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The effects of sleep deprivation, acute hypoxia, and exercise on cognitive performance: A multi-experiment combined stressors study

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ABSTRACT

Introduction: Both sleep deprivation and hypoxia have been shown to impair executive function. Conversely, moderate intensity exercise is known to improve executive function. In a multi-experiment study, we tested the hypotheses that moderate intensity exercise would ameliorate any decline in executive function after i) three consecutive nights of partial sleep deprivation (PSD) (Experiment 1) and ii) the isolated and combined effects of a single night of total sleep deprivation (TSD) and acute hypoxia (Experiment 2).

Methods: Using a rigorous randomised controlled crossover design, 12 healthy participants volunteered in each experiment (24 total, 5 females). In both experiments seven executive function tasks (2-choice reaction time, logical relations, manikin, mathematical processing, 1-back, 2-back, 3-back) were completed at rest and during 20 min semi-recumbent, moderate intensity cycling. Tasks were completed in the following conditions: before and after three consecutive nights of PSD and habitual sleep (Experiment 1) and in normoxia and acute hypoxia ($F_IO_2 = 0.12$) following one night of habitual sleep and one night of TSD (Experiment 2).

Results: Although the effects of three nights of PSD on executive functions were inconsistent, one night of TSD (regardless of hypoxic status) reduced executive functions. Significantly, regardless of sleep or hypoxic status, executive functions are improved during an acute bout of moderate intensity exercise.

Conclusion: These novel data indicate that moderate intensity exercise improves executive function performance after both PSD and TSD, regardless of hypoxic status. The key determinants and/or mechanism(s) responsible for this improvement still need to be elucidated. Future work should seek to identify these mechanisms and translate these significant findings into occupational and skilled performance settings.

1. Introduction

Sleep plays a key role in the regulation of physiology, metabolism, and brain function [1]. In order to sustain optimal health, it is recommended that adults achieve between 7 and 9 h of sleep per night [1,2]. However, recent reviews have highlighted that ~40 % of the global population may experience insufficient sleep [3,4]. Sleep deprivation can range from partial sleep deprivation (PSD), which reflects less than the recommended 7 h of sleep, to total sleep deprivation (TSD) where an individual remains awake all night. Chronic sleep deprivation can result

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in a number of negative health outcomes including increased risk of cardiovascular disease [5], obesity [6], neurodegenerative disorders [7], and depression [8]. In the short-term, sleep deprivation can also result in more immediate symptoms, perhaps the most serious of which is a reduction in cognitive performance, including poor attention span, impaired judgement, reduced emotional capacity, and a reduction in cognitive flexibility [9-13].

Sleep deprivation is often experienced in combination with other stressors. For example, individuals who visit terrestrial high altitude are also likely to experience a disruption to their sleep [14,15]; Kupper et al., [16]; [17]. In addition to sleep deprivation, the reduction in oxygen availability and the resultant biological processes that occur during acute altitude exposure can also result in decrements in cognitive performance [18–22]. Interestingly, some investigations that have examined both sleep and cognitive performance in a hypoxic environment have reported that, when exposed to a hypoxic environment, greater reductions in cognitive performance are observed in those individuals who also have poor markers of sleep [23–26].

The exact neurobiological mechanisms by which both sleep deprivation and hypoxia effect cognitive performance are yet to be elucidated [9,27], although both stressors appear to cause suboptimal functioning of the Prefrontal Cortex (PFC) [20,28]. The PFC is considered to be the primary region of the brain associated with executive functions (e.g. inhibition, working memory, cognitive flexibility) [29]; Langer & Eickhoff, [30]; [31]. The PFC is highly sensitive to its neurochemical environment and is highly susceptible to stress [32–34], it is therefore plausible that a similar underlying neurobiological mechanism contributes to both sleep deprivation and hypoxic induced decrements in cognitive performance. However, our understanding of this potential mechanism is limited by an absence of rigorous, well-designed and controlled empirical combined stressor studies [35,36].

In contrast to the detrimental effects of sleep deprivation and hypoxia on aspects of cognition, there is a wealth of research to suggest that an acute bout of moderate-intensity exercise may improve cognitive performance in both normoxia [37,38]; Etnier et al., [39]; [40–43] and hypoxia [44,45]. Specifically, moderate intensity exercise, defined as 40–79 % of maximal oxygen uptake [46], lasting a minimum of 20 min, but no longer than 2 h, appears to have a positive influence on cognitive performance in normoxia [38] and hypoxia when the duration and the severity of hypoxia is minimal-to-moderate [44]. Our understanding of the mechanism(s) by which exercise may improve cognitive performance is also limited, often clouded by the large disparity in methodologies (e.g. intensity, duration, mode of exercise); however, some of the suggested theories include the catecholamine hypothesis [20], the arousal / "inverted u" theory [47,48], and the interoceptive model [49]. Despite the wide range of testing parameters and outcome measures employed in this literature, one of the most consistent effects of acute moderate-intensity exercise appears to be an improvement in tasks that require executive function and are believed to require the PFC [50]. However, to date it is unclear if moderate intensity exercise is an effective intervention to improve executive functions performance after PSD or TSD (in either a normoxic or hypoxic state).

Given the potential for impaired cognitive performance following insufficient sleep and / or exposure to hypoxic environments (e.g. terrestrial high altitude) in various sporting, recreational, occupational, and clinical settings, research examining the potential benefits of an acute bout of exercise following these stressors is required. Accordingly, for the first time, using a rigorous multi experimental design we tested the following hypotheses, Experiment 1 (PSD): (1a) Three consecutive nights of PSD would reduce executive function at rest; and (1b) regardless of sleep status an acute bout of moderate intensity exercise would improve executive function; Experiment 2 (TSD): (2a) one night of TSD and an acute bout of hypoxia, experienced in isolation and in combination, would reduce executive function at rest; and (2b) regardless of sleep or hypoxic status, an acute bout of moderate intensity exercise would improve executive function relative to rest in the same conditions.

2. General methods

2.1. Participants

A convenience sample of 24 healthy participants took part in this study (Experiment 1 PSD: $n = 12$ (5 females), mean [SD], age: 23 [2] years; height: 170.8 [11] cm; mass: 66 [10] kg; VO_{2max}: 42 [7] $mL{\cdot}min{\cdot}kg^{-1}$; Experiment 2 TSD: $n = 12$ males, mean [SD], age: 26 [4] years; height: 185 [7] cm; mass: 84 [12] kg; VO_{2max}: 46 [9] $mL{\cdot}min{\cdot}kg^{-1}$). All experimental procedures adhered to the standards set by the latest revision of the Declaration of Helsinki, except for registration in a database, and were approved by the Science and Health Faculty Ethics Committee of The University of Portsmouth (project number SHFEC 2021–031 & SHFEC 2018–068 respectively).

Following familiarisation with the laboratory and testing procedures, participants provided written informed consent at least 24 h before the start of the study. Participants were also required to complete the Pittsburgh sleep quality index questionnaire to assess for sleep quality and behaviours [51]. Participants who slept <6 h per day, on average, as well as those with an acute or chronic sleep disorder or worked night shifts were excluded. Participants were non-smokers and were free of any known cardiovascular, respiratory, or neurological disorders. All participants resided at <500 m and had not spent time at altitude for at least three months prior to commencement of the study. All participants were right-handed (not by design) and had a minimum of 1-year university education.

3. Experiment 1 (PSD)

3.1. Methods

3.1.1. Study design and experimental procedures

This experiment employed a within participant, repeated measures, randomised controlled crossover design. Participants were required to visit the laboratory on 5 separate days (Fig. 1). Visit 1 involved a medical screening to assess for any contraindications to taking part, familiarisation with the executive function tasks (described later) and a VO_{2max} test. The health screening consisted of a health history questionnaire, 12-lead electrocardiogram, and assessment of lung function (FEV1/FVC) with all results screened by an independent medical officer. The experimental trials (Visits 2–5) were conducted in two blocks of testing. Same block testing days were separated by 72 h during which the participants either underwent 3 nights of PSD or habitual sleep. There was a minimum of 7 days between the two testing blocks.

Participants were required to record dietary intake, exercise, and sleep in an electronic diary, and to wear an activity monitor for the 96 h prior to the first experimental trial [52]. Participants wore a wrist actigraph (wGT3X-BT, ActiGraph, LLC, Pensacola, FL) on their nondominant arm to record objective sleep parameters (total sleep time (TST), wake activity after sleep onset (WASO), and sleep efficiency) as previously described [53]. The wGT3X-BT device has been recommended for its use in non-clinical population sleep studies [54] and the GT3X version of this device has been found to have similar TST recordings when compared to polysomnography (ICC = 0.64–0.88) [55]. Diaries and activity tracking were continued until the second experimental trial and resumed 96 h before the third experimental trial in order to replicate diet, exercise, and sleep across the study. Participants were instructed to refrain from non-habitual exercise activity, alcohol and caffeine consumption for 12 h before the experimental trials and this was confirmed by the participant before undertaking any testing. During the days between laboratory visits (including the PSD days) participants were instructed to avoid strenuous and non-habitual exercise activity, and avoid alcohol consumption.

Participants arrived at the laboratory at ~0800 and were provided with 500 mL of water. Once instrumented, participants remained seated on a recumbent cycle (custom built) for 15 min whilst baseline

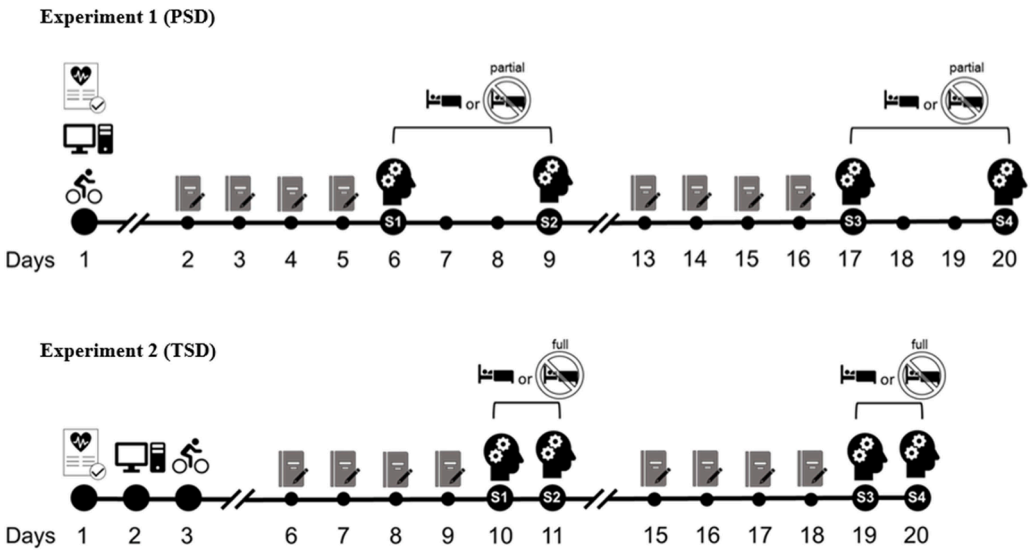

Fig. 1. Schematic of study timeline for experiment 1 and experiment 2. Medical screening, Familiarisation with cognitive tasks, Maximal exercise test, Sleep, exercise, food and fluid diary, Experimental trial, Full night of sleep, Full night of sleep deprivation, three nights of partial sleep deprivation, S1–4: experimentation sessions 1–4.

physiological data was collected. The participants then completed the executive function tasks (described later) at rest. A capillary and venous blood sample was then taken. The participant then started cycling. After 20 min of cycling, the participant then began to simultaneously complete the executive function tasks. Upon completion of the tasks, the participant stopped cycling and a capillary and venous blood sample was taken.

3.1.2. Sleep intervention (PSD)

Between testing days, participants either underwent a PSD protocol, in which they had a sleep opportunity window of only 5 h (0200–0700) for three consecutive nights, similar to previous PSD research [56]. In the control arm, participants had three consecutive nights of habitual sleep (> 7 h of sleep). Participants slept at their own houses and contacted members of the research team every hour until their designated bedtime [52]. The order of PSD or full nights of sleep was counterbalanced.

3.1.3. Exercise

Participants cycled at a wattage equivalent to the power achieved at ~50 % of their VO_{2max} to achieve a moderate intensity in line with the ACSM's Guidelines for Exercise Testing and Prescription [57].

3.2. Measures

3.2.1. Executive function

For each experimental session, executive function was assessed using a series of computerised tasks administered via the Automated Neurophysiological Assessments Metrics (ANAM) system (Cognitive Science Research Center, University of Oklahoma, OK) and delivered using a laptop computer (Acer, TravelMate P, Taiwan). The ANAM software has previously been shown to have good construct validity [58], excellent test re-test reliability [59], and has previously been used to asses cognitive performance in a variety of extreme environments, [60] including hypoxia [61–63], sleep disturbance [64]; [65], and exercise [66,67]. The individual tasks were selected from the ANAM library as they were deemed to require executive function and optimal functioning of the PFC. Further information about the tasks is displayed in Table 1.

To reduce the occurrence of a learning effect, 5 familiarisation trials were completed in accordance with the manufacturer's guidelines. For each of the tasks, mean reaction time for correct responses, accuracy, and throughput were recorded as previously described [68]. The key outcome measure for each of the cognitive tasks was throughput. Throughput is considered a measure of effectiveness of cognitive efficiency and is reported as the number of correct responses per minute of available response time (higher values indicate better performance) [69]. Prior to each testing session participants were provided with written instructions and completed a practice of the testing battery. Participants were requested to respond as accurately and as quickly as possible.

3.2.2. Cerebral oxygenation

The tissue saturation index (TSI) and changes in the concentrations of total haemoglobin (Δ tHb), oxygenated haemoglobin (Δ O_2Hb), and deoxygenated haemoglobin (Δ HHb), were recorded using near infrared spectroscopy (NIRS) (Portalite, Artinis Medical, Elst, The Netherlands) as previously described by our group [18].

3.2.3. Cardiorespiratory variables and blood collection

Minute ventilation (V_E), breathing frequency (f_R), and tidal volume (V_T) were measured using an online gas analysis system (Quark CPET, Cosmed, Italy) and an oro-nasal facemask (7400 series Vmask, Hans Rudolph, USA) containing a turbine flowmeter (ID28, Cosmed, Italy) and heart rate (HR) was measured using a chest strap and monitor (Polar V800, Polar, UK).

Venous blood samples were taken from the antecubital vein at rest and after exercise following the completion of the cognitive battery. Samples were collected into EDTA vacutainers, centrifuged at 4500 g for 10 min at 4 °C. Plasma was aliquoted (1.5 mL in duplicate) and stored at −80 °C for later analysis. Commercially available human enzyme linked immunosorbent assays (ELISA) were used to measure plasma concentrations of cortisol (Calbiotech, Spring Valley, CA, USA). Manufacturer procedures manuals were followed, and repetition plasma freeze-thaw cycles was minimised. Intra-assay coefficient of variation was 6.7 % and the minimum detectable plasma concentration was 20 $ng{\cdot}mL^{-1}$. In addition, to assess blood lactate concentration capillary blood samples

Table 1
Executive function tasks including a brief description of the task.

Task	Brief description	Cognitive domain
Choice reaction time	Multiple trials in which either a * or a 0 appeared on the screen in random order. The participant was required to press a mouse key that corresponded to the symbol appearing on screen.	Inhibition
Logical relations	A pair of symbols was presented "#&" or "&#", together with a statement that describes the order of the symbols. Participants had to press the mouse key that corresponded for the correctness of the statement.	Logical reasoning
Mathematical Processing	The task presents an addition or a subtraction which resulted in a number from 1 to 9, except for 5. The participant had to press the mouse key that corresponded to a result being lower than 5 or higher than 5.	Problem solving
Manikin	A human figure was presented holding a ball in one hand, the figure appeared in various orientations and the participant had to press the mouse key that corresponded to the hand holding the ball.	Spatial orientation
1,2,3-back	A series of numbers were presented on the screen and the participant had to press a mouse key to indicate that the number presented was the same one as the previous number. It had 3 levels of difficulty: 1-back (as described before), 2-back (if the number presented was the same as the one that appeared in two numbers previous), and 3-back (if the number presented was the same as the one that appeared three numbers previous).	Working memory

were taken from the participants' finger and analysed using a Biosen (Biosen C_line, EKF-diagnostic GmbH, Germany).

3.2.4. Subjective outcomes

Sleepiness and mood questionnaires were incorporated into the ANAM and were administered prior to the assessment of executive function. Sleepiness was assessed using the Stanford Sleepiness Scale [70] for which participants were requested to rate their level of sleepiness on a scale from 1 (alert) to 8 (asleep). The scale has been frequently used for both clinical and research purposes and has been shown to be a valid and reliable tool for the subjective measurement of sleepiness [71]. Mood was recorded through the ANAM Mood Scale II. Participants rated their agreement on a Likert scale (0–6, from 'not at all' to 'very much') for seven mood states: anger, anxiety, depression, fatigue, happiness, restlessness, and vigour and all components were clearly explained to participants before the experiment. This scale has been previously assessed for its reliability and validity, showing a strong correlation with the other widely used mood scales, such as the Profile of Mood States [72,73].

3.3. Statistical analyses

All statistical analyses were performed using SPSS Statistics, version 26.0 (IBM Corp., Armonk, NY, USA). The distribution of data was assessed using descriptive methods (skewness, outliers, and distribution plots) and inferential statistics (Shapiro–Wilk test). Data are presented as mean (SD) unless otherwise stated and statistical significance was accepted at $p < 0.05$.

Objective sleep parameters were averaged for the 3 nights preceding the experimental session. Paired sample T-tests were used to assess the sleep differences in: TST, time in bed, WASO, and sleep efficiency between conditions (Control vs PSD). A one-way repeated measure analysis of variance (ANOVA) was used to assess whether there were any statistically significant differences between exercise intensity and task performance (throughput) at rest over the three experimental sessions performed without PSD. There were no differences (all $p > 0.05$) detected between these sessions. Therefore, the experimental session following the three nights of full sleep (Control) and the session following the PSD protocol were utilised for data analysis.

A two-way (Sleep status [habitual sleep, PSD] x Exercise [Rest, Exercise]) repeated measures ANOVA was used to assess main and interaction effects for throughput, cerebral oxygenation (TSI %, O_2Hb, HHb, tHb), cardiorespiratory variables (HR, V_E), blood lactate concentration, cortisol concentration, sleepiness, and mood. When interactions were detected, a post-hoc analysis using Bonferroni corrections was employed. For all physiological variables data were averaged for the time period in which the participant was completing the executive function tasks.

4. Results

4.1. Sleep intervention (PSD)

By design and as expected, participants in the PSD spent less time in bed than during habitual sleep (Table 2). Similarly, PSD also resulted in individuals sleeping less compared to habitual sleep. Self-reported sleep confirmed these findings in a subsample of 5 participants (the other 7-participants had missing data).

4.2. Exercise

All participants exercised at a moderate intensity equivalent to 45.6 ± 3.0 % and 46.1 ± 3.6 % of their VO_{2max} in the CON and in the PSD conditions respectively ($p = 0.701$). Similarly, exercising V_E (36.8 ± 6.4 vs 37.2 ± 6 L·min^{-1}, $p = 0.643$) and blood lactate (1.5 ± 0.8, vs 1.8 ± 1.1 mmol·L^{-1}, $p = 0.109$) did not differ between conditions. RPE was 12 ± 1 and 12 ± 2 for the CON and the PSD conditions respectively.

4.3. Executive functions

Individual throughput values and the associated statistics are displayed in Fig. 2. Mean values and the associated statistics can also be found in the Table 1 of the supplementary materials. After 3 nights of PSD, a significant main effect for sleep status was observed for the choice reaction time task, indicating that throughput values were lower overall after PSD. In contrast, a significant main effect for sleep status was also observed for the logical relations and the manikin task; however, throughput was higher after PSD. A significant main effect for exercise was observed for all tasks, with the exception of the 2-back task, indicating an improvement in performance during exercise compared to rest

Table 2
Sleep variables in the control and partial sleep deprivation conditions. Data presented as means (SD) and analysed by Paired sample T-test. [1]Objective measurements obtained via actigraphy ($n = 12$, 5 females). [2]Self reported data ($n = 5$, 2 females). WASO, wake activity after sleep onset.

Variables	Control	PSD	Difference	p value
Actigraph[1]				
Time in bed (hh:mm)	07:46 (00:35)	04:54 (00:10)	02:52 (00:37)	**< 0.001**
Total sleep time (hh:mm)	06:30 (00:45)	04:27 (00:13)	02:03 (00:39)	**< 0.001**
WASO (min)	69.93 (28.27)	26.69 (15.72)	42.23 (18.19)	**< 0.001**
Sleep Efficiency (%)	84 (7)	90 (5)	6 (5)	**< 0.001**
Self report[2]				
Time in bed (hh:mm)	08:19 (00:45)	05:02(00:05)	03:16 (00:46)	**< 0.001**
Awakenings (min)	10 (12)	4 (9)	5.5 (14.4)	0.218
Sleepiness (score)	2.8 (1.2)	3.6 (0.5)	0.8 (1.01)	0.065

in all sleep conditions. No other main or interaction effects were observed.

4.4. Cardiorespiratory variables, cerebral oxygenation, and cortisol

Physiological, cerebral oxygenation, and cortisol data are displayed in Table 3. A main effect for sleep status was observed for HR ($F_{(1,11)} = 13.19$, $p = 0.004$), with HR higher after PSD. As expected there was also a main effect for exercise ($F_{(1,11)} = 208.55$, $p < 0.001$), with HR higher during exercise compared to rest. No main effects or interactions were observed for TSI; however, a main effect for exercise was observed in O_2Hb ($F_{(1,9)} = 154.74$, $p < 0.001$), HHb ($F_{(1,9} = 6.91$, $p = 0.027$), and tHb ($F_{(1,9)} = 132.79$, $p < 0.001$). No interaction effects were observed for any of the cardiorespiratory or cerebral oxygenation variables. A significant main effect was observed for exercise with mean cortisol concentrations decreasing from resting to exercise in both control and PSD conditions ($F_{(1,11)} = 9.33$, $p = 0.011$). There was no main effect for sleep status nor a significant interaction between sleep status and exercise.

4.5. Subjective variables

There was a significant main effect for sleep status and exercise for fatigue ($F_{(1,11)}$ 7.324, $p = 0.020$, $F_{(1,11)} = 6.301$, $p = 0.029$, respectively) and vigour ($F_{(1,11)} = 8.842$, $p = 0.013$, $F_{(1,11)} = 17.489$, $p = 0.002$, respectively). There were no other significant effects observed in mood. A significant interaction ($F_{(1,11)} = 5.5$, $p = 0.039$) was observed in the sleepiness scale scores. Post-hoc analysis (Wilcoxon signed-rank test) evidenced that sleepiness scores at rest were increased by PSD ($z = 3.176$, $p = 0.001$). However, exercise restored sleepiness scores to control levels ($p > 0.05$).

4.6. Brief summary of experiment 1 (PSD)

The findings of Experiment 1 (PSD) suggest that executive function, when measured at rest, was not impaired after three nights of PSD with the exception of the choice reaction time task. However, regardless of sleep status, moderate intensity exercise improved performance relative to rest for six of the seven tasks. TSD represents a far more severe dose of sleep deprivation. Therefore, in the second experiment we investigated whether exercise would have the same beneficial effects on executive function after the isolated and combined effects of a single night of TSD (with and without an acute bout of hypoxia).

5. Experiment 2 (TSD)

5.1. Methods

5.1.1. Study design and experimental procedures

This experiment employed a within participant, repeated measures controlled crossover design in which participants were required to visit the laboratory on 6 occasions (Fig. 1). For Visit 1 the participant undertook a medical screening as described above and a finger prick blood sample. The blood sample was assessed for haemoglobin irregularity (HemoCue® Hb 201^+ system, HemoCue AB, Ängelholm, Sweden). If haemoglobin did not fall between 13.8 and 17.2 g $dL,^{-1}$ a venous blood sample was collected and sent for a full blood count with sickle cell and thalassemia screening. Visit 2 included a VO_{2max} test and familiarisation with the executive function tasks as previously described. Visits 3–6 were the experimental sessions. The four experimental session were completed in two blocks of testing, with each block consisting of two consecutive days of testing. During one of the blocks of testing the participants undertook a habitual night of sleep between testing days. For the other block of testing the participant undertook one night of TSD. During each day of testing the particpants completed the tests of executive function at rest and during exercise, in both normoxia (F_IO_2: 0.21) and hypoxia (F_IO_2: 0.12). There was a minimum of 7 days between each block of testing. The order of hypoxia and normoxia and sleep deprivation or a full night of sleep was determined using a counterbalanced design. Participants were blinded as to whether they were in the normoxic or hypoxic condition.

For the 96 h preceding the first experimental trial, participants were required to keep a diary documenting their food and fluid intake, exercise, and sleep behaviour (sleep time, wake time, and subjective sleep quality). During this period participants were instructed to refrain from the consumption of alcohol or caffeine and avoid strenuous exercise for 24 h before the trial and this was verified as previously described. Prior to each visit thereafter, participants were instructed to replicate, as closely as possible, their food and fluid intake, exercise, and sleep behaviour for the four days preceding their next bout of testing.

For each experimental trial the participant arrived at the laboratory at ~0800 where they ate a standardised breakfast and were provided with 500 mL of water. The participant was then instrumented and seated on the cycle ergometer as described above. The participant rested for 15 min before providing a baseline blood sample. A portable altitude generator (Cloud 9, Sporting Edge, Basingstoke, UK) was then switched on and the participant began breathing either normoxic or hypoxic gas depending upon condition. For the normoxic condition the respiratory tubing was not connected to the generator; however, the machine was still turned on so that the same noise was present in both conditions. To allow for physiological data to stabilise and plateau, participants rested for 30 min before completing the tasks [18]. The participants then started cycling and after 20 min of cycling they began to simultaneously complete the executive function tasks. Upon completion of the tasks, the participant stopped cycling, was de-instrumented and had a 90-minute break / washout period during which they consumed a standardised lunch. The participant then completed the exact same protocol in the afternoon. However, if the participant was normoxic in the morning they were hypoxic in the afternoon, and vice versa. Once the day of testing was complete the participant either had a habitual night of sleep or remained awake all night (i.e. TSD). The following day the participant returned to undertake an identical day of testing.

5.1.2. Sleep intervention (TSD)

For the 4 days leading up to each testing session, and for the testing block in which the participants had a normal night of sleep, the participants were requested to follow their normal sleeping pattern and aim to achieve between 7 and 9 h of sleep. Upon waking, the participant recorded the time they went to bed, the time that they woke up, whether they woke in the night, and their level of sleepiness using the Stanford Sleepiness Scale [74] (described earlier).

For the sleep deprivation aspect of this experiment, participants undertook one night of TSD. Due to the outbreak of COVID-19 participants undertook the sleep deprivation aspect of the experiment in one of two settings in line with changes in regulations at the University of Portsmouth (where the study took place) and across the country (UK) as a whole. The participants who were tested pre-COVID-19 remained overnight at the University under the supervision of a member of the research team ($n = 4$). Participants who were tested during the pandemic undertook the night of sleep deprivation at their own home ($n = 8$). These participants were required to contact members of the research team via text message every hour throughout the night. In accordance with our previous work, the participants were allowed to watch television, play computer games, or read [75]. Participants were advised to avoid any moderate-strenuous activity and to eat to hunger.

5.1.3. Exercise

Exercise intensity across sessions was matched using rating of perceived exertion (RPE). The participant was instructed to cycle at an RPE of 12 (6–20 scale, 12: between light and somewhat hard) [76,77], with the workload adjusted on the participant's instruction.

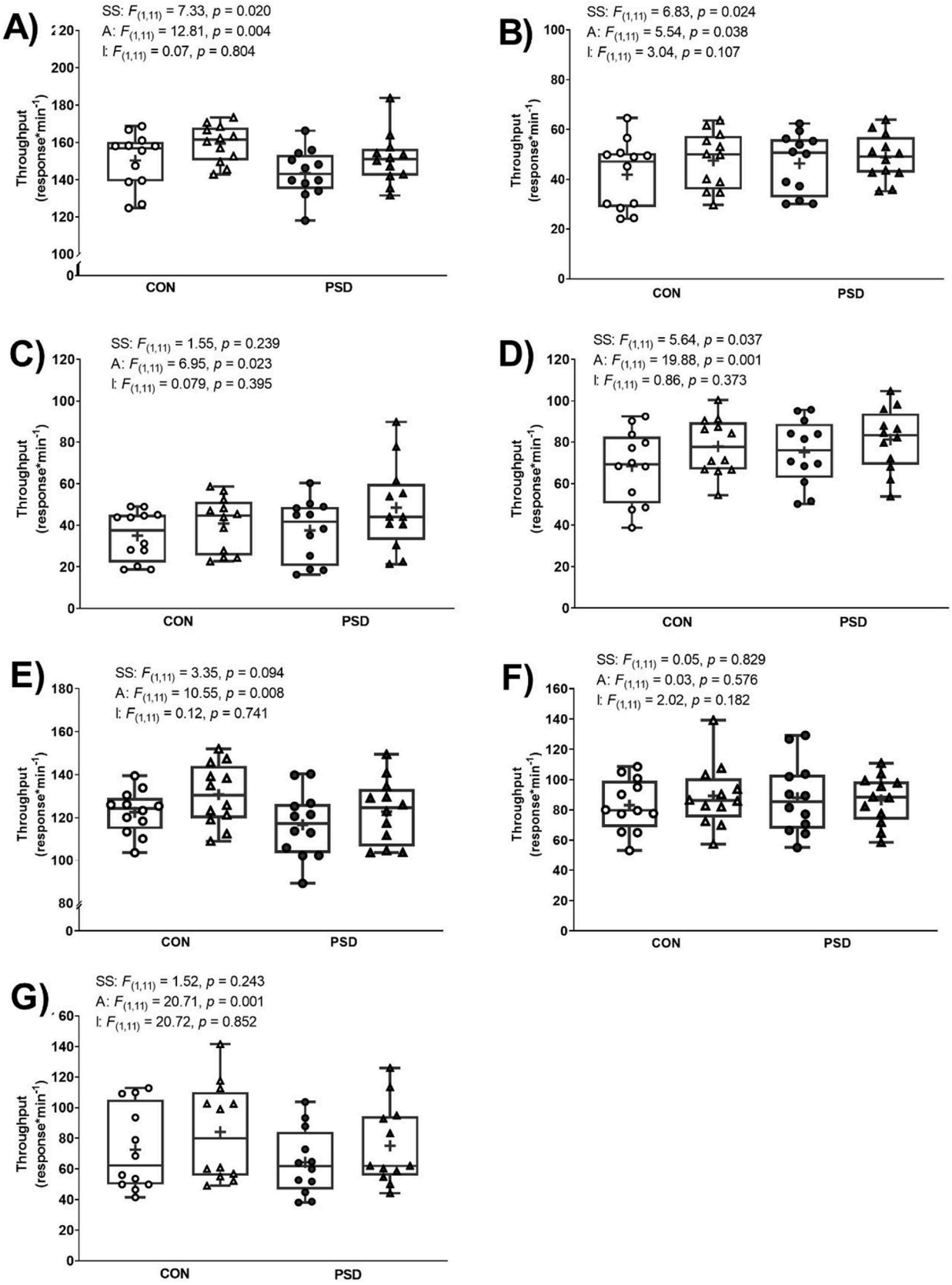

Fig. 2. Individual throughput values for (A) Choice reaction time, (B) Logical relations, (C) Mathematical processing, (D) Manikin, (E) 1-back, (F) 2-back, and (G) 3-back tasks completed at rest and during exercise after three nights of habitual sleep and three nights of partial sleep deprivation (PSD). Figure shows individual values, range, lower and upper quartile, median, and mean (+). p values represent main and interaction effects from a 2 [PSD, CON] x 2 [Rest, Exercise] repeated measures analysis of variance. ss = sleep status, A = Activity, I = Interaction. ○ = resting control, ● = resting PSD, △ = exercise control, ▲ = exercise PSD.

Table 3
Cardiorespiratory, cerebral oxygenation, and cortisol data at rest and during exercise after three nights of habitual sleep and three night of partial sleep deprivation (n = 12, except for cerebral oxygenation which is n = 10). Data are mean ± SD and data were analysed using a two-way (sleep status [control, PSD] x exercise [rest, exercise) repeated measures ANOVA. HR, heart rate; TSI, tissue saturation index, O_2Hb oxygenated haemoglobin, HHb, deoxygenated haemoglobin, tHb, total haemoglobin.

	Habitual sleep		PSD		Main and interaction effects		
Variable	Rest	Exercise	Rest	Exercise	Sleep status	Exercise	Interaction
HR (beats·min^{-1})	76 ± 7	119 ± 11	80 ± 9	126 ± 12	**$F_{(1,11)} = 13.19$, $p = 0.004$**	**$F_{(1,11)} = 208.55$, $p < 0.001$**	$F_{(1,11)} = 1.55$, $p = 0.238$
Cortisol (nmol·L^{-1})	266.1 ± 75.1	225.1 ± 80.6	277.5 ± 91.6	227.6 ± 82.1	$F_{(1,11)} = 0.236$, $p = 0.637$	**$F_{(1,11)} = 9.33$, $p = 0.011$**	$F_{(1,11)} = 0.105$, p 0.752
TSI (%)	71 ± 3	69 ± 2	69 ± 3	68 ± 3	$F_{(1,9)} = 2.67$, $p = 0.137$	$F_{(1,9)} = 3.93$, $p = 0.078$	$F_{(1,9)} = 0.21$, $p = 0.657$
O_2Hb (μM)	1.41 ± 1.52	8.78 ± 1.93	1.67 ± 2.02	9.90 ± 2.67	$F_{(1,9)} = 0.66$, $p = 0.437$	**$F_{(1,9)} = 154.74$, $p < 0.001$**	$F_{(1,9)} = 1.78$, $p = 0.214$
HHb (μM)	−0.93 ± 1.01	−0.15 ± 1.55	−1.90 ± 1.45	−1.09 ± 2.09	$F_{(1,9)} = 2.92$, $p = 0.121$	**$F_{(1,9)} = 6.91$ $p = 0.027$**	$F_{(1,9)} = 0.01$, $p = 0.971$
tHb (μM)	0.48 ± 1.36	8.64 ± 2.39	−0.24 ± 2.50	8.81 ± 3.39	$F_{(1,9)} = 0.06$, $p = 0.800$	**$F_{(1,9)} = 132.79$, $p < 0.001$**	$F_{(1,9)} = 0.9$, $p = 0.366$

5.2. Measures

5.2.1. Executive function, cerebral oxygenation, blood collection, and subjective variables

Executive function, cerebral oxygenation, blood collection, and subjective variables were performed using the methods described in Experiment 1.

5.2.2. Cardiorespiratory variables

Minute ventilation (V_E), breathing frequency (f_R), tidal volume (V_T), pressure of end tidal carbon dioxide ($P_{ET}CO_2$) and pressure of end tidal oxygen ($P_{ET}O_2$) were measured using an online gas analysis system (Quark CPET, Cosmed, Italy) and an oro-nasal facemask (7400 series Vmask, Hans Rudolph, USA) containing a turbine flowmeter (ID28, Cosmed, Italy). The inspiratory valve was connected to the Cloud 9 generator allowing the participant to breath the hypoxic gas mixture (in the normoxic condition the other end of the tubing was not connected). Peripheral oxygen saturation (SpO_2) was measured continuously using pulse oximetry at the earlobe (Quark CPET, Cosmed, Rome, Italy). If end tidal O_2 ($P_{ET}O_2$) or end tidal CO_2 ($P_{ET}CO_2$) fell below 45 and 25 mmHg, respectively, for three consecutive breaths, or if SpO_2 went below 65 %, testing was stopped and the tubing delivering the hypoxic gas was immediately removed and the participant withdrawn as previously described [18]. Heart rate (HR) was monitored via a three-lead electrocardiogram (HME Lifepulse, HME Ltd, Potters Bar, UK) and recorded continuously using an analogue to digital data acquisition system (PowerLab 16sp, AD Instruments, Castle Hill, Australia).

5.3. Statistical analyses

All statistical analyses were performed using SPSS Statistics, version 24.0 (IBM Corp., Armonk, NY, USA). The distribution of data was assessed using descriptive methods (skewness, outliers, and distribution plots) and inferential statistics (Shapiro–Wilk test). Data are presented as mean (SD) unless otherwise stated and statistical significance was accepted at $p < 0.05$.

A one-way repeated measure analysis of variance (ANOVA) was used to assess whether there were any statistically significant differences between task performance (throughput) at rest over the three experimental sessions performed (i.e. without TSD). There were no differences (all $p > 0.05$) detected between sessions for normoxia or hypoxia, at rest or during exercise. Therefore, as in Experiment 1, data from sessions 2 and 4 were used for analysis.

To examine the isolated and combined effects of TSD and hypoxia at rest and during exercise, a series of three two-way ANOVA's were conducted. Firstly, to examine the effects of sleep status, a two-way ANOVA (sleep status [TSD, habitual sleep] x exercise [rest, exercise]) was used to assess main and interaction effects for throughput, cerebral oxygenation (TSI %, O_2Hb, HHb, tHb), cardiorespiratory variables (HR, $V_{E,}$ SpO_2), sleepiness, and mood. When interactions were detected, a post-hoc analysis using Bonferroni corrections was used. To examine the effects of hypoxia, a second two-way ANOVA (environment [normoxia, hypoxia] x exercise [rest, exercise]) was used to assess main and interaction effects for the same variables. Finally, to examine the effects of exercise on the combination of TSD and hypoxia a third two-way ANOVA (environment and sleep status [TSD normoxia, TSD hypoxia] x exercise [rest, exercise]) was again used to assess the same variables. A paired samples T-test was used to compare cortisol values upon entering the laboratory. Finally, to compare exercise intensity, a one-way ANOVA (normoxia, hypoxia, normoxic TSD, and hypoxic TSD) was used to analyse VO_2 between conditions.

6. Results

Of the 12 participants that started experiment 2 (TSD) 9 were able to complete all of the experimental trials. One participant was evacuated from the chamber due to an adverse event (fainting) during a hypoxic exposure and therefore completed only the normoxic elements of the study. A second participant was unable to complete the testing due to relocation during the COVID-19 pandemic and did not undertake the sleep deprivation. A final participant was unable able to complete the hypoxic trial after the night of sleep deprivation due to feeling unwell; however, this participant was still able to complete the executive function tasks in normoxia before being withdrawn.

6.1. Exercise

VO_2 data indicated that particpants were exercising at an intensity equivalent to 44 ± 5 %, 38 ± 5 %, 38 ± 5 %, and 33 ± 5 % of their normoxic VO_{2max}, in normoxia, hypoxia, normoxic TSD, and hypoxic TSD respectively. This was significantly different between conditions ($F_{(2.312,20.80)} = 12.06$, $p < 0.001$) with intensity higher in normoxia compared to hypoxia ($p = 0.020$), in normoxia compared to normoxic TSD ($p = 0.049$), and in normoxia compared to hypoxic TSD ($p = 0.005$). However, self-reported RPE remained at 12 for all participants throughout.

6.2. Executive functions

Throughput values for each of the tasks and the associated statistics can be found in the Table 2 and 3 of the supplementary materials.

6.2.1. Total sleep deprivation

A significant main effect for both sleep status and exercise were observed for the choice reaction time (sleep status, $F_{(1,10)} = 5.76$, $p = 0.037$; exercise, $F_{(1,10)} = 6.09$, $p = 0.033$) and manikin (sleep status, $F_{(1,10)} = 20.79$, $p = 0.001$; exercise, $F_{(1,10)} = 14.41$, $p = 0.004$) tasks, indicating that throughput values were lower overall after sleep deprivation; however, exercise improved performance relative to rest in both conditions. A significant interaction was observed for the logical relations, mathematical processing, 1-back and 2 back tasks. Post hoc analysis revealed a reduction in resting performance in the TSD condition that was then restored during exercise. No main or interaction effects were observed for the 3-back tasks. Data for all tasks in which a significant interaction or main effect of exercise were observed are displayed in Fig. 3.

6.2.2. Hypoxia

A significant main effect for exercise was observed for logical relations ($F_{(1,10)} = 6.83, p = 0.026$) and 3-back ($F_{(1,10)} = 12.28, p = 0.006$)

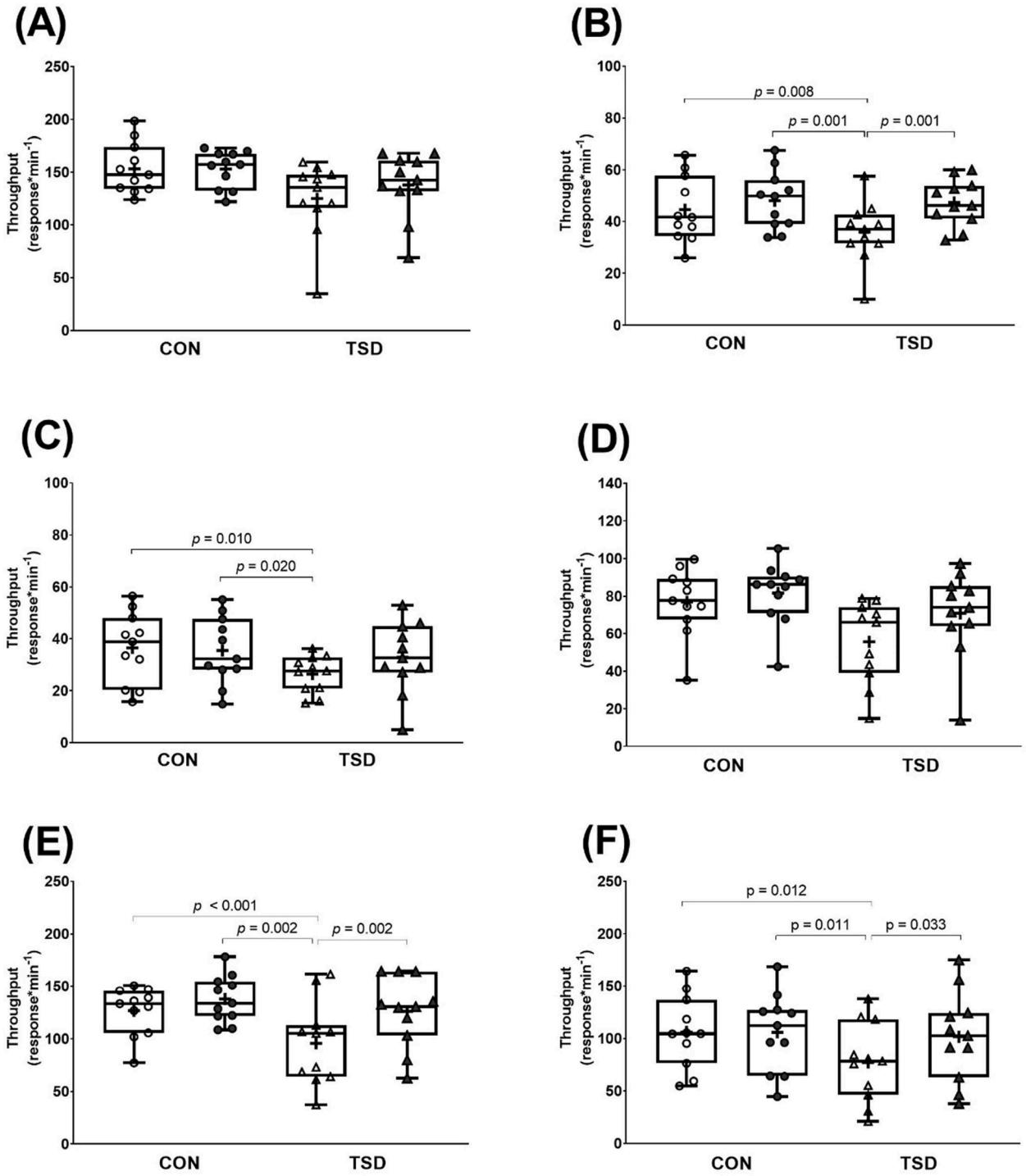

Fig. 3. Individual throughput values for (A) Choice reaction time, (B) Logical relations, (C) Mathematical processing, (D) Manikin, (E) 1-back, and (F) 2-back, tasks completed at rest and during exercise after habitual sleep or one night of total sleep deprivation (TSD). Data are individual values, range, lower and upper quartile, median, and mean (+). *p* values represent main and interaction effects from a 2 [control, TSD] x 2 [rest, exercise] repeated measures analysis of variance: ○ = resting control, ● = resting PSD, △ = exercise control, ▲ = exercise TSD.

tasks indicating that performance was better during exercise compared to rest in both normoxia and hypoxia. No other main effects or interactions were observed.

6.2.3. Total sleep deprivation and hypoxia (combined stressor, Fig. 4)

A significant main effect for both combined stressor and exercise were observed for the logical relations (combined stressor: $F_{(1,8)} = 14.77$, $p = 0.005$; exercise: $F_{(1,8)} = 11.19$, $p = 0.010$) and 2-back (combined stressor, $F_{(1,8)} = 6.73$, $p = 0.032$; exercise: $F_{(1,8)} = 5.33$, $p = 0.049$) tasks, indicating that throughput values were lower overall after combined TSD and hypoxia. However, exercise improved performance relative to rest in both conditions. A significant interaction effect was observed for choice reaction time, mathematical processing, Manikin, 1-back, and 3-back tasks, suggesting a reduction in resting performance after combined hypoxia and TSD at rest that was then restored with exercise. Data for all tasks in which a significant interaction or main effect of exercise were observed are displayed in Fig. 4.

6.3. Cardiorespiratory variables, cerebral oxygenation, and cortisol

The time course of several key physiological variables are displayed in Fig. 5. The associated statistics are available in the supplementary materials.

6.3.1. Total sleep deprivation

As expected there was a significant main effect for exercise in HR ($F_{(1,10)} = 165.3$, $p < 0.001$). For V_E there was a significant main effect for both sleep status $F_{(1,10)} = 6.37$, $p = 0.030$) and exercise ($F_{(1,10)} = 228.8$, $p < 0.001$), with V_E lower overall after TSD but higher during exercise compared to rest. A significant interaction was observed for TSI, however, post hoc analysis revealed no significant differences. A main effect for exercise was observed for O_2Hb ($F_{(1,10)} = 16.86$, $p = 0.002$) and tHb ($F_{(1,10)} = 13.39$, $p = 0.004$) with higher values observed during exercise compared to rest. No other main or interaction effects were observed. There was no difference in cortisol concentration on the morning of testing between habitual sleep and sleep deprivation (284.6 ± 121.6 vs 337.1 ± 279.3 nmol·L^{-1}; $p = 0.474$).

6.3.2. Hypoxia and TSD with hypoxia

Where significant main and interaction effects were observed for physiological variables in hypoxia, the same were observed for TSD and hypoxia in combination, therefore these results are presented together. There was a significant interaction for SpO_2 (Hypoxia, $F_{(1,10)} = 45.01$, $p < 0.001$; TSD with hypoxia, $F_{(1,8)} = 48.69$, $p < 0.001$). Post hoc analysis revealed a reduction in resting values in the hypoxic conditions that were further reduced during exercise. For HR there was a significant interaction for both environment (hypoxia: $F_{(1,10)} = 17.53$, $p = 0.002$; TSD with hypoxia: $F_{(1,\ 8)} = 10.53$, $p = 0.012$) and exercise (hypoxia, $F_{(1,10)} = 198.8$, $p <\ 0.001$; hypoxia with TSD, $F_{(1,8)} = 149.9$, $p < 0.001$) with HR higher overall in hypoxia and higher values observed during exercise compared to rest in both conditions. V_E was increased during exercise in both conditions (hypoxia: $F_{(1,10)} = 316.0$, $p < 0.001$; hypoxia and TSD, $F_{(1,8)} = 158.0$, $p < 0.001$). There was a significant interaction for TSI (hypoxia: $F_{(1,10)} = 11.64$, $p = 0.007$; hypoxia with TSD: $F_{(1,8)} = 5.96$, $p = 0.041$), with post hoc analysis showing lower TSI during exercise in the hypoxic conditions only. There was a significant interaction for both O_2Hb (hypoxia: $F_{(1,10)} = 6.68$, $p = 0.027$; hypoxia with TSD: $F_{(1,8)} = 12.25$, $p = 0.008$) and HHb (hypoxia: $F_{(1,10)} = 40.36$, $p < 0.001$; hypoxia with TSD: $F_{(1,8)} = 28.94$, $p < 0.001$). A significant main effect for exercise was also observed with values higher during exercise compared to rest (hypoxia: $F_{(1,10)} = 40.45$, $p < 0.001$; hypoxia with TSD: $F_{(1,8)} = 37.42$, $p < 0.001$).

6.4. Subjective variables

There were no significant main or interaction effects for any of the mood variables in any of the conditions. For sleepiness, there was a significant main effect for sleep status ($F_{(1,10)} = 30.19$, $p < 0.001$) and exercise ($F_{(1,10)} = 18.78$, $p = 0.002$), indicating that sleepiness was greater after TSD; however, feelings of sleepiness were reduced with exercise in both conditions. In TSD with hypoxia there was also a significant main effect for both sleep status / environment ($F_{(1,8)}$, 55.05, $p < 0.001$) and exercise ($F_{(1,8)} =$ 17.25, $p = 0.003$). No other main effects or interactions were observed.

7. General discussion

This rigorous, controlled, laboratory-based study tested the hypotheses that moderate intensity exercise would improve executive function after three consecutive nights of PSD (Experiment 1), and the isolated and combined effects of one night of TSD and acute hypoxia (Experiment 2). The principal novel findings of this multi-experiment, combined stressor study, are: i) The effects of three nights of PSD on executive functions are inconsistent; ii) one night of TSD reduces executive functions, and iii) regardless of sleep or hypoxic status executive functions are improved during an acute bout of moderate intensity exercise when compared to rest in the same conditions.

The most significant finding from this study is that moderate intensity exercise improves executive functions compared to rest after both PSD and TSD. Exercise has previously been shown to improve or maintain executive function performance (relative to rest) in normoxia [37,38]; Etnier et al., [39]; [40–43] and hypoxia [44,45]; however, to the best of our knowledge this is the first study to demonstrate that exercise may improve executive function after both PSD, TSD, and the combination of TSD and an acute bout of hypoxia. Kojima and colleagues [78] previously demonstrated that performance of the Stroop task following one night of TSD (in isolation) was improved after 20 min of moderate intensity exercise (60 % of VO_2 peak). Although they did not observe a correlation between oxygenation of the PFC and the improvement in cognitive performance, PFC oxygenation was significantly higher during exercise leading the authors to speculate that the exercise induced increase in oxygenation were, at least in part, responsible for the positive effects of exercise on performance.

Using data from both experiments within this study, we conducted an exploratory analysis to examine whether changes in task performance were related to changes in cerebral oxygenation and found no evidence for this relationship. Furthermore, the results of the current study suggest that an acute bout of moderate intensity exercise can ameliorate sleep deprivation induced decrements in executive functions even in a hypoxic environment in which cerebral oxygenation is considerably lower. Similar to previous investigations in hypoxia [79,80], we found that performance is still improved despite the reduction in cerebral oxygenation (compared to normoxic rest). However, the current investigation extends these findings with the novel inclusion of an additional form of psychophysiological stress (TSD). This provides further evidence that there are a number of other important determinants of executive function during exercise. Such determinants likely include alterations in the concentrations of catecholamines and other brain regulating hormones as well as a number of psychophysiological factors such as arousal and motivation. Interestingly, in both experiments we observed limited differences in any of the physiological measures that were taken between sleep deprived and non-sleep deprived conditions both at rest and during exercise. Therefore, whilst the results of the current study offer an exciting avenue for further exploration, future studies, using sophisticated measurements techniques (e.g. brain scanning) are required to understand the key

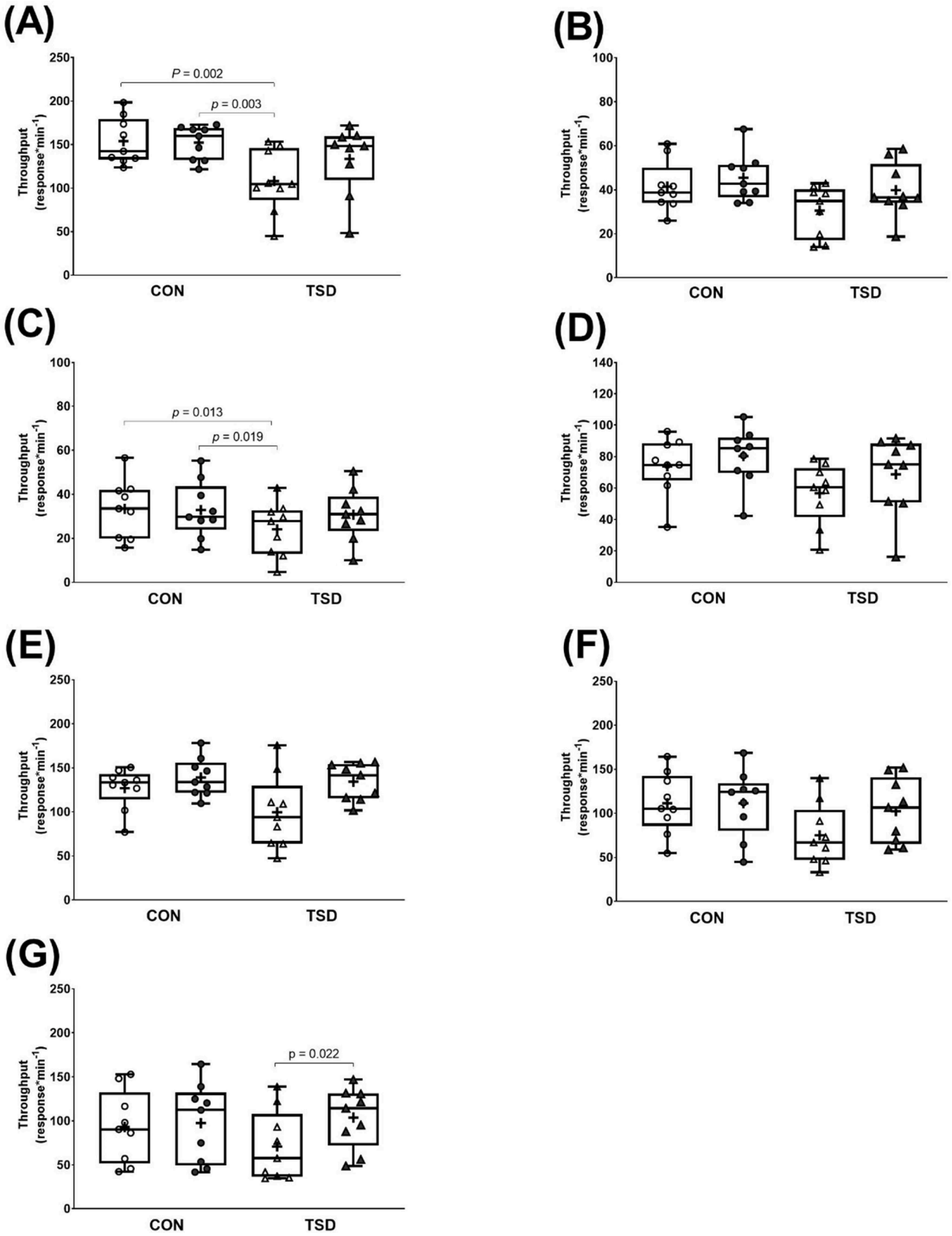

Fig. 4. Individual throughput values for (A) Choice reaction time, (B) Logical relations, (C) Mathematical processing, (D) Manikin, (E) 1-back, (F) 2-back, and (G) 3-back tasks completed at rest and during exercise after habitual sleep or one night of total sleep deprivation (TSD) with acute hypoxia. Figure shows individual values, range, lower and upper quartile, median, and mean (+). *p* values represent main and interaction effects from a 2 [control, TSD] x 2 [rest, exercise] repeated measures analysis of variance: ○ = resting control, ● = resting PSD, △ = exercise control, ▲ = exercise TSD.

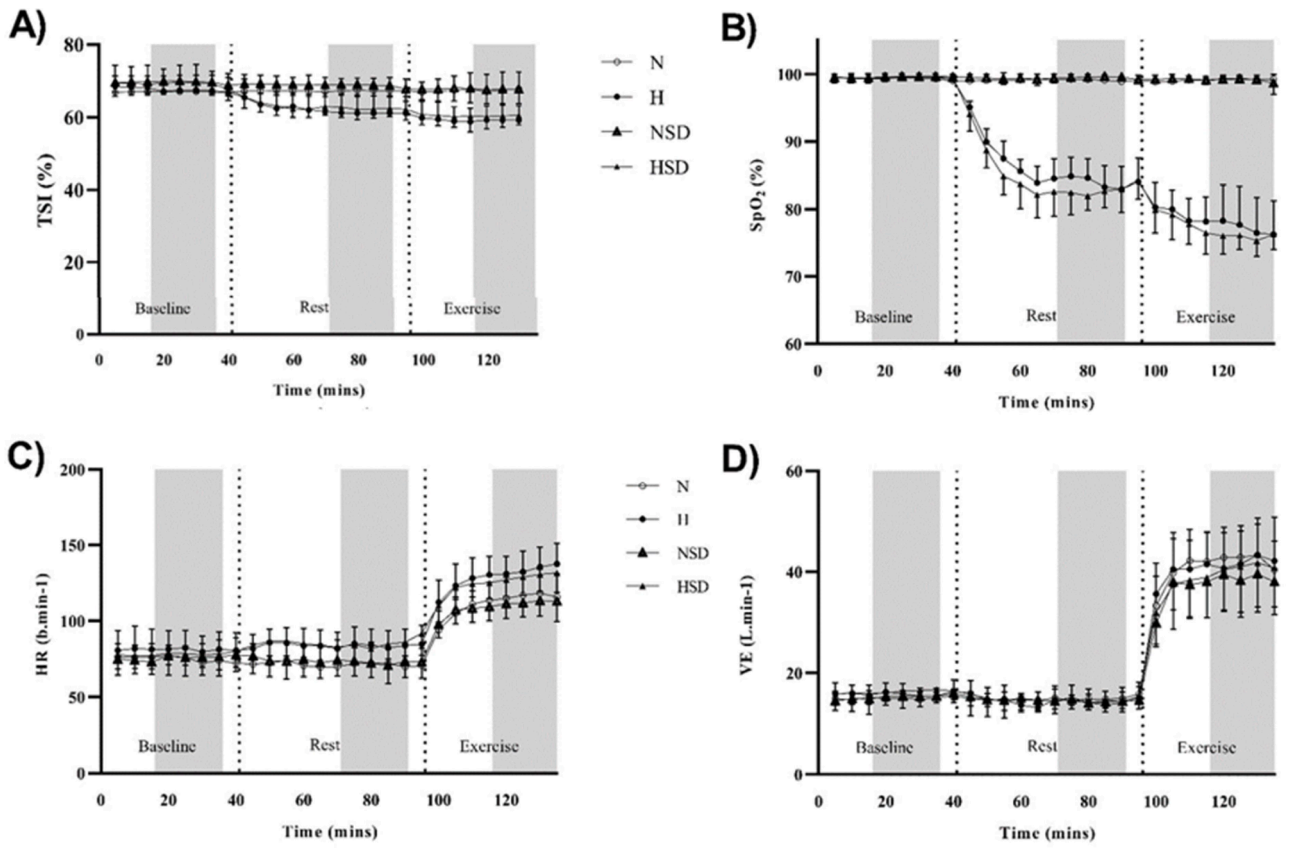

Fig. 5. Measurement of A) tissue saturation index (TSI) B) peripheral oxygen saturation (SpO_2), C) heart rate (HR) and D) minute ventilation (V_E) during experimental trials conducted in normoxia ($n = 12$), hypoxia ($n = 11$), normoxia with sleep deprivation ($n = 10$) and hypoxia with sleep deprivation ($n = 9$). Data are 5-minute mean (SD). Grey shaded area represents when the participant was completing the cognitive tasks.

neurophysiological determinants of cognitive performance after sleep deprivation (with or without hypoxia) and during exercise.

Three nights of PSD appeared to have minimal effects on performance, with only the two-choice reaction time task seeing a reduction, and the logical relations and manikin task improving. Using a similar PSD protocol (three nights of four hours sleep), Stenuit and Kerkhofs [81] also found that reaction time in tasks considered simple were altered, whilst performance in tasks that were considered more complex task remained stable. Miyata et al. [82] also found no observable decrements in working memory performance (2-back) after 3 consecutive nights of 4 h sleep. Furthermore, meta-analyses have also shown that although complex cognitive tasks are impaired by sleep deprivation, reductions in performance appear to be less severe when compared to simple task performance [11,83]. However, the current study extends these findings by demonstrating that executive functions are improved during an acute bout of moderate intensity exercise regardless of the sleep exposure over the previous three nights (i.e. >7.5 or <5 h).

There are several potential explanations for the inconsistencies between tasks. Firstly, executive functions are characterised as a collection of related but separable abilities that regulate lower level cognitive processes to shape complex performance [84]. Whilst some tasks may require a single executive function (or non-executive), others may require the cohesion of multiple executive and non-executive functions to be successful [85]. Therefore, is it not unexpected that the effect of a particular stressor may differ between tasks. Given that greater engagement of various brain centres is required for more complex tasks and that the low level of arousal provided by simple tasks is amplified during sleep loss, this may go some way to explain our findings [83]. There is also large interindividual variability in the need to sleep and therefore the susceptibility to sleep deprivation [56]. Given that the effects of sleep deprivation on cognitive performance (not just executive functions) are proportional to the magnitude of sleep deficit experienced, for some participants, a mild to moderate sleep deficit may not be sufficient to cause detrimental effects for more resilient individuals [9,56], this is particularly pertinent given that the participants in study were primarily university students. Additionally, it is also important to consider the sleep variables that were measured during the control condition. As shown in Table 2, when participants undertook the control condition they achieved an average of 6 h and 30 min sleep. Despite screening for sleep time prior to the study, this is less than the recommended 7–9 hours' sleep. This potentially suggests that a number of participants were sleep deprived (by definition) in the control condition (albeit not as severely) and may also regularly undertake periods in which they experience PSD. Therefore, some individuals may have already adapted to coping with insufficient sleep.

Whilst the above may explain why executive function performance was mostly maintained it is also important to consider why two of the tasks were improved. Given that there was no way of blinding participants to the PSD it is possible that upon undertaking the protocol participants were highly motivated to overcome the anticipated adverse effects of PSD [86]. Future research that examines the effects of PSD should play particular attention to individuals specific sleep needs, possibly adapting their protocol relative to the individual.

As hypothesised and consistent with the literature [9,11,87], the current study revealed that one night of TSD resulted in significant reductions in task performance (Fig. 3) with throughput values reduced for 6 of the 7 tasks. Due to the severity of TSD this was expected; however, that performance of the 3-back task was maintained is surprising. One potential explanation for this finding may be due to the order / timing of the task (i.e. this task was always performed last) and the potential for cognitive fatigue in the latter task(s). Therefore, the lack of difference between control and the TSD conditions may be

attributed to low levels of motivation [49,88]. For example, poor performance during the normoxic control condition may have resulted in a flooring effect meaning that there were no significant differences despite the introduction of stress. However, if true, one would expect that the same behaviour would have occurred in Experiment 1 and this was not the case.

The literature surrounding the impact of moderate hypoxia on cognitive performance is complex [19–22]. Whilst some studies have reported an impairment in task performance across various cognitive domains using F_IO_2 values similar to those used in the current investigation, others have observed no change (for a recent review see Bliemsieder et al., [89]). This variability, whilst perhaps in part due to the large variation in the inter-individual physiological response to hypoxia [90–92] is also undoubtably due to the heterogeneity in methodologies. This includes the duration of hypoxic exposure, the cognitive tasks that were used, and the method with which the hypoxic stimulus was delivered.

In a comprehensive systematic review and meta-analysis, we have previously reported that decrements in cognitive performance, including executive functions, are more pronounced once P_aO_2 is < 60 mmHg [20]. Using an estimate of PaO_2 based on SpO_2 values [93], PaO_2 in Experiment 2 ranged from 47 to 58 mmHg with a mean value of ~50 mmHg. This suggests that the hypoxic dose used was sufficient to elicit a physiological response that would result in a reduction in executive functions for certain individuals. However, whilst PaO_2 may be the key predictor of task performance in hypoxia, there are clearly certain physiological responses that allow some individuals to maintain their performance despite low levels of oxygenation, whilst for others there is a noticeable decline. Although the PFC plays an integral role in the performance of tasks that require executive function(s), including those measured by the tasks used in this investigation, performance is not solely dependent upon the PFC but is rather the product of a series of coordinated processes widely distributed across cortical and subcortical brain regions, interconnected through a series of complex neural networks [94]. Furthermore, neuroimaging studies suggest that there is considerable overlap among the neural systems engaged by different tasks [95]. As such, despite clear evidence that hypoxia reduces oxygenation of the prefrontal lobes [79]; Binks et al., [96]; [97]; Ochi et al., [98] a number of other brain regions may act to compensate when deoxygenation of the PFC takes place [85,99]. Therefore, although individuals experienced a considerable level of desaturation (~Δ 6 %), individual variability in the cerebrovascular reactivity to hypoxia [100] and differences in regional blood flow, which could preserve oxygen delivery, and activation may explain why some individuals are able to maintained performance on certain tasks and others are impaired. Future investigations should look to examine the oxygenation and activation of multiple brain regions simultaneously when completing tasks in hypoxia. Additionally, future work that focuses on a particular executive function rather than a broad range of tasks may help to provide clarity as to which types of tasks are impaired and why. Next, we did not measure brain blood flow in the current investigations, although NIRS provides a within day quantitative measure of tissue oxygenation in the PFC, we are unable to assess the impact of PSD or TSD (with and with hypoxia) on cerebral blood flow and this should be considered in any future investigations. Finally, and importantly, only healthy, young participants were included in this study, and several individuals were withdrawn due to adverse events. It is therefore feasible that the stringent medical screening and withdrawal procedure may have resulted in the exclusion of individuals who may be most susceptible to hypoxia and therefore contributed to our findings.

8. Conclusion

In conclusion, the effects of three nights of PSD on executive functions are inconsistent, while one night of TSD (regardless of hypoxic status) reduced executive functions. Importantly, we have demonstrated that moderate intensity cycling for 20 min improves executive functions after three nights of PSD and one night of TSD, regardless of hypoxic status. The key determinants and/or mechanism(s) responsible for this improvement still need to be elucidated. Future work should seek to identify these mechanisms and translate these findings into occupational and skilled performance settings.

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Declaration of Competing Interest

The authors declare that they have no conflict of interest.

Data availability

Data will be made available on request.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.physbeh.2023.114409.

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