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1　　　　　The effects of fatigued working memory functions on hypothesis

2　　　　　testing during acquisition of a motor skill

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1 Abstract

Implicit motor learning paradigms aim to minimise verbal-analytical engagement in motor performance. Some paradigms do this by decreasing working memory activity during practice, which reduces explicit processes associated with the search for motor solutions (e.g., hypothesis testing). Here we designed a mentally demanding motor task to fatigue working memory prior to motor practice and then tested whether it reduced hypothesis testing. Fifty-nine participants were randomly assigned to complete the mentally demanding motor task (cognitive fatigue group) or to complete an undemanding motor task (non-fatigued control group). Feelings of fatigue, working memory functions, electroencephalography (EEG) Fz power and vagal control were assessed pre- and post-task to quantify the effect of the mentally demanding motor task on cognitive fatigue. Thereafter, an adapted shuffleboard task was completed to determine the impact on hypothesis testing. Hypothesis testing was assessed by self-report, technique changes and equipment-use solutions. Additionally, verbal-analytical engagement in motor performance was (indirectly) gauged with EEG T7-Fz connectivity and T7 power measures. Participants in the cognitive fatigue group reported more fatigue, and displayed moderated working memory functions and Fz theta power. During practice of the shuffleboard task, participants also displayed more technique changes and higher verbal-analytical engagement in motor planning (EEG T7-Fz connectivity), compared to participants in the control group. The mentally demanding motor task suppressed working memory functions, but resulted in more, rather than less, hypothesis testing during shuffleboard practice. The implications are discussed in the context of implicit motor learning theory.

Key words: fatigue, electroencephalography, conscious control, implicit motor learning, executive functions

2   General introduction

It has been claimed that working memory supports the processing, storage and manipulation of information (Baddeley, 1992; Bo & Seidler, 2009; Just & Carpenter, 1992; Kane & Engle, 2002) and underpins explicit motor learning by supporting the development and storage of rules and information about how a motor task is performed (e.g., MacMahon & Masters, 2002; Maxwell, Masters, & Eves, 2003). Limiting the role of working memory in practice has been shown to lead to development and storage of much less information, in a process described as implicit motor learning (Masters, 1992). Masters (1992) demonstrated that participants learned a golf putting skill more implicitly when they practiced while carrying out a concurrent secondary task. The task, random letter generation, was designed to use resources of working memory normally available to process hypotheses about movement solutions. Masters (1992) concluded that motor performance can improve without the accumulation of rules and information about how to perform. Consequently, Masters (1992) argued that this type of learning, implicit motor learning, promotes reduced conscious engagement in performance compared to explicit motor learning (e.g., Masters, 1992; Maxwell et al., 2003).

Masters and colleagues have since developed other implicit motor learning paradigms, such as analogy learning (Liao & Masters, 2001) and error-reduced learning (Maxwell, Masters, Kerr, & Weedon, 2001), which aim to reduce working memory activity during practice. Maxwell et al. (2001), for example, constrained the environment to reduce the amount of errors that occurred during practice, thus reducing the necessity for working memory to be engaged in hypothesis testing because performance was successful. These paradigms, however, influence working memory indirectly, so they do not unconditionally suppress the tendency that people have to use working memory to process hypotheses (e.g., Buszard, Farrow, Zhu, & Masters, 2016). Direct working memory suppression potentially overcomes this issue by blocking access to working memory resources. Zhu et al. (2015), for example, used cathodal (i.e., inhibitory) transcranial direct current stimulation (tDCS) to suppress activity in the left dorsolateral prefrontal cortex (associated with verbal working memory) during practice of a golf putting task. Zhu et al. (2015) concluded that in comparison to sham stimulation (placebo), tDCS of the left dorsolateral prefrontal cortex suppressed verbal working memory activity, thus causing a less explicit, more implicit, mode of learning.

Cognitive fatigue potentially is also a method by which to suppress verbal working memory activity. Cognitive fatigue has been shown to reduce top-down conscious control processes (e.g., Borragan, Slama, Destrebecqz, & Peigneux, 2016; van der Linden, 2011; van

der Linden, Frese, & Meijman, 2003; Wolfgang & Schmitt, 2009). Wolfgang and Schmitt (2009), for example, found that prolonged performance of a Stroop task (480 trials) caused cognitive fatigue, which disrupted performance. The Stroop task (Stroop, 1935) requires participants to name the colour in which colour words are written (e.g., the word 'green' is written in blue). Successful performance requires participants to consciously inhibit their automatic tendency to read and name the written word. Wolfgang and Schmitt (2009) argued that cognitive fatigue reduced cognitive resources available for top-down conscious inhibition of automatic responses (reading) during Stroop performance.

Borragan et al. (2016) examined the effects of cognitive fatigue on learning a serial reaction time task (SRTT). The SRTT requires participants to rapidly press buttons indicating the location of stimuli presented on a screen. Typically, participants are unaware that the order of the stimuli is repeated in a specific sequence, yet they become faster at responding and eventually anticipate accurately the position of each stimulus in the sequence. Borragan et al. (2016) found that cognitive fatigue caused by a TloadDback protocol,[1] improved learning of the sequence. They argued that during repetition of the SRTT, cognitive fatigue inhibited disruptive top-down conscious interference in the task, which was beneficial for implicit (procedural) learning. Consequently, we argued that processing task-relevant information needed for hypothesis testing is likely to be reduced if cognitive fatigue is used to suppress working memory activity prior to motor practice. Less information should, therefore, be stored during motor practice, which should result in implicit motor learning. In a pilot experiment (Hoskens, Boaz-Curry, Buszard & Masters, 2018), we first tested the veracity of the Borragan et al. (2016) protocol by employing it to fatigue participants prior to performing a golf putting task (i.e., ten trials from a distance of 300 cm). The control group watched a nature documentary prior to performing the same golf putting task. Compared to participants in the control group, participants in the fatigue group reported higher subjective feelings of cognitive fatigue, assessed using the Visual Analogue Scale of Fatigue (VASf; Lee, Hicks, & Nino-Murcia, 1990). However, participants neither displayed suppressed working memory activity[2]

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[1] The protocol consisted of three parts: (1) a practice session of the TloadDback task (approx. duration 5 min), (2) determination of maximum cognitive load for the TloadDback task (approx. duration not reported) and (3) TloadDback task performance at individual maximum cognitive load (16 min).

[2] Working memory activity was measured by performance on the Reading Span Task. The Reading Span Task consisted of digits and sentences displayed on a computer monitor in an alternating sequence. Participants were required to recall the sequence of the digits at the end of each trial and to judge as fast as possible whether the sentences made sense or not (e.g., '*Christmas is in December*'). The number of digits (and sentences) gradually increased across blocks of trials, with each block consisting of three trials of a similar sequence length.
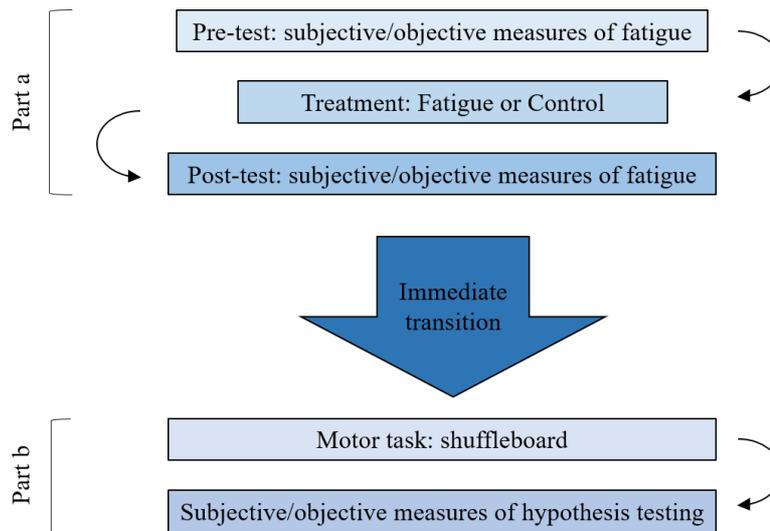
117   as a consequence of fatigue, nor did they display reduced conscious engagement[3] during

118   performance of the putting task. Based on the results of this pilot experiment, we concluded

119   that the Borragan et al. (2016) task may be appropriate for simple motor tasks, which rely

120   primarily on '*where*' to move (e.g., the SRTT task), but not complex motor tasks that require

121   coordination of many degrees of freedom. Such tasks (e.g., golf putting) rely on processes of

122   '*how*' and '*where*' to move. Therefore, the process of solving '*how*' to move is likely to

123   dramatically increase motivation to test hypotheses. Hence, the cognitive fatigue task

124   developed by Borragan et al. (2016) may not have been adequate to override motivation to test

125   hypotheses.

126   Consequently, we developed a new cognitive fatigue task to better disrupt or reduce

127   verbal-analytical engagement (and thus hypothesis testing) in more complex, goal driven sports

128   tasks. We incorporated two important modifications. First, we designed a cognitive fatigue task

129   with greater emphasis on motor control. Second, we focused on working memory efficiency

130   (i.e., information processing), rather than working memory capacity. The executive functions

131   of working memory are thought to play a major role in information processing by *updating* old

132   information with new information, *switching* between incoming information, and *inhibiting*

133   irrelevant incoming information (Karatekin, Lazareff, & Asarnow, 2000; Miyake et al., 2000).

134   These processes are also predicted to play an important role in motor performance (Baumeister,

135   Reinecke, Liesen, & Weiss, 2008; Diamond, 2000; Yogev-Seligmann, Hausdorff, & Giladi,

136   2008). Therefore, our cognitive fatigue task required inhibition, switching and updating in

137   order to catch different coloured balls in a particular sequence. Additionally, we added neural

138   measurement to gather biological evidence of the effects of cognitive fatigue on working

139   memory efficiency and verbal-analytical engagement in motor performance. Finally, the motor

140   task that participants practiced when they were cognitively fatigued was designed so that we

141   could objectively assess hypothesis testing. The experiment was conducted in two parts (A &

142   B). First, we investigated whether working memory suppression was caused by our cognitive

143   fatigue task and second, we asked whether this caused reduced verbal-analytical engagement

144   and hypothesis testing when practicing a complex motor skill, compared to a non-fatigued

145   (control) group (See Figure 1).

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[3] Conscious control was gauged by: (1) assessing the number of movement adjustments during golf putting (an indication of how actively participants were testing hypotheses) and (2) self-reported accounts of the amount of conscious motor processing.

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┌ Part a ┐
    Pre-test: subjective/objective measures of fatigue
          Treatment: Fatigue or Control
    Post-test: subjective/objective measures of fatigue

              Immediate
              transition

┌ Part b ┐
          Motor task: shuffleboard
    Subjective/objective measures of hypothesis testing
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Figure 1. Flow diagram of the procedure used for this study.

3   Experiment 1: Part A

In the first part of the experiment, subjective feelings of fatigue and mental effort were assessed to determine how demanding the newly designed cognitive fatigue task was. Additionally, we measured the effect of the task on the performance of computer-based tasks designed specifically to assess executive functions (inhibition, switching, and updating). Theta (4-7 Hz) power at the frontal midline (i.e., Fz region) of the brain was also measured during performance of the executive function tasks, using electroencephalography (EEG), in order to gauge the effect of cognitive fatigue on working memory activity. The frontal midline Fz site overlies the prefrontal cortex, where working memory activity is thought to occur (e.g., Imburgio & Orr, 2018; Jensen & Tesche, 2002; Klimesch, 1999; Miller & Cohen, 2001), and theta power in the Fz region (Fz theta power) is associated with working memory functions, including information maintenance and processing (Jensen & Tesche, 2002; Sauseng, Griesmayr, Freunberger, & Klimesch, 2010). Research has shown that Fz theta power increases in response to cognitive fatigue, suggesting that working memory functions are impacted negatively (Boksem, Meijman, & Lorist, 2005; e.g., Kato, Endo, & Kizuka, 2009; e.g., Wascher et al., 2014). Wascher et al. (2014), for example, revealed that theta power increased as participants became mentally fatigued during a Simon effect task (4 hours). The Simon effect task is a cognitively demanding spatial stimulus-response compatibility task, which therefore impacts working memory.

168   We also measured cardiac vagal control during performance of the executive function
169   tasks by assessing heart rate variability (HRV), which is the variability in time between
170   heartbeats (Laborde, Mosley, & Mertgen, 2018). The 'neurovisceral integration model'
171   (Thayer, Hansen, Saus-Rose, & Johnsen, 2009) suggests that there is a connection between the
172   prefrontal cortex and the heart through the central autonomic network and the vagus nerve.
173   Specifically, this model suggests that reduced prefrontal cortex activity leads to decreased
174   cardiac vagal control. Consequently, HRV may be an indirect measure of working memory
175   efficiency because of the association between the prefrontal cortex and working memory
176   (Hansen, Johnsen, & Thayer, 2003; Laborde, Furley, & Schempp, 2015; Thayer et al., 2009).
177   Hence, if cognitive fatigue suppresses working memory functions, this should be reflected by
178   reduced cardiac vagal control (i.e., HRV) (Tanaka, Mizuno, Tajima, Sasabe, & Watanabe,
179   2009).

180   We hypothesized that the cognitive fatigue task would require considerable effort and
181   would thus cause high perceived feelings of mental fatigue compared to a non-fatigued control
182   group. We also expected to see decreased performance of the executive function tasks.
183   Furthermore, in this study we predicted that cognitive fatigue would increase Fz theta power
184   and reduce HRV during the executive function tasks compared to no cognitive fatigue.

185   <div align="center">**4   Method**</div>

186   **4.1 Participants and Design**

187   A priori calculation using GPower 3.1.9.2 (Faul, Erdfelder, Lang, & Buchner, 2007), based on
188   an effect size of $\eta^2 = 0.55$ (Borragan et al., 2016), with power set at 0.95 and alpha at 0.05,
189   revealed a desired sample size of 48, or 24 per group. To allow for drop-out, fifty-nine people
190   were recruited to participate in the experiment. To control for handedness,[4] only right-handed
191   people were included. All participants had normal/corrected vision. The participants were
192   instructed not to consume alcohol or drugs 24 hours prior to testing or caffeine 3 hours prior to
193   testing, and to obtain at least 6 hours of sleep the night before testing. A small incentive
194   (10NZD) was provided for participating. A between subjects design was adopted, with
195   participants randomly assigned to a Fatigue group (29 participants, 16 female, mean age =

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[4] Only right-handed participants were included, because hemisphere dominance is potentially influenced by handedness (e.g., Grabowska et al., 2012).

196   24.69 years, SD = 6.26 years)[5] or a Non-fatigue (control) group (28 participants, 17 female,

197   mean age = 23.50 years, SD = 5.38 years), using a random sequence generator. The study

198   received ethical approval from the University Human Research Ethics Committee.

199   **4.2 Treatment Task**

200   Participants were required to complete a ball catching task on a standard table tennis table (276

201   x 153 x 76 cm), during which table tennis balls were projected down the centre line with a table

202   tennis ball machine (Robo-Pong 2040, Newgy industries) starting with a frequency of

203   approximately 23 balls/min. The balls were coloured (white, blue, black and orange) and were

204   mixed regularly in the tray to ensure the colours were randomly dispersed. Participants were

205   instructed to catch the balls with both hands and to place them in a container standing

206   immediately in front of them.

207   *4.2.1   Fatigue group*

208   The task was performed over five levels (approximately 3 min each), which increased

209   incrementally in difficulty. The cognitive fatigue task was designed to target the executive

210   functions of working memory, with the following instructions:

211   "*The ball machine will be shooting different coloured balls to you; you are required to catch*

212   *the balls with both hands and to put them in the container in front of you. But, there is always*

213   *one colour that you are not catching, you just let this ball go* [inhibition]. *During the task, I*

214   [i.e., researcher] *will tell you which colour you are not catching* [switching]. *Each time you*

215   *catch a ball call out loud the colour of the previous ball that came out of the machine* [1-back,

216   updating]. *In between levels, I* [i.e., researcher] *will give you a starting number, and you have*

217   *to count backwards in sevens from that number."*

218   The colour of the ball that was not to be caught switched after every ten trials during

219   the first level of the fatigue task. During the second level, this decreased to every six trials,

220   after which it decreased by one during each subsequent level. The number of colours also

221   changed between levels. During the first level, the colour of the ball that was not to be caught

222   switched between black and blue, but during the second level, the colour not to be caught

223   switched between black, blue, and orange. During the third level, the colour of the ball not to

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[5] Participants were only included in the Fatigue group if they displayed scores indicative of cognitive fatigue following the intervention in two of the following four measures (i.e., inhibition, switching, shifting, self-reported fatigue). Based on this criterion, two participants were excluded from analysis.

224   be caught switched between blue, orange and white, whereas during the fourth and fifth levels,

225   the colour not to be caught switched between all four colours (black, blue, orange, and white).

226   To maintain fatigue, participants were required to count backwards in sevens between levels

227   while the researcher replaced the balls in the ball machine (30 sec).

4.2.2   Non-fatigue (control) group

229   Participants were required to audibly identify the colour of the ball that was caught (0-back).

230   Ball frequency was increased incrementally from approximately 23 balls/min to 37 balls/min

231   across over levels to maintain their engagement in the task. Participants rested between levels

232   (30 sec).

4.3 Measures – manipulation checks

4.3.1   Feelings of fatigue and mental effort

235   Subjective feelings of fatigue were measured with an adapted version of the Visual Analogue

236   Scale of Fatigue (VASf, Lee, et al., 1990). The scale consists of four questions related to fatigue

237   and attention (*e.g., 'how tired are you at this moment?'*). Each question is rated using a Likert

238   scale ranging from '*not at all*' (1) to '*extremely*' (10). The National Aeronautics and Space

239   Administration-Task Load Index (NASA-TLX) was used to measure the amount of mental

240   effort participants utilised while performing the fatigue and non-fatigue (control) task (Hart &

241   Staveland, 1988; Mueller & Piper, 2014). This scale consists of six questions related to mental

242   effort (e.g., '*how hurried or rushed was the pace of the task?').* Responses were marked on a

243   vertical line ranging from '*very low*' (1) to '*very high*' (21). Both scales were presented via

244   *Psychology Experiment Building Language* (PEBL, Mueller & Piper, 2014) and the average

245   was computed for each scale.

4.3.2   Computer-based executive function tasks

247   Three different computer-based executive function tasks were presented via PEBL (Mueller &

248   Piper, 2014). Randomization of task stimuli was performed between and within participants by

249   the PEBL software. The average duration of each task was 1 min and 40 sec.

250   ***Inhibition.*** The Victoria Stroop Task (Troyer, Leach, & Strauss, 2006), which is a brief version

251   of the Stroop task (Stroop, 1935) was used to assess the ability to inhibit irrelevant stimuli. The

252   Victoria Stroop task includes three blocks of twenty-four trials. Block 1, the *dot* block,

253   displayed dots in different colours (see Figure 2). Block 2, the *word* block, displayed random

254   words in different colours (e.g., car, see Figure 2). Block 3, the *interference* block, displayed

names of colours written in a different colour (e.g., yellow written in green letters, see Figure 2). Block 1 and 2 were used for familiarization, whereas Block 3 tested inhibition. Participants were required to indicate the colour of the dot or word by pressing the key representing either red, blue, green or yellow. Trials were repeated if an answer was incorrect. The Victoria Stroop task has been shown to have high test-retest reliability (Troyer et al., 2006).


dot block   *word* block   *interference* block
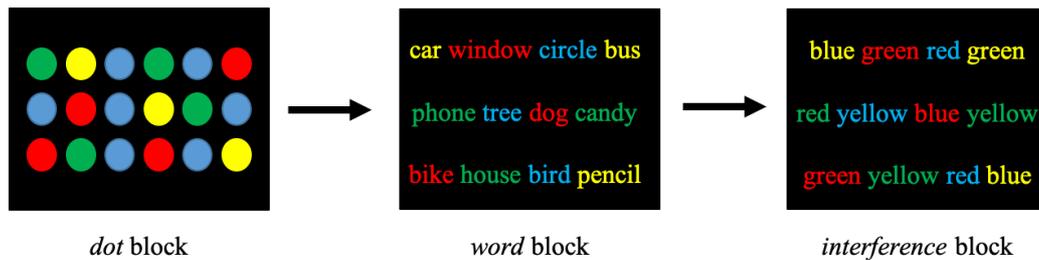
Figure 2. Overview of the Victoria stoop task. The *dot, word* and *interference* blocks are shown from left to right.

Switching. The Plus-Minus task was used to assess the ability to switch between task requirements (Jersild, 1927; Miyake et al., 2000; Spector & Biederman, 1976). The task consisted of three blocks of ten trials. Block 1, the *addition* block required participants to add 3 to each number that was displayed, by typing it on the keyboard (see Figure 3). The next number was then displayed. Block 2, the *subtraction* block, required participants to subtract 3 from each number, and Block 3, the *switching* block, required participants to alternate between adding and subtracting 3 from the displayed number (see Figure 3). To our knowledge, test-retest has not been reported for the Plus-Minus task.



addition block   *subtraction* block   *switching* block
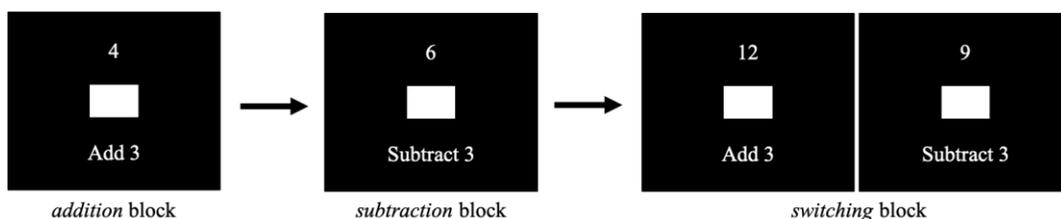
Figure 3. Overview of the Plus-Minus task. The *addition, subtraction* and *switching* block are shown from left to right.

Updating. The N-back task was used to assess updating abilities (Kirchner, 1958; Oberauer, 2005; Salthouse, Atkinson, & Berish, 2003). The task consisted of three blocks. For each block

278 a sequence of letters was displayed, with an inter-stimulus interval of 3000 msec. Block 1
279 required participants to remember the letter displayed one-back in the sequence, and press the
280 shift on the keyboard when the letter they saw was the same as the previous letter. Eleven
281 letters were presented sequentially with the same letter presented in the sequence on four
282 random occasions. Block 2 required participants to recall the letter displayed two back in the
283 sequence and to press the shift key when the letter two back was the same (see Figure 4 for
284 example of 2-back updating). Twelve letters were presented sequentially with the same letter
285 presented two back in the sequence on four random occasions. Block 1 and Block 2 were
286 practice blocks, whereas Block 3 was a test block. Block 3 required participants to recall the
287 letter displayed two back in the sequence and to press the shift key when the letter two back
288 was the same. However, twenty-two letters were presented sequentially with the same letter
289 presented two back in the sequence on six random occasions. The N-back task has adequate
290 test-retest reliability (Soveri et al., 2018).
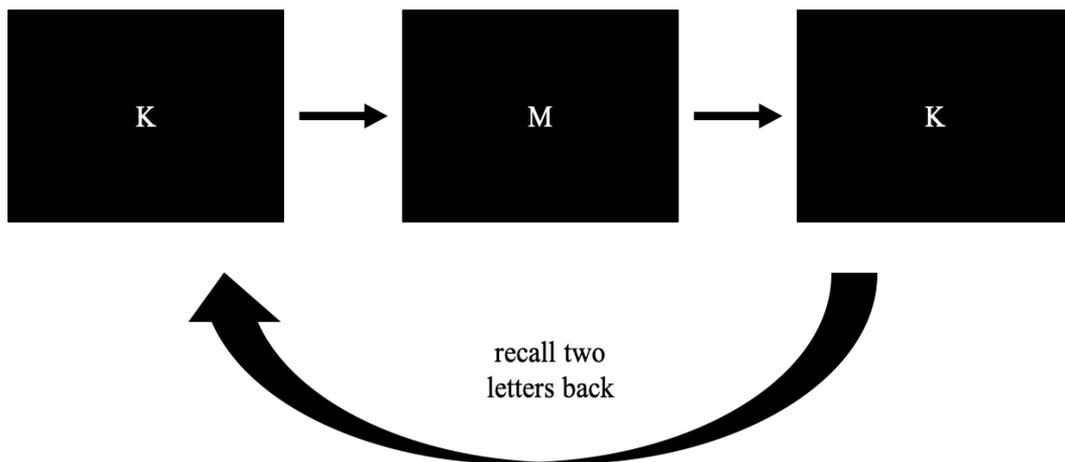
291

292 *Figure 4.* Overview of the 2-back task. An example of a letter sequence is shown, with the
293 letter 'K' representing the 2-back rule.

294 ### 4.3.3 EEG power

295 EEG was used to assess cortical activity during the computer-based executive function tasks.
296 EEG was recorded from eight active electrodes, six of which were positioned over specific
297 regions of the brain, using the 10-20 system (Jaspers, 1958): T7, T8, Fz, F3, FP1, Cz.
298 Additionally, two electrodes were placed on the right and left mastoids (Neuroprene 8-
299 electrode cap, Neuroelectrics, Barcelona, Spain). Common Mode Sense (CMS) and Driven
300 Right Leg (DRL) electrodes were used to increase the common mode rejection ratio of the EEG
301 signals. EEG signals were amplified and digitized at 1024 Hz, with 24-bit resolution
302 (Neurosurfer, Neuroelectrics, Barcelona, Spain).

4.3.4 Cardiac vagal control

304 Cardiac vagal control during the executive function tasks was obtained by measuring heart rate

305 (HR) activity (beats per minute, BPM), from which HRV was extrapolated. A RS800CX Polar

306 HR monitor system was used (Polar Electro, Kempele, Finland). The system has previously

307 been validated for measuring HR activity (Weippert et al., 2010). The signal (received from a

308 chest strap) was stored in Polar ProTrainer 5^{tm} software and offline cleaned and analysed with

309 Kubios software (standard version, 3.3, Biosignal, Analysis and Medical Imaging Group,

310 University of Kuopio, Finland, developed in Matlab 2012a; Tarvainen, Niskanen, Lipponen,

311 Ranta-Aho, & Karjalainen, 2014).

312 **4.4 Procedure**

313 Participants were informed about the context of the study and signed an informed consent form

314 before providing general demographics prior to the start of the experiment. An EEG cap and

315 HR monitor band were fitted and a 4 min EEG and HR resting state assessment was performed

316 (2 min with closed eyes and 2 min with open eyes). Detailed instructions about each task in the

317 experiment were provided in order to minimize explanation time between tasks. Participants

318 completed the VASf scale and the three computer-based executive function tasks (Victoria

319 Stroop, Plus-Minus, and N-back) pre-fatigue and post-fatigue (or control). The NASA-TLX

320 was completed post-fatigue (or control) task. The task (fatigue or non-fatigue) was performed

321 at five levels (total duration around 15 min). To ensure that participants remained engaged in

322 the task, they were informed that it was important to complete all five levels in order to proceed

323 to the next part of the experiment (i.e., Experiment 1: Part B).

324 **4.5 Data analyses**

325 *4.5.1 Computer-based executive function tasks*

326 *Inhibition.* Performance was determined by the amount of responses made to successfully

327 complete the Victoria Stroop task (score) and task duration for each of the three task conditions

328 (*dot, word, interference*).[6] The inhibition-cost for the *interference* block was computed by

329 relating the amount of trials (inhibiton-cost$_{score}$) and duration time (inhibiton-cost$_{duration}$) of the

330 *interference* block with the *dot* block and the *word* block:

---

[6] Non-native English speakers (N = 8) were excluded from this analysis because their performance on an English version Stroop task may not have accurately represented their inhibition ability (Rosselli et al., 2002).

331
$$\text{Inhibition-cost} = \textit{interference block} - \frac{(\textit{dot block} * \textit{word block})}{(\textit{dot block} + \textit{word block})}$$

332   The inhibition costs were computed to control for any gross psychomotor speed (Strickland,

333   D'Elia, James, & Stein, 1997). A higher score indicates worse performance on the interference

334   block (Strickland et al., 1997).

335   ***Switching.*** Performance was determined by the number of correct answers (i.e., score),

336   completion time and median reaction time (RT) for the three different blocks in the Plus-Minus

337   task.[7] The switching-costs were computed by relating the score of the *switching* block with the

338   average of the *adding* and *subtracting* blocks, separately for number of correct answers

339   (switching-cost$_{score}$), RT (switching-cost$_{RT}$) and completion time (switching-cost$_{duration}$)

340   (Miyake et al., 2000):

341
$$\text{Switching-cost} = \textit{switching block} - \frac{\textit{addition block} + \textit{subtraction block}}{2}$$

342   The switching-costs were computed to control for any overall difficulties with mathematical

343   performance (Miyake et al., 2000). However, the switching-cost$_{score}$ entails an opposite

344   interpretation from the switching-cost$_{duration}$ and switching-cost$_{RT}$. A higher switching-cost$_{score}$

345   means more correct answers for the switching block compared to the other two blocks (addition

346   and subtraction), whereas higher switching-cost$_{duration}$ and switching-cost$_{RT}$, means longer

347   response time for the switching block compared to the other two blocks.

348   ***Updating.*** Performance was determined by calculating the number of correct responses,[8]

349   together with RT on the correct target letter trials (i.e., when response is required) on the N-

350   back task.

351   ***4.5.2   EEG power***

352   EEG signals captured during performance of the executive function tests were processed

353   offline using EEGlab software (version 14, Delorme & Makeig, 2004), running on Matlab

354   software (MathWorks, Inc., USA version 2018b). The data was resampled to 250 Hz and band

355   pass filtered (1-35Hz band pass filter), re-referenced to the average of the two mastoids and

356   de-trended. Baseline correction (200ms before time of interest) was completed and

---

[7] Participants unable to achieve more than five correct answers in either addition or subtraction block during the pre-test were excluded (N = 1).

[8] The score was taken from all trials, including the correct response to non-target letters (not responding) and target letters (responding). This was done, because otherwise, performance would only be computed from six trials.

357 electromyography (EMG) and electrooculography (EOG) artefacts were removed using Blind

358 Source Separation (AAR plug in; Gomez-Herrero et al., 2006), and Least Mean Squares

359 regression (Gomez-Herrero et al., 2006; Haykin, 1996). The signals were bundled into epochs

360 and then subjected to a threshold-based artefact removal procedure, where any 250 msec

361 window containing signal fluctuations exceeding ±75 μV was rejected.

362 The clean signal was subjected to time frequency analysis to obtain the estimated

363 instantaneous theta power for 28 sec (the maximum duration after artefact removal) of each of

364 the three executive function tasks. This analysis was performed by convolving the fast Fourier

365 transform (FFT) power spectrum of the signal with a family of complex Morlet wavelets and

366 eventually taking the inverse FFT (Cohen, 2014). Power at each frequency bin was defined as

367 the squared magnitude of the results of the convolution and averaged across the theta (4-7 Hz)

368 frequency band. To ensure normal distribution, all power estimates were subjected to a

369 logarithmic ($\log_{10}$) transformation prior to statistical analysis.

4.5.3 Cardiac vagal control

371 The HRV (measure of cardiac vagal control) was obtained from the HR activity during the

372 executive function tasks (3 min and 30 sec in total). Artefacts were filtered out using the

373 automatic medium filter. Thereafter, high frequency (HF-HRV) power (0.15-0.4 Hz) in msec

374 was obtained using fast Fourier transform (Tarvainen et al., 2014), which was then subjected

375 to logarithmic (log10) transformation. *Reactivity* measures of HF-HRV (pre-test and post-test)

376 were determined by calculating the differences between the HRV during the baseline and

377 executive function task performance (Laborde et al., 2018; Laborde, Mosley, & Thayer, 2017).

4.5.4 Statistical approach

379 VASf scores were subjected to a 2 x 3 repeated measure analysis of variance (ANOVA): Group

380 (Fatigue, Non-fatigue) x Test (Baseline, Pre-, Post-). Performance, theta power and *reactivity*

381 HF-HRV during the executive function tasks were all subjected to 2 x 2 repeated measure

382 analyses of variance (ANOVA): Group (Fatigue, Non-fatigue) x Test (Pre-, Post-). An

383 independent t-test was used to compare between group scores on the NASA-TLX scale.

384 Sphericity and normality checks were performed, and controlled for when needed. When main

385 effects or interactions were found, separate ANOVAs were conducted and post-hoc tests were

386 Bonferroni corrected. Effect sizes are reported as partial η squared (η_p^2), with the

387 values .01, .06, and .14 indicating relatively small, medium and large effect sizes, respectively

388 (Cohen, 1988). Cohen's *d* effect size is reported for the independent t-test, with the values 0.2,

389   0.5 and 0.8 indicating relatively small, medium and large effect sizes, respectively (Cohen,

390   1988). The statistical tests were performed using SPSS (IBM, version 25.0) computer software.

391   Significance was set at $p = .05$ for all statistical tests.

392   <div align="center">**5   Results**</div>

393   **5.1 Feelings of fatigue**

394   For VASf, a main effect of Group was not evident, $F(1,51) = 2.88$, $p = .096$, $\eta_p^2 = .05$, but a

395   main effect of Test was evident, $F(1.75,89.34) = 12.42$, $p < .001$, $\eta_p^2 = .20$. Post-hoc analysis

396   revealed higher scores for the post-test compared to both the baseline ($p < .010$) and the pre-

397   test ($p < .001$), which did not differ ($p = 1.00$). Further insight into the Test effect was revealed

398   by a Group x Test interaction, $F(2,102) = 3.41$, $p = .037$, $\eta_p^2 = .06$ (see Figure 5). Follow-up

399   repeated measures ANOVAs for each group separately, revealed no differences across Test in

400   the non-fatigued (control) group, $F(2,50) = 1.92$, $p = .157$, $\eta_p^2 = .07$, but significant differences

401   were evident in the fatigued group, $F(1.54,40.03) = 12.81$, $p < .001$, $\eta_p^2 = .33$. Post-hoc analysis

402   showed that scores in the fatigued group were significantly higher in the post-test compared to

403   both the baseline ($p < .010$) and pre-test ($p < .001$), which did not differ ($p = .427$).
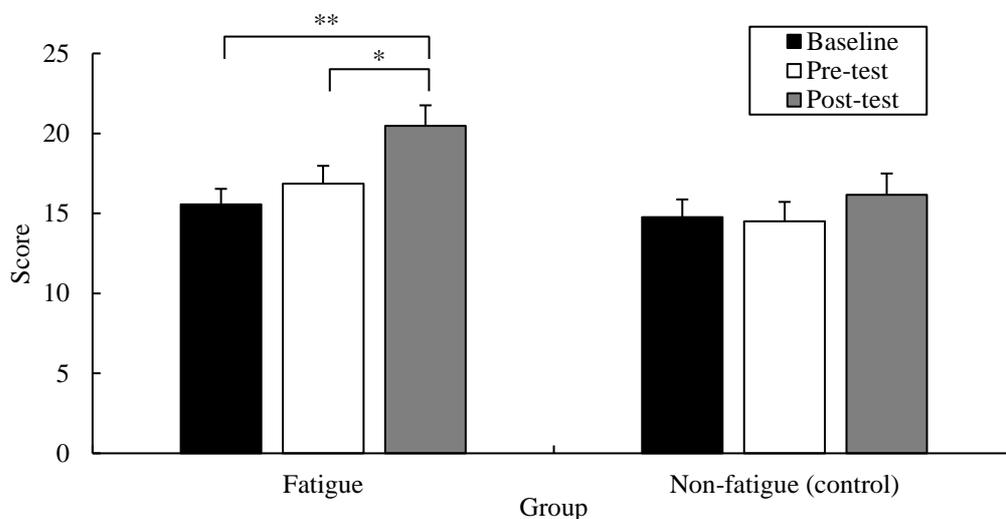
405   *Figure 5.* Mean score on the Visual Analog scale of Fatigue (VASf) for each group at

406   baseline, pre-test and post-test. Error bars represent standard error of the mean. *$p < .05$, **p

407    $< .001$.

408 **5.2 Mental effort**

409 Score on the NASA-TLX (administered at post-test) was significantly higher in the fatigued

410 group (Mean = 76.97, SD = 13.18) compared to the non-fatigued (control) group (Mean =

411 53.75, SD = 23.84), $t(41.79) = 4.53$, $p < .001$, $d = 1.21$.

412 **5.3 Executive functions**

413 *5.3.1 Inhibition*

414 For the Stroop task inhibition-cost$_{score}$ (see formula in Method),[9] neither a main effect of Group,

415 $F(1,46) = 0.04$, $p = .840$, $\eta_p^2 < .01$, nor of Test, $F(1,46) = 1.12$, $p = .295$, $\eta_p^2 = .02$, was revealed.

416 A Group x Test interaction was evident, $F(1,46) = 4.13$, $p = .048$, $\eta_p^2 = .08$ (see Figure 3.6).

417 Separate post-hoc tests for each group revealed that inhibition-cost$_{score}$ was significantly lower

418 (i.e., better performance) in the non-fatigued (control) group during the post-test compared to

419 the pre-test ($p = .032$), but not in the fatigued group ($p = .506$).

420 For the inhibition-cost$_{duration}$, neither a main effect of Group, $F(1,44) = 0.73$, $p = .398$,

421 $\eta_p^2 = .02$, nor of Test, $F(1,44) = 1.98$, $p = .167$, $\eta_p^2 = .04$, was revealed. A Group x Test

422 interaction was not evident, $F(1,44) = 0.53$, $p = .469$, $\eta_p^2 = .01$.[10]

423
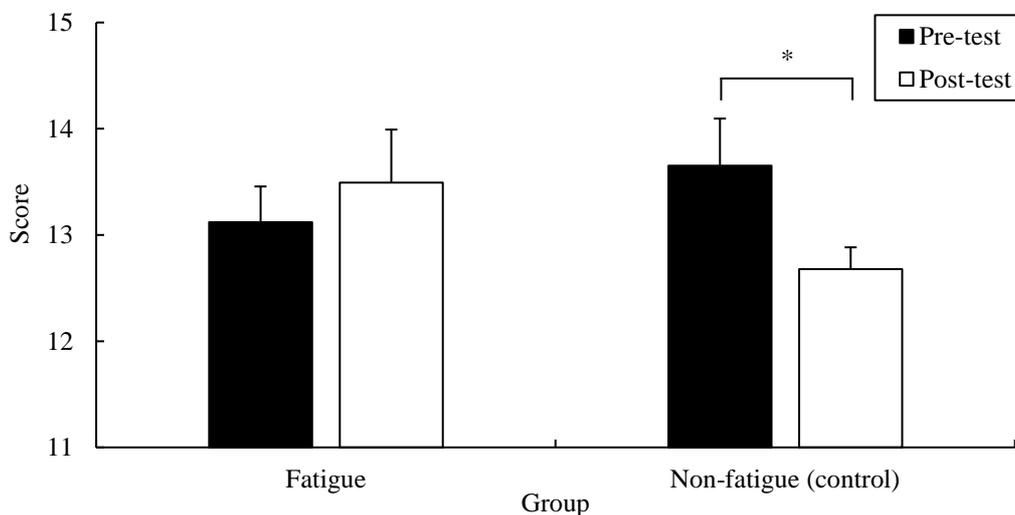
424

425 *Figure 6.* Inhibition-cost$_{score}$ for the Stroop task for each group at pre-test and post-test. The

426 higher the inhibition-cost$_{score}$ the higher the number of attempts needed to complete the

---

[9] Logarithmic (log10) transformation was performed to control for skewness (Troyer et al., 2006).

[10] See Table 1 in Appendix for all mean and SD values for non-significant results.

427 *interference* block (i.e., worse performance). Error bars represent standard error of the mean.

428 *p < .05.

5.3.2 *Switching*

430 For Plus-Minus switching-cost$_{score}$ (see formula in Method),[11] neither a main effect of Group,

431 $F(1,53) = 2.96$, $p = .091$, $\eta_p^2 = .05$, nor of Test, $F(1,53) = 3.11$, $p = .083$, $\eta_p^2 = .06$, was found.

432 However, a Group x Test interaction was evident, $F(1,53) = 4.73$, $p = .034$, $\eta_p^2 = .08$ (see Figure

433 7). Post-hoc analysis for each group revealed that the switching-cost$_{score}$ was significantly lower

434 (i.e., better performance) in the non-fatigued (control) group during the post-test compared to

435 the pre-test, ($p = .010$) but not in the fatigued group ($p = .773$).

436
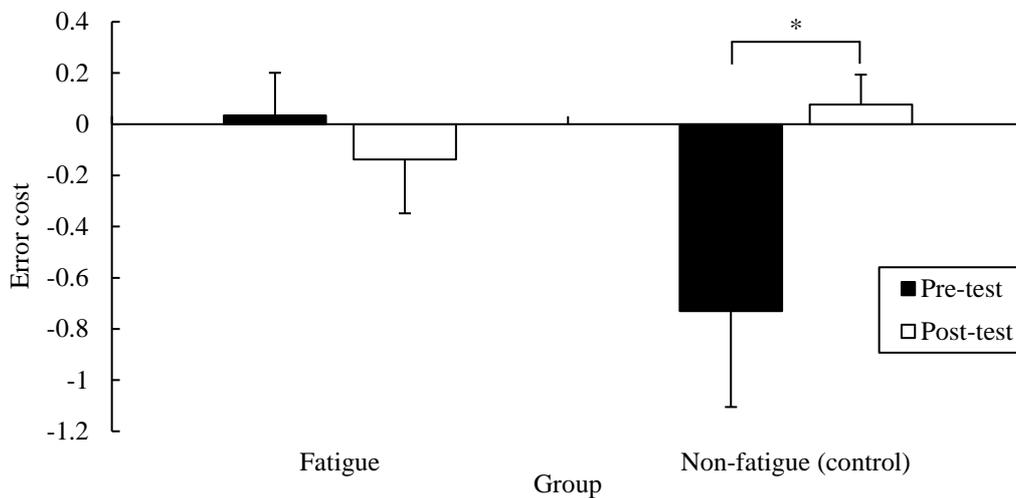
437

438 *Figure 7.* Switching-cost$_{score}$ for the Plus-Minus task for each group at pre-test and post-test.

439 The higher the switching-cost$_{RT}$ the higher the median RT for the switching block, compared

440 to the addition and subtraction blocks. Error bars represent standard error of the mean. *p

441 < .05.

442 For the Plus-Minus switching-cost$_{duration}$, significant main effects were not found for

443 Group, $F(1,52) = 0.13$, $p = .717$, $\eta_p^2 < .01$, or for Test, $F(1,52) = 0.14$, $p = .713$, $\eta_p^2 < .01$, and

444 there was no Group x Test interaction, $F(1,52) = 2.19$, $p = .145$, $\eta_p^2 = .04$.
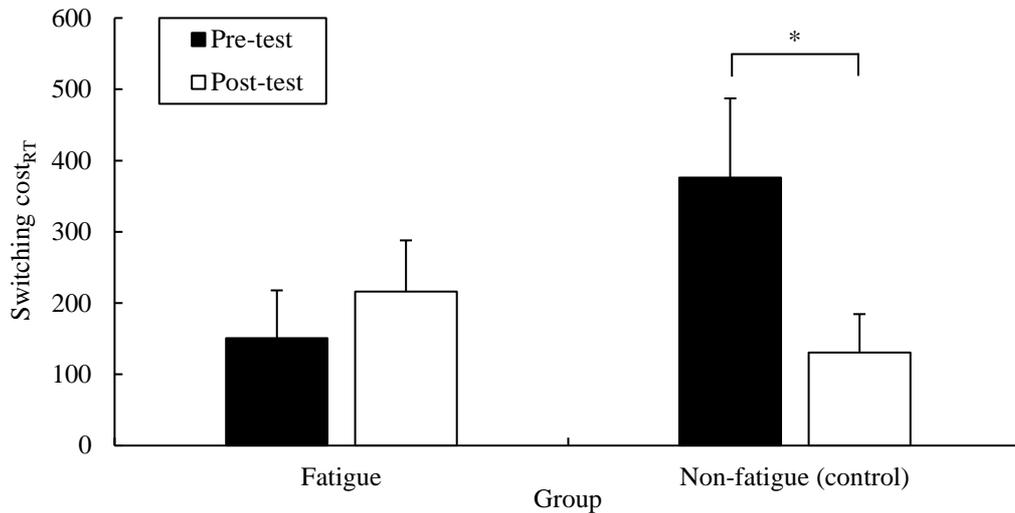
445 For the Plus-Minus switching-cost$_{RT}$, neither a main effect of Group, $F(1,51) = 0.70$, p

446 $= .407$, $\eta_p^2 = .01$, nor of Test, $F(1,51) = 1.47$, $p = .232$, $\eta_p^2 = .03$, was evident. However, there

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[11] Logarithmic (log10) transformation was performed to control for skewness (Templeton, 2011).

447   was a Group x Test interaction, $F_{(1,51)} = 4.37$, $p = .041$, $\eta_p^2 = .08$ (see Figure 8). Separate post-

448   hoc tests for each group revealed that switching-cost$_{RT}$ was significantly lower (i.e., better

449   performance) in the non-fatigued (control) group during the post-test compared to the pre-test

450   ($p = .036$), but not in the fatigued group ($p = .511$).

451

452

453   *Figure 8.* Switching-cost$_{RT}$ for the Plus-Minus task for each group at pre-test and post-test.

454   The higher the switching-cost$_{RT}$ the higher the median RT for the switching block, compared

455   to the addition and subtraction blocks. Error bars represent standard error of the mean. *p

456   $< .05$.

457   ### 5.3.3   Updating

458   For the N-back scores,[12] main effects were not evident for Group, $F_{(1,39)} = 1.84$, $p = .183$, η_p^2

459   $= .05$, or for Test, $F_{(1,39)} = 2.56$, $p = .118$, $\eta_p^2 = .06$. An interaction was not present, $F_{(1,39)}$

460   $= 0.05$, $p = .824$, $\eta_p^2 < .01$.

461   For RTs, main effects were not evident for Group, $F_{(1,39)} = 2.62$, $p = .114$, $\eta_p^2 = .06$,

462   or for Test, $F_{(1,39)} = 0.77$, $p = .387$, $\eta_p^2 = .02$. An interaction was not present, $F_{(1,39)} = 0.07$,

463   $p = .792$, $\eta_p^2 < .01$.

---

[12] Logarithmic (log10) transformation was performed to control for skewness (Engelhardt, Harden, Tucker-Drob, & Church, 2019).

464 **5.4 EEG power**

465 *5.4.1 Inhibition*

466 For EEG theta power in the Fz region during the Stroop task, main effects were not found for

467 Group, $F(1,27) = 0.41$, $p = .529$, $\eta_p^2 = .02$, or for Test, $F(1,27) = 0.51$, $p = .482$, $\eta_p^2 = .02$.

468 However, a Group x Test interaction was present, $F(1,27) = 6.51$, $p = .017$, $\eta_p^2 = .19$ (see Figure

469 9). Separate post-hoc tests for each group revealed that theta power was significantly lower

470 during the post-test compared to the pre-test in the non-fatigued (control) group ($p = .045$), but

471 not in the fatigued group ($p = .188$).

472
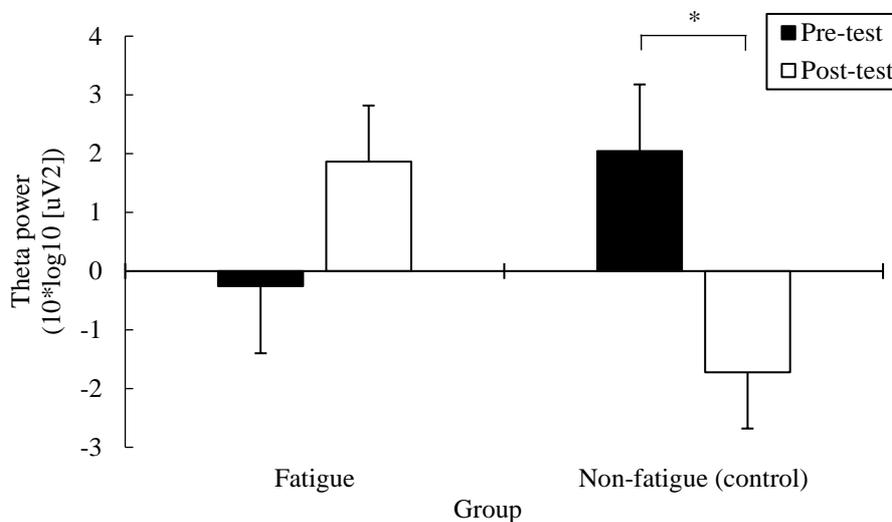
473

474 *Figure 9.* Mean theta (4-7 Hz) power for each group during the Stroop task at pre-test and

475 post-test. Error bars represent standard error of the mean. *$p < .05$.

476 *5.4.2 Switching*

477 Neither a main effect of Group, $F(1,29) = 1.32$, $p = .260$, $\eta_p^2 = .04$, nor of Test, $F(1,29) = 1.02$,

478 $p = .321$, $\eta_p^2 = .03$, was evident for Fz theta power during the Plus-Minus task. A Group x Test

479 interaction was not evident, $F(1,29) = 0.03$, $p = .856$, $\eta_p^2 < .01$.

480 *5.4.3 Updating*

481 No main effect of Group, $F(1,26) = 0.23$, $p = .638$, $\eta_p^2 = .01$, or of Test, $F(1,26) = 0.01$, p

482 $= .927$, $\eta_p^2 < .001$, was evident for the Fz theta power during the N-back task, and a Group x

483 Test interaction was not found, $F(1,26) = 1.88$, $p = .183$, $\eta_p^2 = .07$.

19

5.5 Cardiac vagal control

The *reactivity* HF-HRV measure revealed no main effects for Group, $F(1,45) = 2.08$, $p = 157$, $\eta_p^2 = .04$, or Test, $F(1,45) = 0.52$, $p = .475$, $\eta_p^2 = .01$. A Group x Test interaction was not present, $F(1,45) = 0.01$, $p = .931$, $\eta_p^2 < .01$.

6 Discussion

The cognitive fatigue task caused increased feelings of fatigue and greater mental effort was reported by participants in the cognitive fatigue treatment than participants in the control treatment. With respect to executive functions of working memory, both inhibition and switching performance improved significantly from pre-test to post-test in the non-fatigued (control) group, suggesting that a learning effect occurred. No such improvements occurred in the fatigued group, so the cognitive fatigue task may have interfered with both inhibition and switching, as hypothesised. Updating, as represented by performance on the N-back task, showed no differential effects between the two groups, suggesting that updating was unaffected by the cognitive fatigue task in this experiment. Previous studies suggest that the updating function relies on different cognitive processes compared to inhibition and switching functions (Imburgio & Orr, 2018; St Clair-Thompson, 2011; Zhang et al., 2015). Zhang et al. (2015), for example, suggested that the inhibition and switching functions are related to cognitive flexibility, whereas updating is related to cognitive stability. Cognitive stability is thought to reflect goal maintenance, while cognitive flexibility reflects the ability to adapt to the environment (Frober, Raith, & Dreisbach, 2018). However, previous studies suggest that cognitive flexibility (i.e., inhibition and switching) is important for verbal-analytical processes, associated with hypothesis testing, such as movement specific reinvestment (Park et al., 2020) and rumination (Yang, Cao, Shields, Teng, & Liu, 2017).[13]

We predicted that Fz theta power during the executive function tasks would increase from pre-test to post-test in the cognitively fatigued group compared to the non-fatigued (control) group. Fz theta power was not significantly different between groups during switching or updating, but during the inhibition task, a group by test interaction was evident. Theta power increased from pre-test to post-test among participants in the fatigued group (although not significantly). However, theta power decreased significantly from pre-test to post-test in the non-fatigued (control) group. There is debate regarding how changes in Fz theta

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[13] Movement specific reinvestment requires the flexibility to conscious manipulate explicit knowledge to control movements (Masters & Maxwell, 2008). Rumination (or rehearsal), presumably is important for refining movements (e.g., Masters et al., 1993).

power during cognitive tasks should be interpreted, with some studies claiming that changes in theta power may be associated with engagement in the task, and others claiming that changes may be associated with recruitment of mental resources (see Wascher et al., 2014, for a discussion on this). Decreased Fz theta power at post-test in the non-fatigued group implies that participants recruited fewer mental resources during the executive function tasks, perhaps because of familiarity or learning effects. Participants in the non-fatigued (control) group displayed improved performance of the executive functions tasks in the post-test, which supports this possibility. Additionally, previous research has shown that good cognitive performance is associated with reduced Fz theta power (Klimesch, 1999). In contrast, higher Fz theta power for the inhibition task at post-test in the cognitively fatigued group may indicate that participants recruited additional mental resources to compensate for the effects of fatigue on the executive functions of working memory. This explanation is supported by the fact that participants displayed stable performance of the executive function tasks when they were fatigued (i.e., post-test).

HRV was used as an indirect measure of working memory activity based on the neurovisceral integration model (Hansen et al., 2003; Thayer et al., 2009). We expected HRV to be lower during the executive function tasks post-fatigue compared to pre-fatigue, and compared to no fatigue (control). However, no significant effects were found. Recent studies have reported that HRV responses can differ as a function of specific executive functions (Jennings, Allen, Gianaros, Thayer, & Manuck, 2015; Kimhy et al., 2013; Laborde et al., 2018), so it would be of interest to examine HRV during specific executive function in future studies.[14]

Based on the findings, we concluded that the motor specific cognitive fatigue task that we developed has potential to suppress working memory activity and, therefore, disrupt or reduce verbal-analytical engagement (and thus hypothesis testing) in more complex, goal driven movements, such as those employed during sports.

7 Experiment 1: Part B

Having established some evidence for the efficacy of our cognitive fatigue task by revealing increased feelings of fatigue and moderation of executive functions, we therefore investigated whether the intervention caused reduced hypothesis testing during practice of an adapted shuffleboard task. The task required participants to use a paddle to slide a disk to a given target.

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[14] We were unable to analyse HRV separately for inhibition, switching and updating because the task durations were too short brief for reliable analysis (average duration 1 min and 40 sec) (Laborde et al., 2017).

544 The contours of the paddle were shaped to allow participants to use many different solutions
545 for the task. Behavioural and psychophysiological measures were obtained to determine the
546 extent of hypothesis testing. The behavioural measures consisted of self-ratings of technique
547 (Maxwell et al., 2001; Maxwell, Masters, & Poolton, 2006), number of paddle solutions and
548 number of technique changes (Maxwell et al., 2001).

549 The psychophysiological measures consisted of two cortical measures of high-alpha
550 EEG power over the left temporal (T7) region and connectivity between T7 and the mid-frontal
551 (Fz) regions, to examine verbal-analytical engagement during movement, which we predicted
552 to be associated with hypothesis testing (Maxwell et al., 2001).

553 The T7 region place an important role in processing verbal-analytical knowledge
554 (Kaufer & Lewis, 1999; Sperry, 1974), and neural activation of the T7 area has been used to
555 indirectly gauge verbal-analytical processes during motor task performance (Hatfield, Landers,
556 & Ray, 1984; Haufler, Spalding, Santa Maria, & Hatfield, 2000; Kerick et al., 2001; van Duijn,
557 Hoskens, & Masters, 2019). Specifically, these studies have revealed that increased high alpha
558 power (10-12 Hz)[15] over the T7 region during motor planning is associated with lower levels
559 of verbal-analytical processes (Hatfield et al., 1984; Haufler et al., 2000; Kerick et al., 2001;
560 van Duijn et al., 2019).

561 The Fz region is near the motor areas deputed to motor planning (Cooke et al., 2015;
562 Shibasaki & Hallett, 2006). Based on this, previous studies have computed connectivity
563 between the T7 and Fz regions (i.e., high-alpha T7-Fz connectivity) to measure the extent of
564 verbal-analytical engagement in motor planning (Cooke, 2013; Gallicchio, Cooke, & Ring,
565 2016; Hatfield & Hillman, 2001; Zhu, Poolton, Wilson, Maxwell, & Masters, 2011). Zhu et al.
566 (2011), for example, revealed that during movement preparation (4 sec before movement
567 initiation) participants with a lower propensity to consciously control their movements[16]
568 displayed lower T7-Fz connectivity compared to participants with a higher propensity to
569 consciously control their movements. Based on this evidence, T7 power and T7-Fz
570 connectivity are potentially valuable markers of the effect of cognitive fatigue on hypothesis
571 testing in a motor task (see Cooke, 2013; Hatfield & Hillman, 2001, for reviews).

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[15] High-alpha power is inversely related to neural activity (e.g., Gallicchio, Cooke, & Ring, 2017; Klimesch, 1999).

[16] Conscious control was measured by the Movement Specific Reinvestment Scale (Masters, Eves, & Maxwell, 2005; Masters & Maxwell, 2008).

572   We hypothesized that the cognitive fatigue task would suppress the inhibition and
573   switching functions of working memory during the adapted shuffleboard task, compared with
574   the non-fatigued (control) group, thus interfering with the ability to test hypotheses about
575   performance. Consequently, we expected that in the cognitively fatigued group participants
576   would self-report fewer technique changes, test fewer paddle solutions and display fewer
577   technique changes than participants in the non-fatigued (control) group. They were also
578   expected to display lower levels of T7-Fz connectivity and higher high alpha T7 power.

579   **8   Method**

580   **8.1 Participants and Design**

581   See Participants and Design, Experiment 1: Part A. Participants who completed the fatigue or
582   non-fatigue (control) treatment in Part A remained in the laboratory and immediately
583   completed the adapted shuffleboard task.

584   **8.2 Shuffleboard Task**

585   Immediately after the cognitive fatigue/control protocol, participants were required to use a
586   wooden paddle (see Figure 10) to practice shuffling a wooden disk (1.3 cm thick, diameter 5.2
587   cm) to a target circle (diameter 10 cm) on a smooth board, which extended lengthways from
588   the participant (120 x 360 cm). The contours of the paddle were shaped inconsistently to
589   provide participants many different methods by which to direct the disk to the target. The
590   number of different methods used was adopted as an objective measure of hypothesis testing.
591   The target was projected onto the board by an overhead projector and a camera above the target
592   captured the outcome position of the wooden disk after each trial. A video camera was used to
593   capture the movements of the participant during each trial.

594

595   *Figure 10.* Shuffleboard disk and paddle

8.3 Measures

8.3.1 Shuffleboard task

Radial error (cm) was obtained as a performance measure. Radial error represented the distance between the final position of the disk and the centre of the target. *ScorePutting* software (written in National Instruments LabVIEW) was used to compute the radial error from a photograph taken with a camera that was placed directly above the target (Neumann & Thomas, 2008).

8.3.2 Behavioural measures of hypothesis testing

Participants were asked to rate how motivated they were to perform the shuffleboard task (scale 1–10), in order to control for potential influences of motivation on task performance (Boksem, Meijman, & Lorist, 2006). No significant differences in motivation were revealed between Groups, $t(53) = -1.295$, $p = .201$, $d = 0.35$.

Self-reported technique changes were conducted by asking the participants to rate how often they changed their technique during each block of twenty trials (scale 1–10). Additionally, two researchers blinded to treatment group independently viewed the video data and counted the number of paddle solutions and the number of changes in technique during each block of trials. Paddle solutions were defined as the different ways in which the paddle was used (see Figure 10), and changes in technique were defined as the different ways in which the paddle was moved. A high degree of correlation was evident between the scores of the two researchers for both measures - $ICC_{average\ measures\ stick} = 0.80$, 95% confidence interval 0.29-0.94, $F(11,11) = 4.92$, $p = .007$ and $ICC_{average\ measures\ technique} = 0.86$, 95% confidence interval 0.33-0.94, $F(11,11) = 5.16$, $p = .006$ (Hallgren, 2012).

8.3.3 Psychophysiological measures of hypothesis testing

EEG data was examined during the motor preparation phase of each trial of the shuffleboard task. The EEG data was obtained and processed using the same protocol as in Experiment 1: Part A (see Methods). Participants rested their head on a chin rest prior to each trial and were asked to only focus on the target (to reduce eye movements). They were instructed to remain as still as possible during when performing the task. Participants started preparing the movement when the disk was placed in front of them and initiated their movement when the target appeared on the board. EEG activity was determined for the high alpha frequency band (10-12 Hz), as this frequency is associated with global cortico-communication (Klimesch, 1999).

8.4 Procedure

Participants rated their motivation before starting the shuffleboard task, which consisted of three blocks of 20 shuffleboard trials (each block took an average of 6 min and 40 sec to complete). Participants were instructed to slide the disk onto the target as accurately as possible and to initiate their movement when the target appeared on the table. The position of the disk was recorded by photograph after each trial. The target then disappeared and the researcher collected the disk and presented it for the next trial. This was done to standardise the inter-trial interval and to reduce the need for participants to move between trials. When the final block of practice trials was completed, participants completed a self-report rating of the number of technique changes they had made in each block of trials.

8.5 Data analysis

8.5.1 EEG connectivity and power measures

The EEG data was analysed by first generating epochs consisting of 5 sec prior until 2 sec after the target appeared (i.e., movement initiation) for each trial. Thereafter, the same filtering and cleaning procedures employed in Part A were applied to the epochs (see Experiment 1: Part A, Methodology, for more details). A threshold-based artefact removal procedure was performed, deleting epochs with values $\pm$ 75 µV to clean the signal (Deeny, Hillman, Janelle, & Hatfield, 2003). Exclusion of participants from further analysis occurred if too many epochs (more than 25%) had to be deleted.[17] The alpha frequency band (8-12 Hz) was adjusted for each participant based on their individual alpha frequency (IAF) peak, determined from the baseline measure described in Experiment 1: Part A (IAF toolbox, Corcoran, Alday, Schlesewsky, & Bornkessel-Schlesewsky, 2018). The clean signal was then subjected to time frequency analysis to obtain estimated instantaneous high alpha frequency power for 3 sec prior to movement initiation.

Phase angles were also obtained from the time frequency analysis and were used to compute inter-site phase clustering connectivity (ISPC, Cohen, 2014) between the left temporal (T7) and frontal (Fz) regions in the high alpha frequency band for the 3 sec prior to movement initiation. We calculated the $ISPC_{trial}$ using the following function:

$$ISPC_{xy}(f) = \left| n^{-1} \sum_{t=1}^{n} e^{i(\theta_x(tf) - \theta_y(tf))} \right|$$

---

[17] Due to technical issues with the EEG equipment, twenty-one participants had to be excluded from this analysis (19 participants were retained in each group).

656 N is the number of data points, i is the imaginary operator, θ_x and θ_y are the phase angles of the

657 recorded signal at two different scalp locations, t is the trial and f is the frequency bin. The

658 $e^{i(\theta_x(tf)-\theta_y(tf))}$ represents the complex vector with magnitude 1 and angle θ_x - θ_y, $n^{-1}\sum_{t=1}^{n}(.)$

659 denotes averaging over time points, and $|.|$ is the module of the averaged vector (Cohen, 2014;

660 Lachaux, Rodriguez, Martinerie, & Varela, 1999). ISPC is assigned as a value between 0 (no

661 functional connection) and 1 (perfect functional connection). Finally, a Z-transformed (inverse

662 hyperbolic tangent) was performed to ensure normal distribution (e.g., Gallicchio et al., 2016;

663 Zhu et al., 2011).

8.5.2 Statistical approach

665 All measures were subjected to a 2 x 3 repeated measures ANOVA Group (Fatigue, Non-

666 fatigue) x Block (Block 1, Block 2, Block 3). Sphericity and normality checks were performed

667 and controlled for when necessary. Separate ANOVAs with Bonferroni corrections were

668 performed when main effects or interactions were found. Effect sizes are reported as partial η

669 squared (η_p^2), with the values .01, .06 and .14 indicating relatively small, medium and large

670 effect sizes, respectively (Cohen, 1988). The statistical tests were performed using SPSS (IBM,

671 version 25.0) computer software. Significance was set at $p = .05$ for all statistical tests.

9 Results

9.1 Behavioural measures of hypothesis testing

9.1.1 Self-reported technique changes

675 No main effect was found for Group, $F(1,55) = 0.26$, $p = .610$, $\eta_p^2 = .01$, but there was a main

676 effect for Block, $F(1.47,81.03) = 26.33$, $p < .001$, $\eta_p^2 = .32$ (see Figure 11). Post-hoc analysis

677 revealed that participants reported that they made more changes in Block 1 compared to Block

678 2 ($p = .003$) and Block 3 ($p < .001$), with more changes in Block 2 than Block 3 ($p < .001$). A

679 Group x Block interaction was not present, $F(2,110) = 0.01$, $p = .988$, $\eta_p^2 < .01$.

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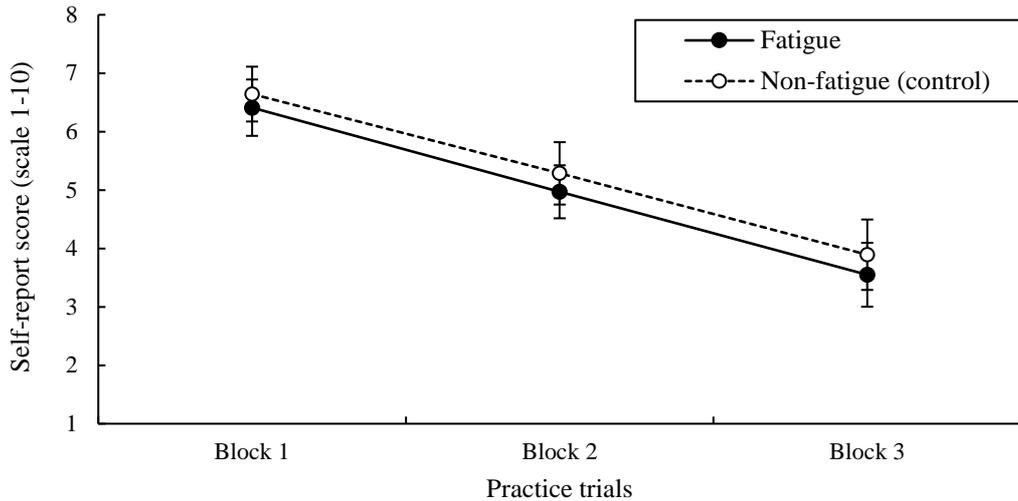
681

682 *Figure 11.* Mean score on the self-report of technique change for each group by block of

683 trials. Error bars represent standard error of the mean.

9.1.2 Number of paddle solutions

685 A main effect was not present for Group, $F(1,52) = 0.13$, $p = .717$, $\eta_p^2 < .01$, but an effect was

686 present for Block, $F(1.79,92.79) = 37.07$, $p < .001$, $\eta_p^2 = .42$ (see Figure 12). Post-hoc analysis

687 revealed that participants used significantly more solutions in Block 1 compared to Block 2 (p

688 $< .001$) and Block 3 ($p < .001$), and more solutions in Block 2 than Block 3 ($p = .005$). A Group

689 x Block interaction was not present, $F(2,104) = 0.05$, $p = .953$, $\eta_p^2 < .01$.

690

691

692 *Figure 12.* Mean number of paddle solutions for each group by block of trials. Error bars

693 represent standard error of the mean.

694 *9.1.3 Technique changes*

695 A main effect of Group was evident, $F(1,51) = 4.69$, $p = .035$, $\eta_p^2 = .08$ (see Figure 13),
696 indicating significantly more technique changes in the fatigued group than the non-fatigued
697 (control) group over the three blocks of trials. A main effect was also evident for Block,
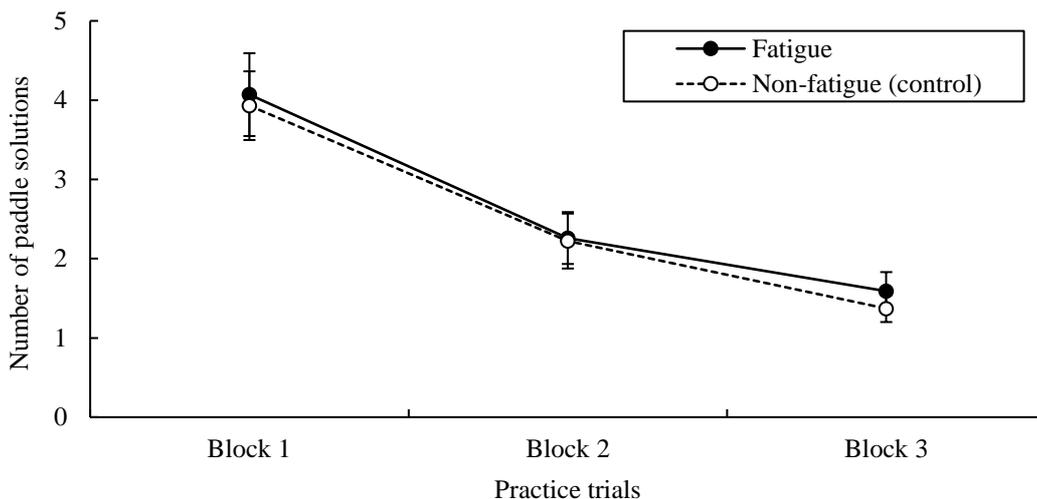698 $F(1.67,85.05) = 25.12$, $p < .001$, $\eta_p^2 = .33$, with post-hoc analysis revealing a significantly
699 higher number of technique changes in Block 1 compared to Block 2 ($p < .001$) and Block 3
700 ($p < .001$). Block 2 and Block 3 were not significantly different ($p = 1.00$). An interaction
701 between Group and Block was absent, $F(2,102) = 0.55$, $p = .580$, $\eta_p^2 = .01$.

702
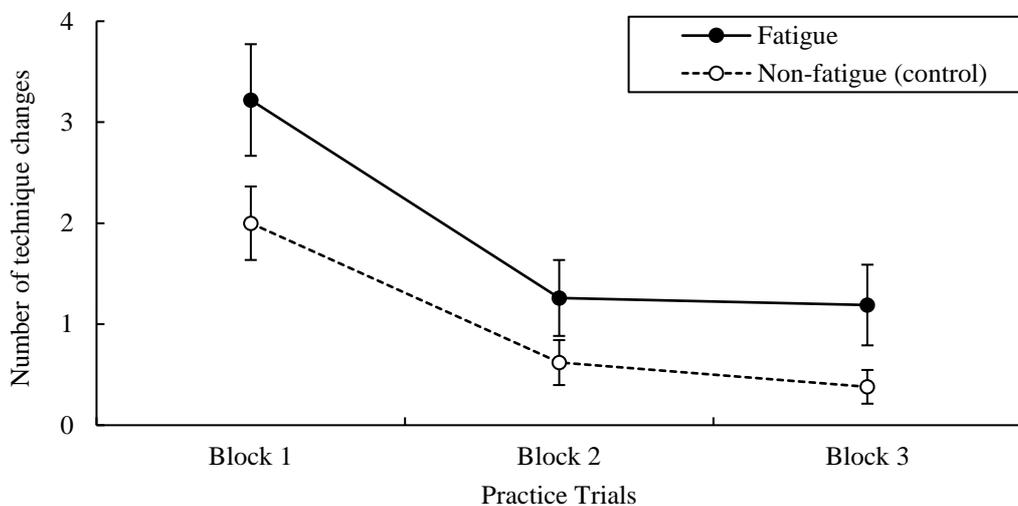
703

704 *Figure 13*. Mean number of technique changes for each group by block of trials. Error bars
705 represent standard error of the mean.

706 **9.2 Psychophysiological measures of hypothesis testing**

707 *9.2.1 T7-Fz connectivity*

708 A main effect was found for Group, $F(1,32) = 5.83$, $p = .022$, $\eta_p^2 = .15$ (see Figure 14),
709 indicating significantly higher T7-Fz connectivity in the fatigued group than the non-fatigued
710 (control) group over the three blocks of trials. Neither a main effect of Block, $F(2,64) = 1.18$,
711 $p = .315$, $\eta_p^2 = .04$, nor a Group x Block interaction, $F(2,64) = 1.09$, $p = .344$, $\eta_p^2 = .03$, were
712 present.

713
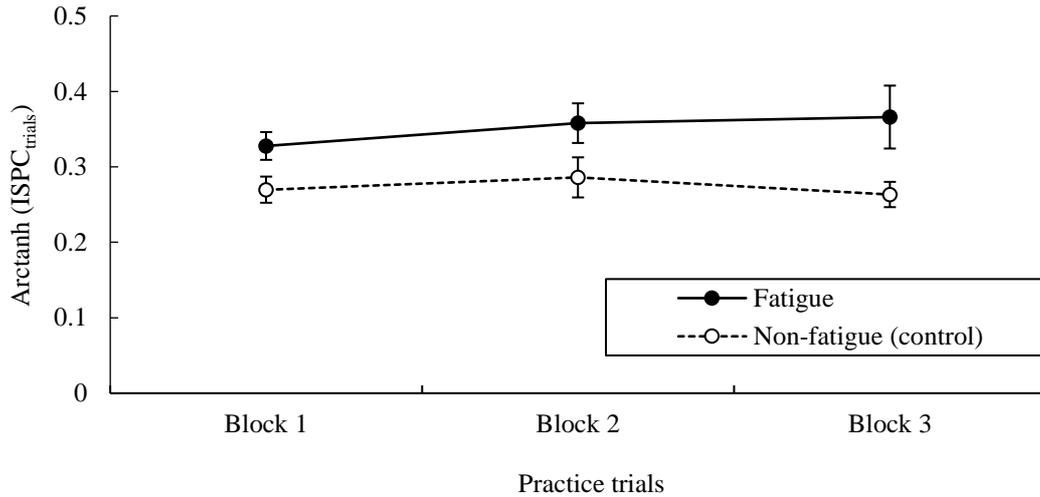
715 *Figure 14.* Mean ISPCtrials connectivity for each group by block of trials. Error bars

716 represent standard error of the mean.

9.2.2 T7 high alpha power

718 Main effects were not present for Group, $F(1,32) = 0.70$, $p = .408$, $\eta_p^2 = .02$, or for Block,

719 $F(2,64) = 1.78$, $p = .177$, $\eta_p^2 = .05$. A Group x Block interaction was not present, $F(2,64) =$

720 1.99, $p = .145$, $\eta_p^2 = .06$ (see Table 2 in Appendix for mean and SD values).

9.3 Shuffleboard performance

722 A main effect of Group was not evident for radial error, $F(1,50) = 3.53$, $p = .066$, $\eta_p^2 = .07$. A

723 main effect of Block was evident, $F(1.81,90.52) = 79.19$, $p < .001$, $\eta_p^2 = .61$ (see Figure 15).

724 Radial error was significantly higher in Block 1 compared to Block 2 ($p < .001$) and Block 3

725 ($p < .001$), and higher in Block 2 compared to Block 3 ($p = .002$). A significant interaction was

726 not revealed, $F(2,100) = 1.08$, $p = .344$, $\eta_p^2 = .02$.

727
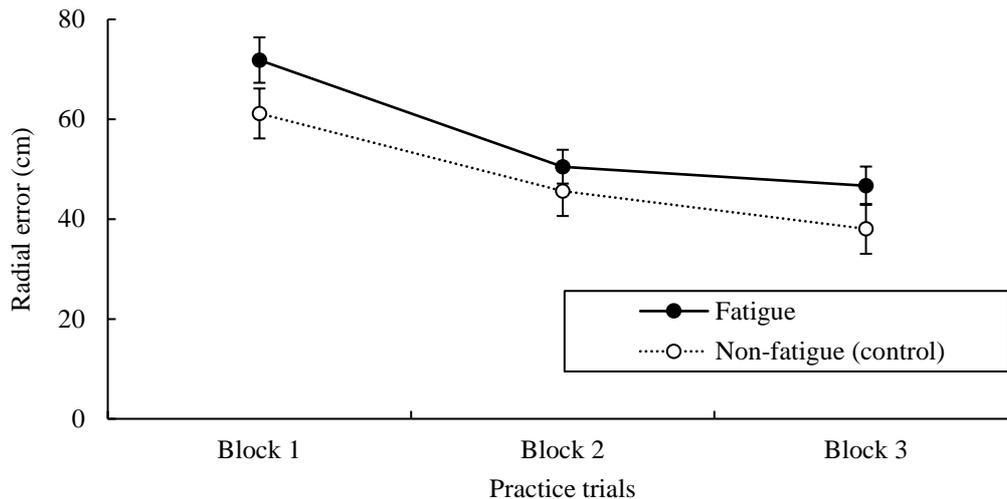
Figure 15. Mean radial error (cm) for each group by block of trials. Error bars represent
standard error of the mean.

10 Discussion

Behavioural measures of hypothesis testing suggested that participants tested more hypotheses
in the first block of the shuffleboard task compared with the later blocks. This is consistent
with traditional views of learning (e.g., Fitts & Posner, 1967), which suggest that as learning
progresses processing of performance becomes less cognitive.

   We found no between-group differences in self-reported changes in technique or in the
number of paddle solutions that participants used, although more technique changes occurred
in the fatigued group. It is possible that participants were unaware of the way in which they
altered their kinematics during performance and thus under-reported their technique changes.
Furthermore, it has been argued that the assessment of declarative knowledge via self-report
should consist of a qualitative analysis of the information produced by the participants, rather
than by a simple Likert scale as used in this study (Shanks & John, 1994). It is also possible
that participants did not use many different paddle solutions, but instead chose to alter their
technique by leveraging the degrees of freedom made available by the human motor apparatus
(Bernstein, 1996).

   The technique changes, however, suggest that the cognitive fatigue task did not supress
hypothesis testing; in fact, hypothesis testing increased. Consistent with this finding, high alpha
power for the T7 region was not significantly different between the fatigued and non-fatigued
group, suggesting that verbal-analytical activity in general (e.g., self-talk) was the same, but
verbal-analytical engagement in motor performance (i.e., increased high alpha T7-Fz

connectivity) was significantly higher in the fatigued group across all shuffleboard blocks. Performance accuracy (radial error) improved during practice, but was not different between groups.

A limitation of the experiment is that we did not include a shuffleboard baseline measure and, therefore, we cannot fully discount the possibility that increased verbal-analytical engagement in the fatigued group might have been a result of the shuffleboard skill level of the participants. However, a baseline shuffleboard task would have provided an opportunity to accumulate explicit knowledge about the task, which would have confounded our measures of hypothesis testing. Furthermore, we cannot preclude the possibility that the effects of cognitive fatigue dissipated over time. Future studies should, therefore, include a measure of fatigue during the shuffleboard task to establish whether fatigue remained for the total duration of the 60 trials.

In contrast to our expectations, participants in the fatigued group did not appear to perform the shuffleboard task with reduced verbal-analytical engagement or demonstrate less hypothesis testing; in fact, they displayed more technique changes (indicative of testing more hypotheses) and showed higher levels of verbal-analytical engagement in the motor task compared to non-fatigued participants.

11 General Discussion

Implicit approaches to motor learning argue that explicit (i.e., verbal-analytical) control of movement can disrupt procedural (i.e., automatized) control of motor performance. Implicit motor learning paradigms (e.g., Masters, 1992), therefore, seek to promote procedural control of movement by reducing hypothesis testing during learning. In pilot work (Hoskens et al., 2018), we found that a computer-based cognitive fatigue task developed by Borragan et al. (2016) did not deplete cognitive resources needed for hypothesis testing during complex movements. We concluded that the cognitive fatigue task that Borragan et al. (2016) employed was not sufficiently mentally demanding to reduce verbal-analytical engagement when learning complex motor skills. We suggested that a more movement-specific cognitive fatigue task should be developed. Based on our pilot work, we designed a cognitive fatigue task that was motor focused and which challenged information processing (i.e., executive functions of working memory).

In Part A of the experiment, we found that participants in the cognitively fatigued group reported feelings of greater fatigue and mental effort compared to participants in the non-

782   fatigued (control) group. These effects were revealed after performance of a relatively short

783   treatment task (i.e., 15 min). This study is, therefore, consistent with other recently developed

784   short duration cognitive fatigue paradigms (e.g., Borragan et al., 2019; O'Keeffe, Hodder, &

785   Lloyd, 2020; Trejo et al., 2015), suggesting that cognitive fatigue can be achieved effectively

786   by performing brief, mentally demanding tasks. Of the three executive functions of working

787   memory, the inhibition and switching functions were disrupted by the cognitive fatigue task,

788   but the updating function was not. Differences in Fz theta power (i.e., prefrontal cortex activity)

789   were only found during inhibition. Nevertheless, previous studies have argued that inhibition

790   and switching are most important for hypothesis testing (Park et al., 2020; Yang et al., 2017),

791   so we concluded that the motor specific cognitive fatigue task had potential to reduce verbal-

792   analytical engagement in motor performance and thus had potential to create conditions for

793   implicit motor learning by suppressing executive functions associated with hypothesis testing.

794   Subsequently, the second part of the study examined whether the motor specific

795   cognitive fatigue task, indeed, suppressed hypothesis testing during practice of a novel motor

796   skill. However, in contrast to our expectations, a higher number of changes in technique

797   occurred in the fatigued group compared to the non-fatigued (control) group during practice of

798   the shuffleboard task. Technique changes are thought to reflect hypothesis testing, with

799   performers altering their movements in order to become more successful at the task. Consistent

800   with this, participants in the fatigued group also displayed greater verbal-analytical engagement

801   in motor planning (T7-Fz connectivity) (e.g., Cooke et al., 2015; Kerick et al., 2001; Zhu et al.,

802   2011). These findings suggest that the cognitive fatigue task may have primed the performer

803   to use more cognitive resources during motor performance to compensate for the side effects

804   of fatigue. However, fatigue might have also resulted in disrupted executive functions, causing

805   reduced ability to *inhibit* processing irrelevant information and inefficient *switching* between

806   incoming information. Lorist et al. (2009) found that cognitive fatigue disrupted efficient

807   activation of the areas of the brain that were crucial for effective performance by causing

808   increased neural activity across the whole brain (i.e., reduced interhemispheric inhibition).

809   Consequently, by increasing compensatory effort into motor planning (e.g., trying harder),

810   participants in our study may have inadvertently diverted resources away from critical cortical

811   regions. This may have disrupted efficient processing of information (disrupted inhibition and

812   switching). These findings have their parallels in Attentional Control Theory (ACT, Eysenck

813   et al., 2007), which seeks to explain the effects of anxiety on performance. Possibly, fatigue

814   acts in a similar fashion to anxiety by raising concerns about maintaining effective

815 performance. ACT theory argues that such concerns disrupt processing efficiency, especially

816 with respect to inhibition and switching (as we found). However, individuals can compensate

817 for the negative effects of such disruptions by increasing mental effort. Eysenck et al. (2007)

818 claimed that mental effort is deployed to inhibit stimulus driven, bottom-up responses by

819 replacing them with goal-driven, top-down processes. Participants in our study may have used

820 explicit hypothesis testing to maintain goal-driven, top-down behaviour (see for example,

821 Nieuwenhuys & Oudejans, 2012).

822   Given that Zhu et al. (2015) did claim to have caused implicit motor learning by using

823 tDCS to suppress activity in the prefrontal cortex (i.e., associated with working memory), it is

824 possible that our motor focused cognitive fatigue protocol was not sufficiently stringent to

825 completely suppress working memory functions. Future studies should utilize more stringent

826 methods to suppress working memory activity prior to motor practice. Hypoxia, for example,

827 has been revealed to reduce available cognitive resources because the body prioritizes

828 support for the cardiac system in reduced oxygen environments (McMorris, Hale, Barwood,

829 Costello, & Corbett, 2017; Yan, Zhang, Gong, & Weng, 2011).

830   Altogether, the results of our study do give insight into how cognitively demanding

831 tasks affect cognitive processes during both computer-based executive function tasks and

832 relatively complex motor tasks. Cognitively fatiguing motor control, using tasks such as ours,

833 may not be desirable if it primes greater verbal-analytical processing of motor skills in

834 novices. However, such an approach may be desirable if it primes greater verbal-analytical

835 processing in experts who are refining their skills (e.g., Toner & Moran, 2014, 2015), or in

836 tasks where successful performance is a function of both motor and cognitive components,

837 such as in Esports (Martin-Niedecken & Schättin, 2020) or surgery (e.g., Masters, Poolton,

838 Abernethy, & Patil, 2008). In tasks like these, cognitive fatigue may prime greater verbal-

839 analytical processing, which might facilitate cognitive components of the task, such as

840 decision-making.

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1172 **Appendix**

1173 Table 1. Mean and SD values of the non-significant results for measures in Experiment 1:

1174 Part A, for each group and test.

Group	Fatigue				Non-fatigue (control)			
	Pre-test		Post-test		Pre-test		Post-test	
	M	SD	M	SD	M	SD	M	SD
Inhibition-cost$_{duration}$	18.07	9.47	17.09	5.21	20.85	10.57	17.75	7.34
Switching-cost$_{duration}$	1.44	5.65	2.56	5.43	3.28	5.42	1.42	3.50
Updating score	11.50	0.69	20.75	1.62	11.62	0.74	21.14	0.96
Updating RT	757.6	175.2	703.5	170.7	844	301	815.1	303.3
Theta Fz power: Switching	0.70	3.93	4-0.6	4.95	-1.09	6.83	-2.02	3.42
Theta Fz power: Updating	-1.27	5.10	0.85	5.41	-0.12	8.53	-1.97	4.51

	-0.16	0.41	-0.19	0.38	-0.01	0.35	-0.03	0.35
HRV								

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1176 Table 2. Mean and SD value for high alpha T7 power in Experiment 1: Part B for each group

1177 by block of trials.

Group	Fatigue		Non-fatigue (control)	
	M	SD	M	SD
Block 1	-0.32	1.18	0.43	0.59
Block 2	0.56	1.32	0.32	0.89
Block 3	0.43	0.85	0.56	1.63

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