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# Effort-related cardiac activity under cognitive fatigue: the role of success importance

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## ABSTRACT

In real-world settings, performing successive tasks of varying difficulty and motivational value often leads to cognitive fatigue (CF). While several theories address issues related to the direction or initiation of goal-directed behavior, extensions grounded on Motivational Intensity Theory (MIT) specifically predict effort intensity. According to MIT, for tasks with known and fixed difficulty, effort increases proportionally with perceived difficulty, as long as success is possible and the required effort is justified by success importance. The present study examined whether avoidance instructions—designed to elevate the upper limit of potential motivation—could modulate the relationship between cognitive fatigue and effort. Participants completed a sequential-task paradigm while effort-related cardiovascular responses, specifically the preejection period (PEP), were recorded. Consistent with our hypotheses, following a prolonged fatigue-induction period, participants in the avoidance-instruction condition exhibited a significant physiological rebound, exerting higher effort and achieving superior performance on a subsequent difficult task. In contrast, participants without avoidance instructions showed a decline in effort. Crucially, subjective fatigue remained high across groups, suggesting that while CF inflates perceived task difficulty, it does not necessarily lead to disengagement. Instead, sufficiently potent motivational stimuli, such as avoidance-based instruction, can justify the high mobilization of resources required to perform despite prolonged cognitive engagement.

**Keywords:** motivational intensity theory, effort, cognitive fatigue, avoidance instruction, preejection period

## COGNITIVE FATIGUE & SUCCESS IMPORTANCE

1           Daily life constantly requires us to regulate our thoughts and actions, whether driving,  
2 working, or interacting with others. This ability depends on cognitive control, a set of processes  
3 that guide behavior when automatic responses are insufficient. Key components include working  
4 memory, sustained attention, and cognitive flexibility, each of which incurs an intrinsic cost—  
5 mental effort (Botvinick & Braver, 2015; Shenhav et al., 2017; Silvestrini et al., 2022). Crucially,  
6 mental effort is voluntary, reflecting an individual’s decision to allocate cognitive resources to  
7 achieve goal-directed behavior (Brehm & Self, 1989; Kurzban, 2016; Shenhav et al., 2017;  
8 Silvestrini et al., 2022). This decision is influenced by factors such as motivation, emotional state,  
9 and attentional demands, which determine how much effort an individual is willing to invest  
10 (Inzlicht et al., 2014). In sum, mental effort reflects the voluntary allocation of cognitive resources  
11 to meet task demands and can be expressed through decision-making, subjective experience,  
12 and physiological or neural mobilization during task engagement (Richter et al., 2016; Shenhav  
13 et al., 2017; Wolpe et al., 2024).

### 14 **Cognitive fatigue**

15           Cognitive fatigue (CF) is a transient psychological and neurophysiological state that  
16 significantly influences effort. It is characterized by feelings of discomfort and reduced energy,  
17 and impairs the ability to sustain optimal performance on cognitively demanding tasks (Boksem  
18 & Tops, 2008; Van Cutsem et al., 2017; Pessiglione et al., 2025). CF can manifest as reduced  
19 mental clarity, diminished motivation, or a subjective sense of being “washed out”, along with  
20 behavioral performance declines and neurophysiological alterations in central and peripheral  
21 systems (Kok, 2022; Kunasegaran et al., 2023; Schamphoeleer et al., 2025). Emerging evidence  
22 suggests that CF may be partly driven by metabolic accumulation during prolonged cognitive  
23 activity, which in turn disrupts cognitive control processes (André et al., 2019; Salihu et al., 2022).  
24 For instance, high-demand cognitive activity has been shown to increase glutamate/glutamine  
25 diffusion in the lateral prefrontal cortex compared with low-demand activity (Wiehler et al., 2022).

26 Mechanistic studies like these are critical for understanding the neurocognitive basis of CF but  
27 often require substantial resources and extended time-on-task protocols. A complementary  
28 approach examines how CF influences effort, using frameworks such as Motivational Intensity  
29 Theory (MIT) to generate precise, testable hypotheses (Brehm & Self, 1989; Wright, 1996).

### 30 **Motivational Intensity Theory**

31 Many contemporary theories view CF as a signal that modulates willingness to exert effort  
32 according to perceived cost-benefit trade-offs. When perceived costs (e.g., sustained effort) rise  
33 relative to expected benefits (e.g., rewards, goal attainment, or avoidance of negative outcomes),  
34 individuals are more likely to disengage and shift toward alternative goals (Hockey, 2011; Kurzban  
35 et al., 2013; Inzlicht et al., 2014). In contrast, MIT focuses specifically on effort intensity rather  
36 than on the direction or selection of goal-directed behavior (Wright, 2008; Richter et al., 2016).  
37 Within this framework, effort is considered costly, and individuals tend to avoid investing more  
38 than necessary to conserve resources (Brehm & Self, 1989). Specifically, MIT proposes that effort  
39 intensity is driven by two factors: perceived task difficulty and success importance. When task  
40 difficulty is fixed and known, effort increases linearly with perceived task difficulty, but only as  
41 long as the required effort does not exceed the upper limit set by success importance (Figure 1a).  
42 This produces a non-monotonic effort-allocation pattern. Early manipulations of task difficulty  
43 supported this prediction: effort increased with task difficulty but stopped when success was  
44 impossible, or effort was no longer justified, indicating disengagement (Richter et al., 2008;  
45 Gendolla et al., 2019). Subsequent research has extended these findings to more indirect  
46 manipulations that influence perceived difficulty, such as mood states, biological age, ability  
47 beliefs, pain, and experienced CF (see Richter et al., 2016, for a review).

### 48 ***Cognitive Fatigue and Perceived Task Difficulty***

49 Extending the framework of MIT, Wright (2014) proposed that CF increases perceived task  
50 difficulty (Figure 1b), making tasks feel more demanding when individuals are fatigued compared

51 to when they are rested (Wright & Stewart, 2012; Wright, 2014; Wright & Mlynski, 2019).  
52 Specifically, Wright's predictions regarding effort under fatigue are as follows: (1) fatigued  
53 individuals invest more effort than rested individuals as long as success remains possible and  
54 worthwhile, (2) they disengage at a lower objective difficulty level, creating a window of difficulty  
55 within which effort responses are weaker for fatigued performers, and (3) the point at which  
56 fatigued and rested individuals stop investing effort is determined by success importance (i.e.,  
57 the upper limit of potential motivation), which moderates the CF-effort relationship. In a previous  
58 study (Place et al., 2025), we tested the second prediction by employing a sequential-task  
59 paradigm (Baumeister et al., 1998). Participants first completed either a difficult working memory  
60 (WM) task or watched a neutral documentary, followed by a difficult  $n$ -back task. Those who had  
61 completed the WM task reported higher subjective fatigue and exhibited reduced cardiovascular  
62 responses during the subsequent task relative to participants who had watched the  
63 documentary. These results suggest that CF increases perceived task difficulty and accelerates  
64 the point at which effort is judged as unjustified, leading fatigued individuals to disengage earlier  
65 than rested participants. Building on this work, the present study examines how factors that  
66 increase success importance modulate the CF-effort relationship (i.e., the third prediction  
67 concerning success importance). MIT posits that perceived task difficulty is not the sole  
68 determinant of effort; variables that enhance the upper limit of potential motivation, such as  
69 financial rewards, can also influence effort allocation.

#### 70 ***Variables affecting success importance***

71 Consistent with MIT, we focus on variables that influence success importance under  
72 conditions of fixed and known task difficulty<sup>1</sup>. In this context, effort intensity should be  
73 proportional to perceived task difficulty as long as success is possible and justified (Figure 1a).

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<sup>1</sup> When task difficulty is unclear, effort intensity is expected to vary with success importance (Richter & Gendolla, 2009)

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74 When success importance is high, individuals should invest high effort to cope with difficult  
75 demands, whereas low success importance makes the required effort unjustified, leading to  
76 earlier disengagement (Richter, 2016; Chatelain & Gendolla, 2016). Several studies have  
77 examined how success importance moderates the influence of CF on effort. For instance, Wright  
78 et al. (2013) used a sequential task paradigm in which participants first completed an easy (low  
79 fatigue) or difficult (high fatigue) mental arithmetic task, followed by a difficult scanning task.  
80 Success importance was manipulated via ego-involvement instructions: participants were told  
81 that their performance either reflected important abilities and career potential (high importance)  
82 or had no such implications (low importance). Results showed that fatigued participants  
83 exhibited stronger cardiovascular responses when success importance was high, but attenuated  
84 responses when it was low. Similar findings across related paradigms (Wright et al., 2007, 2012)  
85 indicate that fatigue increases effort only when success remains both possible and worthwhile.  
86 When success importance is low, or when task demands are perceived as too high, effort  
87 decreases. Importantly, these findings suggest that success importance plays a critical role in  
88 sustaining effort during high-difficulty tasks, especially under CF, which amplifies perceived task  
89 difficulty (Figure 1c).

90 However, most prior studies have relied on relatively short fatigue inductions (e.g., ~ 5  
91 minutes), which may limit ecological validity, as more prolonged fatigue is common in real-world  
92 settings. Moreover, although MIT predicts that individuals should disengage and invest no effort  
93 when success is impossible or not sufficiently important, empirical findings rarely show  
94 complete disengagement. Instead, individuals tend to remain partially engaged, exhibiting  
95 reduced effort rather than full disengagement. This issue is recognized as a limitation in MIT and  
96 highlights the need for further research on full disengagement (Richter, 2015; Stanek & Richter,  
97 2021). The present study adds value by using a prolonged fatigue-induction task to examine the  
98 dynamic evolution of effort as fatigue accumulates.

99 **Psychophysiological Indicators of Effort**

100 A central challenge lies in objectively measuring the effects of CF and incentive value on  
101 effort. Building on extensions of MIT and related frameworks, effort and performance can be  
102 dissociated, meaning effort may increase without observable changes in performance  
103 (compensatory effort), increase despite declining performance (motivational misdirection), or  
104 decrease while performance is maintained through strategic adjustments (Locke & Latham,  
105 1990; Wright, 1996; Wolff et al., 2025). Although self-reports are commonly used to assess effort,  
106 they suffer from important limitations: individuals may interpret scales differently, fail to notice  
107 their level of effort or fatigue, or be influenced by social desirability or transient affective states  
108 such as frustration, boredom, or drowsiness (Pessiglione et al., 2025). Together, these limitations  
109 underscore the need for more objective physiological indices of effort.

110 Building on Obrist's active coping approach, which shows that imposed and controllable  
111 task demands elicit sympathetic activation (Obrist, 1981), Wright (1996) proposed that, within  
112 MIT, mental effort is reflected in this activation. Sympathetic activation affects the heart by  
113 increasing heart rate (HR), speeding conduction, and enhancing myocardial contraction  
114 (inotropic effect). Because HR reflects both sympathetic and parasympathetic influences, it does  
115 not provide a specific measure of effort. In contrast, myocardial contractility is predominantly  
116 influenced by sympathetic activity, and minimally by parasympathetic input, making it a more  
117 precise marker of effort-related activation (Richter et al., 2016). Researchers therefore focus on  
118 the preejection period (PEP), the interval between the onset of left ventricular depolarization (R-  
119 onset on the electrocardiogram, ECG) and the opening of the aortic valve (B-point on the  
120 impedance cardiogram, ICG), which marks the start of blood ejection (Newlin & Levenson, 1979;  
121 Sherwood et al., 1990; Berntson et al., 2004; Lozano et al., 2007; Kelsey, 2012). Typical PEP values  
122 range from 90 to 130 ms, with shorter PEP reflecting increased myocardial contractility and effort,  
123 and longer PEP indicating reduced contractility and lower effort (Richter et al., 2016; Gendolla et

124 [al., 2019; Mallat et al., 2020](#)). A recent meta-analysis confirms PEP as a robust index of effort  
125 while highlighting the importance of contextual validation across psychological tasks ([Albinet et](#)  
126 [al., 2024](#)). Because PEP can be influenced by preload and afterload, it is best interpreted  
127 alongside other cardiovascular measures such as blood pressure and HR ([Krohova et al., 2017](#)).  
128 In the present study, PEP served as the main indicator to test MIT predictions regarding effort  
129 under conditions of CF and incentive.

### 130 **Overview and Predictions**

131 Building on the MIT framework and our previous work ([Place et al., 2025](#)), this study  
132 explored how avoidance-based increases in success importance modulate effort allocation  
133 under CF during consecutive difficult tasks. All participants completed a sequential paradigm  
134 ([Baumeister et al., 1998](#)) with cognitively difficult tasks: a 30-minute first task (time-on-task),  
135 consistent with recent recommendations for inducing CF without excessive boredom  
136 ([Schampheleer et al., 2025](#)), followed by a 10-minute subsequent task. Half of the participants  
137 received an avoidance-based motivational instruction before the subsequent task. Participants  
138 were instructed to outperform a previously achieved individual performance criterion, ensuring  
139 that task difficulty is fixed and known<sup>2</sup>.

140 Our first hypothesis concerns the effect of CF during the first task. According to classic  
141 MIT, effort increases with perceived task difficulty as long as success is possible and the required  
142 effort is justified; disengagement occurs when perceived task difficulty exceeds the upper limit  
143 set by potential motivation. In relatively easy tasks, CF-related increases in perceived difficulty  
144 may elicit compensatory increases in effort, as the task remains manageable. In contrast, when  
145 a task is already difficult from the outset, there is little room for such compensatory adjustments.

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<sup>2</sup> Participants completed a familiarization phase with both tasks prior to the experimental session. Familiarization with the second task allowed participants to experience it, calibrate their performance, and establish a performance criterion before the avoidance manipulation, ensuring that task difficulty was subjectively known and stable for the subsequent task.

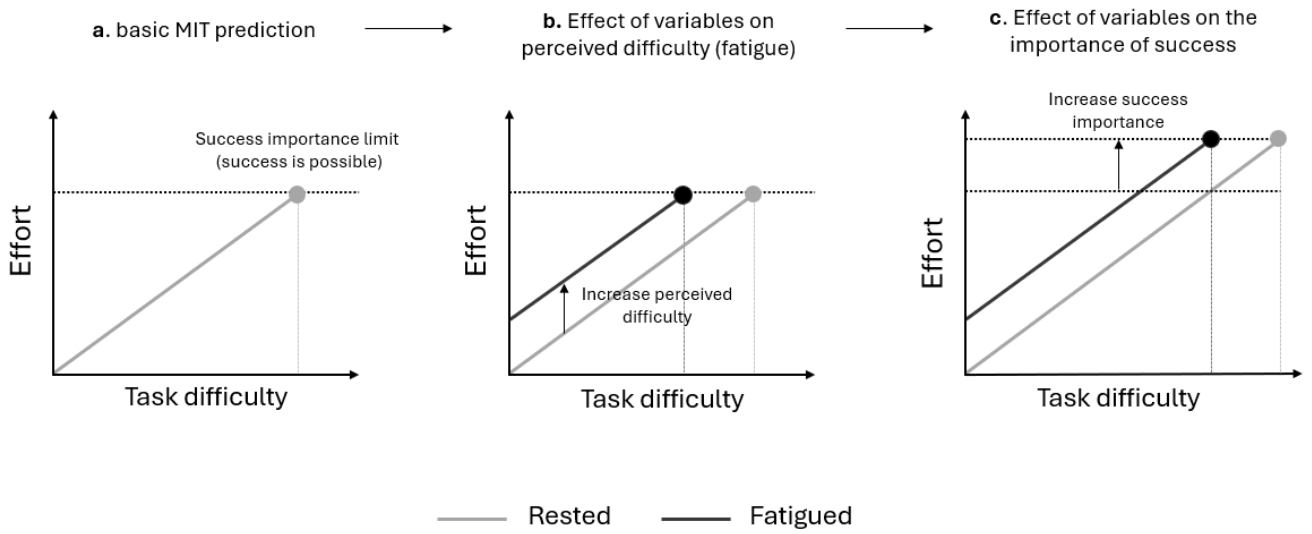
## COGNITIVE FATIGUE & SUCCESS IMPORTANCE

146 In this context, we propose that disengagement does not occur abruptly but rather unfolds  
147 gradually over time-on-task. Consistent with this view, previous studies have shown that effort  
148 can still be observed under conditions of high task difficulty and low success importance,  
149 suggesting that disengagement is not always abrupt or characterized by zero effort (Richter, 2015;  
150 Stanek & Richter, 2021).

151 Accordingly, we predicted that as CF accumulates and the task is of low success  
152 importance during the difficult 30-minute task, perceived task difficulty would progressively  
153 approach or slightly exceed the upper limit set by potential motivation, rendering effort  
154 increasingly unjustified. Rather than disengaging completely, participants were expected to  
155 remain engaged while gradually reducing the intensity of effort allocation. This progressive  
156 disengagement was expected to be reflected in a gradual decline in cardiovascular response  
157 across the task (i.e., increased PEP, Hypothesis 1).

158 Our main predictions concern the transition from the end of the first task to the  
159 subsequent task. Despite high task difficulty and accumulated CF, we predict that the avoidance  
160 instruction will increase the upper limit set by potential motivation, thereby making the required  
161 effort justified (Figure 1c). According to MIT, this should result in greater effort-related  
162 cardiovascular response (i.e., decreased PEP) in the avoidance condition. Conversely, control  
163 participants, for whom success importance remains low, are expected to continue disengaging  
164 as perceived task difficulty exceeds the upper limit. This should result in a lower cardiovascular  
165 response during the second task relative to the end of the first task. Accordingly, we predict that  
166 participants in the avoidance condition will allocate significantly more effort than control  
167 participants during the second task. This hypothesis will be tested using a planned contrast,  
168 assigning weights of 1 to the avoidance group and -1 to the control group (Hypothesis 2).

169



170 **Figure 1.** Effort as a function of task difficulty across three stages: (a) effort increases with task  
 171 difficulty up to a maximum determined by success importance; (b) cognitive fatigue moderates  
 172 this relationship; (c) combined effects of cognitive fatigue and variables that enhance success  
 173 importance. Conceptual illustration adapted from Wright (2014), Richter et al. (2016), and Gendolla et al.  
 174 (2019)

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## METHODS

### 187 **Reporting**

188 We report all focal measures and analyses, the rationale for the sample size, all data  
189 exclusions, and all experimental manipulations. Additional tables are provided in the online  
190 supplementary materials.

### 191 **Participants**

192 Forty-four participants aged 18-26 years ( $M_{age} = 21.84$ ,  $SD = 2.06$ ; eight men) were  
193 recruited from the University of Toulouse, France. All participants provided written informed  
194 consent before participation and received a 20-euro voucher as compensation. They were  
195 randomly assigned to either the avoidance motivation (AM) group ( $n = 22$ ; three men) or the  
196 control group ( $n = 22$ ; four men). Because CF and effort can be influenced by factors such as time  
197 of day, stimulant intake, and sleep, all sessions were conducted in the morning (between 9 a.m.  
198 and 12 p.m.) Participants were asked to avoid consuming stimulating drinks for 24 hours before  
199 the assessment and to get seven hours of sleep the night before. Given the cardiovascular  
200 measures, participants were also required to have no history of cardiovascular disease and to  
201 abstain from medications that could interfere with cardiovascular response.

### 202 **Sample and Power calculation**

203 Previous between-subjects research has reported medium-sized effects on PEP ( $\eta^2 = .09$ ;  
204  $f \approx .31$ ) when comparing high versus low incentive conditions under fear primes (Chatelain &  
205 Gendolla, 2016). To adopt a conservative approach, this effect size was reduced to a moderate  
206 level ( $f = .25$ ) for *a priori* sensitivity analyses. The main hypothesis, namely the impact of  
207 avoidance instruction, involved a within-between interaction in a repeated-measures design. An  
208 initial estimate of the required sample size was obtained through a sensitivity analysis conducted  
209 with G\*power (Faul et al., 2007) for a 2 (Group: AM vs. Control) x 2 (Task: Block 3 vs. TNT); see

12

210 Figure 2) mixed-design ANOVA, assuming a medium effect size ( $f = 0.25$ ),  $\alpha = 0.05$ , and power =  
211 0.80. This analysis indicated that a sample size of 44 participants provides adequate sensitivity  
212 to detect medium-sized main and interaction effects. Finally, data were analyzed using linear  
213 mixed-effects models, which are well-suited for modeling repeated measures and the associated  
214 within-subject dependency while accounting for inter-individual differences.

### 215 **Ethical approval**

216 The study followed the Declaration of Helsinki. The local ethics review committee at the  
217 University of Toulouse approved the protocol.

### 218 **Procedure**

219 Upon arrival, participants were welcomed and familiarized with the experimental setup  
220 and equipment to minimize novelty effects. They were then seated comfortably at a computer,  
221 gave written informed consent, and had cardiovascular sensors attached before the  
222 experimental software was started. The experiment was fully computerized, and task  
223 instructions were delivered automatically (E-Prime, Psychology Software Tools, Pittsburgh, PA).  
224 Sessions (AM, control) were randomized such that neither the experimenter nor the participant  
225 was aware of the assigned condition, ensuring a double-blind design.

226 To establish a physiological baseline, participants first watched a 10-minute neutral  
227 animal documentary and were instructed to remain relaxed and still to minimize movement  
228 artifacts (Piferi et al., 2000). Next, participants completed a familiarization session for the  
229 Toulouse N-back task (TNT, 1-back version), which involved 60-second blocks interspersed with  
230 ten-second rest periods to reduce learning effects. They also performed a brief practice of the  
231 updating working memory (WM) task used for fatigue induction, consisting of ten 24-second  
232 trials. A standardized five-minute break followed the familiarization period, after which the main  
233 experimental protocol began. This consisted of 30 minutes of the WM updating task (time-on-  
234 task: blocks 1, 2, 3) followed by a 10-minute TNT task, forming a sequential-task paradigm. No

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235 performance feedback was provided at any point. Fatigue was assessed using visual analog  
236 scales (VAS) before and after the fatigue induction phase and immediately before the TNT task.  
237 Cardiovascular activity was recorded continuously, except during familiarization. Figure 2  
238 illustrates the experimental protocol.

239 **Avoidance instruction.** In the AM condition, participants were informed directly on the computer  
240 screen before the second task (i.e., TNT) that performing worse than in the last three  
241 familiarization blocks could result in the task being extended by up to 20 minutes. The  
242 performance criterion to be achieved (i.e., the average of the last three familiarization blocks) was  
243 also displayed on the screen. Previous research has shown that, following prolonged and  
244 demanding effort, such manipulations act as a strong incentive by increasing the importance of  
245 success, effort, and performance (Hopstaken et al., 2015, 2016). In reality, the TNT task always  
246 lasted 10 minutes.

### 247 **Tasks**

#### 248 ***Toulouse N-back task (Figure 3a)***

249 The Toulouse N-back task is an adapted 1-back version of the classic *n*-back task,  
250 developed by Causse et al. (2017). In this version, each stimulus is a simple arithmetic operation,  
251 and participants must compute the result and compare it to that of the previous trial. This  
252 adaptation increases task difficulty and WM demands by engaging both processing and storage  
253 rather than simply memorizing isolated items (Barrouillet & Camos, 2021). Additionally, reliance  
254 on visual strategies is reduced because the element to be remembered is not directly visible but  
255 must be calculated. *N*-back tasks have been widely used to assess sustained WM engagement,  
256 as they strongly recruit cognitive control and require high levels of task engagement (Owen et al.,  
257 2005; Kearney-Ramos et al., 2014; Westbrook & Braver, 2015).

258 Each session consisted of 240 trials, with 48 unique arithmetic operations using multiples  
259 of five (e.g., 15 + 40, 65 – 20). Operations were presented randomly and included both additions

260 and subtractions, with a target rate of 30%. Stimuli were displayed at the center of the screen in  
261 Calibri (70 pt) for 2,000 ms, followed by a 500-ms interstimulus interval. Participants were  
262 instructed to respond as quickly and accurately as possible to both targets and non-targets by  
263 pressing one of two buttons. Responses were recorded using E-Prime software and a PST Serial  
264 Response Box (version 3.0, Psychology Software Tools, Pittsburgh, PA, USA).

### 265 ***WM updating task (Figure 3b)***

266 Participants completed a modified version of the updating task developed by Capa et al.  
267 (2011), similar to the version used in our previous study (Place et al., 2025). Each trial began with  
268 a fixation cross, followed by a three-digit number that participants were instructed to memorize.  
269 Participants then updated this number step by step according to a sequence of six arithmetic  
270 operations, consisting of simple additions or subtractions ( $\pm 1$ ,  $\pm 2$ , or  $\pm 3$ ). To keep the task  
271 difficulty consistent, all intermediate and final values for each digit were limited to single-digit  
272 values (0-9). At the end of each trial, participants entered the final updated number using the  
273 keyboard. The task comprised 75 trials, each lasting 24 seconds, with the initial numbers,  
274 operation sequences, and expected responses varying across trials.

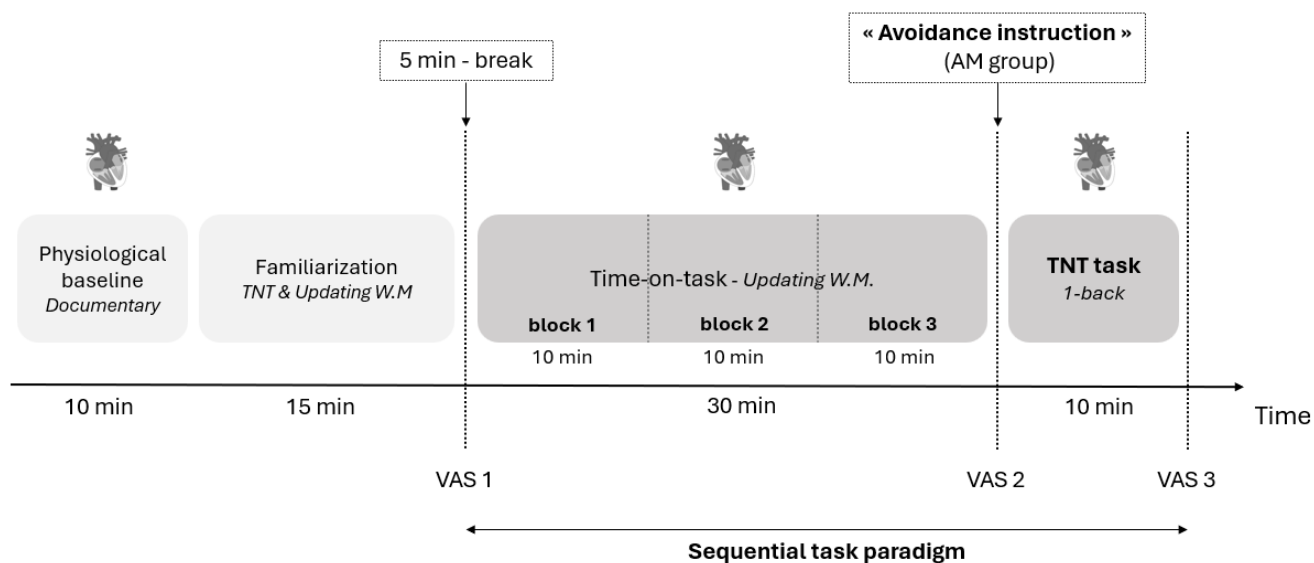
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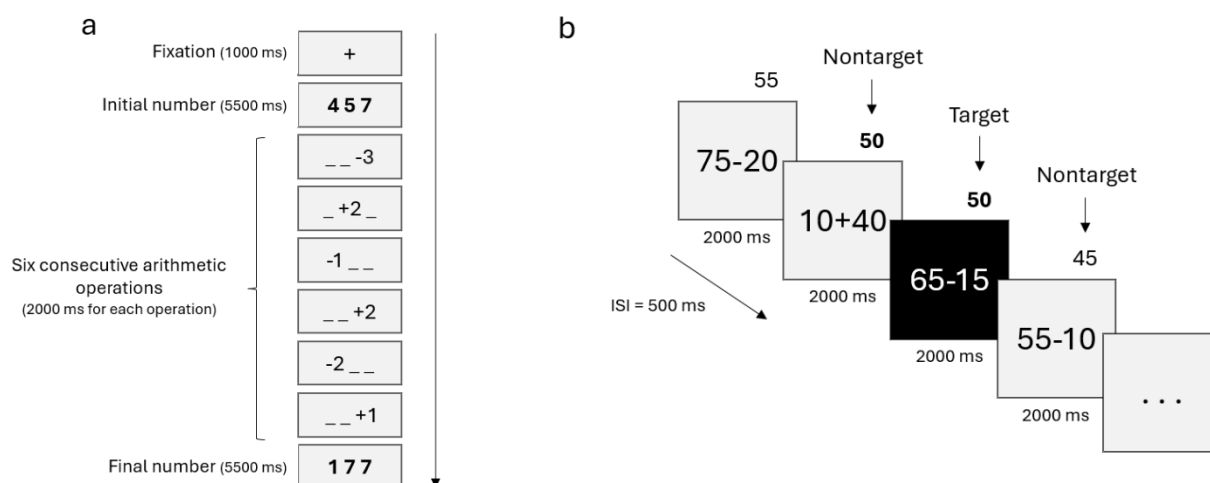
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Figure 2. Overview of the experimental protocol.



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Figure 3. Example trials for the WM updating (a) and TNT tasks (b).

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ISI: interstimulus interval.

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288 **Measures and Data Processing**289 ***Subjective measures***

290 Subjective fatigue was assessed at three time points: before and after the fatigue  
291 induction phase, and after the TNT task. Participants indicated their current level of fatigue on a  
292 VAS ranging from 0 (“no fatigue”) to 100 (“extreme fatigue”).

293 ***Behavioral measures***

294 Performance was quantified using perceptual sensitivity ( $d'$ ), an index from signal  
295 detection theory (SDT) reflecting participants' ability to discriminate targets from non-targets.  
296 This measure provides more nuanced information than simple accuracy, particularly in the  
297 context of CF (see [Wylie et al., 2021](#)). Perceptual sensitivity was calculated as:

298

$$299 \quad d' = z(pHit) - z(pFA)$$

300

301 where  $z$  is the inverse of the standard normal cumulative distribution,  $pHit$  is the  
302 proportion of correctly identified target stimuli (Hits), and  $pFA$  is the proportion of non-target  
303 stimuli incorrectly identified as targets (False Alarms; FA). In addition to  $d'$ , overall accuracy  
304 (percentage of correct responses) and reaction times (RTs) were analyzed.

305 ***Cardiovascular measures***

306 Cardiovascular activity was recorded using a BIOPAC system (MP160; ©BIOPAC Systems  
307 Inc., Goleta, USA) at a sampling rate of 2000 Hz. ECG signals were obtained via three disposable  
308 electrodes (EL501) placed on the right and left clavicles and the left lower rib. ICG was measured  
309 using two pairs of disposable Ag/AgCl electrodes (LEAD1) in a tetrapolar configuration on the left  
310 side of the participant's neck and chest (xiphoid level, left mid-axillary line). ECG and ICG signals  
311 were amplified using dedicated modules (ECG100C and NICO100C). Before electrode  
312 placement, the skin was prepared with an abrasive paste to reduce impedance.

313           **Signal preprocessing.** Raw ECG and ICG signals were processed in AcqKnowledge (version  
314 5.0.6). Signals were band-pass filtered (0.1-40 Hz, FIR), and ICG signals were further denoised  
315 using the Daubechies-8 wavelet method with adaptive thresholding (Chabchoub et al., 2016). R-  
316 peaks were automatically detected from the ECG and visually inspected; ectopic beats were  
317 corrected by interpolation.

318           **Time-domain analysis.** HR was computed from the corrected RR intervals. PEP was  
319 defined as the interval between the onset of the ECG R-wave and the ICG B-point (Berntson et  
320 al., 2004). B-points were estimated using a polynomial function based on RZ intervals of valid  
321 heartbeats (Lozano et al., 2007) and visually inspected for accuracy, with manual corrections  
322 applied when necessary (Sherwood et al., 1990).

### 323 **Statistical Analyses**

324           Statistical analyses were conducted using R v4.5.2, RStudio (Posit team, 2025), and JASP  
325 (JASP Team, 2025). Behavioral performance on the TNT task<sup>3</sup> ( $d'$ , accuracy, RTs) was compared  
326 between groups using independent-samples  $t$ -tests. Subjective fatigue (VAS) and cardiovascular  
327 responses (PEP, HR) were analyzed using linear mixed-effects models (LMMs) implemented with  
328 the *lmer* function from the *lmerTest* package (Kuznetsova et al., 2017). Degrees of freedom and  
329  $p$ -values for fixed effects were estimated using Satterthwaite's approximation. Participants were  
330 included as random intercepts. Random slopes were not included due to the limited number of  
331 repeated measures and to ensure model convergence. Model assumptions, including visual  
332 inspection of residual plots (Q-Q plots and residuals vs. fitted values), confirmed that  
333 assumptions of normality and homoscedasticity were met.

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<sup>3</sup> No behavioral analyses were conducted on the time-on-task (updating WM) due to the limited number of trials per 10-minute segment (i.e., 25 trials) and because only the final response was recorded, preventing assessment of intermediate arithmetic steps.

334 Subjective fatigue was modeled as a function of Time (VAS 1, 2, 3), Group (AM vs. Control),  
335 and their interaction. Cardiovascular responses were analyzed using two complementary  
336 modeling approaches corresponding to the study hypotheses. To account for resting  
337 physiological differences, the mean of the final three minutes of the baseline period was included  
338 as a centered covariate. For Hypothesis 1 (time-on-task effects), a LMM assessed the impact of  
339 CF across the entire sample, with Time (Blocks 1-3 of the time-on-task period) treated as a  
340 categorical fixed factor. Significant effects were explored using post-hoc comparisons of  
341 Estimated Marginal Means (EMMs) implemented in the *emmeans* package (Lenth, 2016),  
342 applying Kenward-Roger degrees of freedom approximation and Bonferroni adjustments.

343 For Hypothesis 2 (avoidance instructions), LMMs included Group (AM vs. Control) and  
344 Time (Block 3 vs. TNT) as fixed factors, along with their interaction. When a significant Group x  
345 Time interaction emerged, planned contrasts, established *a priori*, were used to test the effect of  
346 avoidance instructions during the TNT task by comparing groups at TNT (contrast weights: AM =  
347 1; Control = -1), while controlling for Block 3 (weights = 0, 0). Additional simple effects were used  
348 to examine how effort changed from Block 3 to TNT within each group. Data were visualized using  
349 *ggplot2* (Wickham, 2011). The significance level was set at  $\alpha = .05$ , with 95% confidence intervals  
350 (CI).

## 351 RESULTS

### 352 Subjective Data

353 There was a significant main effect of Time,  $F(2,84) = 53.03, p < .001, \eta p^2 = .56$ . Post-hoc  
354 comparisons showed a significant increase in self-reported fatigue from VAS 1 ( $M = 40.93$ ) to VAS  
355 2, ( $M = 72.27; t(84) = 9.38, p < .001, d = 2.00$ ) and VAS 3 ( $M = 68.91; t(84) = 8.37, p < .001, d =$   
356  $1.79$ ). However, no further increase was observed between VAS 2 and VAS 3 ( $p = .951$ ). No  
357 significant main effect of group ( $F(1,42) = 1.61; p = .211, \eta p^2 = .04$ ) or Group x Time interaction ( $F$

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358 (2, 84) = 0.90;  $p = .411$ ,  $\eta p^2 = .02$ ) was observed. Estimated marginal means (EMMs)  $\pm$  95%  
359 confidence intervals are provided in Table 1.

360

Time	AM - EMM [95% CI]	Control - EMM [95% CI]
VAS 1	40.09 [31.35, 48.83]	41.77 [33.04, 50.51]
VAS 2	69.14 [60.40, 77.87]	75.41 [66.67, 84.15]
VAS 3	63.59 [54.85, 72.33]	74.23 [65.49, 82.96]

361

362 **Table 1.** Descriptive statistics for self-reported fatigue in the AM and Control groups at three time  
363 points: before Block 1 (VAS 1), after Block 3 (VAS 2), and after the TNT task (VAS 3). Values are  
364 EMMs [95% CI] from the LMM. VAS = Visual Analog Scale.  $n = 22$  per group.

### 365 Behavioral Data<sup>4</sup>

366 Performance on the TNT task was compared between groups using independent two-  
367 tailed  $t$ -tests. A significant difference emerged for perceptual sensitivity ( $d'$ ),  $t(42) = 2.51$ ,  $p = .016$ ,  
368  $d = 0.76$ , with the AM group demonstrating higher perceptual sensitivity ( $M = 2.18$ ,  $SE = 0.13$ ) than  
369 the Control group ( $M = 1.63$ ,  $SE = 0.18$ ). In contrast, no significant differences were observed for  
370 accuracy ( $p = .154$ ,  $d = .44$ ) or RTs ( $p = .742$ ,  $d = 0.10$ ). Complete descriptive statistics for all  
371 behavioral indices, including means and standard errors, are available in the supplemental  
372 materials.

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<sup>4</sup> Note that descriptive statistics (mean values for accuracy and RTs) of the familiarization period for the TNT task are provided in the Supplementary Materials for readers interested in the evolution of learning in this task.

373 **Cardiovascular Data<sup>5</sup>**

374 Physiological baseline data (PEP, HR) were averaged across the final three minutes of  
375 recording. Internal consistency was excellent (all Cronbach's  $\geq .994$ ), indicating high temporal  
376 stability of the resting state. Preliminary independent-samples *t*-tests with Group as the between-  
377 subjects factor revealed no significant differences between the AM and Control groups ( $ps \geq$   
378  $.506$ ). Table 2 displays the raw baseline values for both groups. As noted in the Statistical  
379 Analyses section, data were analyzed using LMM. To ensure the stability of our findings, we  
380 conducted sensitivity analyses using traditional approaches (e.g., ANCOVAs on reactivity scores  
381 and the Llabre procedure; Llabre et al., 1991), all of which yielded a consistent pattern of results.  
382 Figure 1 in the Supplemental Materials illustrates these raw PEP reactivity scores during the time-  
383 on-task and TNT task.

384 **Hypothesis 1: Time-on-task effects**

385 LMMs were conducted with PEP and HR as dependent variables, Time (Block 1, 2, 3) as a  
386 fixed factor, and centered baseline as a covariate. Table 3 displays the EMMs and 95% CIs  
387 adjusted by the LMM for both measures. For PEP, a significant main effect of Time was observed,  
388  $F(2,86) = 8.27, p < .001, \eta p^2 = .16$ . Post-hoc comparisons revealed a significant increase in PEP  
389 from Block 1 to Block 2 ( $t(86) = 2.95, p = .012, d = 0.63$ ), and from Block 1 to Block 3 ( $t(86) = 3.90,$   
390  $p < .001, d = 0.63$ ). No significant difference was found between Block 2 and Block 3 ( $p = 1.000$ ).  
391 A similar significant main effect of Time was observed for HR,  $F(2,86) = 3.12, p = .049, \eta p^2 = .07$ .  
392 Post-hoc tests showed a significant decrease in HR between Block 1 and Block 3 ( $t(86) = 2.48, p$   
393  $= .045, d = 0.53$ ). No other pairwise comparisons reached significance (all  $ps \geq .430$ ).

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<sup>5</sup> The sample included only a small number of male participants ( $n = 7$ ), preventing any reliable statistical comparisons between genders.

394 **Hypothesis 2: Avoidance instructions effects**

395 LMMs were conducted with PEP and HR as dependent variables, Group (AM vs. Control) and  
396 Time (Block 3 vs. TNT) as fixed factors, and centered baseline as a covariate. Table 4 displays the  
397 EMMs and 95% CIs adjusted by the LMM for both measures. For PEP, a significant Group x Time  
398 interaction was observed,  $F(1,42) = 15.85, p < .001, \eta p^2 = .27$ . An *a priori* theory-driven contrast  
399 revealed a significant difference between groups during the TNT task,  $t(47.2) = 2.83, p = .007, d =$   
400  $0.82$ , with the AM group exhibiting lower PEP values (indicating higher effort) than the Control  
401 group, in line with Hypothesis 2 (see Figure 4, left). Additional post-hoc comparisons showed a  
402 significant decrease in PEP from Block 3 to the TNT task in the AM group,  $t(42) = 3.50, p = .007, d$   
403  $= 1.06$ , whereas no significant change was found in the control group,  $t(42) = 2.13, p = .234, d =$   
404  $0.64$ . No main effects of Time,  $F(1,42) = 0.94, p = .339, \eta p^2 = .02$ , or Group,  $F(1,41) = 3.37, p =$   
405  $.074, \eta p^2 = .08$ , were observed. For HR, a similar pattern emerged with a significant Group x Time  
406 interaction,  $F(1,42) = 13.01, p < .001, \eta p^2 = .24$ . The *a priori* contrast confirmed a significant  
407 difference at TNT,  $t(45.8) = 2.13, p = .038, d = 0.63$ , with higher HR in the AM group compared to  
408 the Control group (see Figure 4, right). Follow-up simple effects showed a significant increase in  
409 HR for the AM group between Block 3 and the TNT task,  $t(42) = 3.63, p = .005, d = 1.09$ , while no  
410 significant change was observed for the Control group,  $t(42) = 1.47, p = .891, d = 0.44$ . Consistent  
411 with the PEP results, there were no significant main effects for Time,  $F(1,42) = 2.32, p = .135, \eta p^2$   
412  $= .05$ , or Group,  $F(1,41) = 1.75, p = .194, \eta p^2 = .04$ .

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Group	PEP	HR
AM	104.72 ± 1.40	78.19 ± 1.95
Control	102.58 ± 2.88	80.19 ± 3.57

419  
 420 **Table 2.** Descriptive statistics for raw cardiovascular baseline data. Values are presented as  
 421 mean ± standard error (SE). PEP = preejection period (in ms), HR = heart rate (in bpm), AM =  
 422 avoidance motivation group.

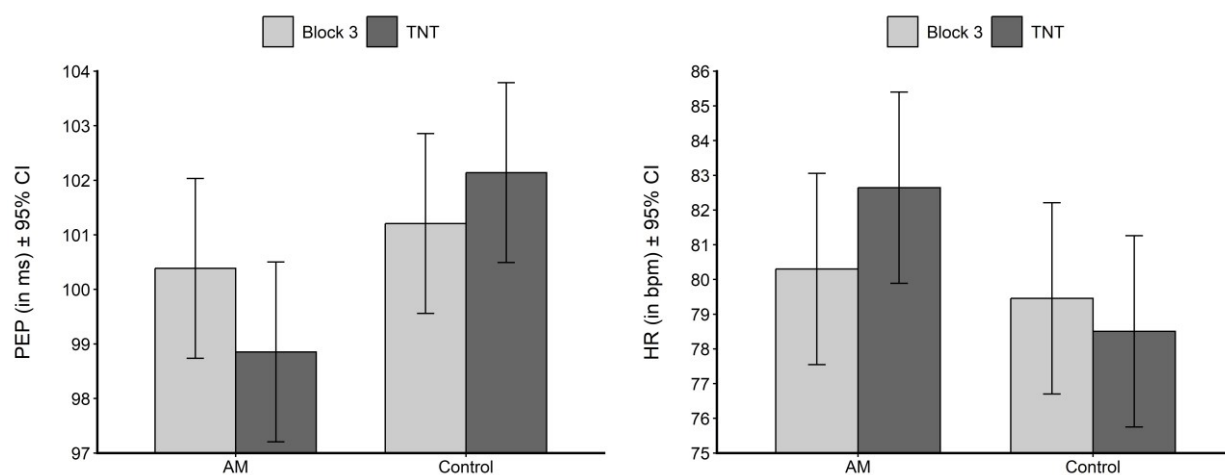
Time	PEP - EMM [95% CI]	HR - EMM [95% CI]
Block 1	99.60 [98.32, 100.87]	80.94 [78.94, 82.93]
Block 2	100.50 [99.23, 101.78]	80.31 [78.31, 82.31]
Block 3	100.80 [99.52, 102.07]	79.88 [77.88, 81.88]

424  
 425 **Table 3.** Descriptive statistics for preejection period (PEP, in ms) and heart rate (HR, in bpm)  
 426 across all participants ( $n = 44$ ) during the time-on-task period (Blocks 1-3, Hypothesis 1). Values  
 427 represent estimated marginal means (EMMs) and 95% confidence intervals (CIs) derived from the  
 428 linear mixed models (LMMs).

Time	PEP - EMM [95% CI]		HR - EMM [95% CI]	
	AM	Control	AM	Control
Block 3	100.39 [98.73, 102.03]	101.21 [99.55, 102.86]	80.30 [77.55, 83.06]	79.46 [76.70, 82.21]
TNT	98.85 [97.20, 100.5]	102.14 [100.49, 103.79]	82.64 [79.89, 85.40]	78.51 [75.75, 81.26]

430  
 431 **Table 4.** Descriptive statistics for preejection period (PEP, in ms) and heart rate (HR, in bpm)  
 432 across avoidance motivation (AM) and Control groups during Block 3 and the TNT task  
 433 (Hypothesis 2). Values represent estimated marginal means (EMMS) and 95% confidence  
 434 intervals (CIs) from linear mixed models (LMMs).

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437 **Figure 4.** Preejection period (PEP, in ms; left) and heart rate (HR, in bpm; right) across Block 3 and  
438 the TNT task in the avoidance motivation (AM) and Control groups. Values are estimated marginal  
439 means (EMMs); error bars represent 95% confidence intervals (CIs) derived from the linear mixed  
440 models (LMMs).

441

## DISCUSSION

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Consistent with MIT (Brehm & Self, 1989) and its later extensions (Wright, 1996, 2014), our primary hypothesis (Hypothesis 2) predicted that fatigued participants would exert greater effort (indexed by lower PEP) when provided with an avoidance-based instruction during a task of fixed and known difficulty. Before addressing this core prediction, it was essential to establish that the time-on-task manipulation successfully elicited CF (Hypothesis 1).

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Following the time-on-task period, participants reported a marked increase in subjective fatigue, accompanied by a reduction in effort-related cardiovascular responses. Specifically, PEP<sup>6</sup> increased from Block 1 to Block 2, reflecting an early reduction in effort intensity, and

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<sup>6</sup> The observed increase in PEP was accompanied by a decrease in HR, which helps rule out potential confounding effects of cardiac preload (Frank-Starling mechanism) (Albinet et al., 2024). While we did not directly assess hemodynamic factors (Krohova et al., 2017), the stability of the seated position, and the HR trend support the interpretation of PEP as a reliable index of myocardial contractility here.

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450 remained stable through Block 3. Although we expected a more linear decline, this plateau  
451 suggests that participants reached a sustainable level of reduced effort. Crucially, PEP values  
452 remained shorter (100.8 ms) than baseline levels (103.7 ms) at the end of the task, confirming  
453 that some level of effort was still being invested despite CF. This is further supported by the  
454 significant decrease in HR from the beginning to the end of the task, reinforcing the physiological  
455 evidence of reduced myocardial activity over time. These results replicate previous research  
456 showing that prolonged engagement in a difficult initial task induces heightened subjective  
457 fatigue alongside reduced physiological effort (Lorcery et al., 2024; Daneshgar-Pironneau et al.,  
458 2025).

459         The rise in self-reported fatigue confirms that our time-on-task manipulation was  
460 effective. This increase is closely tied to a rise in perceived task difficulty, consistent with recent  
461 evidence (Engle-Friedman et al., 2018; Goh et al., 2022). According to MIT, fatigued participants  
462 should exert more effort as long as success remains possible and justified (Wright, 2014). If the  
463 required effort, inflated by fatigue, exceeds the upper limit set by potential motivation, MIT  
464 predicts abrupt disengagement, characterized by zero effort. In the present study, however, effort  
465 did not collapse. Instead, under conditions of high task difficulty and low importance of success,  
466 PEP increased and then stabilized. This pattern can be interpreted as a strategic reduction in  
467 effort intensity rather than a full withdrawal, suggesting that participants may have recalibrated  
468 their investment rather than disengaging entirely. As shown by Hopstaken et al. (2015), such  
469 progressive disengagement can unfold over extended periods, suggesting that our observed  
470 subsequent plateau represents an intermediate stage of effort regulation.

471         Although formal performance measures for this phase were limited (see Footnote 3),  
472 participants maintained an accuracy level of approximately 60% throughout the task. While MIT  
473 primarily focuses on effort intensity rather than behavioral outcomes—which can be influenced  
474 by strategic adjustments (Locke & Latham, 1990)—this sustained level of accuracy provides

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475 converging evidence that participants remained engaged and did not fully disengage, despite  
476 increasing subjective fatigue and reduced physiological effort.

477         Together, these findings suggest that, during prolonged high-difficulty tasks,  
478 disengagement may unfold gradually rather than abruptly. This limitation of strictly binary  
479 disengagement accounts has already been noted by MIT researchers ([Richter, 2015](#); [Stanek &  
480 Richter, 2021](#)). However, most MIT research examining the influence of CF on effort has focused  
481 on brief tasks and clearly separated difficulty levels ([Wright et al., 2003, 2007](#); [Stewart et al.,  
482 2009](#); [Wright et al., 2013](#)), which makes it difficult to examine how effort behaves near the  
483 disengagement threshold. These results underscore the need to extend MIT to sustained-effort  
484 contexts, in which disengagement may emerge gradually over time. Such an extension is  
485 particularly relevant given that many real-world activities require continuous, long-term  
486 investment of effort.

487         Alternative explanations for the observed reduction in physiological response, such as  
488 habituation or boredom, cannot be entirely ruled out. However, the nature of the WM updating  
489 task and preliminary familiarization training minimizes the likelihood of task automatization.  
490 Future studies would benefit from incorporating direct measures of boredom and neural indices  
491 of time-on-task fatigue, such as EEG theta and alpha oscillations ([Tran et al., 2020](#); [Kok, 2022](#)), to  
492 complement insights obtained from peripheral measures.

493         In summary, the time-on-task task period successfully induced a state of CF  
494 characterized by marked subjective fatigue and a strategic reduction in physiological effort. This  
495 provided the necessary conditions to test our core prediction: whether avoidance-based  
496 instructions could increase the upper limit of potential motivation, thereby justifying the higher  
497 compensatory investment required to perform despite CF (Hypothesis 2).

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499 Consistent with Hypothesis 2, participants provided with avoidance instructions (AM  
500 group) mobilized significantly more effort than the Control group. Specifically, the AM group  
501 exhibited shorter PEP (reflecting higher myocardial contractility) and higher HR during the TNT  
502 task (see Figure 4). Beyond a mere difference between groups, we observed a physiological  
503 rebound within the AM group: effort intensity increased significantly from the end of the time-on-  
504 task (Block 3) to the subsequent task. This rebound demonstrates that avoidance instructions  
505 effectively elevate the upper limit of potential motivation, justifying a higher mobilization of  
506 resources even under conditions of CF. While CF increases perceived task difficulty, the  
507 avoidance instruction increases success importance, ensuring that the required effort remains  
508 justified rather than exceeding the participants' potential motivation limit.

509 In contrast, while the Control group did not show a further decline, their PEP values are  
510 close to resting levels, reflecting a lack of compensatory effort. This suggests that in the absence  
511 of strong motivational incentives, participants are unwilling to invest the additional resources  
512 required to meet task difficulty under CF. Interestingly, subjective fatigue remained high across  
513 both groups, regardless of the instruction. This dissociation is important as the motivational  
514 effect of the avoidance instruction did not alleviate the subjective experience of fatigue, but  
515 instead increased the willingness to exert effort. This indicates that CF primarily inflates  
516 perceived task difficulty, while effort allocation remains flexible and highly responsive to shifts in  
517 success importance. This also confirms that the previous reduction in effort was a strategic  
518 choice to conserve resources (Brehm & Self, 1989) rather than a biological exhaustion of capacity.

519 Although the joint effects of CF and success importance are rarely investigated within the  
520 MIT framework, our findings converge with research on implicit affective states. For instance,  
521 sadness or fear has been shown to inflate perceived task difficulty, leading to disengagement  
522 when incentives are low because the required effort is no longer justified. Conversely, high  
523 incentives restore engagement by rendering the effort worthwhile (Freydefont & Gendolla, 2012;

524 [Chatelain & Gendolla, 2016](#)). In our study, the avoidance instruction acted as a “motivational  
525 safeguard”, similar to a high incentive. By increasing the importance of success, it raised the  
526 upper limit of potential motivation. This justified the intense engagement required to meet the  
527 difficulty of the TNT task, despite the CF. Consistent with this interpretation, the present results  
528 align with broader psychophysiological evidence showing increased effort following avoidance  
529 instructions or financial reward during prolonged tasks ([Boksem et al., 2006](#); [Hopstaken et al.,](#)  
530 [2015, 2016](#); [Herlambang et al., 2019](#)).

531 Finally, we examined whether this physiological activation translated into improved task  
532 functioning. In the AM group, higher effort was accompanied by significantly greater perceptual  
533 sensitivity ( $d'$ ), whereas the Control group exhibited lower  $d'$  values. The absence of significant  
534 effects on accuracy or RTs, paired with the boost in  $d'$ , suggests that the additional effort was  
535 precisely allocated to enhancing stimulus discrimination and the overall quality of information  
536 processing ([Wickens, 2001](#)). This result is consistent with recent evidence showing that  
537 perceptual sensitivity is a more sensitive behavioral marker than accuracy or RTs in the context  
538 of CF and effort allocation ([Wylie et al., 2021](#); [Wójcik & Nęcka, 2024](#)).

539  
540 While these findings provide novel insights, several limitations should be considered.  
541 First, we did not include a non-fatigued control group, which limits our ability to determine  
542 whether avoidance instructions exert similar effects in the absence of fatigue. Second, our  
543 sample was predominantly composed of women, reducing the generalizability of the results to  
544 the broader population. Third, although we followed recommended procedures for PEP  
545 measurement ([Albinet et al., 2024](#)), the avoidance-instruction manipulation may have induced  
546 some stress. Within the MIT framework, however, any process that mobilizes effort—including  
547 stress—is considered part of goal-directed resource allocation ([Wright, 1996](#); [Richter et al., 2016](#);  
548 [Gendolla et al., 2019](#)). While PEP is the robust index of  $\beta$ -adrenergic activity, future studies could

549 complement peripheral measures with neural indicators to disentangle underlying mechanisms  
550 and better capture the complexity of cognitive effort. Additionally, although subjective fatigue  
551 was assessed, other psychological factors that may influence effort (e.g., boredom, motivation)  
552 were not directly measured. Finally, investigating the combined effects of CF and motivational  
553 manipulations, such as avoidance versus reward, would provide further insight into how effort is  
554 strategically allocated over prolonged tasks.

## CONCLUSION

555  
556 The present study shows that effort intensity is not a monotonic phenomenon, as success  
557 importance can moderate the impact of CF on effort. When a motivational stimulus is sufficiently  
558 important to raise the upper limit of potential motivation above perceived task difficulty,  
559 participants still mobilize substantial effort to perform. Notably, avoidance-based instructions  
560 emerged as a particularly robust stimulus, enabling participants to stay engaged and achieve  
561 superior performance.

562 Furthermore, these results validate the integration of MIT with objective physiological  
563 measures as a rigorous framework for investigating effort dynamics in sequential-task paradigms.  
564 However, our data also suggest that classical MIT needs an update for sustained-effort contexts.  
565 An extension of the model would better account for the progressive recalibration of effort  
566 observed during prolonged engagement, moving beyond the traditional prediction of an abrupt  
567 “zero-effort” collapse once potential motivation is exceeded.

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**CRedit authorship contribution statement.**

**Ugo Place:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rémi**

**L. Capa:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

**Declaration of competing interest.**

None.

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## REFERENCES

- 573 Albinet, C. T., De Faria, C., & Causse, M. (2024). Cardiac Pre-Ejection Period to Index Motivation and Effort  
574 Mobilization in Cognitive Studies : A Critical Narrative Review. *Journal of Psychophysiology*, 38(2),  
575 81-101. <https://doi.org/10.1027/0269-8803/a000332>
- 576 André, N., Audiffren, M., & Baumeister, R. F. (2019). An Integrative Model of Effortful Control. *Frontiers in*  
577 *Systems Neuroscience*, 13, 79. <https://doi.org/10.3389/fnsys.2019.00079>
- 578 Barrouillet, P., & Camos, V. (2021). The time-based resource-sharing model of working memory. *Working*  
579 *memory: State of the science*, 85-115.
- 580 Baumeister, Bratslavsky, E., Muraven, M., & Tice, D. M. (1998). Ego depletion : Is the active self a limited  
581 resource? *Journal of Personality and Social Psychology*, 74(5), 1252-1265.  
582 <https://doi.org/10.1037/0022-3514.74.5.1252>
- 583 Berntson, G. G., Lozano, D. L., Chen, Y.-J., & Cacioppo, J. T. (2004). Where to Q in PEP. *Psychophysiology*,  
584 41(2), 333-337. <https://doi.org/10.1111/j.1469-8986.2004.00156.x>
- 585 Boksem, M. A. S., Meijman, T. F., & Lorist, M. M. (2006). Mental fatigue, motivation and action monitoring.  
586 *Biological Psychology*, 72(2), 123-132. <https://doi.org/10.1016/j.biopsycho.2005.08.007>
- 587 Boksem, M. A. S., & Tops, M. (2008). Mental fatigue : Costs and benefits. *Brain Research Reviews*, 59(1),  
588 125-139. <https://doi.org/10.1016/j.brainresrev.2008.07.001>
- 589 Botvinick, M., & Braver, T. (2015). Motivation and Cognitive Control : From Behavior to Neural Mechanism.  
590 *Annual Review of Psychology*, 66(1), 83-113. <https://doi.org/10.1146/annurev-psych-010814-015044>  
591
- 592 Brehm, J. W., & Self, E. A. (1989). The Intensity of Motivation. *Annual Review of Psychology*, 40(1),  
593 109-131. <https://doi.org/10.1146/annurev.ps.40.020189.000545>
- 594 Capa, R. L., Bustin, G. M., Cleeremans, A., & Hansenne, M. (2011). Conscious and Unconscious Reward  
595 Cues Can Affect a Critical Component of Executive Control : (Un)conscious Updating?  
596 *Experimental Psychology*, 58(5), 370-375. <https://doi.org/10.1027/1618-3169/a000104>
- 597 Causse, M., Peysakhovich, V., & Mandrick, K. (2017). Eliciting Sustained Mental Effort Using the Toulouse  
598 N-Back Task : Prefrontal Cortex and Pupillary Responses. In K. S. Hale & K. M. Stanney (Éds.),  
599 *Advances in Neuroergonomics and Cognitive Engineering* (Vol. 488, p. 185-193). Springer  
600 International Publishing. [https://doi.org/10.1007/978-3-319-41691-5\\_16](https://doi.org/10.1007/978-3-319-41691-5_16)
- 601 Chabchoub, S., Mansouri, S., & Salah, R. B. (2016). Impedance cardiography signal denoising using  
602 discrete wavelet transform. *Australasian Physical & Engineering Sciences in Medicine*, 39(3),  
603 655-663. <https://doi.org/10.1007/s13246-016-0460-z>
- 604 Chatelain, M., & Gendolla, G. H. E. (2016). Monetary incentive moderates the effect of implicit fear on  
605 effort-related cardiovascular response. *Biological Psychology*, 117, 150-158.  
606 <https://doi.org/10.1016/j.biopsycho.2016.03.014>
- 607 Daneshgar-Pironneau, S., Audiffren, M., Lorcery, A., Benraïss, A., Mirabelli, F., Gargioli, D., & André, N.  
608 (2025). Endurance Athletes Are More Resistant to Mental Fatigue Than Nonathletes. *Research*  
609 *Quarterly for Exercise and Sport*, 1-12. <https://doi.org/10.1080/02701367.2025.2501972>
- 610 Engle-Friedman, M., Mathew, G. M., Martinova, A., Armstrong, F., & Konstantinov, V. (2018). The role of  
611 sleep deprivation and fatigue in the perception of task difficulty and use of heuristics. *Sleep*  
612 *Science*, 11(02), 74-84. <https://doi.org/10.5935/1984-0063.20180016>
- 613 Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G\*Power 3 : A flexible statistical power analysis  
614 program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, 39(2),  
615 175-191. <https://doi.org/10.3758/BF03193146>

## COGNITIVE FATIGUE & SUCCESS IMPORTANCE

- 616 Freydefont, L., & Gendolla, G. H. E. (2012). Incentive moderates the impact of implicit anger vs. Sadness  
617 cues on effort-related cardiac response. *Biological Psychology*, 91(1), 120-127.  
618 <https://doi.org/10.1016/j.biopsycho.2012.04.002>
- 619 Gendolla, G. H. E., Wright, R. A., & Richter, M. (2019). Advancing Issues in Motivation Intensity Research :  
620 Updated Insights from the Cardiovascular System. In G. H. E. Gendolla, R. A. Wright, & M.  
621 Richter, *The Oxford Handbook of Human Motivation* (p. 372-392). Oxford University Press.  
622 <https://doi.org/10.1093/oxfordhb/9780190666453.013.21>
- 623 Goh, H.-T., Stewart, J. C., Becker, K., & Hung, C.-J. (2022). Perceived effort for reaching is associated with  
624 self-reported fatigue. *Journal of Motor Behavior*, 54(1), 14-26.  
625 <https://doi.org/10.1080/00222895.2021.1871877>
- 626 Herlambang, M. B., Taatgen, N. A., & Cnossen, F. (2019). The Role of Motivation as a Factor in Mental  
627 Fatigue. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 61(7),  
628 1171-1185. <https://doi.org/10.1177/0018720819828569>
- 629 Hockey. (2011). *A motivational control theory of cognitive fatigue*. [https://psycnet.apa.org/record/2010-](https://psycnet.apa.org/record/2010-06007-008)  
630 06007-008
- 631 Hopstaken, J. F., Van Der Linden, D., Bakker, A. B., Kompier, M. A. J., & Leung, Y. K. (2016). Shifts in  
632 attention during mental fatigue : Evidence from subjective, behavioral, physiological, and eye-  
633 tracking data. *Journal of Experimental Psychology: Human Perception and Performance*, 42(6),  
634 878-889. <https://doi.org/10.1037/xhp0000189>
- 635 Hopstaken, J. F., van der Linden, D., Bakker, A. B., & Kompier, M. A. J. (2015). A multifaceted investigation  
636 of the link between mental fatigue and task disengagement : Mental fatigue and task  
637 disengagement. *Psychophysiology*, 52(3), 305-315. <https://doi.org/10.1111/psyp.12339>
- 638 Inzlicht, M., Schmeichel, B. J., & Macrae, C. N. (2014). Why self-control seems (but may not be) limited.  
639 *Trends in Cognitive Sciences*, 18(3), 127-133. <https://doi.org/10.1016/j.tics.2013.12.009>
- 640 JASP Team. (2025). *JASP (Version 0.95.4)[Computer software]*. <https://jasp-stats.org/>
- 641 Kearney-Ramos, T. E., Fausett, J. S., Gess, J. L., Reno, A., Peraza, J., Kilts, C. D., & James, G. A. (2014).  
642 Merging Clinical Neuropsychology and Functional Neuroimaging to Evaluate the Construct  
643 Validity and Neural Network Engagement of the *n*-Back Task. *Journal of the International  
644 Neuropsychological Society*, 20(7), 736-750. <https://doi.org/10.1017/S135561771400054X>
- 645 Kelsey, R. M. (2012). Beta-adrenergic cardiovascular reactivity and adaptation to stress : The cardiac pre-  
646 ejection period as an index of effort. In R. A. Wright & G. H. E. Gendolla (Éds.), *How motivation  
647 affects cardiovascular response : Mechanisms and applications*. (p. 43-60). American  
648 Psychological Association. <https://doi.org/10.1037/13090-002>
- 649 Kok, A. (2022). Cognitive control, motivation and fatigue : A cognitive neuroscience perspective. *Brain and  
650 Cognition*, 160, 105880. <https://doi.org/10.1016/j.bandc.2022.105880>
- 651 Krohova, J., Czippelova, B., Turianikova, Z., Lazarova, Z., Tonhajzerova, I., & Javorka, M. (2017). Preejection  
652 Period as a Sympathetic Activity Index : A Role of Confounding Factors. *Physiological Research*,  
653 S265-S275. <https://doi.org/10.33549/physiolres.933682>
- 654 Kunasegaran, K., Ismail, A. M. H., Ramasamy, S., Gnanou, J. V., Caszo, B. A., & Chen, P. L. (2023).  
655 Understanding mental fatigue and its detection : A comparative analysis of assessments and  
656 tools. *PeerJ*, 11, e15744. <https://doi.org/10.7717/peerj.15744>
- 657 Kurzban, R. (2016). The sense of effort. *Current Opinion in Psychology*, 7, 67-70.  
658 <https://doi.org/10.1016/j.copsy.2015.08.003>
- 659 Kurzban, R., Duckworth, A., Kable, J. W., & Myers, J. (2013). An opportunity cost model of subjective effort  
660 and task performance. *Behavioral and Brain Sciences*, 36(6), 661-679.  
661 <https://doi.org/10.1017/S0140525X12003196>

## COGNITIVE FATIGUE & SUCCESS IMPORTANCE

- 662 Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). **lmerTest** Package : Tests in Linear Mixed  
663 Effects Models. *Journal of Statistical Software*, 82(13). <https://doi.org/10.18637/jss.v082.i13>
- 664 Lenth, R. V. (2016). Least-Squares Means : The R Package **lsmeans**. *Journal of Statistical Software*, 69(1).  
665 <https://doi.org/10.18637/jss.v069.i01>
- 666 Llabre, M. M., Spitzer, S. B., Saab, P. G., Ironson, G. H., & Schneiderman, N. (1991). The Reliability and  
667 Specificity of Delta Versus Residualized Change as Measures of Cardiovascular Reactivity to  
668 Behavioral Challenges. *Psychophysiology*, 28(6), 701-711. <https://doi.org/10.1111/j.1469-8986.1991.tb01017.x>  
669
- 670 Locke, E. A., & Latham, G. P. (1990). *A theory of goal setting & task performance* (p. xviii, 413). Prentice-  
671 Hall, Inc.
- 672 Lorcery, A., André, N., Benraïss, A., Pingault, M., Mirabelli, F., & Audiffren, M. (2024). Engagement of  
673 mental effort in response to mental fatigue : A psychophysiological analysis. *Psychology of Sport  
674 and Exercise*, 74, 102660. <https://doi.org/10.1016/j.psychsport.2024.102660>
- 675 Lozano, D. L., Norman, G., Knox, D., Wood, B. L., Miller, B. D., Emery, C. F., & Berntson, G. G. (2007).  
676 Where to B in dZ/dt. *Psychophysiology*, 44(1). <https://doi.org/10.1111/j.1469-8986.2006.00468.x>
- 677 Mallat, C., Cegarra, J., Calmettes, C., & Capa, R. L. (2020). A Curvilinear Effect of Mental Workload on  
678 Mental Effort and Behavioral Adaptability : An Approach With the Pre-Ejection Period. *Human  
679 Factors: The Journal of the Human Factors and Ergonomics Society*, 62(6), 928-939.  
680 <https://doi.org/10.1177/0018720819855919>
- 681 Newlin, D. B., & Levenson, R. W. (1979). Pre-ejection Period : Measuring Beta-adrenergic Influences Upon  
682 the Heart. *Psychophysiology*, 16(6), 546-552. <https://doi.org/10.1111/j.1469-8986.1979.tb01519.x>  
683
- 684 Obrist, P. A. (1981). *Cardiovascular Psychophysiology : A Perspective*. Springer Science & Business  
685 Media.
- 686 Owen, A. M., McMillan, K. M., Laird, A. R., & Bullmore, E. (2005). N-back working memory paradigm : A  
687 meta-analysis of normative functional neuroimaging studies. *Human Brain Mapping*, 25(1),  
688 46-59. <https://doi.org/10.1002/hbm.20131>
- 689 Pessiglione, M., Blain, B., Wiehler, A., & Naik, S. (2025). Origins and consequences of cognitive fatigue.  
690 *Trends in Cognitive Sciences*, 29(8), 730-749. <https://doi.org/10.1016/j.tics.2025.02.005>
- 691 Piferi, R. L., Kline, K. A., Younger, J., & Lawler, K. A. (2000). An alternative approach for achieving  
692 cardiovascular baseline : Viewing an aquatic video. *International Journal of Psychophysiology*,  
693 37(2), 207-217. [https://doi.org/10.1016/S0167-8760\(00\)00102-1](https://doi.org/10.1016/S0167-8760(00)00102-1)
- 694 Place, U., Paubel, P.-V., & Capa, R. L. (2025). Cardiovascular responses to mental fatigue in a sequential  
695 task paradigm. *International Journal of Psychophysiology*, 215, 113210.  
696 <https://doi.org/10.1016/j.ijpsycho.2025.113210>
- 697 Posit team. (2025). *RStudio : Integrated development environment for R* [Manual]. Posit Software, PBC.  
698 <http://www.posit.co/>
- 699 Richter, M. (2015). Goal pursuit and energy conservation : Energy investment increases with task demand  
700 but does not equal it. *Motivation and Emotion*, 39(1), 25-33. <https://doi.org/10.1007/s11031-014-9429-y>  
701
- 702 Richter, M. (2016). The Moderating Effect of Success Importance on the Relationship Between Listening  
703 Demand and Listening Effort. *Ear & Hearing*, 37(1), 111S-117S.  
704 <https://doi.org/10.1097/AUD.0000000000000295>
- 705 Richter, M., Friedrich, A., & Gendolla, G. H. E. (2008). Task difficulty effects on cardiac activity.  
706 *Psychophysiology*, 45(5), 869-875. <https://doi.org/10.1111/j.1469-8986.2008.00688.x>

## COGNITIVE FATIGUE & SUCCESS IMPORTANCE

- 707 Richter, M., & Gendolla, G. H. E. (2009). The heart contracts to reward : Monetary incentives and  
708 preejection period. *Psychophysiology*, 46(3), 451-457. <https://doi.org/10.1111/j.1469->  
709 8986.2009.00795.x
- 710 Richter, M., Gendolla, G. H. E., & Wright, R. A. (2016). Three Decades of Research on Motivational  
711 Intensity Theory. In *Advances in Motivation Science* (Vol. 3, p. 149-186). Elsevier.  
712 <https://doi.org/10.1016/bs.adms.2016.02.001>
- 713 Salihu, A. T., Hill, K. D., & Jaberzadeh, S. (2022). Neural mechanisms underlying state mental fatigue : A  
714 systematic review and activation likelihood estimation meta-analysis. *Reviews in the*  
715 *Neurosciences*, 33(8), 889-917. <https://doi.org/10.1515/revneuro-2022-0023>
- 716 Schampheleer, E., Habay, J., Proost, M., Arauz, Y. L. A., Russell, S., Roose, M., Bian, C., Meeusen, R., De  
717 Pauw, K., & Roelands, B. (2025). Current Practices for Mental Fatigue Quantification and  
718 Induction in Movement Science : Introducing the SPeCIFy Guidelines. *Sports Medicine*, 55(10),  
719 2387-2413. <https://doi.org/10.1007/s40279-025-02286-3>
- 720 Shenhav, A., Musslick, S., Lieder, F., Kool, W., Griffiths, T. L., Cohen, J. D., & Botvinick, M. M. (2017).  
721 Toward a Rational and Mechanistic Account of Mental Effort. *Annual Review of Neuroscience*,  
722 40(1), 99-124. <https://doi.org/10.1146/annurev-neuro-072116-031526>
- 723 Sherwood, A., Allen, M. T., Fahrenberg, J., Kelsey, R. M., Lovallo, W. R., & Doornen, L. J. P. (1990).  
724 Methodological Guidelines for Impedance Cardiography. *Psychophysiology*, 27(1), 1-23.  
725 <https://doi.org/10.1111/j.1469-8986.1990.tb02171.x>
- 726 Silvestrini, N., Musslick, S., Berry, A. S., & Vassena, E. (2022). An integrative effort : Bridging motivational  
727 intensity theory and recent neurocomputational and neuronal models of effort and control  
728 allocation. *Psychological Review*. <https://doi.org/10.1037/rev0000372>
- 729 Stanek, J. C., & Richter, M. (2021). Energy investment and motivation : The additive impact of task demand  
730 and reward value on exerted force in hand grip tasks. *Motivation and Emotion*, 45(2), 131-145.  
731 <https://doi.org/10.1007/s11031-020-09862-2>
- 732 Stewart, C. C., Wright, R. A., Azor Hui, S., & Simmons, A. (2009). Outcome expectancy as a moderator of  
733 mental fatigue influence on cardiovascular response. *Psychophysiology*, 46(6), 1141-1149.  
734 <https://doi.org/10.1111/j.1469-8986.2009.00862.x>
- 735 Tran, Y., Craig, A., Craig, R., Chai, R., & Nguyen, H. (2020). The influence of mental fatigue on brain  
736 activity : Evidence from a systematic review with meta-analyses. *Psychophysiology*, 57(5),  
737 e13554. <https://doi.org/10.1111/psyp.13554>
- 738 Van Cutsem, J., Marcora, S., De Pauw, K., Bailey, S., Meeusen, R., & Roelands, B. (2017). The Effects of  
739 Mental Fatigue on Physical Performance : A Systematic Review. *Sports Medicine*, 47(8),  
740 1569-1588. <https://doi.org/10.1007/s40279-016-0672-0>
- 741 Westbrook, A., & Braver, T. S. (2015). Cognitive effort : A neuroeconomic approach. *Cognitive, Affective, &*  
742 *Behavioral Neuroscience*, 15(2), 395-415. <https://doi.org/10.3758/s13415-015-0334-y>
- 743 Wickens, T. D. (2001). *Elementary Signal Detection Theory*. Oxford University Press.
- 744 Wickham, H. (2011). Ggplot2. *WIREs Computational Statistics*, 3(2), 180-185.  
745 <https://doi.org/10.1002/wics.147>
- 746 Wiehler, A., Branzoli, F., Adanyeguh, I., Mochel, F., & Pessiglione, M. (2022). A neuro-metabolic account of  
747 why daylong cognitive work alters the control of economic decisions. *Current Biology*, 32(16),  
748 3564-3575.e5. <https://doi.org/10.1016/j.cub.2022.07.010>
- 749 Wójcik, N., & Nęcka, E. (2024). Working hard but not tired? The influence of task valuation on mental  
750 fatigue, effort investment, and task performance. *Quarterly Journal of Experimental Psychology*,  
751 77(3), 656-674. <https://doi.org/10.1177/17470218231183708>

## COGNITIVE FATIGUE & SUCCESS IMPORTANCE

- 752 Wolff, W., Hack, L., Halperin, I., Holgado, D., Englert, C., Zech, A., Schüler, J., Bieleke, M., Shenhav, A., &  
753 Martarelli, C. (2025). *When effort fails : Instances and reasons for effort-performance decoupling*.  
754 PsyArXiv. [https://doi.org/10.31234/osf.io/3uces\\_v1](https://doi.org/10.31234/osf.io/3uces_v1)
- 755 Wolpe, N., Holton, R., & Fletcher, P. C. (2024). What Is Mental Effort : A Clinical Perspective. *Biological*  
756 *Psychiatry*, 95(11), 1030-1037. <https://doi.org/10.1016/j.biopsych.2024.01.022>
- 757 Wright, R. A. (1996). Brehm's theory of motivation as a model of effort and cardiovascular response. In  
758 *The psychology of action : Linking cognition and motivation to behavior* (p. 424-453). The Guilford  
759 Press.
- 760 Wright, R. A. (2008). Refining the Prediction of Effort : Brehm's Distinction between Potential Motivation  
761 and Motivation Intensity. *Social and Personality Psychology Compass*, 2(2), 682-701.  
762 <https://doi.org/10.1111/j.1751-9004.2008.00093.x>
- 763 Wright, R. A. (2014). Presidential address 2013 : Fatigue influence on effort—considering implications for  
764 self-regulatory restraint. *Motivation and Emotion*, 38(2), 183-195.  
765 <https://doi.org/10.1007/s11031-014-9406-5>
- 766 Wright, R. A., Junious, T. R., Neal, C., Avello, A., Graham, C., Herrmann, L., Junious, S., & Walton, N.  
767 (2007). Mental fatigue influence on effort-related cardiovascular response : Difficulty effects and  
768 extension across cognitive performance domains. *Motivation and Emotion*, 31(3), 219-231.  
769 <https://doi.org/10.1007/s11031-007-9066-9>
- 770 Wright, R. A., Martin, R. E., & Bland, J. L. (2003). Energy resource depletion, task difficulty, and  
771 cardiovascular response to a mental arithmetic challenge. *Psychophysiology*, 40(1), 98-105.  
772 <https://doi.org/10.1111/1469-8986.00010>
- 773 Wright, R. A., & Mlynski, C. (2019). Fatigue determination of inhibitory strength and control : A babe in a  
774 bath. *Motivation Science*, 5(1), 66-78. <https://doi.org/10.1037/mot0000114>
- 775 Wright, R. A., Patrick, B. M., Thomas, C., & Barreto, P. (2013). When fatigue promotes striving :  
776 Confirmation that success importance moderates resource depletion influence on effort-related  
777 cardiovascular response. *Biological Psychology*, 93(2), 316-324.  
778 <https://doi.org/10.1016/j.biopsycho.2013.02.016>
- 779 Wright, R. A., Shim, J. J., Hogan, B. K., Duncan, J., & Thomas, C. (2012). Interactional influence of fatigue  
780 and task difficulty on cardiovascular response : Demonstrations involving an aerobic exercise  
781 challenge. *Psychophysiology*, 49(8), 1049-1058. <https://doi.org/10.1111/j.1469-8986.2012.01390.x>
- 783 Wright, R. A., & Stewart, C. C. (2012). Multifaceted effects of fatigue on effort and associated  
784 cardiovascular responses. In R. A. Wright & G. H. E. Gendolla (Éds.), *How motivation affects*  
785 *cardiovascular response : Mechanisms and applications*. (p. 199-218). American Psychological  
786 Association. <https://doi.org/10.1037/13090-010>
- 787 Wylie, G. R., Yao, B., Sandry, J., & DeLuca, J. (2021). Using Signal Detection Theory to Better Understand  
788 Cognitive Fatigue. *Frontiers in Psychology*, 11, 579188.  
789 <https://doi.org/10.3389/fpsyg.2020.579188>