Extended Sleep Maintains Endurance Performance Better than Normal or Restricted Sleep

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ABSTRACT

ROBERTS, S. H. S.,W.-P. TEO, B. AISBETT, and S. A. WARMINGTON. Extended SleepMaintains Endurance Performance Better than Normal or Restricted Sleep. *Med. Sci. Sports Exerc.*, Vol. 51, No. 12, pp. 2516–2523, 2019. **Purpose:** The cumulative influence of sleep time on endurance performance remains unclear. This study examined the effects of three consecutive nights of both sleep extension (SE) and sleep restriction (SR) on endurance cycling performance. **Methods:** Endurance cyclists/triathletes (n = 9) completed a counterbalanced crossover experiment with three conditions: SR, normal sleep (NS), and SE. Each condition comprised seven days/nights of data collection (−2, −1, D1, D2, D3, D4, and +1). Sleep was monitored using actigraphy throughout. Participants completed testing sessions on days D1–D4 that included an endurance time-trial (TT), mood, and psychomotor vigilance assessment. Perceived exertion (RPE) was monitored throughout each TT. Participants slept habitually before D1; however, time in bed was reduced by 30% (SR), remained normal (NS), or extended by 30% (SE) on nights D1, D2, and D3. Data were analyzed using generalized estimating equations. **Results:** On nights D1, D2, and D3, total sleep time was longer ($P < 0.001$) in the SE condition (8.6 ± 1.0, 8.3 ± 0.6, and 8.2 ± 0.6 h, respectively) and shorter ($P < 0.001$) in the SR condition (4.7 ± 0.8, 4.8 ± 0.8, and 4.9 ± 0.4 h) compared with NS (7.1 ± 0.8, 6.5 ± 1.0, and 6.9 ± 0.7 h). Compared with NS, TT performance was slower ($P < 0.02$) on D3 of SR (58.8 ± 2.5 vs 60.4 ± 3.7 min) and faster ($P < 0.02$) on D4 of SE (58.7 ± 3.4 vs 56.8 ± 3.1 min). RPE was not different between or within conditions. Compared with NS, mood disturbance was higher, and psychomotor vigilance impaired, after SR. Compared with NS, psychomotor vigilance improved after SE. **Conclusion:** Sleep extension for three nights led to better maintenance of endurance performance compared with normal and restricted sleep. Sleep restriction impaired performance. Cumulative sleep time affects performance by altering the perceived exertion of a given exercise intensity. Endurance athletes should sleep >8 h per night to optimize performance. **Key Words:** RECOVERY, FATIGUE, ATHLETE, EXTRA SLEEP, SPORTS

Endurance athletes experience high levels of physical and psychological stress during training and competition (1). For example, elite road cyclists pedal more than 30,000 km·yr^{-1}, and during stage races, will compete for 4–6 h·d^{-1} on consecutive days (1). Sleep is considered an important recovery behavior that may help athletes tolerate such demands (2); however, the influence of sleep on endurance performance remains unclear.

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No study, to our knowledge, has investigated the effects of sleep extension (i.e., increased habitual total sleep time [TST]) on endurance performance. In nonendurance athletes, sleep extension has been reported to improve the serving accuracy of tennis players (3) and the shooting accuracy and sprint times of basketballers (4). However, in the latter study, the absence of a control arm suggests improvements may have been attributable to training adaptations rather than sleep extension (4).

Studies investigating the effects of sleep restriction (SR) (i.e., decreased habitual TST) on endurance performance have reported equivocal findings (5–10). Moreover, these studies have often recruited untrained participants (5,6,9), assessed performance using relatively brief (<30 min) intermittent (5,6) or graded exercise (9) tests, or examined the effects of a single night of SR (5,6,8,10).

Given many endurance athletes (e.g., road cyclists) train or compete for prolonged periods (≥60 min), and on consecutive days, and in light of evidence that athletes' sleep is often disturbed during training and competition (11), further investigation of the cumulative effects of sleep time on endurance performance is required. The present study examined the effects of both sleep extension and restriction across three consecutive nights on endurance cycling performance.

METHODS

Participants

Nine males (mean ± SD; age, 30 ± 6 yr, $\dot{V}O_{2max}$: 63 ± 6 mL·kg^{-1}·min^{-1}) were recruited from cycling (n = 7) and triathlon (n = 2) clubs. Athletes were considered "trained" according to adapted criteria for classifying cyclists (≥1 yr competitive racing, ≥3 training sessions per week, $\dot{V}O_{2max}$ ≥ 55 mL·kg^{-1}·min^{-1}) (12). To screen for sleep problems and high anxiety, inclusion criteria required a score ≤5 in the Pittsburgh Sleep Quality Index (13) and ≤40 in the State-Trait Anxiety Inventory (14). Participants did not habitually consume high levels of caffeine (mean ± SD; caffeine products per day, 2 ± 1). The Morningness–Eveningness Questionnaire determined that participants were mostly "moderate morning" types (n = 5), with the remainder being "definite morning" (n = 2) or "intermediate" (n = 2) types (15). The study was approved the Deakin University Human Research Ethics Committee, and informed consent was obtained before participation.

Overview

Participants completed a counterbalanced crossover experiment with three conditions: sleep restriction (SR), normal sleep (NS), and sleep extension (SE). Beforehand, participants had their habitual sleep monitored for a minimum of four nights and undertook two familiarization sessions that included an incremental exercise test and a practice time trial (TT), respectively. Each condition comprised seven consecutive days/nights (−2, −1, D1, D2, D3, D4, and +1) of data collection (Fig. 1). Participants undertook four testing sessions (D1–D4) at the Deakin University Human Research and Performance Laboratory. During these sessions, participants completed an endurance TT, subjective mood evaluation, and a psychomotor vigilance task. For all conditions, participants slept habitually before D1. However, for the three subsequent "intervention" nights (D1, D2, and D3), habitual "time in bed" was either reduced by 30% (SR), extended by 30% (SE), or remained normal (NS). Required time in bed for the intervention nights was calculated according to participants' habitual sleep recorded before the experiment. Participants were prescribed bedtimes and get-up times on nights D1, D2, and D3 to ensure the required time in bed was achieved. Bedtimes and get-up times were tailored to individual chronotype to maximize the likelihood of modifying "total sleep time" rather than simply "time in bed." For example, sleep extension for a "morning type" was prescribed by predominantly advancing bedtime rather than delaying get-up time. To minimize the effect of circadian variations on performance, all testing commenced between 6:00 and 9:00 AM. Testing start times were consistent for each participant on D1 of each condition and on D2, D3, and D4 of the NS condition (mean ± SD, start time, 7:08 AM ± 31 min). Testing start times on D2, D3, and D4 of the SE condition were slightly later to allow for prescribed time in bed increases (mean ± SD, start time, 7:48 AM ± 37 min). Testing start times on D2, D3, and D4 of the SR condition were slightly earlier to reduce idle time after waking and, thus, minimize the risk falling back asleep (start time, 6:32 AM ± 30 min). No circadian variation in prolonged (e.g., 60-min) endurance performance has been established for time of day differences such as those that occurred in the present study (e.g., 6:30 vs 7:50 AM) (16). All participants had either morning or intermediate chronotypes, and all routinely trained in the morning. Thus, all testing was undertaken at a time when participants would normally be awake (15) and when they would often be training. Consumption of caffeine and alcohol was prohibited on days −1 to D4. Athletes were experienced racers, so dietary requirements were self-determined. However, to prevent discrepancies in energy availability, athletes recorded (e.g., 7 AM; 1 cup oats with milk) and replicated their dietary intake for each condition. Exercise was prohibited on days −1 to D4 (other than that required for the experiment). However, to accommodate preferred preparation and recovery strategies, participants were permitted to exercise lightly on days −2, +1, and +2 and were required to replicate this exercise between conditions. Participants recorded all exercise so load could be quantified (17). No differences between conditions were noted on days before or after laboratory testing [see Table, Supplemental Digital Content 1, Self-reported training load (arbitrary units) calculated as the product of exercise time (min) and session perceived exertion (0–10 scale), http://links.lww.com/MSS/B660]. A minimum 7-d washout period was required between D4 of a condition and D1 of the next condition.

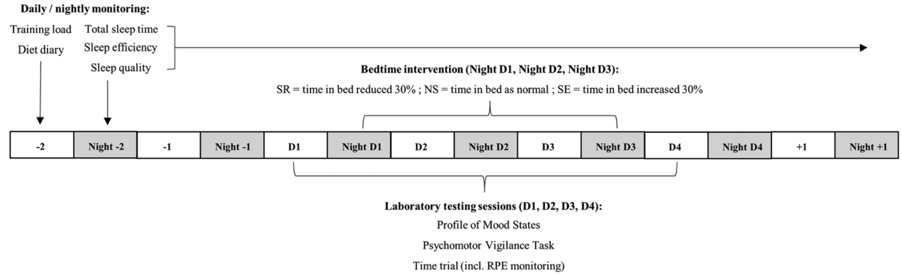

FIGURE 1—Overview of data collection across the eight days/seven nights of each condition. Training load and diet were self-reported every day. TST, sleep efficiency, and subjective sleep quality were monitored throughout (−2 to +1). Bedtimes were prescribed on nights D1 to D3 according to the condition being undertaken. Laboratory testing was undertaken on days D1 to D4.

Incremental Test

On a cycle ergometer (Excalibur Sport, Lode, Groningen, Netherlands) controlled using compatible software (Lode Ergometry Manager 9, Lode, Groningen, the Netherlands), participants cycled for 3 min at 75, 125, and 175 W respectively, before workload increased by 25 W every minute until volitional exhaustion. An Innocor metabolic system (DK-5260; Innovision, Odense, Denmark) determined maximal oxygen uptake $\dot{V}O_{2max}$ and anaerobic threshold (AT).

Time-trial Protocol

Target work for the TT was the estimated work expended when cycling at AT for 1 h:

$$\text{work (kJ)} = \frac{(W_{AT} \times 3600)}{1000}$$

Power at AT (W_{AT}) was determined from a regression of the relationship between oxygen uptake $\dot{V}O_{2max}$ and power (W) for the first three workloads of the incremental test. The ergometer was set to linear mode and pedaling resistance was calculated according to the formula:

$$W_{AT} = \text{linear factor} \times \text{preferred pedal rate}^2$$

where the linear factor ensured W_{AT} occurred at the participant's preferred pedal rate per minute (rpm). A strong correlation has been demonstrated between W_{AT} and 1-h TT performance ($r = 0.8$, $P < 0.05$) (18). Participants completed one practice TT to refine their pacing strategy. During the TT, work completed (kJ) was displayed on a computer screen. No other feedback or encouragement was provided.

Measures

Sleep. Participants wore activity monitors (Actical MiniMitter; Philips Respironics, Bend, OR) on their nondominant wrist from day −2 to day +2 to monitor sleep (19,20). Activity counts were recorded in 1-min epochs and downloaded using a device specific interface unit (ActiReader, Philips Respironics). Raw data were processed with a validated manufacturer proprietary algorithm (Actical version 3.10) set to a medium sleep–wake threshold (<40 counts per minute scored sleep) (19,20). This threshold has shown 87% agreement with polysomnography when identifying sleep and wake states in elite cyclists (20). To verify or identify misclassified sleep/wake states, participants completed a sleep diary that required them to record the time of day (i.e., to the nearest minute) they "began attempting to sleep" and the time of day they "woke up for the last time" for all sleep episodes (21). No daytime naps were permitted from day −1 until completion of testing on D4. For all sleep episodes, the total amount of sleep obtained (i.e., TST) and the percentage of time in bed spent asleep (i.e., sleep efficiency) were determined. For analysis, TST was aggregated from the end of one night's main sleep to the end of the next night's main sleep. Mean sleep efficiency was calculated for all sleep episodes during the same period. Subjective sleep quality (SQ) was recorded in the sleep diary upon waking each morning on a 5-point Likert scale (i.e., 1 = very good, 2 = good, 3 = average, 4 = poor, 5 = very poor).

Time trial. Overall finishing time (minutes) was recorded. Target work was divided into four equal splits, and perceived exertion (6–20 scale) was recorded during the final minute of splits 1–3 and immediately upon completion of split four (22).

Preliminary testing. Before the TT, upon arriving at the laboratory, participants completed psychometric testing. The Profile of Mood States assessed the feelings of participants "right now" across 65 mood descriptors, providing scores for total mood disturbance, tension, depression, anger, vigor, fatigue, and confusion (23). Participants completed a touch screen version of the psychomotor vigilance task (PVT) on a tablet device using the application sleep-2-Peak (version 2.2.1; Proactive Life LLC, New York, NY). This version of the PVT has been validated against traditional PVT methods (24). The PVT measured reaction times to visual stimuli occurring at varying intervals over 10 min. The mean response time and the number of lapses >500 ms were recorded.

Statistical analysis. Mean and SD were calculated for all variables. Generalized estimating equations with exchangeable correlation structures and robust SE analyzed mean changes in outcome variables. Initial models tested for period and carryover effects; however, no such effects were found ($P > 0.05$). Models analyzed two- or three-way interactions for the factors "condition," "day," and "split" (RPE only). Where interactions were significant ($P < 0.05$), pairwise models were run for each "day." A P value <0.025 was used to account for multiple comparisons. Additional models analyzed the main effects of "day" for each condition. A P value <0.05 was used. For sleep variables, nights −2 and −1 served as baseline values in separate models. For all other variables, D1 served as a baseline value. Analyses were performed using the Statistical Package for the Social Sciences for Windows (version 24.0; IBM Corp., Armonk, NY).

RESULTS

Sleep. TST (Fig. 2A) on nights D1, D2, and D3 was longer ($P < 0.001$) in the SE condition (8.6 ± 1.0, 8.3 ± 0.6, and 8.2 ± 0.6 h, respectively) and shorter ($P < 0.001$) in the SR condition (4.7 ± 0.8, 4.8 ± 0.8, and 4.9 ± 0.4 h) compared with NS (7.1 ± 0.8, 6.5 ± 1.0, and 6.9 ± 0.7 h). On night −2 (i.e., two nights before commencement of laboratory testing) TST was longer ($P < 0.01$) in the SR condition (7.4 ± 1.0 h) compared with SE (6.9 ± 1.0 h). On night D4 (i.e., after the final laboratory testing session), TST was longer in the SR condition (7.5 ± 0.8 h) compared with SE (6.6 ± 0.9 h, $P < 0.001$) and NS (7.1 ± 0.7 h, $P < 0.02$), whereas TST was also longer ($P < 0.02$) in the NS condition compared with SE. On night +1, TST tended ($P = 0.025$) to be longer in the SR (7.6 ± 1.8 h) condition compared with SE (6.6 ± 1.3 h).

Within the SR condition, TST was shorter ($P < 0.01$) on nights D1, D2, and D3 compared with nights −2 and −1, longer ($P < 0.02$) on night +1 compared with night −1, and shorter

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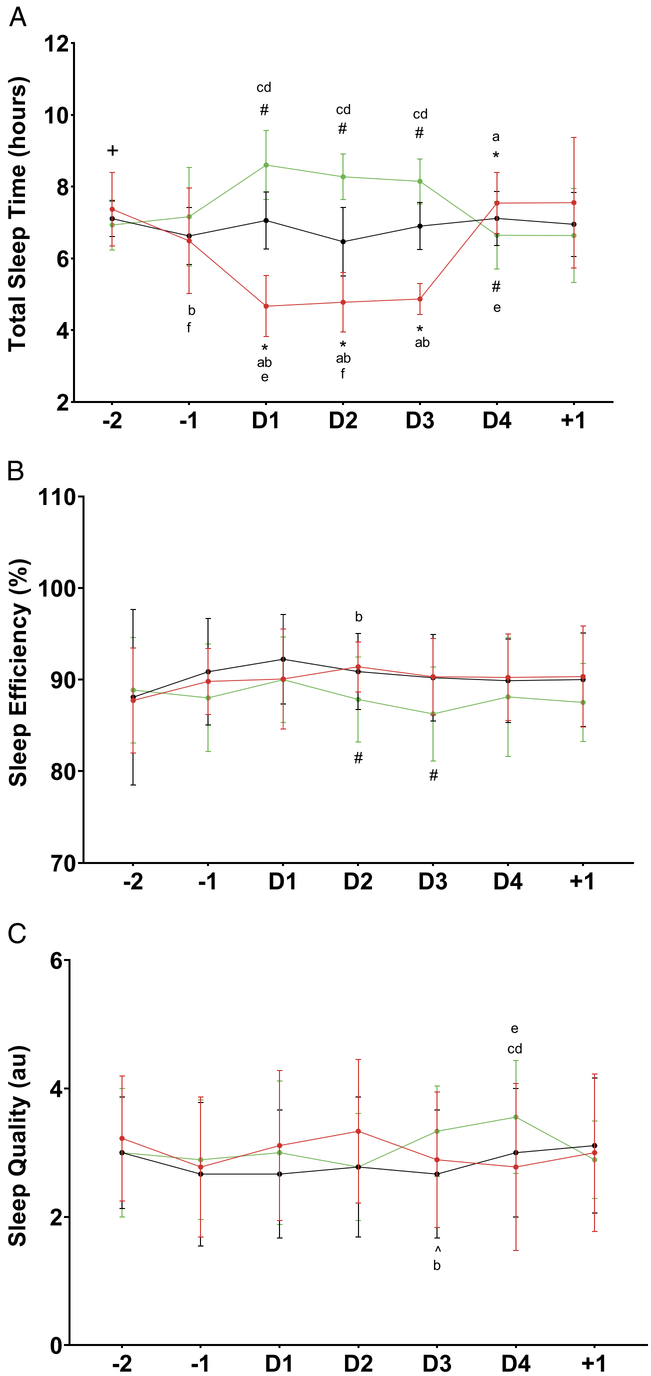

FIGURE 2—TST (A), sleep efficiency (B), and subjective SQ (C) for SR (*red line*), NS (*black line*), and sleep extension (*green line*) conditions. Bedtime and get-up time interventions prescribed for nights D1, D2, and D3. #Different ($P < 0.025$) to both NS and SR. *Different ($P < 0.025$) to both NS and sleep extension. +Difference ($P < 0.025$) between SR and sleep extension only. ^Difference ($P < 0.025$) between NS and sleep extension only. ^{a,b}Differences ($P < 0.05$) within SR condition compared with −1 (a) and −2 (b). ^{c,d}Differences ($P < 0.05$) within sleep extension condition compared with −1 (c) and −2 (d). ^{e,f}Differences ($P < 0.05$) within NS condition compared with −1 (e) and −2 (f).

($P < 0.01$) on night −1 compared with night −2. Within the NS condition, TST was shorter ($P < 0.05$) on nights −1 and D2 compared with night −2, and longer ($P < 0.05$) on nights D1 and D4 compared with night −1. Within the SE condition, TST was longer ($P < 0.01$) on nights D1, D2, and D3 compared with nights −2 and −1.

On night D2, sleep efficiency (Fig. 2B) was lower ($P < 0.01$) in the SE condition (88% ± 5%) compared with SR (91% ± 3%) and NS (91% ± 4%). On night D3, sleep efficiency was lower ($P < 0.025$) in the SE condition (86% ± 5%) compared with SR (90% ± 4%) and NS (90% ± 5%). Within the SR condition, sleep efficiency was higher ($P < 0.01$) on night D2 compared with baseline night −2.

On night D3, SQ (Fig. 2C) was better ($P < 0.01$) in the NS condition (2.7 ± 1.0) compared with SE (3.3 ± 0.7). On night D4, SQ tended to be better ($P = 0.039$) in the SR condition (2.8 ± 1.3) compared with SE (3.6 ± 0.9). Within the SR condition, SQ was better ($P < 0.05$) on night D3 compared with baseline night −2. Within the NS condition, SQ was worse ($P < 0.05$) on night D4 compared with baseline night −1. Within the SE condition, SQ was worse ($P < 0.05$) on night D4 compared with baseline nights −2 and −1. [See Table, Supplemental Digital Content 2, Bedtime, get-up time, time in bed (TIB), TST, sleep efficiency (SE), subjective sleep quality (SQ), time-trial (TT) finishing time, and TT mean power output for each experimental condition, http://links.lww.com/MSS/B661.]

Time-trial performance. As shown in Figure 3, time was slower ($P < 0.02$) on D3 of SR (60.4 ± 3.7 min) compared with NS (58.8 ± 2.5 min). Time was slower ($P < 0.02$) on D4 of SR (62.0 ± 5.2 min) and NS (58.7 ± 3.4 min) compared with SE (56.8 ± 3.1 min). Within the SR condition, time was slower ($P < 0.05$) on D2 and D4 compared with D1 and tended to be slower ($P = 0.053$) on D3 compared with D1. [See Table, Supplemental Digital Content 2, Bedtime, get-up time, time in bed (TIB), TST, sleep efficiency (SE), subjective sleep quality (SQ), time-trial (TT) finishing time, and TT mean power output for each experimental condition, http://links.lww.com/MSS/B661.]

Time-trial perceived exertion. There was no difference in perceived exertion for any split between conditions, or any split between days within conditions (Table 1) PVT.

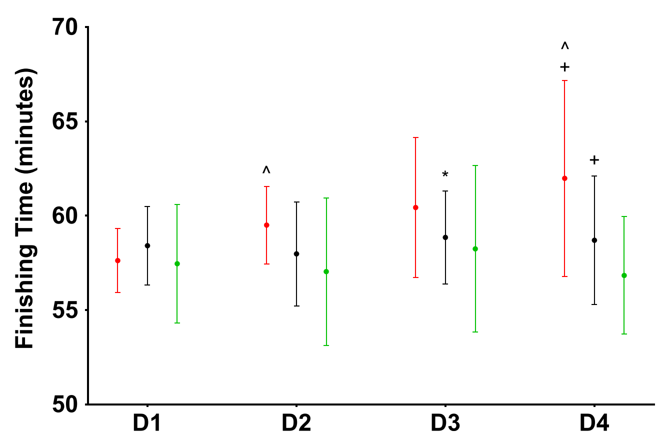

FIGURE 3—Finishing time (mean ± SD) for each time-trial across the 4 d (D1–D4) of testing. SR (red line), NS (black line), and sleep extension (green line). *Different ($P < 0.025$) to SR. +Different ($P < 0.025$) to sleep extension. ^Different ($P < 0.05$) to D1 of the same condition.

TABLE 1. Ratings of perceived exertion recorded for each split during the time trials.

Day	D1				D2				D3				D4			
Time-Trial Split	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
SR	14 ± 1	16 ± 1	17 ± 1	19 ± 1	14 ± 2	16 ± 2	17 ± 2	19 ± 1	14 ± 2	16 ± 1	17 ± 2	19 ± 1	14 ± 1	16 ± 1	17 ± 2	19 ± 1
NS	14 ± 1	16 ± 1	17 ± 1	19 ± 1	15 ± 1	16 ± 1	17 ± 1	19 ± 1	15 ± 1	16 ± 1	17 ± 2	19 ± 1	15 ± 1	16 ± 2	17 ± 1	19 ± 1
SE	14 ± 1	16 ± 1	17 ± 1	19 ± 1	15 ± 1	16 ± 1	17 ± 1	19 ± 1	15 ± 2	16 ± 1	17 ± 2	19 ± 1	15 ± 2	16 ± 2	17 ± 2	19 ± 1

Data are presented as means ± SD. D1–D4, testing days 1 to 4. No significant differences for any split between conditions (P > 0.025) or any split between days within conditions (P > 0.05).

Psychomotor vigilance task. Mean response time (Table 2) was faster (P < 0.025) on D3 and D4 of SE compared with SR and NS and faster (P < 0.025) on D4 of NS compared with SR. Within the SR condition, mean response time was slower (P < 0.05) on D2, D3, and D4 compared with D1. Within the NS condition, mean response time was slower (P < 0.05) on D2 and D4 compared with D1. Within the SE condition, mean response time was faster (P < 0.05) on D4 compared with D1. Lapses were fewer (P < 0.025) on D3 and D4 of SE compared with SR and NS. Lapses were fewer on D4 of NS compared with SR. Within the SR condition, lapses were greater (P < 0.05) on D3 and D4 compared with D1.

Profile of mood states. Total mood disturbance (Table 2) was higher (P < 0.025) on D3 and D4 of SR compared with NS and SE. Within the SR condition, total mood disturbance was higher (P < 0.05) on D2, D3, and D4 compared with D1. Confusion was higher (P < 0.025) on D3 and D4 of SR compared with NS and SE. Within the SR condition, confusion was higher (P < 0.05) on D3 and D4 compared with D1. Fatigue was higher (P < 0.025) on D2, D3, and D4 of SR compared with SE and higher (P < 0.025) on D3 and D4 of SR compared with NS. Within the SR condition, fatigue was higher (P < 0.05) on D2, D3, and D4 compared with D1. Within the NS condition, fatigue was higher (P < 0.05) on D4 compared with D1. Within the SE condition, fatigue was higher (P < 0.05) on D3 and D4 compared with D1. Vigor was lower (P < 0.025) on D2, D3, and D4 of SR compared with SE, and lower on D3 of SR compared with NS. Vigor was higher (P < 0.025) on D4 of SE compared with NS. Within the SR condition, vigor was lower (P < 0.05) on D2, D3, and D4 compared with D1. Within the NS condition, vigor was lower (P < 0.05) on D3 and D4 compared with D1.

DISCUSSION

Three nights of sleep extension better maintained endurance performance compared with both normal and restricted sleep. Compared with NS, extending sleep time for three consecutive nights by an average of 90, 108, and 78 min, respectively, improved performance by 3%, or ~2 min across a ~60-min TT. By contrast, reducing sleep for two consecutive nights by an average of 144 and 102 min, respectively, slowed TT performance by 3%, or ~1.5 min. Within the SR condition, performance was slower on days 2 and 4 compared with day 1. However, performance was consistent over time in the normal and extended sleep conditions.

Sleep extension and endurance performance. Few studies have examined the effects of sleep extension on athletic performance. Although extending sleep has been reported to improve sport-specific skill execution and sprint times (3,4), this is the first study to examine the performance of endurance athletes. Moreover, previous studies examining sleep extension in athletes have used self-reported sleep times (3) or have not included a control arm (4). By contrast, the present study objectively monitored sleep and adopted a three-armed crossover design. In the present study, athletes habitually slept ~6.5–7.0 h per night, similar to sleep durations reported in elite athletes (11). Although a minimum 7 h of sleep per night is recommended for good health (25), our findings suggest that this may not be sufficient to optimize endurance performance. In fact, on sleep extension nights, athletes slept, on average, 8.4 h per night (Fig. 2A), similar to previous studies reporting improved athletic performance when sleep time was extended to 8.4 h (4) and 8.9 h (3) per night. Therefore, we recommend athletes sleep >8 h per night to optimize performance. Sleep efficiency was consistently above 85% (Fig. 2B), the minimum efficiency recommended for good health (26). However, sleep extension led to lower sleep efficiency compared with normal and restricted sleep, and poorer subjective SQ over time, perhaps indicative of reduced homeostatic sleep pressure (i.e., sleep "need") (27). Therefore, sleep extension led to better maintenance of performance despite reductions in sleep efficiency. Although future research should examine the precise effect of sleep efficiency and subjective sleep quality, on endurance performance, we recommend practitioners, with the help of valid sleep monitoring/assessment tools (20,28), work with athletes to optimize both sleep quantity and quality.

Sleep restriction and endurance performance. The extent of accumulated sleep pressure may moderate the effect of SR on endurance performance. Compared with NS, we found performance was unaffected by one night, but impaired after two nights, of SR (i.e., <5 h TST per night). Previously, a severe SR protocol whereby cyclists slept 2.4 h for one night led to slower 3 km TT performance compared with 7.1 h of sleep (10). In endurance athletes, the maximal workload achieved during a graded exercise test was unaffected when the previous night's sleep opportunity was reduced by 3 h (8) but was lower when sleep opportunity was reduced by 4 h (7). In taekwondo athletes, reducing sleep by 3–4 h for one night did not affect distance covered during an intermittent test in the morning (5) but reduced distance covered in the evening (6). Collectively, these findings suggest that performance is likely impaired as sleep pressure/debt accumulates. Apparently contrary to this hypothesis, one study found that time to exhaustion during a graded exercise test was unaffected after three consecutive nights of 2.5 h sleep (9). Moreover, in the present study, we found performance was not statistically slower (P = 0.09) on day 4 of SR compared with NS. This

TABLE 2. Outcomes of preliminary testing conducted before time trials.

	SR				NS				SE			
	D1	D2	D3	D4	D1	D2	D3	D4	D1	D2	D3	D4
Profile of mood states												
Total mood disturbance	2 ± 11	10 ± 10***	25 ± 14**,***	28 ± 12**,***	3 ± 13	3 ± 14	9 ± 14*	13 ± 18*	2 ± 10	6 ± 23	7 ± 13	4 ± 10
Anger	2 ± 2	2 ± 1	3 ± 2	2 ± 2	3 ± 2	2 ± 1	2 ± 2	2 ± 2	3 ± 2	4 ± 6	4 ± 5	2 ± 3
Confusion	4 ± 2	6 ± 3	8 ± 2**,***	9 ± 3**,***	5 ± 3	4 ± 3	5 ± 4*	5 ± 4*	4 ± 2	4 ± 5	4 ± 3	4 ± 2
Depression	2 ± 2	2 ± 2	4 ± 4	3 ± 3	2 ± 2	2 ± 3	3 ± 2	1 ± 1	3 ± 2	4 ± 6	4 ± 5	2 ± 3
Fatigue	4 ± 4	7 ± 4**,***	11 ± 4**,***	14 ± 5**,***	4 ± 3	6 ± 4	7 ± 5*	9 ± 6*,***	4 ± 2	4 ± 3	7 ± 5***	6 ± 4***
Tension	8 ± 6	5 ± 3	6 ± 4	7 ± 4	6 ± 4	4 ± 3	6 ± 3	6 ± 3	6 ± 4	7 ± 5	6 ± 2	5 ± 2
Vigor	17 ± 4	13 ± 3**,***	7 ± 5**,***	7 ± 3**,***	18 ± 5	14 ± 6	13 ± 5*	10 ± 8**	17 ± 6	17 ± 6	17 ± 7	16 ± 5
PVT												
Mean response time (ms)	347 ± 26	365 ± 30***	374 ± 31**,***	392 ± 40**,***	348 ± 34	363 ± 30***	360 ± 28**	363 ± 28*,**,***	349 ± 32	353 ± 22	346 ± 27	332 ± 29***
Lapses (>500 ms)	2 ± 1	3 ± 2	4 ± 2**,***	5 ± 5**,***	2 ± 1	3 ± 2	3 ± 1**	3 ± 2*,**	2 ± 1	2 ± 1	1 ± 1	1 ± 1

Data are presented as means ± SD. D1–D4, laboratory testing days 1 to 4.
*Different ($P < 0.025$) compared with SR.
**Different ($P < 0.025$) compared with SE.
***Different ($P < 0.05$) compared with D1 of condition.

may reflect, on the part of at least some of the athletes tested, a subconscious increase in motivation for the final TT of the sequence as the fear of premature fatigue diminishes, akin to the "end-spurt" effect demonstrated within endurance tasks (29). Nonetheless, within the SR condition, performance was slower on days 2 and 4 compared with day 1. Therefore, collectively, the present findings suggest athletes should avoid short or restricted sleep, particularly on consecutive nights, for optimal endurance performance.

Cumulative sleep time and perceived exertion. Cumulative sleep time did not affect RPE scores, which were consistently near maximal upon TT completion, despite differences in TT finishing times between conditions (Table 1). According to the linear nature of the TT protocol, finishing times corresponded to mean power output (see Table, Supplemental Digital Content 2, which shows time and power output for each TT, http://links.lww.com/MSS/B661); thus, compared with NS, athletes' perceived exertion for a given power output was higher after SR (e.g., D3) and lower after sleep extension (e.g., D4). Perceived exertion reflects the effort required to overcome fatigue, and according to the psychobiological model of exercise tolerance, athletes disengage from an endurance task when perceived effort is greater than the maximum effort they are willing to exert or believe they are capable of exerting (30). Our findings suggest that total sleep obtained over two to three nights appears to alter the intensity (i.e., power output) at which these "effort thresholds" occur. Increased perceived exertion during exercise has been associated with mental fatigue (31). Although we did not measure mental fatigue *per se*, we speculate that previous cumulative sleep time affects the level of mental fatigue experienced, or tolerated, during an endurance task. In fact, sleep extension has been shown to increase pain tolerance (i.e., ability to withstand pain) in healthy adults (32), which may explain higher power outputs for a given RPE after three nights of sleep extension. Evidence that SR impaired mood and psychomotor vigilance, whereas sleep extension improved vigor and psychomotor vigilance (Table 2), further supports speculation that mental/psychological determinants of endurance performance (e.g., attentional focus on pacing, response inhibition, etc.) were likely affected by sleep extension and restriction (33).

Limitations. Participants were well-trained male endurance athletes; therefore, inferences for elite and/or female athletes may require caution. Caffeine withdrawal symptoms peak 20–51 h after abstinence (34); therefore, symptoms may have impaired performances on D1. However, given the crossover nature of the experiment, this is unlikely to affect findings. Participants slept ~30 min more on night −2 of SR compared with SE, potentially confounding results. However, TST for the 48 h before D1 was no different (~14 h, see Table, Supplementary Digital Content 2, http://links.lww.com/MSS/B661) between conditions. Therefore, differences on night −2 are unlikely to affect findings. On D2, D3, and D4, mean start times of testing sessions differed slightly between conditions (see Overview section), potentially confounding results due to circadian

APPLIED SCIENCES

variation in endurance capacity. However, performance differences between conditions did not manifest until after consecutive days of either SR (e.g., D3) or extension (e.g., D4). Thus, circadian effects cannot explain findings as any effects on performance should have occurred as soon as start times differed (e.g., D2). In addition, findings from studies examining time of day effects on prolonged endurance performances (e.g., 60 min) have been equivocal (16), and any effects of small time of day changes, such as those occurring in the current study (e.g., ~40-min difference between start times of the NS condition and the SR/SE conditions), have not been established.

CONCLUSIONS

Sleep extension for three consecutive nights better maintained prolonged self-paced endurance performance compared with both normal and restricted sleep. Sleep restriction impaired endurance performance. Sleep time accumulated over two to three nights appears to influence performance by altering the perceived exertion of a given exercise intensity. Athletes should aim to sleep >8 h per night to optimize endurance performance.

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The results of this study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. Results do not constitute endorsement by the American College of Sports Medicine.

Spencer Roberts, Wei-Peng Teo, Brad Aisbett, and Stuart Warmington declare they have no conflict of interest.

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