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Acute Evening High-Intensity Interval Training may Attenuate the Detrimental Effects of Sleep Restriction on Long-Term Declarative Memory

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Abstract

Recent evidence shows that a nap and acute exercise synergistically enhanced memory. Additionally, human-based cross-sectional studies and animal experiments suggest that physical exercise may mitigate the cognitive impairments of poor sleep quality and sleep restriction, respectively. We evaluated whether acute exercise may offset sleep restriction’s impairment of long-term declarative memory compared to average sleep alone. A total of 92 (82% females) healthy young adults (24.6 ± 4.2 years) were randomly allocated to one of four evening groups: sleep restriction only (S5, 5-6 hours/night), average sleep only (S8, 8-9 hours/night), high-intensity interval training (HIIT) before restricted sleep (HIITS5) or HIIT before average sleep (HIITS8). Groups either followed a 15-minute remote HIIT video or rest period in the evening (7:00 p.m.) prior to encoding 80 face-name pairs. Participants completed an immediate retrieval task the same evening and a delayed retrieval task the next morning, after their respective sleep opportunities (documented subjectively). Long-term declarative memory performance was assessed with the discriminability index (d') during the recall tasks. We found that the d' of S8 (0.58 ± 1.37) was not significantly different from those of HIITS5 (-0.03 ± 1.64, p = 0.176) and HIITS8 (-0.20 ± 1.28, p = 0.092), except the S5 (-0.35 ± 1.64, p = 0.038) at the delayed retrieval. Similarly, the d' of HIITS5 was not significantly different from those of HIITS8 (p = 0.716) and S5 (p = 0.469). These results suggest that the acute evening HIIT partially reduced the detrimental effects of partial sleep restriction on long-term declarative memory.

Keywords: Sleep restriction, declarative memory, discriminability index, acute exercise, high-intensity interval training.
Statement of Significance

A combination of a nap and acute moderate-intensity exercise enhanced long-term memory performance in young adults, whereas exercise training has demonstrated neuroprotective effects on hippocampal-dependent memory in sleep-deprived animals. Furthermore, cross-sectional data suggest that exercise may mitigate the cognitive impairments of poor sleep quality in humans. Here, we show for the first time that performing acute bout of high-intensity exercise before a night-time sleep restriction dampened the detrimental effect of sleep restriction on long-term declarative memory. This novel finding extends knowledge on exercise-sleep interaction on declarative memory and has implications for using acute exercise as a countermeasure to memory deficits of short-term sleep loss. Future studies should investigate the moderators of the exercise-sleep interaction on long-term declarative memory in sleep loss.
Introduction

Despite the importance of adequate sleep duration for maintaining optimal brain and cognitive functioning [1,2], the prevalence of insufficient sleep is increasing, with over a third of adults aged 18-64 years old sleeping less than the recommended 7 to 9 hours per night [3,4]. A good night’s sleep is essential for memory processes, namely encoding, consolidation, and retrieval [2,5]. In particular, post-learning nocturnal non-rapid eye movement (NREM) sleep rich in slow-wave sleep (SWS) promotes hippocampus-dependent declarative memory consolidation [2,5,6]. In contrast, sleep deprivation potentially impairs the hippocampus-dependent declarative memory consolidation [6–8]. Consequently, studies have shown that short sleep duration (<7 hours per night) is associated with adverse health outcomes [9,10] and impaired cognitive functioning including poor attention, decreased concentration, and impaired memory [1,6,11,12].

Pharmacological interventions for improving sleep and cognition have limited effectiveness [13,14]. Cognitive behavioral therapies, although effective for treating insomnia, can be expensive and difficult to access [15,16]. Alternatively, accumulating evidence suggests that acute cardiovascular or aerobic exercise is a promising, non-pharmacological approach for improving brain health and memory functions [17]. In addition to improving sleep [18], exercise also enhances memory [19–22] by inducing several physiological processes that modify key aspects of sleep essential for memory processing [23–25]. The beneficial effects of exercise on memory are modulated by factors such as the frequency, intensity, duration, and timing of exercise relative to the stages of memory formation [20,21], as well as persons’ fitness levels [26]. For example, the meta-analysis by Roig et al. [21] revealed that acute exercise performed before encoding of memory trace led to moderate and moderate-to-large effect enhancements on short-term and long-term memories respectively [21]. Furthermore, acute high-intensity exercise occurring before the
encoding or early memory consolidation phase induced greater effects on long-term memory in young adults [19,27]. This effect may result from the positive relationship between exercise intensity and brain-derived neurotrophic factors (BDNF) [28–31], as well as the activation of molecular pathways (e.g., long-term potentiation) that subserve long-term memory [32,33]. These studies suggest that acute exercise improves memory in a time-dependent fashion by priming the molecular processes involved in the encoding and consolidation of newly acquired information [17,32].

Although both physical exercise and sleep can individually enhance memory [2,17], emerging evidence suggests that they may also interact synergistically to improve memory in adults [17,34,35]. Notably, the work by Mograss et al. [35] provided the first empirical evidence that exercise (i.e., 40-minute moderate-intensity cycling) and sleep (i.e., a 60-minute daytime NREM nap) operated synergistically to improve memory in 115 young adults. Additionally, cross-sectional interactive associations between physical activity and sleep on executive functions [36,37] or memory [34] in adults indicate that physical exercise may mitigate the cognitive deficits of poor sleep quality. In animal studies [38,39], but not in humans [40], exercise training resulted in neuroprotective effects on hippocampal-dependent short-term and long-term memory, possibly by preventing decreases in BDNF [38,39]. To the best of our knowledge, however, no studies have investigated the extent to which acute exercise may compensate for the detrimental effects of sleep restriction on declarative memory.

In addition to inducing greater energy expenditure [41] and gains in cardiorespiratory fitness [42,43], high-intensity interval training (HIIT), characterized by very intense exercise bouts interspersed with short rest intervals, is a time-efficient alternative to continuous moderate-
intensity training, which requires longer exercise duration (e.g., 30-60 minutes) [44,45]. Given that lack of time is a major barrier to exercise [46,47], a low-volume HIIT paradigm may have greater uptake in the general population [46,47]. HIIT can be performed in the home environment [45,48], particularly HIIT programs employing body-weight resistance aerobic exercises [49,50]. Moreover, HIIT may augment the memory effects of sleep [1,2,5] or provide memory enhancement that is superior or comparable to moderate-intensity exercise [31,51–54]. While daytime moderate-to-vigorous intensity exercise is often recommended for improving sleep [55–57], an early evening high-intensity exercise may also promote phase advance of circadian sleep propensity, enhance physiological recovery and subsequent sleep [58]. In contrast to popular belief, meta-analyses have shown that acute evening exercise of low-to-moderate [59,60] or high intensity [60,61] occurring 2 to 4 hours before bedtime do not disrupt subsequent nocturnal NREM sleep. In this context, HIIT in the early evening period may be particularly convenient and practical for some individuals to incorporate exercise habits into their daily routines. This timing of HIIT may be ideal for the evening- and/or neither-type chronotypes [62–65], as well as the morning types at risk of potential sleep disturbance following late-evening HIIT [66].

The objective of this study was to estimate the extent to which a remote, evening HIIT intervention performed in the evening prior to encoding (learning) would compensate for the negative effect of sleep restriction on long-term declarative memory (assessed with face-name association tasks) compared with an average sleep opportunity alone in healthy young adults. It was hypothesized that the acute evening HIIT would decrease the long-term declarative memory impairment after a few hours of sleep restriction. Based on prior research [35], we also hypothesized that acute evening HIIT would enhance long-term declarative memory recall following an average nocturnal sleep compared with an average sleep alone.
Methods

Study design

We conducted a home-based, remote study with a between-subject design comprising of four groups in a 2 (restricted sleep, 5-6 hours/night or average sleep, 8-9 hours/night) x 2 (HIIT or no exercise) design (Figure 1). To comply with the restrictions related to the COVID-19 pandemic, participants completed all the study procedures remotely through video conferencing (i.e., zoom) and/or remote access to research computers via TeamViewer software (v15.34.4, GmbH, Germany). Depending on the group, participants completed 3 or 4 online meetings (lasting 20 to 45 minutes) on 3 separate days for orientation and practice sessions involving the HIIT intervention (exercise groups only), and the memory task. The memory task (Face-Name Tasks) consisted of three phases: encoding, immediate retrieval, and delayed recall after either an average or a restricted night-time sleep opportunity in the participants’ home environment. This study was approved by the institutional ethics review board at Concordia University. All participants signed an informed consent form and provided verbal consent recorded via video conferencing.

Participants

One hundred and eight (87 females, 21 males) healthy participants were initially recruited for this study from August, 2020 to August, 2022. Participants were young adults aged 18 to 35 years old with good sleep quality and reported having light to moderate physical activity levels based on metabolic equivalent (MET)-minute per week [67]. We excluded volunteers who had a past or current history of sleep, psychiatric, neurological, or other medical conditions, and/or were shift workers or had traveled through more than one-time zone within the last month prior to the study. In addition, participants who were obese, pregnant or taking medications with a known effect on sleep and cognition, as well as having uncorrected visual problems were excluded from the study.
We excluded participants with obesity (i.e., BMI ≥30 kg/m\(^2\)) since we could not objectively assess sleep disorders such as obstructive sleep apnea (OSA) through baseline polysomnography-the gold standard diagnostic test [68]. Obstructive sleep apnea increases progressively with increasing BMI and obesity is associated with OSA [69] and impaired cognitive function [70,71]. However, participants with high risk of sleep apnea were excluded using the STOP-Bang questionnaire (SBQ: cut-off ≥5) [72]. Those participants without access to a functional computer compatible with the memory tasks software (PsychoPy v3.0.7, Open Science Tools Ltd.) and/or internet connectivity were excluded.

The final analysis was conducted on a total of 92 participants. The exclusion of 16 participants from the initial sample (N = 108) was due to non-adherence to the sleep protocol (n = 7), obesity (n = 2), missing recall data (n = 5), and the other 2 either took a nap or exercised on the study day (Figure 2).

**Recruitment and screening**

Participants were recruited through local flyers and advertisements on the Concordia university campus and in the community, as well as via social media platforms including Facebook and Instagram. Persons who initially expressed interest in participating in the study were asked to complete an online consent form prior to the screening questionnaires. Detailed descriptions of the screening questionnaires are published elsewhere [35]. Briefly, participants’ subjective sleep quality and daytime sleepiness were assessed using the Pittsburgh Sleep Quality Index (PSQI) [73] and the Epworth Sleepiness Scale (ESS) [74] respectively. Participants were screened for sleep disorders using the Insomnia Severity Index (ISI) [75] and the STOP-Bang Questionnaire (SBQ: for assessing the risk of obstructive sleep apnea) [72] and the Ullanlinna Narcolepsy Scale (UNS)
Participants’ mood or psychological disorders were assessed with the Beck Depression Inventory (BDI-II) [77] and the Beck Anxiety Inventory (BAI) [78]. We used the Morning-Eveningness Questionnaire (MEQ) to assess participants’ chronotype [79] and the short version of the International Physical Activity Questionnaire (IPAQ) to estimate participants’ levels of physical activity in MET-minutes per week. The participants’ eligibility to participate in the study was determined by the scores of their completed questionnaires against the standard cut-off scores for each questionnaire (Supplementary, Table S1). Where necessary, follow-up telephone calls or interviews were made to verify participants’ information. Eligible participants were then asked to fill out a sleep diary to ensure a consistent sleep schedule for at least 4 days prior to the experimental evening including their sleep on the experimental night.

**Orientation and familiarization**

Three to seven days prior to the scheduled experimental evening, participants underwent a virtual orientation with a practice session. Prior to this online meeting, participants received instructions and web-links to download the software (PsychoPy3 v.3.0.7, Open Science Tools Ltd) for the memory tasks (Face-Name task), the pre-recorded HIIT instructional video, and instructions for the software installations and the HIIT session. During the orientation, participants were given detailed information about the various components of the study protocol including the software to be used, HIIT intervention, Borg’s scale for monitoring exercise intensity, memory tasks and the sleep restriction protocol. The PsychoPy (v.3.0.7) software needed for the Face-Name memory tasks and remote access control software (TeamViewer) was installed on participants’ computers. After the software installations, the encoding and retrieval practice tasks were run to test the specific keys for the encoding (left and right arrow keys) and the retrieval (“u”, “i”, “o”, and “p” keys) tasks. In addition, participants were introduced to the HIIT video and were also asked to
perform one set of 20 seconds each of the HIIT exercises to familiarize themselves with the HIIT protocol and to ensure they could correctly and safely perform them. This phase was carried out by trained kinesiologists and physiotherapists. Participants were instructed to arrange for a spacious place and wear comfortable clothes and shoes for the exercise. We also asked participants to refrain from strenuous exercise from the day of orientation to the experimental day and avoid napping, caffeine or alcohol intake and cigarette smoking in the 24 hours preceding the experimental evening. As a safety measure, participants were instructed to stop the exercise if they experienced any cardiorespiratory or musculoskeletal signs and symptoms such as chest pain, cyanosis, difficulty breathing, dizziness or lightheadedness, intense muscle cramps or intense back or join pains. In the event of such adverse effects, they were asked to report by completing the HIIT symptom checklist (Supplementary Document S1).

Most importantly, participants were informed about their expected exercise intensity estimated based on each participant’s age-predicted maximal heart rate (HR_{max}) using the formula: (220 – age) × (0.85 to 0.95) [80,81], corresponding to 85-95% of HR_{max} [42,82]. This intensity range was equivalent to the rating of perceived exertion (RPE) scores of 15-19 (i.e., “very hard” to “very, very hard”) on the Borg’s scale (i.e., 6-20 scale) [83] for 18-35 year range. The participants were instructed to achieve their individualized target exercise intensity (i.e., RPE of 15-19 corresponding to 85-95% of HR_{max}) based on increases in heart rate, breathing rate, sweating and muscle fatigue during the exercise intervention [84]. Although the preferred approach is to conduct a laboratory-based cardiorespiratory fitness test (i.e., maximal oxygen consumption test, VO_{2max}) to directly determine exercise capacity, or alternatively, conduct a field test of cardiorespiratory fitness, as well as objectively monitor exercise intensity (using a heart rate monitor or accelerometer), these could not be performed because of the COVID-19 pandemic-related
lockdowns and movement restrictions. We also did not have access to remote activity monitoring methods (e.g., Verisense system, Shimmer Research Ltd [85]) to objectively assess participants’ compliance with the exercise protocol.

**Sample size and randomization**

Based on a prior study [35] that found an interaction between acute moderate-intensity exercise and a NREM nap on declarative memory ($\eta_p^2 = 0.053$, power = 71.1%), using G*power (v.3.1.9.6), a priori sample size calculation showed that 116 participants were needed for this study at the same study power. Participants were randomized using computer-generated random numbers by a research assistant who did not participate in other aspects of the study. The randomization was completed using the Microsoft Excel’s “RANDBETWEEN” and “CHOOSE” functions. These functions were combined as: (CHOOSE(RANDBETWEEN(1,4),"Ss","S8","HIITS5","HIITS8")) to randomly and equally assign (i.e., 1:1:1:1 ratio) participants into one of the four groups: (1) Ss: sleep restriction (5-6 hour sleep opportunity), (2) S8: average sleep only (8-9 hour sleep opportunity), (3) HIITS5: HIIT plus sleep restriction, and (4) HIITS8: HIIT plus average sleep opportunity. The group allocation was stratified by sex (CHOOSE(RANDBETWEEN(1,2),"male","female")). Participants’ allocation was concealed until 24 hours before experimental evening procedures.

**Experimental procedures**

On the experimental day, participants were asked to rest, be fully hydrated, have a bottle of water, and eat no less than 2 hours before the exercise session. At 6:45 pm on the experimental evening, participants in the HIIT groups met remotely with research assistants to prepare for the HIIT session at 7:00 pm. After the exercise session, participants were at liberty to take a 5-10-minute
shower and have a light meal. Participants attended a second online meeting that evening to undertake the memory tasks (i.e., encoding and immediate recall) at either 10:00 pm for the average sleep or 11:00 pm for sleep restriction groups. Afterwards, the average sleep groups went to bed at 11:00 pm until 7:30 am the next morning, while the sleep restriction groups went to bed from 12:30 am to 6:00 am. All participants were phoned at their respective bedtimes and wake times to ensure adherence to the sleep opportunities. Finally, the participants attended their last zoom meeting and completed the delayed recall tasks an hour after waking (i.e., 7:00 am and 8:30 am, respectively for the restricted and average sleep groups, Figure 1). Upon completion, all participants received a participation compensation.

The HIIT and no-exercise interventions

Participants in the exercise groups (HIITS$_5$ and HIITS$_8$) completed a 15-minute HIIT intervention during which the work phase of the HIIT was expected to be performed at an average RPE corresponding to 85-95% of their age-predicted HR$_{max}$. The choice of the 15-minute HIIT protocol was in accordance with the current physical activity guidelines, which recommend that adults should accumulate at least 150 minutes of moderate-intensity physical activity or 75 minutes of vigorous-intensity exercise per week [86]. Participants exercised alongside the pre-recorded video. The HIIT intervention consisted of a 2-minute warm-up, a 6-minute work phase of high-intensity intervals at an average RPE corresponding to 85-95% of participants’ age-predicted HR$_{max}$, interspersed with 6 minutes of passive rest periods in a 1:1 work phase to rest ratio fashion and a cool-down session (Figure S1). Participants started the HIIT session with the warm-up consisting of 4 exercises (i.e., spot running, jumping jacks, high knees, and squats) at low to moderate intensity (RPE of 11-13) lasting 30 seconds each. This was followed by the actual HIIT workouts comprising 6 intervals including side jump skating, squat jump, caterpillar walk with contralateral
shoulder tap, reverse lunge with hop, burpees, and mountain climbers, designed in a Tabata style (Figure S1). Participants performed 3 repetitions of each interval lasting 20 seconds (i.e., 6 minutes: 6 intervals x 3 sets x 20 seconds) and each repetition was followed by 20 seconds of passive rest (i.e., 6 minutes: 6 rest intervals x 3 x 20 seconds). The participants ended the HIIT session with a cool-down comprising of stretching and breathing exercises. Immediately after the HIIT session, participants gave their overall RPE during the work phase and resting phase using the Borg’s scale [83] and also completed a 4-item questionnaire for their feedback on the HIIT intervention (Supplementary Document S1). Although not monitored remotely via zoom, the non-exercise groups (S₅ and S₈) were asked to observe a sedentary procedure (i.e., sitting) for 15 minutes at home.

**Assessment of outcomes**

**Long-term declarative memory**

We used a modified version of the face-name association task to assess long-term declarative memory recall [87]. The memory tasks consisted of three stages: encoding (learning), immediate and delayed retrieval sessions. Each stage of the memory task was preceded by a short practice task. For each task, the full set of instructions were read to participants before they started the task. During the encoding session, participants were presented with 80 face-name pairs (50% females) only once to memorize for immediate and delayed retrievals. The photographs and associated names were presented on their computer screen for 5 seconds using the PsychoPy software (v 3.0.7). The participants were required to select either “yes” or “no” with the “left” or “right” arrow keys of their computers’ keyboard, respectively in response to the question: “does the name match the face?”. On average, this stage took approximately 10 minutes. At the end of the encoding task, participants were asked to rate their sleepiness during the task by using the Karolinska
sleepiness scale (KSS) – a 9-item questionnaire rating from 1 to 9 corresponding to “extremely alert” to “very sleepy”, respectively. Participants were allowed up to a five-minute break before the immediate retrieval task.

During the immediate and delayed retrievals, participants were presented with a set of 120 faces on their computer screen, where 40 of them were new faces added to the encoded stimuli as “foils”. The participants were required to select the correct face-name pairs as presented during encoding session by using the “u”, “i”, and “o” keys of their computers’ keyboard for the first, second and the third name options respectively, or selected “new” with the “p” key, if the face was not familiar (i.e., not previously seen during encoding). Whereas the immediate retrieval of the face-name tasks was done immediately (~5-10 minutes) after encoding, the delayed retrieval retest was conducted after the overnight average or restricted sleep opportunity. The retrieval tasks took approximately 20 minutes.

The primary outcome was long-term memory performance assessed with the discriminability index (d’) at the delayed retrieval and the difference in d’ (i.e., delayed - immediate retrievals). The d’ indicates a participant’s ability to discriminate between old and new items during the retrievals [88]. The d’ was calculated using the formula: $d' = Z_{HT} - Z_{FA}$ [88,89]; where the $Z_{HT}$ and $Z_{FA}$ are the z scores of the hit (HT) and the false alarm (FA) rates, respectively. The HT is the probability that the participant classifies an old item as old, whereas the FA is the probability of classifying a new item as old [88]. The higher the value of d’, the higher the sensitivity to discriminate stimuli [88]. Secondary outcomes included the self-reported sleep variables, as well as the motivation, performance, and sleepiness ratings at both the immediate and delayed retrievals. Participants rated their motivation, perceived task difficulty and performance with subjective scales (i.e., 0, low to
10, high), as well as rating of their sleepiness (using KSS) at the end of the retrieval tasks.

**Baseline and experimental night-time sleep quality**

Sleep quality was assessed 4 days prior to and the night following the experimental procedures with the consensus sleep diary [90]. Baseline sleep quality was assessed as the average of the 4 days preceding the experimental night. The sleep variables from the online sleep diary assessed were: 1) time in bed – total time spent in bed, 2) total sleep time (TST) is the amount of sleep duration (hours) from sleep onset to time out of bed, 3) sleep onset latency (SOL), the amount of time (minutes) participants took to fall asleep, 4) sleep efficiency (SE) defined as the percent of the time asleep out of the amount of time spent in bed, 5) wake after sleep onset (WASO) is the estimated amount of time (minutes) awake during sleep after initial sleep onset [90], and 6) awakenings, calculated as the estimated total number of nocturnal awakenings.

**Statistical analysis**

Data were analyzed with SPSS (version 28). Data were checked for a normality of distribution with the Shapiro-Wilks test. We conducted a two-way analysis of variance (ANOVA) with interaction analyses between the exercise (HIIT or no exercise) and sleep (average or restricted sleep) conditions on the memory performance outcome (d’) at the immediate and delayed retrievals and their difference score (delayed - immediate retrievals). Where significant main effects of exercise and/or sleep as well as their interaction effects occurred, post hoc analyses with Bonferroni correction were performed to determine the differences in memory performance between the groups. An analysis of covariance was conducted to assess the effects of RPE during the HIIT on the differences in d’ between the HIIT groups at the immediate and delayed retrievals, as well as the difference in d’ (delayed – immediate retrievals). We used one-way ANOVA (TIB, TST, and SE) or Kruskal Wallis test (SOL, awakenings WASO) to compare the sleep variables at
baseline and the experimental night between the groups. Additionally, one-way ANOVA was used to compare the KSS, motivation, performance difficulty and perceived performance of the memory tasks scores between the groups. For all tests, statistical significance was set at $p \leq 0.05$. 
Results

Participants’ characteristics

The final analysis was conducted on a total of 92 participants (82% female) with an average age of 24.6 (SD, 4.2) years and a normal BMI ($M = 22.2$, $SD = 2.9$ kg/m²). On average, participants were moderately physically active ($M = 1627.32$, $SD = 776.61$ MET-minute) with an intermediate chronotype ($M = 54.91$, $SD = 8.82$). About 52%, 41% and 7% of the participants were students, workers and unemployed, respectively. There were no significant differences between the groups in the demographic, psychological, chronotype and activity characteristics, except for PSQI score ($F(3, 88) = 4.223$, $p < 0.008$; Table 1), which was lower in the S₅ ($M = 2.38$, $SD = 1.21$) compared to the S₈ ($M = 3.57$, $SD = 1.61$, $p = 0.009$). For the exercise groups (HIITS₅ and HIITS₈), the mean expected RPE corresponding to 85-95% of participants’ age-predicted $HR_{max}$ was from 16.3 (SD = 0.52) to 18.7 (SD = 0.5) while the observed RPE during the HIIT session was 17.5 (SD = 1.0). There were no significant differences in the RPE ratings at baseline ($p = 0.760$), as well as during the exercise ($p = 0.330$) and the resting phases ($p = 0.992$) of the HIIT session between the HIITS₅ and HIITS₈.

Memory performance accuracy

Table 2 shows 2x2 ANOVAs with interaction analyses of exercise (HIIT or no-HIIT) and sleep (average or restricted sleep) conditions on the discriminability index ($d'$) at the immediate and delayed retrievals, and their difference (delayed – immediate retrievals). There were no statistically significant main effects of the exercise [$F(1, 88) = 0.015$, $p = 0.903$, $\eta_p^2 = 0.001$] and sleep [$F(1, 88) = 0.602$, $p = 0.440$, $\eta_p^2 = 0.007$] conditions and their interaction [$F(1, 88) = 3.267$, $p = 0.074$, $\eta_p^2 = 0.036$] on the $d'$ at the immediate retrieval (Table 2; Figure 3).
There was a significant interaction between the effects of the exercise and sleep on the d' at the delayed retrieval \([F(1, 88) = 3.006, p = 0.050, \eta_p^2 = 0.033]\) without significant main effects of the exercise \([F(1, 88) = 0.532, p = 0.468, \eta_p^2 = 0.006]\) and sleep \([F(1, 88) = 1.468, p = 0.229, \eta_p^2 = 0.016]\) conditions (Table 2; Figure 4). Post hoc comparisons with Bonferroni correction showed that the d' of S₈ \((M = 0.58, SD = 1.37)\) was not statistically different from that of HIITS₅ \((M = -0.03, SD = 1.64, p = 0.176, d = 0.404)\) and HIITS₈ \((M = -0.20, SD = 1.28, p = 0.092, d = 0.581)\); but was significantly higher than that of S₅ \((M = -0.35, SD = 1.64, p = 0.038, d = 0.611)\). The d' of HIITS₅ \((M = -0.03, SD = 1.64)\) was not significantly different from those of S₅ \((M = -0.35, SD = 1.64, p = 0.469, d = 0.192)\) and HIITS₈ \((M = -0.20, SD = 1.28, p = 0.716, d = 0.116)\), as did the difference between S₅ \((M = -0.35, SD = 1.64)\) and HIITS₈ \((M = -0.20, SD = 1.28, p = 0.735, d = 0.102)\) at the delayed retrieval (Figure 4).  

In addition, the exercise \([F(1, 88) = 1.631, p = 0.205, \eta_p^2 = 0.018]\) and sleep \([F(1, 88) = 1.035, p = 0.312, \eta_p^2 = 0.012]\) conditions and their interaction \([F(1, 88) = 0.129, p = 0.720, \eta_p^2 = 0.001]\) showed no significant main effects on the difference in the d' (delayed - immediate retrievals) (Table 2, Figure 5).  

An analysis of covariance revealed no significant effects of RPE during the HIIT on the differences in d' between HIITS₅ and HIITS₈ at the immediate \((p = 0.212, \eta_p^2 = 0.037)\) and delayed \((p = 0.184, \eta_p^2 = 0.042)\) retrievals, as well as the difference in d' \((p = 0.673, \eta_p^2 = 0.004)\) (Table S2).  

**Performance and sleepiness ratings**

A one-way ANOVA showed that the ratings of performance \((p = 0.771)\), performance difficulty \((p = 0.148)\), motivation \((p = 0.059)\) and KSS score \((p = 0.116)\) during the immediate retrieval task
were not significantly different between the groups (Figure S2 A-D). During the delayed retrieval, while perceived performance and performance difficulty ratings were not significantly different between the groups ($p = 0.465$ and $p = 0.823$, respectively), motivation ($p = 0.030$) and KSS ($p < 0.001$) scores showed group differences (Figure S3 A-D). Follow-up analyses showed that the HIITS$_5$ ($p = 0.073$) and HIITS$_8$ ($p = 0.612$) had similar motivation to the S$_8$ whose motivation level at the delayed retrieval was significantly higher than that of S$_5$ ($p = 0.041$) (Figure S3 A). The KSS score was significantly higher in the S$_5$ relative to the S$_8$ ($p < 0.001$) and HIITS$_8$ ($p < 0.001$), while the sleepiness score was not significantly different between the HIITS$_5$ and S$_8$ ($p = 0.595$), as well as between HIITS$_5$ and HIITS$_8$ ($p = 0.144$) (Figure S3 D).

**Sleep quality**

Participants’ self-reported sleep of the 4 nights preceding the experimental evening were comparable between the groups ($p > 0.05$, Table 3). As expected, TIB $F(3,89) = 190.41$, $p < 0.001$ and TST $F(3,89) = 405.59$, $p < 0.001$ showed significant group differences in the night following the experimental procedures (Table 4). The sleep restriction groups slept significantly shorter than the average sleep conditions: TIB (S$_5$ and S$_8$, HITS$_5$ and HITS$_8$, S$_8$ and HITS$_5$, S$_5$ and HIITS$_8$, $p < 0.001$) and TST (S$_5$ and S$_8$; HITS$_5$ and HITS$_8$; S$_8$ and HITS$_5$, S$_5$ and HIITS$_8$, $p < 0.001$). Only the SOL showed a significant group difference ($p = 0.027$) where the S$_5$ slept faster compared to S$_8$ ($p = 0.026$, $d = -0.883$) and HIITS$_8$ ($p = 0.036$, $d = 0.751$) (Table 4).
Discussion

To the best of our knowledge, this study is the first to evaluate the extent to which acute exercise may compensate the long-term declarative memory impairment of sleep restriction in adults. As hypothesized, whereas acute sleep restriction impaired long-term declarative memory (S₅ vs. S₈), acute evening HIIT attenuated the memory impairment caused by sleep restriction on long-term memory performance relative to the average sleep condition (HIITS₅ vs. S₈). We found no statistically substantial difference in the discriminability index between the average sleep alone (S₈) and the exercise conditions (HIITS₅ and HIITS₈), except the sleep restriction alone condition (S₅) during the delayed retrieval. However, the discriminability index of the HIITS₅ was not statistically higher than that of the S₅. In addition, the difference in the discriminability index between the delayed and immediate retrievals was comparable between the conditions. Contrary to our hypothesis, the acute evening HIIT intervention did not increase memory performance after an average nocturnal sleep in the HIITS₈.

The results of this study show that while sleep restriction impaired long-term declarative memory, a short bout of acute exercise at a high intensity appeared to have a neuroprotective effect by partially diminishing the negative impact of sleep restriction on long-term declarative memory performance at the delayed retrieval. This novel finding adds important insights to the growing body of literature on the exercise-sleep interaction on cognition [34–37]. Our findings partly support cross-sectional studies that suggest that physical exercise may mitigate the cognitive deficits of poor sleep quality [34,36,37].

Although a few human experimental studies have evaluated the interactions between exercise, total sleep deprivation and cognition, they have mainly focused on the protective effects of exercise on
executive functions and fatigue as opposed to memory [40,91]. For example, Slutsky et al. [91] assessed the effects of a 15-minute low-intensity cycling (40% of heart rate reserve) versus a seated control condition on cognitive performance including working memory in 24 active young adults and found no group difference in cognitive performance. Moreover, they administered the exercise intervention after the 24-hour sustained wakefulness and did not also assess the mediating effects of the acute low-intensity exercise on long-term memory [91].

Conversely, the potential of exercise to protect against sleep restriction-induced memory impairments has been previously investigated in a series of animal studies using regular or chronic exercise training protocols and sleep deprivation protocols mainly targeting REM sleep [38,39,92]. These animal studies demonstrated neuroprotective effects of a regular pre-sleep deprivation exercise training on short-term and long-term memory [38,39]. Their findings provide rich insights into how acute exercise may mitigate the negative impact of sleep restriction on memory. For example, Zagaar et al. [39] observed that 4 weeks of regular treadmill exercise prior to a 24-hour sleep deprivation prevented impairments of spatial learning, short-term memory (radial arm water maze) and early phase long-term potentiation in the CA1 neurons of rats’ hippocampus. Specifically, they found that regular exercise prevented the sleep deprivation-induced down-regulation of important signaling molecules such as BDNF and the phosphorylated calcium–calmodulin dependent protein kinase II (caMKII) critical for the induction and expression of long-term potentiation, a cellular correlate of learning and memory [93,94]. In another study by Zagaar et al. [38], 4 weeks of exercise training prior to a 24-hour sleep deprivation also preserved long-term memory and long-term potentiation by preventing decreases in levels of BDNF and phosphorylated cyclic adenosine monophosphate (cAMP) response element-binding protein (P-CREB) typical of sleep deprivation. In humans, studies testing the effects of acute exercise on
circulating BDNF indicated a dose-response relationship with high-intensity exercises leading to greater increases in BDNF than low intensity exercises [26,29,30,51,52], although levels comparable to those induced by moderate-intensity protocols have also been reported [54].

Contrary to our hypothesis, the acute evening HIIT intervention did not improve memory performance in HIITSs over and beyond that of Ss at the delayed recall. This was an unexpected finding given previous evidence for a positive synergistic effects of acute daytime exercise and a nap on enhancing long-term memory [35]. Notably, Mograss et al. [35] found that a single session of a 40-minute moderate-intensity (60% HRmax) cycling before a 60-minute NREM nap operated synergistically to enhance long-term recognition memory better than the effects of exercise or nap alone in a sample of 115 young adults [35]. This discrepancy in findings may be attributed to methodological differences between this study and that of Mograss et al [35]. While this study used a remote, evening protocol of HIIT before night-time sleep in a home environment and tested association memory, their study used a laboratory-based daytime protocol of moderate-intensity cycling before a short nap and assessed recognition memory in a relatively larger sample of young adults but with fitness levels similar to those of this study. It has been shown that the relationship between acute exercise and memory may vary based on the exercise intensity, temporality of exercise and the memory type evaluated [95]. This relationship may also be moderated by fitness levels [21,96]; however, studies have reported no influence of objective physical activity levels on the effects of acute exercise on long-term memory [97,98].

Previous research has shown that high-intensity exercise occurring prior to memory encoding improved long-term memory [99–101] by enhancing encoding of the memory stimuli and priming specific neural networks for the memory formation [27,32]. Although our memory performance
results did not show a statistically significant group difference at the immediate retrieval (evaluating encoding), the HIITS₈ appeared to have a lower discriminability index relative to the S₈, suggesting a possible poorer encoding. It is possible that our moderately and less active participants may not have fully recovered from the brain’s haemodynamic and neural activity changes due to the novel HIIT at the time of encoding (i.e., 2.8 hours post-exercise). This could be explained by the transient hypofrontality hypothesis [102], which is dependent on exercise intensity [103] and fitness level [104], possibly affecting recovery after exercise. Thus, allowing recovery from the psychophysiological responses to the exercise, as well as recovering from fatigue and reduced vigilance known to decline cognitive performance [104] may maximize the cognitive effects of high-intensity exercise [26,105].

In the present study, sleep-dependent memory consolidation indicated by the change scores in the discriminability index showed no significant group differences. Our sleep restriction protocol did not target the entire first half of the night during which SWS is predominant [1,6,7], probably resulting in a non-significant difference in the change scores across the conditions. Despite finding no evidence for a disturbed sleep the night following the exercise, we may have missed any post-exercise night-time sleep disruption particularly in the HIITS₈ due to lack of objective sleep measurements. Acute high-intensity exercise in the evening has been shown to cause sympathetic hyperactivity [106], elevate core body temperature (CBT) and/or interfere with nocturnal CBT decline [107,108]. These can potentially impair sleep by delaying sleep onset [109] and causing arousals during night-time sleep [57]. A previous meta-analysis of acute high-intensity exercises performed 2-4 hours before bedtime decreased REM sleep by 2.3% without disruptive changes in other objective sleep variables [61].
Another possible explanation for our results is that this study was underpowered (N = 92, power = ~53% for the interaction effect), and we would have required a relatively larger sample size (N = 116) to observe a similar combined effect of exercise and sleep on memory in the exercise conditions (HIITS₈ and HIITS₅) as previously reported [35]. Additionally, the motivation scores of the exercise conditions (HIITS₈ HIITS₅) were not significantly different from that of the S₈.

This study has limitations with implications for future studies. In addition to being underpowered and not using objective sleep measurements, the present study did not directly estimate exercise capacity (e.g., VO₂max measurement) or use a field test of cardiorespiratory fitness to determine the exercise intensity and to confirm that the groups had comparable physical fitness levels. We also did not objectively monitor exercise intensity during the HIIT with wearable tools (e.g., heart rate monitors or accelerometers) nor used remote activity monitoring tools (e.g., Verisense system, Shimmer Research Ltd [85]) due to the lockdowns and movement restrictions imposed locally during the COVID-19 pandemic. Nonetheless, our participants’ average RPE (~18) during the HIIT was within the RPE range (i.e., 15-19) corresponding to 85-95% of their age-predicted HRₘₐₓ. Further analysis showed that RPE was not a significant covariate for the difference in memory performance between the HIIT groups (HIITS₅ and HIITS₈). Whether the participants’ RPE scores precisely matched their expected exercise intensity range could not be objectively confirmed in this study. Nonetheless, RPE is a valid measure of exercise intensity and correlates with heart rate [83,84,110]. Future remote studies should use activity monitors or remote monitoring methods (e.g., Verisense system, Shimmer Research Ltd [85]) to assess adherence to exercise intensity and the overall fidelity of the exercise protocol. Furthermore, future studies may employ controlled, laboratory-based moderate- and/or high-intensity exercise protocols, directly measuring cardiorespiratory fitness to determine exercise intensity and further evaluate the
mediating effects of acute and/or chronic exercises on declarative memory in sleep restriction. Another limitation of this study was that we did not standardize the memory task times across all four groups. Finally, we recruited only healthy young adults with no sleep or psychological disorders and the majority were females (82%), limiting the generalizability of our results. Future studies may be conducted in the populations at risk of sleep loss due to work, sleep disorders or lifestyle, while ensuring equivalent distribution of both sexes.

**In conclusion**, this study demonstrates that acute partial sleep restriction negatively impacted long-term declarative memory performance. However, a short bout of acute evening HIIT appeared to partially decrease the detrimental effects of the sleep restriction. The acute evening HIIT intervention before an average night-time sleep did not enhance long-term declarative memory over and above that of the average sleep alone condition. Future studies are needed to understand how best to maximize the effects of acute exercise in offsetting the deleterious effects of sleep loss on long-term declarative memory.

**Acknowledgments**

We wish to thank our sleep lab volunteers and interns (Luca Delli Colli, Felicia Vacirca, Erika Ross, Chris Dimopoulos and Marlon Ibuna Quilatan) for their technical support. We would also like to thank the kinesiologists (Samantha St Jules and Eva Peyrusqué) who created the HIIT video for the evening HIIT intervention. In addition, we wish to thank our study coordinator (Madeline Dickson) and our participants for their participation in this study.

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Disclosure Statement

Financial Disclosure: None.

Nonfinancial Disclosure: None.

Author Contributions

MM and TTDV: participated in the study conceptualization and design, obtained funding, supervised data collection and edited the manuscript. EF: contributed to the study conceptualization and design, data collection, final statistical analysis, results interpretation, drafting and editing the manuscript. TZ: contributed to, data collection, and preliminary statistical analysis. AP: data collection, results interpretation and edited the manuscript. MA-L; LB, EMR and VP: study design, results interpretation, and edited the manuscript. All authors read and approved the submitted version of the manuscript.

Data Availability Statement

The data underlying this article will be shared on reasonable request to the corresponding author.
References


50. Frimpong E, Dafkin C, Donaldson J, Millen AME, Meiring RM. The effect of home-based low-volume, high-intensity interval training on cardiorespiratory fitness, body composition


Figure Captions

**Figure 1:** Study protocol. HIIT: high-intensity interval training; HRmax: maximal heart rate; RPE: rate of perceived exertion. S₅: sleep restriction (5-6 hour/night sleep opportunity); S₈: average sleep (8-9 hour/night sleep opportunity); HIITS₅: HIIT plus sleep restriction; HIITS₈: HIIT plus average sleep opportunity.

**Figure 2:** Flow diagram showing participant recruitment. BMI: body mass index; HIIT: high-intensity interval training; TIB: time in bed; TST: total sleep time; SD: standard deviation. Groups: S₈: average sleep; S₅: sleep restriction; HIITS₈: HIIT plus average sleep opportunity and HIITS₅: HIIT plus sleep restriction.

**Figure 3:** Comparisons of the immediate retrieval discriminability index (d') between the non-exercise and high-intensity exercise groups. Groups: S₅: sleep restriction; S₈: average sleep opportunity; HIITS₅: HIIT plus sleep restriction; HIITS₈: HIIT plus average sleep opportunity; d: Cohen’s d. Means ± SEM.

**Figure 4:** Comparisons of the delayed retrieval discriminability index (d') between the non-exercise and high-intensity exercise groups. Groups: S₅: sleep restriction; S₈: average sleep opportunity; HIITS₅: HIIT plus sleep restriction; HIITS₈: HIIT plus average sleep opportunity. Means ± SEM; d: Cohen’s d. Means ± SEM. * Significant, p = 0.038.

**Figure 5:** Comparisons of the difference in discriminability index (delayed – immediate retrieval) between the non-exercise and high-intensity exercise groups. Groups: S₅: sleep restriction; S₈: average sleep opportunity; HIITS₅: HIIT plus sleep restriction; HIITS₈: HIIT plus average sleep opportunity; d: Cohen’s d. Means ± SEM.
Table Captions

Table 1: Participants’ Characteristics.

N = 92. Sex (females (males)) and occupation presented as numbers. Other data presented as Means (SD).

Groups; S₈: average sleep opportunity; S₅: sleep restriction; HIITS₈: HIIT plus average sleep opportunity; and HIITS₅: HIIT plus sleep restriction. HIIT: high-intensity interval training; F: females (N = 75, 81.5%); M: males (N = 17, 18.5%); PSQI: Pittsburgh Sleep Quality Index; ESS: Epworth Sleepiness Scale; MEQ: Morningness-Eveningness Questionnaire; MEQ: Morningness-Eveningness Questionnaire; BDI: Beck Depression Inventory; BAI: Beck Anxiety Inventory; ISI: Insomnia Severity Index; SBQ: Obstructive Sleep Apnea Questionnaire; UNS: Ullanlinna Narcolepsy Scale; EHI: Edinburgh Handedness Inventory; MEG: Morningness-Eveningness Questionnaire; IPAQ: International Physical Activity Questionnaire; BMI: Body Mass Index. MET-min/wk: Metabolic Equivalent-Minutes per week.

a PSQI: significantly different between S₈ vs. S₅, p = 0.009.

Table 2: 2x2 ANOVA with Interaction Analysis Between the HIIT and Sleep Conditions on Memory Performance.

N = 92; *p ≤ 0.05. Groups: S₈: average sleep opportunity (n=23); S₅: sleep restriction (n=24); HIITS₈: HIIT plus average sleep opportunity (n=21); HIITS₅: HIIT plus sleep restriction (n=24). d': discriminability index; ηp²: partial eta-squared; SS: Type III Sum of Squares; df: degree of freedom; MS: Mean Square.

Table 3: Sleep Diary Variables Four Days Before the Evening Experimental Procedures.

N=92. Data are presented as Mean (SD). Groups; S₈: average sleep opportunity; S₅: sleep
restriction; HIITS₈: HIIT plus average sleep opportunity; and HIITS₅: HIIT plus sleep restriction.
HIIT: high-intensity interval training; TIB: time in bed; TST: total sleep time is the amount of
sleep duration between the time in bed and time out of bed; AWK: number of awakenings after
sleep onset; SOL: sleep onset latency; SE: sleep efficiency is the percent of the time asleep out of
the amount of time spent in bed; WASO: wake after sleep onset.

γ One-Way analysis of variance (ANOVA).

# Kruskal-Wallis Test.

Table 4: Sleep Diary Variables of the Night Following the Experimental Procedures
N=92; *P < 0.05. Data are presented as Mean (SD).

Groups; S₈: average sleep opportunity; S₅: sleep restriction; HIITS₈: HIIT plus average sleep; and
HIITS₅: HIIT plus sleep restriction.
HIIT: high-intensity interval training; TIB: time in bed; TST: total sleep time is the amount of
sleep duration between the time in bed and time out of bed; AWK: number of awakenings after
sleep onset; SOL: sleep onset latency; SE: sleep efficiency is the percent of the time asleep out of
the amount of time spent in bed; WASO: wake after sleep onset.

γ One-way analysis of variance (ANOVA).

# Kruskal-Wallis Test.

a TIB: Significantly different between S₅ & S₈; HITS₅ & HITS₈; S₈ & HITS₅ (all, p < 0.001).

b TST: Significantly different between S₅ & S₈; HITS₅ & HITS₈; S₈ & HITS₅ (all, p < 0.001).

c SOL: Significantly different between S₈ & S₅ (p = 0.026); and between S₅ & HITS₈ (p = 0.031).
Supplementary tables and figures

Supplementary Tables

Table S1: Study Exclusion Criteria and Cut-off Scores.

*If the participant provided information pertinent to the exclusion criteria or exceeded the cut-off score threshold for the questionnaire items, they were ineligible to participate. BAI = Beck Anxiety Inventory, BDI-II = Beck Depression Inventory, ESS = Epworth Sleepiness Scale, IPAQ = International Physical Activity Questionnaire, ISI = Insomnia Severity Index, OSA = Obstructive sleep apnea, PSQI = Pittsburgh Sleep Quality Index, SBQ = STOP-Bang Questionnaire, UNS = Ullanlinna Narcolepsy Scale.

Table S2: Analysis of Covariance for Memory Performance by the HIIT Groups with Rating of Perceived Exertion as a Covariate.

N = 45. Groups: HIITS5: HIIT plus sleep restriction (n=24); HIITS8: HIIT plus average sleep opportunity (n=21). d’: discriminability index; SS: Type III Sum of Squares; df: degree of freedom; MS: Mean Square; η³: partial eta-squared.

Supplementary Figures

Figure S1: The high-intensity interval training (HIIT) intervention comprising of warm-up, Tabata HIIT and cool-down.

Figure S2: Comparisons of the immediate retrieval motivation, perceived performance, performance difficult and sleepiness scores across the groups. A: motivation; B: perceived performance; C: performance difficulty; and D: sleepiness score. S5: sleep restriction; S8: average sleep opportunity; HIITS5: HIIT plus sleep restriction; HIITS8: HIIT plus average sleep opportunity. Means ± SEM.
Figure S3: Comparisons of the delayed retrieval motivation, perceived performance, performance difficult and sleepiness scores across the groups. A: motivation; B: perceived performance; C: performance difficulty; and D: sleepiness score. Groups: S5: sleep restriction; S8: average sleep opportunity; HIITS5: HIIT plus sleep restriction and HIITS8: HIIT plus average sleep opportunity. Means ± SEM.

Supplementary Documents - Document S1: Checklist or Criteria To End The HIIT Exercise.
Figure 1.

<table>
<thead>
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<th>Experimental Groups</th>
<th>Pre-experimental night</th>
<th>Experimental night and morning</th>
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<td></td>
<td>Prescreening</td>
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Figure 2.

Enrollment

Assessed for eligibility (n= 334)

Excluded (n= 226)
Not meeting inclusion criteria (n= 191)
Declined to participate (n= 28)
Declined at orientation due to computer issues (n= 7)

Randomized (n= 108)

S8: n = 29

S8: n = 29

HIITS8: n = 25

HIITS8: n = 25

Allocation

S8: n = 29

HIITS8: n = 25

Analysis

Analyzed (n = 23)
Excluded (n = 6):
Missing recall data (n=3)
BMI > 30 (n=1)
Napped on study day (n=1)
Exercised on study day (n=1)

Analyzed (n = 24)
Excluded (n = 5):
TST > 6 h study night (n = 3)
TST = 3.2 h study night (n = 1)
Missing recall data (n =1)

Analyzed (n = 24)
Excluded (1):
Missing data (n=1)

Analyzed (n = 21)
Excluded (n = 4):
BMI > 30 (n = 1)
TIB = 7.5 h study night (n= 3)
Figure 3.

$p = 0.634, d = 0.143$

$p = 0.139, d = 0.456$

$p = 0.271, d = 321$

$p = 0.085, d = 0.514 \quad p = 0.541, d = 0.180$

$p = 0.450, d = 0.228$
Figure 4.

\[ p = 0.735, d = 0.102 \]

\[ p = 0.469, d = 0.192 \]

\[ p = 0.176, d = 0.404 \]

\[ p = 0.038^*, d = 0.611 \]

\[ p = 0.092, d = 0.581 \]

\[ p = 0.716, d = 0.116 \]
Figure 5.

- $p = 0.858, d = 0.054$
- $p = 0.249, d = 0.353$
- $p = 0.521, d = 0.187$
- $p = 0.335, d = 0.285$
- $p = 0.104, d = 0.484$
- $p = 0.645, d = 0.139$
### Table 1: Participants’ Characteristics

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<td>19 (5)</td>
<td>18 (3)</td>
<td>20 (4)</td>
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Occupation

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</table>

N = 92. Sex (females (males)) and occupation presented as numbers. Other data presented as Means (SD).

Groups; S8: average sleep opportunity; S5: sleep restriction; HIITS8: HIIT plus average sleep opportunity; and HIITS5: HIIT plus sleep restriction. HIIT: high-intensity interval training; F: females (N = 75, 81.5%); M: males (N = 17, 18.5%); PSQI: Pittsburgh Sleep Quality Index; ESS: Epworth Sleepiness Scale; MEQ: Morningness-Eveningness Questionnaire; BDI: Beck Depression Inventory; BAI: Beck Anxiety Inventory; ISI: Insomnia Severity Index; SBQ: Obstructive Sleep Apnea Questionnaire; UNS: Ullanlinna Narcolepsy Scale; EHI: Edinburgh Handedness Inventory; MEG: Morningness-Eveningness Questionnaire; IPAQ: International Physical Activity Questionnaire; BMI: Body Mass Index. MET-min/wk: Metabolic Equivalent-Minutes per week.
PSQI: significantly different between S8 vs. S5, \( p = 0.009 \).

Table 2: 2x2 ANOVA with Interaction Analysis Between the HIIT and Sleep Conditions on Memory Performance

<table>
<thead>
<tr>
<th>Variables</th>
<th>Source</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>P</th>
<th>( \eta^2_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Immediate retrieval ( d' )</td>
<td>HIIT/no-HIIT</td>
<td>0.036</td>
<td>1</td>
<td>0.036</td>
<td>0.015</td>
<td>0.903</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>Average/restricted sleep</td>
<td>1.430</td>
<td>1</td>
<td>1.430</td>
<td>0.602</td>
<td>0.440</td>
<td>0.007</td>
</tr>
<tr>
<td></td>
<td>Interaction</td>
<td>7.760</td>
<td>1</td>
<td>7.760</td>
<td>3.267</td>
<td>0.074</td>
<td>0.036</td>
</tr>
<tr>
<td></td>
<td>Error</td>
<td>209.028</td>
<td>88</td>
<td>2.375</td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>218.390</td>
<td>92</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delayed retrieval ( d' )</td>
<td>HIIT/no-HIIT</td>
<td>1.193</td>
<td>1</td>
<td>1.193</td>
<td>0.532</td>
<td>0.468</td>
<td>0.006</td>
</tr>
<tr>
<td></td>
<td>Average/restricted Sleep</td>
<td>3.294</td>
<td>1</td>
<td>3.294</td>
<td>1.468</td>
<td>0.229</td>
<td>0.016</td>
</tr>
<tr>
<td></td>
<td>Interaction</td>
<td>6.745</td>
<td>1</td>
<td>6.745</td>
<td>3.006</td>
<td>0.050*</td>
<td>0.033</td>
</tr>
<tr>
<td></td>
<td>Error</td>
<td>197.459</td>
<td>88</td>
<td>2.244</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Total</td>
<td>208.770</td>
<td>92</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Difference in ( d' )</td>
<td>HIIT/no-HIIT</td>
<td>2.814</td>
<td>1</td>
<td>2.814</td>
<td>1.631</td>
<td>0.205</td>
<td>0.018</td>
</tr>
<tr>
<td>(delayed – immediate retrieval)</td>
<td>Average/restricted Sleep</td>
<td>1.784</td>
<td>1</td>
<td>1.784</td>
<td>1.035</td>
<td>0.312</td>
<td>0.012</td>
</tr>
<tr>
<td></td>
<td>Interaction</td>
<td>0.223</td>
<td>1</td>
<td>0.223</td>
<td>0.129</td>
<td>0.720</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>Error</td>
<td>151.773</td>
<td>88</td>
<td>1.725</td>
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<td></td>
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</tr>
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<td></td>
<td>Total</td>
<td>156.665</td>
<td>92</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

\( N = 92; *p \leq 0.05. \)

Groups: S8: average sleep opportunity (n=23); S5: sleep restriction (n=24); HIIT8: HIIT plus average sleep opportunity (n=21); HIIT5: HIIT plus sleep restriction (n=24).

d': discriminability index; \( \eta^2_p \): partial eta-squared; SS: Type III Sum of Squares; df: degree of freedom; MS: Mean Square.
Table 3: Sleep Diary Variables Four Days Before the Evening Experimental Procedures

<table>
<thead>
<tr>
<th>Variable</th>
<th>$S_8$ (N = 23)</th>
<th>$S_5$ (N = 24)</th>
<th>HIITS$_8$ (N = 21)</th>
<th>HIITS$_5$ (N = 24)</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIB (h)$^\gamma$</td>
<td>9.26 (0.73)</td>
<td>9.2 (0.99)</td>
<td>8.90 (0.52)</td>
<td>9.14 (0.99)</td>
<td>0.677</td>
</tr>
<tr>
<td>TST (h)$^\gamma$</td>
<td>7.96 (0.78)</td>
<td>8.08 (0.68)</td>
<td>7.99 (0.53)</td>
<td>8.09 (0.65)</td>
<td>0.865</td>
</tr>
<tr>
<td>SOL (min)$^#$</td>
<td>15.32 (8.60)</td>
<td>11.10 (6.96)</td>
<td>14.23 (7.03)</td>
<td>13.43 (6.46)</td>
<td>0.145</td>
</tr>
<tr>
<td>AWK (number)$^#$</td>
<td>0.86 (0.73)</td>
<td>0.98 (1.16)</td>
<td>0.63 (0.62)</td>
<td>0.50 (0.56)</td>
<td>0.210</td>
</tr>
<tr>
<td>WASO (min)$^#$</td>
<td>6.98 (6.70)</td>
<td>6.44 (9.90)</td>
<td>4.43 (6.06)</td>
<td>3.08 (3.35)</td>
<td>0.126</td>
</tr>
<tr>
<td>SE (%)$^\gamma$</td>
<td>87.17 (5.66)</td>
<td>88.60 (6.30)</td>
<td>89.82 (3.57)</td>
<td>89.09 (5.76)</td>
<td>0.245</td>
</tr>
</tbody>
</table>

$N=92$. Data are presented as Mean (SD).

Groups; $S_8$: average sleep opportunity; $S_5$: sleep restriction; HIITS$_8$: HIIT plus average sleep opportunity; and HIITS$_5$: HIIT plus sleep restriction.

HIIT: high-intensity interval training; TIB: time in bed; TST: total sleep time is the amount of sleep duration between the time in bed and time out of bed; AWK: number of awakenings after sleep onset; SOL: sleep onset latency; SE: sleep efficiency is the percent of the time asleep out of the amount of time spent in bed; WASO: wake after sleep onset.

$^\gamma$ One-Way analysis of variance (ANOVA).

$^\#$ Kruskal-Wallis Test.
Table 4: Sleep Diary Variables of the Night Following the Experimental Procedures

<table>
<thead>
<tr>
<th>Variable</th>
<th>S₈ (N = 23)</th>
<th>S₅ (N = 24)</th>
<th>HIITS₈ (N = 21)</th>
<th>HIITS₅ (N = 24)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIB (h)ᵃ⁻ᵇ</td>
<td>8.74 (0.40)</td>
<td>6.0 (0.66)</td>
<td>8.74 (0.40)</td>
<td>5.9 (0.67)</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>TST (h)ᵃ⁻ᵇ</td>
<td>8.09 (0.30)</td>
<td>5.4 (0.54)</td>
<td>7.96 (0.39)</td>
<td>5.20 (0.19)</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>SOL (min)ᶜ⁻ᵇ</td>
<td>14.22 (7.00)</td>
<td>8.50 (5.92)</td>
<td>15.62 (12.37)</td>
<td>12.29 (7.03)</td>
<td>0.027*</td>
</tr>
<tr>
<td>AWK (number)ᶜ</td>
<td>1.09 (1.41)</td>
<td>0.96 (1.12)</td>
<td>0.76 (1.00)</td>
<td>0.33 (0.70)</td>
<td>0.065</td>
</tr>
<tr>
<td>WASO (min)ᶜ</td>
<td>5.04 (7.02)</td>
<td>3.25 (4.98)</td>
<td>4.29 (7.91)</td>
<td>2.02 (5.26)</td>
<td>0.078</td>
</tr>
<tr>
<td>SE (%)ᵃ⁻ᵇ</td>
<td>92.58 (3.86)</td>
<td>89.93 (5.90)</td>
<td>91.08 (5.38)</td>
<td>88.35 (7.75)</td>
<td>0.102</td>
</tr>
</tbody>
</table>

N=92; *P < 0.05. Data are presented as Mean (SD).

Groups; S₈: average sleep opportunity; S₅: sleep restriction; HIITS₈: HIIT plus average sleep; and HIITS₅: HIIT plus sleep restriction.

HIIT: high-intensity interval training; TIB: time in bed; TST: total sleep time is the amount of sleep duration between the time in bed and time out of bed; AWK: number of awakenings after sleep onset; SOL: sleep onset latency; SE: sleep efficiency is the percent of the time asleep out of the amount of time spent in bed; WASO: wake after sleep onset.

ᵃ One-way analysis of variance (ANOVA).
ᵇ Kruskal-Wallis Test.
ᶜ TIB: Significantly different between S₅ & S₈; HIITS₅ & HIITS₈; S₈ & HIITS₅ (all, p < 0.001).
ᵈ TST: Significantly different between S₅ & S₈; HIITS₅ & HIITS₈; S₈ & HIITS₅ (all, p < 0.001).
ᵉ SOL: Significantly different between S₈ & S₅ (p = 0.026); and between S₅ & HIITS₈ (p = 0.031).
SUPPLEMENTAL MATERIALS

Supplementary Table Captions

Table S1: Study Exclusion Criteria and Cut-off Scores. *If the participant provided information pertinent to the exclusion criteria or exceeded the cut-off score threshold for the questionnaire items, they were ineligible to participate. BAI = Beck Anxiety Inventory, BDI-II = Beck Depression Inventory, ESS = Epworth Sleepiness Scale, IPAQ = International Physical Activity Questionnaire, ISI = Insomnia Severity Index, OSA = Obstructive sleep apnea, PSQI = Pittsburgh Sleep Quality Index, SBQ = STOP-Bang Questionnaire, UNS = Ullanlinna Narcolepsy Scale.

Table S2: Analysis of Covariance for Memory Performance by the HIIT Groups with Rating of Perceived Exertion as a Covariate.

N = 45. Groups: HIITS5: HIIT plus sleep restriction (n=24); HIITS8: HIIT plus average sleep opportunity (n=21). d': discriminability index; SS: Type III Sum of Squares; df: degree of freedom; MS: Mean Square; $\eta^{2}$: partial eta-squared.

Supplementary Figure Captions

Figure S1: The high-intensity interval training (HIIT) intervention comprising of warm-up, Tabata HIIT and cool-down.

Figure S2: Comparisons of the immediate retrieval motivation, perceived performance, performance difficult and sleepiness scores across the groups. A: motivation; B: perceived performance; C: performance difficulty; and D: sleepiness score. Ss: sleep restriction; S8: average sleep opportunity; HIITS5: HIIT plus sleep restriction; HIITS8: HIIT plus average sleep opportunity. Means ± SEM.
**Figure S3**: Comparisons of the delayed retrieval motivation, perceived performance, performance difficult and sleepiness scores across the groups. **A**: motivation; **B**: perceived performance; **C**: performance difficulty; and **D**: sleepiness score. Groups: **Ss**: sleep restriction; **S8**: average sleep opportunity; HIITSs: HIIT plus sleep restriction and HIITS8: HIIT plus average sleep opportunity. Means ± SEM.

**Document S1**: Checklist or Criteria To End The HIIT Exercise.
**Supplementary Tables**

**Table S1: Study Exclusion Criteria and Cut-off Scores**

<table>
<thead>
<tr>
<th>Exclusion criteria</th>
<th>Cut-Off Scores for exclusion*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Being outside the target age range (18-35 years old)</td>
<td></td>
</tr>
<tr>
<td>2. Evidence of chronic medical or psychological disorders</td>
<td>BAI score &gt;36</td>
</tr>
<tr>
<td></td>
<td>BDI-II score &gt;20</td>
</tr>
<tr>
<td>3. Evidence of poor sleep quality or sleep disorders</td>
<td>ISI score &gt; 14</td>
</tr>
<tr>
<td></td>
<td>SBQ score indicating high risk of OSA</td>
</tr>
<tr>
<td></td>
<td>UNS score &gt; 14</td>
</tr>
<tr>
<td></td>
<td>Irregularities or abnormalities in sleep/wake cycles during actigraphy screening</td>
</tr>
<tr>
<td></td>
<td>PSQI &gt;5</td>
</tr>
<tr>
<td>4. Excessive daytime sleepiness</td>
<td>ESS &gt;10</td>
</tr>
<tr>
<td>5. Regular use of psychotropic or hypnotic medication</td>
<td>Self-report on sleep diary or during actigraphy and sleep diary confirmation</td>
</tr>
<tr>
<td>6. Shift work or having travelled through more than one time zone in the past month</td>
<td></td>
</tr>
<tr>
<td>7. Regular vigorous intensity exercise</td>
<td>IPAQ score &gt; 3000</td>
</tr>
</tbody>
</table>

*If the participant provided information pertinent to the exclusion criteria or exceeded the cut-off score threshold for the questionnaire items, they were ineligible to participate.

BAI = Beck Anxiety Inventory, BDI-II = Beck Depression Inventory, ESS = Epworth Sleepiness Scale, IPAQ = International Physical Activity Questionnaire, ISI = Insomnia Severity Index, OSA = Obstructive sleep apnea, PSQI = Pittsburgh Sleep Quality Index, SBQ = STOP-Bang Questionnaire, UNS = Ullanlinna Narcolepsy Scale.
Table S2: Analysis of Covariance for Memory Performance by the HIIT Groups with Rating of Perceived Exertion as a Covariate

<table>
<thead>
<tr>
<th>Variables</th>
<th>Source</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>P</th>
<th>η_p²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Immediate retrieval d'</td>
<td>Groups (HIITS₅/HIITS₈)</td>
<td>1.148</td>
<td>1</td>
<td>1.148</td>
<td>0.549</td>
<td>0.463</td>
<td>0.013</td>
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<tr>
<td></td>
<td>RPE</td>
<td>3.363</td>
<td>1</td>
<td>3.363</td>
<td>1.607</td>
<td>0.212</td>
<td>0.037</td>
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<tr>
<td></td>
<td>Error</td>
<td>87.879</td>
<td>42</td>
<td>2.092</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>92.481</td>
<td>45</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delayed retrieval d'</td>
<td>Groups (HIITS₅/HIITS₈)</td>
<td>0.254</td>
<td>1</td>
<td>0.254</td>
<td>0.117</td>
<td>0.734</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td>RPE</td>
<td>3.957</td>
<td>1</td>
<td>3.957</td>
<td>1.829</td>
<td>0.184</td>
<td>0.042</td>
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<tr>
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<td>Error</td>
<td>90.891</td>
<td>42</td>
<td>2.164</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>95.679</td>
<td>45</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Difference in d' (delayed –</td>
<td>Groups (HIITS₅/HIITS₈)</td>
<td>0.379</td>
<td>1</td>
<td>0.379</td>
<td>0.220</td>
<td>0.641</td>
<td>0.005</td>
</tr>
<tr>
<td>immediate retrieval)</td>
<td>RPE</td>
<td>0.310</td>
<td>1</td>
<td>0.310</td>
<td>0.180</td>
<td>0.673</td>
<td>0.004</td>
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<td>Error</td>
<td>72.210</td>
<td>42</td>
<td>1.719</td>
<td></td>
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<tr>
<td></td>
<td>Total</td>
<td>74.342</td>
<td>45</td>
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<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

N = 45.

Groups: HIITS₅: HIIT plus sleep restriction (n=24); HIITS₈: HIIT plus average sleep opportunity (n=21).

d': discriminability index; SS: Type III Sum of Squares; df: degree of freedom; MS: Mean Square; η_p²: partial eta-squared.
Supplementary Figures

Figure S1.

**Warm up**

1A : Running on spot

<table>
<thead>
<tr>
<th>Week Phases</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>00:30</td>
</tr>
</tbody>
</table>

1B : Jumping Jack

- Jump on the spot by opening and closing the legs and arms simultaneously. Working on the balls of your feet and keep your head up.

<table>
<thead>
<tr>
<th>Week Sets</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>00:30</td>
</tr>
</tbody>
</table>

1C : High Knees On Spot

- Keep your back straight, head up and abs tight. Move your arms, front hand at shoulder height, elbows at 90 degrees. Working on the balls of your feet.

<table>
<thead>
<tr>
<th>Week Sets</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>00:30</td>
</tr>
</tbody>
</table>

1D : Squat

- Feet shoulder width apart, go down until your knees are at 90°. Raise your arms to shoulder height.

<table>
<thead>
<tr>
<th>Week Sets</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>00:30</td>
</tr>
</tbody>
</table>
## Tabata

### 1A : Side Jump Skating + touch ground
- Standing, start on 1 foot body tilted in skating style. Head above the support foot, jump sideways to the other foot while swinging your arms and touch the ground. Weight on the front part of the foot. Keep your back straight, looking forward.

**Easy version : don't touch the ground, slow your pace.**

<table>
<thead>
<tr>
<th>Week</th>
<th>Sets</th>
<th>Duration</th>
<th>Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>00:20</td>
<td>00:20</td>
</tr>
</tbody>
</table>

### 1B : Squat Jump
- Start in a vertical position. Go down to squat and jump vertically with as much speed as possible. Keep your back straight, your abs tight and your head up.

**Easy version: squat (no jumping)**

<table>
<thead>
<tr>
<th>Week</th>
<th>Sets</th>
<th>Duration</th>
<th>Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>00:20</td>
<td>00:20</td>
</tr>
</tbody>
</table>

### 1C : Caterpillar Walk and Shoulder Tap
- Stand with legs straight, walk on your hands to get to a plank position and touch your hand to your opposite shoulder. Bring legs back to get to the starting position, legs straight. Keep your back straight and abs tight.

**Easy version: Caterpillar walk.**

<table>
<thead>
<tr>
<th>Week</th>
<th>Sets</th>
<th>Duration</th>
<th>Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>00:20</td>
<td>00:20</td>
</tr>
</tbody>
</table>

### 1D : Reverse lunge and hop
- Take a step back and bend both knees. Go back up on your front leg and hop while lifting your back knee up. Alternate both legs.

**Easy version: no hop, just bring your knee up.**

<table>
<thead>
<tr>
<th>Week</th>
<th>Sets</th>
<th>Duration</th>
<th>Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>00:20</td>
<td>00:20</td>
</tr>
</tbody>
</table>

### 1E : Burpees
- Go down, place hands on the ground shoulder-width apart. As you go to plank position, lower chest and thighs toward the ground. Push-up as you bring your feet under your hips. Jump vertically with full hip and knee extension. Repeat the sequence.

**Easy version: don't bring your chest to the ground.**

<table>
<thead>
<tr>
<th>Week</th>
<th>Sets</th>
<th>Duration</th>
<th>Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>00:20</td>
<td>00:20</td>
</tr>
</tbody>
</table>

### 1F : Mountain climber
- In plank position, alternate pulling your knees under your body. Keep abs tight and head up.

<table>
<thead>
<tr>
<th>Week</th>
<th>Sets</th>
<th>Duration</th>
<th>Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>00:20</td>
<td>00:20</td>
</tr>
</tbody>
</table>
Figure S1: The high-intensity interval training (HIIT) intervention comprising of warm-up, Tabata HIIT and cool-down.
Figure S2. Comparisons of the immediate retrieval motivation, perceived performance, performance difficult and sleepiness scores across the groups. A: motivation; B: perceived performance; C: performance difficulty; and D: sleepiness score. S5: sleep restriction; S8: average sleep opportunity; HIITS5: HIIT plus sleep restriction; HIITS8: HIIT plus average sleep opportunity. Means ± SEM.
Figure S3.

**Figure S3**: Comparisons of the delayed retrieval motivation, perceived performance, performance difficult and sleepiness scores across the groups. **A**: motivation; **B**: perceived performance; **C**: performance difficulty; and **D**: sleepiness score. Groups: **S5**: sleep restriction; **S8**: average sleep opportunity; **HIITS5**: HIIT plus sleep restriction and **HIITS8**: HIIT plus average sleep opportunity. Means ± SEM.
SUPPLEMENTARY DOCUMENTS

Document S1: Checklist or Criteria To End The HIIT Exercise

Please stop the exercise if you experience any of the following symptoms/signs or complete it after the HIIT exercise:

- Chest pain
  - Yes ☐ No ☐
- Bluish discoloration of hands or feet (Cyanosis)
  - Yes ☐ No ☐
- Cramping or pains in the lower leg
  - Yes ☐ No ☐
- Difficulty breathing
  - Yes ☐ No ☐
- Dizziness, fainting or light-headedness
  - Yes ☐ No ☐
- Severe back or joint pains
  - Yes ☐ No ☐

Please complete this feedback questionnaire after the exercise:

1. Did you enjoy the HIIT exercises?   Highly ☐ Moderately ☐ Lightly ☐ No ☐
2. Were the exercises difficult to complete?   Highly ☐ Moderately ☐ Lightly ☐ No ☐
3. Did you feel like stopping the exercises?   Yes ☐ No ☐
4. Would you like to adopt the HIIT exercises?   Yes ☐ No ☐