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1 Engagement of mental effort in response to mental fatigue: A psychophysiological analysis

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15 1. Introduction

16 Mental fatigue is a universal human experience. Studying for exams, tackling complex
17 work tasks, or simply keeping up with a mentally taxing flow of information are common
18 activities that often induce mental fatigue. Fatigue or the perception of fatigue that results
19 from the deployment of effort during effortful activities does not necessarily lead to the
20 sudden cessation of the activity. Rather, fatigue may be viewed as a regulatory signal
21 generated by the organism that indicates a high consumption of energy during or following
22 an effortful activity that can be generally interpreted as a decrease in available resources.
23 Individuals may then adopt two main behavioral patterns. The first consists of the
24 deployment of compensatory mental effort intended to maintain the level of performance
25 despite fatigue (Hockey, 1997; 2011), while the second entails a disengagement of effort
26 that leads to a performance decrement (Mangin et al., 2023). These two behavioral patterns
27 can coexist within the same task but can operate at different moments in the task (e.g.,
28 compensatory effort in the middle of the task and disengagement of effort at the end of the
29 task). Within the framework of cost-benefit theories, people adapt their effort continuously
30 and the choice of their behavior depends on the comparison between the costs of effort and
31 the benefits of expending effort (André et al., 2019; Shenhav et al., 2013). However,
32 characterizing these patterns offers the advantage to understand participant's behavior in
33 effortful tasks. The objective of this study is to explore the underlying psychophysiological
34 mechanisms of effort engagement in response to mental fatigue.

35 Mental effort should be seen as a mechanism that estimates the amount of energy the
36 organism must expend to achieve a relevant goal and allocates that effort to the task (André
37 et al., 2019). This effort-based decision making process is commonly assumed to be based on
38 the state of the organism and the constraints of the task (André et al., 2019; Shenhav et al.,

39 2013). In investigating behavioral patterns of effort allocation employed during tasks
40 inducing mental fatigue, reliable physiological measures such as heart rate variability (HRV)
41 and preejection period (PEP) could provide objective and relevant indicators of how people
42 adapt to mental fatigue (Mulder et al., 2004; Wright, 1996). Effort is associated with the
43 cardiovascular system (Obrist, 1976), which is influenced by the two antagonist branches of
44 the autonomic nervous system (the sympathetic and parasympathetic branches). HRV is the
45 fluctuation in the time intervals between heartbeats. Its is under the influence of the
46 sympathetic and parasympathetic systems but mainly reflects parasympathetic activity
47 (Shaffer & Ginsberg, 2017); it can be studied through time domain measures (e.g., standard
48 deviation of all NN intervals, SDNN; root mean square of the successive differences, RMSSD),
49 frequency domain measures (e.g., high frequency, HF; low frequency, LF) or nonlinear
50 measures (e.g., entropy). Studies have found an inverse relationship between effort and HRV
51 as mental effort increases, HRV decreases (Aasman et al., 1987; De Rivecourt et al., 2008,
52 2008; Delliaux et al., 2019; Fairclough & Mulder, 2012; Mizuno et al., 2011). However, HRV
53 cannot be considered as a marker of mental effort.

54 In contrast to HRV, PEP is a direct measure of sympathetic activity (Benschop et al.,
55 1994). The PEP is determined based on changes in the force of contraction of the heart,
56 which is under the influence of the sympathetic beta-adrenergic activity (Benschop et al.,
57 1994) and corresponds to the time interval between the onset of the ventricular excitation
58 and the opening of the left ventricular valve (Berntson et al., 2004). Changes in the PEP have
59 been shown to be related to changes in mental effort during cognitive tasks, with the
60 allocation of more mental effort corresponding to shorter PEP (Mallat et al., 2020; Richter et
61 al., 2008). These measures are reliable and precise indicators of effort mobilization.

62 Mental fatigue is characterized by a temporary feeling of tiredness and/or a lack of
63 energy that arises from intense and/or prolonged periods of demanding cognitive activities
64 (Pageaux & Lepers, 2018). Mental fatigue is mainly studied by using a time-on-task protocol
65 involving long and effortful cognitive tasks (Boksem et al., 2005; Mackworth, 1968; Matuz et
66 al., 2019). It has also been studied with the sequential-task protocol (Baumeister et al.,
67 1998), which involves observing mental fatigue during a second task (the dependent task)
68 that follows an initial effortful task (the depleting task). Simultaneous use of both protocols
69 in the same experiment can help examine how effort is deployed over time during long and
70 effortful tasks, and the effect of that effort deployment on tasks performed subsequently
71 (Mangin et al., 2022).

72 Disengagement of effort is one possible response to mental fatigue; it involves a
73 reduction or withdrawal of mental effort during complex or difficult tasks leading to a
74 performance decline (Hockey, 2013; Hopstaken et al., 2015). This response occurs when the
75 objectives of a task can no longer be effectively achieved due to the effects of mental
76 fatigue. This does not mean that the task is abandoned but rather that performance cannot
77 be maintained with minimal effort. Conversely, cognitive compensatory mental effort
78 involves increased mental effort to counteract or at least limit the negative impact of mental
79 fatigue on performance.

80 Disengagement of effort can be observed by a decrease in performance (e.g., a
81 lengthening of the reaction time, an increase in error rate), risky decision making or a
82 preference for low-effort tasks (Hockey, 1997). Disengagement of effort not only leads to a
83 decrease in performance but also correlates with a decrease in neurophysiological activity
84 (i.e., sympathetic or neuronal activity).

85 Shingledecker & Holding (1974), for example, examined how mental effort allocation was
86 affected by mental fatigue using a decision-making task. This task required participants to
87 assess multiple electrical circuits to identify faults by employing one of three distinct
88 strategies: an intensive strategy associated with a higher probability of success (checking
89 three resistors), a moderate strategy with a balanced likelihood of success (two resistors),
90 and a less demanding strategy (one resistor) associated with a higher risk of reduced
91 performance. This study included nineteen students from the Naval and Air Force School
92 who were divided into two groups: a control group and a fatigue group. In the fatigue group,
93 participants underwent a period of 24 to 32 hours of continuous work involving a battery of
94 multiple tasks before performing the decision-making task; these tasks included three
95 monitoring tasks performed alongside other tasks, such as arithmetic, target identification,
96 and code locking. Compared to the control group, participants in the fatigue group
97 demonstrated a stronger preference toward less-demanding behaviors, even at the cost of
98 increased potential errors, compared to the control group.

99 Hopstaken et al. (2015) also investigated the link between mental fatigue and task
100 disengagement by using a time-on-task protocol. Twenty participants completed an n-back
101 task with increasing levels of difficulty (1, 2 and 3 back tasks) for 2 hours. During the task, the
102 pupil diameter (i.e., an index of sympathetic activity), the amplitude of the event-related
103 potential P3 (i.e., a positive deflection in activity approximately 300 ms following the
104 presentation of a stimulus) and self-reported mental fatigue were measured. Both pupil
105 diameter and P3 amplitude are indices of mental effort allocation. After participant
106 completed six 18-min blocks of the n-back task, the reward was manipulated by telling the
107 participants that if they improved their performance, the task would be shorter. This reward
108 was intended to check for a reengagement of effort. The authors have shown that the

109 decrease in performance was associated with a decrease in pupil diameter and P3
110 amplitude, which are interpreted as disengagement from the task and an increase in
111 perceived fatigue. Nevertheless, despite the high subjective level of mental fatigue reported
112 by the participants, the reward helped the participants to reengage effort in the cognitive
113 task, which was marked by an increase in pupil diameter and P3 amplitude.

114 Similarly, Matuz et al. (2021) investigated the effect of mental fatigue on HRV as a
115 function of time-on-task and on recovery. Forty-four participants were split into 2 groups
116 and either performed a Gatekeeper task (dual 2-back task combining visual and auditory
117 stimuli) or watched a documentary for approximately 90 min. After the task, both groups
118 had a break for 12 min and then the fatigue group completed 1 more block of the
119 gatekeeper task while the other group watched another documentary. The results showed
120 no change in performance during the 90-min gatekeeper task, an increase in different HRV
121 parameters (RMSSD, pNN50, HF) with time-on-task and an increase in perceived fatigue. This
122 pattern of results was interpreted as a progressive disengagement of effort throughout the
123 depleting task. After the 12-min break, participants were able to increase their performance
124 for the last block and showed a reengagement of effort as observed by the decrease in the
125 RMSSD component of HRV.

126 These studies illustrate the impact of mental fatigue on effort engagement. They reveal a
127 gradual disengagement of effort over time, and a shift toward low-effort behaviors.
128 However, rewards and rest can facilitate re-engagement of effort in the task despite mental
129 fatigue. Compensatory effort, another behavioral pattern, has also been observed when
130 people are engaged in effortful tasks.

131 Hockey et al. (1998) conducted a study to investigate the impact of sleep deprivation on
132 the use of compensatory control. In this study, 16 operators were placed in a simulated air

133 management system, with conditions similar to those in spacecraft's crew cabin or a
134 hyperbaric chamber; participants were either sleep-deprived or had a normal night of sleep.
135 They found that sleep-deprivation did not significantly affect the operators' performance in
136 the primary task, which involved maintaining air pressure within specified limits. However,
137 they observed changes in their performance during secondary tasks, such as increased
138 reaction time to respond to alarms and changes in task management strategies, including
139 more frequent system value checks. These findings underscore the capacity to maintain
140 performance through compensatory effort on primary performance in situations where
141 errors could have serious safety implications, even with sleep deprivation.

142 At the neurophysiological level, Wang et al. (2016) studied compensatory neural
143 mechanisms in the face of mental fatigue. Fourteen healthy younger adults performed a
144 Stroop task for 160 min while event-related potentials (ERP), indicators of neural responses
145 to specific stimuli, were recorded. They observed a compensation phase during the first 80
146 min, characterized by increased amplitudes of late ERP components in the antero-frontal
147 region and significant associations with task performance. This compensatory effort was
148 followed by a decompensation phase, marked by accelerated performance decline and
149 decreased ERP amplitude (i.e., a disengagement of effort).

150 Extending the evidence linking increased brain activity to increased mental effort Abi-
151 Jaoude et al. (2018) investigated the neural correlates of inhibitory control. In their study,
152 functional magnetic resonance imaging was used while 19 participants inhibited their eye
153 blinking across 6 blocks, each lasting 1-min, separated by 1-min intervals of rest.
154 Performance gradually declined, accompanied by a corresponding increase in the frequency
155 of eye blinks. This inhibition coincided with a notable increase in effortful control marked by
156 an increased activity in prefrontal-control regions including the inferior frontal gyrus,

157 dorsolateral prefrontal cortex, dorsal anterior cingulate cortex, supplementary motor area
158 and caudate. In this experiment, participants employed a compensatory mental effort
159 characterized by an increase in frontal activity. However, this effort proved inadequate for
160 sustaining performance levels.

161 These different results demonstrate the dynamic nature of effort engagement, which is
162 mainly supported by prefrontal areas. It has been shown that effort is compromised in the
163 presence of mental fatigue, resulting in a disengagement of effort. Nevertheless, these
164 results also highlight the potential influence of the task environment and motivation on
165 initiating or restoring task engagement, whether this effect is driven by rewards or rest.

166 The main objective of this study is to investigate participants' effort engagement under
167 mental fatigue by examining both physiological and behavioral measures. Additionally, the
168 study aims to assess subsequent task performance, providing valuable insights into the
169 effects of mental fatigue on subsequent effort engagement in physical tasks. First, we
170 hypothesize that performance on the dependent task (endurance handgrip task) will be
171 relatively impaired after the fatiguing task (30-min Stroop task) compared to the control task
172 (watching a documentary). Second, we hypothesize that during the fatiguing task,
173 performance decrements will be accompanied by a disengagement of mental effort resulting
174 in a decrease in sympathetic activation (i.e., an increase in PEP reactivity) and an increase in
175 parasympathetic activation (i.e., a decrease in HF power and RMSSD) as a function of time-
176 on-task. In contrast, during the control task (watching a documentary), we expect no
177 changes in sympathetic and parasympathetic activity.

178 2. Method

179 2.1. Participants and design

180 The sample size was determined using G*Power software, with a moderate effect
181 size on the sequential task effect ($f = 0.25$; based on Experiment 3 from Mangin et al., 2021,
182 with $\alpha = .05$, and power = .80); this analysis indicated that 51 participants were sufficient
183 to detect an effect. We choose to recruit 58 participants from the sport sciences faculty at
184 the University of Poitiers and through local press announcements to reach this target sample
185 size given the expected dropouts. Eight participants withdrew from the experiment due to
186 its extended duration (three 60-90-min sessions in total). The final sample size was 50
187 participants (25 females) with a mean age of 27.63 years ($SD = 11.80$). All participants
188 provided informed consent after receiving verbal explanations about the procedure. The
189 local ethics committee approved the experiment (Tours-Poitiers Ethical Committee, CER-TP
190 2020-11-05).

191 2.1.1. Procedure

192 The experiment required 3 separate sessions to be completed, and each session was
193 separated by a maximum of 3 weeks. At the beginning of the first session, participants
194 completed a demographic questionnaire and a health questionnaire. A few hours before
195 each session they were asked to refrain from psychostimulant substances (cigarettes,
196 caffeine, drugs, sleeping pills) and exhausting physical activity. Then, they were familiarized
197 with a modified Stroop and the time-to-exhaustion (TTE) handgrip task. In the second and
198 third sessions, participants wore electrodes for electrocardiography (ECG) and thoracic
199 impedance cardiography (ICG) measurements. At the beginning of each session, they rested
200 while watching a sunset video for 10 minutes (i.e., baseline measurements). Following the
201 rest period, participants performed maximal voluntary contractions (MVCs) and then the
202 cognitive task for 30 min. Throughout the experiment, participants provided ratings of
203 perceived fatigue. In addition, boredom and motivation before the TTE handgrip task were

204 measured just after the cognitive task. These subjective measures were collected using
205 visual analog scales (VAS) displayed on a computer screen, ranging from 0% to 100% (a more
206 detailed description is available in the supplementary material S1). The control task
207 (documentary viewing) and the fatiguing task (Stroop task) took place in separate sessions
208 and the order of these two sessions was counterbalanced between participants (Mangin et
209 al., 2021).

210 2.2 Materials and measures

211 2.2.1 Effortful cognitive task (modified Stroop task)

212 Participants completed a computerized version of the incongruent Stroop task with E-
213 prime software and S-R response box (version 2.0, Psychology Software Tools, Pittsburgh,
214 PA, USA). They responded vocally to color words presented on a computer screen, while
215 their responses and response time were recorded with a microphone. The task consisted of
216 888 trials and lasted 29.6 min. Each trial lasted 2 seconds; the specific time course each trial
217 is presented in supplementary material S1. The entire task comprised an equal number of
218 'reading' and 'naming' trials (i.e., the participants were instructed to name the color of the
219 ink with which the word is shown on the screen) and the order of presentation of the color
220 words was completely random. The data were divided into 4 parts to analyze the time-on-
221 task effect, each part corresponding to 222 trials and lasting 7 min and 30 s. We calculated
222 different parameters, such as the error rate, the omission rate and the reaction time (RT),
223 for the correct trials.

224 2.2.2 Control task

225 Participants watched a 30-min documentary, "Earth" by Alastair Fothergill and Mark
226 Linfield (2007), which was used in similar experiments (Mangin et al., 2021, 2022). At the

227 end of the session, participants completed a multiple-choice questionnaire to verify that
228 they watched the documentary attentively.

229 2.2.3 TTE handgrip task

230 During the TTE handgrip task, participants maintained a force level at 13% (\pm 1%) of their
231 MVC as long as possible. Visual feedback showing their force production was provided on a
232 computer screen. Each variation in force production corresponded to the movement of a
233 needle on a circular gauge. The target force was represented by a green arc ranging from
234 12% to 14% of the MVC. TTE was defined as the time at which the produced force had fallen
235 below the limit of 12% for 2 s. Participants were unaware of the elapsed time or specific
236 force values during the task. TTE was calculated offline from the beginning of the force signal
237 to the exhaustion time. For more details on the calibration of the gauge, see supplementary
238 material S2. During the TTE handgrip task, perceptions of effort and muscle pain were
239 assessed every 30 s (see supplementary materials for more details).

240 2.2.4 Cardiovascular measures

241 ICG and ECG were recorded during the rest period (10 min) and during the cognitive
242 tasks (30 min). As the PEP can be influenced by factors such as ventricular filling (i.e.,
243 preload) and arterial pressure (i.e., afterload), heart rate and arterial pressure were
244 monitored to accurately attribute any changes in PEP to beta-adrenergic sympathetic
245 activity. Systolic blood pressure (SBP) and diastolic blood pressure (DBP) were measured
246 (mmHg) at the end of the 10-min baseline period and after the 30-min cognitive task. BP was
247 measured with a digital automatic blood pressure monitor (OMRON-MIT Elite). The blood
248 pressure cuff was placed over the brachial artery above the elbow of the participant's
249 nondominant arm. ICG and ECG were recorded continuously using a BIOPAC MP160 system
250 at 2000 Hz. For the ECG, three electrodes were placed on the right and left shoulders (right

251 arm and left arm) and on the left side under the pectoral muscles, on the lower edge of left
252 rib cage (left leg). For ICG, electrodes were placed on the right and left trapezius and on the
253 right and left middle axillary line at the height of the xiphoid process.

254 2.2.5 Physiological measures analysis

255 A more detailed description of the PEP calculation is available in supplementary
256 material S3. The first minute of the 10-min baseline recording was removed, leaving 9
257 periods of 1 min each. Then, the average of the 9 PEPs was calculated, resulting in a single
258 PEP baseline score for each session. The intraclass correlation coefficients for the PEP
259 baseline were 0.993 for the control and 0.996 for the Stroop session. In the same way, the
260 30 min of the mental task (control and Stroop task) was composed of 30 mean values
261 representing 1 min each. PEP is interpreted by examining reactivity scores, which represent
262 changes in PEP compared to the baseline. To calculate the reactivity score, the baseline PEP
263 scores for each participant were subtracted from the corresponding PEP scores during the
264 mental task, following the method described by Llabre et al. (1991). A total of 30 reactivity
265 scores were obtained, reflecting the PEP changes during the entire duration of the mental
266 tasks. These 30 min recordings were averaged among 4 periods of 7.5 min each.

267 Heart rate variability indices were calculated by using Kubios HRV Premium software,
268 version 3.5.0. The ECG signal was used as the input for the analysis. Prior to the analysis, a
269 medium automatic artifact correction algorithm was applied. For the assessment of HRV, the
270 RMSSD was selected as the time-domain parameter. Additionally, the HF parameter was
271 chosen as the frequency-domain parameter of HRV. HRV indices were calculated for the four
272 7.5-min parts of the mental task.

273 2.2.6 Individual behavioral patterns of effort investment

274 To analyze individual behavioral patterns of effort investment, we computed for each
275 participant their inverse efficiency score, a score that combines reaction time and errors, the
276 two most important indicators of performance (Bruyer & Brysbaert, 2011; Liesefeld &
277 Janczyk, 2019). This score was calculated as follows: mean correct reaction time for naming
278 trials / (1-proportion of decision errors for naming trials). Then, we computed changes in
279 their inverse efficiency score and preejection period by subtracting the index obtained in the
280 fourth part from the index obtained in the first part.

281 2.5.6. Statistical analyses

282 Statistical analyses were performed using JASP software, including two-way
283 repeated-measures ANOVA and paired sample t tests when appropriate. Effect sizes were
284 reported using partial eta-squared (η_p^2). Greenhouse–Geisser correction was applied if the
285 sphericity assumption was violated. Post hoc comparisons were corrected using the
286 Bonferroni procedure.

287 3 Results

288 Behavioral and subjective analyses were conducted on all 50 participants' data, while
289 physiological analyses were performed with the data from only 49 subjects due to faulty
290 signal recording for one subject.

291 3.1 Manipulation checks

292 3.1.1 Perceived difficulty

293 A t test was conducted on the self-reported difficulty of the control and the Stroop
294 task. As expected, the Stroop task ($M = 72.100$, $SD = 15.027$) was perceived as more difficult
295 than the control task ($M = 17.640$, $SD = 19.340$): $t(49) = 16.674$, $p < .001$, $d = 2.358$.

296 3.1.2 Perceived fatigue

297 We conducted an ANOVA on self-reported fatigue with Time and Session (Stroop and
298 control) as repeated-measures factors. The interaction between Time and Session was
299 significant: $F(1.956, 95.839) = 11.566, p < .001, \eta_p^2 = .191$. Before the mental task, the level
300 of fatigue was the same in both conditions ($M = 33.050, SD = 21.809, p = 1.000$). The level of
301 fatigue did not increase between the points before ($M = 33.870, SD = 23.998$) and after the
302 control task ($M = 39.660, SD = 24.866, p = 1.000$). In contrast and as expected, the level of
303 fatigue increased between the points before ($M = 32.320, SD = 19.620$) and after the Stroop
304 task ($M = 57.140, SD = 24.482, p < .001$). Finally, the level of fatigue after the handgrip task
305 was the same across the two sessions ($M = 54.100, SD = 23.637, p = .343$). The level of
306 fatigue did not increase between the points after the mental ($M = 39.660, SD = 24.866$) and
307 after the physical task ($M = 49.900, SD = 22.380$) in the control session ($p = .067$). It also did
308 not increase between the points after the Stroop task ($M = 57.140, SD = 24.482$) and the
309 physical task ($M = 58.300, SD = 24.893, p = 1.000$).

310 3.2 Behavioral results

311 3.2.1 Performance during the modified Stroop task

312 We conducted an ANOVA with Time-on-task (periods 1, 2, 3 and 4) as a repeated-
313 measures factor on omission rate, error rate, and mean RT.

314 The omission rate increased significantly with Time-on-task: $F(1.888, 92.524) = 5.759,$
315 $p = .005, \eta_p^2 = .105$. The omission rate increased significantly from the first ($M = .133, SD =$
316 $.148$) to the fourth period ($M = .205, SD = .199$) of the Stroop task ($p < .001$).

317 We conducted an ANOVA with Time-on-task and Trial type (reading and naming) as
318 repeated-measures factors on the mean RTs of correct responses. The interaction between
319 Time-on-task and Trial type was significant: $F(2.574, 126.140) = 14.051, p < .001, \eta_p^2 = .223$.
320 The mean RT for the reading trials did not change over the four periods (all $p > .05; M =$

321 629.779 ms; $SD = 85.745$). In contrast, RT increased for the naming trials from the first ($M =$
322 765.614 ms, $SD = 78.845$) to the fourth period ($M = 787.803$ ms, $SD = 81.438$, $p = .020$). In
323 addition, the mean RT was consistently shorter for the reading trials than for naming trials
324 during the 4 periods of the task (all $p < .001$).

325 Another ANOVA with the same design was conducted on error rate. The interaction
326 between Time-on-task and Trial type was not significant: $F(2.027, 99.300) = 1.039$, $p = .358$,
327 $\eta_p^2 = .021$. However, the main effect of Time-on-task was significant: $F(2.308, 113.099) =$
328 14.211, $p < .001$, $\eta_p^2 = .225$. The error rate decreased from the first ($M = .068$, $SD = .067$) to
329 the fourth ($M = .055$, $SD = .069$) period of the task for both types of trials ($p < .001$). The
330 main effect of Trial type was also significant: $F(1, 49) = 50.717$, $p < .001$, $\eta_p^2 = .509$. The error
331 rate was consistently lower for the reading trials ($M = .011$, $SD = .021$) than for naming trials
332 ($M = .038$, $SD = .036$) during the 4 periods of the task (all $p < .001$).

333 3.2.2 Performance on the subsequent handgrip task

334 We conducted a paired sample t test with Session as a repeated-measures factor
335 (control and Stroop) on the TTE during the handgrip task. Participants squeezed the handgrip
336 longer after the control task ($M = 9.188$ min, $SD = 3.898$) than after the Stroop task ($M =$
337 8.313 min, $SD = 2.985$): $t(49) = 2.233$, $p = .030$, $d = .316$. The analysis of the participant's
338 MVC is presented in supplementary material S5.

339 3.3 Physiological results

340 3.3.1 PEP reactivity

341 We conducted an ANOVA with Time-on-task (periods 1, 2, 3 and 4) and Task (Stroop
342 and control) as repeated-measures factors on PEP reactivity. The interaction between Time-
343 on-task and Session was significant: $F(2.091, 100.391) = 8.718$, $p < .001$, $\eta_p^2 = .186$. PEP
344 reactivity increased more sharply during the Stroop task than during the control task (see

345 Figure 1). In addition, post hoc comparisons indicated that the PEP reactivity score was lower
346 during the Stroop task than during the control task (all $p < .05$), regardless the period. During
347 the control session, PEP reactivity significantly increased ($p < .001$) between the first ($M =$
348 3.197 ms, $SD = 3.340$) and the second period ($M = 5.196$ ms, $SD = 3.587$) but did not change
349 between the other periods (all $p > .05$). In addition, PEP reactivity increased significantly
350 between the first ($M = 3.197$ ms, $SD = 3.340$) and the fourth ($M = 6.089$ ms, $SD = 4.658$)
351 period of the control task ($p < .001$). During the Stroop task, PEP reactivity increased
352 significantly between the first ($M = -3.865$ ms, $SD = 6.577$) and the second period ($M = -.597$
353 ms, $SD = 6.442$, $p < .001$), and between the second and the third period ($M = 1.481$ ms, $SD =$
354 6.344 , $p = .002$). In addition, PEP reactivity increased significantly between the first ($M = -$
355 3.865 ms, $SD = 6.577$) and the fourth period ($M = 2.382$ ms, $SD = 7.251$) of the Stroop task (p
356 $< .001$).

357 -----
358 Insert Figure 1 here
359 -----

360 3.3.2 Heart rate variability

361 An ANOVA with Session and Time-on-task (baseline, periods 1, 2 and 3 of the mental
362 task) as repeated-measures factors was conducted on the high frequency (HF) measure of
363 HRV. The interaction between Session and Time-on-task reached significance: $F(2.098,$
364 $100.705) = 12.227$, $p < .001$, $\eta_p^2 = .203$. At baseline, HF values were not significantly different
365 between the control and Stroop sessions ($p = 1.000$). During the 4 periods, HF values were
366 lower in the Stroop task than during the control task (all $p < .05$). In the Stroop task, HF
367 power increased between the first ($M = 5.392$ log-HF, $SD = 1.131$) and the fourth periods (M
368 $= 5.720$ log-HF, $SD = 1.120$): $p = .003$. In the control task, HF power did not change as a

369 function of Time-on-task (all $p = 1.000$). Other cardiovascular measures, such as heart rate,
370 breathing rate, systolic and diastolic blood pressure are available in supplementary material
371 S6.

372 Results concerning RMSSD are included in supplementary material and are quite
373 similar to those of the HF.

374 3.4 Individual behavioral patterns of effort investment

375 We conducted an analysis of individual behavioral patterns during the Stroop task by
376 using a plot that integrates changes in the preejection period reactivity (horizontal axis) and
377 performance on naming trials with the inverse efficiency score (vertical axis). On the
378 horizontal axis, a positive score indicates an increase in sympathetic activity, while a
379 negative score indicates a decrease. On the vertical axis, a positive score reflects a decrease
380 in performance, whereas a negative score indicates an improvement.

381 This plot reveals that 6% of participants exhibited a decrease in performance coupled
382 with increased sympathetic activity, suggesting non-efficient compensatory effort. Another
383 6% showed both improved performance and increased sympathetic activity, indicating a
384 compensatory effort. A large proportion of 35% participants demonstrated improved
385 performance alongside decreased sympathetic activity, suggesting a learning effect. The
386 largest proportion of participants (49%) showed a decrease in both performance and
387 sympathetic activity, indicating a disengagement of effort.

388 -----

389 Insert Figure 2 here

390 -----

391 4 Discussion

392 The aim of this study was to investigate participants' response to mental fatigue in terms
393 of effort engagement. The two important aspects of this study were (1) to examine the
394 evolution of effort engagement during the depleting and control tasks and (2) to
395 simultaneously use time-on-task and sequential-task protocols to examine the effects of
396 mental fatigue on the behavioral and subjective responses of the participants. We found
397 that with increasing fatigue during the mental task, cardiac measures indicated a decrease in
398 sympathetic activity (assessed with PEP) and an increase in parasympathetic activity
399 (assessed with HRV), suggesting a disengagement of effort and supporting our hypotheses.
400 This disengagement was further evidenced at the behavioral level by a decline in
401 performance during the TTE handgrip task that followed the fatiguing task; there was a
402 significant reduction of 9.523% in comparison to the control cognitive task. During the
403 Stroop task, participants changed their behavior over time prioritizing accuracy over speed,
404 as indicated by the lengthening of reaction times involving inhibitory control (i.e., naming
405 trials) and an increase in the omission rate, coupled with a simultaneous reduction in error
406 rate across both trial types. The analyses of individual responses revealed that the largest
407 proportion of participants (49%) demonstrated a disengagement of effort leading to a
408 decrease in performance. In contrast, 35% were able to increase their performance with a
409 decrease in sympathetic activity. Compensatory effort was observed only among 12% of
410 participants, highlighted by an increase in sympathetic activity.

411 4.1. Effort expenditure during the mental tasks

412 Participants' PEP reactivity, reflecting changes from a resting state, was found to be
413 higher during the Stroop task than during the documentary viewing task, indicating higher
414 sympathetic activity and suggesting higher effort investment. In addition, the significant
415 interaction between measures over the four periods and the two conditions suggests a

416 habituation effect in both tasks. Indeed, a decrease in PEP reactivity was observed for both
417 conditions. Nevertheless, the most important decrease in sympathetic activity in the Stroop
418 task showed that there is another factor involved in addition to the habituation effect (i.e., a
419 decrease in arousal). This sharper decrease in sympathetic activity can be explained either by
420 a voluntary disengagement of effort (as a result of boredom or fatigue or effort minimization
421 strategy) or the automation of certain processes (i.e., stimulus identification). The
422 automation of a series of operations is generally accompanied by maintaining or improving
423 the performance of the system. In contrast, effort disengagement should be accompanied by
424 a decrease in performance. It appeared that performance during the Stroop task declined
425 with an increase in the omission rate and the mean reaction time for the trials requiring
426 inhibitory control (i.e., naming trials) from the first to the fourth period. Our results rather
427 are more consistent with a disengagement of effort rather than with an automation process.

428 Moreover, measures such as heart rate, systolic blood pressure, and diastolic blood
429 pressure were not affected during the Stroop task, suggesting that the changes in PEP were
430 specifically related to mental effort allocation rather than factors associated with preload or
431 afterload (Sherwood et al., 1990). These findings are consistent with prior research that has
432 employed PEP as a measure of effort mobilization during mentally demanding tasks (Mallat
433 et al., 2020; Richter et al., 2008). These results were also consistent with the HF component
434 of HRV, which reflects parasympathetic activity. These findings collectively support the
435 notion of effort disengagement during the Stroop task in response to mental fatigue,
436 providing empirical support for our hypotheses.

437 4.2. Decrease in arousal

438 The decrease in sympathetic activity observed during the two mental tasks may be
439 due to a decrease in arousal. A low state of arousal can be attributed to various factors,

440 including a lack of interest, tasks that are too easy, or repeated presentations of the same
441 stimuli. Self-reported boredom during the mental tasks was relatively low ($M = 31.47$);
442 participants did not report feeling more bored during the Stroop task compared to the
443 control task. This finding has been observed in studies with similar designs (Mangin et al.,
444 2021, 2022). Another plausible explanation is habituation of the participants to the task
445 demands. Initially, the task may have been highly demanding and stressful, but as
446 participants became more familiar with the task, it likely became less stressful. To minimize
447 the confounding effects of arousal and automating processing in future studies, it would be
448 beneficial to use tasks that are less repetitive and able to be automatically processed, and
449 that require a high level of concentration throughout the task. From that perspective, a
450 depleting task involving updating of working memory throughout the task, thus being more
451 difficult to perform automatically, could be a better choice. Another choice, would be to
452 measure the arousal level during depleting and control tasks with EEG indices.

453 4.3. Motivational aspect of task disengagement

454 Some authors have postulated that disengagement of effort might be due to a shift of
455 motivation and/or attention (Inzlicht et al., 2014; Kurzban et al., 2013) or an imbalance
456 between costs and benefits (Boksem & Tops, 2008; Shenhav et al., 2013). The present
457 experiment examined the motivation to perform the TTE handgrip task (after the control or
458 Stroop task) with a subjective scale (see supplementary material S7). There was as significant
459 difference in motivation to perform the TTE handgrip task according to the preceding mental
460 task. This result implies that the motivation to perform the physical task was impacted by
461 the cognitive load of the mental task. However, this decrease of motivation did not correlate
462 significantly with the decrease of performance during the TTE handgrip task (see
463 supplementary material S9). This result is not line with the motivational hypothesis (Inzlicht

464 et al., 2014), suggesting that motivation to perform the handgrip endurance task plays a role
465 in the decrease of performance observed in this experiment.

466 4.4. Effort minimization behavior

467 Effort minimization refers to the reduction of effort in anticipation of a longer or
468 upcoming effortful task (Radel et al., 2017). In the present experiment, participants were not
469 informed of the duration of the Stroop task. It is possible that participants may have
470 conserved their effort, anticipating a long duration for the Stroop task and knowing they
471 needed to reserve effort for the subsequent TTE handgrip task. To test the effort
472 minimization hypothesis in a future experiment, participants could be given a choice
473 between a low-effort and a high-effort task following a long and difficult task. Another
474 possibility would be to manipulate the probability to perform an effortful task after the
475 depleting or control task. The participant's expectations regarding task duration could also
476 be manipulated and scenarios in which they anticipated a short or an extended task duration
477 could be compared; then, whether different behavioral patterns of effort investment are
478 employed under these distinct expectations could be observed.

479 4.5. Compensatory effort as a possible behavioral pattern

480 The engagement of compensatory processes to maintain performance can be
481 observed under specific conditions, particularly in individuals with limited resources and
482 heightened susceptibility to fatigue, such as patients with chronic fatigue (André et al., 2021)
483 or traumatic brain injury (Kohl et al., 2009). Factors such as rewards (Boksem et al., 2006)
484 and perceived difficulty (Hsu et al., 2017; J. Wang et al., 2022) may play a role in motivating
485 individuals to allocate their effort and employ compensatory behaviors to mitigate the
486 impact of fatigue and sustain performance.

487 Interestingly, our correlational analyses revealed a significant negative association
488 between the increase in omissions and change in PEP reactivity over time during the Stroop
489 task (see supplementary material S9). Specifically, participants who exhibited a higher
490 increase in omissions throughout the Stroop task also showed a greater stability in PEP
491 reactivity, indicating less changes in their effort allocation ($r = -.336, p < .05$). This finding
492 suggests that participants who relied more on compensatory behaviors, as evidenced by
493 stable PEP reactivity, experienced difficulty in maintaining task performance, as reflected by
494 increased omissions. It appears that these compensatory mechanisms may be employed by
495 participants who are particularly challenged by the cognitive demands of the Stroop task.
496 The perception of task difficulty may play a role in the utilization of such compensatory
497 behaviors. In line with this proposition, we observed a significant negative correlation ($r = -$
498 $.444, p = .001$) between the participant's perception of task difficulty during the Stroop task
499 and the influence of mental fatigue on the subsequent TTE handgrip task (see
500 supplementary material S9). This correlation suggests that greater perceived difficulty of the
501 Stroop task during the task is linked to a smaller decrease in performance on the subsequent
502 handgrip task, providing further arguments that the higher perception of difficulty during the
503 depleting task implies the use of compensatory behavioral patterns in the subsequent task.

504 4.6. Limitations

505 Some limitations of the current study can be highlighted. First, due to limitations in
506 measuring PEP with impedance cardiography (ICG) during physical tasks, i.e., the tendency
507 for artifacts from movements and contraction of the neck muscles to be present in the
508 recording, it was not possible to observe effort engagement at a physiological level during
509 the second task (i.e., handgrip task). It will be important to develop and share more efficient

510 algorithms or explore alternative measures to compensate for these artifacts in future
511 research.

512 Moreover, the present study examined the disengagement of effort during the fatiguing
513 task through variations in sympathetic activity as indicated by PEP reactivity. However, it
514 would be beneficial to combine PEP with measures such as electroencephalography (EEG) or
515 event-related potentials (ERPs), which are known to be influenced by mental fatigue
516 (Hopstaken et al., 2015; Tran et al., 2020). To our knowledge, the link between these two
517 measures has not been investigated during effortful tasks. Such an integration of measures
518 could provide a more comprehensive understanding of the cognitive and physiological
519 processes underlying effort disengagement.

520 Notably, the PEP during the third and fourth periods of the Stroop task was longer than
521 that at the baseline, indicating that the sympathetic activity during baseline was higher than
522 at the end of the Stroop task. This finding may be attributed to the difficulty in capturing a
523 true baseline state during the resting condition.

524 4.7. Concluding remarks

525 In conclusion, this study makes a significant contribution to our understanding of effort
526 mobilization in the presence of mental fatigue. Decreased sympathetic activity, as reflected
527 by changes in PEP and HRV, further supports effort disengagement during the fatiguing task,
528 and on a subsequent task, as corroborated by the decline in performance.

529 Within the domain of sports and exercise psychology, these findings have important
530 implications for understanding the effects of acute mental fatigue on effort engagement.
531 They indicate that acute mental fatigue following cognitively demanding tasks is detrimental
532 to endurance performance, leading to diminished effort allocation at the behavioral and
533 autonomic levels. Further research should explore effort investment in the face of mental

534 fatigue across various profiles (e.g. endurance athletes, mindfulness experts or video game
535 players). Additionally, exploring effective training techniques, as suggested by recent studies
536 on brain endurance training (Dallaway et al., 2021; Staiano et al., 2023), can enhance
537 resistance to mental fatigue and open novel directions for optimizing performance.

538 However, the underlying mechanisms contributing to this disengagement, including
539 effort minimization behavior, decreased arousal, and the influence of mental fatigue,
540 warrant further investigation. To extend our understanding of effort investment in the
541 context of mental fatigue, future studies should adopt a multidimensional approach,
542 incorporating markers such as those derived from fMRI to explore neural connectivity within
543 and between large-scale neuronal networks involved in the engagement of effortful control.
544 Additionally, it is important to study compensatory effort investment in populations with
545 chronic fatigue, as they may exhibit increased susceptibility to acute mental fatigue by
546 revealing the interplay between chronic and acute mental fatigue (André et al., 2021;
547 Mangin et al., 2023). Including these diverse populations will improve our understanding of
548 how different contexts and individual characteristics influence effort engagement.
549 Ultimately, this understanding can inform the development of behavioral patterns of effort
550 investment and interventions to mitigate the negative impact of mental fatigue (Jacquet et
551 al., 2023) and improve sustained effort engagement in various life domains (for a review, see
552 Audiffren et al., 2022).

553

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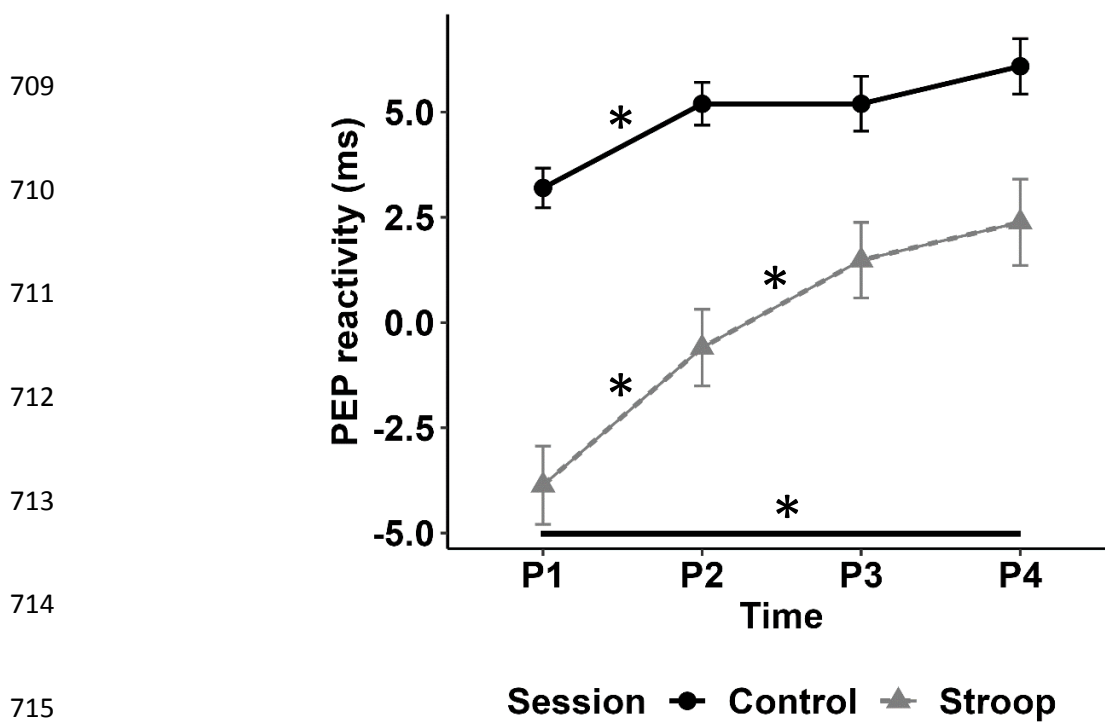
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707 **Figure 1:** Preejection-period reactivity as a function of session and time-on-task (Periods 1, 2, 3, and
708 4)

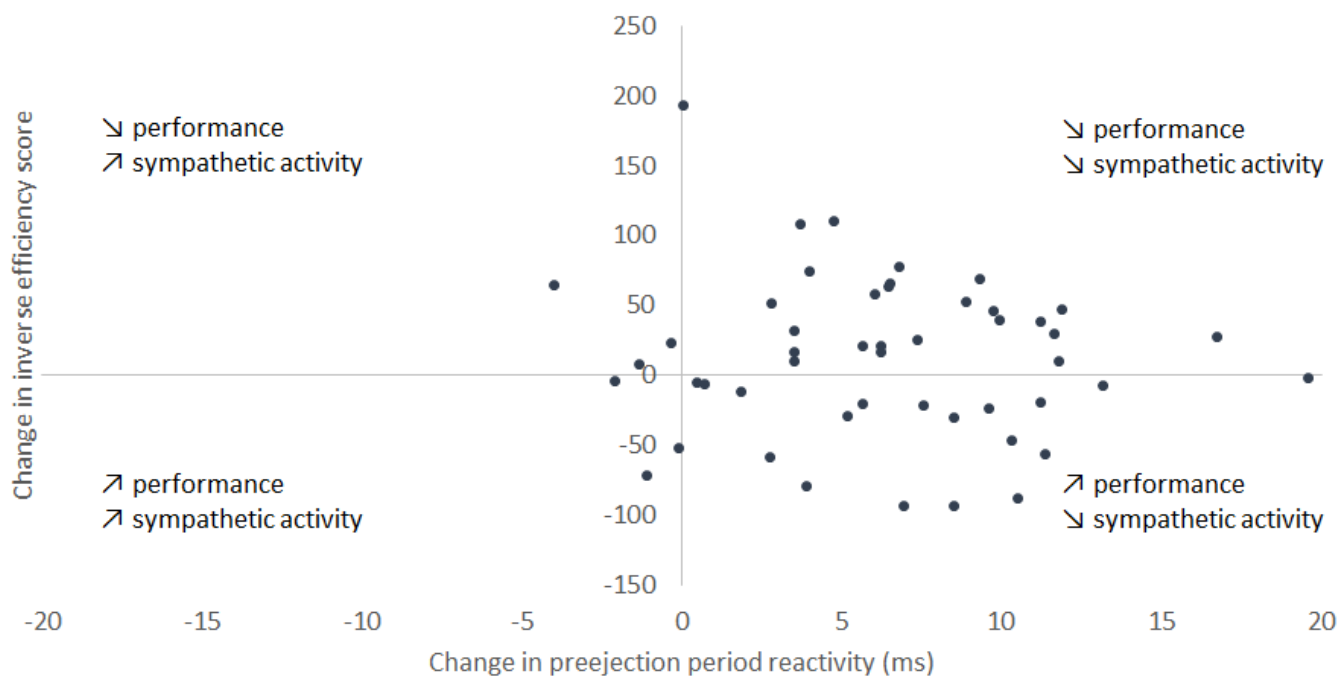


717 Note: P1 = Period 1; P2 = Period 2; P3 = Period 3; P4 = Period 4; Errors bars represent the standard

718 error. * = $p < .05$.

719

720 **Figure 2:** Change in individual inverse efficiency score for naming trials as a function of change in pre-
 721 ejection period reactivity during the Stroop task



722 Note: each point represents a participant. Inverse efficiency score for naming trials = mean reaction
 723 time for correct responses / (1-proportion of decision errors). Change in preejection period reactivity
 724 and change in inverse efficiency score was calculated as the index obtained in part 4 minus the index
 725 obtained in part 1.

726

727