Submitted to BioRxiv

Type of article: original research

Draft version #1 (2026/03/19), submitted for peer review.

Mental fatigue impairs cycling endurance performance and perception of effort, but not muscle activation

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Running head: mental fatigue and cycling endurance performance

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CRediT statement.

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Conflict of interest statement.

All authors have declared that no competing interests exist.

Use of AI Generated Tools.

The authors used ChatGPT (version 5.2, OpenAI) to assist with English language editing and grammar improvement during manuscript preparation. After using this tool, the authors reviewed and edited the content as needed and takes full responsibility for the content of the published article. All scientific content, data interpretation, and conclusions were generated solely by the authors.

Funding statement

Benjamin Pageaux is supported by the Chercheur Boursier Junior 1 award from the Fonds de Recherche du Québec—Santé

Abstract.

Mental fatigue is induced by prolonged engagement in cognitively demanding tasks and impairs endurance performance. The neuropsychophysiological mechanisms underlying this decreased performance remain unclear, with suggestion that mental fatigue may disrupt motor command and consequently muscle activation. We aimed to test this hypothesis in a repeated cross-over design study in which 18 participants completed two experimental sessions involving a time-to-exhaustion cycling test at 80% of peak power output. Each cycling task was preceded by 1h of a prolonged Stroop task (Stroop session) or a neutral control task (Control session). Perception of effort and surface electromyography from ten lower-limb muscles of the right leg were recorded at regular intervals during cycling. Mental fatigue was higher in the Stroop compared to the Control session (p = .002). Endurance cycling time was 111 ± 160 s shorter in the Stroop than in the Control session (p = .009). No significant differences in electromyography parameters were observed between Stroop and Control sessions, for any muscle (p > .05). Perception of effort was higher in the Stroop session from the onset of the cycling task (p = .006), and the rate of increase in perception of effort was significantly higher in the Stroop than Control session (p = .031). Our findings do not support the hypothesis that mental fatigue alters motor control or increases central motor command, as no changes in muscle activation were detected. Conversely, our results reinforce the notion that prolonged cognitive engagement impairs endurance performance primarily through an increased perception of effort. Future research should consider combining surface electromyography with more sensitive neurophysiological techniques to investigate potential subtle changes in motor drive during dynamic, whole-body tasks under mental fatigue.

Keywords.

Cognitive exertion; physical performance; motor command; electromyography; perceived exertion

Impact statement.

Our study confirms that mental fatigue induced by prolonged cognitive exertion impairs cycling endurance performance. By combining measurements of perceptual responses and multi-muscle surface EMG during the endurance task, we observed that the decreased endurance performance is related to an increased perceived effort in the presence of mental fatigue, not related to alterations in motor command.

Introduction.

Mental fatigue is a psychobiological state induced by prolonged engagement in demanding cognitive tasks (Boksem and Tops 2008; Marcora et al. 2009). Subjectively, mental fatigue is characterized by an increase in tiredness and lack of energy (Boksem and Tops 2008), and an aversion to continuing or initiating tasks (Müller and Apps 2019). Objectively, mental fatigue alters cognitive functioning, leading to decreased cognitive performance or the maintenance of performance at the cost of increased effort (Mangin and Pageaux 2025). Beyond the negative effect of mental fatigue on cognitive performance, numerous studies have also reported its detrimental effects on physical performance (Van Cutsem et al. 2017; Brown et al. 2020; Pageaux and Lepers 2018; Giboin and Wolff 2019). Mental fatigue has been shown to reduce endurance performance in isometric tasks performed to exhaustion (Bray et al. 2008; Pageaux et al. 2013; Alix-Fages et al. 2023). The impairment in endurance performance has also been observed during cycling and running endurance tests (Marcora et al. 2009; MacMahon et al. 2014; Smith et al. 2016; Martin et al. 2016). This reduction in endurance performance has been proposed to be associated with a higher-than-normal perception of effort (Marcora et al. 2009; Pageaux and Lepers 2018).

The perception of effort during a physical task, defined as the conscious awareness of how hard, heavy, and strenuous the task feels (Marcora 2010), is a key regulator of endurance performance (Pageaux 2014; Marcora et al. 2008; Marcora and Staiano 2010). At the behavioral level, building on the intensity of motivation theory (Brehm and Self 1989; Richter et al. 2016), the perception of effort can be linked to the regulation of endurance performance through the psychobiological model of endurance performance (Marcora 2019; Marcora et al. 2008; Pageaux 2014). According to this framework, task disengagement, also referred to as exhaustion or task failure, occurs when an individual exerts the maximal effort they are willing to invest in the task. This upper limit is determined by the individual's motivation to succeed (Marcora 2019; Marcora et al. 2008; Pageaux 2014). Previous studies have

118 demonstrated that, for the same mechanical output, the perception of effort increases following
119 prolonged engagement (≥ 30 min) in cognitive tasks (Marcora et al. 2009; Pageaux et al. 2013). This
120 heightened perception of effort leads individuals to reach the maximum effort they are willing to exert
121 earlier, resulting in task disengagement and impaired endurance performance.

122 Understanding the neurophysiological alterations that lead to an increased perception of effort in
123 the presence of fatigue could help unravel the origins of the detrimental effects of mental fatigue on
124 endurance performance. The perception of effort is generated by the brain's processing of sensory
125 signals. Although the nature of these signals remains debated, converging evidence suggests that effort
126 perception originates from signals related to the motor command (for reviews, see Marcora (2009);
127 Bergevin et al. (2023); Mangin and Pageaux (2026)). During voluntary muscle contractions, motor
128 commands are sent to the working muscles, and an efference copy of these motor commands, referred
129 to as the corollary discharge, is transmitted to cortical areas involved in sensory processing (Christensen
130 et al. 2007; McCloskey). The corollary discharge model proposes that perceived effort is generated
131 through the brain's processing of this signal (De Morree et al. 2012; Bergevin et al. 2023). Within this
132 framework, an alteration in perceived effort during physical tasks may result from changes in motor
133 commands and their corollary discharges, from altered brain processing of these signals, or from both.

134 In line with this model, the increase in perceived effort under mental fatigue may be linked to
135 specific modulations of frontal cortex activity, potentially driven by metabolic alterations (Barakat et al.
136 2025; Pessiglione et al. 2025). Among frontal brain areas, the anterior cingulate cortex is likely a key
137 structure in the negative effects of mental fatigue on the perception of effort, and consequently, on
138 endurance performance. The anterior cingulate cortex plays a crucial role in cognitive control and effort-
139 based decision-making (Shenhav et al. 2016), and its activity increases during demanding cognitive tasks
140 (Carter et al. 1998; Pardo et al. 1990). Specific cingulate regions project extensively to premotor and
141 motor cortices, as well as to the spinal cord, all key structures involved in motor command and control

142 (Medford and Critchley 2010; Paus 2001; Gillies et al. 2019). These connections suggest that cognitively
143 demanding tasks inducing mental fatigue could disrupt motor command by altering prefrontal circuitry
144 involved in the regulation of the motor command during task execution. Such interactions may influence
145 muscle activation and could explain reports of increased muscle activity under mental fatigue during
146 isometric exercise (Bray et al. 2008; Jacquet et al. 2021). However, a recent study observed that mental
147 fatigue induced by a prolonged Stroop task, while decreasing dorsiflexion isometric endurance
148 performance, did not affect motor command and muscle fibers recruitment assessed with high density-
149 electromyography (EMG) (Alix-Fages et al. 2023). The discrepancies between these studies highlight the
150 need to further investigate how mental fatigue influences muscle activation, particularly during dynamic
151 exercise modalities, such as cycling, which better reflect real-world exercise condition. Indeed, isometric
152 contractions may not fully capture the complexity of motor control during ecological movement. In this
153 context, increased vastus lateralis activity has been observed during a submaximal cycling task under
154 mental fatigue (Pageaux et al. 2015). However, because cycling requires the coordinated activation of
155 multiple muscles (So et al. 2005), the results of Pageaux et al. (2015), which focused on a single muscle,
156 do not provide a comprehensive understanding of the effects of mental fatigue on muscle activation and
157 should therefore be replicated using a more comprehensive assessment of lower-limb muscle activation.

158 The present study aimed to investigate whether the presence of mental fatigue is associated with
159 alterations in muscle activation during dynamic exercise. In secondary analysis, we aimed to replicate the
160 negative effect of mental fatigue on endurance performance. We selected cycling as the endurance
161 exercise because it allows for a more precise and comprehensive analysis of lower-limb muscle EMG
162 activity compared to running, as previously performed in our laboratory (Hug et al. 2019). We
163 hypothesized that mental fatigue would increase perception of effort and alter lower limb muscle
164 activation, thereby reducing endurance performance.

165

Methods.

Participants

Twenty participants (8 female; age: 22 ± 5 years; height: 175 ± 12 cm; weight: 68 ± 14 kg) participated in this repeated cross-over design study. Participants reported engaging in 2-6 h of moderate physical activity per week, but did not report extensive cycling training history and were not currently active cyclists. Participants were instructed to refrain from engaging in any strenuous lower-limb physical activity during the 24 h preceding each laboratory visit. Participants were provided with written instructions detailing all study procedures but were unaware of its objectives and hypotheses. They were not informed that the cognitive task was used to induce mental fatigue and modify the subsequent endurance performance. Written informed consent was obtained from each participant. This study adhered to the standards outlined in the latest revision of the Declaration of Helsinki (with the exception of registration in a database) and was approved by the Nantes University ethics committee (n° IRB: IORG0011023).

Two participants were excluded after reporting engagement in strenuous physical activity a few hours prior to the experimental testing. As a result, 18 participants were included in the statistical analysis. This sample size was constrained by the time resources available for the MSc students recruited as experimenters on this study, and we recruited as much participants as possible in this given time (Lakens 2022). A sensitivity analysis revealed that with our sample size (n = 18), the minimal detectable effect size (Cohen's d) for a paired t-test is 0.70 with 80% power and $\alpha = 0.05$. Regarding our Statistical Parametric Mapping (SPM) analysis, as it includes a correction for temporal smoothness and multiple comparisons across the time series, the actual minimal detectable effect size is likely higher. Thus, only medium-to-large effects could be reliably detected in our study.

189 **Study design and overview of the laboratory visits**

190 This study was a within-subject design, with participants visiting the laboratory on three separate
191 occasions. The first visit was a familiarization session, and the second and third visits were the control
192 and experimental sessions (randomized, counterbalanced order). All visits were spaced at least 72 h
193 apart. The control and experimental sessions were identical, except for the cognitive task performed:
194 watching a documentary (Control session) or performing a Stroop task (Stroop session). Each session
195 began with questionnaires about mental fatigue and motivation. EMG electrodes were then placed on
196 ten muscles of the right leg and signal quality was verified (see the *"Electromyography"* section).
197 Participants then engaged either in 1 h of the Stroop task or 1 h of viewing an emotionally neutral
198 documentary. Mental fatigue, motivation and boredom were measured during and post Stroop and
199 documentary. Then, participants promptly transferred to the cycle ergometer and performed a cycling
200 time to exhaustion test at 80% of their peak power output (PPO) until exhaustion.

201

202 **Visit 1: Familiarization and incremental test**

203 Participants began by determining their preferred pedaling cadence on a cycle ergometer set up in
204 hyperbolic mode (Excalibur Sport, Lode, Groningen, Netherlands). Participants cycled for 1 min at 100 W,
205 followed by 1 min at 175 W, and 1 min at 250 W. Participants were instructed to cycle at a freely chosen
206 cadence between 60–90 rpm, and this preferred cadence was recorded for each stage. If a participant
207 did not report at least a moderate effort when cycling at 250W, additional 1-min bouts with increments
208 of 50 W were performed until the participant had to produce a moderate effort. The preferred cadence
209 recorded at the power output closest to 80% of the participant's PPO was used during the time to
210 exhaustion test performed in the Control and Stroop sessions (72 ± 6 rpm).

211 After a 5-min rest, participants performed an incremental test at their predetermined preferred
212 cadence, starting at 100 W with increments of 25 W every minute until exhaustion. Exhaustion was
213 defined as either voluntary disengagement from the test or the inability to maintain the target cadence
214 within ± 3 rpm for more than 3 s. The last fully completed stage was used to determine the participant's
215 PPO. This PPO (mean of 250 ± 65 W), was used to determine the workload for the time to exhaustion
216 tests performed in the Control and Stroop sessions. Participants were then familiarized with the Stroop
217 task. If the participants did not clearly demonstrate an understanding of the instructions, they had to
218 complete additional blocks until they fully grasped the task. Then, participants were provided with
219 detailed instructions on how to dissociate effort and muscle pain perceptions, and how to report the
220 intensity of each perception with the CR100 scale (Borg and Kaijser 2006; Pageaux et al. 2020). Finally,
221 participants performed the cycling time to exhaustion test at 80% PPO for familiarization.

222

223 **Visit 2 and 3: Stroop and Control sessions.**

224 Participants began each session by engaging, in a randomized and counterbalanced order, for 60-
225 min in an experimental (Stroop task) or control (watched a documentary) session. In the control and
226 Stroop sessions, mental fatigue and motivation to perform the cycling task were assessed before, at 30-
227 min (mid), and immediately post cognitive tasks. Boredom was also measured mid and post cognitive
228 tasks. Upon completing the questionnaires, participants transferred to the cycle ergometer to begin the
229 cycling time to exhaustion test. Mental fatigue and motivation to perform the cycling time to exhaustion
230 test was also measured before and after the test. An overview of the Control and Stroop sessions is
231 presented in Figure 1.

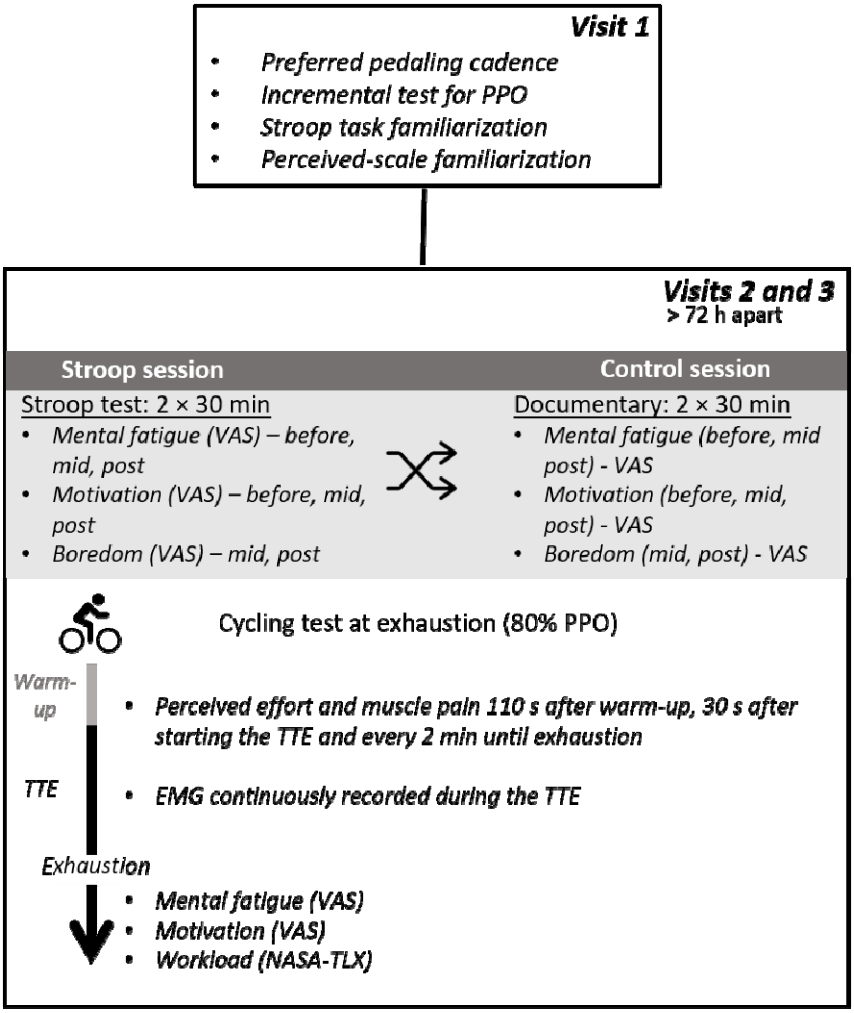


Figure 1. Overview of the experimental and control sessions. Participants visited the laboratory on three distinct occasions. The first visit was dedicated to peak power output (PPO) measurement and familiarization procedures. The second and third visits were the experimental sessions. After completing either a one-hour Stroop task (Stroop session; two 30-min blocks) or watching a documentary (control session), participants performed a 3-min warm-up at 40% PPO, followed by a time-to-exhaustion test at 80% PPO. Participants reported their perceived effort and muscle pain at regular intervals during the cycling test**.** Electromyographic (EMG) activity was continuously recorded and analyzed over the 20 pedaling cycles preceding each effort and pain perception measurement. We used visual analogue scales to measure mental changes in mental fatigue, motivation and boredom during the sessions. Participants completed the NASA-TLX at the very end of the procedure.

Stroop task. Participants performed a modified version of the incongruent Stroop task (Mangin et al. 2021). The task was performed while seated in an isolated room, using the SuperLab® software (Cedrus, USA), displayed on a 16-inch monitor placed on a desk directly in front of the participant. In visit

247 1, participants familiarized with the Strop task by completing two blocks of 24 words. In the
248 experimental session, participants completed the incongruent Stroop task for 1 h, with two bouts of 30-
249 min separated by a 1-min period for mental fatigue, motivation and boredom measurement. Each trial
250 began with the presentation of a fixation cross point enclosed in either a square or a circle for 50 ms at
251 the center of the screen that was positioned in front of the participant. The fixation cross alone
252 remained in the middle of the screen for 400 ms. Immediately after this preparatory signal, a word, the
253 response signal, appeared at the center of the screen and remained visible until the participant
254 responded orally. In cases of omission, the response signal was displayed for 1250 ms before being
255 replaced by a fixation cross for 300 ms. If a participant responded before the end of the 1250 ms, a
256 fixation cross appeared at the center of the screen and remained visible for the remainder of the 1250
257 ms, plus an additional 300 ms. As a result, each trial lasted exactly 2 seconds. The response signals
258 consisted of color names (i.e., red, blue, yellow, or green) written in an incongruent ink color (e.g., red
259 written in blue). In this task, the meaning of the word was always incongruent with the ink color used to
260 display it. When the fixation cross was enclosed in a square, participants were instructed to read the
261 word, whereas when it was enclosed in a circle, they were required to name the color of the ink. In 50%
262 of the trials, participants were required to read the word, while in the remaining 50%, they had to name
263 the ink color. This 50/50 distribution was chosen to minimize learning effects during the incongruent
264 Stroop task (Dulaney and Rogers 1994), and to increase task difficulty by engaging cognitive flexibility in
265 addition to inhibitory control. The order of trial presentation was randomized.

266 *Documentary watching.* Each participant watched the French version of the documentary *Home* by
267 Y.A. Bertrand. This documentary has been used as an appropriate control condition in the context of
268 mental fatigue studies (Jacquet et al. 2021). The duration of this control task was matched to that of the
269 Stroop task. Participants sat in an isolated room, where the documentary was projected onto a screen
270 positioned 1 m in front of them.

271 *Cycling time to exhaustion test*. After completion of the cognitive tasks and following a 3-min
272 warm-up at 40% PPO, participants completed a time to exhaustion test at 80% PPO at their preferred
273 cadence determined in visit 1. Participants had to remain seated on the saddle. To prevent changes in
274 hip angle caused by lowering the hands on the handlebars, participants were instructed to keep their
275 hands in the same position throughout the test (i.e., on top of the handlebars). Both instructions were
276 visually controlled by the experimenters. Participants reported the intensity of perceived effort and
277 muscle pain every 2 min during the task. No encouragement was provided at any point during the time-
278 to-exhaustion test.

279 Endurance performance was quantified as time to exhaustion, defined as the time at which
280 participants voluntarily disengaged from the task or were unable to maintain their preferred cadence (±
281 3 rpm) for more than 3 s despite receiving a standardized, neutral, verbal reminder to return to the
282 target cadence. No motivational encouragement was provided during the test. To compare EMG and
283 perceptual responses during the Stroop and Control sessions, we used individual isotime analysis (Nicolò
284 et al. 2019). For each participant, their shortest time to exhaustion across the Stroop and Control
285 sessions was defined as 100% isotime. Two other time points, corresponding to 0% and 50% of this 100%
286 isotime, were then calculated for each participant and session. The 0% isotime time point was always the
287 first measurement available during the time to exhaustion test.

288

289 **EMG**

290 *EMG recording and electrode placement.* Surface EMG was continuously recorded at 2000 Hz
291 during the cycling exercise using a wireless EMG system (Wave Plus wireless system, Cometa, Bareggio
292 MI, Italy) and dedicated software (WavePlus 1.4.0, Cometa, Bareggio MI, Italy). Data were collected for
293 ten muscles of the right lower limb: gluteus maximus (GMax), semitendinous (ST), biceps femoris (BF),

294 vastus medialis (VM), vastus lateralis (VL), rectus femoris (RF), gastrocnemius medialis (GM),
295 gastrocnemius lateralis (GL), soleus (SOL) and tibialis anterior (TA). A pair of self-adhesive Ag/AgCl
296 electrodes (Covidien, Mansfield, MA, USA) was placed on each muscle with a 20-mm center-to-center
297 inter-electrode distance. Electrode placements followed SENIAM recommendations, with the skin
298 shaved and cleaned with alcohol to minimize impedance. To prevent movement-induced artifacts, the
299 wireless EMG units were secured with adhesive tape. The electrode positions established during visit 2
300 was marked to ensure consistent placement in visit 3.

301

302 *Data analysis.* Custom-written Matlab (Mathworks, Natick, USA) routines were used to process
303 EMG data, using the open-source Biomechanical Toolkit library (Barre and Armand 2014). Raw EMG
304 signals were band-pass filtered between 10 Hz-450 Hz (Butterworth zero-lag 4th order), full-wave
305 rectified, and low-pass filtered at 10 Hz (Butterworth zero-lag 2nd order). All EMG data were time-
306 normalized to a cycling cycle over 360 points.

307 During the cycling time-to-exhaustion test, EMG data were extracted at four time points: 0%, 50%,
308 and 100% isotime, as well as at exhaustion. For each muscle, session, and time point, up to 20
309 consecutive pedaling cycles were initially extracted. Following visual inspection, cycles affected by
310 transient artifacts (e.g., movement-induced spikes or signal disturbances related to cable interference)
311 were excluded (see EMG data curation). To ensure a fully balanced within-subject design across
312 participants, sessions, muscles, and time points, the minimum common number of artifact-free cycles
313 available across all conditions was determined (16 cycles). Accordingly, exactly 16 complete pedaling
314 cycles were retained for each participant, muscle, session, and time point for subsequent analyses.

315 For EMG amplitude normalization, signals were normalized to the maximal value of the mean EMG
316 profile obtained at 0% isotime for each muscle and each session. Specifically, for each participant,

317 muscle, and session, the 16 retained pedaling cycles at 0% isotime were averaged to compute a
318 representative mean EMG waveform. The peak amplitude of this mean waveform was then used as the
319 normalization reference for all corresponding time points within the same session. This procedure
320 ensured within-session normalization while preserving valid between-session comparisons and avoiding
321 potential confounding influences associated with maximal voluntary contractions or separate
322 normalization tasks. After amplitude normalization, the full time-normalized EMG waveform of each
323 retained cycle was preserved without temporal averaging across cycles in order to maintain intra-
324 individual and inter-cycle variability. Mean and standard deviation waveforms were computed for
325 descriptive visualization purposes only. The normalized EMG profiles were subsequently analyzed using
326 Statistical Parametric Mapping to compare activation patterns between conditions across the pedaling
327 cycle (see *Statistical Analysis*).

328 To determine whether mental fatigue influenced the consistency of neuromuscular activation, we
329 performed a variability analysis of the EMG signal. For each muscle, time point (isotime levels and
330 exhaustion), and condition (Stroop vs. Control), the point-by-point standard deviation of the EMG signal
331 across the 16 retained cycles was calculated over the pedaling cycle. These standard deviation
332 waveforms were used as indices of inter-cycle variability. Differences in variability between sessions
333 were assessed using paired SPM1D t-tests, conducted separately for each muscle and time point. This
334 approach allowed us to examine whether mental fatigue altered the stability and temporal consistency
335 of muscle activation across repeated pedal strokes.

336

337 *EMG data curation.* EMG data were curated prior to statistical analysis to ensure signal quality and
338 balanced statistical comparisons. Electrodes presenting persistent signal loss or severe artifacts in one of
339 the two sessions (e.g., low signal-to-noise ratio, movement-induced interference, or signal dropout
340 during prolonged acquisition) were excluded from analysis in both sessions to maintain within-subject

comparability. Across the 340 total muscle recordings (10 muscles × 18 participants × 2 sessions), 21 recordings (6%) were excluded due to poor signal quality. After electrode exclusion, the number of participants retained per muscle for complete 2 sessions was: SOL (n = 17), RF (n = 14), VL (n = 15), BF (n = 13), GL (n = 17), TA (n = 17), VM (n = 17), ST (n = 16), GMax (n = 14), and GM (n = 14). A total of 2720 pedaling cycles were collected across all participants and sessions. Following visual inspection, 83 cycles (3%) were removed due to transient artifacts. After this selection, the minimum common number of valid cycles across all participants, sessions, muscles, and time points was 16 cycles, which were retained for statistical analysis to ensure a fully balanced repeated-measures design.

Psychological variables

Visual analog scales (VAS) were used to assess participants' mental fatigue, motivation, and boredom. The VAS was printed as 100-mm horizontal lines, and participants responded to each scale-specific question by placing a vertical mark on the line. For each VAS, the left and right anchors and specific question, as well as the timing of each measurement, are described below.

Mental fatigue. In the control and Stroop sessions, participants reported their level of mental fatigue before the cognitive tasks, after completing half of the cognitive task (30 min), immediately after the cognitive task, and after the cycling time-to-exhaustion test. The VAS was anchored with "not fatigued at all" and "extremely fatigued" on the left and right ends of the scale. The following question was positioned above the VAS: *"What is your current level of mental fatigue, which is your feeling of exhaustion and lack of energy?"* (Jacquet et al. 2021).

Motivation. Because fatigue could influence motivation (Müller and Apps 2019) and that the effort allocated in a task is related to the motivation to perform the task (Richter et al. 2016), we measured changes in motivation. Participants reported their level of motivation related (i) to the cognitive tasks

364 before the tasks, midway through the cognitive tasks (30 min) and immediately after the cognitive tasks;
365 and (ii) the cycling task before and immediately after the task. The VAS was anchored with "not
366 motivated at all" and "extremely motivated" on the left and right ends of the scale. The following
367 question was positioned above the VAS before the cognitive and cycling tasks, halfway through the
368 cognitive tasks, and after the cognitive and cycling tasks, respectively: *"What is your motivation to*
369 *perform the task at hand?"*, *"What is your motivation to continue the task you have just completed?"*,
370 *"What is your motivation to repeat the task you have just completed?"*

371 *Boredom*. Because boredom has been identified as a confounding factor in the development of
372 mental fatigue (Mangin and Pageaux 2025), we measured changes in boredom during the cognitive
373 tasks. Participants reported their level of boredom midway through the cognitive tasks and immediately
374 after the cognitive tasks. The VAS was anchored with "not bored at all" and "extremely bored" on the
375 left and right ends of the scale. The following question was positioned above the VAS: *"Were you bored*
376 *during the task you just completed?"*

377

378 During the cycling warm-up and time to exhaustion tests, participants reported the intensity of
379 their perceived effort and muscle pain using the CR100 scale (Borg and Kaijser 2006) at specific and
380 consistent time points: 110 s after the start of the warm-up at 40% PPO, 30 s after starting the time to
381 exhaustion test at 80% PPO, and every 2 min afterwards and at exhaustion. Details for each perception
382 are presented below.

383 *Perceptions of effort.* Participants rated the intensity of their perceived effort to cycle. They were
384 asked to refer to their sensations of how hard and intense it felt to move their legs and breathe.
385 Participants were explicitly instructed to consider only their perception of effort and not any other
386 exercise-related perceptions such as muscle pain or fatigue (Bergevin et al. 2023; Pageaux 2016). The

387 CR100 scale ranges from 0 (no effort at all) to 100 (maximal effort), with maximal effort anchored to the
388 most intense exertion the participant had ever experienced during a physical task. Modifications were
389 made to the scale's 0 and 100 anchors to explicitly incorporate the term "effort" (Jacquet et al. 2021).
390 The scale includes verbal anchors corresponding to different intensity levels, such as weak/light (score of
391 13), moderate (23), strong/heavy (50), and very strong (70). Participants could report values above 100 if
392 they perceived an effort exceeded their maximal effort previously experienced (i.e., rating 100). To
393 enhance understanding, each participant was provided with verbal examples of "no effort at all" (e.g.,
394 sitting and relaxing without cognitive engagement) and "maximal effort" (e.g., the most intense effort
395 they had ever experienced during a high intensity whole-body physical task).

396 *Perceptions of muscle pain.* Muscle pain was assessed during the cycling task, as it is known to
397 influence endurance performance and to develop during endurance exercise (O'Connor and Cook 1999).
398 Participants used a separate modified CR100 scale to assess muscle pain, with the word "pain" explicitly
399 incorporated into the anchor descriptions: 0 (no pain at all) and 100 (maximal pain). Similar to the
400 perceived effort scale, memory anchoring was used to define the 100-point reference. Participants were
401 instructed to rate "the intensity of pain they felt during the exercise", focusing specifically on localized
402 sensations in the leg muscles. These sensations were described as potentially including feelings of
403 burning, intense, or sharp pain (O'Connor and Cook 1999). It was emphasized that participants should
404 not confuse or equate their ratings of effort with their perception of pain (Bergevin et al. 2023; Pageaux
405 2016). To ensure proper use of the scale, each participant was provided with verbal examples illustrating
406 "no muscle pain" and "maximal muscle pain" as reference points.

407 *Subjective workload.* Participants reported their perceived workload at the end of each
408 experimental session using the NASA-TLX scale (Hart and Staveland 1988), that consists of six items, i.e.,
409 (i) mental demand, (ii) physical demand, (iii) temporal demand, (iv) performance, (v) effort, and (vi)
410 frustration. Participants rated each item on a scale divided into twenty equal intervals anchored by a

411 bipolar descriptor (i.e., high/low). This score was multiplied by five, resulting in a final score between 0
412 and 100 for each item.

413

414 **Statistics.**

415 Except for EMG data analyzed with Matlab, statistical analysis was conducted with Jamovi 1.2.27.

416 *Time to exhaustion.* Paired *t*-tests were conducted to assess differences in endurance performance
417 between sessions (Stroop vs. Control).

418 *EMG.* To assess differences in muscle activation patterns between Stroop and Control sessions, we
419 performed time-series analyses using Statistical Parametric Mapping (SPM1D v0.4 Matlab library)
420 (Pataky et al. 2013). EMG signals were analyzed across the normalized pedaling cycle (0–100%), with
421 separate analyses conducted for each muscle. For the isotime series (0%, 50%, and 100%) during the
422 time to exhaustion test, a two-way repeated-measures ANOVA was used, with session (Stroop vs.
423 Control) and isotime point (three isotime levels) as within-subject factors. This analysis allowed us to
424 evaluate the evolution of muscle activation across the task duration and whether this evolution differed
425 between Stroop and Control sessions under increasing fatigue. In addition, paired t-tests were
426 conducted using SPM1D to specifically compare both sessions at task failure. Isolating these comparisons
427 enabled targeted hypothesis testing without unnecessarily complicating the factorial design. Each
428 analysis was based on 16 complete pedaling cycles per subject, per session, and per time point, with no
429 temporal averaging, to preserve within-subject variability and cycle-to-cycle dynamics. Muscles were
430 analyzed individually, rather than as a factor in the statistical models, based on physiological and
431 methodological rationale. Each muscle has a distinct activation profile and biomechanical function during
432 cycling, and comparing signals with fundamentally different temporal shapes would violate the
433 assumptions of time-series based SPM analysis. Treating each muscle independently ensured both

434 physiologically meaningful and statistically appropriate comparisons. Statistical significance was set at α
435 = 0.05 for all SPM analyses.

436 *Perceptual responses.* To assess the effect of session on perceptions of effort and muscle pain,
437 paired *t*-tests were conducted on perceptual responses recorded during the warm-up and at exhaustion.
438 A two-way repeated measures ANOVA [session (Stroop vs. Control) × time (0%, 50% and 100% isotime)
439 was conducted for perceptual responses during the time to exhaustion test.

440 *Mental fatigue, motivation and boredom.* Repeated measured ANOVA were used to assess
441 changes over time in these variables in each session (Stroop vs. Control). For mental fatigue, the factor
442 time included four levels: pre cognitive task, midway through the cognitive task, post cognitive task and
443 post cycling. For motivation to perform the cognitive tasks, the factor time included three levels: pre
444 cognitive task, midway through the cognitive task, post cognitive task. For motivation to perform the
445 cycling tests, the factor time included two levels: pre cycling and post cycling. For boredom, the factor
446 time included two levels: midway through the cognitive task and post cognitive task.

447 The normality of the data was verified using the Shapiro-Wilk test and visual inspection of the QQ
448 plots. For pairwise comparisons, when the data deviated from a normal distribution, we employed the
449 Wilcoxon signed-rank test. In these instances, we present the results of both the Student *t*-test and the
450 Wilcoxon rank test. Post-hoc comparisons of the repeated measures ANOVA were corrected for multiple
451 comparisons with the Holm-Bonferroni method. The alpha level for statistical significance was set at $\alpha \leq$
452 0.05. Effects size are reported as partial eta squared (η_p^2), and thresholds for small, moderate, and large
453 effects were set at 0.01, 0.07, and 0.14, respectively (Cohen 1988). Cohen's *d* were calculated when *t*-
454 tests were performed and thresholds for small, moderate and large effects were set at 0.2, 0.5, and 0.8
455 respectively (Cohen 1988). When a Wilcoxon rank test was performed, the rank biseral correlation (r_{rb}) is
456 reported. Greenhouse-Geisser correction to the degrees of freedom was applied when violations of
457 sphericity were present. All data are presented as means ± standard deviation, unless stated.

Results.

Manipulation checks for mental fatigue induction

Mental fatigue. Mental fatigue increased overtime ($F(2, 34) = 29.19$, $p < .001$, $n_p^2 = .632$) and was higher in the Stroop than in the Control session (main effect of session: $F(1, 17) = 8.36$, $p = .010$, $n_p^2 = .330$). The session × time interaction reached significance ($F(3, 51) = 4.02$, $p = .012$, $n_p^2 = .191$), and the details of the posthoc comparisons are presented in Figure 2A. Participants reported similar levels of mental fatigue pre cognitive task in the Stroop and Control sessions ($t(17) = -0.879$, $p = .783$, $d = .207$, *95%CI* [-.671, .263]), but higher levels of mental fatigue post cognitive task in the Stroop compared to the Control session ($t(17) = -3.55$, $p = .015$, $d = -.837$, *95%CI* [-1.367, -.288]).

Motivation. Motivation to perform the cognitive tasks decreased overtime ($F(2, 34) = 94.36$, $p < .001$, $n_p^2 = .847$) and was lower in the Stroop than in the Control session (main effect of session: $F(1, 17) = 5.88$, $p = .027$, $n_p^2 = .257$). The session × time interaction reached significance ($F(2, 34) = 5.99$, $p = .006$, $n_p^2 = .261$), and details of the posthoc results are presented in Figure 2B. Pre cognitive task, participants reported similar levels of motivation in the Stroop and Control sessions ($t(17) = -.175$, $p = .863$, $d = -.041$, *95%CI* [-.503, .422]). Midway through cognitive tasks, participants were more motivated to continue in the Control than in the Stroop session ($t(17) = 3.382$, $p = .011$, $d = .797$, *95%CI* [.256, 1.321]). Post cognitive tasks, participants reported similar levels of motivation to repeat the cognitive task they had just completed ($t(17) = 2.027$, $p = .117$, $d = .478$, *95%CI* [-.017, .960]). Motivation (Figure 2C) to perform the cycling tests decreased from pre to post test ($F(1, 17) = 12.49$, $p = .003$, $n_p^2 = .424$), with no difference between sessions ($F(1, 17) = .108$, $p = .476$, $n_p^2 = .006$) and no session × time interaction ($F(1, 17) = .003$, $p = .956$, $n_p^2 < .001$).

Boredom. VAS scores for boredom were 4.0 ± 2.8 and 4.3 ± 3.0 at midway and post task for the Control session, and 5.3 ± 2.5 and 6.5 ± 2.7 for the Stroop session. Participants were more bored when

performing the Stroop task than when watching the documentary (main effect of session: $F(1, 17) = 6.61$, $p = .020$, $n_p^2 = .280$). Boredom increased from midway to post task ($F(1, 17) = 7.80$, $p = .012$, $n_p^2 = .314$), with no session × time interaction ($F(1, 17) = 2.39$, $p = .140$, $n_p^2 = .123$).

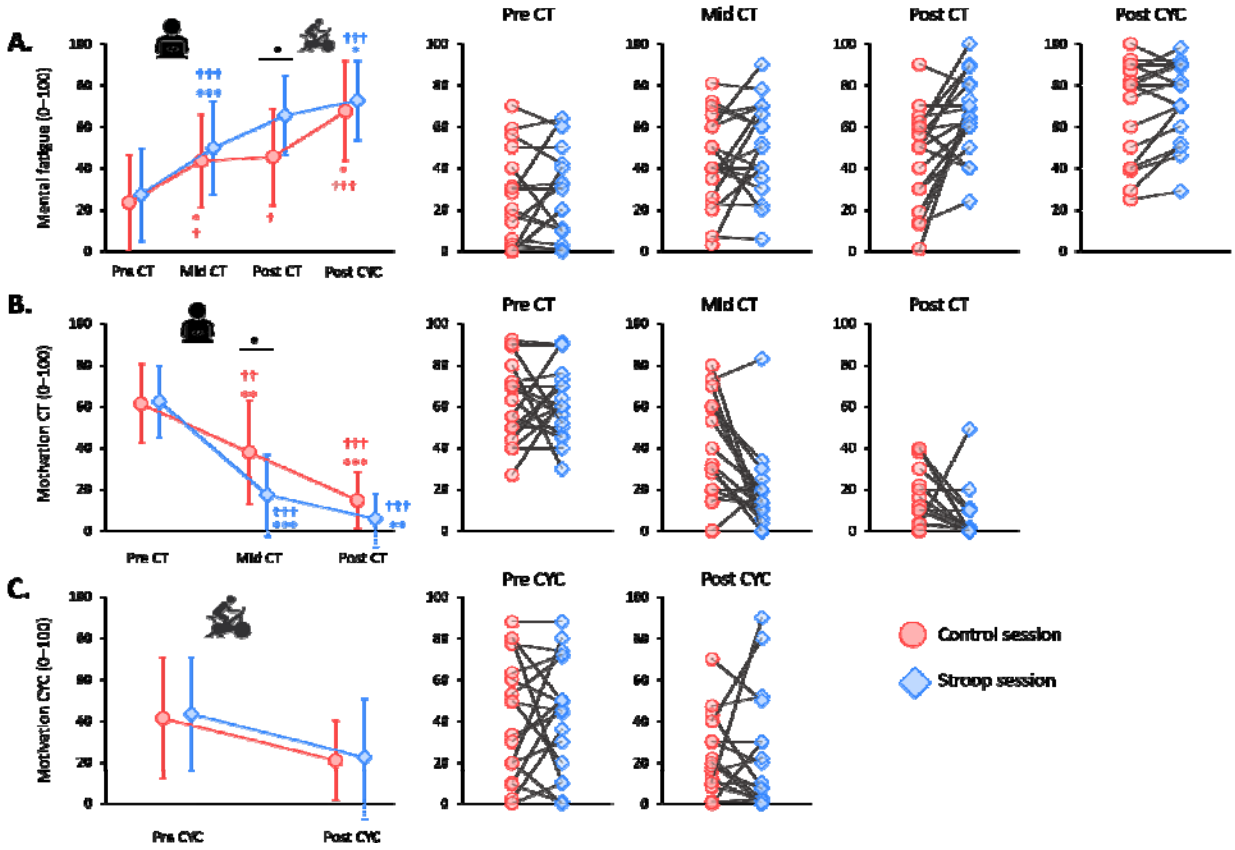
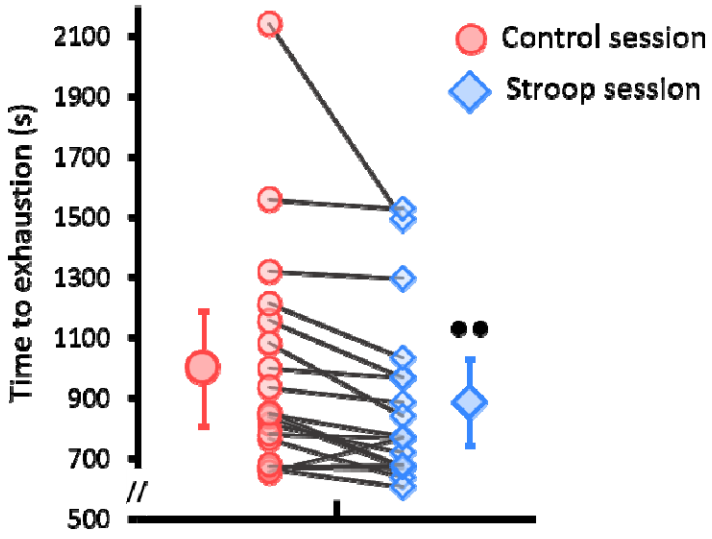


Figure 2. Changes in mental fatigue and motivation during the control (documentary) and Stroop sessions. Panel A shows mean and individual values for mental fatigue level before the cognitive tasks (pre CT), midway through the cognitive tasks (mid CT), immediately after the cognitive tasks (post CT) and after the cycling time to exhaustion test (post CYC). Panel B shows mean and individual values for motivation to perform the cognitive task measured pre CT, mid CT and post CT. Panel C shows mean and individual values for motivation to perform the cycling time to exhaustion test measured pre CYC and post CYC. The symbol • indicates a difference between sessions at the same time point; * indicates a difference with the previous time point within the same session; † indicates a difference with pre CT within the same session. One symbol denotes $p < .05$, two symbols denote $p < .01$, three symbols denote $p < .001$. Data are presented as mean ± standard deviation.

520 **Cycling time to exhaustion**

521 There was no order effect ($t(17) = 0.36$, $p = .726$, $d = -.121$, *95%CI* [-.773, .539]). The time to
522 exhaustion in the first session (793 ± 114) did not differ from the time to exhaustion in the second
523 session (812 ± 199).

524 The time to exhaustion decreased by 9.3 ± 11 % (-111 ± 160 s) in the Stroop compared with the
525 Control session ($t(17) = 2.95$, $p = .009$, $d = .694$, *95%CI* [.169, 1.200]). Due to deviation from a normal
526 distribution, we also employed a Wilcoxon rank test, which confirmed the difference between sessions
527 ($W = 159$, $p = .001$, $r_{rb} = .860$). In 83% of participants (15 out of 18), endurance performance was shorter
528 in the Stroop compared with the documentary session (Figure 3).



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530 **Figure 3. Cycling endurance performance**. The cycling time to exhaustion at 80% peak power
531 output is displayed for the Control (documentary) and Stroop sessions. Large circles and diamonds
532 represent mean data ± standard deviation, while small circles and diamonds indicate individual data
533 points connected by solid lines. •• denotes a significant difference between sessions ($p < 0.01$).
534

535 **Electromyography**

536 SPM analyses revealed no significant main effect of session (Stroop vs. Control) on EMG activation
537 profiles for any muscle at any of the examined time points (Figure 4 and Supplementary Material S1).

This absence of difference was also observed for both the time-specific comparison at exhaustion, with no significant session-related detected for any muscle (SPM statistic = t; df = 16; $p > .05$; clusters = none) (Figure 5). Similarly, in the two-way repeated-measures ANOVA conducted across the isotime points (0%, 50%, and 100%), the main effect of session remained non-significant, and no significant session × isotime point interaction was observed (Table 1). In contrast, a significant main effect of isotime point was observed in specific phases of the pedaling cycle in a subset of muscles: GMax, VL, ST, and GM (Figure 4, Table 1). For clarity reason, data for the RF, BF, VM, SOL and GL are presented as supplementary material S1. Individual data for EMG analysis are provided as supplementary material S2.

The variability analysis revealed no differences in inter-cycle EMG variability between the Stroop and Control sessions, for any muscle and at any of the tested time points (exhaustion, and the three isotime points). Paired SPM1D t-tests conducted on the standard deviation profiles of the EMG signal did not identify any significant clusters in favor of either session. These results suggest that mental fatigue did not affect the consistency or temporal stability of muscle activation patterns during the cycling test.

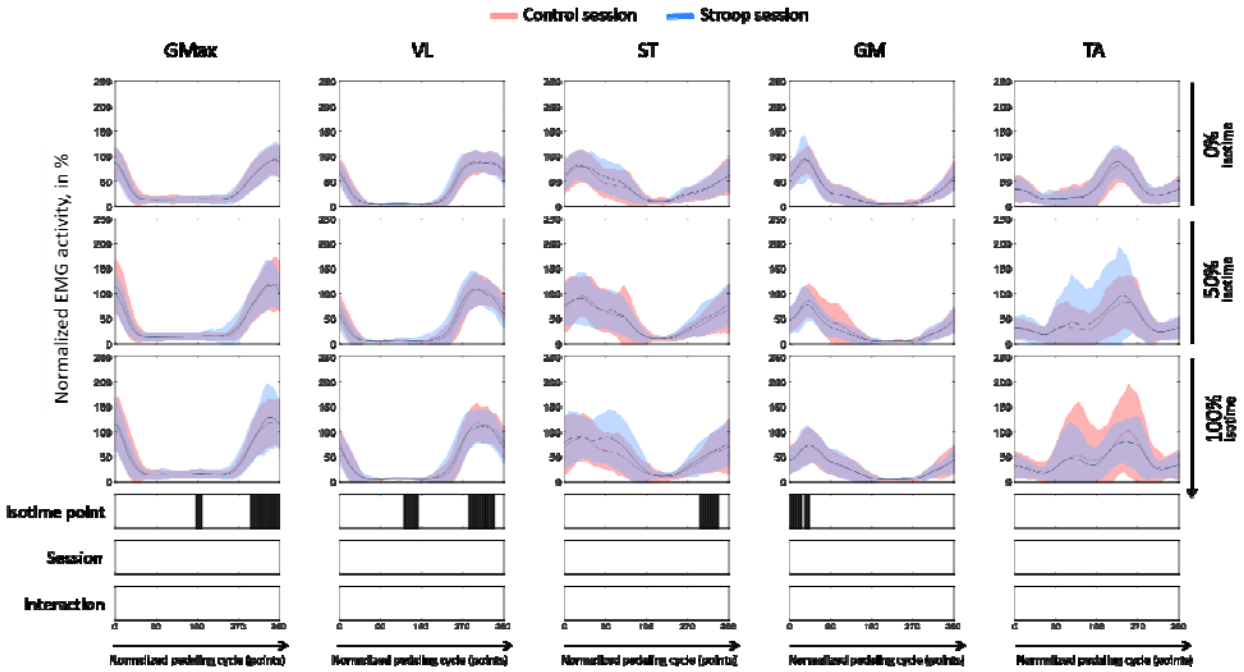

Figure 4. Electromyographic (EMG) activity of the lower limb muscles during the cycling time to exhaustion test for the control (documentary) and Stroop sessions. Electromyographic (EMG) activity of

the gluteus maximus (GMax), vastus lateralis (VL), semi tendinous (ST), gastrocnemius medialis (GM) and tibialis anterior (TA) muscles throughout the pedaling cycle. EMG activity was measured at three isotime points (0%, 50%, and 100% – from top to bottom). Data are presented for two sessions: control (solid red line) and Stroop (solid blue line). The x-axis represents the normalized pedaling cycle (points), while the y-axis indicates normalized EMG activity. Solid lines represent the average muscle activity, with shaded areas denoting the standard deviation. Significant differences ($p < 0.05$) over time, assessed using a two-way repeated-measures ANOVA with factors task session (Stroop vs. Control) and isotime (0%, 50%, and 100%), combined with Statistical Parametric Mapping analysis, are indicated by vertical black bars beneath each graph.

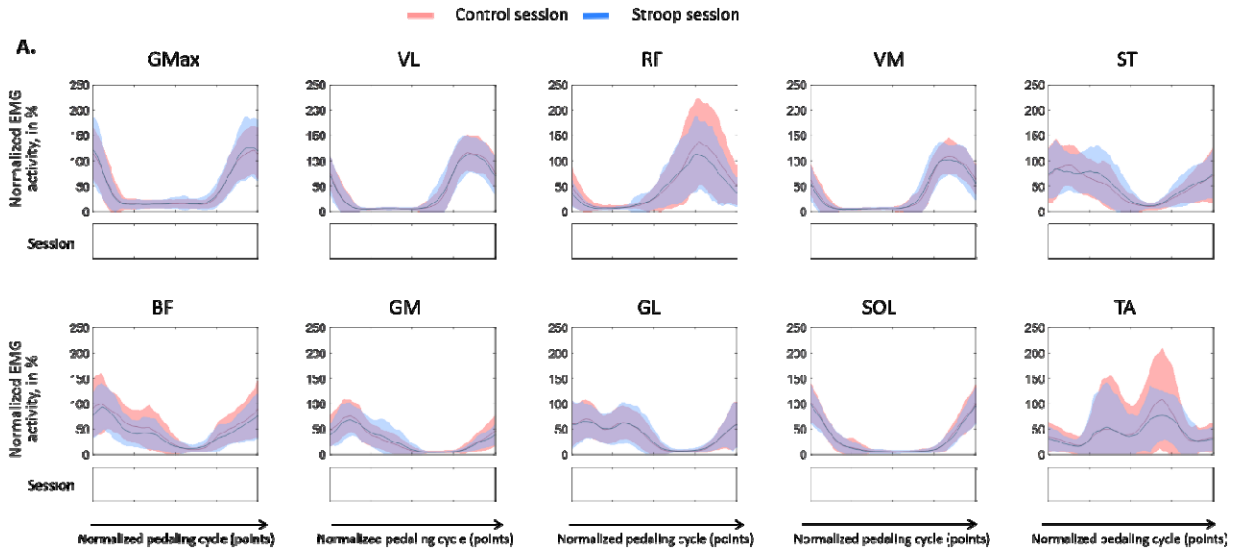

Figure 5. Electromyographic (EMG) activity of the lower limb muscles at exhaustion for the control (documentary) and Stroop sessions. EMG activity of the gluteus maximus (GMax), vastus lateralis (VL), rectus femoris (RF), vastus medialis (VM), semi tendinous (ST), biceps femoris (BF), gastrocnemius medialis (GM), gastrocnemius lateralis (GL), soleus (SOL) and tibialis anterior (TA) muscles throughout the pedaling cycle. Data are presented for two sessions: control (solid red line) and Stroop (solid blue line). The x-axis represents the normalized pedaling cycle (points), while the y-axis indicates normalized EMG activity. Solid lines represent the average muscle activity, with shaded areas denoting the standard deviation. Statistical differences were calculated using a paired t-test with task session (Stroop vs. control) combined with Statistical Parametric Mapping analysis.

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584 **Table 1.** SPM1D results for EMG activity during the cycling time-to-exhaustion test (isotime analysis)

Muscle	Tested effect	SPM statistic	df	p (corrected)	Significant cluster and cycle phase (%)
RF	Session	F	1,16	> 0.05 (z_max = 11.84, z_threshold = 18.64)	–
	Isotime	F	2,26	> 0.05 (z_max = 7.42, z_threshold = 9.30)	–
	Session × Isotime	F	2,26	> 0.05 (z_max = 4.43, z_threshold = 9.30)	–
GMax	Session	F	1,13	> 0.05 (z_max = 2.76, z_threshold = 18.72)	–
	Isotime	F	2,26	0.00046; < 0.0001	[174 – 190]; [293 – 359]
	Session × Isotime	F	2,26	> 0.05 (z_max = 4.08, z_threshold = 9.33)	–
VL	Session	F	1,14	> 0.05 (z_max = 4.15, z_threshold = 17.65)	–
	Isotime	F	2,28	< 0.0001; < 0.0001	[139 – 172]; [280 – 340]
	Session × Isotime	F	2,28	> 0.05 (z_max = 4.96, z_threshold = 9.03)	–
BF	Session	F	1,12	> 0.05 (z_max = 5.69, z_threshold = 19.37)	–
	Isotime	F	2,24	< 0.0001; 0.0443	[307 – 331]; [338 – 340]
	Session × Isotime	F	2,24	> 0.05 (z_max = 5.41, z_threshold = 9.45)	–
ST	Session	F	1,15	> 0.05 (z_max = 8.36, z_threshold = 16.83)	–
	Isotime	F	2,30	< 0.0001	[294 – 338]
	Session × Isotime	F	2,30	> 0.05 (z_max = 4.13, z_threshold = 8.79)	–
TA	Session	F	1,16	> 0.05 (z_max = 1.85, z_threshold = 16.17)	–
	Isotime	F	2,32	> 0.05 (z_max = 7.15, z_threshold = 8.60)	–
	Session × Isotime	F	2,32	> 0.05 (z_max = 1.85, z_threshold = 8.60)	–
VM	Session	F	1,16	> 0.05 (z_max = 8.39, z_threshold = 16.56)	–
	Isotime	F	2,32	< 0.0001; < 0.0001; 0.0167	[92 – 120]; [127 – 177]; [281 – 312]
	Session × Isotime	F	2,32	> 0.05 (z_max = 3.52, z_threshold = 8.75)	–

GM	Session	F	1,13	> 0.05 (z_max = 3.62, z_threshold = 18.59)	–
	Isotime	F	2,26	< 0.0001; 0.0027	[0 – 27]; [31 – 43]
	Session × Isotime	F	2,26	> 0.05 (z_max = 2.69, z_threshold = 9.28)	–
SOL	Session	F	1,16	> 0.05 (z_max = 3.98, z_threshold = 16.70)	–
	Isotime	F	2,32	0.0107	[73 – 82]
	Session × Isotime	F	2,32	> 0.05 (z_max = 2.81, z_threshold = 8.80)	–
GL	Session	F	1,16	> 0.05 (z_max = 9.60, z_threshold = 16.62)	–
	Isotime	F	2,32	> 0.05 (z_max = 3.69, z_threshold = 8.77)	–
	Session × Isotime	F	2,32	> 0.05 (z_max = 4.48, z_threshold = 8.77)	–

Statistical Parametric Mapping (SPM1D) two-way repeated-measures ANOVAs were performed on normalized surface electromyography (EMG) signals over the full pedaling cycle (0–360%). Session (Stroop vs. Control) and Isotime (0%, 50%, and 100% of individual isotime) were entered as within-subject factors. For each muscle, F-statistics, degrees of freedom (df), and Random Field Theory–corrected *p*-values are reported. When present, significant supra-threshold clusters ($p < .05$, corrected) are indicated together with the corresponding phase(s) of the pedaling cycle (%). For non-significant effects, the maximum test statistic (z_max) and the critical threshold (z_threshold*)* from SPM1D are reported, as exact *p*-values are not provided when no supra-threshold cluster is detected.
RF, rectus femoris; GMax, gluteus maximus; VL, vastus lateralis; BF, biceps femoris; ST, semitendinosus; TA, tibialis anterior; VM, vastus medialis; GM, gastrocnemius medialis; SOL, soleus; GL, gastrocnemius lateralis.

Perceptual responses.

Perception of effort. Mean and individual data are presented in Figure 6A. Participants perceived the warm-up more effortful in the Stroop compared to the Control session ($t(17) = -3.149$, $p = .006$, $d = -.742$, *95%CI* [-1.258, -.210]). Due to deviation from a normal distribution, we also employed a Wilcoxon rank test which confirmed the difference between session ($W = 4.50$, $p = .003$, $r_{rb} = -.915$). During the time to exhaustion test, analysis of the isotime values revealed a higher perception of effort in the Stroop compared to the Control session (main effect of session: $F(1, 17) = 7.18$, $p = .016$, $n_p^2 = .297$). The perception of effort increased overtime ($F(2, 34) = 133.09$, $p < .0.001$, $n_p^2 = .887$), with no session × time interaction ($F(2, 34) = 1.00$, $p = .377$, $n_p^2 = 0.056$). At exhaustion, participants reported the same intensity of perceived effort between sessions ($t(17) = -1.016$, $p = .324$, $d = -.239$, *95%CI* [-.705, .233]) .

Perceptions of muscle pain. Mean and individual data are presented in Figure 6B. During the warm-up, participants reported a similar level of muscle pain between the Stroop and Control sessions ($t(17) = -1.550$, $p = .140$, $d = -.365$, *95%CI* [-.838, .118]). Due to deviation from a normal distribution, we also employed a Wilcoxon rank test, which also suggested no difference between sessions ($W = 35.50$, $p = .299$, $r_{rb} = -.324$). During the time to exhaustion test, analysis of the isotime values suggested a higher muscle pain intensity in the Stroop compared to the Control session, without reaching significance (main effect of session: $F(1, 17) = 3.952$, $p = .063$, $n_p^2 = .189$). Muscle pain increased overtime ($F(2, 34) = 90.023$, $p < .001$, $n_p^2 = .841$), with no session × time interaction ($F(2, 34) = .693$, $p = .507$, $n_p^2 = .039$). At exhaustion, participants reported the same intensity of muscle between sessions ($t(17) = .373$, $p = .713$, $d = .088$, *95%CI* [-0.376, 0.550]). Due to deviation from a normal distribution, we also employed a Wilcoxon rank test, which also suggested no difference between sessions ($W = 34.00$, $p = .964$, $r_{rb} = -.030$).

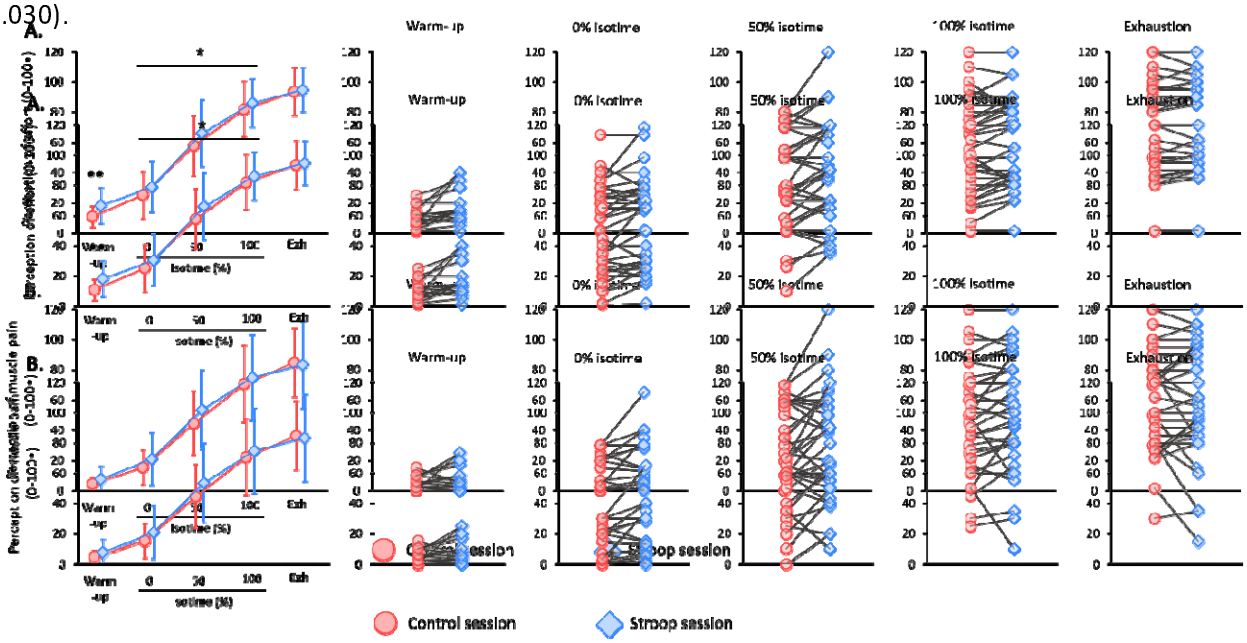

Figure 6. Perceptions of effort and muscle pain during the cycling exercise for the control (documentary) and Stroop sessions. Panel A shows mean and individual values for the perception of effort during the warm-up performed at 40% peak power output (PPO) and the time to exhaustion test at 80% PPO. During the time to exhaustion test, data are presented at four time points: 0%, 50% and 100% individual isotime, and at exhaustion. Panel B shows mean and individual values for the perception of muscle pain at the same time points. For clarity, the warm-up and exhaustion phases fall into a grey

area: the warm-up was performed at a different pedaling intensity (40% PPO), and the exhaustion data were collected at a non-isotime time point. The symbol • indicates a difference between sessions at the same time point; * indicates a main effect of session during the isotime. One symbol denotes $p < .05$, two symbols denote $p < .01$. Data are presented as mean ± standard deviation.

NASA-TLX. The Control and Stroop sessions differed on the following NASA-TLX items: mental demand (58 ± 32 vs. 81 ± 16, respectively; $p = .007$, $d = .73$, *95%CI* [.198, 1.240]), performance (29 ± 24 vs. 39 ± 27; $p = .049$, $d = .49$, *95%CI* [-.008, .983]), and frustration (34 ± 26 vs. 49 ± 32, respectively; $p = .008$, $d = .70$, *95%CI* [.176, 1.210]). No difference was reported for the other items related to physical and temporal demand, and effort (all $p > .05$, $d = .14$–$.38$).

640 ## Discussion.

641 This study examined the effects of mental fatigue induced by a prolonged demanding cognitive
642 task, compared with a control task, on cycling endurance performance, effort perception and surface
643 EMG-derived muscle activation. Mental fatigue reduced endurance performance and increased the
644 perception of effort, but did not alter EMG-related parameters during the cycling endurance task.

645 **No EMG Evidence of Altered Motor Command Under Mental Fatigue**

646 Our first objective was to investigate whether the increased perceived effort in the presence of
647 mental fatigue was associated with alterations in muscle activation during cycling. Our hypothesis of
648 altered muscle activation was grounded on prior evidence reporting changes in EMG activity following
649 prolonged mental exertion during upper- and lower-limb isometric tasks (Bray et al. 2008; Graham et al.
650 2014; Jacquet et al. 2021; Budini et al. 2014), as well as during a submaximal cycling task (Pageaux et al.
651 2015). Collectively, these findings suggest that mental fatigue may affect central motor command during
652 subsequent physical tasks, potentially contributing to the observed increased perceived effort.

653 Because cycling requires the coordinated activation of multiple muscles (So et al. 2005), the study
654 by Pageaux et al. (2015), which focused on a single muscle, does not provide a comprehensive
655 understanding of the effects of mental fatigue on muscle activation during a whole-body endurance task.
656 Therefore, we aimed to extend these findings by examining muscle activation using surface EMG
657 recordings from ten lower-limb muscles to better capture peripheral indices of motor command.
658 Contrary to our hypothesis, mental fatigue did not alter muscle activation patterns. This result aligns
659 with a recent work that reported no changes in high density-EMG-derived neurophysiological outcomes
660 (i.e., motor unit activity, common synaptic inputs) following a 30-min Stroop task and a subsequent
661 isometric contraction to failure (Alix-Fages et al. 2023). Given that our study was powered to detect

662 medium-to-large effect, our results, together with those of Alix-Pages et al. (2023), suggest that mental
663 fatigue either does not affect EMG-derived measures of muscle activation, or that its effects are small.

664 Several interpretations can be proposed to account for the absence of significant effects on EMG
665 parameters. First, neural control differs between single-joint and whole-body exercises (Sidhu et al.
666 2013). The dynamic nature of cycling likely leads to EMG patterns distinct from those observed during
667 isometric, single-joint tasks and may permit compensatory strategies that mask subtle neural
668 modulations detected under constrained isometric conditions (Bray et al. 2008; Graham et al. 2014;
669 Jacquet et al. 2021). Second, EMG-derived measures reflect peripheral manifestations of motor
670 command rather than the initial supraspinal processes involved in motor planning and motor command
671 generation. Because mental fatigue induces changes at a supraspinal level, it is possible that
672 compensatory adjustments occur during the early stages of motor command planning or generation,
673 before transmission through the corticospinal pathway. In such a case, muscle activation could remain
674 unchanged despite altered supraspinal activity. Accordingly, while our results suggest that the neural
675 information reaching the muscles is similar in the presence and absence of mental fatigue, alterations at
676 earlier stages of motor command generation cannot be excluded. For instance, it has been reported that
677 continuous repetition of motor imagery inducing mental fatigue decreased corticospinal excitability
678 measured with transcranial magnetic stimulation (Nakashima et al. 2021; Nakashima et al. 2022). Third,
679 the absence of changes in EMG-derived muscle activation suggests that the observed decline in
680 endurance performance is unlikely to primarily result from alterations in motor command. This
681 interpretation aligns with recent evidence suggesting that mental fatigue may instead reflect metabolic
682 alterations within brain regions involved in cognitive control (Pessiglione et al. 2025; Wiehler et al. 2022;
683 Barakat et al. 2025). Because effort is also perceived during cognitive tasks (Mangin and Pageaux 2026) ,
684 such metabolic disturbances may increase the perceived cost of effort, thereby contributing to the
685 higher perceived effort observed under mental fatigue. Notably, these metabolic changes have been

686 proposed to increase the cost of cognitive control, biasing decision-making toward low-effort actions
687 associated with immediate rewards (Barakat et al. 2025; Pessiglione et al. 2025). In the context of a
688 cycling time-to-exhaustion test, such low-effort actions would correspond to premature task
689 disengagement.

690

691 **Mental Fatigue Impairs Endurance Performance.**

692 Our second objective was to replicate the detrimental effect of mental fatigue on endurance
693 performance. Participants began the sessions with similar levels of mental fatigue in both sessions.
694 However, mental fatigue was significantly higher following 1 h of the Stroop task compared with 1 h of
695 watching a neutral documentary. Because boredom increased to a similar extent in both sessions, the
696 greater rise in perceived mental fatigue observed during the Stroop task cannot be attributed to
697 differences in boredom over time (Mangin and Pageaux 2025), confirming that the Stroop task
698 successfully induced a specific state of mental fatigue compared with the documentary condition.

699 Interestingly, although motivation to perform the cognitive task decreased to a greater extent in
700 the Stroop session, participants reported similar levels of motivation to perform the cycling endurance
701 task in both sessions. This observation not only supports the negative effect of mental fatigue on
702 motivation (Müller and Apps 2019), but also suggests that the reduction in motivation induced by mental
703 fatigue may be task-specific and primarily related to the cognitive task used to induce mental fatigue.
704 Furthermore, because participants reported similar levels of motivation to perform the cycling task in
705 each session, changes in endurance performance cannot be attributed to alterations in cycling-specific
706 motivation.

707 In line with our hypothesis, mental fatigue impaired cycling endurance performance. This finding
708 aligns with previous studies that used the Stroop task to induce mental fatigue and examine its impact

709 on physical performance (Bray et al. 2008; Smith et al. 2016; Boat et al. 2018; Pageaux et al. 2014).
710 Although the effect of mental fatigue on physical performance has recently been questioned (Holgado et
711 al. 2021b), particularly when endurance and maximal force outcomes are not clearly distinguished
712 (Holgado et al. 2023; Holgado et al. 2021a), the preponderance of evidence indicates that mental fatigue
713 selectively impairs endurance performance. In contrast, maximal force production appears largely
714 unaffected (Brown et al. 2020; Pageaux and Lepers 2018).

715 Importantly, endurance and maximal force performance rely on distinct physiological and
716 psychological regulatory mechanisms that should be considered in theoretical models of mental fatigue
717 (Briand et al. 2025). Maximal force performance predominantly depends on anaerobic energy systems
718 and involves brief all-out efforts with minimal regulation over time. In contrast, endurance performance
719 relies predominantly on aerobic metabolism and requires continuous regulation of effort, either through
720 persistence decisions in time-to-exhaustion tasks or pace management during time trials (Pageaux and
721 Lepers 2018; Englert et al. 2021). Accordingly, as mental fatigue is proposed to alter perceived effort, its
722 detrimental effects are more likely to manifest in endurance than in maximal force performance.

723 Our results align with this theoretical framework. During the Stroop session, participants reported
724 a higher perceived effort from the onset of the cycling warm-up, which remained elevated throughout
725 the cycling test and led them to reach their maximal perceived effort earlier. In line with the prediction
726 of the psychobiological model of endurance performance, this higher perception of effort led to
727 premature task disengagement and decreased endurance performance. For instance, Bray et al. (2008)
728 reported a ~20% reduction in handgrip endurance following a shorter Stroop cognitive task (220 s). A
729 meta-analysis reported that the duration of the cognitive task has a limited influence on the magnitude
730 of performance impairment (Giboin and Wolff 2019). Consistent with this, we observed a ~10% decrease
731 in endurance performance following a 60-min Stroop task, which is lower than the ~20% decrease
732 reported by Bray et al. (2008) and others who used shorter Stroop tasks ranging from 3 to 30 minutes

733 (Giboin and Wolff 2019). Further, the elevated perception of effort observed from the onset of the
734 cycling task, along with the significantly higher rate of increase in perception of effort during cycling in
735 the Stroop session (6.7 ± 2.5 vs. 6.0 ± 1.8 units/min, respectively; p = .031), reinforces previous findings
736 (Marcora et al. 2009; Pageaux et al. 2014; Smith et al. 2016) and provides further experimental evidence
737 that mental fatigue impairs endurance performance primarily through an increased perception of effort.

738 **Limitations and perspectives for future research**

739 Because our study was powered to detect medium-to-large effects, future studies with larger
740 sample sizes are needed to rule out small effects of mental fatigue on muscle activation assessed using
741 surface EMG. Further, surface EMG provides only a peripheral index of motor command. Given the
742 proposed link between perceived effort and motor command (Bergevin et al. 2023; De Morree et al.
743 2012), future research should investigate the effects of mental fatigue on motor command during
744 dynamic exercise using brain-level measures, especially transcranial magnetic stimulation. Further,
745 recent advances in electroencephalography and data analysis have enabled its application during cycling
746 (Pirlot et al. 2025), making it a promising tool for this purpose. In particular, combining
747 electroencephalography with EMG to measure corticomuscular coherence (Petersen et al. 2012) may
748 help identify supraspinal alterations occurring early in motor command generation in the presence of
749 mental fatigue, or alternatively, provide evidence against their involvement.

750 **Conclusions**

751 Prolonged cognitive engagement inducing mental fatigue impaired cycling endurance performance
752 by increasing perceived effort. This increased perceived effort occurred in the absence of detectable
753 changes in EMG-derived muscle activation during cycling. This dissociation between perceptual and
754 neuromuscular responses suggests that the detrimental effects of mental fatigue on endurance
755 performance are primarily driven by central mechanisms involved in effort regulation and task
756 disengagement. Future studies should determine whether combining surface EMG with more sensitive

757 neurophysiological approaches can reveal subtle alterations in motor command associated with mental
758 fatigue during dynamic, whole-body exercise.

759 ## References

760 Alix-Fages C, Jiménez-Martínez P, de Oliveira DS, Möck S, Balsalobre-Fernández C, Del Vecchio A (2023)
761 Mental fatigue impairs physical performance but not the neural drive to the muscle: a
762 preliminary analysis. Eur J Appl Physiol 123 (8):1671-1684. doi:10.1007/s00421-023-05189-1
763 Barakat A, Brochard J, Pessiglione M, Godin JP, Cuenoud B, Xin L, Clairis N, Sandi C (2025)
764 Neurometabolic predictors of mental effort in the frontal cortex. Transl Psychiatry 15 (1):344.
765 doi:10.1038/s41398-025-03554-6
766 Barre A, Armand S (2014) Biomechanical ToolKit: Open-source framework to visualize and process
767 biomechanical data. Comput Methods Programs Biomed 114 (1):80-87.
768 doi:10.1016/j.cmpb.2014.01.012
769 Bergevin M, Steele J, Payen de la Garanderie M, Feral-Basin C, Marcora SM, Rainville P, Caron JG,
770 Pageaux B (2023) Pharmacological blockade of muscle afferents and perception of effort: a
771 systematic review with meta-analysis. Sports Medicine 53 (2):415-435. doi:10.1007/s40279-022-
772 01762-4.
773 Boat R, Atkins T, Davenport N, Cooper S (2018) Prior self-control exertion and perceptions of pain and
774 motivation during a physically effortful task. Prog Brain Res 240:19-34.
775 doi:10.1016/bs.pbr.2018.08.007
776 Boksem MA, Tops M (2008) Mental fatigue: costs and benefits. Brain Res Rev 59 (1):125-139.
777 doi:10.1016/j.brainresrev.2008.07.001.
778 Borg E, Kaijser L (2006) A comparison between three rating scales for perceived exertion and two
779 different work tests. Scand J Med Sci Sports 16 (1):57-69. doi:10.1111/j.1600-0838.2005.00448.x.
780 Bray SR, Martin Ginis KA, Hicks AL, Woodgate J (2008) Effects of self-regulatory strength depletion on
781 muscular performance and EMG activation. Psychophysiology 45 (2):337-343.
782 doi:10.1111/j.1469-8986.2007.00625.x.
783 Brehm JW, Self EA (1989) The intensity of motivation. Annu Rev Psychol 40:109-131.
784 doi:10.1146/annurev.ps.40.020189.000545
785 Briand J, Mangin T, Tremblay J, Pageaux B (2025) Bridging Inductive and Deductive Reasoning: A Proposal
786 to Enhance the Evaluation and Development of Models in Sports and Exercise Science. Sports
787 Med 55 (11):2707-2719. doi:10.1007/s40279-025-02289-0
788 Brown DMY, Graham JD, Innes KI, Harris S, Flemington A, Bray SR (2020) Effects of Prior Cognitive
789 Exertion on Physical Performance: A Systematic Review and Meta-analysis. Sports Med 50
790 (3):497-529. doi:10.1007/s40279-019-01204-8
791 Budini F, Lowery M, Durbaba R, De Vito G (2014) Effect of mental fatigue on induced tremor in human
792 knee extensors. J Electromyogr Kinesiol 24 (3):412-418. doi:10.1016/j.jelekin.2014.02.003.
793 Carter CS, Braver TS, Barch DM, Botvinick MM, Noll D, Cohen JD (1998) Anterior cingulate cortex, error
794 detection, and the online monitoring of performance. Science 280 (5364):747-749.
795 doi:10.1126/science.280.5364.747
796 Christensen MS, Lundbye-Jensen J, Geertsen SS, Petersen TH, Paulson OB, Nielsen JB (2007) Premotor
797 cortex modulates somatosensory cortex during voluntary movements without proprioceptive
798 feedback. Nat Neurosci 10 (4):417-419. doi:10.1038/nn1873
799 Cohen J (1988) Statistical power analysis for the behavioral sciences. Erlbaum. Hillsdale, NJ

De Morree HM, Klein C, Marcora SM (2012) Perception of effort reflects central motor command during movement execution. Psychophysiology 49 (9):1242-1253. doi:10.1111/j.1469-8986.2012.01399.x.

Dulaney CL, Rogers WA (1994) Mechanisms underlying reduction in Stroop interference with practice for young and old adults. J Exp Psychol Learn Mem Cogn 20 (2):470. doi:10.1037//0278-7393.20.2.470.

Englert C, Pageaux B, Wolff W (2021) Self-control in sports. Society for Transparency, Openness, and Replication in Kinesiology Z. Zenko & L. Jones (Eds.), Essentials of exercise and sport psychology: An open access textbook:pp. 509–529

Giboin L-S, Wolff W (2019) The effect of ego depletion or mental fatigue on subsequent physical endurance performance: A meta-analysis. Performance Enhancement & Health 7 (1-2):100150. doi:https://doi.org/10.1016/j.peh.2019.100150

Gillies MJ, Huang Y, Hyam JA, Aziz TZ, Green AL (2019) Direct neurophysiological evidence for a role of the human anterior cingulate cortex in central command. Auton Neurosci 216:51-58. doi:10.1016/j.autneu.2018.09.004

Graham JD, Sonne MW, Bray SR (2014) It wears me out just imagining it! Mental imagery leads to muscle fatigue and diminished performance of isometric exercise. Biol Psychol 103:1-6. doi:10.1016/j.biopsycho.2014.07.018

Hart SG, Staveland LE (1988) Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In: Advances in psychology, vol 52. Elsevier, pp 139-183

Holgado D, Mesquida C, Román-Caballero R (2023) Assessing the Evidential Value of Mental Fatigue and Exercise Research. Sports Med 53 (12):2293-2307. doi:10.1007/s40279-023-01926-w

Holgado D, Sanabria D, Perales JC, Vadillo MA (2021a) Correction: Mental Fatigue Might be Not So Bad for Exercise Performance After All: A Systematic Review and Bias-Sensitive Meta-Analysis. J Cogn 4 (1):32. doi:10.5334/joc.178

Holgado D, Troya E, Perales JC, Vadillo MA, Sanabria D (2021b) Does mental fatigue impair physical performance? A replication study. Eur J Sport Sci 21 (5):762-770. doi:10.1080/17461391.2020.1781265

Hug F, Vogel C, Tucker K, Dorel S, Deschamps T, Le Carpentier É, Lacourpaille L (2019) Individuals have unique muscle activation signatures as revealed during gait and pedaling. J Appl Physiol 127 (4):1165-1174. doi:10.1152/japplphysiol.01101.2018.

Jacquet T, Lepers R, Poulin-Charronnat B, Bard P, Pfister P, Pageaux B (2021) Mental fatigue induced by prolonged motor imagery increases perception of effort and the activity of motor areas. Neuropsychologia 150:107701. doi:10.1016/j.neuropsychologia.2020.107701.

Lakens D (2022) Sample Size Justification. Collabra: Psychology 8 (1). doi:10.1525/collabra.33267

MacMahon C, Schücker L, Hagemann N, Strauss B (2014) Cognitive fatigue effects on physical performance during running. J Sport Exerc Psychol 36 (4):375-381. doi:10.1123/jsep.2013-0249

Mangin T, André N, Benraiss A, Pageaux B, Audiffren M (2021) No ego-depletion effect without a good control task. Psychol Sport Exerc 57:102033. doi:https://doi.org/10.1016/j.psychsport.2021.102033

Mangin T, Pageaux B (2025) It is time to stop using the terminology “passive” fatigue. Motiv Sci. doi:https://doi.org/10.1037/mot0000375

Mangin T, Pageaux B (2026) Effort and its perception revisited: How physical-domain insights could lead toward a unified theory. Cogn Affect Behav Neurosci. doi:10.3758/s13415-026-01411-7

Marcora S (2009) Perception of effort during exercise is independent of afferent feedback from skeletal muscles, heart, and lungs. J Appl Physiol (1985) 106 (6):2060-2062. doi:10.1152/japplphysiol.90378.2008

847 Marcora S (2019) Psychobiology of fatigue during endurance exercise. In: Endurance performance in
848 sport. Routledge, pp 15-34
849 Marcora SM (2010) Effort: perception of. In: Goldstein, E Bruce, ed Encyclopedia of Perception Sage, Los
850 Angeles, pp 380-383 ISBN 978-1-4129-4081
851 Marcora SM, Bosio A, de Morree HM (2008) Locomotor muscle fatigue increases cardiorespiratory
852 responses and reduces performance during intense cycling exercise independently from
853 metabolic stress. Am J Physiol Regul Integr Comp Physiol 294 (3):R874-R883.
854 doi:10.1152/ajpregu.00678.2007.
855 Marcora SM, Staiano W (2010) The limit to exercise tolerance in humans: mind over muscle? Eur J Appl
856 Physiol 109 (4):763-770. doi:10.1007/s00421-010-1418-6
857 Marcora SM, Staiano W, Manning V (2009) Mental fatigue impairs physical performance in humans. J
858 Appl Physiol (1985) 106 (3):857-864. doi:10.1152/japplphysiol.91324.2008
859 Martin K, Staiano W, Menaspà P, Hennessey T, Marcora S, Keegan R, Thompson KG, Martin D, Halson S,
860 Rattray B (2016) Superior inhibitory control and resistance to mental fatigue in professional road
861 cyclists. PloS one 11 (7):e0159907. doi:10.1371/journal.pone.0159907.
862 McCloskey DI Corollary Discharges: Motor Commands and Perception. In: Comprehensive Physiology. pp
863 1415-1447. doi:https://doi.org/10.1002/cphy.cp010232
864 Medford N, Critchley HD (2010) Conjoint activity of anterior insular and anterior cingulate cortex:
865 awareness and response. Brain Struct Funct 214 (5-6):535-549. doi:10.1007/s00429-010-0265-x
866 Müller T, Apps MAJ (2019) Motivational fatigue: A neurocognitive framework for the impact of effortful
867 exertion on subsequent motivation. Neuropsychologia 123:141-151.
868 doi:10.1016/j.neuropsychologia.2018.04.030
869 Nakashima A, Moriuchi T, Matsuda D, Hasegawa T, Nakamura J, Anan K, Satoh K, Suzuki T, Higashi T,
870 Sugawara K (2021) Corticospinal excitability during motor imagery is diminished by continuous
871 repetition-induced fatigue. Neural Regen Res 16 (6):1031-1036. doi:10.4103/1673-5374.300448
872 Nakashima A, Moriuchi T, Matsuda D, Nakamura J, Fujiwara K, Ikio Y, Hasegawa T, Mitunaga W, Higashi T
873 (2022) Continuous Repetition Motor Imagery Training and Physical Practice Training Exert the
874 Growth of Fatigue and Its Effect on Performance. Brain Sci 12 (8). doi:10.3390/brainsci12081087
875 Nicolò A, Sacchetti M, Girardi M, McCormick A, Angius L, Bazzucchi I, Marcora SM (2019) A comparison
876 of different methods to analyse data collected during time-to-exhaustion tests. Sport Sci Health
877 15 (3):667-679. doi:https://doi.org/10.1007/s11332-019-00585-7
878 O'Connor PJ, Cook DB (1999) Exercise and pain: the neurobiology, measurement, and laboratory study of
879 pain in relation to exercise in humans. Exerc Sport Sci Rev 27:119-166
880 Pageaux B (2014) The psychobiological model of endurance performance: an effort-based decision-
881 making theory to explain self-paced endurance performance. Sports Med 44 (9):1319-1320.
882 doi:10.1007/s40279-014-0198-2
883 Pageaux B (2016) Perception of effort in exercise science: definition, measurement and perspectives. Eur
884 J Sport Sci 16 (8):885-894. doi:10.1080/17461391.2016.1188992.
885 Pageaux B, Clos P, Impellizzeri F, Audiffren M, Stapley P, Grémeaux V, Perrey S, O'Connor PJ, Marcora
886 SM, Lepers R, Laroche D (2020) Towards Standardized Instructions For Measuring Perception Of
887 Effort And Muscle Pain During Physical Exercise. Med Sci Sports Exerc 52 (7S):499.
888 doi:10.1249/01.mss.0000679556.09727.4b
889 Pageaux B, Lepers R (2018) The effects of mental fatigue on sport-related performance. Prog Brain Res
890 240:291-315. doi:10.1016/bs.pbr.2018.10.004
891 Pageaux B, Lepers R, Dietz KC, Marcora SM (2014) Response inhibition impairs subsequent self-paced
892 endurance performance. Eur J Appl Physiol 114 (5):1095-1105. doi:10.1007/s00421-014-2838-5.

Pageaux B, Marcora SM, Lepers R (2013) Prolonged mental exertion does not alter neuromuscular function of the knee extensors. Med Sci Sports Exerc 45 (12):2254-2264. doi:10.1249/MSS.0b013e31829b504a

Pageaux B, Marcora SM, Rozand V, Lepers R (2015) Mental fatigue induced by prolonged self-regulation does not exacerbate central fatigue during subsequent whole-body endurance exercise. Front Hum Neurosci 9:67. doi:10.3389/fnhum.2015.00067.

Pardo JV, Pardo PJ, Janer KW, Raichle ME (1990) The anterior cingulate cortex mediates processing selection in the Stroop attentional conflict paradigm. Proc Natl Acad Sci U S A 87 (1):256-259. doi:10.1073/pnas.87.1.256

Pataky TC, Robinson MA, Vanrenterghem J (2013) Vector field statistical analysis of kinematic and force trajectories. J Biomech 46 (14):2394-2401. doi:10.1016/j.jbiomech.2013.07.031

Paus T (2001) Primate anterior cingulate cortex: where motor control, drive and cognition interface. Nat Rev Neurosci 2 (6):417-424. doi:10.1038/35077500.

Pessiglione M, Blain B, Wiehler A, Naik S (2025) Origins and consequences of cognitive fatigue. Trends Cogn Sci 29 (8):730-749. doi:10.1016/j.tics.2025.02.005

Petersen TH, Willerslev-Olsen M, Conway BA, Nielsen JB (2012) The motor cortex drives the muscles during walking in human subjects. J Physiol 590 (10):2443-2452. doi:10.1113/jphysiol.2012.227397

Pirlot T, Baron B, Scholler V, Grappe F, Pageaux B, Groslambert A (2025) A Comparative Analysis Between National-Level and Young Professional Road Cyclists: A Psychophysiological Approach. Int J Sports Physiol Perform 20 (11):1471-1480. doi:10.1123/ijspp.2025-0016

Richter M, Gendolla GH, Wright RA (2016) Three decades of research on motivational intensity theory: What we have learned about effort and what we still don't know. Adv Motiv Sci 3:149-186. doi:https://doi.org/10.1016/bs.adms.2016.02.001

Shenhav A, Cohen JD, Botvinick MM (2016) Dorsal anterior cingulate cortex and the value of control. Nat Neurosci 19 (10):1286-1291. doi:10.1038/nn.4384

Sidhu SK, Cresswell AG, Carroll TJ (2013) Corticospinal responses to sustained locomotor exercises: moving beyond single-joint studies of central fatigue. Sports Med 43 (6):437-449. doi:10.1007/s40279-013-0020-6.

Smith MR, Coutts AJ, Merlini M, Deprez D, Lenoir M, Marcora SM (2016) Mental Fatigue Impairs Soccer-Specific Physical and Technical Performance. Med Sci Sports Exerc 48 (2):267-276. doi:10.1249/mss.0000000000000762

So RC, Ng JK-F, Ng GY (2005) Muscle recruitment pattern in cycling: a review. Phys Ther Sport 6 (2):89-96. doi:https://doi.org/10.1016/j.ptsp.2005.02.004

Van Cutsem J, Marcora S, De Pauw K, Bailey S, Meeusen R, Roelands B (2017) The Effects of Mental Fatigue on Physical Performance: A Systematic Review. Sports Med 47 (8):1569-1588. doi:10.1007/s40279-016-0672-0

Wiehler A, Branzoli F, Adanyeguh I, Mochel F, Pessiglione M (2022) A neuro-metabolic account of why daylong cognitive work alters the control of economic decisions. Curr Biol 32 (16):3564-3575.e3565. doi:10.1016/j.cub.2022.07.010