Ruby, Smallwood, Engen, & Singer, 2013; Smallwood & Schooler, 2015; Stawarczyk et
572 al., 2011). As it has been done with the intentionality in the present study, future research should
573 therefore have to bring to light the impact of temporal focus, emotional valence and subjective
574 relevance of the current thought, which seem to be the most promising thought features to
575 explain that MW while driving is detrimental or not. Indeed, it seems that the temporality and
576 the occurrence of MW are related: the more people have future-oriented thoughts, the more
577 they wander (Baird et al., 2011). It also seems that emotional valence and temporality are linked
578 (Smallwood & Schooler, 2015) and a bidirectional relationship between negative emotion and
579 MW have been highlighted (Smallwood & Schooler, 2015; Techer, 2016). When we consider
580 that the emotional valence of off-task thoughts affect cognitive performances (Banks, Welhaf,
581 Hood, Boals, & Tartar, 2016), all mind wandering seem not be equal. Considering links
582 between temporality and other thoughts features, it is therefore highly likely that the content of
583 a wandering thought and particularly its temporality seems promising to explain a higher
584 disruptive effect on drivers (Lemercier et al., 2014).

585 Finally, once links between thoughts features and their impacts on drivers will be questioned
586 and spelled out, a detection algorithm of MW could be developed. The idea is to use the gaze
587 fixity and others relevant behavioral (e.g., deviations in the vehicle's lateral position: Lemerrier
588 et al., 2015) and physiological (e.g., pupil dilation: Konishi et al., 2017) indicators to assess the
589 presence of MW. The final objective being to merge it together to improve the ability of an
590 algorithm to spot MW when it is disruptive. To do so, the selected indicators must be evaluated
591 on their sensitivity, specificity and robustness. It could be also possible to take into account the
592 driving context to better prevent car crash risk. The objective is to monitor drivers' attentional
593 states and pinpoint times when driver's mind dangerously drifts away. Such solution is entirely
594 in continuation with work achieved years ago on distraction using a layered algorithm, dynamic
595 bayesian networks and supervised clustering (Liang et al., 2007; Liang & Lee, 2014). It is
596 therefore critical to collect both physiological and behavioral data to expand our understanding
597 of MW through a data triangulation method, use these data mining methodologies to detect MW
598 while driving and then still improve road safety.

599 Conflict of interest

600 All authors declare they have no conflict of interest

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