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► To cite this version:

Wajdi Souissi, Omar Hammouda, Mohamed Ayachi, Achraf Ammar, Amir Khcharem, et al.. Partial sleep deprivation affects endurance performance and psychophysiological responses during 12-minute self-paced running exercise. *Physiology & behavior*, 2020, 227, pp.113165 -. 10.1016/j.physbeh.2020.113165 . hal-03491510

HAL Id: hal-03491510

<https://hal.science/hal-03491510>

Submitted on 21 Sep 2022

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Partial sleep deprivation affects endurance performance and psychophysiological responses during 12-minute self-paced running exercise

Submission type: Original investigation

Running Head: Sleep loss and self-paced exercise

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Abstract

Purpose: This study aimed to investigate the effects of partial sleep deprivation (PSD) on physical performance and psychophysiological responses during 12-minute self-paced running exercise. **Methods:** Twenty runners (20.8 ± 1.1 years, 70.6 ± 4.9 kg, 175.1 ± 3.9 cm) performed, in a randomized order, two running self-paced field exercises after a normal sleep night (CONT, bedtime from 22:30 h to 06:30 h) and one night of PSD (bedtime from 00:30 h to 04:30 h). Core temperature and motivation were recorded before exercise. Speed, covered distance, heart rate (HR), rating of perceived exertion (RPE) and respiratory parameters (i.e., minute ventilation (VE), oxygen uptake (VO_2) and carbon dioxide production (VCO_2)) were assessed during exercise. Blood lactate concentration [La] was assessed 2 min after exercise. Simple reaction times (SRT), mood and barrage test (BT) were assessed before and after exercise. **Results:** Higher RPE ($p=0.01$, $d=0.90$) and lower physical performance (i.e., $p=0.001$, $d=0.59$ for running speed and $p=0.01$, $d=0.7$ and $\Delta (\%)=-6\%$ for covered distance) following PSD were obtained compared to CONT. Similarly, PSD attenuated core temperature ($p=0.01$, $d=0.84$), HR ($p=0.006$, $\eta^2=0.45$), VE ($p=0.001$, $\eta^2=0.73$), VO_2 ($p=0.001$, $\eta^2=0.96$), BT ($p<0.0005$, $\eta^2=0.86$), SRT ($p=0.0009$, $\eta^2=0.44$) and mood ($p<0.0005$). However, VCO_2 , [La] and motivation score were not affected by sleep conditions. **Conclusion:** The decrease of ~~endurance running~~ performance and the increased ~~of~~ physical discomfort ~~in runners~~ after PSD could be ~~explained by lower the origin~~ of the lower cardio-respiratory responses to the 12-minute self-paced exercise. Effective strategies should be introduced to overcome the deterioration of physical performance and physiological responses after PSD.

Keywords: Sleep loss, running exercise, oxygen uptake, RPE, psycho-cognitive performance, pacing strategy

1. Introduction

Adequate sleep (6–8 hours per night regularly) is considered fundamental for human health [1]. It has restorative effects on immune system, endocrine function and cognitive performance [2]. Equally, from an athletic perspective, sufficient sleep plays a major role in athletes' physiological, cognitive and physical performances [3]. Unfortunately, elite athletes wake up early and obtain a less sleep duration due to the nervousness during heavy training and prior to competition [4,5]. Furthermore, athletes usually use electronic devices at night such as TVs, computers, smart-phones, and tablets which could result in sleep disturbance, low sleep quality (caused by the blue light derived), as well as low sleep duration [6,7]. Since sleep loss is a common occurrence in athletes, this could have a significant detrimental impact upon their physical performance during competition [3].

Most of the previous researches have reported a decrease in endurance performance following total sleep deprivation [4,8–12]. However, conflicting findings have been reported following a partial sleep deprivation (PSD) [4,8–10]. Particularly, some previous studies have shown a decline in time to exhaustion [8] and time trial performance [4] during different modalities of cycling trials (i.e., submaximal cycling at 85% of peak power output and 3-km self-paced cycling) in response to PSD. However, findings from other studies showed that endurance [9] and intermittent [10] running performances as well as cycling to exhaustion performance were not affected following PSD. These discrepancies could be related to methodological issues and study designs, such as the sleep deprivation procedures (e.g., duration and time), the exercise protocol and the small sample sizes [3].

The impact of sleep deprivation on cardiorespiratory parameters presented also controversial findings during endurance exercises [3]. Indeed, following one night of sleep deprivation, cardiorespiratory parameters such as heart rate (HR), minute ventilation (VE) and oxygen consumption (VO_2) decreased during time to exhaustion exercise [8,11,12], but were

maintained during submaximal endurance exercise [8,13,14]. These conflicting findings suggest that the extent, influence and mechanisms of sleep deprivation affecting endurance performance remain uncertain.

Otherwise, despite that athlete's pacing behavior is widely recognized as an essential determinant to optimize performance in endurance time-trial events [15], to the best of the authors' knowledge, only one study has explored the effect of PSD on endurance performance during self-paced cycling exercise [4]. Results from this investigation suggest that 2.4 h of sleep restriction may alter the pacing strategy (i.e., average of power output) of recreational cyclists.

Additionally, sleep loss increases perceptual strain and altered emotion and cognitive functions. Therefore, as reviewed by Halson and Juliff [1], total and partial sleep deprivation has been found to negatively influence cognitive function and psychomotor performance through reduced vigilance, accuracy and alertness [16–19]. In fact, four hours of PSD increased reaction times in 12 handball goal keepers compared with a control night [18]. In addition, sleep deprivation is associated with altered mood state accessed using profile of mood states [3,20–22] which is considered as one of the contributors of the decline of endurance performance. Moreover, perceived exertion was altered in response to total and partial sleep deprivation [3].

Taken together, it seems that the effect of PSD on endurance performance and cardiorespiratory function during self-paced exercise is still unclear. Furthermore, the majority of studies investigating the effect of sleep deprivation on physical and physiological responses have used treadmill or cycle ergometer material. However, rare are the based-sleep deprivation studies assessing physical performance using field running tests. **The field running tests are more adapted to the middle distance runners than the laboratory tests. Moreover, physiological responses to self-paced running exercise differ between outdoor**

track and treadmill intermittent running or indoor track and treadmill running exercises.

Therefore, the aim of the present study was to determine the effect of PSD on pacing, physiological and psychological responses during a 12-minute self-paced field running exercise in collegiate middle-distance runners.

We hypothesized that PSD resulted in a decrement of endurance performance and impaired perceptual and cardiorespiratory responses.

2. Methods

2.1 Participants

Twenty male runners (age: 20.8 ± 1.1 years, weight: 70.6 ± 4.9 kg, and height: 175 ± 4 cm, body mass index (BMI): 23.3 ± 1.6 kg.m⁻²) volunteered to participate in this study. They trained regularly 3 hour/day, 4 days/week for 5 years at least, and they participated in national competitions. Participants presented an “intermediate” (n=12) or “moderate morning” (n=8) chronotype [23]. All of them were non-smokers, without any pathological sleep disorders and did not consume alcoholic drinks. Participants have a normal vigilance (Epworth score = 3.28 ± 1.25) and a good sleep quality (Pittsburgh sleepiness scale index (PSQI) score = 4.91 ± 0.92) [24]. They signed an informed consent to participate in the experiment after being informed about the experimental protocol and the potential risks and benefits of the study. The protocol was approved by the local Institutional Review Board (CPP SUD N° 0183/19) and carried out according to the guidelines of the Helsinki Declaration for human experimentation.

2.2 Experimental design

Experiments were carried out between the 1st and the 20th of March in the local Sport Science Institute containing a Research & Training Center, a Laboratory and a 400m circular running track. During this period, environmental temperature, humidity and wind ranged from 16°C

to 18.5°C, 55% to 62% and 2.5 to 4.17 m.s⁻¹, respectively. Luminosity was > 2000 lux during field tests and <5 lux during sleep. The experimental design took place in a 400m circular running track. As runners, participants were familiarized with 3000 m running time-trial. Furthermore, one week before the experimental sessions, participants performed two familiarization sessions with the experimental protocol at 10:00 h to avoid any training adaptation to the specific time of day (TOD) [25]. In a randomized crossover design, participants performed two self-paced running field exercise, at the same TOD (between 15:30 h and 17:30 h), following two sleep conditions (a control night (CONT) or one night of PSD). In the CONT condition, they were asked to go to bed at 22:30 h and to wake up at 06:30 h. In the PSD condition, participants were allowed to sleep only between 00:30 h and 04:30 h. The test sessions were done the following day in the afternoon. Both test sessions were performed at the same TOD and were interspersed by 72 h of rest.

During the two experimental conditions, participants visited the laboratory at 19:00 h, ate a standardized dinner, and went to the Research & Training Center at 20:00 h. They were allowed to do free passive activities (e.g., reading books, watching TV, doing homework, listen to music, playing cards or video games) until the bedtime for each condition (22:30 h for the CONT and 00:30 h for the PSD) when they were asked to go bed in their sleep rooms (lights and device off, comfortably warm, dark and quiet room). In CONT condition, participants were awakened at 06:30 h and in PSD condition they were awakened at 04:30 h to do free passive activity for 2 h. After that, they went to the laboratory and consumed a standardized breakfast at 07:00 h. Then, they attend their classroom sessions from 08:00 h to 12:00 h, ate a standardized lunch and do free passive activity in the laboratory until the time of the test. From 15:30 h to 17:30 h, participants performed the testing sessions. In each condition, runners were asked to rate their sleepiness using the Hooper questionnaire [26] and their motivation before exercise. Also, before and after performing the running protocol,

participants were asked to rate their mood and to accomplish cognitive tests (reaction time, barrage test). Oral temperature was measured before exercise using a digital clinical thermometer (Omron, accuracy: 0.05°C) inserted sublingually for at least 3 min [19]. During the 12-minute self-paced exercise, heart rate (HR), minute ventilation (VE), oxygen consumption (VO₂) and carbon dioxide production (VCO₂) were assessed. Blood lactate level [La] was measured after the exercise (Figure 1). All participants were requested to avoid the practice of vigorous physical activity during the testing day and at least two days before each test session. They were given instructions about sleep and diet. During the experimental period, daily isocaloric meals were standardized as follow: breakfast at 07:00 h, lunch at 12:00 h and dinner at 19:00 h. Furthermore, food ingestion, caffeine or stimulants were not allowed 24 h before the experimental sessions. Participants were observed continuously by the experimenters.

2.3 Sleep assessment

In the present study sleep duration was calculated as “time in bed” which represent the difference between bedtime and awakening time. In both CONT and PSD condition, sleep duration was assessed subjectively using the sleep diary. By eliciting detailed information on daily sleep duration over a specific time period, this subjective sleep duration measure was recognized as an accepted standard for self-reported sleep duration [27]. In contrast to objective measures (e.g., Polysomnography, wrist actigraphy), which are time-intensive and resource-consuming, sleep diary was also recognized as practicable means of collecting sleep duration data in typical at-home sleep [28]. Besides time diary, time to go bed and time to wake-up in CONT (i.e., 22:30 h and 06:30 h) and PSD (00:30 h and 04:30 h) conditions were controlled using the observation by the experimenters and the artificial illumination (i.e., set at 200 lux to impose awakening and <5 lux during sleep) [7]. After waking-up, participants were not allowed to spend any other time in bed or use opportunities for naps.

2.4 Endurance performance

The running speed and the covered distance were measured using a GPS (GPEXE, Italy) that provides a direct measurement of speed. The speed expressed in km/h was averaged every two minutes during the 12 min self-paced running test to assess the runners' pacing strategy.

2.5 Physiological variables

2.5.1 Cardiorespiratory parameters

The cardiorespiratory parameters were assessed using a gas analyser (K4B², Cosmed, Italy) connected to the heart rate monitor Polar H10 (Finland). The K4B² allows measuring the cardiorespiratory exchanges at rest and at submaximal and maximal exercises. VE, VO₂, VCO₂, and HR were averaged every 2 minutes during the 12-minute running test.

2.5.2 Blood lactate concentration [La]

Two minutes following the self-paced exercise, 5 µl sample of whole fresh blood was taken from the fingertip and analyzed for lactate concentration (mmol/l) using a portable analyzer (lactate Pro2, Arkay, Shiga, Japan).

2.6 ~~Sleep test and psycho-cognitive~~ Subjective variables

2.6.1 Pittsburgh Sleep Quality Index (PSQI)

Sleep quality was assessed using the PSQI questionnaire. It consists of nineteen items classified into seven components: subjective sleep quality, sleep latency, usual sleep duration, sleep efficiency, sleep disorders, use of sleeping pills and daytime dysfunction over the past month [24]. The score for each component is ranging from zero (no difficulty) to three (severe difficulty). Adding the scores of the seven components contributes to the overall PSQI score ranging from zero (no difficulty) to twenty-one (major difficulties). A score above five is associated with poor sleep quality.

2.6.2 Epworth Sleepiness Scale (ESS)

The ESS assesses the daytime sleepiness with a scale of eight elements. Participants assign a score of “0” to “3” for each situation where there is “no chance” for “0”, a low chance for “1”, “a moderate chance” for “2” and “a high chance” for “3” to fall asleep. The score obtained from the scale ranges from “0” to “24”. A score above 10 indicates an “abnormal score”, which is associated with poor sleep quality.

2.6.3 Hooper questionnaire

The Hooper questionnaire is a validated self-reporting scale that allows participants to rate the subjective estimation of the quality of the prior night sleep as well as fatigue, stress, and muscle soreness levels [26]. The four items were recorded 15 minutes before each experimental session on a scale ranging from “1” “very very low” to “7” “very very high” indicating very, very bad for sleep quality and very, very high for stress, fatigue, and muscle soreness levels.

2.6.4 Motivation

Motivation was assessed using a visual analogic scale (VAS). It is a reliable and a valid scale which assess many psychological variables [29]. In the present study, VAS was used to estimate motivation to exercise in CONT and PSD conditions. Participants were asked to rate their motivation by placing a mark on 10 cm line (from “very low” to “very high”).

2.6.5 Rating of perceived exertion (RPE)

The Borg scale is a reliable indicator of physical discomfort, has sound psychometric properties, and is strongly correlated with several other physiological measures of exertion [30]. Every 2 minutes during exercise, participants were requested to rate their subjective exertion for the physical task on a 15-point Likert scale ranging from “6” (very very light) to “20” (very very hard).

2.6.6 Profile of Mood State (POMS)

The French version of the POMS questionnaire [31] was used was used to access mood. It consists of 65-items classified into seven different subscales; anxiety-tension (ANX), anger-hostility (ANG), confusion-perplexity (CONF), depression-discouragement (DEP), fatigue-inertia (FAT), vigor-activity (VIG) and interpersonal relationship (REL). Items were scored using five point linkert scale ranging from 0 (not at all) until 4 (extremely). Higher scores indicated higher prevalence of the actual mood state. The POMS (TMD) score is calculated as follows: $TMD = (ANX + COL + CONF + DEP + FAT) - VIG$. This score ranges from 32 (highest score) to 200 (bad score). Subjects are asked to complete the questionnaire before and after running test.

2.6.7 Reaction times (SRT)

The reaction time to different visual stimuli was measured using Reaction program (Reaction 2.1, Lyon, France) which allows to measure the simple reaction time (SRT) (The time between a simple stimulus and an expected reaction) and the choice reaction times (CRT) (The time between a requesting treatment stimulus and an expected response [32]. The reaction time tests are composed of 19 series of 30 reaction times (ms) at the onset of a visual stimulus with an interval of [2000 ms; 6000 ms] separating two successive stimuli. Participants were asked to press a button as quickly as possible to a visual stimulus shown on the computer screen under different conditions: the appearance of figures and the comparison of figures. The reaction time, the number of faults as well as the numbers of the omissions were recorded at the end of the tests.

2.6.8 The barrage test (BT)

The BT is a psychometric task which allows to measure the attentional performance [18]. The participants are asked to bar as quickly as possible 3-digit numbers presented on a sheet of paper within 45 seconds. The number of targets is 187 with 2 to 8 numbers of 3 digits

randomly departed per line. The numbers are separated by a point, preceded and followed by a space. A point is granted for each of the 187 targets correctly detected.

2.7 Statistical analyses

Statistical tests were conducted using STATISTICA Software (Statistica version 13, Maisons-Alfort, France). All data are presented as mean \pm standard deviation (SD). The Shapiro-Wilk W-test revealed that VE, VO₂, VCO₂, HR, POMS, reaction times (SRT and CRT) and speed were normally distributed. Physiological variables (HR, VE, VO₂ and VCO₂) and speed were analyzed using a two-way repeated measures ANOVA [2 sleep conditions (CONT and PSD) \times 6 times (every 2 minutes of exercise)]. All ANOVA effect sizes were calculated as partial eta squared (η^2). POMS items and reaction times (SRT and CRT) and BT were analyzed using repeated measures ANOVA [2 sleep conditions (CONT and PSD) \times 2 times (before and after exercise)]. When significant main or interaction effects were observed, pairwise comparisons were performed using Bonferroni post-hoc test. RPE, Hooper being not normally distributed, were analyzed using Friedman nonparametric analysis of variance (ANOVA) and pairwise comparisons were conducted using the Wilcoxon test. Paired samples t-test was used to determine differences of covered distance, [La] and motivation across sleep conditions. Effect sizes were calculated using Cohen (d) test [33]. Wilcoxon test was used to compare the oral temperature differences between conditions at rest. Statistical significance was identified at $p < 0.05$. Pearson Correlation was conducted to examine the relationships between parametric variables, and Spearman correlation was conducted to examine the relationships between non-parametric variables. When statistical software demonstrated significance levels of $p = 0.000$, this has been corrected by $p < 0.0005$ according to Kinnear and Gray [34].

3. Results

3.1 Physical performance

3.1.1 Covered distance

Statistical analysis showed a significantly greater covered distance in CONT compared to PSD condition (3033 ± 11 m vs. 2862 ± 13 m, respectively) ($t=5.46$, $p=0.01$, $d=0.7$, Δ (%) =6%).

3.1.2 Speed

Repeated measure ANOVA revealed a significant effect of sleep condition ($F_{(1,19)}=29.8$, $p<0.0005$, $\eta p^2=0.61$) and a significant effect of time ($F_{(5,95)}=12.90$, $p<0.0005$, $\eta p^2=0.40$). Bonferroni post-hoc test revealed that speed was significantly higher in CONT condition compared to PSD ($0.0005<p<0.02$) (Figure 2). However, there was no significant interaction (time \times condition) for speed.

3.2 Physiological variables

3.2.1 Cardiorespiratory parameters

The two-way repeated measure ANOVA revealed a significant interaction (time \times condition) for VO_2 ($F_{(5,95)}=6.35$, $p<0.0005$, $\eta p^2=0.25$). However, there was no significant interaction for HR, VE, and VCO_2 . A significant effect of sleep condition was observed for HR ($F_{(1,19)}=8.62$, $p<0.0005$, $\eta p^2=0.31$), VE ($F_{(1,19)}=7.90$, $p=0.01$, $\eta p^2=0.23$) and VO_2 ($F_{(1,19)}=24.75$, $p<0.0005$, $\eta p^2=0.56$) with greater response following the CONT condition ($p=0.001$) compared to PSD. However, VCO_2 does not differ between conditions ($F_{(1,19)}=2.65$, $p=0.11$, $\eta p^2=0.12$). Moreover, the statistical analysis showed a significant effect of exercise in all cardiorespiratory parameters (HR ($F_{(5,95)}=12.06$, $p=0.008$, $\eta p^2=0.38$), VE ($F_{(5,95)}=170.98$, $p<0.0005$, $\eta p^2=0.89$), VO_2 ($F_{(5,95)}=220.48$, $p<0.0005$, $\eta p^2=0.92$) and VCO_2 ($F_{(5,95)}=41.32$, $p<0.0005$, $\eta p^2=0.68$) with values significantly increased every 2 min of the 12 min self-paced running exercise (Table 1).

3.2.2 Lactate concentration

The paired Student t-test did not reveal a significant effect of sleep condition on [La] (10.84 ± 2.68 vs. 11.43 ± 2.74 mmol/l in CONT and PSD, respectively).

3.2.3 Oral temperature

There was a significant main effect of sleep condition on oral temperature at rest (test=7.99, $p < 0.0005$, $d = 0.84$) with lower values following PSD compared with CONT (36.36 ± 0.21 °C vs. 36.82 ± 0.25 °C).

3.3 Psycho-cognitive variables

3.2.4 Hooper scale

There was a significant effect of sleep condition on score of sleep (test=4.25, $p < 0.0005$, $d = 0.59$), stress (test=4.01, $p < 0.0005$, $d = 0.51$) and fatigue (test=4.13, $p < 0.0005$, $d = 0.67$). Sleepiness, stress and fatigue scores were higher in PSD compared to CONT ($p < 0.0005$ for all, Table 2). There was no significant effect of sleep condition on muscle soreness.

3.2.5 Rating of perceived exertion

Freedman test conducted on RPE revealed a significant effect of sleep condition and exercise (test=139.14, $p = 0.01$, $d = 0.90$). The pairwise comparisons (Wilcoxon test) revealed that RPE scores after PSD were significantly higher in comparison with CONT ($p = 0.01$ for all, Figure 3).

3.2.6 Motivation

Student t-test for paired samples showed no significant effect of sleep condition on motivation score ($t = 1.03$, $p = 0.32$, $d = 0.25$).

3.2.7 Profile of mood states

The results of the POMS after the CONT and the PSD conditions are presented in Table 3. The statistical analysis revealed that depression, confusion, fatigue, and anxiety increased and vigor decreased after the PSD in comparison with the CONT at rest and following exercise ($p < 0.0005$ for all).

3.2.8 Reaction times

For SRT, there was a significant effect of condition ($F_{(1,19)}=15.19$, $p=0.0009$, $\eta p^2=0.44$) and exercise ($F_{(1,19)}=6.10$, $p=0.02$, $\eta p^2=0.24$). The Bonferroni post-hoc test showed that the SRT decreased following exercise in PSD condition ($p=0.03$) and the SRT is lower in CONT compared to PSD immediately after exercise ($p=0.006$). However, for CRT, there was no significant effect of condition ($F_{(1,19)}=2.55$, $p>0.05$, $\eta p^2=0.11$) or exercise ($F_{(1,19)}=2.71$, $p>0.05$, $\eta p^2=0.12$).

3.2.9 Barrage test

ANOVA showed a significant main condition effect ($F_{(1,19)}=122.20$, $p<0.0005$, $\eta p^2=0.86$) on BT score. Bonferroni post-hoc test revealed a higher BT score in CONT condition compared with PSD at rest ($p<0.0005$) and following exercise ($p<0.0005$) (Table 4).

3.4 Correlations

Pearson correlation showed a significant correlation between RPE with all physiological responses in CONT ($0.85<r<0.94$) condition. However, during PSD condition RPE was only significantly correlated with VE ($r=0.86$) and HR ($r=0.94$) responses. No significant correlations were found between (i) physical performance and physiological responses, (ii) physical and cognitive performances, and (iii) physical performances and HOOPER or POMS items (Table 5).

4. Discussion

The present study investigated the effects of one night of PSD on endurance physical performance, pacing strategy, and psychophysiological responses to a 12-minute self-paced running exercise. The primary findings indicated that pacing and endurance performance were impaired following PSD. Moreover, cardio-respiratory parameters, RPE and Hooper items were altered following PSD compared to CONT.

In the present study, covered distance was impaired by 6% following PSD. Accordingly, previous studies reported a decrease in 3 km cycling time trial performance following 2.4 h of sleep restriction [4] or time to exhaustion at constant-load trial (85% of peak power output) following PSD [8]. Moreover, most of the previous studies showed a decrease in endurance performance with PSD [4,21] or total sleep deprivation [11–13,35–37]. However, some studies reported an unchanged time to exhaustion in response to PSD [9] or total sleep deprivation [11,14,38]. The discrepancy between studies may be related to the experimental procedures: Sleep intervention (total sleep deprivation or PSD at the beginning, at the end of night or in the middle of the night), fitness level, low statistical power due to small sample size, exercise protocols used, prior experience to sleep deprivation and time of day effect [3].

In the present study, runners rated a higher RPE after PSD compared to CONT condition. These findings are consistent with previous studies reporting an increased RPE as a response to 8 minutes cycling exercise at a constant work load or 20-minute treadmill running after a total sleep deprivation [3]. According to the psychobiological model of Marcora and Staiano [29], it was suggested that mentally fatiguing conditions and increased perceived exertion may impair physical performance. Findings from the present study confirm this suggestion and showed that the higher RPE and Hooper (i.e., feelings of fatigue, depression, anger and sleepiness) scores following the PSD condition were accompanied with a decrease in the covered distance and the runners' pacing behavior during the 12-min self-paced running trial. In addition, cognitive process seems to be impaired following PSD. Indeed, reaction time (simple or choice) was higher and BT was lower in PSD compared to CONT. As previously shown, cognitive performance fluctuates depending on whether subjects were sleep deprived or not with a best cognitive performance at 18h:00 in the CONT to total sleep deprivation [19]. Furthermore, four hours of PSD at the end of the night decreased attentional capacities and increased constant attention in 12 handball goal keepers compared with a normal sleep

deprivation [18]. Likewise, PSD impaired constant attention, selective attention and visual-spatial ability and recognition and impacted decision making process at rest and following self-paced exercise [3]. Accordingly to a previous study [19], the present finding demonstrated that the impairment of vigilance was concomitant with decreased oral temperature in PSD. In our study, we explained the decrement of the endurance performance by a higher ~~perceived exertion~~ RPE during the running time trial exercise in PSD condition. The PSD is associated with C and S process disturbance [39]. The impairment of the two process results in mood impairment (depression), which can lead to a higher RPE rated in the PSD condition compared to the CONT condition. In this context, the perceived exertion is an important determinant of the physical performance as reported by Pageaux et al. [40].

Additionally, the present PSD protocol altered pacing behavior during the self-paced running exercise resulting in a decrease of average speed during the PSD condition compared the CONT condition. The impaired speed could be explained by the altered physiological function. In this context, Skein et al. [20] observed a slowing down of pacing behavior (i.e., speed average) during repeated sprint exercises for three consecutive days and following a 30-h sleep deprivation. Similarly, using a 2.4 h PSD, Chase et al. [4] demonstrated a significant decrement of pacing behavior (i.e., average of power output) during 3 km cycling exercise.

Moreover, the present findings showed that PSD negatively affected cardiorespiratory parameters with decreased VO_2 , VE and HR compared to CONT. These trends indicated that the lower physical performance after PSD drops the physiological responses to the 12 min running exercise. The present results are consistent with previous researches showing reduced ventilatory responses following total [11,12,14] or partial sleep deprivation [8], but in contrast with other studies showing that HR, VO_2 and VCO_2 were not affected by sleep loss [3]. The contradiction between studies could be due to the exercise intensity/modality and the

sleep deprivation protocol with longer sleep deprivation and/or higher exercise intensity (e.g., self-paced) were suggested to result in higher cardiorespiratory alteration [8,12–14]. Indeed, in response to a submaximal cycling exercise conducted in the laboratory, the majority of previous studies failed to report a significant effect of sleep deprivation on cardiorespiratory parameters [9,12,14]. However, the present study reported a decreased HR, VO_2 , and VE following PSD compared to CONT in response to the 12-min self-paced running exercise in which runners are encouraged to perform as fast as possible. These results could be explained by the alteration of the autonomic nervous system [3] resulting in a higher parasympathetic activity. Likewise, given the similar magnitude in the responses of cardiorespiratory parameters, pacing behavior and total covered distance following PSD, it seems that the alterations of cardiorespiratory parameters are in the origin of the decreased performance during PSD compared to CONT condition. In this context, it is widely accepted that running economy and fractional utilization of $\text{VO}_{2\text{max}}$ are important variables that sets the endurance performance [41].

Our results reported no significant effect of PSD on [La]. In this context, and contrarily to some previous studies [10,37,42], it has been reported that [La] response to endurance exercise remained unchanged following PSD [35,37,43,44]. The exercise and sleep deprivation modality could explain the divergences of [La] responses with sleep deprivation implemented at the beginning and the end of the night was suggested to decrease [La] response to exhaustion exercise [10]. Our results showed that the lower physical performance leads to lower physiological response during the 12 minutes running-self paced exercise in the one hand. In the other hand, participants rated a higher RPE after the PSD condition compared to the CONT condition which could explain in part the decrease of endurance performance following the PSD condition. Our results are consisting with previous research

demonstrating that the higher RPE drives in a lower physical performance in athletes during running exercise [40].

Regarding the present correlation results, main significant correlations were found between RPE and physiological parameters which confirm that RPE is an important indicator of physiological responses to physical exercise and can be a useful tool to control the exercise intensity during a based-metabolic physical effort [40]. Particularly, RPE showed to be correlated with VO_2 and temperature in CONT but not in PSD condition. These results indicate that the high post-exercise RPE following PSD is not only caused by exercise induced fatigue but also by PSD induced physical and mental fatigue [35]. Thus, it can be suggested that effort perception in response to based-endurance exercise is a multifactor-dependent parameter with sleep habits seems to be one important factor. However, further long-term studies are needed to confirm this suggestion.

To the authors' knowledge, the present study is the first to investigate the effect of PSD on physical performance and psychophysiological responses to a self-paced running exercise in athletic populations. However, the absence of an objective measurement of the sleep quantity and quality (e.g., polysomnography) could limit the final conclusion of the present study. Moreover, the difference in time awake between the trials could be a limitation to the experimental design. Furthermore, the data of the present study are specific to male runners and could not be systematically generalized to other sports activities.

5. Conclusion

The present study showed that a PSD at the beginning and the end of the night negatively affects endurance performance, cardiorespiratory and psychological responses to 12-minute self-paced exercise in runners. Consequently, effective strategies (e.g., caffeine supplementation, napping etc.) should be introduced to overcome the deterioration of

athletes' physical performance and psychophysiological responses to endurance exercise after PSD.

6. Acknowledgements

The authors wish to thank all the participants for their maximal effort and cooperation.

7. Declaration of Interest

The authors report no conflicts of interest, no relevant disclosures and no external financial support. The authors alone are responsible for the content and writing of the paper.

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Figures captions

Figure 1: The experimental design of the study (CONT: control group; PSD: partial sleep deprivation group; HR: heart rate; VE: ventilation minute; VO₂: oxygen uptake; VCO₂: carbon dioxide production, and RPE: rating of perceived exertion)

Figure 2: Mean (\pm SD) values of speed obtained during the 12-min self-paced running exercise performed following control night (CONT) and one night of partial sleep deprivation (PSD).

* Significant difference from the 2 min time point, $p < 0.05$, ** Significant difference from the 10 min time point, $p < 0.05$, # Significant effect of sleep condition ($p < 0.01$).

Figure 3: Mean values (\pm standard deviation) for rating of perceived exertion during the self-paced running exercise following a normal sleep night (CONT) and one night of partial sleep deprivation (PSD). * Significant effect of time ($p < 0.01$), # Significant effect of sleep condition ($p < 0.01$).

Table 1: Mean (\pm standard deviation) values for speed, heart rate (HR), minute ventilation (VE), oxygen consumption (VO₂) and carbon dioxide production (VCO₂) during the self-paced running exercise following a normal sleep night (CONT) or partial sleep deprivation (PSD).

* Significant difference from the 2 min time point ($p < 0.01$), # Significant main effect of sleep condition ($p < 0.05$).

Table 2: Mean (\pm standard deviation) values for Hooper scores (sleep, stress, fatigue and muscle soreness) following control night (CONT) and one night of partial sleep deprivation (PSD).

Significant sleep condition effect, $p < 0.0005$.

Table 3: Mean (\pm standard deviation) values for profile of mood state (POMS) at rest and following 12 minute running exercise performed following control night (CONT) and one night of partial sleep deprivation (PSD).

* Significant effect of exercise ($p < 0.0005$), # Significant effect of sleep condition ($p < 0.0005$).

Table 4: Mean (\pm standard deviation) values for simple reaction time (SRT), choice reaction time (CRT) and constant attention (CA) following a control night (CONT) and one night of partial sleep deprivation (PSD). # Significant effect of sleep condition ($P < 0.0005$).

Table 5: Correlation between physical performance, physiological parameters and psychocognitive parameters.

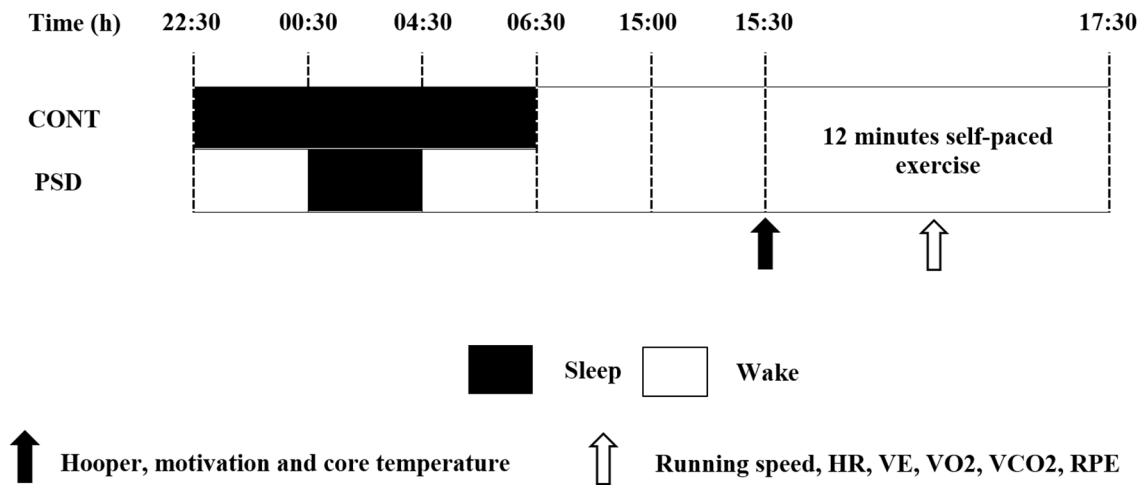


Figure 1: The experimental design of the study (CONT: control group; PSD: partial sleep deprivation group; HR: heart rate; VE: ventilation minute; VO₂: oxygen uptake; VCO₂: carbon dioxide production, and RPE: rating of perceived exertion)

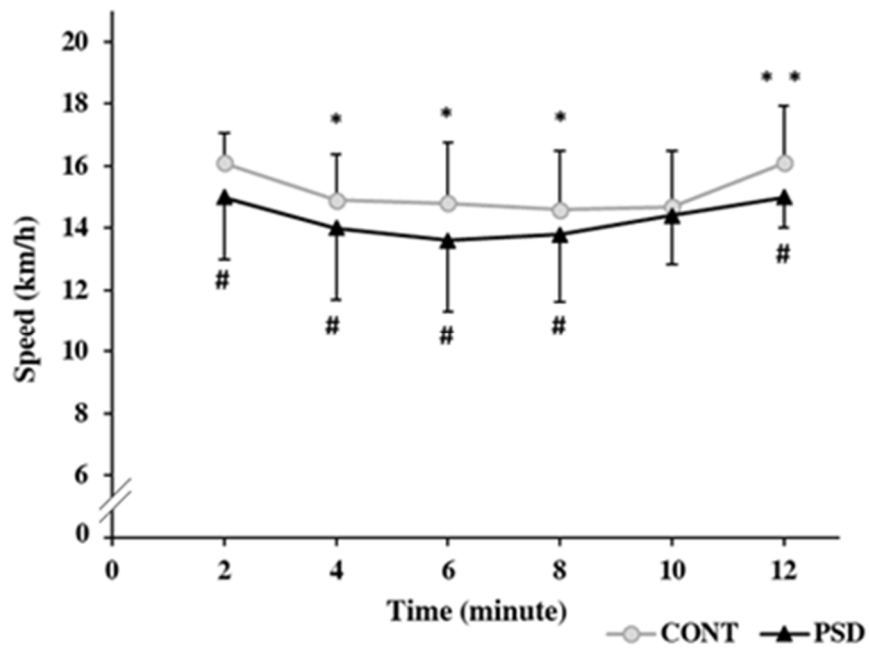


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* Significant difference from the 2 min time point, $p < 0.05$, ** Significant difference from the 10 min time point, $p < 0.05$, # significant effect of sleep condition ($p < 0.01$).

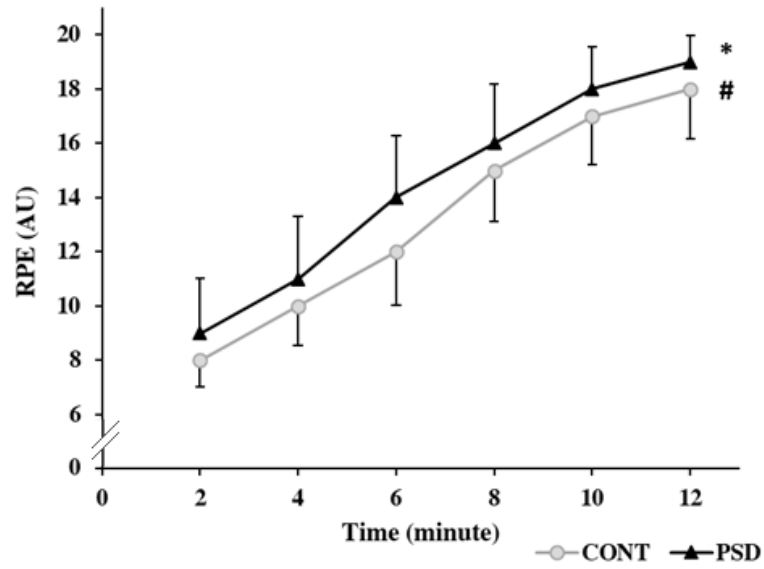


Figure 3: Mean values (\pm standard deviation) for rating of perceived exertion during the self-paced running exercise following a normal sleep night (CONT) and one night of partial sleep deprivation (PSD). * Significant effect of exercise ($p < 0.01$), # significant effect of sleep condition ($p < 0.01$).

Table 1: Mean (\pm standard deviation) values for speed, heart rate (HR), minute ventilation (VE), oxygen consumption (VO_2) and carbon dioxide production (VCO_2) during the self-paced running exercise following a normal sleep night (CONT) or partial sleep deprivation (PSD).

* Significant difference from the 2 min time point ($p < 0.01$), # Significant main effect of sleep condition ($p < 0.05$).

Time		2 min *	4 min *	6 min *	8 min *	10 min *	12 min *
HR (beats/min)	CONT #	160 \pm 11	169 \pm 11	177 \pm 8	179 \pm 8	181 \pm 8	183 \pm 9
	PSD	158 \pm 12	166 \pm 11	173 \pm 10	174 \pm 12	177 \pm 11	177 \pm 12
	Δ (%)	1.71	2.22	2.39	3.11	2.40	3.09
VE (l/min)	CONT #	81 \pm 15	109 \pm 15	112 \pm 13	116 \pm 11	118 \pm 12	123 \pm 16
	PSD	78 \pm 16	103 \pm 16	107 \pm 16	109 \pm 15	113 \pm 16	114 \pm 17
	Δ (%)	3.60	5.63	4.63	5.60	4.28	6.79
VO_2 (ml/min/kg)	CONT #	43 \pm 5	51 \pm 5	54 \pm 5	55 \pm 5	56 \pm 5	58 \pm 5
	PSD	40 \pm 7	46 \pm 8	49 \pm 8	50 \pm 8	49 \pm 7	51 \pm 7
	Δ (%)	8.49	8.35	8.19	8.60	10.56	12.30
VCO_2 (l/min)	CONT #	3.0 \pm 0.7	3.9 \pm 0.7	3.7 \pm 0.5	3.7 \pm 0.5	3.6 \pm 0.5	3.7 \pm 0.6
	PSD	3.3 \pm 0.8	4.1 \pm 0.7	3.9 \pm 0.7	3.9 \pm 0.7	3.8 \pm 0.8	3.7 \pm 0.7
	Δ (%)	10.14	6.80	5.29	4.26	4.44	1.18

Table 2: Mean (\pm standard deviation) values for Hooper scores (sleep, stress, fatigue and muscle soreness) following control night (CONT) and one night of partial sleep deprivation (PSD).

[#] Significant effect of sleep condition, $p < 0.0005$.

	CONT	PSD
Sleep	2.30 \pm 0.47	4.20 \pm 0.70 [#]
Stress	2.00 \pm 0.65	3.75 \pm 0.64 [#]
Fatigue	1.85 \pm 0.49	3.40 \pm 0.50 [#]
Muscle soreness	1.70 \pm 0.47	2.15 \pm 0.75

Table 3: Mean (\pm standard deviation) values for profile of mood state (POMS) at rest and following 12 minute-running exercise performed following control night (CONT) and one night of partial sleep deprivation (PSD).

* Significant effect of exercise ($p < 0.0005$), # Significant effect of sleep condition ($p < 0.0005$).

	Rest		Post-exercise	
	CONT	PSD	CONT	PSD
Tension	3.60 \pm 2.14	8.35 \pm 2.03 #	11.25 \pm 5.94 *#	12.65 \pm 4.15 *#
Anger	3.85 \pm 1.93	7.25 \pm 1.92 #	6.25 \pm 2.90 *#	10.1 \pm 3.29 *#
Confusion	4.25 \pm 3.16	7.70 \pm 3.08 #	7.05 \pm 3.05 *#	9.30 \pm 3.28 *#
Depression	2.35 \pm 1.87	5.70 \pm 3.11 #	5.60 \pm 3.08 *#	8.85 \pm 3.36 *#
Fatigue	4.15 \pm 1.73	7.70 \pm 2.20 #	10.10 \pm 5.42 *#	12.55 \pm 5.22 *#
Vigor	19.10 \pm 1.71	15.60 \pm 2.52 #	10.2 \pm 5.30 *#	9.00 \pm 2.32 *#

Table 4: Mean (\pm standard deviation) values for simple reaction time (SRT), choice reaction time (CRT) and constant attention (CA) following a control night (CONT) and one night of partial sleep deprivation (PSD). # Significant effect of sleep condition ($P < 0.0005$).

	CONT		PSD	
	Before exercise	After exercise	Before exercise	After exercise
SRT (ms)	254.40 \pm 55.78	396.50 \pm 74.56	282.25 \pm 73.94 #	422.55 \pm 73.95 #
CRT (ms)	295.95 \pm 87.15	426.35 \pm 71.25	352.90 \pm 105.72 #	446.60 \pm 81.37 #
CA (BT)	58.70 \pm 5.44	55.70 \pm 5.31	47.45 \pm 5.25 #	48.55 \pm 4.44 #

Table 5: Correlations between physical performance, physiological parameters and psycho-cognitive parameters.

Sleep Conditions			CONT					PSD					
		Physical performance		RPE	Psycho-cognitive variables			Physical performance		RPE	Psycho-cognitive variables		
Parameters		Speed	Distance		BT	SRT	CRT	Speed	Distance		BT	SRT	CRT
Physical performance	Speed-performance												
	Covered-distance	1		p>0.05		p>0.05		1		p>0.05		p>0.05	
Physiological parameters	VE			r=0.85 p=0.03						r=0.86 p=0.03			
	VO2	p>0.05		r=0.86 p=0.03		N/A		P>0.05		p>0.05		N/A	
	HR			r=0.94 p=0.004						r=0.94 p=0.004			
	Temperature			r=0.61 p=0.004						p>0.05			