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1 **The effects of a single night of complete and partial sleep deprivation on**
2 **physical and cognitive performance: a Bayesian Analysis.**

3
4 **Running Head:** Sleep disruption and athletic performance

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10

11

12

13 **Abstract**

14 This study investigated the effects of complete and partial sleep deprivation on multiple aspects
15 of athletic performance.

16 Ten males completed a cognitive function test, maximal handgrip strength, countermovement
17 jump (CMJ) and a 15 min all out cycling test to assess aerobic performance. These tests were
18 performed following 3 different sleep conditions; normal sleep (CON), a 4 hr sleep opportunity
19 (PART) and complete sleep deprivation (DEP). Data were analysed using a Bayesian multi-
20 level regression model to provide probabilities of impairment (p=%).

21 Aerobic performance, CMJ and handgrip strength were impaired by 11.4% (p=100%), 10.9%
22 (p=100%) and 6% (p=97%) following DEP, while aerobic performance and CMJ were highly
23 likely impaired by 4.1% (p=90%) and 5.2% (p=94%) following PART. Cognitive reaction
24 time was not impacted by PART or DEP. In contrast the accuracy of responses was highly
25 likely impaired by 2% (91) following DEP, while there was less certainty of impaired accuracy
26 following PART (-1%, p=73).

27 Multiple aspects of physical and cognitive performance were impacted by sleep deprivation.
28 The greatest detrimental effects were seen for aerobic performance and CMJ. Partial sleep
29 deprivation equating to 4 hrs of sleep causes subtle, but potentially important negative
30 impairments on athletic performance.

31 **Key Words:** Sleep disruption, deprivation, athletic performance, exercise.

32

33 **Introduction**

34 Athletes are reported to be at an increased risk of disrupted or impaired sleep (Gupta, Morgan,
35 & Gilchrist, 2017). During routine training and out of competition periods, the sleep of elite
36 athletes appears only slightly worse than matched controls (Leeder, Glaister, Pizzoferro,
37 Dawson, & Pedlar, 2012); however, there are a range of scenarios which can further impair or
38 restrict sleep of athletes. For example, early morning training, which is common in many
39 sports, has been shown to severely restrict the amount of sleep acquired (Sargent, Halson, &
40 Roach, 2014). While competition itself can also have a negative impact upon sleep; in a cohort
41 of elite Australian athletes, 64% reported impaired sleep prior to competition, with anxiety and
42 ‘simply not being able to sleep’ being the most commonly reported issues (Juliff, Halson, &
43 Peiffer, 2015). More recent research by the same group has suggested that high trait anxiety,
44 but not catecholamine concentration, may be important in sleep following evening fixtures
45 (Juliff, Peiffer, & Halson, 2018). Athletes also regularly travel long distances in order to
46 compete, sometimes with minimal time to compensate for the potentially negative effects of
47 travel fatigue and/ or jetlag (Roberts, Teo, & Warmington, 2018). Both short (up to 6.5 hr) and
48 long-haul (6.5-32.0 hr) travel have been shown to impair sleep and with further negative
49 impacts upon mood and fatigue (Thornton et al., 2018). There may also be important
50 considerations for the growing number of people participating in ultra-endurance events which,
51 due to the extended length of some of these events, can require athletes to remain awake for
52 longer than the normal wake period. Indeed, there is evidence that athletes who adopt a pre-
53 race sleep management strategy achieve faster race completion times than those who do not
54 (Poussel et al., 2015), while a recent analysis of the sleep habits of ultra-marathoners reported
55 that, only 21% of participants had a strategy to manage sleep (e.g. through micronaps) during
56 the event (Martin, Arnal, Hoffman, & Millet, 2018).

57 Amongst athletes and coaches, sleep is widely considered essential for optimal athletic
58 performance (Venter, 2014), yet this supposition has not always been supported in well-
59 controlled studies. While it is important to consider that the impaired sleep experienced by
60 athletes is often accompanied by other features such as pre-competition anxiety (as discussed
61 above), and is therefore not identical in nature to forced sleep deprivation in a laboratory
62 setting, studies of sleep deprivation do provide a basis to study the effects of impaired sleep.

63 A recent review (Fullagar et al., 2015) reported considerable variation in the reported effects
64 of sleep deprivation on athletic performance. While the authors concluded that athletic
65 performance is likely impaired, the extent and nature of this impairment was still unclear. This

66 is partly due to potential differences in the duration of the sleep deprivation employed in
67 various studies, with some studies employing as much as 64 hrs of sleep deprivation (Takeuchi,
68 Davis, Plyley, Goode, & Shephard, 1985) and others as little as 3 hrs reduced sleep time
69 (Mougin et al., 1991). Even at the more extreme end of the sleep deprivation spectrum, findings
70 are not consistent; for example, a recent study reported no change in maximal strength or
71 aerobic performance following 60 hrs of sleep deprivation (Vaara et al., 2018). In contrast other
72 studies have reported impaired aerobic performance (Oliver, Costa, Laing, Bilzon, & Walsh,
73 2009) and maximal strength (Bulbulian, Heaney, Leake, Sucec, & Sjöholm, 1996) from 24 hrs
74 of sleep deprivation.

75 The majority of studies have examined the effect of sleep deprivation of 24 hrs or greater, while
76 far fewer studies have investigated the potentially subtler effects of partial sleep deprivation or
77 sleep disruption (see Fullagar et al., 2015 for a thorough review). Importantly, this is more
78 likely to be what is experienced by athletes during competition and routine training. To date
79 no studies have made direct comparisons across multiple sleep interventions and
80 methodological differences make it difficult to make comparisons between the likely impact
81 of different durations of sleep deprivation or disruption. A regular feature described in the field
82 of sleep deprivation and exercise performance is the large variability in potentially detrimental
83 effects on a given performance measure. Indeed, one study reported that endurance
84 performance was impaired by 45% in some participants while others performed marginally
85 better, or at least within the established error of the test itself (Martin, 1981). This issue,
86 combined with the fact that these types of studies have relatively low sample sizes means that
87 traditional null hypothesis significance testing (NHST) may not be an appropriate for detecting
88 potentially subtle effects, especially those likely seen following partial sleep deprivation. For
89 these reasons we have taken a Bayesian approach to the analysis.

90 The aim of the current study was to compare the impact of one night of sleep deprivation and
91 partial sleep deprivation (a 4 hr sleep opportunity) across several broad domains that underpin
92 exercise performance including aerobic, anaerobic, maximal strength and cognitive
93 performance. We selected a series of measures which would have minimal impact on
94 subsequent tests and that have high reliability and stability. It was hypothesised that
95 performance would be negatively impacted by one night of sleep deprivation and this would
96 be to a greater extent than partial sleep deprivation.

97

98

99 **Methods**

100

101 **Participants**

102 Ten recreationally active males (aged 27 ± 6 years, height 182 ± 8 cm, weight 88 ± 8 kg, $\dot{V}O_2$
103 $_{max}$ 43 ± 7 ml.kg.min⁻¹) gave written informed consent to participate in the study. Participants
104 completed health screening, physical activity questionnaires and a Pittsburgh Sleep Quality
105 Index (PSQI) as part of the screening procedures (Buysse, Reynolds, Monk, Berman, &
106 Kupfer, 1989). Inclusion criteria were being at least moderately physically active, having
107 previous experience of vigorous exercise, being a nocturnal sleeper and having normal healthy
108 sleep (Global PSQI score <5) (Buysse et al., 1989). Exclusion criteria were being a smoker,
109 recent or ongoing medical conditions that would contraindicate vigorous exercise and taking
110 any medication in the previous 2 weeks. Ethical approval was obtained from the Health and
111 Science research ethics committee (project code-SH16170020-R) and all procedures
112 conformed to the Declaration of Helsinki.

113

114 **Preliminary Testing**

115 Participants first completed an incremental exercise test using an electromagnetically braked
116 cycle ergometer (Lode Excalibur, Groningen, Netherlands). Expired gases were continuously
117 measured using an online gas analysis system (Cortex Biophysik Metalyzer, Germany), while
118 heart rate was measured via a heart rate monitor (RS400, Polar Electro, Finland). The
119 incremental test consisted of 3-minute stages, starting at 100W and increasing by 30W each
120 stage, and continued until volitional exhaustion (as previously described (Cullen, Thomas,
121 Webb, & Hughes, 2016). Participants were instructed to maintain a pedal cadence of 80rpm
122 throughout the test. $\dot{V}O_2$ $_{max}$ was recorded as the highest 30-s period of oxygen consumption.
123 Oxygen consumption values obtained throughout each participant's test were used to plot a
124 linear regression of power output versus oxygen consumption and the resultant equation was
125 then used to determine standardised power outputs for subsequent test sessions. Following the
126 maximal test participants were familiarised with tests to be conducted in subsequent sessions.

127

128 **Study Design**

129

130 **Experimental design**

131 Participants completed 3 three experimental trials in a randomised and counterbalanced order
132 with 7 days between each trial. Testing took place between 07:00 and 09:00 following 3

133 different sleep conditions. For the control condition (CON) participants were instructed to
134 arrive at the laboratory following a normal night's sleep in their own bed. Prior to (PART) and
135 (DEP) conditions, participants arrived at the laboratory the night prior to testing (approximately
136 21:00) and remained under the supervision of the researchers in the laboratory throughout this
137 time until the completion of the experiment the next morning. During PART, participants were
138 allowed a 4-hour sleep opportunity, in a pre-prepared room at their normal bedtime, whereupon
139 they were then awoken by the researcher. While awake during PART and DEP, participants
140 were allowed to conduct sedentary activities such as watching films and talking with the
141 researchers. During this period participants were allowed to drink water but were not permitted
142 to eat until completion of the testing. Participants were instructed to maintain their normal sleep
143 and physical activity routine between trials, this was verified by an actigraph which was worn
144 throughout the study (Actiheart, Version 2.2, CamNTEch Ltd., Cambridge, UK). On the
145 morning of each experimental trial, participants completed a brief sleep diary comprising a
146 subjective estimate of their sleep quality on a 5-point scale (1 being very poor and 5 being very
147 good sleep quality). Data from actigraphs and sleep diaries was used to describe the total sleep
148 duration, subjective sleep quality, time to bed and time awake, experienced prior to CON and
149 PART. Participants were asked to replicate their diet prior to each trial while abstaining from
150 caffeine for 12 hrs prior to commencement of each test session. Within the experimental
151 sessions each test was performed in the same order and in the sequence described below.

152

153 **Test procedures**

154 *Cognitive Function*

155 Participants completed a computerised version of the Stroop test, a common test of executive
156 function, which consisted a total of 80 congruent and incongruent trials. Words were displayed
157 on a black background; in the congruent trials the colour of the font and the word itself were
158 the same, while in the incongruent trials the word and colour of font were different. Participants
159 were instructed to identify the colour of the font (red, green, blue, yellow), by typing the first
160 letter of the corresponding word (R, G, B, Y). Errors rates (i.e. accuracy) and reaction time
161 were calculated following each condition. This version of the Stroop Test has been shown to
162 have good reliability across a one week period as was utilised in the current study (Franzen,
163 Tishelman, Sharp, & Friedman, 1987).

164

165 *Handgrip Strength*

166 Maximal handgrip strength was recorded on the non-dominant hand using a handheld
167 dynamometer (Takei, Tokyo, Japan). Participants stood with their arm abducted above their
168 head, and contracted maximally as they brought their hand to their side, while keeping their
169 hand in a neutral position. Three trials were conducted with 60s rest in between, and the best
170 performance was recorded.

171

172 *Countermovement Jump*

173 Vertical jump height was measured for a counter movement jump (CMJ) performed on an FSL
174 Jump Mat (FSL Scoreboards, Cookstown, Northern Ireland). Participants performed each jump
175 with a vertical torso, with their hands on their hips, and minimal bending of the knees upon
176 landing (Markovic, Dizdar, Jukic, & Cardinale, 2004). Three jumps were performed with 60s
177 rest in between and the best performance was included in the analysis.

178

179 *Aerobic Performance*

180 Participants completed a 15-minute self-paced time trial on a cycle ergometer. The ergometer
181 was placed in linear mode, where power output is dependent upon pedal cadence according to
182 the following equation:

183

184

$$W = L \cdot (\text{RPM})^2$$

185 W= Power output

186 L= Linear factor

187 RPM= Pedal cadence

188

189 The linear factor was set so that the individuals preferred pedal cadence would result in a power
190 output equivalent to 85% of the maximal workload achieved in the maximal test. Participants
191 were instructed to pace themselves to achieve the greatest distance across the entire trial.
192 Subjects could see the elapsed time of the trial but were not given any further information such
193 as pedal cadence or power output. This protocol has been shown to be highly reliable (Driller,
194 2012) and effective for detecting small but meaningful differences in performance (Driller &
195 Halson, 2013). Power output was recorded continuously throughout the trials. In order to assess
196 the pacing profile during each trial, power output was averaged into 60s segments and
197 expressed as percentage of each participant's average power for the specific trial, therefore
198 accounting for any potential differences in overall performance between conditions.

199

200

201 **Data analysis**

202 Descriptive statistics were calculated and are presented as means \pm standard deviations along
203 with median \pm median absolute deviation (MAD) given some data were skewed. Aerobic
204 performance was expressed as the mean power output achieved in each trial. In order to assess
205 any effect of sleep condition on pacing in the aerobic test, a Bayesian multilevel random slopes
206 model with individual slopes for individuals allowed to vary across time was fitted using a
207 uniform prior. To model differences between conditions for each measure, a series of Bayesian
208 models were fitted to the data ranging from traditional linear models to multilevel models with
209 random intercepts. These models were fitted using both normal and skew normal distributions.
210 Prior information was incorporated into each model type ranging from uniform priors to
211 increasingly informative priors aimed at regularising the models to avoid unreasonable
212 parameter estimates. This resulted in 80 models being fitted, 16 for each measure.

213 Bayesian analysis was used because it allows the incorporation of domain specific knowledge,
214 permits direct probability statements to be made about parameters (population level effects),
215 lets zero effects to be determined, provides estimates of uncertainty around parameter values
216 that are more intuitively interpretable than those from traditional (NHST) and avoids recent
217 concerns about the misinterpretation of p-values (Wasserstein & Lazar, 2016) and the
218 appropriateness of using statistical significance as a scientific decision making tool (Amrhein,
219 Greenland, & McShane, 2019). The probabilities and percentages reported can be interpreted
220 as the probability or percentage of a difference between the control condition and the respective
221 sleep condition. Effect sizes (Cohen's d) were calculated in order to assist with assessing the
222 practical significance of the findings.

223 Leave-One-Out cross-validation (LOO) was used to determine the best model for difference
224 between control and the sleep deprivation conditions for each measure. The best models, in
225 terms of out-of-sample prediction accuracy, are those with the lowest LOO Information
226 Criterion (LOOIC) (Vehtari, Gelman, & Gabry, 2016). The models that included informative
227 priors had the lowest LOOIC. The results from these models are reported alongside models
228 fitted with uniform priors. Uniform priors produce coefficients that are very similar to those of
229 traditional frequentist methods and so reporting the results of these models together allows a
230 direct comparison of the impact of incorporating appropriate prior information into models.

231 All analyses were conducted using R (R Core Team, 2018) and with the brms package
232 (Bürkner, 2017) which uses Stan (Stan Development Team, 2018) to implement a Hamiltonian
233 Markov Chain Monte Carlo (MCMC) with a No-U-Turn Sampler. All models were checked

234 for convergence ($\hat{r} = 1$), with the graphical posterior predictive checks showing simulated data
235 under the best fitted models compared well to the observed data with no systematic
236 discrepancies (Gabry, Simpson, Vehtari, Betancourt, & Gelman, 2017).

237

238 **Results**

239

240 *Sleep Characteristics*

241 Prior to CON participants fell asleep at 22:34 ± 00:27 hrs (range 22:00- 23:15 hrs), waking at
242 06:18 ± 0:47 hrs (range= 05:30-08:00 hrs) and sleeping for 467 ± 42 mins (range= 420-535
243 mins). Prior to PART, participants fell asleep at 22:53 ± 00:33 hrs (range=22:16-23:59),
244 were woken up at 02:34 ± 0:37 hrs (range=02:15-03:59) having slept for 218 ± 21 mins (range
245 180-240 mins). Subjective sleep quality (5-point scale, 1 being very poor -5 being very good
246 sleep) was 3.3 ± 0.8 (range= 2-4) for CON and 2.6 ± 0.7 (range= 1-3) for PART. Differences
247 in the time participants fell asleep, total sleep time, and sleep quality were
248 fitted using Bayesian multilevel models with and without informative priors. There was a clear
249 difference in total sleep time between sleep conditions with a 100% chance that PART had an
250 estimated 220 minutes less sleep than CON (estimated difference= -241 mins, 95% CI= -266
251 to -212 mins). The results suggest that prior to PART, participants fell asleep, on average, an
252 estimated 19 mins later than they did before CON with a 63% chance of a difference (estimated
253 difference= 19 mins, 95% CI= 1 to 40 mins). The probability of reporting subjective sleep as
254 ‘average’ (3 out of 5) was similar between conditions, 62% and 59% for CON and PART
255 respectively, while the probability of ‘poor’ sleep (2 out of 5) was higher for PART (33%) than
256 CON (2%) and the probability of ‘good’ sleep was higher for CON (32%) than PART (1%).

257

258 *Performance Tests*

259 The means and medians of the physical test variables suggests total sleep deprivation lowers
260 aerobic performance, reduces CMJ height and handgrip strength. While partial sleep
261 deprivation also had an effect, it had a lower impact on physical performance (see table 1). The
262 means and medians for cognitive accuracy show decreases in performance in psychological
263 variables, with cognitive accuracy decreasing and reaction times increasing for both partial and
264 full sleep deprivation (see table 2). Given the data for aerobic performance, handgrip strength,
265 cognitive accuracy and cognitive reaction time are skewed, the median is the better average to
266 consider for these measures.

267

xxx Insert Tables 1 & 2 Here xxx

268

269 Parameter estimates for the physical performance variables from the Bayesian models fitted
270 with uniform priors show a high probability of a decrease in performance following full sleep
271 deprivation, with probabilities of a difference ranging from 97 - 100% (see table 3). The effect
272 of partial sleep deprivation was more uncertain with all 95% credible intervals including zero.
273 For partial sleep deprivation there is high probability ($p=93\%$, $d=-0.63$) of a detrimental effect
274 on aerobic performance (Fig.1A) and CMJ ($p=94\%$, $d=-0.69$, Fig. 1B) but not for handgrip
275 strength where a zero effect was found to be highly likely ($p=53\%$, $d=0.02$ see Fig. 1C).
276 Similar detrimental effects were highly likely ($p=91\%$, $d=-0.2$) for cognitive accuracy (Fig.
277 2A) after total sleep deprivation but not for cognitive reaction time, where no effect was found
278 to be highly probable ($p=63\%$, $d=0.0$, Fig. 2B). Partial sleep deprivation had a lower probability
279 ($p=73\%$, $d=-0.26$) of impairing cognitive accuracy and an even lower probability of an effect
280 on cognitive reaction time (Fig. 4A and Fig. 2B respectively).

281

282 The same conclusions can be drawn from the Bayesian models fitted using informative priors.
283 There was a negative impact on aerobic performance, CMJ height partial and total sleep
284 deprivation, handgrip strength was only impaired following total sleep deprivation (see table
285 4). Nonetheless, the differences across conditions were reduced. Informative priors had no
286 impact on cognitive accuracy estimates but resulted in lower estimates for the increase
287 cognitive reaction times, particularly for partial sleep deprivation (see table 4).

288

289 **xxx Insert Table 3 & 4 Here xxx**

290 **xxx Insert Figure 1 Here xxx**

291 **xxx Insert Figure 2 Here xxx**

292

293 The results of Bayesian multilevel random slopes model suggest that there were minimal
294 differences between conditions in for the pacing throughout the aerobic test (Deprivation v
295 Control= -3.68% , 95%CI $[-12.34: 4.88]$, Partial v Control= -2.13 , 95%CI $[-10.22: 6.49]$; see
296 Fig. 3).

297

298 **xxx Insert Figure 3 Here xxx**

299

300 **Discussion**

301 In the current study we found that multiple physical and cognitive aspects of human
302 performance were highly likely to be negatively impacted by partial sleep and complete sleep
303 deprivation, relative to a night of normal sleep. Detrimental effects were lower in magnitude
304 and less likely across all domains following partial sleep deprivation, with no impact at all on
305 maximal handgrip strength. With regard to cognitive performance, we found that sleep
306 deprivation did not impair reaction time, but it did impair the accuracy of responses to the
307 Stroop task. In addition to confirming the negative effects of a single night of complete sleep
308 deprivation, we present novel findings that a single night of modest sleep deprivation is likely
309 to have a negative impact upon sporting performance, although the nature and extent is
310 dependent upon the specifics of the event.

311 Following a single night of complete sleep deprivation, aerobic performance and CMJ were
312 the most likely physical performance metrics to be impaired ($p=99\%$ and $p=100\%$ respectively)
313 and were also impaired to a greater extent ($d=-1.33$ and $d=-1.28$ respectively) than maximal
314 handgrip strength ($p=97\%$, $d=-0.77$). In terms of cognitive performance, the accuracy, but not
315 reaction time of responses was highly likely impaired following a night of complete sleep
316 deprivation ($p=91\%$, $d=-0.61$). Following partial sleep deprivation, aerobic performance and
317 CMJ were still highly likely to be impaired ($p=92\%$ and $p=94\%$ respectively) but to a lesser
318 extent ($d=-0.63$ and $d=-0.69$) than following complete sleep deprivation. These subtle
319 differences in performance could be important in athletic competitions that are regularly
320 decided by small margins.

321 Our results are in agreement with the findings of previous research that have reported impaired
322 aerobic (Chen, 1991; Oliver et al., 2009; Temesi et al., 2013), anaerobic (Bulbulian et al., 1996;
323 Skein, Duffiedl, Edge, Short, & Mundel, 2011; Takeuchi et al., 1985) and cognitive
324 performance (Williamson & Feyer, 2000) following one night of complete sleep deprivation,
325 but contradicts other studies (Goodman, Radomski, Hart, Plyley, & Shephard, 1989; Vaara et
326 al., 2018). The conflicting results are potentially due to differences in the specific tests used.
327 For example, Oliver et al. (2009) suggested that a distance test, such as the one used in the
328 current study, might have a smaller signal to noise ratio than incremental exercise tests which
329 were used by Vaara et al. (2018) and Goodman et al (1989). These differences are potentially
330 explained by the altered perception of effort experienced following sleep deprivation
331 (Keramidas, Gadefors, Nilsson, & Eiken, 2018), given that incremental tests only require a
332 relatively short period of discomfort in contrast to distance tests. In the current study aerobic
333 performance appears to be impaired due to a consistently lower power output throughout rather
334 than an alteration in pacing strategy (see Fig. 3). It may be that endurance events which require

335 self-pacing and prolonged high intensity efforts are more susceptible to impaired performance
336 than those which do not, and indeed it could be argued that this may be more widely applicable
337 to sporting performance where self-pacing is common (Konings & Hettinga, 2018). As such it
338 could be that longer endurance events such as the marathon are impacted a greater extent
339 (Fullagar et al., 2015). This may be even more important in the context of ultramarathons where
340 sleep deprivation is common. For example, response times have been shown to be impaired
341 following an ultramarathon (Hurdie et al., 2015), which is in contrast to the findings of our
342 study as we found that reaction time in the Stroop test was not impacted, but the accuracy of
343 responses was. This could be construed as conflicting the majority of findings showing
344 impaired reaction time (Fullagar et al., 2015), however, it does reflect similar findings reported
345 when using the Stroop test (Lucas, Anson, Palmer, Hellemans, & Cotter, 2009). This further
346 emphasises that the reported responses are highly specific to the test chosen.

347 Comparatively few studies have investigated the impact of partial sleep deprivation on
348 performance, highlighting the novelty of our study but making direct comparisons to the
349 literature more difficult. One previous study reported that a sleep intervention equating to 3 hrs
350 less sleep than normal did not result in changes in maximal aerobic or anaerobic performance
351 (Mougin et al., 1991). However, this study only had 7 participants and was likely statistically
352 underpowered to demonstrate an effect. In the current study, we found that physical
353 performance was highly likely to be impaired with the exception of maximal handgrip strength,
354 which was maintained. Indeed handgrip strength was maintained in the morning following
355 partial sleep deprivation, but was significantly impaired in the evening (Souissi et al., 2008).

356 From an applied perspective, athletes who experience disrupted sleep may not compete until
357 the afternoon or evening, and therefore performance may well be more greatly impaired than
358 in our study. It is important to consider that our findings are specific to the time of day that the
359 testing was carried out (7:00-9:00am), and while many domestic sporting events routinely take
360 place in the afternoon, many events during major international competitions are scheduled
361 early in the morning (for a variety of reasons). A further complicating factor when comparing
362 the results of studies of shortened sleep is that there may also be effect on the quality of sleep,
363 yet this is not always reported (for example see Souissi et al., 2008). In our study, we afforded
364 participants a 4 hr sleep opportunity, whereby they attempted to fall asleep at their normal
365 bedtime and were woken 4 hrs later. We found a reasonably high chance (63%) that participants
366 would fall asleep slightly later than usual (on average 19 mins later) in PART than CON, while
367 there was also a high probability that subjective sleep quality was impaired, suggesting some
368 subtle effects on *how* people slept as well as simply having shorter sleep. In this regard it should

369 be acknowledged that our data are limited to subjective measures of sleep quality and the
370 addition of more detailed measures through polysomnography (for example) may provide
371 additional information about the important characteristics of sleep in these circumstances.
372 Across all outcome measures we found considerable individual variation in responses, i.e. not
373 all participants appear to be negatively impacted by sleep deprivation, a trait that is common
374 within similar studies (Keramidas et al., 2018; Oliver et al., 2009). This is an important issue
375 and one that potentially explains some of the conflicting results within the existing literature
376 as it will likely lead to skewed data, which may mask any effects using traditional NHST. As
377 such a particular strength of the current study was the use of Bayesian analysis and probabilities
378 of effect which we feel is more representative of the true responses. However, further research
379 should investigate the variability in individual responses, and the underpinning mechanisms,
380 to the potentially negative effects of sleep deprivation, as this may help in the development of
381 countermeasures to mitigate performance impairments following sleep loss. Indeed, a perhaps
382 under researched component within this context is the influence of chronotype. It is well
383 established that an athlete's chronotype can have a significant impact on athletic performance
384 (Vitale & Weydahl, 2017) and it may be that there are subtle interactions between chronotype
385 and whether an individual is susceptible to impaired performance following sleep deprivation.
386 Some limitations should be taken into account when considering the current study. In many
387 situations, sleep deprivation or disruption may be accompanied by changes in nervous activity
388 that accompany competition and may have wider effects than seen in the current study.
389 Although very difficult to replicate, this may be an important aspect for future research to
390 investigate. While we have attempted to assess a broad array of measures of human
391 performance, we did not assess other crucial aspects of sporting performance such co-
392 ordination, or repeated sprint performance. Finally, the participants, while accustomed to
393 vigorous exercise and training were not highly trained or competitive athletes, however
394 performing a highly controlled study of this nature with repeated testing would be incredibly
395 difficult while also maintaining adequate control of confounding factors (e.g. demanding
396 training schedules and regular competition).

397

398 **Practical implications**

399 Even a fairly modest reduction in sleep was shown to have subtle, but potentially important,
400 negative effects on both aerobic performance and CMJ performance. Athletes and coaches
401 should plan ahead to minimise any potentially negative impacts upon sleep. Coaches should be
402 aware that scheduling of early practices can reduce sleep to the degree seen in this study and

403 therefore should not expect optimal performances (or training) in these circumstances.
404 Athletes, coaches and support staff should seek countermeasures to these detrimental effects.
405

406 **Conclusion**

407 Multiple aspects of physical and cognitive performance were impaired by a single night of
408 sleep deprivation and partial sleep deprivation. These effects were smaller following partial
409 sleep deprivation, with handgrip strength also maintained following partial sleep deprivation.
410 These findings are important for athletes who may experience even moderate sleep deprivation
411 prior to competition as it is highly likely to impact their performance.
412
413

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539 **Tables**

540 **Table 1.** Descriptive statistics (Mean \pm Standard Deviation and Median \pm Median Absolute
 541 Deviation) of physical measurements in conditions

Condition	Mean Power (W)		Counter Movement Jump (Cm)		Hand Grip Strength (Kg)	
	Mean \pm SD	Median \pm MAD	Mean \pm SD	Median \pm MAD	Mean \pm SD	Median \pm MAD
Control	225 \pm 42	236 \pm 28.2	36.7 \pm 5.2	35.1 \pm 4.2	50.6 \pm 4.7	51.0 \pm 5.9
Partial	212 \pm 46	217 \pm 50	34.8 \pm 4.5	34.3 \pm 4.7	50.6 \pm 6.3	49.8 \pm 7.4
Deprivation	197 \pm 61	194 \pm 72	32.7 \pm 4.5	32.5 \pm 0.6	47.6 \pm 7.2	45.3 \pm 4.2

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545 **Table 2.** Descriptive statistics (Mean \pm Standard Deviation and Median \pm Median Absolute
 546 Deviation) of psychological measurements in all sleep conditions

Condition	Cognitive Accuracy (%)		Cognitive Reaction Time (ms)	
	Mean \pm SD	Median \pm MAD	Mean \pm SD	Median \pm MAD
Control	96 \pm 3	97 \pm 4	903 \pm 145	827 \pm 94
Partial	95 \pm 3	96 \pm 3	931 \pm 156	913 \pm 217
Deprivation	94 \pm 5	94 \pm 6	916 \pm 165	944 \pm 243

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549 **Table 3.** Comparisons of the differences in physical performance tests between conditions
 550 from models with flat and informative priors

Measure	Comparison of conditions	Uniform Prior			Informative Prior		
		Estimated Difference	95% CI	%<0†	Estimated Difference	95% CI	%<0†
Mean Power (W)	Deprivation<Control	-27.4	-44.82: -9.06	99	-25.7	-47.18: -5.25	99
Mean Power (W)	Partial <Control	-12.8	-30.90: 5.20	92	-12.14	-28.31: 4.51	93
CMJ (cm)	Deprivation<Control	-3.94	-6.60: -1.32	100	-3.84	-6.40: -1.27	100
CMJ (cm)	Partial <Control	-2.22	-4.77: 0.54	94	-2.13	-4.68: 0.51	94
Hand grip strength (kg)	Deprivation<Control	-3.26	-6.76: 0.34	97	-2.87	-5.99: 0.50	95
Hand grip strength (kg)	Partial <Control	-0.07	-3.43: 3.25	53	0.09	-2.97: 2.97	47

551 † the percentage of the posterior distribution of the difference that falls below zero

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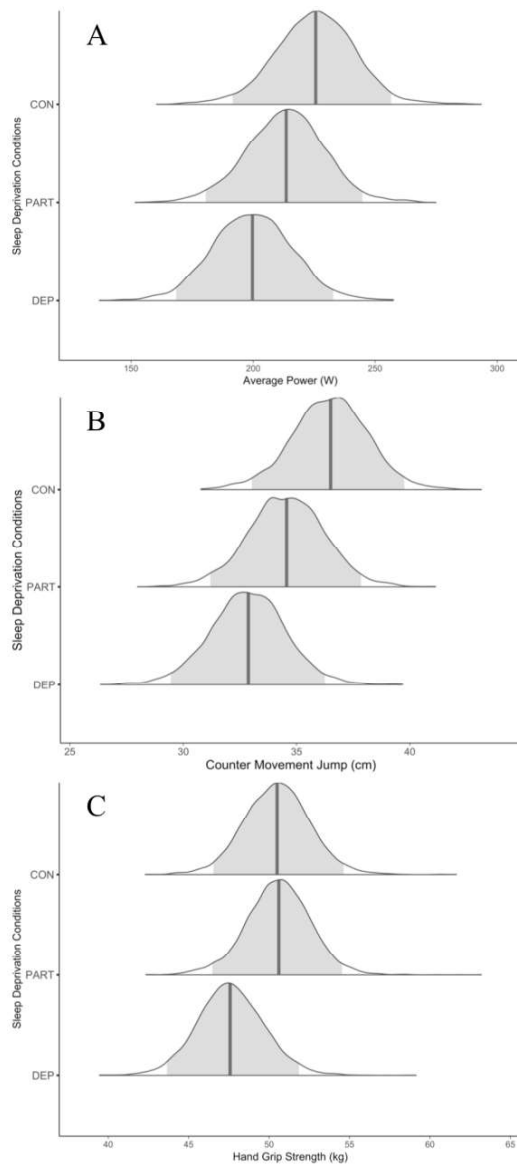
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554 **Table 4.** Comparisons of the differences in cognitive performance between conditions from
 555 models with flat and informative priors

Measure	Comparison of conditions	Uniform Prior			Informative Prior		
		Estimated Difference	95% CI	%<0†	Estimated Difference	95% CI	%<0†
Cognitive accuracy (%)	Deprivation<Control	-2	-6: 0.01	91	-0.02	-0.06:0.01	90
Cognitive accuracy (%)	Partial <Control	-1	-4: 0.02	73	-0.01	-0.05: 0.03	72
Cognitive RT (ms)	Deprivation<Control	-15.27	-129.69: 116.86	63	-15.25	-132.35: 117.50	52
Cognitive RT (ms)	Partial <Control	8.63	-111.13: 140.57	46	7.81	-108.95 139.09	38

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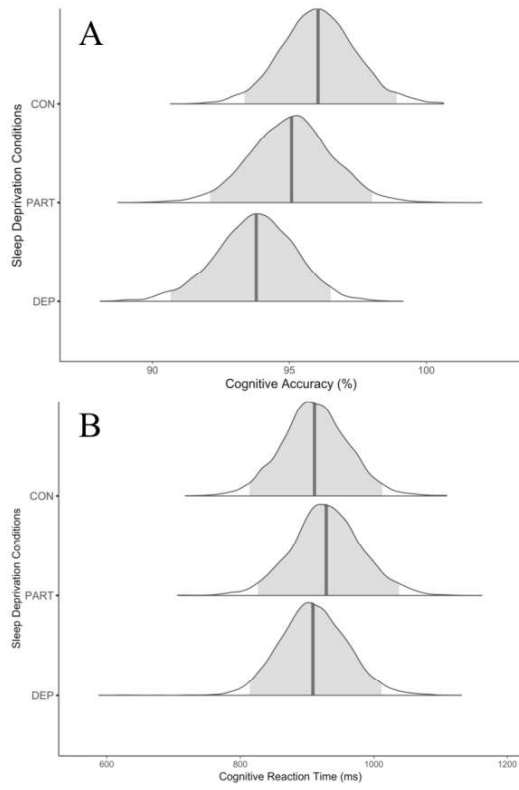
† the percentage of the posterior distribution of the difference that falls below zero

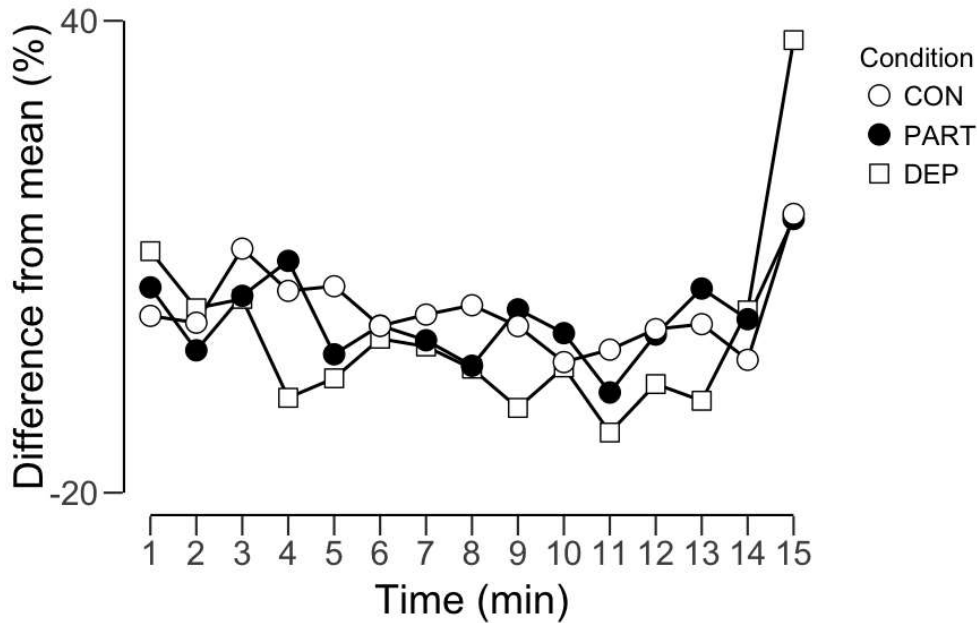


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 559 **Figure 1.**
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Figure 2.





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565 **Figure 3.**

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568 **Figure Captions**

569 **Figure 1.** The effects of sleep condition on physical performance. A comparison of the
570 posterior distributions for average power output during the 15-minute cycle time trial (A),
571 countermovement jump height (B) and handgrip strength (C) for each sleep condition as
572 predicted by the best model with 95% credible intervals.

573 **Figure 2.** The effects of sleep condition on cognitive performance. A comparison of the
574 posterior distributions for ‘cognitive accuracy’ (A) and ‘cognitive reaction time’ (B) for each
575 sleep condition as predicted by the best model with 95% credible intervals.

576 **Figure 3.** Effect of sleep condition on pacing profile during the aerobic test as displayed by the
577 percentage deviation away from the mean power in the individual trial. Effects are not indicated
578 on the figure.

579

1 **The effects of a single night of complete and partial sleep deprivation on**
2 **physical and cognitive performance: a Bayesian Analysis.**

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24
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32 **Abstract**

33 This study investigated the effects of complete and partial sleep deprivation on multiple aspects
34 of athletic performance.

35 Ten males completed a cognitive function test, maximal handgrip strength, countermovement
36 jump (CMJ) and a 15 min all out cycling test to assess aerobic performance. These tests were
37 performed following 3 different sleep conditions; normal sleep (CON), a 4 hr sleep opportunity
38 (PART) and complete sleep deprivation (DEP). Data were analysed using a Bayesian multi-
39 level regression model to provide probabilities of impairment (p=%).

40 Aerobic performance, CMJ and handgrip strength were impaired by 11.4% (p=100%), 10.9%
41 (p=100%) and 6% (p=97%) following DEP, while aerobic performance and CMJ were highly
42 likely impaired by 4.1% (p=90%) and 5.2% (p=94%) following PART. Cognitive reaction
43 time was not impacted by PART or DEP. In contrast the accuracy of responses was highly
44 likely impaired by 2% (91) following DEP, while there was less certainty of impaired accuracy
45 following PART (-1%, p=73).

46 Multiple aspects of physical and cognitive performance were impacted by sleep deprivation.
47 The greatest detrimental effects were seen for aerobic performance and CMJ. Partial sleep
48 deprivation equating to 4 hrs of sleep causes subtle, but potentially important negative
49 impairments on athletic performance.

50 **Key Words:** Sleep disruption, deprivation, athletic performance, exercise.

52 **Introduction**

53 Athletes are reported to be at an increased risk of disrupted or impaired sleep (Gupta, Morgan,
54 & Gilchrist, 2017). During routine training and out of competition periods, the sleep of elite
55 athletes appears only slightly worse than matched controls (Leeder, Glaister, Pizzoferro,
56 Dawson, & Pedlar, 2012); however, there are a range of scenarios which can further impair or
57 restrict sleep of athletes. For example, early morning training, which is common in many
58 sports, has been shown to severely restrict the amount of sleep acquired (Sargent, Halson, &
59 Roach, 2014). While competition itself can also have a negative impact upon sleep; in a cohort
60 of elite Australian athletes, 64% reported impaired sleep prior to competition, with anxiety and
61 'simply not being able to sleep' being the most commonly reported issues (Juliff, Halson, &
62 Peiffer, 2015). More recent research by the same group has suggested that high trait anxiety,
63 but not catecholamine concentration, may be important in sleep following evening fixtures
64 (Juliff, Peiffer, & Halson, 2018). Athletes also regularly travel long distances in order to
65 compete, sometimes with minimal time to compensate for the potentially negative effects of

66 travel fatigue and/ or jetlag (Roberts, Teo, & Warmington, 2018). Both short (up to 6.5 hr) and
67 long-haul (6.5-32.0 hr) travel have been shown to impair sleep and with further negative
68 impacts upon mood and fatigue (Thornton et al., 2018). There may also be important
69 considerations for the growing number of people participating in ultra-endurance events which,
70 due to the extended length of some of these events, can require athletes to remain awake for
71 longer than the normal wake period. Indeed, there is evidence that athletes who adopt a pre-
72 race sleep management strategy achieve faster race completion times than those who do not
73 (Poussel et al., 2015), while a recent analysis of the sleep habits of ultra-marathoners reported
74 that, only 21% of participants had a strategy to manage sleep (e.g. through micronaps) during
75 the event (Martin, Arnal, Hoffman, & Millet, 2018).

76 Amongst athletes and coaches, sleep is widely considered essential for optimal athletic
77 performance (Venter, 2014), yet this supposition has not always been supported in well-
78 controlled studies. While it is important to consider that the impaired sleep experienced by
79 athletes is often accompanied by other features such as pre-competition anxiety (as discussed
80 above), and is therefore not identical in nature to forced sleep deprivation in a laboratory
81 setting, studies of sleep deprivation do provide a basis to study the effects of impaired sleep.

82 A recent review (Fullagar et al., 2015) reported considerable variation in the reported effects
83 of sleep deprivation on athletic performance. While the authors concluded that athletic
84 performance is likely impaired, the extent and nature of this impairment was still unclear. This
85 is partly due to potential differences in the duration of the sleep deprivation employed in
86 various studies, with some studies employing as much as 64 hrs of sleep deprivation (Takeuchi,
87 Davis, Plyley, Goode, & Shephard, 1985) and others as little as 3 hrs reduced sleep time
88 (Mougin et al., 1991). Even at the more extreme end of the sleep deprivation spectrum, findings
89 are not consistent; for example, a recent study reported no change in maximal strength or
90 aerobic performance following 60 hrs of sleep deprivation (Vaara et al., 2018). In contrast other
91 studies have reported impaired aerobic performance (Oliver, Costa, Laing, Bilzon, & Walsh,
92 2009) and maximal strength (Bulbulian, Heaney, Leake, Sucec, & Sjöholm, 1996) from 24 hrs
93 of sleep deprivation.

94 The majority of studies have examined the effect of sleep deprivation of 24 hrs or greater, while
95 far fewer studies have investigated the potentially subtler effects of partial sleep deprivation or
96 sleep disruption (see Fullagar et al., 2015 for a thorough review). Importantly, this is more
97 likely to be what is experienced by athletes during competition and routine training. To date
98 no studies have made direct comparisons across multiple sleep interventions and
99 methodological differences make it difficult to make comparisons between the likely impact

100 of different durations of sleep deprivation or disruption. A regular feature described in the field
1 101 of sleep deprivation and exercise performance is the large variability in potentially detrimental
2 102 effects on a given performance measure. Indeed, one study reported that endurance
3 103 performance was impaired by 45% in some participants while others performed marginally
4 104 better, or at least within the established error of the test itself (Martin, 1981). This issue,
5 105 combined with the fact that these types of studies have relatively low sample sizes means that
6 106 traditional null hypothesis significance testing (NHST) may not be an appropriate for detecting
7 107 potentially subtle effects, especially those likely seen following partial sleep deprivation. For
8 108 these reasons we have taken a Bayesian approach to the analysis.

9 109 The aim of the current study was to compare the impact of one night of sleep deprivation and
10 110 partial sleep deprivation (a 4 hr sleep opportunity) across several broad domains that underpin
11 111 exercise performance including aerobic, anaerobic, maximal strength and cognitive
12 112 performance. We selected a series of measures which would have minimal impact on
13 113 subsequent tests and that have high reliability and stability. It was hypothesised that
14 114 performance would be negatively impacted by one night of sleep deprivation and this would
15 115 be to a greater extent than partial sleep deprivation.

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18 118 **Methods**

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20 120 **Participants**

21 121 Ten recreationally active males (aged 27 ± 6 years, height 182 ± 8 cm, weight 88 ± 8 kg, $\dot{V}O_2$
22 122 $_{max}$ 43 ± 7 ml.kg.min⁻¹) gave written informed consent to participate in the study. Participants
23 123 completed health screening, physical activity questionnaires and a Pittsburgh Sleep Quality
24 124 Index (PSQI) as part of the screening procedures (Buysse, Reynolds, Monk, Berman, &
25 125 Kupfer, 1989). Inclusion criteria were being at least moderately physically active, having
26 126 previous experience of vigorous exercise, being a nocturnal sleeper and having normal healthy
27 127 sleep (Global PSQI score <5) (Buysse et al., 1989). Exclusion criteria were being a smoker,
28 128 recent or ongoing medical conditions that would contraindicate vigorous exercise and taking
29 129 any medication in the previous 2 weeks. Ethical approval was obtained from the Health and
30 130 Science research ethics committee (project code-SH16170020-R) and all procedures
31 131 conformed to the Declaration of Helsinki.

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133 **Preliminary Testing**

134 Participants first completed an incremental exercise test using an electromagnetically braked
135 cycle ergometer (Lode Excalibur, Groningen, Netherlands). Expired gases were continuously
136 measured using an online gas analysis system (Cortex Biophysik Metalyzer, Germany), while
137 heart rate was measured via a heart rate monitor (RS400, Polar Electro, Finland). The
138 incremental test consisted of 3-minute stages, starting at 100W and increasing by 30W each
139 stage, and continued until volitional exhaustion (as previously described (Cullen, Thomas,
140 Webb, & Hughes, 2016). Participants were instructed to maintain a pedal cadence of 80rpm
141 throughout the test. $\dot{V}O_{2 \max}$ was recorded as the highest 30-s period of oxygen consumption.
142 Oxygen consumption values obtained throughout each participant's test were used to plot a
143 linear regression of power output versus oxygen consumption and the resultant equation was
144 then used to determine standardised power outputs for subsequent test sessions. Following the
145 maximal test participants were familiarised with tests to be conducted in subsequent sessions.

147 **Study Design**

149 **Experimental design**

150 Participants completed 3 three experimental trials in a randomised and counterbalanced order
151 with 7 days between each trial. Testing took place between 07:00 and 09:00 following 3
152 different sleep conditions. For the control condition (CON) participants were instructed to
153 arrive at the laboratory following a normal night's sleep in their own bed. Prior to (PART) and
154 (DEP) conditions, participants arrived at the laboratory the night prior to testing (approximately
155 21:00) and remained under the supervision of the researchers in the laboratory throughout this
156 time until the completion of the experiment the next morning. During PART, participants were
157 allowed a 4-hour sleep opportunity, in a pre-prepared room at their normal bedtime, whereupon
158 they were then awoken by the researcher. While awake during PART and DEP, participants
159 were allowed to conduct sedentary activities such as watching films and talking with the
160 researchers. During this period participants were allowed to drink water but were not permitted
161 to eat until completion of the testing. Participants were instructed to maintain their normal sleep
162 and physical activity routine between trials, this was verified by an actigraph which was worn
163 throughout the study (Actiheart, Version 2.2, CamNTEch Ltd., Cambridge, UK). On the
164 morning of each experimental trial, participants completed a brief sleep diary comprising a
165 subjective estimate of their sleep quality on a 5-point scale (1 being very poor and 5 being very

166 good sleep quality). Data from actigraphs and sleep diaries was used to describe the total sleep
167 duration, subjective sleep quality, time to bed and time awake, experienced prior to CON and
168 PART. Participants were asked to replicate their diet prior to each trial while abstaining from
169 caffeine for 12 hrs prior to commencement of each test session. Within the experimental
170 sessions each test was performed in the same order and in the sequence described below.

172 **Test procedures**

173 *Cognitive Function*

174 Participants completed a computerised version of the Stroop test, a common test of executive
175 function, which consisted a total of 80 congruent and incongruent trials. Words were displayed
176 on a black background; in the congruent trials the colour of the font and the word itself were
177 the same, while in the incongruent trials the word and colour of font were different. Participants
178 were instructed to identify the colour of the font (red, green, blue, yellow), by typing the first
179 letter of the corresponding word (R, G, B, Y). Errors rates (i.e. accuracy) and reaction time
180 were calculated following each condition. This version of the Stroop Test has been shown to
181 have good reliability across a one week period as was utilised in the current study (Franzen,
182 Tishelman, Sharp, & Friedman, 1987).

184 *Handgrip Strength*

185 Maximal handgrip strength was recorded on the non-dominant hand using a handheld
186 dynamometer (Takei, Tokyo, Japan). Participants stood with their arm abducted above their
187 head, and contracted maximally as they brought their hand to their side, while keeping their
188 hand in a neutral position. Three trials were conducted with 60s rest in between, and the best
189 performance was recorded.

191 *Countermovement Jump*

192 Vertical jump height was measured for a counter movement jump (CMJ) performed on an FSL
193 Jump Mat (FSL Scoreboards, Cookstown, Northern Ireland). Participants performed each jump
194 with a vertical torso, with their hands on their hips, and minimal bending of the knees upon
195 landing (Markovic, Dizdar, Jukic, & Cardinale, 2004). Three jumps were performed with 60s
196 rest in between and the best performance was included in the analysis.

198 *Aerobic Performance*

199 Participants completed a 15-minute self-paced time trial on a cycle ergometer. The ergometer
200 was placed in linear mode, where power output is dependent upon pedal cadence according to
201 the following equation:

$$W = L \cdot (\text{RPM})^2$$

204 W= Power output

205 L= Linear factor

206 RPM= Pedal cadence

207
208 The linear factor was set so that the individuals preferred pedal cadence would result in a power
209 output equivalent to 85% of the maximal workload achieved in the maximal test. Participants
210 were instructed to pace themselves to achieve the greatest distance across the entire trial.
211 Subjects could see the elapsed time of the trial but were not given any further information such
212 as pedal cadence or power output. This protocol has been shown to be highly reliable (Driller,
213 2012) and effective for detecting small but meaningful differences in performance (Driller &
214 Halson, 2013). Power output was recorded continuously throughout the trials. In order to assess
215 the pacing profile during each trial, power output was averaged into 60s segments and
216 expressed as percentage of each participant's average power for the specific trial, therefore
217 accounting for any potential differences in overall performance between conditions.

220 **Data analysis**

221 Descriptive statistics were calculated and are presented as means \pm standard deviations along
222 with median \pm median absolute deviation (MAD) given some data were skewed. Aerobic
223 performance was expressed as the mean power output achieved in each trial. In order to assess
224 any effect of sleep condition on pacing in the aerobic test, a Bayesian multilevel random slopes
225 model with individual slopes for individuals allowed to vary across time was fitted using a
226 uniform prior. To model differences between conditions for each measure, a series of Bayesian
227 models were fitted to the data ranging from traditional linear models to multilevel models with
228 random intercepts. These models were fitted using both normal and skew normal distributions.
229 Prior information was incorporated into each model type ranging from uniform priors to
230 increasingly informative priors aimed at regularising the models to avoid unreasonable
231 parameter estimates. This resulted in 80 models being fitted, 16 for each measure.

232 Bayesian analysis was used because it allows the incorporation of domain specific knowledge,
1 233 permits direct probability statements to be made about parameters (population level effects),
2 234 lets zero effects to be determined, provides estimates of uncertainty around parameter values
3 235 that are more intuitively interpretable than those from traditional (NHST) and avoids recent
4 236 concerns about the misinterpretation of p-values (Wasserstein & Lazar, 2016) and the
5 237 appropriateness of using statistical significance as a scientific decision making tool (Amrhein,
6 238 Greenland, & McShane, 2019). The probabilities and percentages reported can be interpreted
7 239 as the probability or percentage of a difference between the control condition and the respective
8 240 sleep condition. Effect sizes (Cohen's d) were calculated in order to assist with assessing the
9 241 practical significance of the findings.
10 242 Leave-One-Out cross-validation (LOO) was used to determine the best model for difference
11 243 between control and the sleep deprivation conditions for each measure. The best models, in
12 244 terms of out-of-sample prediction accuracy, are those with the lowest LOO Information
13 245 Criterion (LOOIC) (Vehtari, Gelman, & Gabry, 2016). The models that included informative
14 246 priors had the lowest LOOIC. The results from these models are reported alongside models
15 247 fitted with uniform priors. Uniform priors produce coefficients that are very similar to those of
16 248 traditional frequentist methods and so reporting the results of these models together allows a
17 249 direct comparison of the impact of incorporating appropriate prior information into models.
18 250 All analyses were conducted using R (R Core Team, 2018) and with the brms package
19 251 (Bürkner, 2017) which uses Stan (Stan Development Team, 2018) to implement a Hamiltonian
20 252 Markov Chain Monte Carlo (MCMC) with a No-U-Turn Sampler. All models were checked
21 253 for convergence ($\hat{r} = 1$), with the graphical posterior predictive checks showing simulated data
22 254 under the best fitted models compared well to the observed data with no systematic
23 255 discrepancies (Gabry, Simpson, Vehtari, Betancourt, & Gelman, 2017).

24 256

25 257 **Results**

26 258

27 259 *Sleep Characteristics*

28 260 Prior to CON participants fell asleep at 22:34 ± 00:27 hrs (range 22:00- 23:15 hrs), waking at
29 261 06:18 ± 0:47 hrs (range= 05:30-08:00 hrs) and sleeping for 467 ± 42 mins (range= 420-535
30 262 mins). Prior to PART, participants fell asleep at 22:53 ± 00:33 hrs (range=22:16-23:59),
31 263 were woken up at 02:34 ± 0:37 hrs (range=02:15-03:59) having slept for 218 ± 21 mins (range
32 264 180-240 mins). Subjective sleep quality (5-point scale, 1 being very poor -5 being very good
33 265 sleep) was 3.3 ± 0.8 (range= 2-4) for CON and 2.6 ± 0.7 (range= 1-3) for PART. Differences

266 in the time participants fell asleep, total sleep time, and sleep quality were
267 fitted using Bayesian multilevel models with and without informative priors. There was a clear
268 difference in total sleep time between sleep conditions with a 100% chance that PART had an
269 estimated 220 minutes less sleep than CON (estimated difference= -241 mins, 95% CI= -266
270 to -212 mins). The results suggest that prior to PART, participants fell asleep, on average, an
271 estimated 19 mins later than they did before CON with a 63% chance of a difference (estimated
272 difference= 19 mins, 95% CI= 1 to 40 mins). The probability of reporting subjective sleep as
273 ‘average’ (3 out of 5) was similar between conditions, 62% and 59% for CON and PART
274 respectively, while the probability of ‘poor’ sleep (2 out of 5) was higher for PART (33%) than
275 CON (2%) and the probability of ‘good’ sleep was higher for CON (32%) than PART (1%).

277 *Performance Tests*

278 The means and medians of the physical test variables suggests total sleep deprivation lowers
279 aerobic performance, reduces CMJ height and handgrip strength. While partial sleep
280 deprivation also had an effect, it had a lower impact on physical performance (see table 1). The
281 means and medians for cognitive accuracy show decreases in performance in psychological
282 variables, with cognitive accuracy decreasing and reaction times increasing for both partial and
283 full sleep deprivation (see table 2). Given the data for aerobic performance, handgrip strength,
284 cognitive accuracy and cognitive reaction time are skewed, the median is the better average to
285 consider for these measures.

286 **xxx Insert Tables 1 & 2 Here xxx**

288 Parameter estimates for the physical performance variables from the Bayesian models fitted
289 with uniform priors show a high probability of a decrease in performance following full sleep
290 deprivation, with probabilities of a difference ranging from 97 - 100% (see table 3). The effect
291 of partial sleep deprivation was more uncertain with all 95% credible intervals including zero.
292 For partial sleep deprivation there is high probability (p=93%, d=-0.63) of a detrimental effect
293 on aerobic performance (Fig.1A) and CMJ (p=94%, d=-0.69, Fig. 1B) but not for handgrip
294 strength where a zero effect was found to be highly likely (p=53 %, d=0.02 see Fig. 1C).
295 Similar detrimental effects were highly likely (p=91%, d=-0.2) for cognitive accuracy (Fig.
296 2A) after total sleep deprivation but not for cognitive reaction time, where no effect was found
297 to be highly probable (p=63%, d=0.0, Fig. 2B). Partial sleep deprivation had a lower probability
298 (p=73%, d=-0.26) of impairing cognitive accuracy and an even lower probability of an effect
299 on cognitive reaction time (Fig. 4A and Fig. 2B respectively).

300

1 301 The same conclusions can be drawn from the Bayesian models fitted using informative priors.
2
3 302 There was a negative impact on aerobic performance, CMJ height partial and total sleep
4
5 303 deprivation, handgrip strength was only impaired following total sleep deprivation (see table
6
7 304 4). Nonetheless, the differences across conditions were reduced. Informative priors had no
8
9 305 impact on cognitive accuracy estimates but resulted in lower estimates for the increase
10
11 306 cognitive reaction times, particularly for partial sleep deprivation (see table 4).

12 307

13 308

xxx Insert Table 3 & 4 Here xxx

14 309

xxx Insert Figure 1 Here xxx

15 310

xxx Insert Figure 2 Here xxx

16 311

17 312 The results of Bayesian multilevel random slopes model suggest that there were minimal
18 313 differences between conditions in for the pacing throughout the aerobic test (Deprivation v
19 314 Control= -3.68%, 95%CI [-12.34: 4.88], Partial v Control= -2.13, 95%CI [-10.22: 6.49]; see
20 315 Fig. 3).

21 316

22 317

xxx Insert Figure 3 Here xxx

23 318

24 319 **Discussion**

25 320 In the current study we found that multiple physical and cognitive aspects of human
26 321 performance were highly likely to be negatively impacted by partial sleep and complete sleep
27 322 deprivation, relative to a night of normal sleep. Detrimental effects were lower in magnitude
28 323 and less likely across all domains following partial sleep deprivation, with no impact at all on
29 324 maximal handgrip strength. With regard to cognitive performance, we found that sleep
30 325 deprivation did not impair reaction time, but it did impair the accuracy of responses to the
31 326 Stroop task. In addition to confirming the negative effects of a single night of complete sleep
32 327 deprivation, we present novel findings that a single night of modest sleep deprivation is likely
33 328 to have a negative impact upon sporting performance, although the nature and extent is
34 329 dependent upon the specifics of the event.

35 330 Following a single night of complete sleep deprivation, aerobic performance and CMJ were
36 331 the most likely physical performance metrics to be impaired (p=99% and p=100% respectively)
37 332 and were also impaired to a greater extent (d=-1.33 and d=-1.28 respectively) than maximal
38 333 handgrip strength (p=97%, d=-0.77). In terms of cognitive performance, the accuracy, but not

334 reaction time of responses was highly likely impaired following a night of complete sleep
1 335 deprivation ($p=91\%$, $d=-0.61$). Following partial sleep deprivation, aerobic performance and
2 336 CMJ were still highly likely to be impaired ($p=92\%$ and $p=94\%$ respectively) but to a lesser
3 337 extent ($d=-0.63$ and $d=-0.69$) than following complete sleep deprivation. These subtle
4 338 differences in performance could be important in athletic competitions that are regularly
5 339 decided by small margins.
6
7 340 Our results are in agreement with the findings of previous research that have reported impaired
8 341 aerobic (Chen, 1991; Oliver et al., 2009; Temesi et al., 2013), anaerobic (Bulbulian et al., 1996;
9 342 Skein, Duffiedl, Edge, Short, & Mundel, 2011; Takeuchi et al., 1985) and cognitive
10 343 performance (Williamson & Feyer, 2000) following one night of complete sleep deprivation,
11 344 but contradicts other studies (Goodman, Radomski, Hart, Plyley, & Shephard, 1989; Vaara et
12 345 al., 2018). The conflicting results are potentially due to differences in the specific tests used.
13 346 For example, Oliver et al. (2009) suggested that a distance test, such as the one used in the
14 347 current study, might have a smaller signal to noise ratio than incremental exercise tests which
15 348 were used by Vaara et al. (2018) and Goodman et al (1989). These differences are potentially
16 349 explained by the altered perception of effort experienced following sleep deprivation
17 350 (Keramidas, Gadefors, Nilsson, & Eiken, 2018), given that incremental tests only require a
18 351 relatively short period of discomfort in contrast to distance tests. In the current study aerobic
19 352 performance appears to be impaired due to a consistently lower power output throughout rather
20 353 than an alteration in pacing strategy (see Fig. 3). It may be that endurance events which require
21 354 self-pacing and prolonged high intensity efforts are more susceptible to impaired performance
22 355 than those which do not, and indeed it could be argued that this may be more widely applicable
23 356 to sporting performance where self-pacing is common (Konings & Hettinga, 2018). As such it
24 357 could be that longer endurance events such as the marathon are impacted a greater extent
25 358 (Fullagar et al., 2015). This may be even more important in the context of ultramarathons where
26 359 sleep deprivation is common. For example, response times have been shown to be impaired
27 360 following an ultramarathon (Hurdiel et al., 2015), which is in contrast to the findings of our
28 361 study as we found that reaction time in the Stroop test was not impacted, but the accuracy of
29 362 responses was. This could be construed as conflicting the majority of findings showing
30 363 impaired reaction time (Fullagar et al., 2015), however, it does reflect similar findings reported
31 364 when using the Stroop test (Lucas, Anson, Palmer, Hellemans, & Cotter, 2009). This further
32 365 emphasises that the reported responses are highly specific to the test chosen.
33 366 Comparatively few studies have investigated the impact of partial sleep deprivation on
34 367 performance, highlighting the novelty of our study but making direct comparisons to the

368 literature more difficult. One previous study reported that a sleep intervention equating to 3 hrs
1 369 less sleep than normal did not result in changes in maximal aerobic or anaerobic performance
2
3 370 (Mougin et al., 1991). However, this study only had 7 participants and was likely statistically
4
5 371 underpowered to demonstrate an effect. In the current study, we found that physical
6
7 372 performance was highly likely to be impaired with the exception of maximal handgrip strength,
8
9 373 which was maintained. Indeed handgrip strength was maintained in the morning following
10
11 374 partial sleep deprivation, but was significantly impaired in the evening (Souissi et al., 2008).
12
13 375 From an applied perspective, athletes who experience disrupted sleep may not compete until
14
15 376 the afternoon or evening, and therefore performance may well be more greatly impaired than
16
17 377 in our study. It is important to consider that our findings are specific to the time of day that the
18
19 378 testing was carried out (7:00-9:00am), and while many domestic sporting events routinely take
20
21 379 place in the afternoon, many events during major international competitions are scheduled
22
23 380 early in the morning (for a variety of reasons). A further complicating factor when comparing
24
25 381 the results of studies of shortened sleep is that there may also be effect on the quality of sleep,
26
27 382 yet this is not always reported (for example see Souissi et al., 2008). In our study, we afforded
28
29 383 participants a 4 hr sleep opportunity, whereby they attempted to fall asleep at their normal
30
31 384 bedtime and were woken 4 hrs later. We found a reasonably high chance (63%) that participants
32
33 385 would fall asleep slightly later than usual (on average 19 mins later) in PART than CON, while
34
35 386 there was also a high probability that subjective sleep quality was impaired, suggesting some
36
37 387 subtle effects on *how* people slept as well as simply having shorter sleep. In this regard it should
38
39 388 be acknowledged that our data are limited to subjective measures of sleep quality and the
40
41 389 addition of more detailed measures through polysomnography (for example) may provide
42
43 390 additional information about the important characteristics of sleep in these circumstances.
44
45 391 Across all outcome measures we found considerable individual variation in responses, i.e. not
46
47 392 all participants appear to be negatively impacted by sleep deprivation, a trait that is common
48
49 393 within similar studies (Keramidas et al., 2018; Oliver et al., 2009). This is an important issue
50
51 394 and one that potentially explains some of the conflicting results within the existing literature
52
53 395 as it will likely lead to skewed data, which may mask any effects using traditional NHST. As
54
55 396 such a particular strength of the current study was the use of Bayesian analysis and probabilities
56
57 397 of effect which we feel is more representative of the true responses. However, further research
58
59 398 should investigate the variability in individual responses, and the underpinning mechanisms,
60
61 399 to the potentially negative effects of sleep deprivation, as this may help in the development of
62
63 400 countermeasures to mitigate performance impairments following sleep loss. Indeed, a perhaps
64
65 401 under researched component within this context is the influence of chronotype. It is well

402 established that an athlete's chronotype can have a significant impact on athletic performance
1 403 (Vitale & Weydahl, 2017) and it may be that there are subtle interactions between chronotype
2
3 404 and whether an individual is susceptible to impaired performance following sleep deprivation.
4
5 405 Some limitations should be taken into account when considering the current study. In many
6
7 406 situations, sleep deprivation or disruption may be accompanied by changes in nervous activity
8
9 407 that accompany competition and may have wider effects than seen in the current study.
10
11 408 Although very difficult to replicate, this may be an important aspect for future research to
12
13 409 investigate. While we have attempted to assess a broad array of measures of human
14
15 410 performance, we did not assess other crucial aspects of sporting performance such co-
16
17 411 ordination, or repeated sprint performance. Finally, the participants, while accustomed to
18
19 412 vigorous exercise and training were not highly trained or competitive athletes, however
20
21 413 performing a highly controlled study of this nature with repeated testing would be incredibly
22
23 414 difficult while also maintaining adequate control of confounding factors (e.g. demanding
24
25 415 training schedules and regular competition).
26

27 416

28 417 **Practical implications**

29 418 Even a fairly modest reduction in sleep was shown to have subtle, but potentially important,
30
31 419 negative effects on both aerobic performance and CMJ performance. Athletes and coaches
32
33 420 should plan ahead to minimise any potentially negative impacts upon sleep. Coaches should be
34
35 421 aware that scheduling of early practices can reduce sleep to the degree seen in this study and
36
37 422 therefore should not expect optimal performances (or training) in these circumstances.
38
39 423 Athletes, coaches and support staff should seek countermeasures to these detrimental effects.
40

41 424

42 425 **Conclusion**

43 426 Multiple aspects of physical and cognitive performance were impaired by a single night of
44
45 427 sleep deprivation and partial sleep deprivation. These effects were smaller following partial
46
47 428 sleep deprivation, with handgrip strength also maintained following partial sleep deprivation.
48
49 429 These findings are important for athletes who may experience even moderate sleep deprivation
50
51 430 prior to competition as it is highly likely to impact their performance.
52

53 431

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565 **Tables**

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2 566 **Table 1.** Descriptive statistics (Mean ± Standard Deviation and Median ± Median Absolute
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4 567 Deviation) of physical measurements in conditions

Condition	Mean Power (W)		Counter Movement Jump (Cm)		Hand Grip Strength (Kg)	
	Mean ± SD	Median ± MAD	Mean ± SD	Median ± MAD	Mean ± SD	Median ± MAD
Control	225 ± 42	236 ± 28.2	36.7 ± 5.2	35.1 ± 4.2	50.6 ± 4.7	51.0 ± 5.9
Partial	212 ± 46	217 ± 50	34.8 ± 4.5	34.3 ± 4.7	50.6 ± 6.3	49.8 ± 7.4
Deprivation	197 ± 61	194 ± 72	32.7 ± 4.5	32.5 ± 0.6	47.6 ± 7.2	45.3 ± 4.2

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571 **Table 2.** Descriptive statistics (Mean \pm Standard Deviation and Median \pm Median Absolute
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 2 572 Deviation) of psychological measurements in all sleep conditions

Condition	Cognitive Accuracy (%)		Cognitive Reaction Time (ms)	
	Mean \pm SD	Median \pm MAD	Mean \pm SD	Median \pm MAD
Control	96 \pm 3	97 \pm 4	903 \pm 145	827 \pm 94
Partial	95 \pm 3	96 \pm 3	931 \pm 156	913 \pm 217
Deprivation	94 \pm 5	94 \pm 6	916 \pm 165	944 \pm 243

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575 **Table 3.** Comparisons of the differences in physical performance tests between conditions
 576 from models with flat and informative priors

Measure	Comparison of conditions	Uniform Prior			Informative Prior		
		Estimated Difference	95% CI	%<0†	Estimated Difference	95% CI	%<0†
Mean Power (W)	Deprivation<Control	-27.4	-44.82: -9.06	99	-25.7	-47.18: -5.25	99
Mean Power (W)	Partial <Control	-12.8	-30.90: 5.20	92	-12.14	-28.31: 4.51	93
CMJ (cm)	Deprivation<Control	-3.94	-6.60: -1.32	100	-3.84	-6.40: -1.27	100
CMJ (cm)	Partial <Control	-2.22	-4.77: 0.54	94	-2.13	-4.68: 0.51	94
Hand grip strength (kg)	Deprivation<Control	-3.26	-6.76: 0.34	97	-2.87	-5.99: 0.50	95
Hand grip strength (kg)	Partial <Control	-0.07	-3.43: 3.25	53	0.09	-2.97: 2.97	47

577 † the percentage of the posterior distribution of the difference that falls below zero
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580 **Table 4.** Comparisons of the differences in cognitive performance between conditions from
 581 models with flat and informative priors

Measure	Comparison of conditions	Uniform Prior			Informative Prior		
		Estimated Difference	95% CI	%<0†	Estimated Difference	95% CI	%<0†
Cognitive accuracy (%)	Deprivation<Control	-2	-6: 0.01	91	-0.02	-0.06:0.01	90
Cognitive accuracy (%)	Partial <Control	-1	-4: 0.02	73	-0.01	-0.05: 0.03	72
Cognitive RT (ms)	Deprivation<Control	-15.27	-129.69: 116.86	63	-15.25	-132.35: 117.50	52
Cognitive RT (ms)	Partial <Control	8.63	-111.13: 140.57	46	7.81	-108.95 139.09	38

† the percentage of the posterior distribution of the difference that falls below zero

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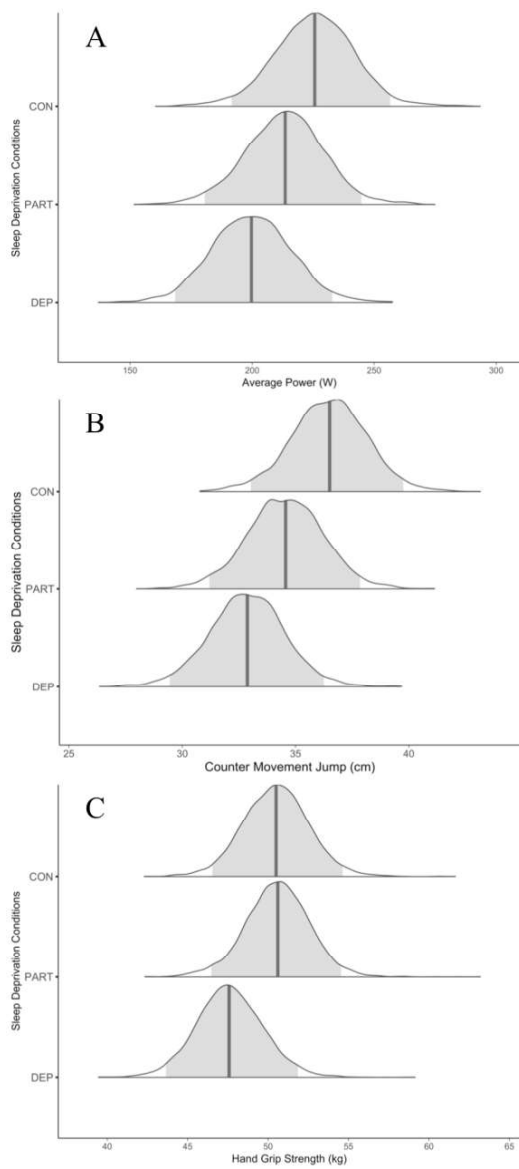


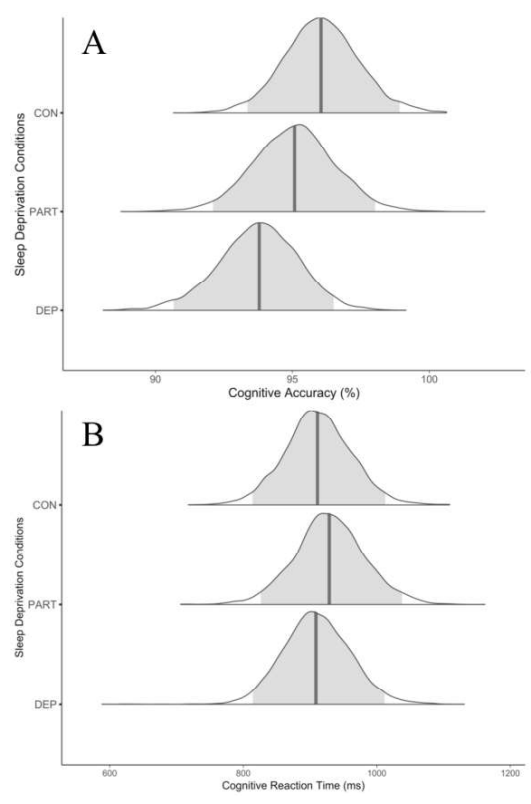
Figure 1.

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Figure 2.



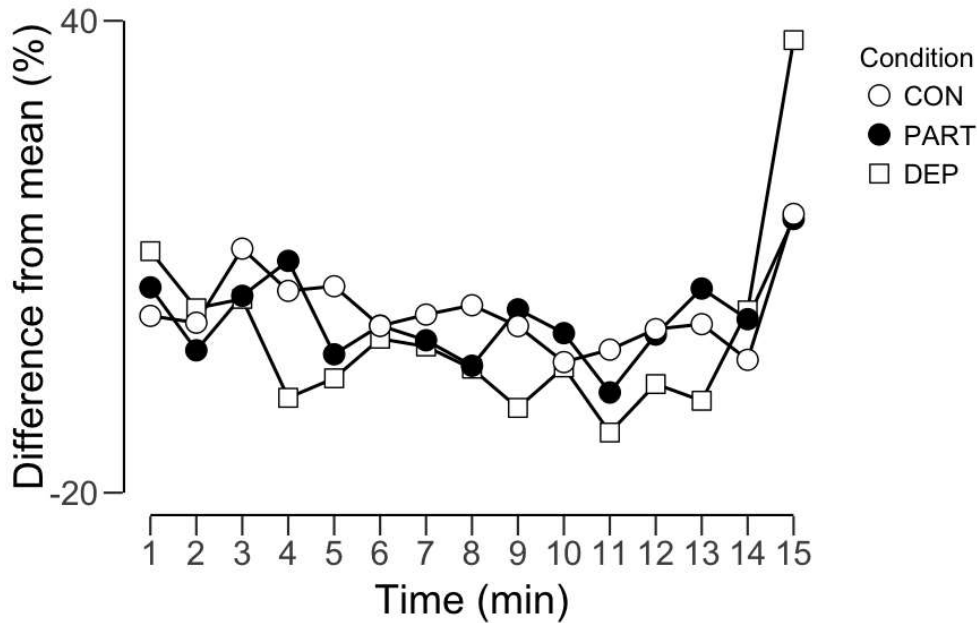


Figure 3.

Figure Captions

Figure 1. The effects of sleep condition on physical performance. A comparison of the posterior distributions for average power output during the 15-minute cycle time trial (A), countermovement jump height (B) and handgrip strength (C) for each sleep condition as predicted by the best model with 95% credible intervals.

Figure 2. The effects of sleep condition on cognitive performance. A comparison of the posterior distributions for ‘cognitive accuracy’ (A) and ‘cognitive reaction time’ (B) for each sleep condition as predicted by the best model with 95% credible intervals.

Figure 3. Effect of sleep condition on pacing profile during the aerobic test as displayed by the percentage deviation away from the mean power in the individual trial. Effects are not indicated on the figure.