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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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Data statement

All raw data, as well as data processing and statistical analysis files (performed using Matlab and Jamovi), are publicly available on the Zenodo repository at the following link:
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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

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

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

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

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

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

170

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.

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

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

206

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

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

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

227

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

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

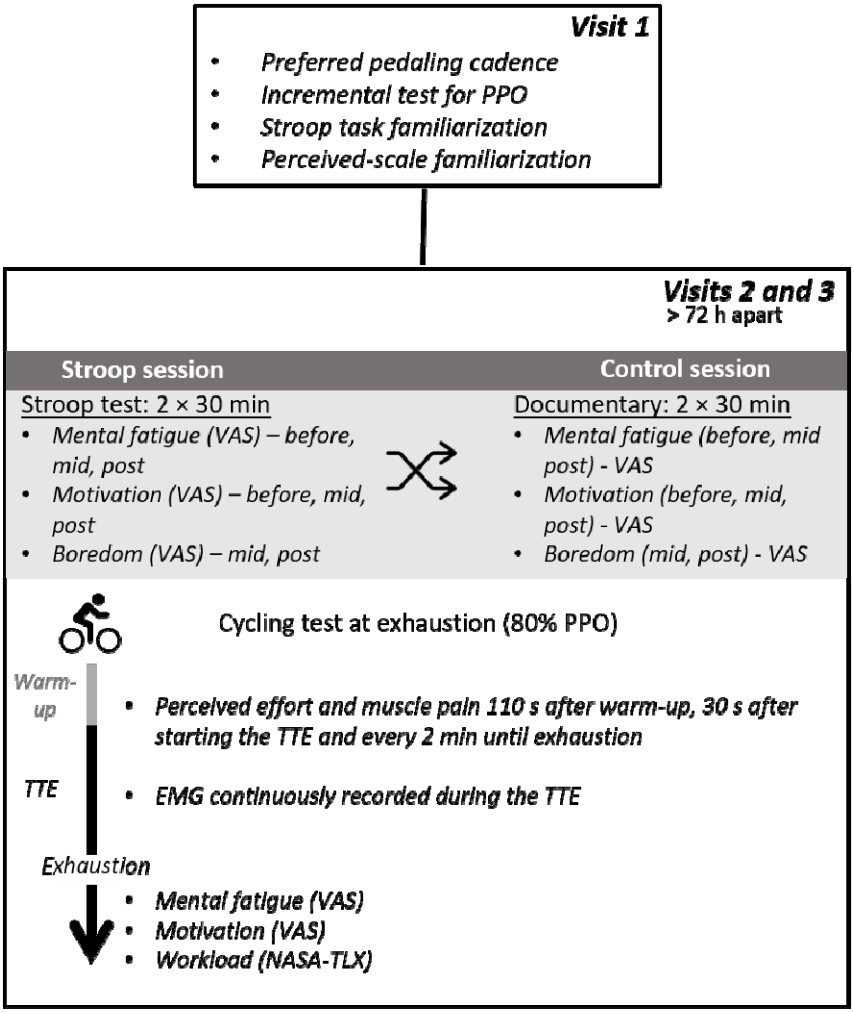


Figure 1. Overview of the experimental and control sessions. Participants visited the laboratory on three distinct occasions. The first visit was dedicated to peak power output (PPO) measurement and familiarization procedures. The second and third visits were the experimental sessions. After completing 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

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

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

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

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

293

294 **EMG**

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

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

306

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

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

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

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

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

341

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

346 comparability. Across the 340 total muscle recordings (10 muscles × 18 participants × 2 sessions), 21
347 recordings (6%) were excluded due to poor signal quality. After electrode exclusion, the number of
348 participants retained per muscle for complete 2 sessions was: SOL (n = 17), RF (n = 14), VL (n = 15), BF (n
349 = 13), GL (n = 17), TA (n = 17), VM (n = 17), ST (n = 16), GMax (n = 14), and GM (n = 14). A total of 2720
350 pedaling cycles were collected across all participants and sessions. Following visual inspection, 83 cycles
351 (3%) were removed due to transient artifacts. After this selection, the minimum common number of
352 valid cycles across all participants, sessions, muscles, and time points was 16 cycles, which were retained
353 for statistical analysis to ensure a fully balanced repeated-measures design.

354

355 **Psychological variables**

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

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

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

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

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

382

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

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

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

401 *Perceptions of muscle pain.* Muscle pain was assessed during the cycling task, as it is known to
402 influence endurance performance and to develop during endurance exercise (O'Connor and Cook 1999).
403 Participants used a separate modified CR100 scale to assess muscle pain, with the word "pain" explicitly
404 incorporated into the anchor descriptions: 0 (no pain at all) and 100 (maximal pain). Similar to the
405 perceived effort scale, memory anchoring was used to define the 100-point reference. Participants were
406 instructed to rate "the intensity of pain they felt during the exercise", focusing specifically on localized
407 sensations in the leg muscles. These sensations were described as potentially including feelings of
408 burning, intense, or sharp pain (O'Connor and Cook 1999). It was emphasized that participants should
409 not confuse or equate their ratings of effort with their perception of pain (Bergevin et al. 2023; Pageaux
410 2016). To ensure proper use of the scale, each participant was provided with verbal examples illustrating
411 "no muscle pain" and "maximal muscle pain" as reference points.

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

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

418

419 **Statistics.**

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

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

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

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

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

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

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

463 **Results.**

464 **Manipulation checks for mental fatigue induction**

465 *Mental fatigue*. Mental fatigue increased overtime ($F(2, 34) = 29.19$, $p < .001$, $n_p^2 = .632$) and was
466 higher in the Stroop than in the Control session (main effect of session: $F(1, 17) = 8.36$, $p = .010$, $n_p^2 =$
467 $.330$). The session × time interaction reached significance ($F(3, 51) = 4.02$, $p = .012$, $n_p^2 = .191$), and the
468 details of the posthoc comparisons are presented in Figure 2A. Participants reported similar levels of
469 mental fatigue pre cognitive task in the Stroop and Control sessions ($t(17) = -0.879$, $p = .783$, $d = .207$,
470 *95%CI* [-.671, .263]), but higher levels of mental fatigue post cognitive task in the Stroop compared to the
471 Control session ($t(17) = -3.55$, $p = .015$, $d = -.837$, *95%CI* [-1.367, -.288]).

472 *Motivation.* Motivation to perform the cognitive tasks decreased overtime ($F(2, 34) = 94.36$, $p <$
473 $.001$, $n_p^2 = .847$) and was lower in the Stroop than in the Control session (main effect of session: $F(1, 17)$
474 $= 5.88$, $p = .027$, $n_p^2 = .257$). The session × time interaction reached significance ($F(2, 34) = 5.99$, $p = .006$,
475 $n_p^2 = .261$), and details of the posthoc results are presented in Figure 2B. Pre cognitive task, participants
476 reported similar levels of motivation in the Stroop and Control sessions ($t(17) = -.175$, $p = .863$, $d = -.041$,
477 *95%CI* [-.503, .422]). Midway through cognitive tasks, participants were more motivated to continue in
478 the Control than in the Stroop session ($t(17) = 3.382$, $p = .011$, $d = .797$, *95%CI* [.256, 1.321]). Post
479 cognitive tasks, participants reported similar levels of motivation to repeat the cognitive task they had
480 just completed ($t(17) = 2.027$, $p = .117$, $d = .478$, *95%CI* [-.017, .960]). Motivation (Figure 2C) to perform
481 the cycling tests decreased from pre to post test ($F(1, 17) = 12.49$, $p = .003$, $n_p^2 = .424$), with no difference
482 between sessions ($F(1, 17) = .108$, $p = .476$, $n_p^2 = .006$) and no session × time interaction ($F(1, 17) = .003$,
483 $p = .956$, $n_p^2 < .001$).

484 *Boredom*. VAS scores for boredom were 4.0 ± 2.8 and 4.3 ± 3.0 at midway and post task for the
485 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 ($F(1, 17) = 2.39$, $p = .140$, $n_p^2 = .123$).

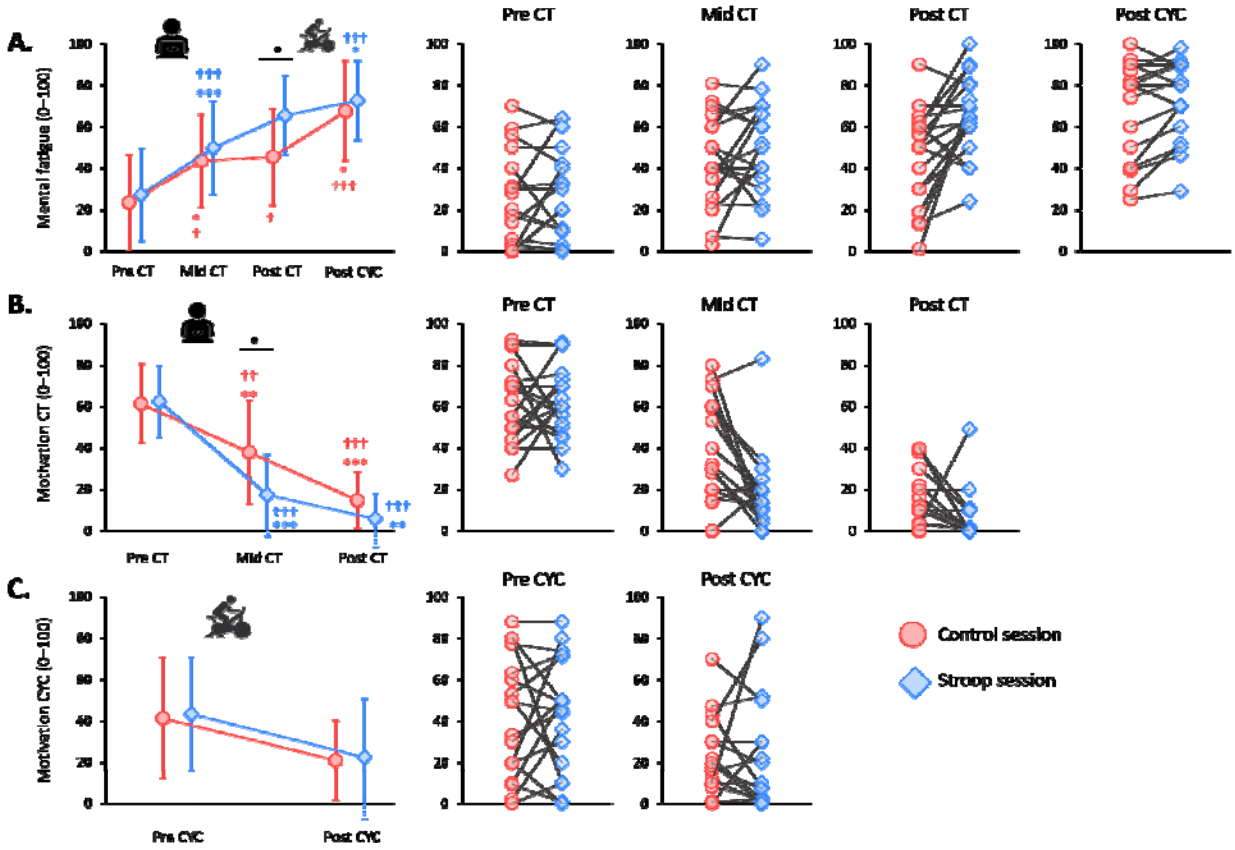
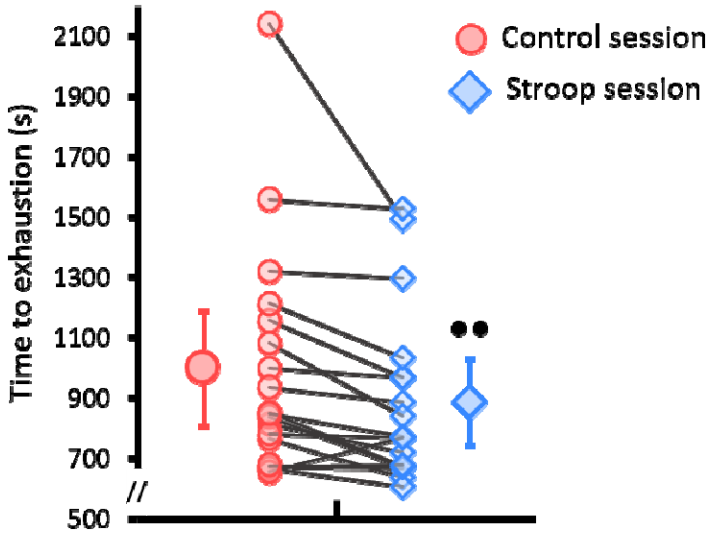


Figure 2. Changes in mental fatigue and motivation during the control (documentary) and Stroop sessions. Panel A shows mean and individual values for mental fatigue level before the cognitive tasks (pre CT), midway through the cognitive tasks (mid CT), immediately after the cognitive tasks (post CT) 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.

525 **Cycling time to exhaustion**

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

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



534

535 **Figure 3. Cycling endurance performance**. The cycling time to exhaustion at 80% peak power
536 output is displayed for the Control (documentary) and Stroop sessions. Large circles and diamonds
537 represent mean data ± standard deviation, while small circles and diamonds indicate individual data
538 points connected by solid lines. •• denotes a significant difference between sessions ($p < 0.01$).
539

540 **Electromyography**

541 SPM analyses revealed no significant main effect of session (Stroop vs. Control) on EMG activation
542 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.

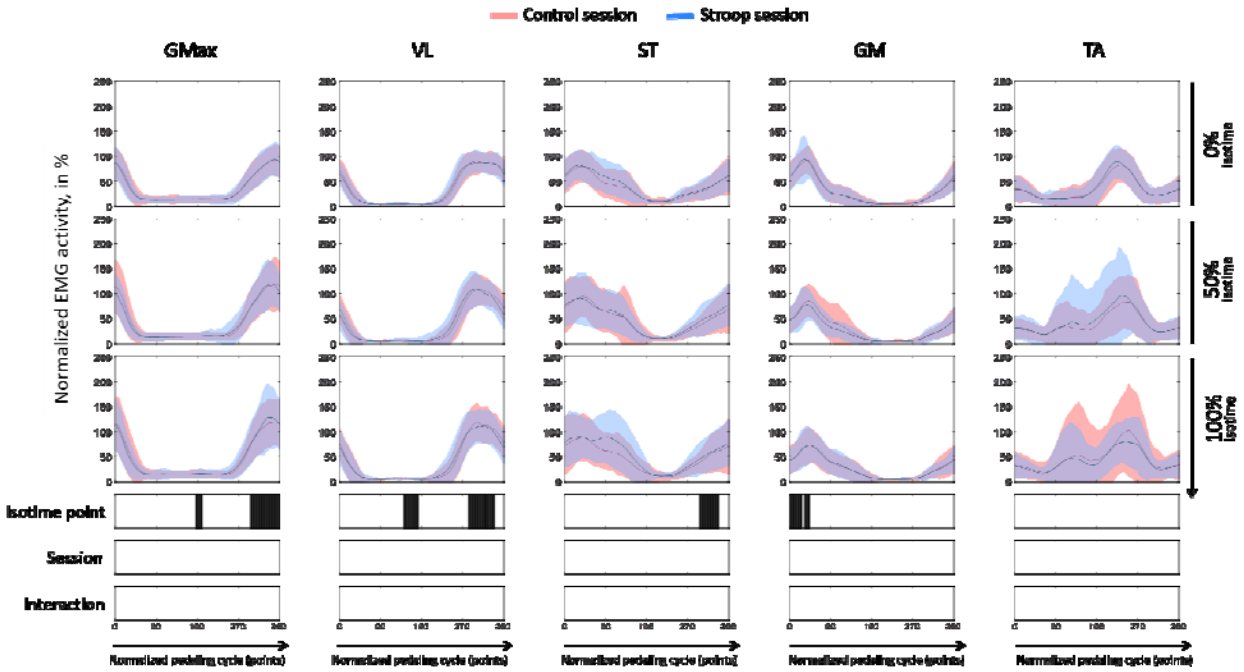


Figure 4. Electromyographic (EMG) activity of the lower limb muscles during the cycling time to exhaustion test for the control (documentary) and Stroop sessions. Electromyographic (EMG) activity of

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.

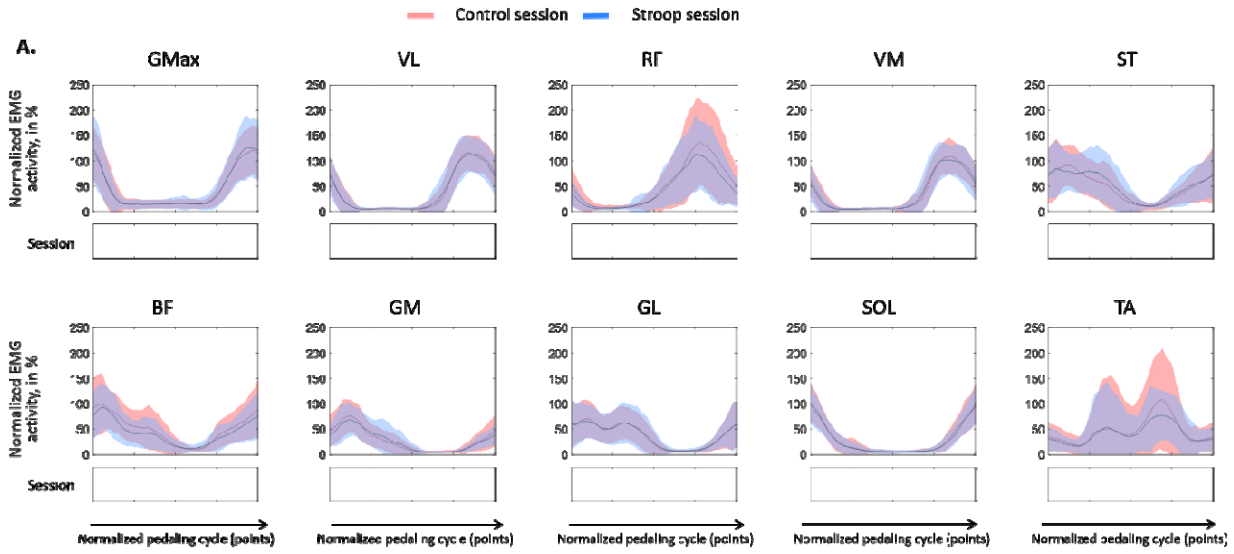


Figure 5. Electromyographic (EMG) activity of the lower limb muscles at exhaustion for the control (documentary) and Stroop sessions. EMG activity of the gluteus maximus (GMax), vastus lateralis (VL), rectus femoris (RF), vastus medialis (VM), semi tendinous (ST), biceps femoris (BF), gastrocnemius medialis (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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589 **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 ($W = 34.00$, $p = .964$, $r_{rb} = -.030$).

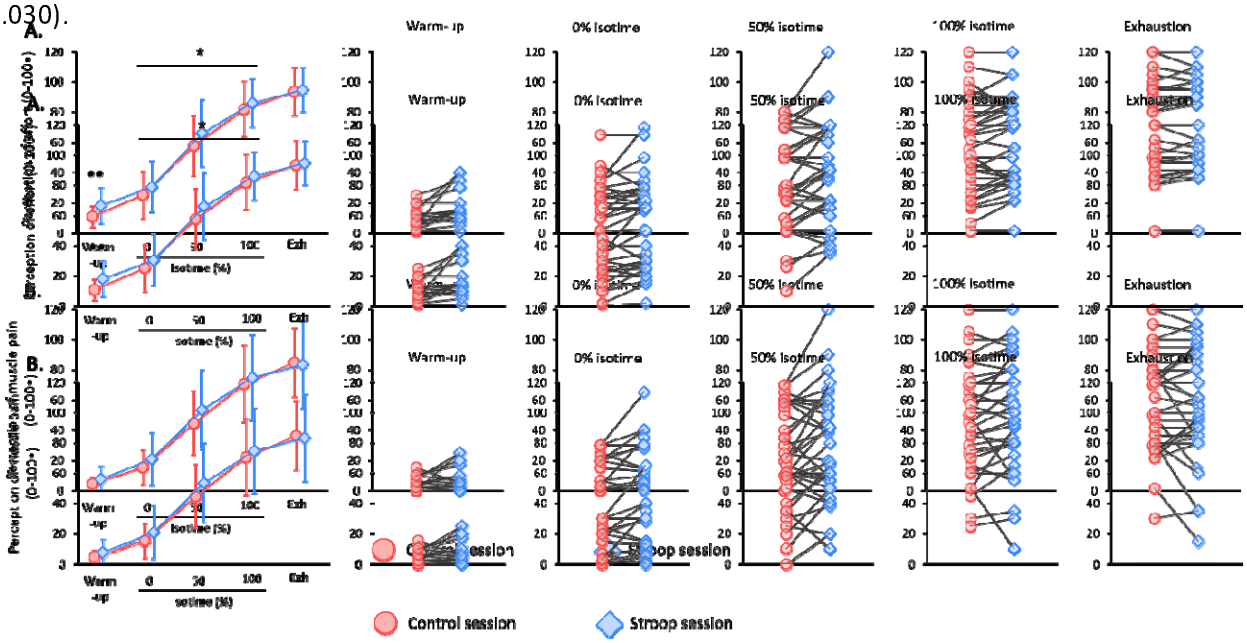

Figure 6. Perceptions of effort and muscle pain during the cycling exercise for the control (documentary) and Stroop sessions. Panel A shows mean and individual values for the perception of effort during the warm-up performed at 40% peak power output (PPO) and the time to exhaustion test at 80% PPO. 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 $p > .05$, $d = .14$–$.38$).

645 ## Discussion.

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

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

651 Our first objective was to investigate whether the increased perceived effort in the presence of
652 mental fatigue was associated with alterations in muscle activation during cycling. Our hypothesis of
653 altered muscle activation was grounded on prior evidence reporting changes in EMG activity following
654 prolonged mental exertion during upper- and lower-limb isometric tasks (Bray et al. 2008; Graham et al.
655 2014; Jacquet et al. 2021; Budini et al. 2014), as well as during a submaximal cycling task (Pageaux et al.
656 2015). Collectively, these findings suggest that mental fatigue may affect central motor command during
657 subsequent physical tasks, potentially contributing to the observed increased perceived effort.

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

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

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

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

695

696 **Mental Fatigue Impairs Endurance Performance.**

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

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

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

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

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

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

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

743 **Limitations and perspectives for future research**

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

755 **Conclusions**

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

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

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