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Received: 12 January 2023 | Revised: 1 June 2023 | Accepted: 20 June 2023

DOI: 10.1111/jsr.13987

RESEARCH ARTICLE

The effect of sleep restriction, with or without high-intensity interval exercise, on behavioural alertness and mood state in young healthy males

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Funding information
National Health and Medical Research Council, Grant/Award Number: GNT2013427

Summary

Mood state and alertness are negatively affected by sleep loss, and can be positively influenced by exercise. However, the potential mitigating effects of exercise on sleep-loss-induced changes in mood state and alertness have not been studied comprehensively. Twenty-four healthy young males were matched into one of three, 5-night sleep interventions: normal sleep (NS; total sleep time (TST) per night = 449 ± 22 min), sleep restriction (SR; TST = 230 ± 5 min), or sleep restriction and exercise (SR + EX; TST = 235 ± 5 min, plus three sessions of high-intensity interval exercise (HIIE)). Mood state was assessed using the profile of mood states (POMS) and a daily well-being questionnaire. Alertness was assessed using psychomotor vigilance testing (PVT). Following the intervention, POMS total mood disturbance scores significantly increased for both the SR and SR + EX groups, and were greater than the NS group (SR vs NS; 31.0 ± 10.7 A.U., [4.4–57.7 A.U.], $p = 0.020$; SR + EX vs NS; 38.6 ± 14.9 A.U., [11.1–66.1 A.U.], $p = 0.004$). The PVT reaction times increased in the SR ($p = 0.049$) and SR + EX groups ($p = 0.033$) and the daily well-being questionnaire revealed increased levels of fatigue in both groups (SR; $p = 0.041$, SR + EX; $p = 0.026$) during the intervention. Despite previously demonstrated physiological benefits of performing three sessions of HIIE during five nights of sleep restriction, the detriments to mood, wellness, and alertness were not mitigated by exercise in this study. Whether alternatively timed exercise sessions or other exercise protocols could promote more positive outcomes on these factors during sleep restriction requires further research.

KEYWORDS
alertness, cognitive function, exercise, mood, sleep, vigilance

1 | INTRODUCTION

The National Sleep Foundation recommends that adults sleep between 7 and 9 h each night (Hirshkowitz et al., 2015). However, inadequate sleep has become increasingly prevalent in modern society, largely due to lifestyle factors and work pressures (Sleep Health Foundation, 2017). In addition to the detrimental effects on the economy and metabolic health (Saner et al., 2018; Sleep Health Foundation, 2017), sleep loss can

impair several aspects of cognitive function (such as alertness, reaction time, executive function, and memory) and reduces mood state, which culminates in reduced efficiency and performance in many occupational tasks (Banks & Dinges, 2007; Lim & Dinges, 2010).

Reductions in alertness and reaction times with inadequate sleep are well-documented (Dinges et al., 1997). Psychomotor vigilance testing (PVT) provides a rapid and simple assessment of alertness (Basner et al., 2011), and is highly sensitive to daytime fatigue and is predictive of real-world tasks such as driving performance (Jackson et al., 2013). Experimental models of both sleep deprivation (>24 h of continuous wakefulness) and sleep restriction (chronic partial reduction of sleep duration) are associated with decreases in PVT-assessed alertness (Dinges et al., 1997). For example, Basner et al. (2011) reported increases in the PVT reaction time and the number of lapses (reaction time > 355 ms) during both sleep deprivation (−33 h of wakefulness) and sleep restriction (5 nights, 4 h time in bed (TIB) each night) (Basner et al., 2011). Sleep loss also leads to impairments in mood state (Short & Louca, 2015); this is commonly evaluated via the profile of mood states (POMS) questionnaire, which assesses feelings of anger, confusion, depression, fatigue, tension, and vigour (McNair et al., 1971). Indeed, previous reports indicate that sleep restriction (−5 h TIB for 7 nights) leads to noticeable increases in perceived fatigue and stress, and decreases in alertness, PVT performance, and overall mood (Dinges et al., 1997). The reductions in mood and cognitive function with inadequate sleep have been suggested to manifest as decreased emotional and mental well-being, reduced occupational-task-specific performance (Banks & Dinges, 2007; Haack & Mullington, 2005), and have also been associated with an increased incidence of accidents, such as motor vehicle collisions (Steele et al., 1999). Therefore, finding novel strategies for mitigating the declines in cognitive function and mood induced by sleep loss are required.

Exercise has well-documented beneficial effects on cardiometabolic health and is purported to improve mood and cognitive function (Bishop et al., 2019; Monleon et al., 2015; Philp et al., 2020). Indeed, acute aerobic exercise has been reported to improve mood (assessed via POMS) for up to 24 h upon completion (Maroulakis & Zervas, 1993; Reed & Ones, 2006) and exercise training can improve mood, alleviate depressive symptoms, and increase cognitive performance (including alertness and vigilance) (Carta et al., 2021; Monleon et al., 2015; Sibold & Berg, 2010). Previous work, including from our own group, has shown that performing high-intensity interval exercise (HIIE) can mitigate the detrimental metabolic effects associated with a period of sleep restriction (de Souza et al., 2017; Lin et al., 2022; Saner et al., 2020; Saner et al., 2021; Sweeney et al., 2020). Despite this, research investigating the potential benefits of performing exercise to counteract the effects of sleep loss on mood and alertness are currently limited. Prior studies have either implemented severe periods of sleep deprivation (30–40 h continuous wakefulness) (LeDuc et al., 2000; Sauvet et al., 2020; Scott et al., 2006), or performed exercise only after the period of sleep restriction (4 h TIB for 3 nights) had concluded (Larsen et al., 2020), with conflicting findings. Therefore, whether performing HIIE throughout a period of sleep restriction can counteract the decreases in mood, alertness, and well-being, remains to be determined. Accordingly, the aim of this study was to examine the effect of sleep restriction (4 h TIB for five nights), with or without HIIE, on mood state, alertness, and well-being in young healthy males. We hypothesised that high-intensity exercise conducted throughout a period of sleep restriction would improve mood state and alertness.

2 | METHODS

2.1 | Participants

Twenty-four healthy, recreationally active males between 18 and 35 years of age volunteered to participate in this study, after having provided written informed consent. All procedures conformed to the standards set by the Declaration of Helsinki and were approved by the Victoria University Human Research Ethics Committee (HRE15-294). Participants were screened to determine their eligibility, and to rule out any pre-existing medical conditions that may have precluded their participation (such as contraindications to exercise). Eligible participants included in the study were (1) not taking any medications during the study, (2) not performing shift work, (3) had regular sleeping habits, and no previously diagnosed sleep disorders, and (4) had not travelled overseas in the previous 2 months. As this study is a secondary analysis from a prior study investigating changes in skeletal muscle mitochondrial respiratory function (Saner et al., 2021), only males were included in this study given the previously documented differences in mitochondrial responses between males and females (Cardinale et al., 2018). Prior to commencing the study, 1 week of habitual sleep was monitored via wristwatch actigraphy and confirmed with sleep diaries; participants who averaged <6 or >9 h sleep per night during the monitoring period were also excluded from the study. Participants completed the Horne-Osteberg morningness-eveningness questionnaire to assess chronotype (Horne & Ostberg, 1976). All participants were classified as having either a moderate evening ($n = 2$), intermediate ($n = 14$), or moderate morning ($n = 8$) chronotype (Table 1).

2.2 | Study overview

The study was conducted in a temperature-controlled (22°C) sleep laboratory with the capacity for three participants to complete the study at any one time; each participant had their own bedroom. Participants were monitored by a member of the research team throughout the study to ensure their safety and adherence to the protocol (and actigraphy watches were worn at all times during the study). Eligible participants attended the exercise physiology laboratory for baseline assessments of anthropometric measurements and aerobic fitness, via a graded exercise test (GXT) to measure peak oxygen consumption ($\dot{V}O_{2peak}$). Following baseline testing, the participants were allocated via minimisation into one of the three experimental groups, in a

TABLE 1 Participant characteristics

	NS ($n = 8$)	SR ($n = 8$)	SR + EX ($n = 8$)	p value
Age (y)	24 ± 4	25 ± 5	24 ± 4	*0.754*
Height (cm)	177 ± 8	179 ± 6	179 ± 7	*0.534*
Mass (kg)	78.7 ± 13.3	74.5 ± 11.7	80.2 ± 9.5	*0.601*
BMI	25.2 ± 3.6	23.3 ± 3.0	24.6 ± 2.5	*0.468*
$\dot{V}O_{2peak}$ (mL.kg^{-1}.min^{-1})	43.7 ± 9.7	47.2 ± 6.7	48.0 ± 5.0	*0.486*
$_{peak}$ (W)	319 ± 59	330 ± 44	362 ± 48	*0.242*
Habitual sleep duration (min)	457 ± 45	428 ± 44	437 ± 39	*0.422*
MEQ score	46 ± 7	46 ± 8	59 ± 7	0.095

Note: Values are mean ± SD. There were no significant differences between the three groups for any of the baseline characteristics.
Abbreviations: $\dot{V}O_{2peak}$, peak oxygen consumption; BMI, body mass index; MEQ, morningness-eveningness chronotype questionnaire; NS, normal sleep; SR, sleep restriction; SR + EX, sleep restriction and exercise; W_{peak}, peak power.

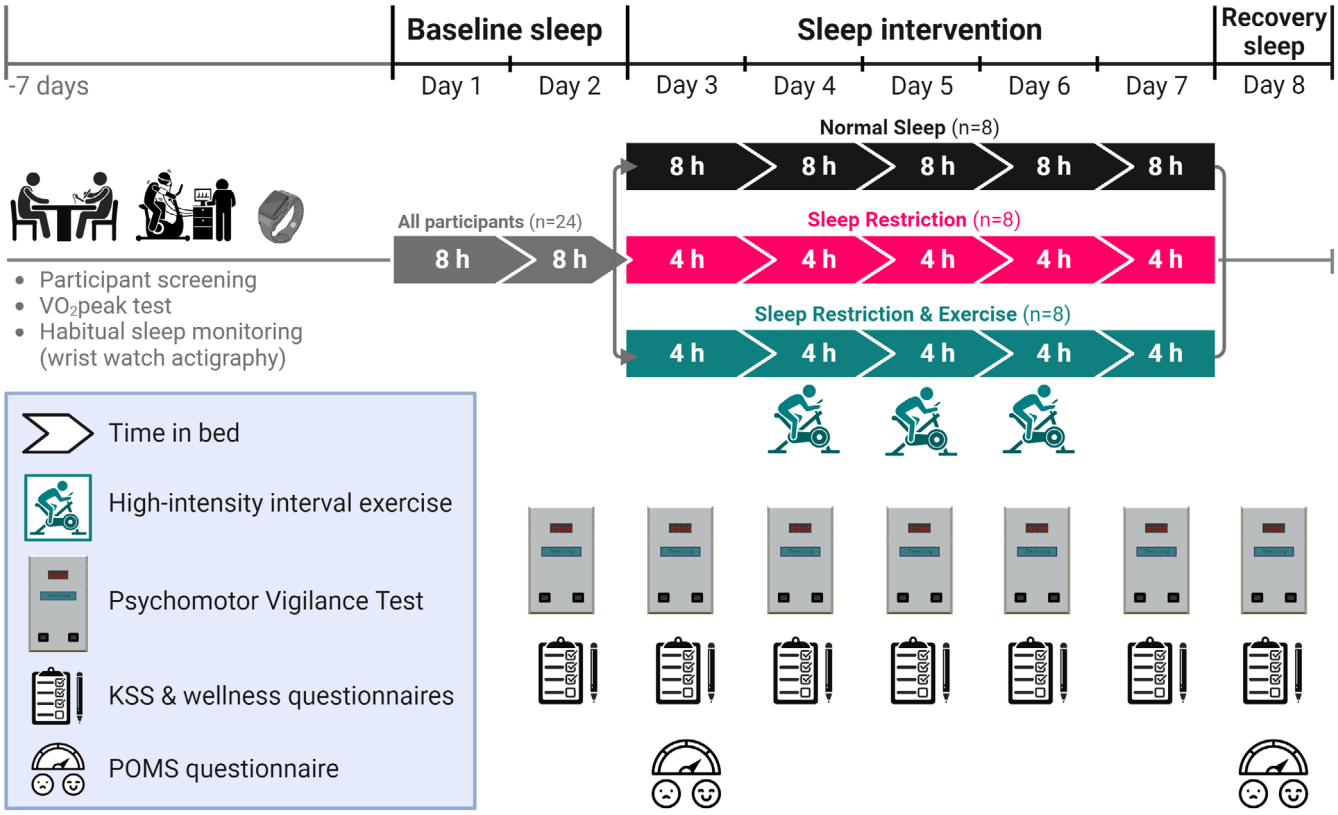

FIGURE 1 Study protocol overview. POMS, profile of mood states; PVT, psychomotor vigilance test; $\dot{V}O_{2peak}$, peak oxygen consumption; HIIE, high-intensity interval exercise; KSS, Karolinska sleepiness scale.

counterbalanced order, so as to minimise differences in between-group baseline measures for age, body mass index (BMI), habitual sleep duration, and $\dot{V}O_{2peak}$. Participants were assigned to either normal sleep (NS, $n = 8$), sleep restriction (SR, $n = 8$), or sleep restriction and exercise (SR + EX, $n = 8$). Physiological data from this cohort of participants (including data relating to glucose tolerance and skeletal muscle analysis) has been previously reported elsewhere (Lin et al., 2022; Saner et al., 2021; Saner & Lee, 2020).

The experimental component of the study consisted of an eight-night stay within the sleep laboratory (Figure 1). All groups completed two initial nights of baseline sleep (8 h time in bed (TIB), 23:00–07:00 h). During the subsequent five-night intervention period, the NS group spent 8 h TIB (23:00–07:00 h), while both SR and SR + EX spent 4 h TIB per night (03:00–07:00 h). Between 23:00 h and 03:00 h, lighting was dimmed to below 15 lux to reduce the effect of lighting on circadian rhythms

(Duffy & Wright Jr., 2005). The SR + EX group also performed three HIIE sessions during the intervention period on day 4, day 5, and day 6 at 10:00 h. The HIIE sessions were not performed on day 7 to avoid the acute effects of exercise on mitochondrial respiratory function (assessed on day 8), being the primary outcome measure of the original study. Following the intervention period, all groups completed a final night of ad libitum recovery sleep. Throughout the study, the participants completed a psychomotor vigilance task (PVT) thrice-daily, subjective sleepiness assessments twice-daily, plus a daily wellness questionnaire. Mood state was assessed via POMS questionnaire before and after the intervention period. Waking hours were spent watching television, reading, working on a computer, or talking to the research team.

2.3 | Dietary and physical activity control

Throughout the study, the participants were provided with a standardised diet consisting of fixed proportions (relative to body mass) of carbohydrates (4.5 $g.kg^{-1}.d^{-1}$), protein (1.5 $g.kg^{-1}.d^{-1}$), and fat (1 $g.kg^{-1}.d^{-1}$). The timing of all meals was kept constant (breakfast – 8 a.m., morning snack – 10:30 a.m., lunch – 12:30 p.m., afternoon snack – 4:30 p.m., dinner – 7 p.m., and evening snack – 9:30 p.m.). Caffeine intake was prohibited throughout the study. Participants were asked to match their habitual step counts by walking outside of the facility at designated periods (mid-morning and mid-afternoon) throughout the day, while accompanied by a member of the research staff. If needed, a brief walk after dinner was performed to meet habitual step counts. Daily step counts were monitored using commercially available and validated step-counting applications on the participants' personal mobile phone devices (i-Health app, Apple Inc., Cupertino, CA, USA; and Samsung Health, Samsung Electronics Co., Ltd, Suwon, South Korea). These results have been reported previously (Saner et al., 2020).

2.4 | Sleep monitoring

Sleep was assessed using wrist-worn activity monitors on the non-dominant wrist (Actiwatch 2, Philips Respironics, USA). These devices were used to objectively measure total sleep time (TST) obtained both habitually (prior to the study) and throughout the study, and subsequently to assess sleep efficiency (percentage of time spent asleep during sleep opportunity), wake after sleep onset (WASO), and sleep onset latency (SOL).

2.5 | Graded exercise test (GXT)

A baseline assessment of aerobic fitness (i.e. peak oxygen uptake; $\dot{V}O_{2peak}$) and peak power ($_{peak}$) was performed on an electronically braked cycle ergometer (Excalibur, V2.0; Lode, Groningen, the Netherlands). Following a standardised warm-up (5 min at 30 W), the participants cycled against an incremental ramp protocol whereby the resistance continually increased by 1 W every 2 s (30 W/min) until volitional exhaustion. Expired air was continuously analysed for O_2 and CO_2 concentrations via a gas analyser (Moxus, AEI Technologies, Pittsburgh, PA, USA). $\dot{V}O_{2peak}$ was defined as the highest consecutive 30 s average of $\dot{V}O_2$ values and the corresponding $_{Peak}$ value.

2.6 | High-intensity interval exercise (HIIE)

The HIIE protocol consisted of 10 × 60 s intervals performed on a cycle ergometer (Velotron; RacerMate) at 90% of each participant's $_{peak}$. Each interval was interspersed with 75 s of active recovery (at 60 W). Each session started with a 3 min warm-up at 60 W. The mean power per interval was 318 ± 53 W, mean HR throughout the protocol was 156 ± 13 bpm, peak HR was 182 ± 12 bpm, and the average rating of perceived exertion (RPE) per interval was 15 ± 2 A.U.

2.7 | Karolinska sleepiness scale (KSS)

Subjective sleepiness was assessed using the Karolinska sleepiness scale (KSS) (Akerstedt & Gillberg, 1990) at 7:50 a.m. (KSS – AM) and 6:50 p.m. (KSS – PM) each day to assess changes in sleepiness throughout the day. Participants were asked to rate their perceived sleepiness on a scale from 1 (extremely alert) to 9 (extremely sleepy).

2.8 | Psychomotor vigilance task (PVT)

The 3 min PVT test is validated and commonly used to objectively assess the effect of sleep loss on fatigue-related changes to behavioural alertness (Basner et al., 2011; Roach et al., 2006). Participants were familiarised with the PVT device and then completed the PVT three times each day during the study; in the morning (7:55 a.m.), the middle of the day (12:25 p.m.), and the evening (6:55 p.m.). On day 8, the participants completed the PVT in the morning only. The PVT was performed as described previously (Basner et al., 2011) on a handheld PVT-192 device (Ambulatory Monitoring Inc., Ardsley, NY). Data presented for the PVT are the daily mean of each PVT performed (Figure 5).

2.9 | Wellness questionnaire

Changes in daily subjective well-being were assessed at 8 a.m. each day with participants asked to complete a general well-being questionnaire, as reported previously (McLean et al., 2010). This questionnaire was used to assess subjective levels of fatigue, general muscle soreness, sleep quality, stress levels, and mood, using a five-point scale (each rated 1–5, with 0.5 increments). A score of 5 indicates an

optimal subjective rating and a score of 1 indicates the lowest subjective rating for each category.

2.10 | Profile of mood states (POMS) questionnaire

Mood was assessed using a 65-item profile of mood states (POMS) questionnaire (McNair et al., 1971) at 8 a.m. on day 3 and day 8. This questionnaire asked participants questions relating to their feelings (based on the previous 7 days) of anger, confusion, depression, fatigue, tension, and vigour. A score ranging from 1 ("Not at all") to 5 ("Extremely") was given for each question. Total mood disturbance is given a score between −32 and 200, and is calculated from the sum of each of the subcategories determined from the POMS questionnaire; tension (0–36), depression (0–60), fatigue (0–28), anger (0–48), confusion (0–28), and the subtraction of vigour (0–32).

2.11 | Statistical analysis

Statistical analyses were conducted using the statistical software package GraphPad Prism (V9.5.1). All data are presented as mean, standard deviation, effect size (ES), and 95% confidence intervals. The magnitude of effects were assessed using standardised effect sizes (ES) (categorised as ≤0.19 trivial, 0.2–0.49 small, 0.5–0.79 moderate and >0.8 large). All data (actigraphy data, KSS, PVT, POMS, wellness questionnaire) were assessed using a two-way repeated measures ANOVA with one between subjects factor (group) and a within-subjects factor (time). Significant effects of interaction (group × time) are reported. Where significant interaction effects were observed, post-hoc testing (using Tukey's multiple comparison correction testing) was performed to identify significant within group or between group differences. Where appropriate, a Greenhouse–Geisser correction was used to adjust for sphericity. Both within group and between group differences are displayed. Participant characteristic data (Table 1) between groups was assessed via one-way ANOVA. The threshold for statistical significance was set at $p < 0.05$. A.U. stands for arbitrary units.

3 | RESULTS

3.1 | Sleep data

Comparisons of sleep duration, SOL, WASO, and sleep efficiency are displayed in Table 2. There was a significant interaction effect for sleep duration ($F[2, 21] = 316$, $p < 0.001$). There were no differences in sleep duration between the groups during the baseline sleep period. However, total sleep duration was significantly less in the SR group (mean difference ± SD, [95% CI], ES, p value) (220 ± 25 min, [202–237 min], ES = 17.1, $p < 0.001$) and the SR + EX group (214 ± 23 min, [197–232 min], ES = 17.7, $p < 0.001$), compared with the NS group during the intervention period. There was no difference in sleep duration during the intervention between the SR and SR + EX groups ($p = 0.718$). Compared with baseline, those in the SR group (222 min ± 20 min, [203–241 min], ES = 17.0 $p < 0.001$) and the SR + EX group (224 ± 9 min, [205–243 min], ES = 30.1, $p < 0.001$) slept significantly less during the intervention, but there was no difference between the baseline and intervention periods for the NS group ($p > 0.999$). There was a significant interaction effect for SOL ($F[2, 21] = 6.34$, $p = 0.007$), with post-hoc testing revealing a significant reduction in SOL during the intervention for the SR (15 ± 12 min, [2–27 min], ES = 2.1, $p = 0.013$) and SR + EX groups (17 ± 11 min, [4–29 min], ES = 2.5. $p = 0.005$), compared with NS. SOL was significantly reduced during the intervention, compared with baseline in the SR group only (18 ± 18 min, [6–30 min], ES = 3.1, $p = 0.003$). There was also a significant interaction effect for WASO ($F[2, 21] = 12.2$, $p < 0.001$). During the intervention, WASO was significantly less in the SR (26 ± 11 min, [13–39 min], ES = 4.6, $p < 0.001$), and SR + EX (19 ± 9 min, [6–32 min], ES = 3.9, $p = 0.003$) groups, compared with NS. There were no differences between the SR and SR + EX groups in any sleep indices. There was no significant interaction effect for sleep efficiency ($F[2, 21] = 0.40$, $p = 0.674$).

3.2 | Karolinska sleepiness scale (KSS)

The KSS was performed twice daily, during the morning (KSS – AM) and evening (KSS – PM). There was a significant interaction effect for

TABLE 2 Actigraphy sleep analysis for the baseline (average of two nights) and the intervention period (average of five nights) for each group

	NS		SR		SR + EX	
	Baseline	Intervention	Baseline	Intervention	Baseline	Intervention
Time in bed (min)	480	480	480	240	480	240
Sleep duration (min)	448 ± 25	449 ± 22	452 ± 17	230 ± 5[a,b]	459 ± 9	235 ± 5[a,b]
SOL (min)	13 ± 8	17 ± 9	21 ± 8	3 ± 2[a,b]	13 ± 8	1 ± 1[b]
WASO (min)	29 ± 12	34 ± 7	25 ± 12	9 ± 3[a,b]	32 ± 14	10 ± 5[a,b]
Sleep efficiency (%)	93 ± 5	93 ± 5	94 ± 4	96 ± 2	95 ± 2	98 ± 2

Note: Values are mean ± SD.

Abbreviations: NS, normal sleep; SOL, sleep onset latency; SR + EX, sleep restriction and exercise; SR, sleep restriction; WASO, wake after sleep onset.

[a]Denotes significantly different from within group baseline.

[b]Denotes significantly different compared with NS during the intervention period, $p < 0.05$.

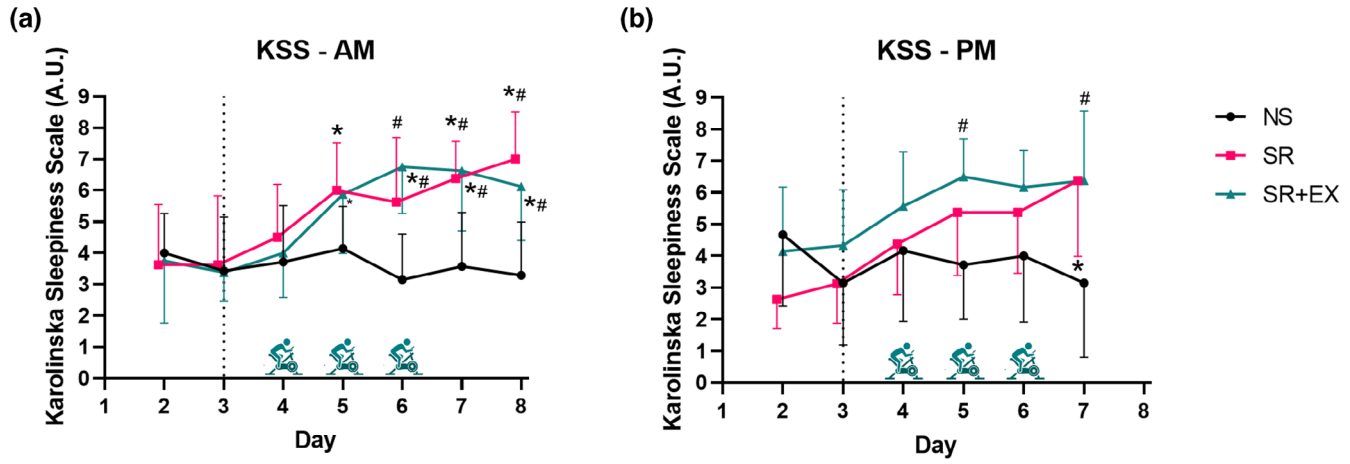

FIGURE 2 Karolinska sleepiness scale (KSS) score. (a) KSS score each morning (KSS – AM) and evening (KSS – PM) throughout the study. Normal sleep (NS), sleep restriction (SR), and sleep restriction and exercise (SR + EX). The dotted line indicates the start of the sleep intervention period and the exercise bike represents days of the study on which high-intensity interval exercise was performed by the SR + EX group. *Denotes significant within-group difference from day 2 or day 3 (baseline). #Denotes significantly different from NS group on the same day, $p < 0.05$.

the KSS – AM ($F[12,119] = 4.09$, $p < 0.001$), with post-hoc analysis indicating that the KSS – AM scores were significantly higher on day 5, day 7, and day 8, compared with baseline ($p < 0.05$) in the SR group (mean difference ± SD, [95% CI], ES, p value, day 2 vs day 8; 3.4 ± 1.2 A.U., [0.7–6.1 A.U.], ES = 1.7, $p = 0.016$) (Figure 2). In the SR + EX group, KSS – AM scores were significantly higher on day 5, day 6, day 7, and day 8, compared with baseline ($p < 0.05$) (day 3 vs day 8; 2.8 ± 1.5 A.U., [0.7–4.8 A.U.], ES = 1.7, $p = 0.012$). The KSS – AM score was higher on day 6, day 7, and day 8 in the SR and SR + EX groups, compared with the NS group ($p < 0.05$) (NS vs SR day 8; 3.7 ± 0.8 A.U., [1.5–5.9 A.U.], ES = 2.3, $p = 0.002$, NS vs SR + EX day 8; 2.8 ± 0.8 A.U., [0.5–5.2 A.U.], ES = 1.6, $p = 0.018$).

There was also a significant interaction effect for the KSS – PM score ($F[10, 92] = 3.40$, $p < 0.001$). In the SR group, there was a significant increase on day 7 compared with baseline (day 2 vs day 7, SR; 3.3 ± 2.4 A.U., [0.2–7.0 A.U.], ES = 1.4, $p = 0.026$). In the SR + EX group, the KSS – PM score was significantly higher on day 5 and day 7, compared with the NS group at the same time point (NS vs SR + EX day 7; 3.2 ± 1.2 A.U., [0.1–6.4 A.U.], ES = 1.4, $p = 0.043$).

3.3 | Daily wellness questionnaire

The daily wellness questionnaire revealed significant interaction effects for fatigue ($F[12, 101] = 4.69$, $p < 0.001$), general muscle soreness ($F[12, 96] = 2.43$, $p = 0.008$), stress levels ($F[12, 102] = 2.90$, $p = 0.002$), and mood ($F[12, 102] = 2.80$, $p = 0.002$), but not sleep quality ($F[12, 101] = 0.517$, $p = 0.899$) (Figure 3). In the SR group, post hoc testing revealed significant increases in fatigue on day 5, day 7, and day 8, compared with baseline (day 2 vs day 8; 2.3 ± 0.5 A.U., [1.4–3.3 A.U.], ES = 6.6, $p < 0.001$). In the SR + EX group, there were significant increases in fatigue on day 5, day 6, day 7, and day 8, compared with baseline (day 3 vs day 8; 1.6 ± 0.9 A.U., [0.0–3.1 A.U.], ES = 1.8, $p = 0.045$). Compared with the NS group, fatigue was increased in the SR group on day 5, day 7, and day 8, and in SR + EX group on day 5, day 6, day 7, and day 8 (NS vs SR day 8; 1.8 ± 0.4 A.U., [0.6–2.9 A.U.], ES = 2.4, $p = 0.006$, and NS vs SR + EX day 8; 1.6 ± 0.3 A.U., [0.3–2.8 A.U.], ES = 1.9, $p = 0.014$). Compared with the NS group, ratings of mood were decreased in the SR group on day 5 and day 8, and also in the SR + EX group on day 5, day 7, and day 8 (NS vs SR day 8; 1.5 ± 0.4 A.U., [0.4–2.6 A.U.], ES = 2.1, $p = 0.013$ and NS vs SR + EX day 8; 1.1 ± 0.4 A.U., [0.2–2.1 A.U.], ES = 1.9, $p = 0.015$). There was also a significant increase in stress in the SR + EX group on day 6, compared with the NS group (NS vs SR + EX day 6; 1.1 ± 0.4 A.U., [0.1–2.2 A.U.], ES = 1.6, $p = 0.038$).

3.4 | Profile of mood states (POMS)

We assessed mood state using the POMS questionnaire, which assesses total mood disturbance (TMD) and six mood variables (tension, anger, fatigue, depression, vigour, and confusion) (Figure 4). There was an interaction effect for TMD ($F[2, 17] = 6.97$, $p = 0.006$), with post-hoc analysis indicating there was a significant within-group difference (mean difference ± SD, [95% CI], ES, p value) from pre- to post-intervention for the SR (26.6 ± 18.9 A.U., [5.4–47.8 A.U.], ES = 1.2, $p = 0.012$) and SR + EX groups (36.1 ± 31.3 A.U., [14.6–57.7 A.U.], ES = 1.7, $p = 0.001$). There was no significant difference in TMD from pre- to post-intervention for the NS group (−6.8 ± 6.8 A.U., [−30.1–16.4 A.U.], ES = 0.5, $p = 0.832$). Compared with the NS group, the post-intervention TMD score was significantly different for both the SR and SR + EX groups (NS post vs SR post; 31.0 ± 10.7 A.U., [4.4–57.7 A.U.], ES = 1.4, $p = 0.020$, NS post vs SR + EX post; 38.6 ± 14.9 A.U., [11.1–66.1 A.U.], ES = 1.7, $p = 0.004$).

There was a significant interaction effect for fatigue ($F[2, 17] = 6.97$, $p = 0.006$), with post-hoc analysis indicating significant

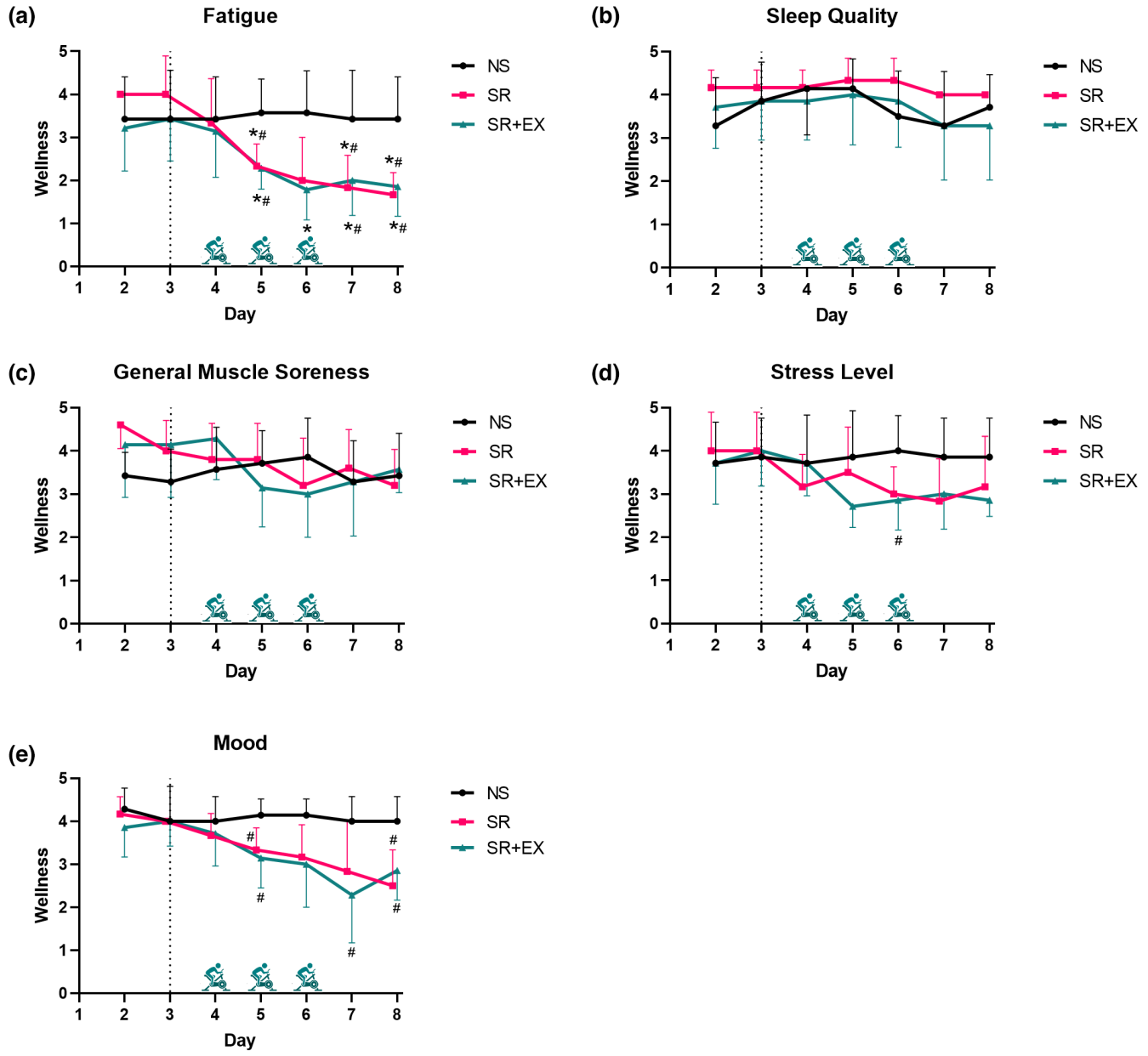

FIGURE 3 Daily wellness questionnaire – perceived wellness for each category was rated on a scale of 1 to 5, with a score of 5 indicating an optimal subjective rating and a score of 1 indicating the lowest subjective rating for each category. (a) Fatigue, (b) Sleep Quality, (c) General Muscle Soreness, (d) Stress Level, (e) Mood. The dotted line indicates the start of the sleep intervention period and the exercise bike represents the days of the study on which high-intensity interval exercise was performed by the SR + EX group. Normal sleep (NS), sleep restriction (SR), and sleep restriction and exercise (SR + EX). *Denotes significant within-group difference from baseline (day 2 or day 3). #Denotes significantly different from NS group at the same time point, $p < 0.05$.

within-group differences for the SR (8.5 ± 7.1 A.U., [2.6–14.3 A.U.], ES = 1.3, $p = 0.004$) and SR + EX groups (10.1 ± 6.7 A.U., [4.2–16.0 A.U.], ES = 1.8, $p < 0.001$). Compared with the NS group, POMS-derived fatigue scores were significantly higher at post-intervention in the SR (8.0 ± 3.5 A.U., [0.4–16.6 A.U.], ES = 1.1, $p = 0.038$) and SR + EX groups (10.7 ± 3.8 A.U., [2.9–18.6 A.U.], ES = 1.7, $p = 0.006$).

There was also an interaction effect for anger ($F[2, 17] = 3.91$, $p = 0.040$), with post-hoc analysis indicating a significant within-group difference from pre- to post-intervention in the SR + EX group (5.7 ± 7.8 A.U., [0.6–10.8 A.U.], ES = 0.7, $p = 0.024$). There was a trend for an interaction effect for the vigour ($F[2, 17] = 3.03$, $p = 0.075$) and confusion ($F[2, 17] = 3.12$, $p = 0.070$) subscale scores, but no interaction effect for the tension ($p = 0.383$) or depression ($p = 0.122$) subscale scores.

3.5 | Psychomotor vigilance test (PVT)

There was a significant interaction effect for mean reaction time ($F[2, 114] = 2.10$, $p = 0.029$). In the SR group, post-hoc analysis

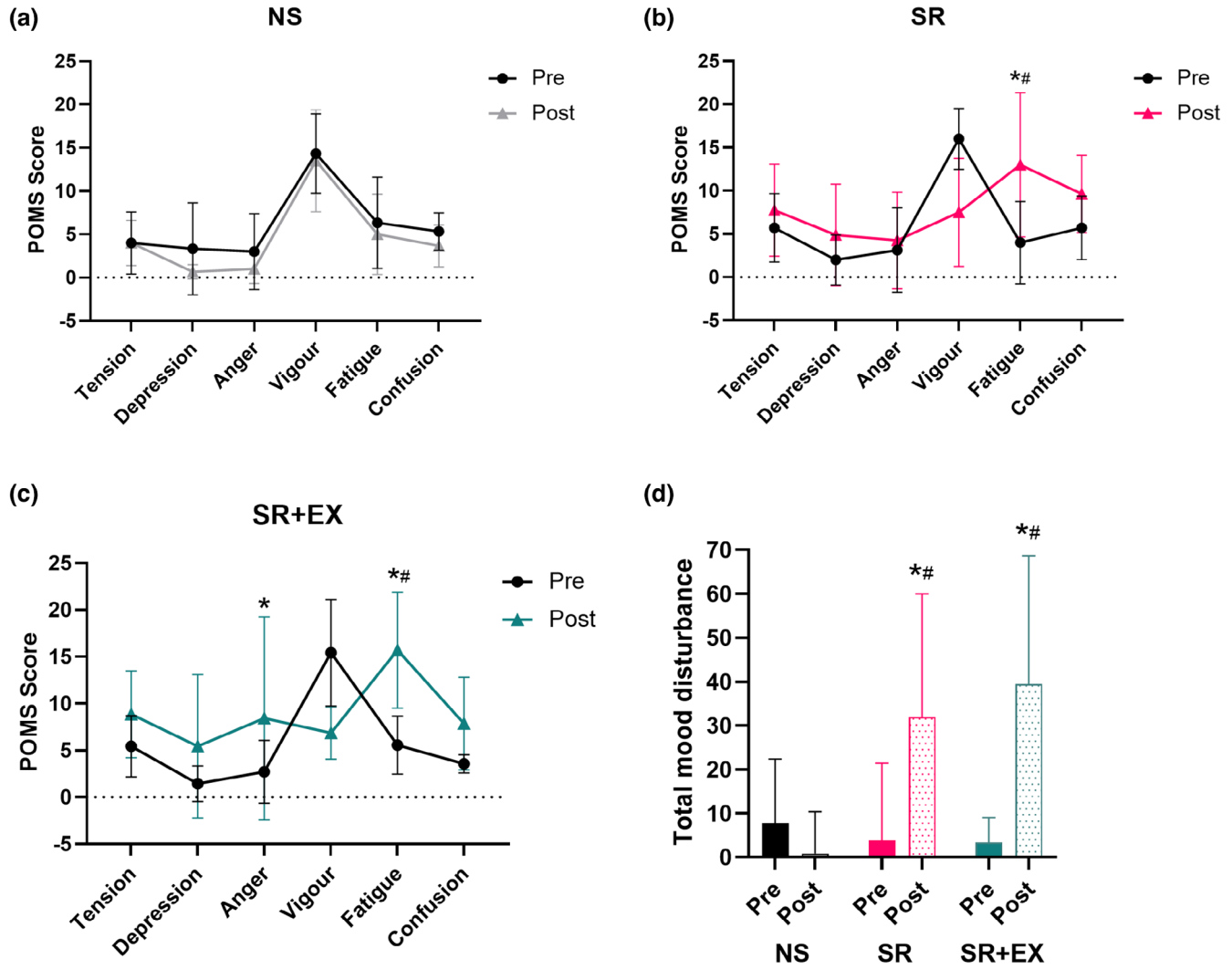

FIGURE 4 Profile of mood states (POMS) questionnaire. Pre- and post-intervention POMS scores presented as iceberg plots for (a) Anger, (b) Confusion, (c) Depression, (d) Fatigue, (e) Tension, (f) Vigour, and (g) Total Mood Disturbance score (bar graph) of each group. Normal sleep (NS), sleep restriction (SR), and sleep restriction and exercise (SR + EX). *Denotes significant within-group difference from pre-intervention. #Denotes significantly different from NS group at same time-point, $p < 0.05$.

indicated there was a significant increase in reaction time on day 5 ($p = 0.045$) and day 7 ($p = 0.049$), compared with baseline (day 3 vs day 7; 16.0 ± 11.3 ms, [0.1–31.9 ms], ES = 0.9, $p = 0.049$). In the SR + EX group, there was a significant increase in reaction time on day 7, compared with baseline (day 3 vs day 7; 30.7 ± 20.1 ms, [2.5–58.9 ms], ES = 1.4, $p = 0.033$). There was also a significant difference between the SR and SR + EX group for mean reaction time on day 7 (SR vs SR + EX; 30.8 ± 14.9 ms, [3.1–58.5 ms], ES = 1.4, $p = 0.029$). There were no significant interaction effects for other assessments (i.e. fastest ($F[12, 120] = 0.95$, $p = 0.500$) or slowest reaction time ($F[12, 120] = 1.84$, $p = 0.121$), reciprocal reaction time ($F[12, 111] = 1.43$, $p = 0.163$, and lapses ($F[12, 108] = 0.60$, $p = 0.834$) of the PVT (Figure 5). Additionally, there was no significant interaction effect ($F[10, 99] = 1.41$, $p > 0.05$) for the reaction time of PVT performed at 12:25 p.m., which was in closest proximity to completion of the HIIE sessions.

4 | DISCUSSION

We report that five nights of sleep restriction (4 h TIB, each night) results in decreases in mood state and alertness, and increases feelings of fatigue. Contrary to our initial hypothesis, performing three sessions of HIIE during this period of sleep restriction did not prevent these detrimental effects. These results suggest that while HIIE may be a viable therapeutic intervention to mitigate the detrimental physiological effects associated with sleep loss, there is a limited benefit of HIIE for maintaining mood and alertness in this context.

The KSS questionnaire and the daily wellness questionnaire revealed significant increases in sleepiness and fatigue, and decreases in mood in the SR group, after only two nights of sleep restriction (i.e. day 5); these effects persisted throughout the remaining intervention. Analysis of the POMS questionnaire also demonstrated increases in the fatigue subscale score and total mood disturbance (a global

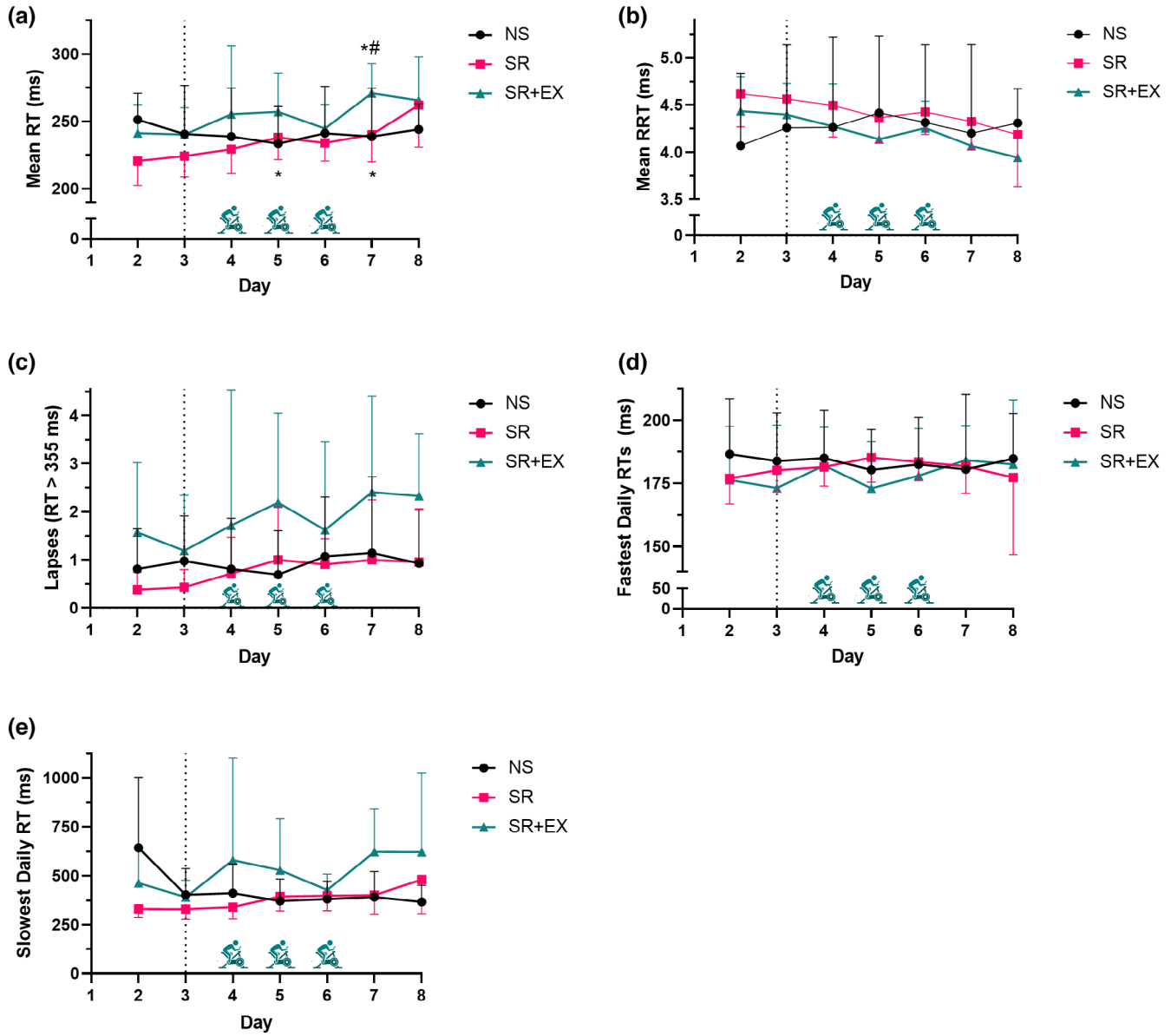

FIGURE 5 Daily psychomotor vigilance test (PVT) responses. (a) Mean reaction time (RT), (b) Mean reciprocal reaction time (RRT), (c) Mean number of lapses (RT > 355 ms), (d) Fastest RTs, and (e) Slowest RTs. Values are mean ± SD. *Denotes significantly different compared with baseline. #Denotes significantly different compared with SR time point, $p < 0.05$.

representation of mood scores). These findings are supported by previous studies that have reported increases in sleepiness, total mood disturbance, and fatigue following similar sleep restriction protocols and sleep deprivation protocols (Banks et al., 2010; Dinges et al., 1997; Larsen et al., 2020). Indeed, following five nights of sleep restriction (4 h TIB each night) Banks et al. (2010) reported that POMS fatigue and KSS scores were increased significantly (Banks et al., 2010). Collectively, these results indicate that our sleep restriction intervention had similar effects on mood state and wellness as previously published research.

We assessed behavioural alertness and reaction times (metrics of cognitive function) using the PVT. Increases in mean reaction time from baseline values were apparent in the SR group on day 5 and day 7 of the study, suggesting that alertness was reduced by the intervention; however, no significant differences in other PVT metrics were observed. These findings are supported by previous studies that indicate a period of sleep restriction reduces PVT-assessed reaction time and alertness (Dinges et al., 1997; Dorrian et al., 2005). Indeed, Basner et al. (2011) reported increases in mean reaction time, reciprocal reaction time, and number of lapses following five nights of sleep restriction (4 h TIB) (Basner et al., 2011). The PVT duration may be an important factor when interpreting and comparing these results (Roach et al., 2006). Our study implemented a 3 min PVT protocol, whereas a 5 or 10 min PVT has been utilised elsewhere (Dinges & Powell, 1985; Lamond et al., 2003). The shorter duration of the PVT (while strongly correlated with 10 min PVTs) may impede the ability

to highlight smaller differences (given the high inter-subject variability) (Goel et al., 2009; Roach et al., 2006; Van Dongen et al., 2004). The changes in reaction time with the sleep restriction interventions in the present study were of a smaller magnitude than reported in Basner et al., 2011 (Basner et al., 2011). These discrepancies may be explained by the number and timing of PVT assessments conducted, which were more frequent and performed later in to the evening compared with the current study, and which may accentuate the impact of the intervention (Zhou et al., 2011). Nonetheless, the impaired reaction time in the SR group suggests the intervention caused reductions in behavioural alertness.

High-intensity interval exercise has been reported to be an enjoyable method for improving mood state and wellness (Reed & Ones, 2006). However, in the present study, the SR + EX group reported increases in sleepiness, and decreases in mood state, similar to those observed in the SR group. In contrast, a prior study reported exacerbated feelings of fatigue when performing exercise (20 min of cycling, every 2 h, at 50% $\dot{V}O_{2max}$) throughout a 30 h period of sleep deprivation, compared with sleep deprivation alone (Scott et al., 2006). However, Larsen et al. (2020) reported that ratings of fatigue were improved, as was the POMS rating of total mood disturbance, following a 20 min session of high-intensity exercise (mean RPE = 15) performed after three nights of sleep restriction (223 ± 27 min TST per night) (Larsen et al., 2020). The direct comparison of these results with the present study is limited due to differences in the length and duration of the sleep interventions employed, plus the timing, intensity, and duration of the exercise protocols, and when the questionnaires were completed. Indeed, in the current study POMS questionnaires were completed 48 h post the completion of the final HIIE session. As such, the acute beneficial effects of exercise on mood state, which have been reported to persist for up to 24 h, may not have been detected in these assessments (Basso & Suzuki, 2017; Maroulakis & Zervas, 1993). Therefore, while exercise is known to improve negative mood states under normal sleep conditions (Reed & Ones, 2006), further research is needed to evaluate its effectiveness under conditions of sleep loss.

In the SR + EX group, there was an increase in PVT mean reaction time compared with baseline on day 7 of the study, and a greater mean reaction time in the SR + EX group compared with the SR group on day 7. This is consistent with the findings from Scott et al. (2006), who reported that mean reaction time (assessed via two-choice reaction testing) was greater in participants who performed intermittent exercise throughout a 30 h period of sleep deprivation, compared with those that did sleep deprivation alone (Scott et al., 2006). In contrast, an earlier study reported that mean reaction time and vigilance, as assessed by a range of work-specific tasks, was equivalent in participants undergoing 40 h of sleep deprivation, with or without 10 min of treadmill exercise (at 70% $\dot{V}O_{2peak}$) every 2 h throughout the intervention (LeDuc et al., 2000). These results can possibly be attributed to the close proximity of the testing to the exercise (i.e. immediately following the session), as exercise has been suggested to improve cognitive function and alertness under regular sleep conditions for up to 2 h (Basso et al., 2015; Joyce et al., 2009). Interestingly, there were no differences in reaction time between groups for the PVT performed 2 h following the completion of the HIIE sessions in the current study. Overall, our findings suggest that performing three sessions of HIIE does not prevent, and may even exacerbate, impairments in reaction time that are induced during a period of sleep restriction. The addition of a normal sleep and exercise group would assist in understanding the potential of exercise to improve alertness in this context.

Further research is warranted to determine if there are circumstances in which exercise may be used within a sleep loss setting to improve mood and cognitive function. Different exercise modalities, such as resistance exercise or moderate-intensity endurance exercise, may provide a more beneficial stimulus under conditions of sleep loss, given the diverse range of physiological and psychological changes induced by each different exercise modality and intensity (Basso & Suzuki, 2017; Chang et al., 2012; Sauvet et al., 2020). The appropriate choice of when to exercise under sleep-restricted conditions is another important consideration, given the potential time-of-day specific effects of exercise (Grgic et al., 2019; Saner & Lee, 2020) and considering that the influence of sleep restriction on mood and alertness, likely increases throughout the day. In this regard, a recent study demonstrated that individual chronotype was an important consideration for interpreting the effect of exercise timing on psychological state and sleep quality (Saidi et al., 2023). Although participants in the current study were classified as either moderate or intermediate chronotypes, this should be another consideration in future research. Furthermore, whether exercise has beneficial effects on mood and alertness when performed during moderate levels of sleep restriction (e.g. 6 h TIB), or in a cohort that habitually experiences disturbed sleep, remains to be determined.

The current study was conducted on a relatively small sample of healthy, young males, and is a secondary outcome from a larger study. As such, further studies are needed to build upon these findings and to elucidate the full effect of exercise on alertness, fatigue, and mood in the context of sleep loss. Indeed, such studies may be particularly relevant in populations that commonly experience sleep loss, such as shift-workers, new parents, military personnel, and athletes (Gay et al., 2004; Philibert, 2005). The addition of a normal sleep and exercise group (e.g. NS + EX) would also have provided further insights into the effect of exercise on mood and cognitive function, and the generalisability of future studies would be improved with the inclusion of female participants. The data for this study were collected over an 18 month period; therefore, there may have been a seasonal influence of results, particularly related to mood outcomes.

To conclude, our data indicate that performing three sessions of HIIE did not prevent the alterations in mood state, wellness, or alertness that are induced by a period of sleep restriction (4 h TIB for five nights). While exercise may offer potential health benefits for a range of sleep-loss-induced detrimental physiological effects, our data suggest that HIIE does not improve alertness and mood state in this context. Further research is warranted to explore how other exercise interventions may affect the cognitive and mood state variables tested herein.

AUTHOR CONTRIBUTIONS

NS, DB, and JB were involved in the conception and design of the work. NS, ML, NP, JB, GR, DB, JB were involved in the acquisition, analysis, or interpretation of the data. All authors were involved in drafting and the approval of the final manuscript. All persons designated as authors qualify for authorship, and all those who qualify for authorship are listed.

ACKNOWLEDGEMENTS

We would like to thank all participants for their involvement in the study. Open access publishing facilitated by Victoria University, as part of the Wiley - Victoria University agreement via the Council of Australian University Librarians.

FUNDING INFORMATION

This publication was supported in part by a Sports Medicine Australia (SMA) Research Foundation Grant to NS, and a National Health and Medical Research Council (NHMRC) grant to DB (GNT2013427).

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Saner, N. J., Lee, M.-C., Pitchford, N. W., Broatch, J. R., Roach, G. D., Bishop, D. J., & Bartlett, J. D. (2023). The effect of sleep restriction, with or without high-intensity interval exercise, on behavioural alertness and mood state in young healthy males. *Journal of Sleep Research*, e13987. https://doi.org/10.1111/jsr.13987