Original citation:

Tom Cullen, Gavin Thomas, Alex J. Wadley & Tony Myers (2019) The effects of a single night of complete and partial sleep deprivation on physical and cognitive performance: A Bayesian analysis, Journal of Sports Sciences, DOI: 10.1080/02640414.2019.1662539

Permanent WRaP URL:

https://eprints.worc.ac.uk/8594/

Copyright and reuse:

The Worcester Research and Publications (WRaP) makes this work available open access under the following conditions. Copyright © and all moral rights to the version of the paper presented here belong to the individual author(s) and/or other copyright owners. To the extent reasonable and practicable the material made available in WRaP has been checked for eligibility before being made available.

Copies of full items can be used for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way.

Publisher's statement:

This is an Accepted Manuscript of an article published online by Taylor & Francis in
Journal of Sports Sciences on 5 Sept 2019, available online:
https://www.tandfonline.com/doi/full/10.1080/02640414.2019.1662539.

A note on versions:

The version presented here may differ from the published version or, version of record, if you wish to cite this item you are advised to consult the publisher's version. Please see the 'permanent WRaP URL' above for details on accessing the published version and note that access may require a subscription.

For more information, please contact wrapteam@worc.ac.uk

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

Running Head: Sleep disruption and athletic performance

Abstract word count: 194

Text only Word Count: 4773

Number of Tables: 4

Number of Figures: 3

Abstract

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

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

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

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

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

Introduction

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

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

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

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

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

Methods

Participants

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

Preliminary Testing

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

Study Design

Experimental design

Participants completed 3 three experimental trials in a randomised and counterbalanced order with 7 days between each trial. Testing took place between 07:00 and 09:00 following 3 different sleep conditions. For the control condition (CON) participants were instructed to arrive at the laboratory following a normal night's sleep in their own bed. Prior to (PART) and (DEP) conditions, participants arrived at the laboratory the night prior to testing (approximately 21:00) and remained under the supervision of the researchers in the laboratory throughout this time until the completion of the experiment the next morning. During PART, participants were allowed a 4-hour sleep opportunity, in a pre-prepared room at their normal bedtime, whereupon they were then awoken by the researcher. While awake during PART and DEP, participants were allowed to conduct sedentary activities such as watching films and talking with the researchers. During this period participants were allowed to drink water but were not permitted to eat until completion of the testing. Participants were instructed to maintain their normal sleep and physical activity routine between trials, this was verified by an actigraph which was worn throughout the study (Actiheart, Version 2.2, CamNTech Ltd., Cambridge, UK). On the morning of each experimental trial, participants completed a brief sleep diary comprising a subjective estimate of their sleep quality on a 5-point scale (1 being very poor and 5 being very good sleep quality). Data from actigraphs and sleep diaries was used to describe the total sleep duration, subjective sleep quality, time to bed and time awake, experienced prior to CON and PART. Participants were asked to replicate their diet prior to each trial while abstaining from caffeine for 12 hrs prior to commencement of each test session. Within the experimental sessions each test was performed in the same order and in the sequence described below.

Test procedures

Cognitive Function

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

Handgrip Strength

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

Countermovement Jump

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

Aerobic Performance

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

$$W = L \cdot (RPM)^2$$

W= Power output
L= Linear factor
RPM= Pedal cadence

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

Data analysis

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

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

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

All analyses were conducted using R (R Core Team, 2018) and with the brms package (Bürkner, 2017) which uses Stan (Stan Development Team, 2018) to implement a Hamiltonian Markov Chain Monte Carlo (MCMC) with a No-U-Turn Sampler. All models were checked for convergence ($\hat{r} = 1$), with the graphical posterior predictive checks showing simulated data under the best fitted models compared well to the observed data with no systematic discrepancies (Gabry, Simpson, Vehtari, Betancourt, & Gelman, 2017).

Results

Sleep Characteristics

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

Performance Tests

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

xxx Insert Tables 1 & 2 Here xxx

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

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

xxx Insert Table 3 & 4 Here xxx

xxx Insert Figure 1 Here xxx

xxx Insert Figure 2 Here xxx

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

xxx Insert Figure 3 Here xxx

Discussion

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

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

Our results are in agreement with the findings of previous research that have reported impaired aerobic (Chen, 1991; Oliver et al., 2009; Temesi et al., 2013), anaerobic (Bulbulian et al., 1996; Skein, Duffiedl, Edge, Short, & Mundel, 2011; Takeuchi et al., 1985) and cognitive performance (Williamson & Feyer, 2000) following one night of complete sleep deprivation, but contradicts other studies (Goodman, Radomski, Hart, Plyley, & Shephard, 1989; Vaara et al., 2018). The conflicting results are potentially due to differences in the specific tests used. For example, Oliver et al. (2009) suggested that a distance test, such as the one used in the current study, might have a smaller signal to noise ratio than incremental exercise tests which were used by Vaara et al. (2018) and Goodman et al (1989). These differences are potentially explained by the altered perception of effort experienced following sleep deprivation (Keramidas, Gadefors, Nilsson, & Eiken, 2018), given that incremental tests only require a relatively short period of discomfort in contrast to distance tests. In the current study aerobic performance appears to be impaired due to a consistently lower power output throughout rather than an alteration in pacing strategy (see Fig. 3). It may be that endurance events which require self-pacing and prolonged high intensity efforts are more susceptible to impaired performance than those which do not, and indeed it could be argued that this may be more widely applicable to sporting performance where self-pacing is common (Konings & Hettinga, 2018). As such it could be that longer endurance events such as the marathon are impacted a greater extent (Fullagar et al., 2015). This may be even more important in the context of ultramarathons where sleep deprivation is common. For example, response times have been shown to be impaired following an ultramarathon (Hurdiel et al., 2015), which is in contrast to the findings of our study as we found that reaction time in the Stroop test was not impacted, but the accuracy of responses was. This could be construed as conflicting the majority of findings showing impaired reaction time (Fullagar et al., 2015), however, it does reflect similar findings reported when using the Stroop test (Lucas, Anson, Palmer, Hellemans, & Cotter, 2009). This further emphasises that the reported responses are highly specific to the test chosen.

Comparatively few studies have investigated the impact of partial sleep deprivation on performance, highlighting the novelty of our study but making direct comparisons to the literature more difficult. One previous study reported that a sleep intervention equating to 3 hrs less sleep than normal did not result in changes in maximal aerobic or anaerobic performance (Mougin et al., 1991). However, this study only had 7 participants and was likely statistically underpowered to demonstrate an effect. In the current study, we found that physical performance was highly likely to be impaired with the exception of maximal handgrip strength, which was maintained. Indeed handgrip strength was maintained in the morning following partial sleep deprivation, but was significantly impaired in the evening (Souissi et al., 2008). From an applied perspective, athletes who experience disrupted sleep may not compete until the afternoon or evening, and therefore performance may well be more greatly impaired than in our study. It is important to consider that our findings are specific to the time of day that the testing was carried out (7:00-9:00am), and while many domestic sporting events routinely take place in the afternoon, many events during major international competitions are scheduled early in the morning (for a variety of reasons). A further complicating factor when comparing the results of studies of shortened sleep is that there may also be effect on the quality of sleep, yet this is not always reported (for example see Souissi et al., 2008). In our study, we afforded participants a 4 hr sleep opportunity, whereby they attempted to fall asleep at their normal bedtime and were woken 4 hrs later. We found a reasonably high chance (63%) that participants would fall asleep slightly later than usual (on average 19 mins later) in PART than CON, while there was also a high probability that subjective sleep quality was impaired, suggesting some subtle effects on *how* people slept as well as simply having shorter sleep. In this regard it should be acknowledged that our data are limited to subjective measures of sleep quality and the addition of more detailed measures through polysomnography (for example) may provide additional information about the important characteristics of sleep in these circumstances.

Across all outcome measures we found considerable individual variation in responses, i.e. not all participants appear to be negatively impacted by sleep deprivation, a trait that is common within similar studies (Keramidas et al., 2018; Oliver et al., 2009). This is an important issue and one that potentially explains some of the conflicting results within the existing literature as it will likely lead to skewed data, which may mask any effects using traditional NHST. As such a particular strength of the current study was the use of Bayesian analysis and probabilities of effect which we feel is more representative of the true responses. However, further research should investigate the variability in individual responses, and the underpinning mechanisms, to the potentially negative effects of sleep deprivation, as this may help in the development of countermeasures to mitigate performance impairments following sleep loss. Indeed, a perhaps under researched component within this context is the influence of chronotype. It is well established that an athlete's chronotype can have a significant impact on athletic performance (Vitale & Weydahl, 2017) and it may be that there are subtle interactions between chronotype and whether an individual is susceptible to impaired performance following sleep deprivation.

Some limitations should be taken into account when considering the current study. In many situations, sleep deprivation or disruption may be accompanied by changes in nervous activity that accompany competition and may have wider effects than seen in the current study. Although very difficult to replicate, this may be an important aspect for future research to investigate. While we have attempted to assess a broad array of measures of human performance, we did not assess other crucial aspects of sporting performance such co-ordination, or repeated sprint performance. Finally, the participants, while accustomed to vigorous exercise and training were not highly trained or competitive athletes, however performing a highly controlled study of this nature with repeated testing would be incredibly difficult while also maintaining adequate control of confounding factors (e.g. demanding training schedules and regular competition).

Practical implications

Even a fairly modest reduction in sleep was shown to have subtle, but potentially important, negative effects on both aerobic performance and CMJ performance. Athletes and coaches should plan ahead to minimise any potentially negative impacts upon sleep. Coaches should be aware that scheduling of early practices can reduce sleep to the degree seen in this study and therefore should not expect optimal performances (or training) in these circumstances. Athletes, coaches and support staff should seek countermeasures to these detrimental effects.

Conclusion

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

References

Amrhein, V., Greenland, S., & McShane, B. (2019). Scientists rise up against statistical significance. *Nature*, *567*(7748), 305–307. https://doi.org/10.1038/d41586-019-00857-9

Bulbulian, R., Heaney, J. H., Leake, C. N., Sucec, A. A., & Sjoholm, N. T. (1996). The effect of sleep deprivation and exercise load on isokinetic leg strength and endurance. *European Journal of Applied Physiology and Occupational Physiology*, *73*(3–4), 273–277. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/8781857

Bürkner, P.-C. (2017). brms : An R Package for Bayesian Multilevel Models Using Stan. *Journal of Statistical Software*. https://doi.org/10.18637/jss.v080.i01

Buysse, D. J., Reynolds, C. F., Monk, T. H., Berman, S. R., & Kupfer, D. J. (1989). The Pittsburgh sleep quality index: A new instrument for psychiatric practice and research. *Psychiatry Research*. https://doi.org/10.1016/0165-1781(89)90047-4

Chen, H. (1991). Effects of 30-h sleep loss on cardiorespiratory functions at rest and in exercise. *Medicine & Science in Sports & Exercise*. https://doi.org/10.1249/00005768-199102000-00008

Cullen, T., Thomas, A. W., Webb, R., & Hughes, M. G. (2016). Interleukin-6 and associated cytokine responses to an acute bout of high-intensity interval exercise: the effect of exercise intensity and volume. *Applied Physiology, Nutrition, and Metabolism*, *41*(8), 803–808. https://doi.org/10.1139/apnm-2015-0640

Driller, M. W. (2012). The reliability of a 30-minute performance test on a Lode cycle ergometer. *Journal of Science and Cycling*.

Driller, M. W., & Halson, S. L. (2013). The effects of wearing lower body compression garments during a cycling performance test. *International Journal of Sports Physiology* *and Performance*. https://doi.org/10.1123/ijspp.8.3.300

Franzen, M. D., Tishelman, A. C., Sharp, B. H., & Friedman, A. G. (1987). An investigation of the test-retest reliability of the stroop colorword test across two intervals. *Archives of Clinical Neuropsychology*. https://doi.org/10.1016/0887-6177(87)90014-X

Fullagar, H. H. K., Skorski, S., Duffield, R., Hammes, D., Coutts, A. J., & Meyer, T. (2015). Sleep and Athletic Performance: The Effects of Sleep Loss on Exercise Performance, and Physiological and Cognitive Responses to Exercise. *Sports Medicine*, *45*(2), 161–186. https://doi.org/10.1007/s40279-014-0260-0

Gabry, J., Simpson, D., Vehtari, A., Betancourt, M., & Gelman, A. (2017). Visualization in Bayesian workflow. Retrieved from http://arxiv.org/abs/1709.01449

Goodman, J., Radomski, M., Hart, L., Plyley, M., & Shephard, R. J. (1989). Maximal aerobic exercise following prolonged sleep deprivation. *International Journal of Sports Medicine*. https://doi.org/10.1055/s-2007-1024936

Gupta, L., Morgan, K., & Gilchrist, S. (2017). Does Elite Sport Degrade Sleep Quality? A Systematic Review. *Sports Medicine*, 1–17. https://doi.org/10.1007/s40279-016-0650-6

Hurdiel, R., Pezé, T., Daugherty, J., Girard, J., Poussel, M., Poletti, L., … Theunynck, D. (2015). Combined effects of sleep deprivation and strenuous exercise on cognitive performances during The North Face® Ultra Trail du Mont Blanc® (UTMB®). *Journal of Sports Sciences*, *33*(7), 670–674. https://doi.org/10.1080/02640414.2014.960883

Juliff, L. E., Halson, S. L., & Peiffer, J. J. (2015). Understanding sleep disturbance in athletes prior to important competitions. *Journal of Science and Medicine in Sport*, *18*(1), 13–18. https://doi.org/10.1016/j.jsams.2014.02.007

Juliff, L. E., Peiffer, J. J., & Halson, S. L. (2018). Night games and sleep: Physiological, neuroendocrine, and psychometric mechanisms. *International Journal of Sports Physiology and Performance*. https://doi.org/10.1123/ijspp.2016-0809

Keramidas, M. E., Gadefors, M., Nilsson, L. O., & Eiken, O. (2018). Physiological and psychological determinants of whole-body endurance exercise following short-term sustained operations with partial sleep deprivation. *European Journal of Applied Physiology*. https://doi.org/10.1007/s00421-018-3869-0

Konings, M. J., & Hettinga, F. J. (2018). Pacing Decision Making in Sport and the Effects of Interpersonal Competition: A Critical Review. *Sports Medicine*. https://doi.org/10.1007/s40279-018-0937-x

Leeder, J., Glaister, M., Pizzoferro, K., Dawson, J., & Pedlar, C. (2012). Sleep duration and quality in elite athletes measured using wristwatch actigraphy. *Journal of Sports*

Sciences, *30*(6), 541–545. https://doi.org/10.1080/02640414.2012.660188

Lucas, S. J., Anson, J. G., Palmer, C. D., Hellemans, I. J., & Cotter, J. D. (2009). The impact of 100 hours of exercise and sleep deprivation on cognitive function and physical capacities. *Journal of Sports Sciences*. https://doi.org/10.1080/02640410902798167

Markovic, G., Dizdar, D., Jukic, I., & Cardinale, M. (2004). Reliability and Factorial Validity of Squat and Countermovement Jump Tests. *The Journal of Strength and Conditioning Research*. https://doi.org/10.1519/1533-4287(2004)18<551:RAFVOS>2.0.CO;2

Martin, B. J. (1981). Effect of sleep deprivation on tolerance of prolonged exercise. *European Journal of Applied Physiology and Occupational Physiology*. https://doi.org/10.1007/BF02332962

Martin, T., Arnal, P. J., Hoffman, M. D., & Millet, G. Y. (2018). Sleep habits and strategies of ultramarathon runners. *PloS One*, *13*(5), e0194705. https://doi.org/10.1371/journal.pone.0194705

Mougin, F., Simon-Rigaud, M. L., Davenne, D., Renaud, A., Garnier, A., Kantelip, J. P., & Magnin, P. (1991). Effects of sleep disturbances on subsequent physical performance. *European Journal of Applied Physiology and Occupational Physiology*. https://doi.org/10.1007/BF00235173

Oliver, S. J., Costa, R. J. S., Laing, S. J., Bilzon, J. L. J., & Walsh, N. P. (2009). One night of sleep deprivation decreases treadmill endurance performance. *European Journal of Applied Physiology*, *107*(2), 155–161. https://doi.org/10.1007/s00421-009-1103-9

Poussel, M., Laroppe, J., Hurdiel, R., Girard, J., Poletti, L., Thil, C., … Chenuel, B. (2015). Sleep Management Strategy and Performance in an Extreme Mountain Ultra-marathon. *Research in Sports Medicine*, *23*(3), 330–336. https://doi.org/10.1080/15438627.2015.1040916

Roberts, S. S. H., Teo, W.-P., & Warmington, S. A. (2018). Effects of training and competition on the sleep of elite athletes: a systematic review and meta-analysis. *British Journal of Sports Medicine*, bjsports-2018-099322. https://doi.org/10.1136/bjsports-2018-099322

Sargent, C., Halson, S., & Roach, G. D. (2014). Sleep or swim? Early-morning training severely restricts the amount of sleep obtained by elite swimmers. *European Journal of Sport Science*. https://doi.org/10.1080/00359198409519486

Skein, M., Duffiedl, R., Edge, J., Short, M. J., & Mundel, T. (2011). Intermittent-Sprint Performance and Muscle Glycogen after 30 h of Sleep Deprivation. *Medicine & Science in Sports & Exercise*, *43*(7), 1301–1311.

https://doi.org/10.1249/MSS.0b013e31820abc5a

Souissi, N., Souissi, M., Souissi, H., Chamari, K., Tabka, Z., Dogui, M., & Davenne, D. (2008). Effect of time of day and partial sleep deprivation on short-term, high-power output. *Chronobiology International*. https://doi.org/10.1080/07420520802551568

Takeuchi, L., Davis, G. M., Plyley, M., Goode, R., & Shephard, R. I. (1985). Sleep deprivation, chronic exercise and muscular performance. *Ergonomics*. https://doi.org/10.1080/00140138508963173

Temesi, J., Arnal, P. J., Davranche, K., Bonnefoy, R., Levy, P., Verges, S., & Millet, G. Y. (2013). Does central fatigue explain reduced cycling after complete sleep deprivation? *Medicine and Science in Sports and Exercise*, *45*(12), 2243–2253. https://doi.org/10.1249/MSS.0b013e31829ce379

Thornton, H. R., Miller, J., Taylor, L., Sargent, C., Lastella, M., & Fowler, P. M. (2018). Impact of short- compared to long-haul international travel on the sleep and wellbeing of national wheelchair basketball athletes. *Journal of Sports Sciences*, *36*(13), 1476–1484. https://doi.org/10.1080/02640414.2017.1398883

Vaara, J. P., Oksanen, H., Kyröläinen, H., Virmavirta, M., Koski, H., & Finni, T. (2018). 60-Hour Sleep Deprivation Affects Submaximal but Not Maximal Physical Performance. *Frontiers in Physiology*, *9*, 1437. https://doi.org/10.3389/fphys.2018.01437

Vehtari, A., Gelman, A., & Gabry, J. (2016). Practical Bayesian model evaluation using leave-one-out cross-validation and WAIC. *Statistics and Computing*. https://doi.org/10.1007/s11222-016-9696-4

Venter, R. E. (2014). Perceptions of team athletes on the importance of recovery modalities. *European Journal of Sport Science*. https://doi.org/10.1080/17461391.2011.643924

Vitale, J. A., & Weydahl, A. (2017). Chronotype, Physical Activity, and Sport Performance: A Systematic Review. *Sports Medicine*. https://doi.org/10.1007/s40279-017-0741-z

Wasserstein, R. L., & Lazar, N. A. (2016). The ASA's Statement on *p* -Values: Context, Process, and Purpose. *The American Statistician*. https://doi.org/10.1080/00031305.2016.1154108

Williamson, A. M., & Feyer, A. M. (2000). Moderate sleep deprivation produces impairments in cognitive and motor performance equivalent to legally prescribed levels of alcohol intoxication. *Occupational and Environmental Medicine*. https://doi.org/10.1136/oem.57.10.649

Tables

Table 1. Descriptive statistics (Mean ± Standard Deviation and Median ± Median Absolute Deviation) of physical measurements in conditions

	Mean Power (W)		Counter Movement Jump (Cm)		Hand Grip Strength (Kg)	
Condition	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

Table 2. Descriptive statistics (Mean ± Standard Deviation and Median ± Median Absolute Deviation) of psychological measurements in all sleep conditions

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

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

		Uniform Prior			Informative Prior		
Measure	Comparison of conditions	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

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

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

		Uniform Prior			Informative Prior		
Measure	Comparison of conditions	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

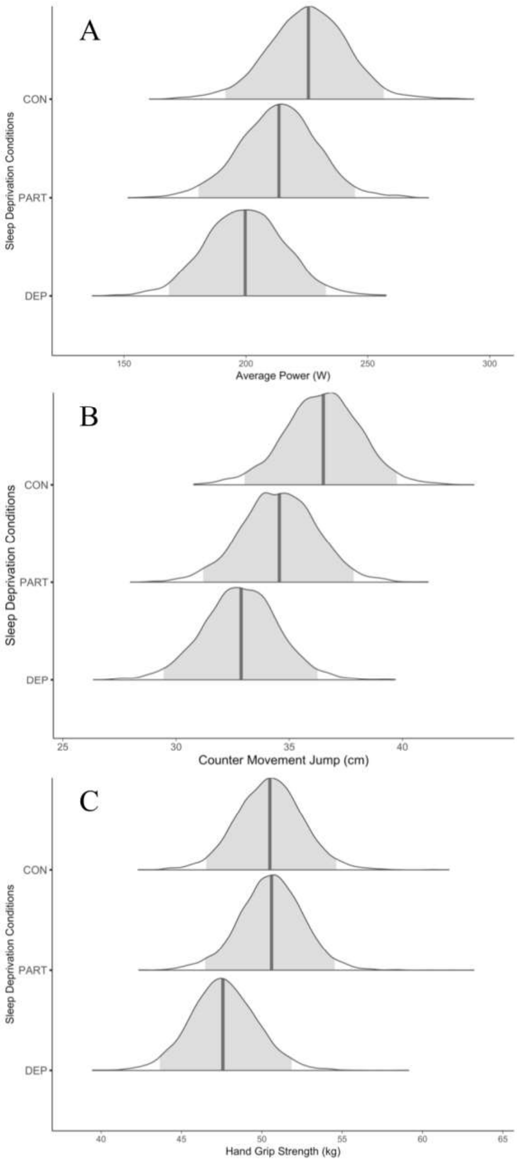
A
CON
PART
DEP
Sleep Deprivation Conditions
150
200
250
300
Average Power (W)
B
CON
PART
DEP
Sleep Deprivation Conditions
25
30
35
40
Counter Movement Jump (cm)
C
CON
PART
DEP
Sleep Deprivation Conditions
40
45
50
55
60
65
Hand Grip Strength (kg)

Figure 1.

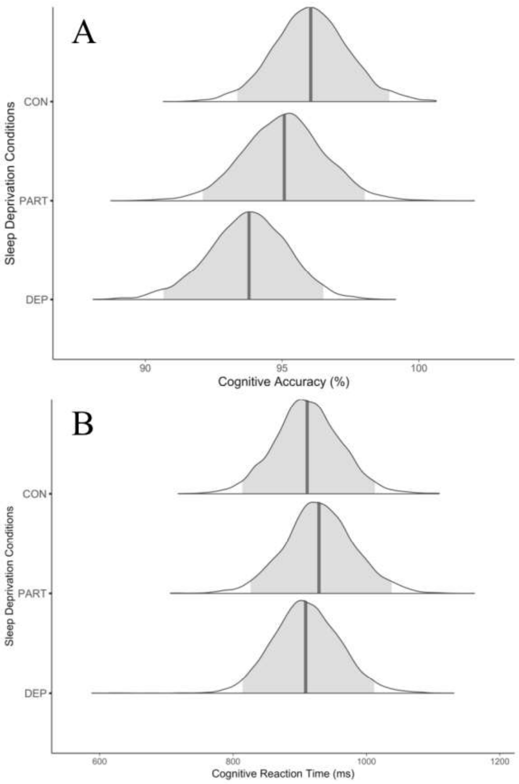
A
Sleep Deprivation Conditions
CON
PART
DEP
90
95
100
Cognitive Accuracy (%)
B
Sleep Deprivation Conditions
CON
PART
DEP
600
800
1000
1200
Cognitive Reaction Time (ms)

Figure 2.

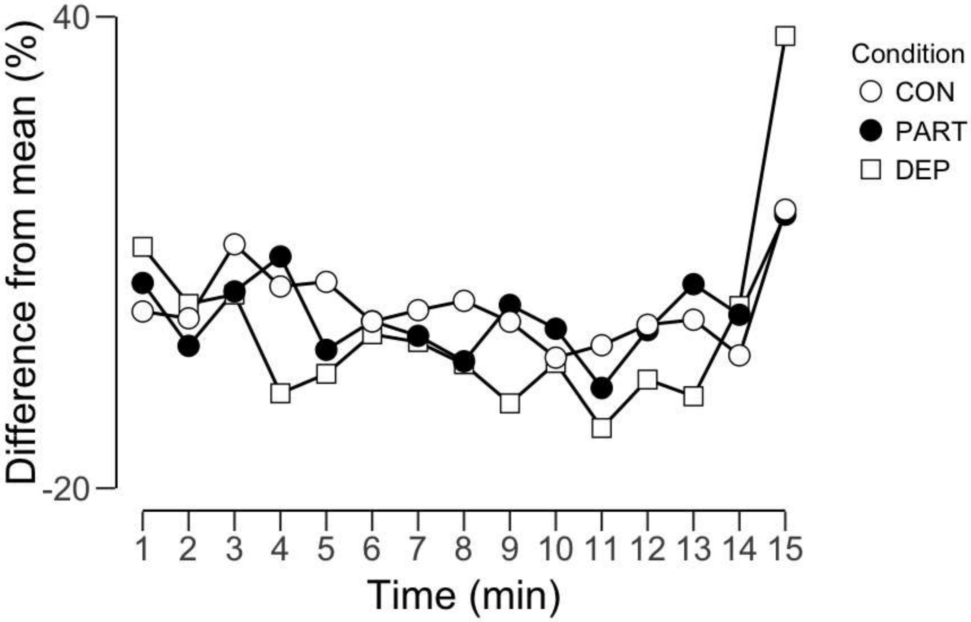

Figure 3.

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 handgripstrength (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.

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

Authors: *Tom Cullen*[1*,2], *Gavin Thomas*[2], *Alex, J. Wadley*[3,4], *Tony Myers*[5].

[1]Centre for Sport Exercise and Life Sciences, Coventry University, Priory Street, Coventry, UK.

[2]School of Sport & Exercise Science, University of Worcester, Henwick Grove, Worcester, UK.

[3]National Centre for Sport and Exercise Medicine, School of Sport, Exercise and Health Sciences, Loughborough University, Epinal Way, Loughborough, UK.

[4]University Hospitals of Leicester NHS Trust, Infirmary Square, Leicester, UK.

[5] Sport, Physical Activity and Health Research Centre, Newman University, Bartley Green, Genners Lane, Birmingham, UK.

*** Current institution**

Corresponding author:

Dr Tom Cullen
Centre for Sport, Exercise and Life Sciences
Coventry University
Priory Street, Coventry, UK, CV1 5FB
Email: ad0189@coventry.ac.uk

Running Head: Sleep disruption and athletic performance

Abstract word count: 194

Text only Word Count: 4773

Number of Tables: 4

Number of Figures: 3

Abstract

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

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

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

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

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

Introduction

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

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

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

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

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

Methods

Participants

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

Preliminary Testing

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

Study Design

Experimental design

Participants completed 3 three experimental trials in a randomised and counterbalanced order with 7 days between each trial. Testing took place between 07:00 and 09:00 following 3 different sleep conditions. For the control condition (CON) participants were instructed to arrive at the laboratory following a normal night's sleep in their own bed. Prior to (PART) and (DEP) conditions, participants arrived at the laboratory the night prior to testing (approximately 21:00) and remained under the supervision of the researchers in the laboratory throughout this time until the completion of the experiment the next morning. During PART, participants were allowed a 4-hour sleep opportunity, in a pre-prepared room at their normal bedtime, whereupon they were then awoken by the researcher. While awake during PART and DEP, participants were allowed to conduct sedentary activities such as watching films and talking with the researchers. During this period participants were allowed to drink water but were not permitted to eat until completion of the testing. Participants were instructed to maintain their normal sleep and physical activity routine between trials, this was verified by an actigraph which was worn throughout the study (Actiheart, Version 2.2, CamNTech Ltd., Cambridge, UK). On the morning of each experimental trial, participants completed a brief sleep diary comprising a subjective estimate of their sleep quality on a 5-point scale (1 being very poor and 5 being very good sleep quality). Data from actigraphs and sleep diaries was used to describe the total sleep duration, subjective sleep quality, time to bed and time awake, experienced prior to CON and PART. Participants were asked to replicate their diet prior to each trial while abstaining from caffeine for 12 hrs prior to commencement of each test session. Within the experimental sessions each test was performed in the same order and in the sequence described below.

Test procedures

Cognitive Function

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

Handgrip Strength

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

Countermovement Jump

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

Aerobic Performance

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

$$W = L \cdot (RPM)^2$$

W= Power output
L= Linear factor
RPM= Pedal cadence

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

Data analysis

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

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

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

All analyses were conducted using R (R Core Team, 2018) and with the brms package (Bürkner, 2017) which uses Stan (Stan Development Team, 2018) to implement a Hamiltonian Markov Chain Monte Carlo (MCMC) with a No-U-Turn Sampler. All models were checked for convergence ($\hat{r} = 1$), with the graphical posterior predictive checks showing simulated data under the best fitted models compared well to the observed data with no systematic discrepancies (Gabry, Simpson, Vehtari, Betancourt, & Gelman, 2017).

Results

Sleep Characteristics

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

Performance Tests

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

xxx Insert Tables 1 & 2 Here xxx

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

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

xxx Insert Table 3 & 4 Here xxx

xxx Insert Figure 1 Here xxx

xxx Insert Figure 2 Here xxx

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

xxx Insert Figure 3 Here xxx

Discussion

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

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

Our results are in agreement with the findings of previous research that have reported impaired aerobic (Chen, 1991; Oliver et al., 2009; Temesi et al., 2013), anaerobic (Bulbulian et al., 1996; Skein, Duffiedl, Edge, Short, & Mundel, 2011; Takeuchi et al., 1985) and cognitive performance (Williamson & Feyer, 2000) following one night of complete sleep deprivation, but contradicts other studies (Goodman, Radomski, Hart, Plyley, & Shephard, 1989; Vaara et al., 2018). The conflicting results are potentially due to differences in the specific tests used. For example, Oliver et al. (2009) suggested that a distance test, such as the one used in the current study, might have a smaller signal to noise ratio than incremental exercise tests which were used by Vaara et al. (2018) and Goodman et al (1989). These differences are potentially explained by the altered perception of effort experienced following sleep deprivation (Keramidas, Gadefors, Nilsson, & Eiken, 2018), given that incremental tests only require a relatively short period of discomfort in contrast to distance tests. In the current study aerobic performance appears to be impaired due to a consistently lower power output throughout rather than an alteration in pacing strategy (see Fig. 3). It may be that endurance events which require self-pacing and prolonged high intensity efforts are more susceptible to impaired performance than those which do not, and indeed it could be argued that this may be more widely applicable to sporting performance where self-pacing is common (Konings & Hettinga, 2018). As such it could be that longer endurance events such as the marathon are impacted a greater extent (Fullagar et al., 2015). This may be even more important in the context of ultramarathons where sleep deprivation is common. For example, response times have been shown to be impaired following an ultramarathon (Hurdiel et al., 2015), which is in contrast to the findings of our study as we found that reaction time in the Stroop test was not impacted, but the accuracy of responses was. This could be construed as conflicting the majority of findings showing impaired reaction time (Fullagar et al., 2015), however, it does reflect similar findings reported when using the Stroop test (Lucas, Anson, Palmer, Hellemans, & Cotter, 2009). This further emphasises that the reported responses are highly specific to the test chosen.

Comparatively few studies have investigated the impact of partial sleep deprivation on performance, highlighting the novelty of our study but making direct comparisons to the literature more difficult. One previous study reported that a sleep intervention equating to 3 hrs less sleep than normal did not result in changes in maximal aerobic or anaerobic performance (Mougin et al., 1991). However, this study only had 7 participants and was likely statistically underpowered to demonstrate an effect. In the current study, we found that physical performance was highly likely to be impaired with the exception of maximal handgrip strength, which was maintained. Indeed handgrip strength was maintained in the morning following partial sleep deprivation, but was significantly impaired in the evening (Souissi et al., 2008). From an applied perspective, athletes who experience disrupted sleep may not compete until the afternoon or evening, and therefore performance may well be more greatly impaired than in our study. It is important to consider that our findings are specific to the time of day that the testing was carried out (7:00-9:00am), and while many domestic sporting events routinely take place in the afternoon, many events during major international competitions are scheduled early in the morning (for a variety of reasons). A further complicating factor when comparing the results of studies of shortened sleep is that there may also be effect on the quality of sleep, yet this is not always reported (for example see Souissi et al., 2008). In our study, we afforded participants a 4 hr sleep opportunity, whereby they attempted to fall asleep at their normal bedtime and were woken 4 hrs later. We found a reasonably high chance (63%) that participants would fall asleep slightly later than usual (on average 19 mins later) in PART than CON, while there was also a high probability that subjective sleep quality was impaired, suggesting some subtle effects on *how* people slept as well as simply having shorter sleep. In this regard it should be acknowledged that our data are limited to subjective measures of sleep quality and the addition of more detailed measures through polysomnography (for example) may provide additional information about the important characteristics of sleep in these circumstances.

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

Practical implications

Even a fairly modest reduction in sleep was shown to have subtle, but potentially important, negative effects on both aerobic performance and CMJ performance. Athletes and coaches should plan ahead to minimise any potentially negative impacts upon sleep. Coaches should be aware that scheduling of early practices can reduce sleep to the degree seen in this study and therefore should not expect optimal performances (or training) in these circumstances. Athletes, coaches and support staff should seek countermeasures to these detrimental effects.

Conclusion

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

Acknowledgments

The authors would like to wholeheartedly thank the participants for their considerable efforts throughout the study. We would also like to thank Dr Matthew Cook and Karolis Kvasas for their assistance with data collection. This research was supported by the National Institute for

Health Research (NIHR) Leicester Biomedical Research Centre. The views expressed are those of the authors and not necessarily those of the NHS, the NIHR or the Department of Health.

References

Amrhein, V., Greenland, S., & McShane, B. (2019). Scientists rise up against statistical significance. *Nature*, *567*(7748), 305–307. https://doi.org/10.1038/d41586-019-00857-9

Bulbulian, R., Heaney, J. H., Leake, C. N., Sucec, A. A., & Sjoholm, N. T. (1996). The effect of sleep deprivation and exercise load on isokinetic leg strength and endurance. *European Journal of Applied Physiology and Occupational Physiology*, *73*(3–4), 273–277. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/8781857

Bürkner, P.-C. (2017). brms : An R Package for Bayesian Multilevel Models Using Stan. *Journal of Statistical Software*. https://doi.org/10.18637/jss.v080.i01

Buysse, D. J., Reynolds, C. F., Monk, T. H., Berman, S. R., & Kupfer, D. J. (1989). The Pittsburgh sleep quality index: A new instrument for psychiatric practice and research. *Psychiatry Research*. https://doi.org/10.1016/0165-1781(89)90047-4

Chen, H. (1991). Effects of 30-h sleep loss on cardiorespiratory functions at rest and in exercise. *Medicine & Science in Sports & Exercise*. https://doi.org/10.1249/00005768-199102000-00008

Cullen, T., Thomas, A. W., Webb, R., & Hughes, M. G. (2016). Interleukin-6 and associated cytokine responses to an acute bout of high-intensity interval exercise: the effect of exercise intensity and volume. *Applied Physiology, Nutrition, and Metabolism*, *41*(8), 803–808. https://doi.org/10.1139/apnm-2015-0640

Driller, M. W. (2012). The reliability of a 30-minute performance test on a Lode cycle ergometer. *Journal of Science and Cycling*.

Driller, M. W., & Halson, S. L. (2013). The effects of wearing lower body compression garments during a cycling performance test. *International Journal of Sports Physiology and Performance*. https://doi.org/10.1123/ijspp.8.3.300

Franzen, M. D., Tishelman, A. C., Sharp, B. H., & Friedman, A. G. (1987). An investigation of the test-retest reliability of the stroop colorword test across two intervals. *Archives of Clinical Neuropsychology*. https://doi.org/10.1016/0887-6177(87)90014-X

Fullagar, H. H. K., Skorski, S., Duffield, R., Hammes, D., Coutts, A. J., & Meyer, T. (2015). Sleep and Athletic Performance: The Effects of Sleep Loss on Exercise Performance, and Physiological and Cognitive Responses to Exercise. *Sports Medicine*, *45*(2), 161–186. https://doi.org/10.1007/s40279-014-0260-0

Gabry, J., Simpson, D., Vehtari, A., Betancourt, M., & Gelman, A. (2017). Visualization in Bayesian workflow. Retrieved from http://arxiv.org/abs/1709.01449

Goodman, J., Radomski, M., Hart, L., Plyley, M., & Shephard, R. J. (1989). Maximal aerobic exercise following prolonged sleep deprivation. *International Journal of Sports Medicine*. https://doi.org/10.1055/s-2007-1024936

Gupta, L., Morgan, K., & Gilchrist, S. (2017). Does Elite Sport Degrade Sleep Quality? A Systematic Review. *Sports Medicine*, 1–17. https://doi.org/10.1007/s40279-016-0650-6

Hurdiel, R., Pezé, T., Daugherty, J., Girard, J., Poussel, M., Poletti, L., … Theunynck, D. (2015). Combined effects of sleep deprivation and strenuous exercise on cognitive performances during The North Face® Ultra Trail du Mont Blanc® (UTMB®). *Journal of Sports Sciences*, *33*(7), 670–674. https://doi.org/10.1080/02640414.2014.960883

Juliff, L. E., Halson, S. L., & Peiffer, J. J. (2015). Understanding sleep disturbance in athletes prior to important competitions. *Journal of Science and Medicine in Sport*, *18*(1), 13–18. https://doi.org/10.1016/j.jsams.2014.02.007

Juliff, L. E., Peiffer, J. J., & Halson, S. L. (2018). Night games and sleep: Physiological, neuroendocrine, and psychometric mechanisms. *International Journal of Sports Physiology and Performance*. https://doi.org/10.1123/ijspp.2016-0809

Keramidas, M. E., Gadefors, M., Nilsson, L. O., & Eiken, O. (2018). Physiological and psychological determinants of whole-body endurance exercise following short-term sustained operations with partial sleep deprivation. *European Journal of Applied Physiology*. https://doi.org/10.1007/s00421-018-3869-0

Konings, M. J., & Hettinga, F. J. (2018). Pacing Decision Making in Sport and the Effects of Interpersonal Competition: A Critical Review. *Sports Medicine*. https://doi.org/10.1007/s40279-018-0937-x

Leeder, J., Glaister, M., Pizzoferro, K., Dawson, J., & Pedlar, C. (2012). Sleep duration and quality in elite athletes measured using wristwatch actigraphy. *Journal of Sports Sciences*, *30*(6), 541–545. https://doi.org/10.1080/02640414.2012.660188

Lucas, S. J., Anson, J. G., Palmer, C. D., Hellemans, I. J., & Cotter, J. D. (2009). The impact of 100 hours of exercise and sleep deprivation on cognitive function and physical capacities. *Journal of Sports Sciences*. https://doi.org/10.1080/02640410902798167

Markovic, G., Dizdar, D., Jukic, I., & Cardinale, M. (2004). Reliability and Factorial Validity of Squat and Countermovement Jump Tests. *The Journal of Strength and Conditioning*

Research. https://doi.org/10.1519/1533-4287(2004)18<551:RAFVOS>2.0.CO;2

Martin, B. J. (1981). Effect of sleep deprivation on tolerance of prolonged exercise. *European Journal of Applied Physiology and Occupational Physiology*. https://doi.org/10.1007/BF02332962

Martin, T., Arnal, P. J., Hoffman, M. D., & Millet, G. Y. (2018). Sleep habits and strategies of ultramarathon runners. *PloS One*, *13*(5), e0194705. https://doi.org/10.1371/journal.pone.0194705

Mougin, F., Simon-Rigaud, M. L., Davenne, D., Renaud, A., Garnier, A., Kantelip, J. P., & Magnin, P. (1991). Effects of sleep disturbances on subsequent physical performance. *European Journal of Applied Physiology and Occupational Physiology*. https://doi.org/10.1007/BF00235173

Oliver, S. J., Costa, R. J. S., Laing, S. J., Bilzon, J. L. J., & Walsh, N. P. (2009). One night of sleep deprivation decreases treadmill endurance performance. *European Journal of Applied Physiology*, *107*(2), 155–161. https://doi.org/10.1007/s00421-009-1103-9

Poussel, M., Laroppe, J., Hurdiel, R., Girard, J., Poletti, L., Thil, C., … Chenuel, B. (2015). Sleep Management Strategy and Performance in an Extreme Mountain Ultra-marathon. *Research in Sports Medicine*, *23*(3), 330–336. https://doi.org/10.1080/15438627.2015.1040916

Roberts, S. S. H., Teo, W.-P., & Warmington, S. A. (2018). Effects of training and competition on the sleep of elite athletes: a systematic review and meta-analysis. *British Journal of Sports Medicine*, bjsports-2018-099322. https://doi.org/10.1136/bjsports-2018-099322

Sargent, C., Halson, S., & Roach, G. D. (2014). Sleep or swim? Early-morning training severely restricts the amount of sleep obtained by elite swimmers. *European Journal of Sport Science*. https://doi.org/10.1080/00359198409519486

Skein, M., Duffiedl, R., Edge, J., Short, M. J., & Mundel, T. (2011). Intermittent-Sprint Performance and Muscle Glycogen after 30 h of Sleep Deprivation. *Medicine & Science in Sports & Exercise*, *43*(7), 1301–1311. https://doi.org/10.1249/MSS.0b013e31820abc5a

Souissi, N., Souissi, M., Souissi, H., Chamari, K., Tabka, Z., Dogui, M., & Davenne, D. (2008). Effect of time of day and partial sleep deprivation on short-term, high-power output. *Chronobiology International*. https://doi.org/10.1080/07420520802551568

Takeuchi, L., Davis, G. M., Plyley, M., Goode, R., & Shephard, R. I. (1985). Sleep deprivation, chronic exercise and muscular performance. *Ergonomics*.

https://doi.org/10.1080/00140138508963173

Temesi, J., Arnal, P. J., Davranche, K., Bonnefoy, R., Levy, P., Verges, S., & Millet, G. Y. (2013). Does central fatigue explain reduced cycling after complete sleep deprivation? *Medicine and Science in Sports and Exercise*. https://doi.org/10.1249/MSS.0b013e31829ce379

Thornton, H. R., Miller, J., Taylor, L., Sargent, C., Lastella, M., & Fowler, P. M. (2018). Impact of short- compared to long-haul international travel on the sleep and wellbeing of national wheelchair basketball athletes. *Journal of Sports Sciences*, *36*(13), 1476–1484. https://doi.org/10.1080/02640414.2017.1398883

Vaara, J. P., Oksanen, H., Kyröläinen, H., Virmavirta, M., Koski, H., & Finni, T. (2018). 60-Hour Sleep Deprivation Affects Submaximal but Not Maximal Physical Performance. *Frontiers in Physiology*, *9*, 1437. https://doi.org/10.3389/fphys.2018.01437

Vehtari, A., Gelman, A., & Gabry, J. (2016). Practical Bayesian model evaluation using leave-one-out cross-validation and WAIC. *Statistics and Computing*. https://doi.org/10.1007/s11222-016-9696-4

Venter, R. E. (2014). Perceptions of team athletes on the importance of recovery modalities. *European Journal of Sport Science*. https://doi.org/10.1080/17461391.2011.643924

Vitale, J. A., & Weydahl, A. (2017). Chronotype, Physical Activity, and Sport Performance: A Systematic Review. *Sports Medicine*. https://doi.org/10.1007/s40279-017-0741-z

Wasserstein, R. L., & Lazar, N. A. (2016). The ASA's Statement on *p* -Values: Context, Process, and Purpose. *The American Statistician*. https://doi.org/10.1080/00031305.2016.1154108

Williamson, A. M., & Feyer, A. M. (2000). Moderate sleep deprivation produces impairments in cognitive and motor performance equivalent to legally prescribed levels of alcohol intoxication. *Occupational and Environmental Medicine*. https://doi.org/10.1136/oem.57.10.649

Tables

Table 1. Descriptive statistics (Mean ± Standard Deviation and Median ± Median Absolute Deviation) of physical measurements in conditions

	Mean Power (W)		Counter Movement Jump (Cm)		Hand Grip Strength (Kg)	
Condition	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

Table 2. Descriptive statistics (Mean ± Standard Deviation and Median ± Median Absolute Deviation) of psychological measurements in all sleep conditions

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

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

		Uniform Prior			Informative Prior		
Measure	Comparison of conditions	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

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

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

		Uniform Prior			Informative Prior		
Measure	Comparison of conditions	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

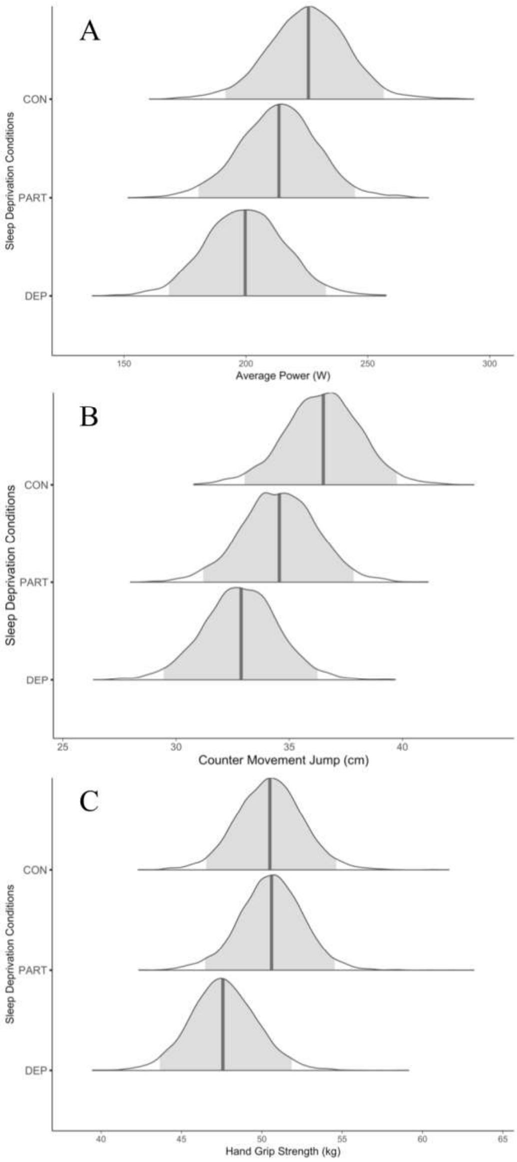
A
CON
PART
DEP
Sleep Deprivation Conditions
150
200
250
300
Average Power (W)
B
CON
PART
DEP
Sleep Deprivation Conditions
25
30
35
40
Counter Movement Jump (cm)
C
CON
PART
DEP
Sleep Deprivation Conditions
40
45
50
55
60
65
Hand Grip Strength (kg)

Figure 1.

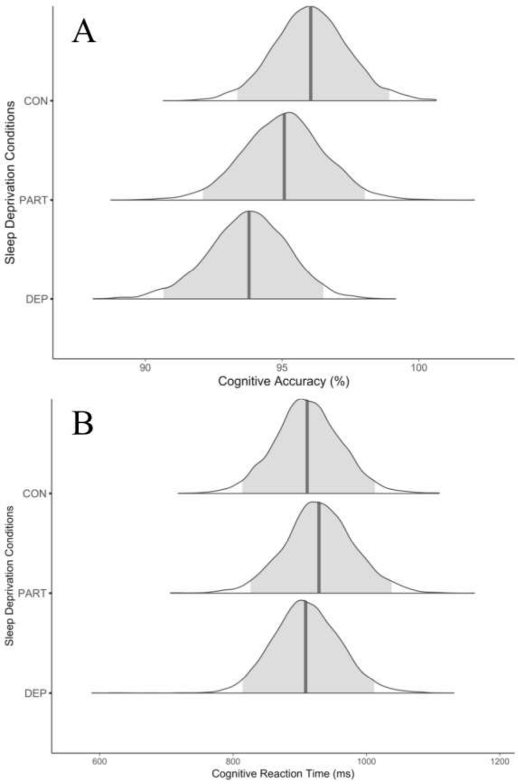
A
Sleep Deprivation Conditions
CON
PART
DEP
90
95
100
Cognitive Accuracy (%)
B
Sleep Deprivation Conditions
CON
PART
DEP
600
800
1000
1200
Cognitive Reaction Time (ms)

Figure 2.

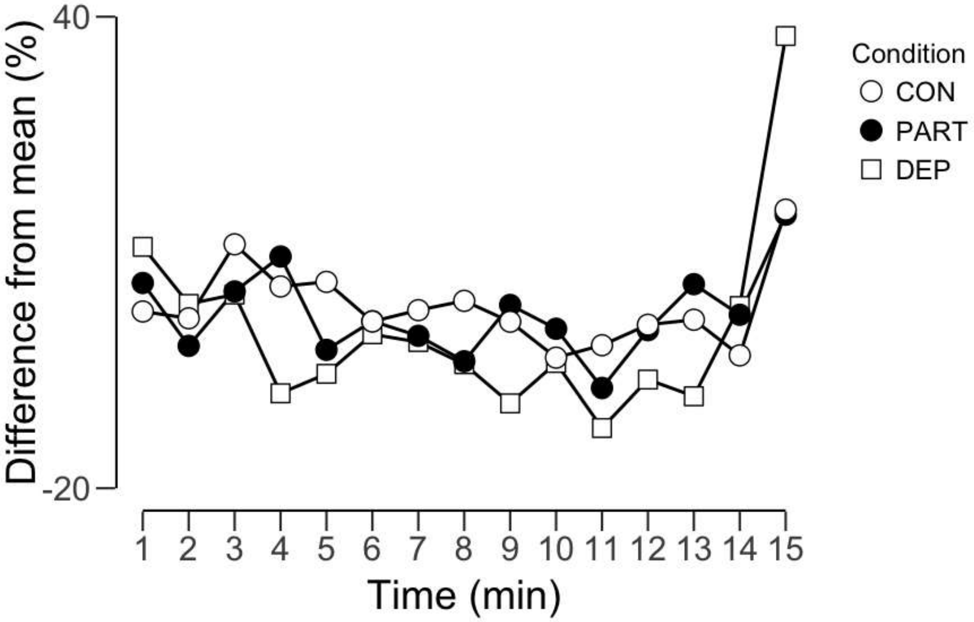

Figure 3.

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 handgripstrength (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.