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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

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

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

56

57

## 2 General introduction

58 It has been claimed that working memory supports the processing, storage and manipulation  
59 of information (Baddeley, 1992; Bo & Seidler, 2009; Just & Carpenter, 1992; Kane & Engle,  
60 2002) and underpins explicit motor learning by supporting the development and storage of  
61 rules and information about how a motor task is performed (e.g., MacMahon & Masters, 2002;  
62 Maxwell, Masters, & Eves, 2003). Limiting the role of working memory in practice has been  
63 shown to lead to development and storage of much less information, in a process described as  
64 implicit motor learning (Masters, 1992). Masters (1992) demonstrated that participants learned  
65 a golf putting skill more implicitly when they practiced while carrying out a concurrent  
66 secondary task. The task, random letter generation, was designed to use resources of working  
67 memory normally available to process hypotheses about movement solutions. Masters (1992)  
68 concluded that motor performance can improve without the accumulation of rules and  
69 information about how to perform. Consequently, Masters (1992) argued that this type of  
70 learning, implicit motor learning, promotes reduced conscious engagement in performance  
71 compared to explicit motor learning (e.g., Masters, 1992; Maxwell et al., 2003).

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

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

90 der Linden, Frese, & Meijman, 2003; Wolfgang & Schmitt, 2009). Wolfgang and Schmitt  
91 (2009), for example, found that prolonged performance of a Stroop task (480 trials) caused  
92 cognitive fatigue, which disrupted performance. The Stroop task (Stroop, 1935) requires  
93 participants to name the colour in which colour words are written (e.g., the word ‘green’ is  
94 written in blue). Successful performance requires participants to consciously inhibit their  
95 automatic tendency to read and name the written word. Wolfgang and Schmitt (2009) argued  
96 that cognitive fatigue reduced cognitive resources available for top-down conscious inhibition  
97 of automatic responses (reading) during Stroop performance.

98         Borrigan et al. (2016) examined the effects of cognitive fatigue on learning a serial  
99 reaction time task (SRTT). The SRTT requires participants to rapidly press buttons indicating  
100 the location of stimuli presented on a screen. Typically, participants are unaware that the order  
101 of the stimuli is repeated in a specific sequence, yet they become faster at responding and  
102 eventually anticipate accurately the position of each stimulus in the sequence. Borrigan et al.  
103 (2016) found that cognitive fatigue caused by a TloadDback protocol,<sup>1</sup> improved learning of  
104 the sequence. They argued that during repetition of the SRTT, cognitive fatigue inhibited  
105 disruptive top-down conscious interference in the task, which was beneficial for implicit  
106 (procedural) learning. Consequently, we argued that processing task-relevant information  
107 needed for hypothesis testing is likely to be reduced if cognitive fatigue is used to suppress  
108 working memory activity prior to motor practice. Less information should, therefore, be stored  
109 during motor practice, which should result in implicit motor learning. In a pilot experiment  
110 (Hoskens, Boaz-Curry, Buszard & Masters, 2018), we first tested the veracity of the Borrigan  
111 et al. (2016) protocol by employing it to fatigue participants prior to performing a golf putting  
112 task (i.e., ten trials from a distance of 300 cm). The control group watched a nature  
113 documentary prior to performing the same golf putting task. Compared to participants in the  
114 control group, participants in the fatigue group reported higher subjective feelings of cognitive  
115 fatigue, assessed using the Visual Analogue Scale of Fatigue (VASf; Lee, Hicks, & Nino-  
116 Murcia, 1990). However, participants neither displayed suppressed working memory activity<sup>2</sup>

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<sup>1</sup> 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).

<sup>2</sup> 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.

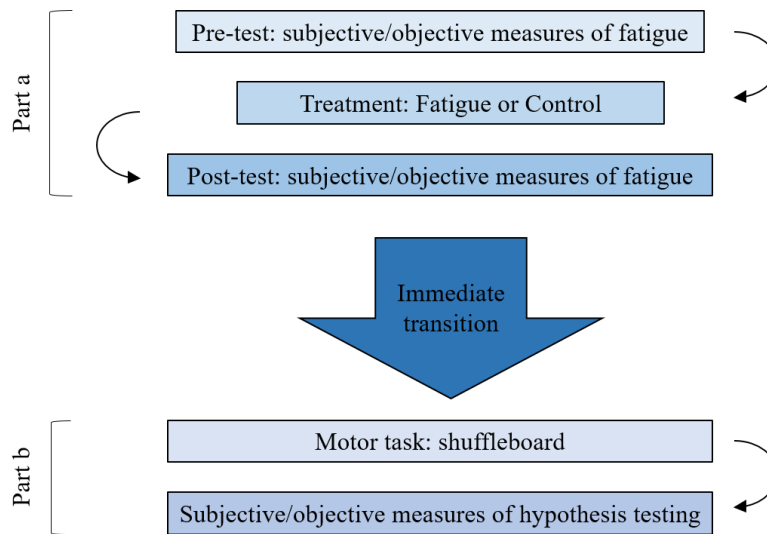
117 as a consequence of fatigue, nor did they display reduced conscious engagement<sup>3</sup> during  
118 performance of the putting task. Based on the results of this pilot experiment, we concluded  
119 that the Borrigan et al. (2016) task may be appropriate for simple motor tasks, which rely  
120 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 Borrigan 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; Yogeve-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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<sup>3</sup> 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.



147

148 *Figure 1.* Flow diagram of the procedure used for this study.

149

### 3 Experiment 1: Part A

150 In the first part of the experiment, subjective feelings of fatigue and mental effort were assessed  
 151 to determine how demanding the newly designed cognitive fatigue task was. Additionally, we  
 152 measured the effect of the task on the performance of computer-based tasks designed  
 153 specifically to assess executive functions (inhibition, switching, and updating). Theta (4-7 Hz)  
 154 power at the frontal midline (i.e., Fz region) of the brain was also measured during performance  
 155 of the executive function tasks, using electroencephalography (EEG), in order to gauge the  
 156 effect of cognitive fatigue on working memory activity. The frontal midline Fz site overlies the  
 157 prefrontal cortex, where working memory activity is thought to occur (e.g., Imburgio & Orr,  
 158 2018; Jensen & Tesche, 2002; Klimesch, 1999; Miller & Cohen, 2001), and theta power in the  
 159 Fz region (Fz theta power) is associated with working memory functions, including  
 160 information maintenance and processing (Jensen & Tesche, 2002; Sauseng, Griesmayr,  
 161 Freunberger, & Klimesch, 2010). Research has shown that Fz theta power increases in response  
 162 to cognitive fatigue, suggesting that working memory functions are impacted negatively  
 163 (Boksem, Meijman, & Lorist, 2005; e.g., Kato, Endo, & Kizuka, 2009; e.g., Wascher et al.,  
 164 2014). Wascher et al. (2014), for example, revealed that theta power increased as participants  
 165 became mentally fatigued during a Simon effect task (4 hours). The Simon effect task is a  
 166 cognitively demanding spatial stimulus-response compatibility task, which therefore impacts  
 167 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 4 Method

### 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  $\eta^2 = 0.55$  (Borrigan 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,<sup>4</sup> 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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<sup>4</sup> 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 )<sup>5</sup> 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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<sup>5</sup> 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).

#### 228 **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).

### 233 **4.3 Measures – manipulation checks**

#### 234 **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.

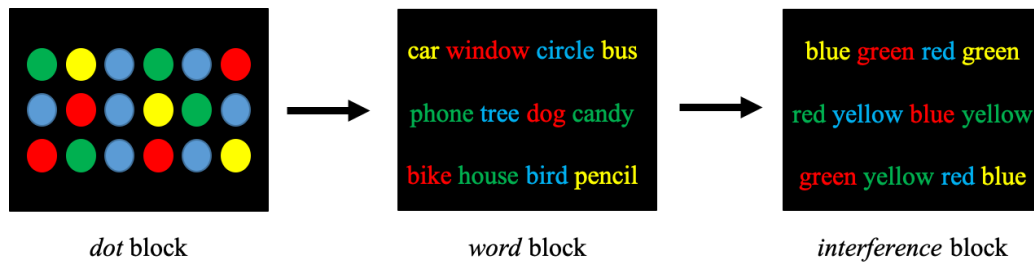
#### 246 **4.3.2 *Computer-based executive function tasks***

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

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

260

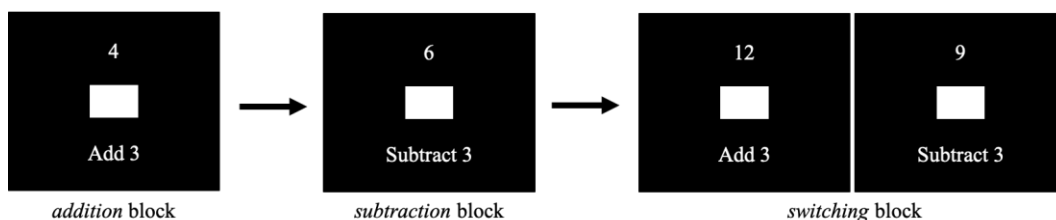


262

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

264 **Switching.** The Plus-Minus task was used to assess the ability to switch between task  
 265 requirements (Jersild, 1927; Miyake et al., 2000; Spector & Biederman, 1976). The task  
 266 consisted of three blocks of ten trials. Block 1, the *addition* block required participants to add  
 267 3 to each number that was displayed, by typing it on the keyboard (see Figure 3). The next  
 268 number was then displayed. Block 2, the *subtraction* block, required participants to subtract 3  
 269 from each number, and Block 3, the *switching* block, required participants to alternate between  
 270 adding and subtracting 3 from the displayed number (see Figure 3). To our knowledge, test-  
 271 retest has not been reported for the Plus-Minus task.

272

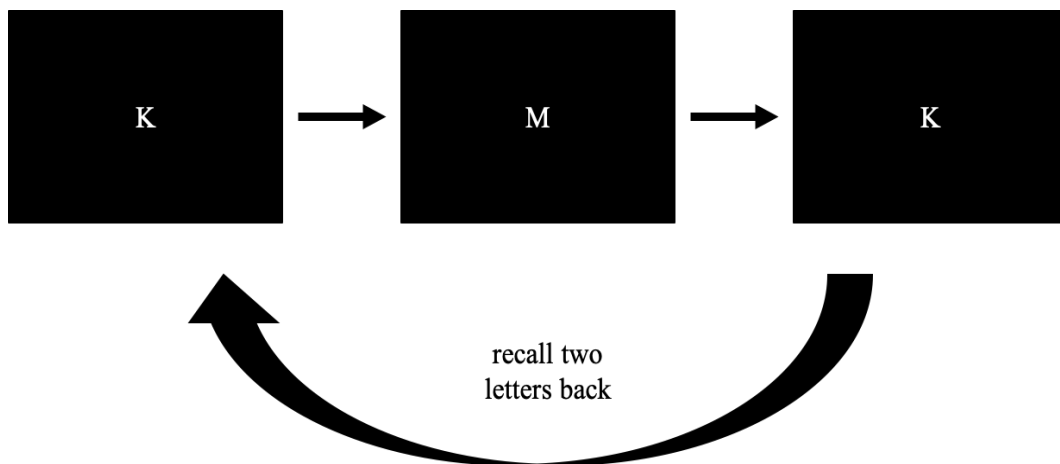


274

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

276 **Updating.** The N-back task was used to assess updating abilities (Kirchner, 1958; Oberauer,  
 277 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, Neuroelectronics, 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, Neuroelectronics, Barcelona, Spain).

#### 303 **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<sup>tm</sup> 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*).<sup>6</sup> The inhibition-cost for the *interference* block was computed by  
329 relating the amount of trials ( $\text{inhibition-cost}_{\text{score}}$ ) and duration time ( $\text{inhibition-cost}_{\text{duration}}$ ) of the  
330 *interference* block with the *dot* block and the *word* block:

---

<sup>6</sup> 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 
$$\text{Inhibition-cost} = \textit{interference} \text{ block} - \frac{(\textit{dot} \text{ block} * \textit{word} \text{ block})}{(\textit{dot} \text{ block} + \textit{word} \text{ block})}$$

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.<sup>7</sup> 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<sub>score</sub>), RT (switching-cost<sub>RT</sub>) and completion time (switching-cost<sub>duration</sub>)  
 340 (Miyake et al., 2000):

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

342 The switching-costs were computed to control for any overall difficulties with mathematical  
 343 performance (Miyake et al., 2000). However, the switching-cost<sub>score</sub> entails an opposite  
 344 interpretation from the switching-cost<sub>duration</sub> and switching-cost<sub>RT</sub>. A higher switching-cost<sub>score</sub>  
 345 means more correct answers for the switching block compared to the other two blocks (addition  
 346 and subtraction), whereas higher switching-cost<sub>duration</sub> and switching-cost<sub>RT</sub>, 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,<sup>8</sup>  
 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

---

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

<sup>8</sup> 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  $\pm 75 \mu\text{V}$  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.

#### 370 **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 ( $\log_{10}$ ) 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).

#### 378 **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  $\eta$  squared ( $\eta_p^2$ ), 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,

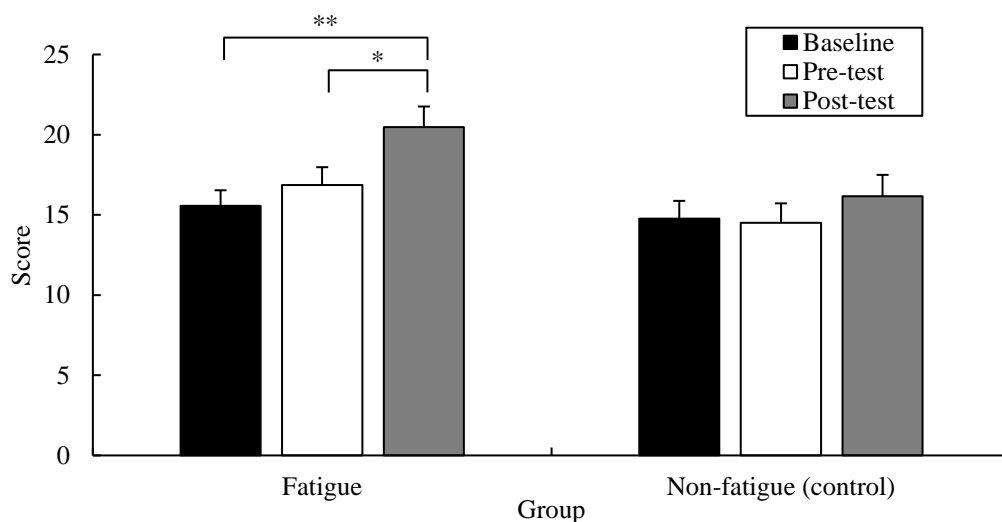
389 0.5 and 0.8 indicating relatively small, medium and large effect sizes, respectively (Cohen,  
390 1988). The statistical tests were performed using SPSS (IBM, version 25.0) computer software.  
391 Significance was set at  $p = .05$  for all statistical tests.

392

## 5 Results

### 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 ( $p = .427$ ).



404

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),  $t(41.79) = 4.53, p < .001, d = 1.21$ .

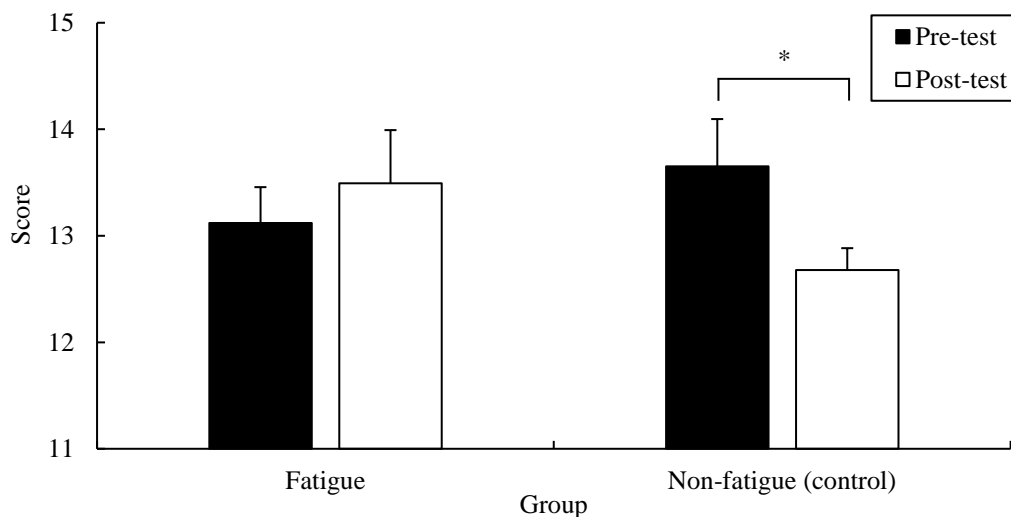
412 **5.3 Executive functions**

413 **5.3.1 Inhibition**

414 For the Stroop task inhibition-cost<sub>score</sub> (see formula in Method),<sup>9</sup> 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<sub>score</sub> 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<sub>duration</sub>, 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,  $F(1,44) = 0.53, p = .469, \eta_p^2 = .01$ .<sup>10</sup>

423



424

425 *Figure 6.* Inhibition-cost<sub>score</sub> for the Stroop task for each group at pre-test and post-test. The  
426 higher the inhibition-cost<sub>score</sub> the higher the number of attempts needed to complete the

---

<sup>9</sup> Logarithmic (log10) transformation was performed to control for skewness (Troyer et al., 2006).

<sup>10</sup> See Table 1 in Appendix for all mean and SD values for non-significant results.

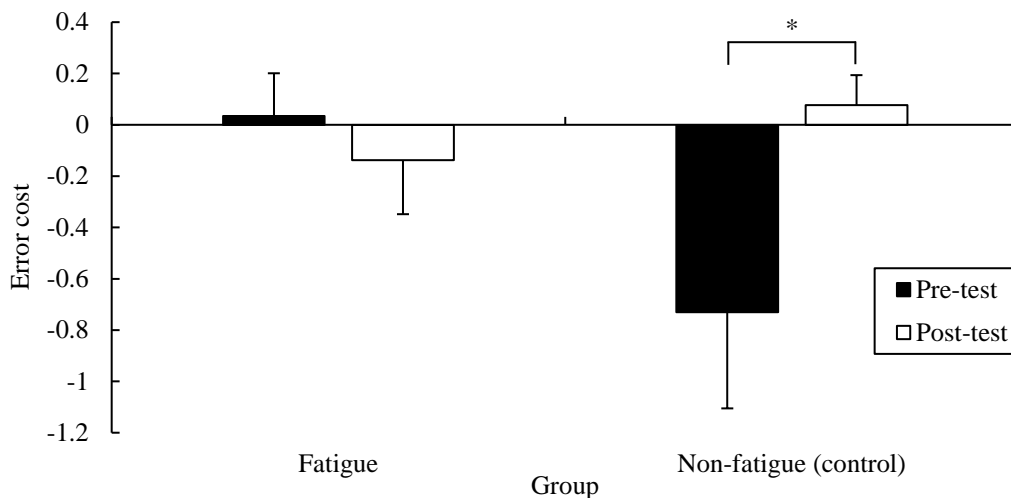
427 *interference* block (i.e., worse performance). Error bars represent standard error of the mean.

428 \* $p < .05$ .

### 429 5.3.2 Switching

430 For Plus-Minus switching-cost<sub>score</sub> (see formula in Method),<sup>11</sup> 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<sub>score</sub> 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<sub>score</sub> for the Plus-Minus task for each group at pre-test and post-test.

439 The higher the switching-cost<sub>RT</sub> 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<sub>duration</sub>, 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,  $F(1,52) = 2.19, p = .145, \eta_p^2 = .04$ .

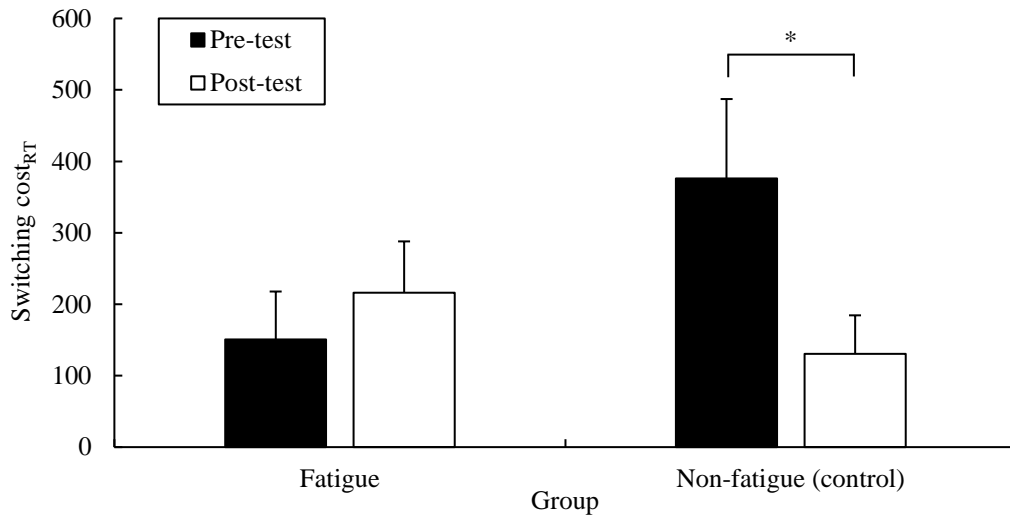
445 For the Plus-Minus switching-cost<sub>RT</sub>, neither a main effect of Group,  $F(1,51) = 0.70, p$   
446  $= .407, \eta_p^2 = .01$ , nor of Test,  $F(1,51) = 1.47, p = .232, \eta_p^2 = .03$ , was evident. However, there

---

<sup>11</sup> Logarithmic (log<sub>10</sub>) 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<sub>RT</sub> 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<sub>RT</sub> for the Plus-Minus task for each group at pre-test and post-test.  
 454 The higher the switching-cost<sub>RT</sub> 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,<sup>12</sup> main effects were not evident for Group,  $F(1,39) = 1.84, p = .183, \eta_p^2 =$   
 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  $p = .792, \eta_p^2 < .01$ .

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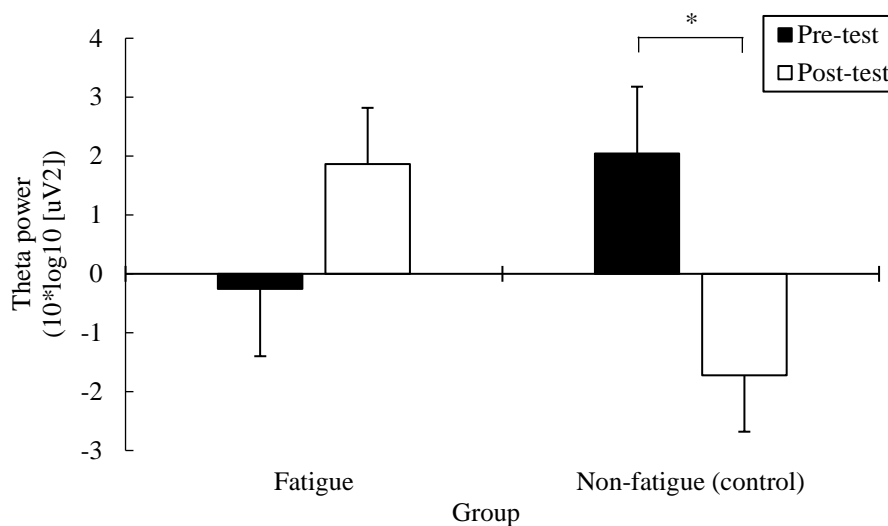
<sup>12</sup> Logarithmic (log<sub>10</sub>) transformation was performed to control for skewness (Engelhardt, Harden, Tucker-Drob, & Church, 2019).

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,  $F(1,26) = 1.88, p = .183, \eta_p^2 = .07$ .

## 484 5.5 Cardiac vagal control

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

## 488 6 Discussion

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

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

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

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

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

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

## 539 **7 Experiment 1: Part B**

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

---

<sup>14</sup> 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)<sup>15</sup> 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<sup>16</sup>  
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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<sup>15</sup> High-alpha power is inversely related to neural activity (e.g., Gallicchio, Cooke, & Ring, 2017; Klimesch, 1999).

<sup>16</sup> 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

### 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.

### 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



## 596 **8.3 Measures**

### 597 **8.3.1 Shuffleboard task**

598 Radial error (cm) was obtained as a performance measure. Radial error represented the distance  
599 between the final position of the disk and the centre of the target. *ScorePutting* software  
600 (written in National Instruments LabVIEW) was used to compute the radial error from a  
601 photograph taken with a camera that was placed directly above the target (Neumann & Thomas,  
602 2008).

### 603 **8.3.2 Behavioural measures of hypothesis testing**

604 Participants were asked to rate how motivated they were to perform the shuffleboard task (scale  
605 1–10), in order to control for potential influences of motivation on task performance (Boksem,  
606 Meijman, & Lorist, 2006). No significant differences in motivation were revealed between  
607 Groups,  $t(53) = -1.295$ ,  $p = .201$ ,  $d = 0.35$ .

608 Self-reported technique changes were conducted by asking the participants to rate how  
609 often they changed their technique during each block of twenty trials (scale 1–10).  
610 Additionally, two researchers blinded to treatment group independently viewed the video data  
611 and counted the number of paddle solutions and the number of changes in technique during  
612 each block of trials. Paddle solutions were defined as the different ways in which the paddle  
613 was used (see Figure 10), and changes in technique were defined as the different ways in which  
614 the paddle was moved. A high degree of correlation was evident between the scores of the two  
615 researchers for both measures -  $ICC_{\text{average measures stick}} = 0.80$ , 95% confidence interval 0.29-0.94,  
616  $F(11,11) = 4.92$ ,  $p = .007$  and  $ICC_{\text{average measures technique}} = 0.86$ , 95% confidence interval 0.33-  
617 0.94,  $F(11,11) = 5.16$ ,  $p = .006$  (Hallgren, 2012).

### 618 **8.3.3 Psychophysiological measures of hypothesis testing**

619 EEG data was examined during the motor preparation phase of each trial of the shuffleboard  
620 task. The EEG data was obtained and processed using the same protocol as in Experiment 1:  
621 Part A (see Methods). Participants rested their head on a chin rest prior to each trial and were  
622 asked to only focus on the target (to reduce eye movements). They were instructed to remain  
623 as still as possible during when performing the task. Participants started preparing the  
624 movement when the disk was placed in front of them and initiated their movement when the  
625 target appeared on the board. EEG activity was determined for the high alpha frequency band  
626 (10-12 Hz), as this frequency is associated with global cortico-communication (Klimesch,  
627 1999).

## 628 **8.4 Procedure**

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

## 638 **8.5 Data analysis**

### 639 **8.5.1 EEG connectivity and power measures**

640 The EEG data was analysed by first generating epochs consisting of 5 sec prior until 2 sec after  
641 the target appeared (i.e., movement initiation) for each trial. Thereafter, the same filtering and  
642 cleaning procedures employed in Part A were applied to the epochs (see Experiment 1: Part A,  
643 Methodology, for more details). A threshold-based artefact removal procedure was performed,  
644 deleting epochs with values  $\pm 75 \mu\text{V}$  to clean the signal (Deeny, Hillman, Janelle, & Hatfield,  
645 2003). Exclusion of participants from further analysis occurred if too many epochs (more than  
646 25%) had to be deleted.<sup>17</sup> The alpha frequency band (8-12 Hz) was adjusted for each participant  
647 based on their individual alpha frequency (IAF) peak, determined from the baseline measure  
648 described in Experiment 1: Part A (IAF toolbox, Corcoran, Alday, Schlesewsky, & Bornkessel-  
649 Schlesewsky, 2018). The clean signal was then subjected to time frequency analysis to obtain  
650 estimated instantaneous high alpha frequency power for 3 sec prior to movement initiation.

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

$$655 \quad \text{ISPC}_{xy}(f) = \left| n^{-1} \sum_{t=1}^n e^{i(\theta_x(tf) - \theta_y(tf))} \right|$$

---

<sup>17</sup> 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,  $\theta_x$  and  $\theta_y$  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  $\theta_x - \theta_y$ ,  $n^{-1} \sum_{t=1}^n (\cdot)$   
659 denotes averaging over time points, and  $|\cdot|$  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).

### 664 **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  $\eta$   
669 squared ( $\eta_p^2$ ), 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.

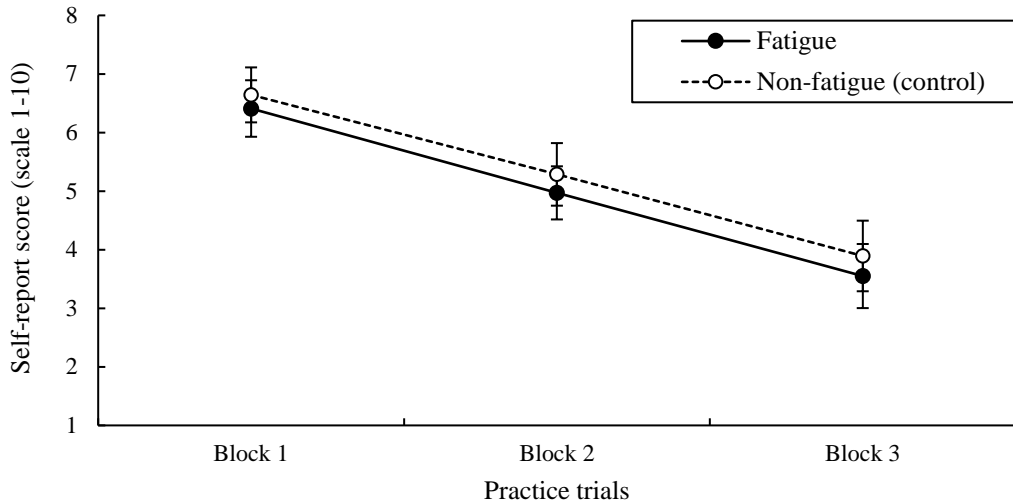
## 672 **9 Results**

### 673 **9.1 Behavioural measures of hypothesis testing**

#### 674 **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,  $F(2,110) = 0.01$ ,  $p = .988$ ,  $\eta_p^2 < .01$ .

680



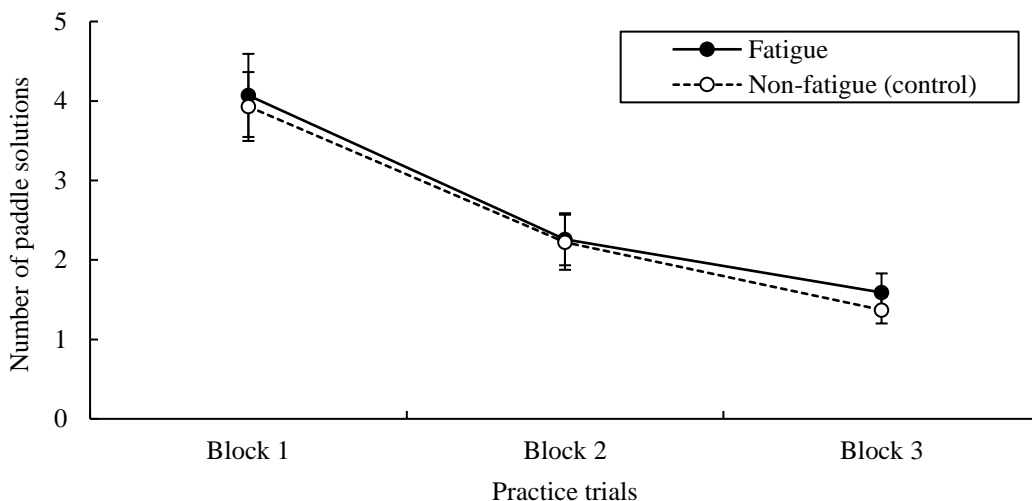
681

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.

684 **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



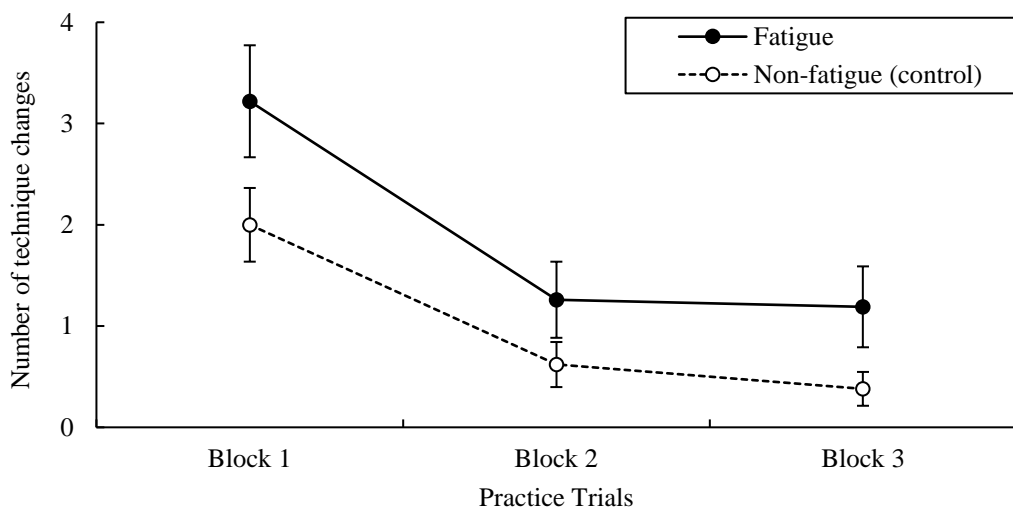
691

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

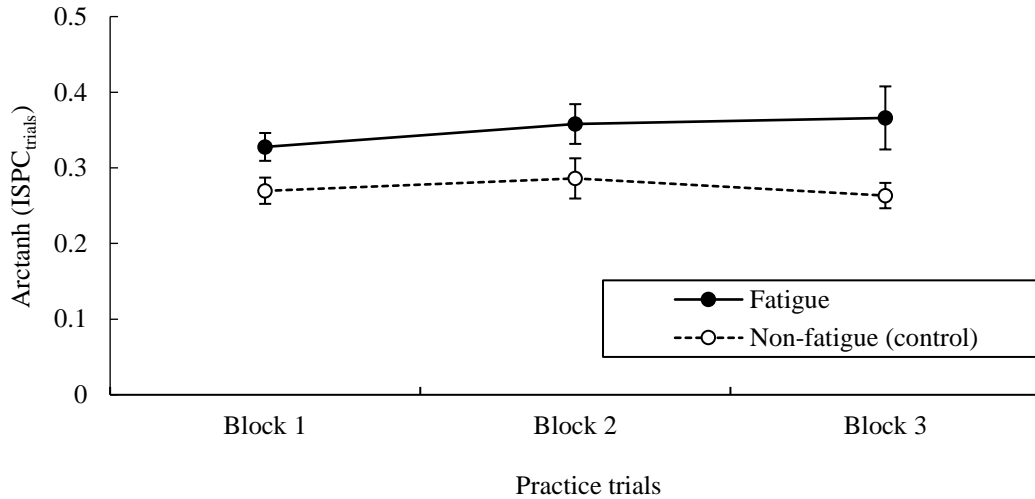
704 *Figure 13.* Mean number of technique changes for each group by block of trials. Error bars  
705 represent standard error of the mean.

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



714

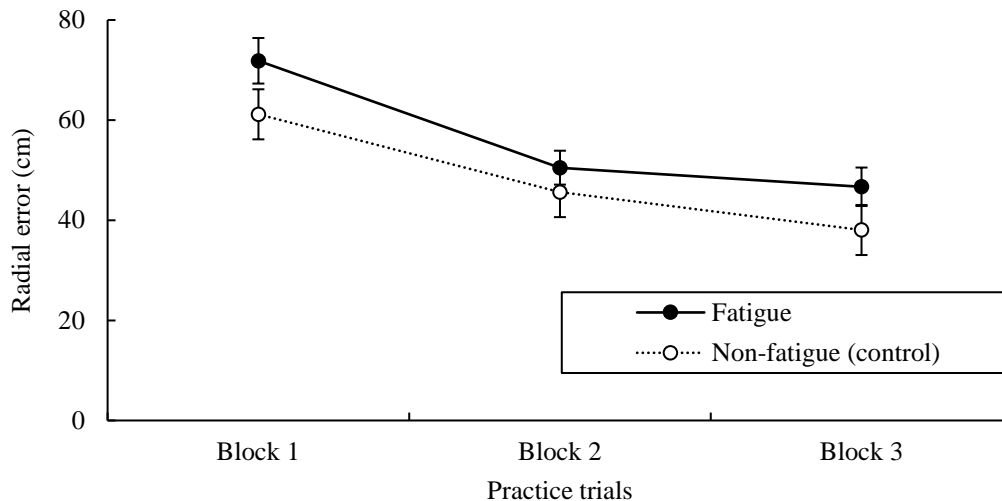
715 *Figure 14.* Mean ISPCtrials connectivity for each group by block of trials. Error bars  
 716 represent standard error of the mean.

717 **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).

721 **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

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

730

## 10 Discussion

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

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

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

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

753 A limitation of the experiment is that we did not include a shuffleboard baseline  
754 measure and, therefore, we cannot fully discount the possibility that increased verbal-analytical  
755 engagement in the fatigued group might have been a result of the shuffleboard skill level of the  
756 participants. However, a baseline shuffleboard task would have provided an opportunity to  
757 accumulate explicit knowledge about the task, which would have confounded our measures of  
758 hypothesis testing. Furthermore, we cannot preclude the possibility that the effects of cognitive  
759 fatigue dissipated over time. Future studies should, therefore, include a measure of fatigue  
760 during the shuffleboard task to establish whether fatigue remained for the total duration of the  
761 60 trials.

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

## 767 **11 General Discussion**

768 Implicit approaches to motor learning argue that explicit (i.e., verbal-analytical) control of  
769 movement can disrupt procedural (i.e., automatized) control of motor performance. Implicit  
770 motor learning paradigms (e.g., Masters, 1992), therefore, seek to promote procedural control  
771 of movement by reducing hypothesis testing during learning. In pilot work (Hoskens et al.,  
772 2018), we found that a computer-based cognitive fatigue task developed by Borrigan et al.  
773 (2016) did not deplete cognitive resources needed for hypothesis testing during complex  
774 movements. We concluded that the cognitive fatigue task that Borrigan et al. (2016) employed  
775 was not sufficiently mentally demanding to reduce verbal-analytical engagement when  
776 learning complex motor skills. We suggested that a more movement-specific cognitive fatigue  
777 task should be developed. Based on our pilot work, we designed a cognitive fatigue task that  
778 was motor focused and which challenged information processing (i.e., executive functions of  
779 working memory).

780 In Part A of the experiment, we found that participants in the cognitively fatigued group  
781 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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## 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 <sub>duration</sub>	18.07	9.47	17.09	5.21	20.85	10.57	17.75	7.34
Switching-cost <sub>duration</sub>	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

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

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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.

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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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