The Effects of Acute High-Intensity Interval Training and Sleep Restriction on Memory: A Pilot Study

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ABSTRACT

The Effects of Acute High-Intensity Interval Training and Sleep Restriction on Memory: A Pilot Study

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Background: Sleep restriction impairs memory, while high intensity interval training (HIIT) improves cognition. Our *objectives* were to assess the feasibility of the study and to obtain preliminary results on the effects of an evening HIIT plus sleep restriction on declarative memory.

Methods: 88 healthy adults (24.6 ± 4.2yrs), completed a sleep diary 4 days prior to and during the experimental night. Participants were randomized into either restricted (~5-6 h/night) or average (~8-9 h/night) sleep opportunity, without (**S_5, S_8 respectively**) or with HIIT (**$HIITS_5$, $HIITS_8$**).

During the experimental night (at 7 p.m.), the HIIT groups completed a 15-min HIIT session while the non-exercise groups had an equivalent period of seated rest. This was followed by face-name recall tasks: *encoding* and *immediate recall sessions* the same evening, and a *delayed recall session* the following morning after an average or restricted sleep opportunity.

Results: Our remote-pilot study showed that all participants in the exercise groups completed the HIIT protocol safely. We found a significant interaction between HIIT and sleep conditions on delayed recall accuracy ($p = 0.042$, $\eta p^2 = 0.049$). Post hoc analysis showed significant differences for delayed recall accuracy between $HIITS_8$ and S_8 (81.64±14.64 vs. 93.95±10.71, $p = 0.013$, respectively) and between S_5 and S_8 (82.87 ± 16.66 vs. 93.95 ± 10.71, $p = 0.023$, respectively).

Conclusion: Acute evening HIIT hindered the positive effects of sleep on memory. Additionally, HIIT did not compensate for the memory impairment of sleep restriction.

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Contribution of Authors

Tehila Zvionow
As a master student, I took part in every aspect of the project. I programed/coded the memory task on Psycho.Py version 3. I recruited, screened and scheduled participants for the study. I ensured participants followed the protocol and maintained consistent sleep/wake schedules. I scored questionnaires and sleep diaries. I assisted in data collection, carried out orientation and machine testing, supervised remotely HIIT intervention and administered cognitive task remotely. I was in charge of training volunteers and students in all areas of the study. Finally, I conducted statistical analysis.

Thien Thanh Dang-Vu
As my supervisor and the director of the Sleep, Cognition and Neuroimaging Lab at Concordia University, Dr. Dang-Vu conceptualized the study, was involved in the design of the entire pilot study, co-wrote the grant and oversaw all aspects of the study.

Melodee Mograss
As a research associate of the Sleep, Cognition and Neuroimaging Lab at Concordia University, Dr. Mograss co-conceptualized the study, wrote the grant for this project, and oversaw all aspects of the study.

Emmanuel Frimpong
As a project leader and post-doctoral fellow of the project, Dr. Frimpong co-designed the remote HIIT intervention. He assisted in data collection, carried out orientation and machine testing, supervised remotely HIIT intervention, and administered cognitive task remotely. Dr. Frimpong ran the statistical analysis.

Mylene Aubertin-Leheudre
As a co-investigator of our study and a professor at UQAM, Dr. Aubertin-Leheudre conceptualized, co-designed and created the online HIIT video we used in our pilot study.

Madeline Dickson
As the coordinator of the project, Madeline was in charge of creating recruiting participants, screening and scheduling participants in for the study. Madeline ensured that participants followed the protocol and maintained a consistent sleep/wake schedule.

Luca Delli-Colli
As an honor's undergrad student in the HKAP department at Concordia University, Luca assisted in recruiting participants, data collection, carried out orientation and machine testing, and administered cognitive task remotely. Luca's honours thesis piloted 23 participants in the non-exercise average and restricted sleepers in this project.

Marlon Ibuna Quilatan
As an honor's undergrad student in the HKAP department at Concordia University, Marlon assisted in collecting data, carried out orientation and machine testing, supervised remotely HIIT intervention, and administered cognitive task remotely. Marlon's honours thesis analysis of motivational and vigilance factors on memory in 38 participants in the exercise groups and how this could influence the memory.

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As a PhD student in the HKAP department at Concordia University, Dr. Paez assisted in data collection, carried out orientation and machine testing, supervised remotely HIIT intervention, and administered cognitive task remotely.

Chris Dimopoulos

As an honor's undergrad student in the Department of Psychology at Concordia University, Chris' thesis consisted of the analysis of motivational and vigilance factors in 41 of the non-exercise groups and how this could influence the memory. In addition, he administered the pre-screening on-line questionnaires.

Felicia Vacirca

As a volunteer, Felicia assisted in scoring sleep diary.

Erika Ross

As a volunteer, Erika assisted in scoring sleep diary.

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List of abbreviations

S_8: Average sleep group
S_5: Sleep restricted group
$HIITS_8$: High intensity interval training and Average sleep group
$HIITS_5$: High intensity interval training and Sleep restricted group
HIIT: High-intensity interval training
MICT: moderate-intensity continuous training
VO_2max: maximal oxygen consumption
MET-min/week: metabolic equivalent of task minutes per week
HRmax: maximal heart rate
RPE: Borg rating of perceived exertion
BMI: body mass index
PSG: Polysomnography
REM: rapid eye movement
NREM: non-rapid eye movement
SWS: slow-wave sleep
N1: stage 1 of non-rapid eye movement sleep
N2: stage 2 of non-rapid eye movement sleep
N3: stage 3 of non-rapid eye movement sleep
ISI: Insomnia severity index
PSQI: Pittsburgh Sleep Quality Index,
RLS: Restless leg syndrome,
ESS: Epworth Sleepiness Scale
MEQ: Morningness-Eveningness questionnaire
SBQ: Stop Bang Questionnaire
UNS: Ullanlinna Narcolepsy Scale
KSS: Karolinska Sleepiness Scale
IPAQ: International Physical Activity Questionnaire
GAQ: Get Active Questionnaire
EHI: Edinburgh Handedness Inventory
BDI: Beck's Depression Index
BAI: Beck's Anxiety Index
TIB: Time in bed
TST: total sleep time
TA: time awake
Awk(#): number of awakenings
WASO: wake after sleep onset
SOL: sleep onset latency
SE (%): sleep efficiency
RT: reaction time
ICOR: Immediate recall accuracy
DCOR: Delayed recall accuracy
IRT: Immediate reaction time
DRT: Delayed reaction time
IRTC: Immediate reaction time of the correct responses

DRTC: Delayed reaction of the correct responses
RAVLT: Rey Auditory Verbal Learning Test
PVT: psychomotor vigilance test
AHN: adult hippocampal neurogenesis
BDNF: brain-derived neurotropic factor
NMDA: N-methyl-D-aspartate
fMRI: Functional magnetic resonance imaging
AST: actual sleep time
AWT: actual awake time
IT: % of immobility time
MT: movement time
ηp^2: partial eta-squared
SS: Type III Sum of Squares
df: degree of freedom
MS: Mean Square
F: F-value
p: p-value
M: mean
SD: standard deviation
d: cohen's d
t: t-value

1. Introduction

Sleep is crucial to our survival and wellbeing. It plays a key role in cognitive development vital to learning, memory and synaptic plasticity (Frank & Benington, 2006). Reduced sleep time negatively affects public health in many industrialized countries (Hafner et al., 2017). On average, 26% of Canadians, 56% of Japanese, 30% of Germans, 45% of Americans and 35% of UK citizens sleep less than seven hours per night (National Sleep Foundation, 2013). The possible reasons as to why insufficient sleep is prevalent include a 24/7 modern society, stress, sleep disorders and poor lifestyle habits such as alcohol consumption, excessive screen time and sedentary behaviour (Hafner et al., 2017). In 2015, sleep loss costs Canadians 13.5 to 21.4 billion U.S. dollars (Hafner et al., 2017). Lack of sleep has been associated with higher risk of traffic accidents, industrial accidents, medical errors and inefficient work productivity (Nuckols et al., 2009; Pack et al., 1995). Additionally, sleep-deprived individuals performed in cognitive tasks similarly to intoxicated individuals with blood alcohol levels of 0.05 to 0.1% (Williamson & Feyer, 2000).

1.1 Sleep Architecture

On average, most young adults require seven to nine hours of sleep per night (Hirshkowitz et al., 2015). Sleep consists of four to six cycles of alternating non-rapid eye movement (NREM) and rapid eye movement (REM) (Kleitman, 1939; Patel et al., 2021). We cycle through REM/NREM sleep every 90 to 120 minutes. NREM sleep consists of three stages: N1, N2 and N3. N1 is considered to be light sleep and is characterized by theta waves (4-7 Hz), N2 is characterized by spindles (11-16 Hz) and K- complexes (biphasic waves of 0.5-2 Hz) and N3 - also known as deep, slow-wave sleep (SWS) - is characterized by slow waves (0.5-2 Hz, amplitude $\geq$ 75µV) (Berry et al., 2014). On the other hand, REM sleep is characterized by low-amplitude, mixed-frequency waves, vivid dreams, rapid eye movements and muscle atonia to prevent the person from enacting dreams (Berry et al., 2014). During the first part of the night, NREM sleep is predominant with more SWS at the beginning and less toward the end of the night (Plihal & Born, 1997). REM sleep is predominant during the second half of the night, as REM sleep becomes progressively longer (Plihal & Born, 1997).

1.2 Sleep and Memory

Procedural memory (often referred to as non-declarative memory) and declarative memory are two types of memory systems (Squire, 1987). Procedural memory is acquired implicitly through repeated practice. It includes memory for motor skills and procedures (Squire, 1987). Declarative memory consists of learned facts and events or experiences that can be explicitly remembered at a later time (e.g., can be instructed to recall a fact during a task) (Riedel & Blokland, 2015; Squire, 1987). There are two subtypes of declarative memory: recognition and recall memory (Riedel & Blokland, 2015). Recognition memory is defined as the ability to identify information that was previously learned (e.g., recognizing words or pictures) (*Basic Memory Tasks*, 2016; Riedel & Blokland, 2015). Recall memory is defined as the ability to verbalize or to consciously recollect information stored as memory (e.g., stating a fact) (*Basic Memory Tasks*, 2016; Riedel & Blokland, 2015).

Declarative memory is highly dependent on the hippocampus, can be rapidly encoded and is prone to decay, interference and forgetting (Marshall & Born, 2007). There is a three-step process to creating a new memory: 1. Acquisition, 2. Consolidation and 3. Retrieval (Marshall & Born, 2007). Acquisition occurs when new information has been acquired during learning and is encoded into a vulnerable memory trace. Consolidation then stabilizes the acquired information into long-term memory, by integrating it with pre-existing long-term memories. Recalling the stored memory occurs during retrieval (Marshall & Born, 2007).

It is well established that sleep plays a significant role in memory consolidation (Marshall & Born, 2007; Plihal & Born, 1997; Rasch & Born, 2013). Having an adequate sleep hygiene by maintaining a consistent schedule in a comfortable bedroom environment has a positive effect for optimal cognitive function (Almondes et al., 2017; Rasch & Born, 2013). During NREM sleep, slow waves and sleep spindles mediate the consolidation of declarative memory, while REM sleep seems to benefit procedural memory (Fischer et al., 2002; Marshall & Born, 2007). This was first shown in a study by Plihal & Born (1997), in which twenty healthy young adult men were randomized into four study conditions: sleep early, sleep late, wake up early and wake up late. All participants had a learning session prior to their assigned bedtime and a recall session following their assigned wake time (Plihal & Born, 1997). The learning session consisted of the paired-associate word list task[1] (declarative memory) and the mirror-tracing[2] skills (procedural memory). The authors found that when participants slept early, their SWS was five times greater and their REM sleep was 65% shorter compared to when they slept late. The early sleepers had better scores on the declarative memory task, while the late sleepers performed better on the procedural memory task. This study was the first to show the difference between early and late sleepers for consolidating declarative and procedural memory (Plihal & Born, 1997). Another study by Stickgold and colleagues (2000) found that learning occurs in a two-step process involving SWS and REM sleep whereby neuronal changes take place to create long-term memory consolidation. For an average eight-hour sleep period, the performance on visual discrimination task, within 24-hour post training, was improved proportional to the amount of SWS at the beginning of the night and the amount of REM sleep at the end of the night. This improvement accounted for 80% of the variance between participants (Stickgold et al., 2000). In short, a large portion of declarative and procedural memory consolidation occurs following a good quality sleep involving both NREM and REM cycles.

1.3 Memory assessment: Face-Name task

Face-name association tasks assess declarative memory. These types of memory tasks are more challenging than others because the names are selected from a list of common names and are randomly assigned to unfamiliar faces presented on a screen, creating no obvious relationship

[1] Paired-associate word list: Participants were given two different sets of word lists, one for each experimental night. Each list contained twenty-four pairs of nouns that participants were asked to remember. Each participant had an immediate recall session where they were given one word of each pair, and they had to respond with the associated word. This process (learning and immediate recall) was repeated until subjects got at least fifteen pairs correctly (Plihal & Born, 1997).

[2] Mirror-tracing: Participants were given two different sets of six figures and one star, one for each experimental night, to be traced using a mirror as a visual access and an electric stylus that records draw time, number of errors and error time (Plihal & Born, 1997).

between them (Sperling et al., 2003). Face-name encoding in young subjects has been shown to activate the following brain areas: striate, fusiform, prefrontal cortices and the anterior hippocampus (Sperling et al., 2001). Sperling and colleagues (2003) recruited twenty-seven participants (i.e., ten young controls, ten elderly controls and seven Alzheimer's patients) who were asked to remember 84 face-name pairs during an encoding session for later testing. The face stimuli were a mix of people of different ethnicities between 18 and 90 years old and evenly split between both genders. The name stimuli were obtained from a public list of the most common names between 1910 and 1990. Immediately after MRI scanning, participants were tested using twelve face-name pairs, six were old (seen in encoding), four were new (never seen before) and two were repeated (shown multiple times during encoding). Participants were asked to correctly identify the names of face stimuli or to indicate if the face presented was new. The results showed a natural decrease in ability to identify faces and names correctly as the age of controls increased. During the encoding session, young controls had significantly more activation in the superior and inferior prefrontal cortices and less in the parietal cortices compared with the elderly controls. Alzheimer's patients had a significantly lower ability to identify both faces and names and they had greater hippocampal formation activation compared to elderly controls. Briefly, as people age there is a normal decline in declarative memory performance, which is more pronounced in Alzheimer's patients due to hippocampal activity impairments.

Mander and colleagues (2014) also used the face-name memory task in order to test declarative memory. They recruited thirty healthy adults, sixteen of which were young adults and fourteen were older adults (Mander et al., 2014). The participants had an eight-hour sleep opportunity and were scanned in an fMRI machine the next morning two hours after they have woken up while completing the encoding task using 120 face-name pairs. Thirty minutes later, they completed the recognition test outside the fMRI. As a result, older adults had significantly less hippocampal encoding activation compared to young adults. There was a higher hippocampal activation during successful associative encoding compared to unsuccessful ones. In addition, when Mander et al. controlled for age, gender, hippocampus structure, and neurocognitive status, fast sleep spindles in the prefrontal lobe significantly contributed to the accuracy in the tasks. Furthermore, they found that there is an association between fast spindles and next day hippocampal function that is important for next day learning. Aging decreases fast sleep spindles (Louis et al., 1992). This in turn decreases hippocampal activation, causing a decreased learning ability (Mander et al., 2014). However, age alone did not directly have an effect on learning or hippocampal activation. Taken together, declarative memory performance on the face-name association task is indirectly impacted by age and is proportional to hippocampus activation and fast sleep spindles density.

1.4 Cognitive tasks and sleep restriction

Recall and recognition are impaired after sleep loss (Cousins et al., 2018; Lo et al., 2016). In a study by Lo *et al*, teenaged male participants were asked to learn a prose passage by prioritizing the highlighted areas before being assigned to their respective groups: the controls (seven nights of nine hours of sleep opportunity) and the sleep restriction condition (seven nights of five hours of sleep opportunity) (Lo et al., 2016). The participants were asked to recall the passage at baseline immediately after learning, one week later and then at a six-week follow-up. In both groups, the highlighted portion was remembered best at all three time points; however, only the control group had a better recall at one-week follow-up compared to baseline. This implies that sleep duration post-learning plays a significant role in the retention of long-term memory since memory is being consolidated during this time.

Recognition is also impaired by sleep loss (Cousins et al., 2018). Cousins and colleagues wanted to simulate a stressful school week in teenagers by restricting participants' sleep and testing their memory (Cousins et al., 2018). They randomized the teenagers into two groups: the control group (nine hours of Time in Bed (TIB) for five nights) and the experimental group (five hours of TIB for five nights); both groups underwent two baseline nights and three recovery nights of nine hours of TIB. The morning after the fifth experimental night, participants were given an encoding task that consisted of stating whether the 160 images presented to them contained a building or not. After the third recovery night, both groups were shown 240 images (a mix of 160 old and 80 new images) and they were asked to indicate if they had previously seen the image. As a result, participants in the sleep restriction group had significantly lower accuracy during encoding and retrieval sessions compared to the controls. This impairment was not influenced by vigilance because sustained attention was similar for both groups after the recovery period. This suggests a decreased ability to retain new declarative memory following chronic partial sleep deprivation compared to the controls. Hence, sleeping longer to make up for previous sleep loss does not improve memory performance because it was not efficiently consolidated to begin with.

Additionally, one study randomized sixty university students into three groups to study their memory performances using a face-face association memory task[3] (Alberca-Reina et al., 2014). The control group had a sleep opportunity of eight hours (12:00 a.m. to 8:00 a.m.) for three nights. The two experimental groups either had a four-hour sleep opportunity (4:00 a.m. to 8:00 a.m.) on the first night (i.e., pre-training - encoding) or on the second night (i.e., post-training - encoding). The encoding session occurred at 6:30 p.m. on day one, and on days two and three at 11:30 a.m., subjects were asked to complete the retrieval tasks. However, on day two an interference session[4] was completed prior to the retrieval task. As a result, the control group had similar performance during both retrieval tasks. The pre-training sleep restricted group performed better with semantically congruent faces but worse with semantically incongruent faces, while the post-training sleep restricted group had an improved performance regardless of congruency. Furthermore, the pre-training sleep restriction group showed a significant improvement during both retrieval sessions regarding semantic congruency for recognition and recollection indices of accuracy (Hits, false alarms, misses, omissions, and lapses of attention). According to this finding, sleep restriction negatively impacts encoding more so than consolidation.

In summary, sleep loss has a negative effect on recall and recognition performances; specifically, it decreases performance during memory encoding.

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[3] The face-face association task: During encoding, 96 celebrity face pairs along with their professions were shown to participants. For each face-face pair, the profession was either semantically congruent or incongruent. When one face and profession appeared, participants responded whether they corresponded to the ones previously seen. During retrieval, 192 face pairs were presented and participants identified if they were previously coupled. If so, they responded either know (i.e., confident without recollection) or remember (i.e., seen during encoding) (Alberca-Reina et al., 2014).

[4] Interference task: the face pairs were mixed, however congruency remained the same (Alberca-Reina et al., 2014).

1.5 HIIT and Memory

High intensity interval training (HIIT) is defined as repetitive bouts of short to moderate duration exercise at an intensity that is greater than the anaerobic threshold and is interspersed with resting or light exercise recovery periods (Laursen & Jenkins, 2002). Different HIIT protocols have been derived previously, including sprint interval training (≤ 30 sec sprints at ≥100% VO_2max), modified low-volume HIIT (≤ 60 sec intervals at > 90% HRmax) and aerobic interval training (4-min intervals at 80-100% HRmax) (Shepherd et al., 2015). The duration of exercise varies in the evidence-base, with some studies using low volume HIIT (e.g., 8 minutes or 9.5 minutes) and some use high volume HIIT (e.g., 40 minutes) (Eather et al., 2019; Lunt et al., 2014; Weston et al., 2014). Research has shown that HIIT improves declarative memory (Fiorelli et al., 2019; Kao et al., 2018; Kovacevic et al., 2020; Sng et al., 2018). One within-subject study had a sixteen-minute HIIT intervention consisting of a ratio of eight bouts of one minute running to one minute self-pace walking at an intensity of 90% of their maximum heart rate (HRmax) (Kao et al., 2018). Participants performed a visual free recall[5] task to assess verbal memory and a modified flanker[6] task to assess inhibitory control (Kao et al, 2018). HIIT group performed better on the visual free recall task compared to the controls. During the modified flanker task, HIIT group had faster reaction time and less reaction time interference compared to resting conditions (Kao et al., 2018). In a study by Sng and colleagues (2018), participants were asked to rest or to engage in a high-intensity workout for fifteen minutes of increased intensity increments followed by a Rey Auditory Verbal Learning Test (RAVLT)[7]. Those in the exercise group recalled more words on trials six and seven of the RAVLT compared to the resting conditions. Furthermore, the exercise group had a smaller proportion of forgetting words and a greater proportion of word gains at follow-up compared to their baseline (Sng et al., 2018). In a study by Kovacevic and colleagues (2020), older sedentary adults were split into three groups. The first group had a 43-minute HIIT session that consisted of 4 x 4 minutes at 90-95% peak heart rate or 16-18+ on the Borg Rating of Perceived Exertion (RPE)[8] with an active recovery of three minutes at 50-70% HR peak (9-11 RPE). The other two groups either participated in continuous walking for 47 minutes of 70-75% peak heart rate (12-14 RPE) or in whole body stretching for 30 minutes. The HIIT condition yielded the best results for recognition memory performance compared to the moderate continuous training and stretching groups (Kovacevic et al., 2020). Similarly, another study investigated memory in Parkinson's patients by having them perform three different exercise sessions. The first

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[5] Visual Free Recall task (using Neuroscan Stim2 software): 160 words were randomly assigned into four 40-item word lists. Words were presented one at a time. After the last word, participants had 100 seconds to remember the list of words and then they completed an immediate recall session where they were asked to write as many words as possible within 100 seconds. Twelve minutes later they had a delayed recall session (Kao et al., 2018).

[6] Modified Flanker Task (modified version of the Eriksen flanker task): The participant responds to the congruency of white arrows on a black background of a screen. When the central arrow's direction faces the same direction as the left and right arrows, it is congruent and when it faces the opposite direction, it is incongruent. The participants have twenty practice trials, followed by two sets of 100 trials of equal number of congruent/incongruent responses (Kao et al., 2018).

[7] Auditory Verbal Learning Test (RAVLT): Over six consecutive trials, participants had to recall fifteen words. Afterwards, they were given a twenty-minute break followed by a seventh trial. Furthermore, gains (items not recalled on trial n that were recalled in trial n+1) and losses (items recalled in trial n, but not recalled in trial n+1) were documented.

[8] Borg Rating of Perceived Exertion (RPE): Is a scale that assesses the perceived level of exercise intensity. The scale ranges from 6 (very, very light) to 20 (very, very hard) and is indicate a heart range between 60 and 200 beats per minute (Borg, 1982).

session was a 25-minute HIIT training that consisted of an alternating 1:2 ratio of high and moderate intensity exercise on a stationary bike. The following session involved 30 minutes of continuous moderate-intensity training (MICT), and the final one was a 30 minute seated resting. As a result, both HIIT and MICT improved immediate auditory memory, but only HIIT improved attention and sustained attention (Fiorelli et al., 2019).

In summary, HIIT interventions are beneficial for recall and recognition memory compared to control conditions. Not only did participants in HIIT groups outperform the other groups in regard to recall and recognition, but they also displayed a greater short-term and sustained attention.

Mechanism of HIIT and exercise on brain and memory

There are a few mechanisms by which exercise can improve declarative memory. Exercise has been shown to increase the density and growth of the dendritic spine in the CA1 pyramidal neurons and the entorhinal cortex (Eadie et al., 2005; Stranahan et al., 2007). Dendritic spines may contain engram cells (Loprinzi et al., 2017; Ryan et al., 2015). Engram cells are fundamental for memory since they are a group of cells that get activated and reactivated by learning and recall cues, respectively (Tonegawa et al., 2015). Exercising prior to learning may facilitate priming (readiness to accept new information) of engram cells by increasing the excitability of these neurons before encoding (Loprinzi et al., 2017).

Furthermore, brain-derived neurotrophic factor (BDNF) plays a significant role in memory and learning. BDNF is highly sensitive to many types of exercises, and it regulates exercise-enhanced cognitive function (Vaynman et al., 2003, 2004). HIIT and moderate-intensity continuous training (MICT) have been shown to enhance BDNF expression (Freitas et al., 2018; Neeper et al., 1995). In humans, systemic BDNF increased after acute and chronic HIIT (Kujach et al., 2019; Murawska-Cialowicz et al., 2015). Both NMDA and calcium ion influx trigger synthesis and production of BDNF (Fernandes et al., 2017; Vaynman et al., 2004). Additionally, during HIIT, there is a greater blood lactate concentration beyond the lactate threshold. When lactate concentration is increased due to exercise, it activates NMDA receptors (Yang et al., 2014) and increases hippocampal neurogenesis (Lev-Vachnish et al., 2019). Recently, Okamoto and colleagues (2021) randomly assigned rats to Control (45-minute rest on a treadmill), MICT (20 m/min, 30 min/day, 5x/week on a treadmill with no incline), and HIIT (speed progression from 30-40m/min to 60m/min, 10 bouts of 30-second sprinting with no incline interspersed by 2.5 min of recovery, 5x/week) groups (Okamoto et al., 2021). The ratio of exercise time was 6:1 for MICT and 2:1-4:1 for HIIT. After four weeks of training, the duration of the all-out workout period was prolonged. Both HIIT and MICT led to enhanced spatial memory performance during the Morris Water Maze Test[9] and adult hippocampal neurogenesis (AHN). However, HIIT alone enhanced protein levels of hippocampal BDNF signaling. Likewise, Lee et al. (2012) found that resistance wheel running (similar to HIIT: high intensity and short duration) in rodents improved AHN and spatial memory. Briefly, HIIT is a time-efficient exercise that can lead to enhanced hippocampal memory and neurogenesis associated with hippocampal BDNF signaling.

[9] Morris Water Maze Test: Circular water maze tank with a hidden escape platform 1.5 cm below the water surface. To successfully complete the task the rats had to find the platform within 60 seconds, otherwise they failed the task.

1.6 HIIT and Sleep

There has been increasing interest in investigating the effects of HIIT on sleep. However, few studies have researched it, and the ones that did reported mixed findings. While some found that acute HIIT caused negative effects on sleep quality (Bonato et al., 2020; Vitale et al., 2017); others observed either no change or even positive effects on sleep quality (Jurado-Fasoli et al., 2020; Larsen et al., 2019; Myllymäki et al., 2011).

In some studies, evening HIIT has been shown to impair nighttime sleep. Bonato and colleagues (2020) randomized soccer players into two groups: HIIT and small side games, both taking place in the evening (at 8:00 p.m.). The HIIT condition had a 28-minute HIIT that consisted of 4 x 4 minutes at 90-95% HRmax interspersed with three minutes of active recovery at 50-60% HRmax. The control group had to play small-side games which consisted of four versus four players with no goalkeeper. Compared to small-side games, the HIIT group had poorer sleep quality on the following nighttime sleep, meaning that they had increased sleep onset latency (SOL: time it takes to fall asleep), decreased sleep efficiency (SE: sleep duration over time spent in bed) and increased fragmentation index (microarousals during sleep) (Bonato et al., 2020). Next, Vitale and colleagues (2017) conducted their study on two different soccer players' chronotypes (morning and evening types). All participants had to engage in an evening (8:00p.m.) HIIT protocol which consisted of a 4 x 4 minute interval training, running at 90-95% HRmax with three minutes of active recovery at 70% HRmax. The investigators found that the morning chronotype soccer players had poorer sleep quality, while the evening chronotype players had no change in their sleep quality after the evening HIIT intervention. More specifically, actual sleep time[10] (AST), actual awake time[11] (AWT), SE, % of immobility time (IT), and movement time (MT) were negatively affected in morning chronotypes (Vitale et al., 2017). Another similar study was conducted on soccer players that were neither morning nor evening chronotypes (Vitale et al., 2018). As a result, there were no significant changes in any of the objective (actigraphy) and subjective parameters of sleep quality, tiredness or sleepiness at baseline, throughout and after the experiment. This suggests that it is important to take into consideration the chronotype of participants when conducting evening HIIT and sleep studies.

Other studies have shown positive effects of HIIT on sleep quality (Larsen et al., 2019; Myllymäki et al., 2011). In a randomized counterbalanced study by Larsen, et al., inactive middle-aged male participants completed 30 minutes of HIIT cycling (60 seconds of 100%VO_2max work to 240 seconds of 50%VO_2max recovery ratio) between 7:00 p.m. and 8:00 p.m. (Larsen et al., 2019). The investigators found an increase in NREM sleep and a decrease in REM sleep compared to baseline. Additionally, sleep was not disrupted in any of the following sleep parameters: time in bed (TIB), total sleep time (TST), sleep efficiency (SE), sleep onset latency (SOL), wake after sleep onset (WASO), N1, N2 and arousals. In another study, physically fit young adults were counterbalanced to a late-night cycling of 100 Watts (males) or 25 Watts (females) to exhaustion, which started at 9:00 p.m. and lasted on average 35 minutes (Myllymäki et al., 2011). On a following day, they were asked to avoid any type of exercise. After the intervention, NREM sleep increased in the exercise condition in comparison to the resting condition group. However, there

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[10] Actual sleep time[10] (AST): the time between beginning and end of sleep, which is calculated by adding up the amount of sleep epochs and by multiplying it by the length of the epoch in minutes (Vitale et al., 2017).
[11] Actual awake time (AWT): the total time spent awake according to the epoch-by-epoch wake sleep categorization (Vitale et al., 2017).

was no difference between the conditions in regard to subjective and actigraphy sleep quality. Overall, an acute bout of evening high intensity exercise may benefit sleep according to a recent systemic review and meta-analysis by Frimpong et al. (2021). They assessed 15 articles each with an experimental design. They researched the effects of an acute bout of evening high intensity exercise on subjective and objective sleep quality in physically fit and sedentary good sleepers between the ages of 18 to 50 years. Other than having shorter REM sleep duration after exercising half an hour to four hours before bedtime, there were no other sleep disruptions observed compared with no-exercise controls. In fact, they found that high intensity exercise two hours before bedtime improved some sleep factors, such as reducing sleep onset latency and prolonging sleep duration.

In another daytime study, sedentary adults were split into three groups: HIIT, HIIT and whole body electro-myostimulation, and control group (Jurado-Fasoli et al., 2020). The HIIT intervention was performed twice a week for twelve weeks, for a duration of 45 to 65 minutes per week at an intensity of >95% (session 1) and of >120% (session 2) of their maximum oxygen uptake. The control group training consisted of the aerobic sessions which lasted 150 minutes per week at 60-65% of their heart rate reserve (HRR) and the resistance training which lasted 60 minutes per week at 40-50% of their one-repetition max (1-RM). There was no statistical significance between groups on sleep quality and all intervention groups showed a lower score on the Pittsburgh Sleep Quality Index (PSQI). Another study by Eather and colleagues (2020) examined university employees by placing them into a wait-list condition or a work-HIIT condition. The work-HIIT condition had supervised trainings two to three sessions per week for eight weeks. The researcher used a 30-second work to 30-second rest ratio interval and increased it to a 40-second work to 20-second rest ratio between weeks five and eight. On the eighth week, the wait-list condition executed the work-HIIT exercise (Eather et al., 2020). The participants in the work-HIIT group had a high level of satisfaction across all sessions. There was also a small to medium beneficial effect on cardiorespiratory fitness and work productivity, and a large beneficial effect for muscular fitness, HIIT self-efficacy, sleep duration and autonomous motivation to exercise. In addition, participants in the HIIT group enjoyed all their workout sessions, which may have been due to the time efficiency of their HIIT workout and the autonomy it provided.

To conclude, there are a limited number of studies investigating evening HIIT and sleep. There is growing interest in HIIT, as it increases motivation to exercise, does not require equipment, is enjoyable, satisfying, and is perceived to be valuable (Eather et al., 2019). The parameters of the HIIT exercises vary throughout the above-mentioned studies (i.e., different work:rest ratio, intensities, duration, and type of exercise, etc.). This may explain why there are mixed findings regarding the impact of HIIT exercises on sleep variables. The World Health Organization's 2020 exercise and physical activity guidelines recommends 150 to 300 minutes of moderate intensity, or 75 to 150 minutes of vigorous intensity exercise per week for young and older adults (Bull et al., 2020). In some cases, SOL, fragmentation index, SE, AST, AWT, % IT, and MT were negatively impacted after evening HIIT. Other cases, evening HIIT protocols showed no disruption of sleep, while others showed positive effects of sleep such as more NREM sleep and less REM sleep.

1.7 Exercise, partial and complete sleep deprivation and memory

Most human studies that explored sleep deprivation added exercise as an additional stressor to cognitive function rather than investigating it as an intervention method to improve memory.

For example, Scott et al. had participants exercise every two hours throughout the night (Scott et al., 2006), while Hurdiel et al. restricted sleep during an ultra-endurance event which lead to cognitive impairments (Hurdiel et al., 2015). However, one study by Slutsky and colleagues (2017) conducted a 24-hour sleep deprivation study on active healthy young adults who were randomized into two groups after being sleep deprived: the controls and the exercise group. In this study, the participants completed the psychomotor vigilance test (PVT - measured twice)[12] and three verbal working memory tasks with increasing cognitive load (Sternberg memory tasks - Control, Letter, PLUS)[13] (Slutsky et al., 2017). All participants had a baseline night (at home), then they were tested in the morning (in the lab), they went back home (no exercise/napping allowed) and in the evening (back in the lab) they stayed up until the next morning. At this point, they were tested again before and after either sitting down for fifteen minutes on a stationary bike (control) or cycling at 35%-40% of their heart rate reserve (experimental group). As a result, there was an increase in reaction time and lapses, but no change in accuracy as a function of sleep deprivation. There was no difference in performance between the intervention group and the controls in the PVT and the Sternberg memory task.

In summary, limited studies have researched the effects of exercise on long-term memory after sleep restriction. To the best of our knowledge, in humans, researchers have mainly studied the detrimental effects of grueling exercise sessions on memory and attentional processes after a 24-hour sleep deprivation. Thus far, one study examined a brief low intensity intervention post-sleep deprivation, which did not have an effect on cognitive performance.

[12] Psychomotor vigilance test (PVT): It is a five-minute task where participants are instructed to click on the mouse as soon as they notice that the empty circle on their screen begins to fill. The average reaction time above 100ms was calculated. Any reaction time below 100ms was considered a false alarm and any reaction time longer than 500ms was considered a lapse (Slutsky et al., 2017).

[13] Sternberg memory tasks (Control, Letter, PLUS): Four capital letters (**Controls –** Same**; Letter –** different) were presented. For the **PLUS task**, two capital letters were presented, and participants were asked to pay attention to the first letter while thinking of the following alphabetical letter. Then the letters disappeared, leaving a fixation point. This was followed by a lower-case letter. Participants either right (for no match) or left (for match) clicked the mouse (Slutsky et al., 2017).

1.8 Rationale

During busy times, adults are less likely to exercise and more likely to decrease sleep time to less than the recommended number of hours (Ahrberg et al., 2012; Lines et al., 2021; Zunhammer et al., 2014). Hence, more studies are needed to find possible solutions to maintain cognitive function in the face of sleep restriction. Stimulants (e.g., caffeinated drinks, energy drinks, Adderall, etc.) have been used to enhance cognitive function (Plumber et al., 2021). When misused or abused, stimulants can decrease sleep quality, quantity, increase fatigue and risk of insomnia (Plumber et al., 2021). High intensity interval training has shown promising results in improving declarative memory (Fiorelli et al., 2019; Kao et al., 2018; Kovacevic et al., 2020; Sng et al., 2018). This may be a non-pharmacological alternative and may compensate for the detrimental effects of sleep loss.

The 15-minute HIIT protocol was chosen based on the World Health Organization's 2020 exercise and physical activity guidelines (Bull et al., 2020), which recommend at least 150 minutes of moderate intensity, or 75 minutes of vigorous intensity exercise per week for young and older adults. A 15-minute bout of HIIT was chosen based on review of the literature, and to reflect real-world conditions, in which university students and busy young adults may be more likely to engage in low dose, 15-minute HIIT workouts throughout the week to meet this recommendation (Eather et al., 2019). Similarly, Bosch et al (2021) also utilized an acute bout of 15-minute HIIT exercise in their study of the effects of moderate and high intensity exercise on memory and BDNF in men aged 18-34 (Bosch et al., 2021). Similar to Eather et al (2019), we used a 1:1 work to rest ratio with a short work interval period (20 seconds of work, 20 seconds of rest), which is ideal for inactive or less fit individuals including university students who do not meet the physical activity recommendations (Eather et al., 2019).

An evening HIIT protocol was chosen for a number of reasons. An evening time may be more convenient for individuals in our study's age group and occupation (students) to exercise (Buman et al., 2014). Additionally, a meta-analysis by Stultz (2019) found that low to moderate-intensity exercises completed a few hours to bedtime did not disturb subsequent night's sleep, but rather benefited it (Stutz et al 2019). Furthermore, cross-sectional studies (Brand et al., 2014; Buman et al., 2014) and a meta-analysis of experimental studies (Frimpong et al., 2021) have also found that evening vigorous or high-intensity exercises do not disrupt objectively measured sleep. Indeed, according to a cross-sectional study of 1000 adults (23-60 years old) from the 2013 National Sleep Foundation Sleep in America Poll, evening vigorous intensity did not change subsequent nighttime self-reported sleep quality (i.e., no change or improved quality and duration) (Buman et al., 2014). Furthermore, Pontifex et al. (2016) showed that the timing of the exercise relative to the timing of the memory task matters. Pontifex et al found that having participants exercise an hour before an encoding session improved memory performance more than having memory encoding take place prior to exercise (Pontifex et al., 2016).

The time of evening for the HIIT exercise was chosen based on review of the literature. Based on the findings of a previous meta-analysis (Frimpong et al 2021), an early evening HIIT was administered that allowed 2.8 – 3.8 hours of recovery periods between the cessation of the HIIT and the memory tasks (encoding session). When cognitive tasks are conducted immediately after exercise, the size of the effect following exercise is affected by the amount of time that passes between exercise and cognitive testing and the intensity of the exercise such that a high intensity exercise enhances cognition if there is a delay between the exercise session and the cognitive task (Chang et al., 2012). Moreover, the acute effects of long-term memory is more durable (than other cognitive measures) and that long-term memory of information learned before the acute exercise could be observable even after a long delay (Labban & Etnier, 2018). Given that participant in this study had light to moderate activity levels, a relatively longer recovery period was necessary. Additionally, individuals need at least 2-hours to recover from a HIIT intervention (e.g., cerebrovascular metrics alterations) (Burma et al., 2020).

For our study, a face-name association task was selected to test declarative memory, based on review of the literature. A previous study by Mograss et al (2020) used a recognition memory task with no immediate recall. For this pilot study, however, we wanted to assess immediate recall (encoding), delayed recall (long-term memory) and consolidation (the difference between the two tasks) with a face-name association task. This task has previously been used to investigate declarative memory (Mander et al., 2014; Sperling et al., 2003).

The original plan was to run an in-lab study using a 40-minute moderate-intensity protocol on a bike ergometer and collecting objective sleep measures (similar to Mograss et al., 2020). Given the recent COVID-19 pandemic and the related public health measures and restrictions, we needed to create a remote-pilot study by using an HIIT protocol which did not require laboratory-based equipment. Indeed, the facilities were closed, and it was no longer feasible to continue with the planned lab-based protocol. Therefore, alternative home-based exercise methods were warranted to adapt to these restrictions. Hence, a HIIT video was created as an affordable protocol not requiring equipment nor in-person supervision. To the best of our knowledge, there are no studies investigating the combined effects of acute sleep restriction and evening HIIT on memory performances in healthy young adults.

2. Objectives & Hypotheses

2.1 Objectives

1) The primary objective of this pilot study was to assess the feasibility, acceptability and safety of the HIIT, including maintaining the intensity (i.e., 85-95% of HRmax) and the fidelity of the exercise program. To make sure the memory task is the appropriate level of difficulty for this population and that participants adhere to the sleep schedules.

2) The secondary objective was to determine whether a brief bout of HIIT exercise alleviates declarative memory impairment caused by acute sleep restriction compared to controls and to calculate the effect sizes of the various conditions on main outcomes.

We conducted exploratory analysis to determine if group differences in memory performance are related to motivation level, performance effort & difficulty and subjective sleepiness prior to the tasks.

2.2 Hypotheses

1) We hypothesized this protocol would be feasible. We believed that participants would be able to complete the exercise protocol safely and maintain the exercise intensity throughout the session. We expected the memory task to be challenging and to have a high adherence rate to the sleep schedules.

2) We expected participants in the exercise HIIT groups to have a better memory performance compared to participants in the counterpart non-HIIT groups.

3. Methods

3.1 Study design

The design of this pilot study was a factorial design with two factors: exercise and sleep. The participants randomly assigned to one of four groups: 1) Exercise and ~5.5h sleep opportunity (HIITS5), 2) No exercise and ~5.5h sleep opportunity (S5), 3) Exercise and ~8.5h sleep opportunity (HIITS8), and 4) No exercise and ~8.5h sleep opportunity (S8).

This protocol was a fully online/remote study. All the necessary materials (HIIT video, instructions, memory tasks, etc.) were sent to participants via email. Online links to the consent form, the screening questionnaires and the sleep diary were sent out to participants to fill out. Participants completed the protocol in their homes and therefore needed to have enough space to exercise, a quiet room with no distractions and a computer that is compatible with the memory tasks.

3.2 Participants

We recruited a total of 88 healthy, average sleepers (22 ± 1 per group), between the ages 18 and 35 years, who were sedentary (with low-to-moderate levels of physical activity). Individuals with medical conditions, psychological issues, sleep disorders or individuals who took medications that influence sleep were excluded from the study (Table 1).

Advertisements included posting ads on the PERFORM Centre website and on social media platforms such as Facebook and Instagram. Once we received emails from interested individuals, we sent them two links. The first contained the on-line consent form and the second included the screening questionnaires. Once completed, to assess if individuals met the eligibility criteria, a trained volunteer scored the questionnaires using cut-off scores (Table 1). Eligible participants filled out a sleep diary for at least four days prior to the study and the following morning. We ensured participants were maintaining a consistent sleep schedule, meaning their bedtime was prior to 12:30 a.m. and wake time was eight to nine hours later. If they were unable to maintain a consistent sleep-wake schedule, they were excluded.

Sample size calculations

A sample size calculation was done based on a previous study (Mograss et al., 2020) that found a significant interaction ($p = 0.014$, $np^2 = 0.053$) between moderate intensity exercise and a nap (60-minute NREM nap, starting from sleep onset latency) on declarative memory. Using a G*power software (version 3.1) and inputting the $np^2 = 0.053$, the estimated effect size is 0.237 ($\alpha = 0.05$) for a total of 143 participants was required to determine an interaction between HIIT and sleep on declarative memory. Then using our sample size of 88 participants and inputting the $np^2 = 0.049$ from the significant delayed recall interaction ($p = 0.042$), the estimated effect size was 0.227 ($\alpha = 0.05$) and the power of this pilot study was 55.8%.

Table 1: Exclusion criteria

Exclusion Criteria	Grounds for exclusion
1. Being outside the target age range (18-35 years old)	
2. Evidence of chronic medical condition or mental disorder	BAI score > 26 (1993 ref.) BDI-II score > 20
3. Evidence of sleep disorders	ISI score > 14 SBQ score > 5 indicating high risk of OSA UNS score > 14 RLS ESS > 11 PSQI > 7 Clear irregularities in sleep/wake cycles during sleep diary screening
4. Regular use of psychotropic or hypnotic medication	Self-report on sleep diary
5. Shift work or having travelled through more than one time zone (one time zone is only one hour difference) in the past month	
6. Regular vigorous intensity exercise	IPAQ score > 3000
7. Alcohol, marijuana & cigarette smoking	less than 10/week (smoking), occasional (free for the past week marijuana), alcohol (5/week)

Note. BAI= Beck Anxiety Inventory, BDI-II= Beck Depression Inventory, IPAQ= International Physical Activity Questionnaire, RLS = Restless leg syndrome, PSQI = Pittsburgh Sleep Quality Index, ESS = Epworth Sleepiness Scale, ISI= Insomnia Severity Index, OSA= Obstructive sleep apnea, SBQ= STOP-Bang Questionnaire, UNS= Ullanlinna Narcolepsy Scale.*If the participant gave any indication that they matched any of the exclusion criteria during the on-line pre-screen, they were deemed ineligible to participate.

3.3 Screening

We screened for participants' medical, psychological, sleep and physical status.

Medical History: In order to screen participants' medical background, they filled out the Adult Medical History Form and the Get Active Questionnaire (GAQ) (*Adult-Medical-History-Form.Pdf*, n.d.; *GAQ_ReferenceDoc_2pages.Pdf*, n.d.). The questionnaires helped determine whether the participants had medical problems that may have hindered their ability to exercise or perform the procedure. Participants were provided a list of medications, allowing us to exclude individuals who took medications that influenced their sleep or any cardiovascular health conditions.

Sleep History: The sleep questionnaires included the Insomnia Severity Index (ISI), Pittsburgh Sleep Quality Index (PSQI), Restless leg syndrome (RLS), Epworth Sleepiness Scale (ESS), Morningness-Eveningness questionnaire (MEQ), Stop Bang Questionnaire (SBQ), Ullanlinna Narcolepsy Scale (UNS).

The ISI is a seven-item questionnaire used to screen insomnia (Chahoud et al., 2017; Morin et al., 2011). Chronic insomnia is defined by the inability to fall asleep or to maintain sleep for at least three nights per week over a three-month period, associated with daytime function impairment (Roth, 2007). The ISI scores ranging from 0-7, 8-14, 15-21 and 22-28 indicate no clinical insomnia, mild insomnia, moderate insomnia and severe insomnia, respectively (Morin et al., 2011). We used a cut-off score above 14 for our exclusion criteria. The PSQI is a nineteen-item questionnaire, used to assess subjective sleep quality and sleep disturbances over the past month (Buysse et al., 1989). Scores range from 0 to 21 indicating no difficulty sleeping to severe difficulty sleeping (Buysse et al., 1989). For the PSQI, our cut-off score was above 7. RLS is a condition whereby individuals present all four of the following clinical symptoms: 1) urge to move leg at rest, 2) increasing urge to move limb during prolonged periods of inactivity, 3) relieved after movement, and 4) urge is worse in the evening or night (Allen et al., 2003). The Cambridge-Hopkins diagnostic questionnaire for RLS (CH-RLSq) is a seven-item questionnaire that assesses the focal nature of experience, complaints of restless feeling, degree the feeling could not be resisted, the past circadian pattern, RLS frequency and pain complaints in addition to all four diagnostic criteria (Allen et al., 2009). Scoring is defined as having RLS or not and those who had it were be excluded. The SBQ is an eight-item screening tool used to assess the risk of obstructive sleep apnea (OSA) (Chung et al., 2012; Hu et al., 2019). OSA is defined by decreased or lack of airflow during sleep causing a decrease in oxygen saturation and is often terminated by arousals during sleep (De Backer, 2013). The more questions answered "Yes" in the SBQ, the higher risk of apnea. Scores ranging from 5 to 8 indicate a high probability of moderate or severe OSA (Chung et al., 2012). Hence, our cut-off for this questionnaire was 5 and higher. The UNS is a tool containing eleven items used to screen for narcolepsy characterized by severe daytime sleepiness and an uncontrollable muscle weakness or paralysis during the day (i.e., Cataplexy) (Hoshino et al., 2019; Hublin et al., 1994). Our cut-off score for UNS was above 14, which is suggestive of Narcolepsy with Cataplexy (Hublin et al., 1994). The ESS, an eight-item questionnaire, measures subjective daytime sleepiness and the likelihood of falling asleep during normal daytime activities such as watching TV or driving (Johns, 1991). The ESS has a score range of 0 to 10 that indicates normal sleepiness, while a score of 16 and above indicates severe sleepiness; therefore, we used a cut-off score above 11. The MEQ is a nineteen-item tool used to assess individuals' chronotype

(Horne & Ostberg, 1976). Individuals were characterized as morning chronotype (score 59-86), evening chronotype (score 16-41), or neither chronotype (score 42-58).

Psychological History: Participants were screened for psychological symptoms with the Beck Depression Inventory II (BDI-II) and the Beck Anxiety Inventory (BAI). The BDI-II evaluates depressive symptoms (Beck et al., 1996). It contains twenty-one items that assess depressive symptoms ranging from 0 (not indicative of depression) to 3 (highly indicative of depression). Scores below 19 suggests minimal to mild depression, while a score of 20 or 21 suggest moderate depression. The cut-off score for BDI-II was 20 and over. Next, BAI is a twenty-one-item questionnaire that measures the severity of anxiety symptoms experienced in the past month on a scale of 0 (not at all anxious) to 3 (severely anxious) (Beck et al., 1988). Scores classify anxiety as minimal (0-7), mild (8-15), moderate (16-25) and severe (26-63) (Beck & Steer, 1993). For this study, the cut-off score for BAI was 26 and over.

Other Questionnaires: The International Physical Activity Questionnaire (IPAQ) was administered to screen participants physical activity levels within the past week (Craig et al., 2003). A score below 600 metabolic equivalent of task minutes per week (MET-min/week) is considered low physical activity or inactivity, a score range of 600-2999 MET-min/week is considered moderate physical levels, and a score of 3000 MET-min/week and over is considered vigorous level of physical activity (IPAQ International Physical Activity Questionnaire, 2005). The cut-off score for the IPAQ was 3000 MET-min/week.

The Edinburgh Handedness Inventory (EHI) determines if the participants are right-handed, left-handed or ambidextrous (Oldfield, 1971). It was used to determine keyboard arrangement in the task.

3.4 Experimental Procedure

A few days before the study, participants received instructions along with links to download the Face-Name task folder and Psycho.Py3 V.3.0.7 program on their computer. The participant and a research assistant then had a zoom meeting where the participant ran a practice session for the tasks. Furthermore, the participants received a link to a fifteen-minute HIIT video with instructions (e.g., wear proper attire and have water). Up to three days before the study night, a zoom meeting was scheduled between the participant and a kinesiologist to practise each exercise at low intensity and volume to ensure proper technique and safety. During this orientation session, participants were made aware that they should report any signs or symptoms they experience during the exercise intervention from a checklist we provided them (Appendix B). If this occurred, participants were told to end the HIIT exercise. The day before the study, participants were asked not to drink any stimulating drinks past 12:00 p.m., such as coffee, tea, hot chocolate, energy drinks and the like until they had completed the study. They were asked to avoid exercising and taking a nap the day of and to avoid consuming alcohol 24 hours before the experimental night until the study’s completion. This was monitored by self-report and a follow-up interview with the participants.

Exercise/Rest:

The day before the study night participants were randomized to one of four groups: $HIITS_5$ (experimental group), S_5 (control 1), $HIITS_8$ (control 2) and S_8 (control 3) (Figure 1). Depending on their respective groups, at 7:00 p.m., participants were either not engage in any physical activity (rest) or had a fifteen-minute HIIT (Tabata style) that consisted of six interval training exercises (Side jump skating, squat jump, caterpillar walk & shoulder tap, reverse lunge & hop, burpees, mountain climbers) of 20 seconds each repeated three times at 85-95% of HRmax or an RPE score of 15-19 (Figure 2; Figure 7, Appendix A).

Between each repetition there was a 20-second passive rest period (Figure 2). The warm-up and the cool down sessions were included in the same video. The warm-up lasted two minutes containing four 30 seconds exercises (i.e., running on the spot, jumping jacks, high knees and squats). And the cool down included three stretching exercises of 20 seconds each (i.e., shoulder stretch, quadriceps stretch and forward bending keeping the legs straight) plus five repetitions of respiratory sequence. Immediately after the HIIT intervention, participants were asked to fill out a four-item questionnaire that provided us feedback on the HIIT (Appendix B).

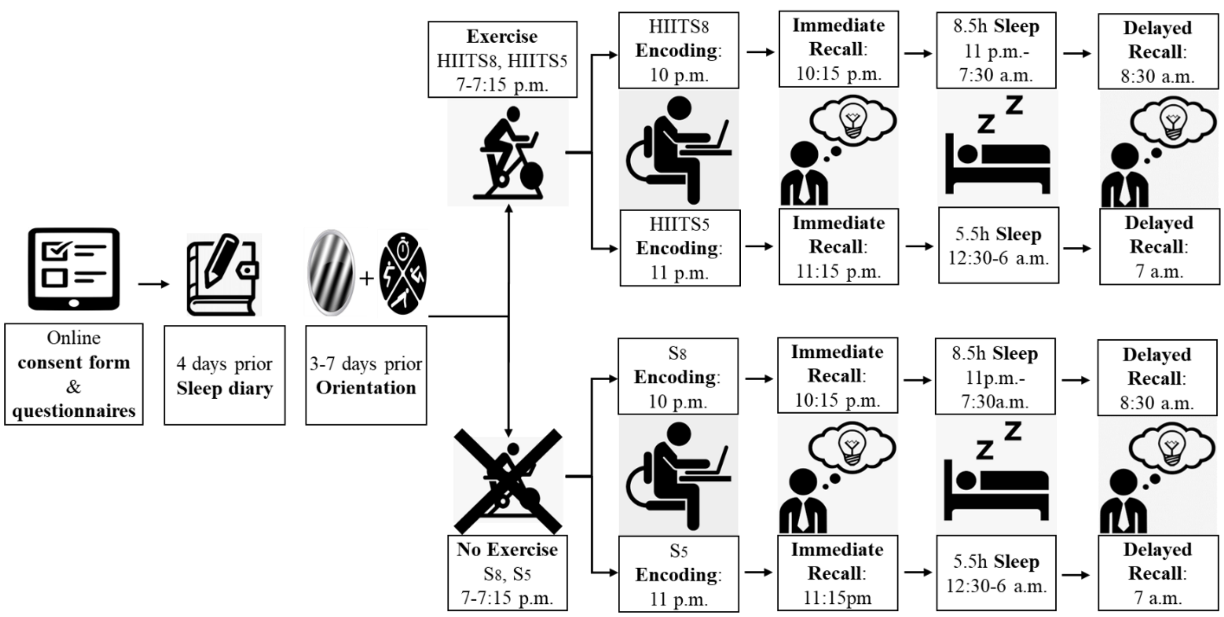
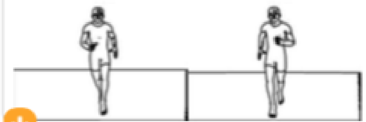


Figure 1: Remote, on-line home-Based Protocol

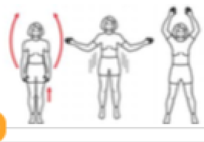
Warm up

1A : Running on spot



Week	Phases	Duration
1	1	00:30

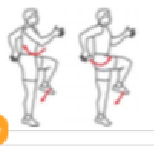
1B : Jumping Jack



- 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.

Week	Sets	Duration
1	1	00:30

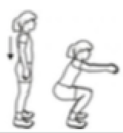
1C : High Knees On Spot



- 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.

Week	Sets	Duration
1	1	00:30

1D : Squat

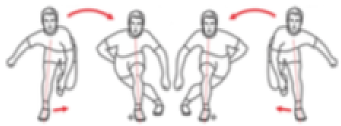


- Feet shoulder width apart, go down until your knees are at 90°. Raise your arms to shoulder height.

Week	Sets	Duration
1	1	00:30

Tabata

1A : Side Jump Skating + touch ground

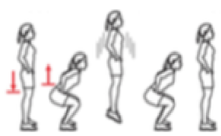


- Standing, start on 1 foot body tilted in skating style. Head above the support foot, jump sideways to the other foot while swinging your arms and touch the ground. Weight on the front part of the foot. Keep your back straight, looking forward.

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

Week	Sets	Duration	recovery
1	3	00:20	00:20

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)

Week	Sets	Duration	recovery
1	3	00:20	00:20

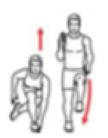
1C : Caterpillar Walk and Shoulder Tap

- 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.

Week	Sets	Duration	recovery
1	3	00:20	00:20

1D : Reverse lunge and hop

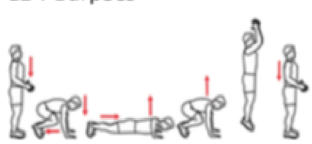


-Take a step back and bend both knees. Go back up on your front leg and hop while lifting your back knee up. Alternate both legs.

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

Week	Sets	Duration	recovery
1	3	00:20	00:20

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.

Week	Sets	Duration	recovery
1	3	00:20	00:20

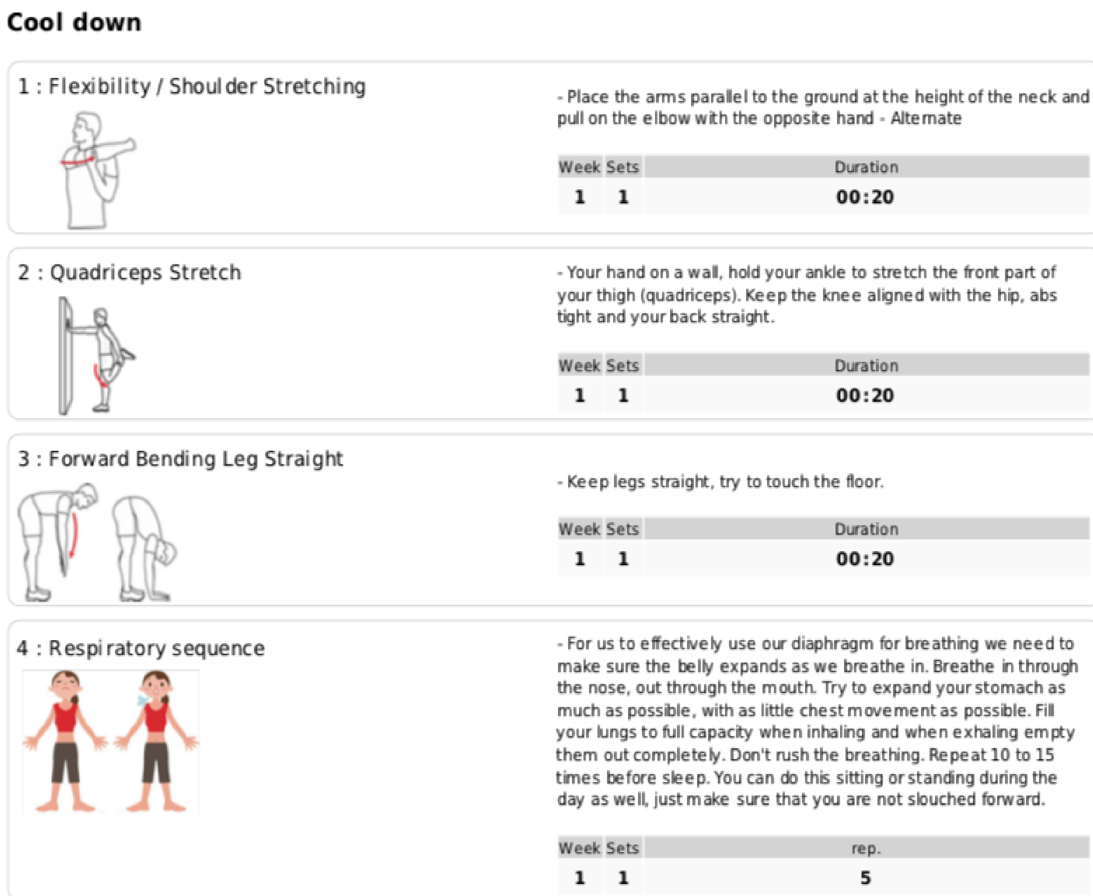


Figure 2: HIIT warm up, Tabata, cool down

Encoding and immediate recall tasks:

At 9:30 p.m. (for S_8 & $HIITS_8$) or 10:30 p.m. (for S_5 & $HIITS_5$), the research assistant and the participant joined a zoom meeting. During this meeting, the participant consented verbally a second time, while they were being recorded. Before starting the task, the research assistant gave participants instructions on each face-name memory task and answered any questions participants might have.

The practice encoding and the encoding tasks had similar instructions. Participants were asked to memorize face-name pairs that appeared on their computer screen for five seconds at a time (Figure 3). Then the following screen included the question, 'does the name match the face?' where participants answered 'yes' or 'no' using the left and right arrow keys. Once participants gave an answer, the following face-name pair appeared and so on. The practice encoding had eight face-name pairs, while the encoding task had 80 face-name pairs (40 F, 40 M). At the end of the encoding task, participants were asked to rate their sleepiness using the Karolinska Sleepiness Scale (KSS) by pressing a number key on their keyboard between 1 and 9 ranging from extremely alert to very sleepy (Figure 8, Appendix A). Once completed, participants were allowed to take a five-minute break before starting the practice retrieval.

The practice retrieval and retrieval tasks had similar instructions. However, the practice retrieval helped participants get familiar with the task and the faces used were the ones seen during the practice encoding task plus a new face (Figure 3). This time participants had to get used to using the ‘u’, ‘i’, and ‘o’ keys on their keyboard to select the appropriate name that corresponded to the face or to press the ‘p’ key to select the ‘new’ option if they had not seen the face before. During the retrieval tasks, participants were asked to respond as quickly and accurately as possible. There were 80 old faces (seen during the encoding) and 40 new faces for a total of 120 faces (60 M, 60 F). Within the three name options, all faces included a lure name (i.e., name that was seen during the encoding, but did not match the face on the screen). At the end of the immediate retrieval task, participants were asked to rate on three separate scales ranging from 0 to 10 their motivation to complete the task, their performance, and the difficulty of the task. Finally, they were asked to rate their sleepiness using the KSS.

Sleep:

The participants in the average sleep condition were given an eight to nine-hour sleep opportunity (8.5 hrs +/-30min) from ~11:00 p.m. to 7:30 a.m. (Figure 1). The participants in the sleep restriction condition were given a five to six-hour sleep opportunity (5.5 hrs +/-30min) from ~12:30 a.m. to 6:00 a.m. The research assistant called participants at bedtime and wake time to ensure that participants were following the protocol. Participants’ whose time in bed and total sleep time were not within the expected ranges were excluded from the analysis.

Delayed recall:

An hour after participants woke up, at 7:00 a.m. ($HIITS_5$ and S_5) or at 8:30 a.m. ($HIITS_8$ and S_8), they joined a zoom meeting with the research assistant. During this meeting, the participants completed the practice retrieval and the delayed retrieval with the same set of instructions and scales as the previous night. The delayed retrieval had a different set of 40 new faces compared with the immediate retrieval. After the tasks were complete, there were three .csv files that were generated from Psycho.Py. Participants attached these files to an email and sent it to our email address: exslprestricted@gmail.com. On this morning, the research assistant asked participants to fill out the sleep diary for the last time. At this point, the study was complete, and participants received monetary compensation by mail.

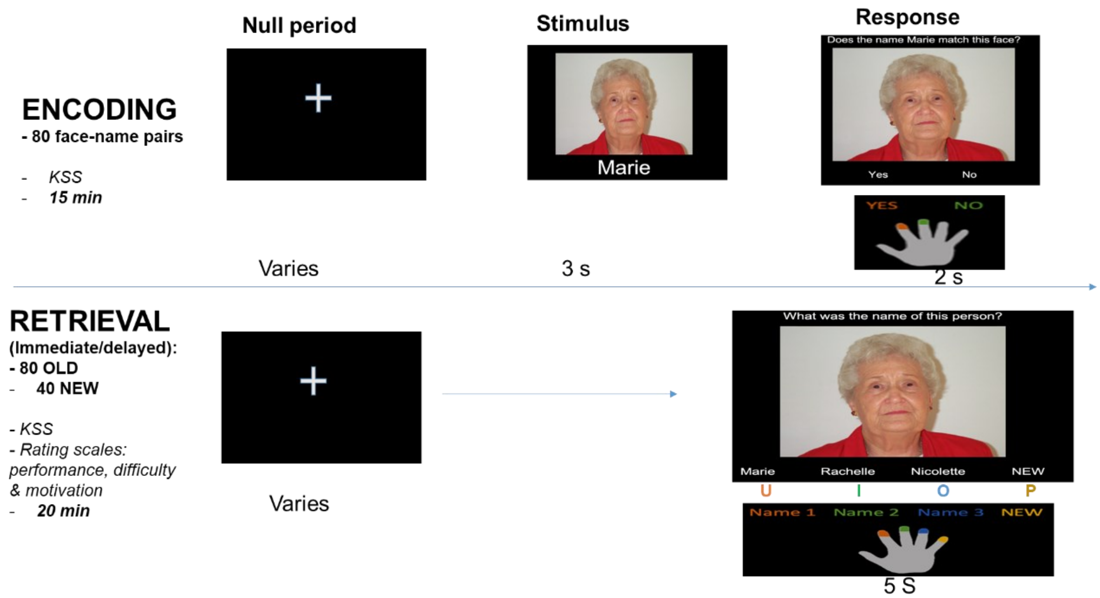


Figure 3: Face-name association memory task.

Feasibility and Adherence:

The feasibility of the study was assessed based on the proportion of participants completing the study, the dropout rate, the proportion of subjects completing the HIIT protocol at the prescribed intensity level (85-95% of age-predicted HRmax), with or without adverse effects, and the self-reported performance, motivation and difficulty of the recall tasks. In addition, summary of participants' feedback rating of the HIIT intervention (i.e., enjoyment of the HIIT, motivation to complete the HIIT, difficulty level, adoption of the HIIT to their daily routines) was assessed. We also assessed participants' adherence to our study procedures. We reviewed participants' sleep diaries on a daily basis to ensure that they adhered to the study sleep schedule. In addition, we assessed intervention adherence (or intervention fidelity), or how similarly participants performed the exercise during the study compared to the exercise designed in our protocol, by observing their performance of the exercises during the orientation and study night and assessing it with a custom checklist (Bellg et al., 2004). We monitored and recorded the participants' perceived exertion (Borg RPE) at every session to ensure adherence to the prescribed exercise intensity. The HIIT session was recorded via video conferencing (i.e., zoom) and those videos were reviewed following the HIIT to assess adherence to the protocol.

Potential adverse effects during or after HIIT were monitored. Participants were given a checklist that included signs and symptoms they may have experienced during the HIIT protocol and that would be cause for cessation of the HIIT (Appendix B). The level of difficulty of the memory task was assessed with self-reported Likert scales on difficulty of the task and the performance during the task. In addition, we wanted to see if there was a ceiling effect. The sleep schedule adherence was assessed using the sleep diary entries.

4. Statistical Analysis

Participants' demographic and screening questionnaire scores was summarized for each group as means and standard deviations (SD). The means of all sleep diary variables were calculated for four nights prior to the study night and for the experimental procedure night. Normality of distribution for all variables was assessed using Kolmogorov-Smirnov and Shapiro Wilks tests. Variables satisfying normality criteria were evaluated using ANOVA and Pearson Correlations; otherwise, we used the Kruskal Wallis test and Spearman's Correlation. Two-way ANOVA was used to test the interaction between sleep condition (5.5 hours vs. 8.5 hours sleep opportunity) and exercise condition (HIIT vs. No exercise) on the overnight change in memory recall. Pairwise comparisons tests followed when statistically significant differences was achieved. For each subjective scale and subjective sleepiness measures, a one-way ANOVA was used to compare means, followed by a post-hoc test for significantly different results. Pearson's correlation was used to investigate the associations between sleep variables and performance metrics. Cohen's d and partial eta squared was used to calculate the effect size. One-Way ANOVAs were generated to assess the differences of the difficulty, performance and motivation of the memory task between groups. The averages accuracy was calculated.

We used descriptive statistics to calculate the proportion of dropout, adherence to the sleep schedule, and participants adherence to completing the HIIT.

5. Results

5.0 Description of Study participants

Table 2 shows the demographic information and screening questionnaire scores. A total of 88 healthy participants were successfully recruited and randomized into four groups: $HIITS_5$, $HIITS_8$, S_5, S_8. Out of the total number of participants, 82% were females. Similar to a previous study in our lab by Mograss et al. (2020), who had a majority of female participants (i.e., 61%). The average age of participants was 24.6 ± 4.2 years old and was similar between groups ($p = 0.259$). The mean BMI was 22.3 ± 3.0 and was similar between groups ($p = 0.916$). All participants met the normal (or mild) cut-off scores for adults on all the screening questionnaires based on the literature. The sleep, psychological, chronotype and physical activity questionnaires' scores were similar between groups ($p > 0.05$), except for the PSQI which was significantly different between groups ($p = 0.019$). Post hoc analysis showed that S_8 had a significantly higher score indicating a worse sleep quality compared to S_5 ($p = 0.007$), $HIITS_5$ ($p = 0.007$), $HIITS_8$ ($p = 0.019$). This means that participants had minimal anxiety, were not depressed, were sedentary, were neither morning or evening chronotypes and were healthy sleepers.

Table 2: Demographic Variables and Screening Questionnaire by Group (mean ± SD)

Variable	S_8 (N = 21)	S_5 (N = 23)	HIIT S_8 (N = 22)	HIIT S_5 (N = 22)	Main effect p-value	Cut-off
Sex, F(M)	17 (4)	19 (4)	18 (4)	18 (4)	N/A	N/A
Age	25.38 (4.13)	25.22 (3.98)	23.82 (4.85)	23.77 (3.96)	0.259	18-35
BMI	21.68 (3.94)	22.19 (2.72)	22.33 (3.06)	22.57 (2.85)	0.916	> 30
PSQI	3.57 (1.21)	2.48 (1.28)	2.59 (1.33)	2.45 (1.22)	0.019*	> 7
ESS	3.57 (2.29)	4.74 (3.83)	3.95 (2.51)	3.82 (2.65)	0.131	> 14
MEQ	54.00 (8.88)	54.74 (10.63)	57.14 (8.75)	54.32 (8.57)	0.129	N/A
BDI	3.19 (3.77)	2.65 (3.51)	2.41 (4.19)	2.64 (3.02)	0.655	> 20
BAI	2.76 (2.14)	3.43 (4.41)	3.18 (2.67)	3.18 (3.36)	0.952	> 26
ISI	2.33 (3.22)	1.70 (1.72)	2.32 (3.39)	2.14 (2.42)	0.995	> 14
SBQ	0.52 (0.68)	0.57 (0.73)	0.32 (0.57)	0.59 (0.73)	0.540	> 5
UNS	4.67 (3.17)	5.83 (4.14)	4.50 (2.06)	5.14 (1.88)	0.439	> 14
EHI	18.90 (4.83)	12.03 (18.90)	15.82 (9.21)	14.64 (9.00)	0.277	N/A
IPAQ	1375.96 (817.00)	1813.63 (715.23)	1598.91 (688.81)	1760.52 (898.54)	0.171	> 3000

N=88; Groups: Restricted sleepers & HIIT (HIITS5); Average sleepers & HIIT (HIITS8); Average Sleepers (S8); Restricted Sleepers (S5).

PSQI = Pittsburgh Sleep Quality Index, ESS = Epworth Sleepiness Scale, 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, MEQ = Morningness-Eveningness Questionnaire; IPAQ = International Physical Activity Questionnaire, BMI = Body Mass Index.

$p < 0.05$ *

One-Way ANOVA (Age, ESS, MEQ); Kruskal Wallis (PSQI, BDI, BAI, ISI, EHI, SBQ, UNS, IPAQ).

Pairwise comparisons for PSQI:

There are significant differences between groups: S_8 and HIITS$_8$ (p=0.019); S_8 and S_5 (p=0.007); S_8 and HIITS$_5$ (p=0.007).

5.1 Feasibility of the pilot study

Our primary objective was to assess the feasibility of this remote pilot study. Figure 4 shows the Inclusion/Exclusion Flow Chart. About 36.8% of all eligible participants either withdrew (n = 32; 19.6%) from the study or were lost to follow-up (n = 28; 17.2%). In summary, the reasons for withdrawal from the study included busy schedules (n = 10), loss of interest (n = 11), computer issues (n = 4), unforeseen circumstances (n = 5) and uncomfortable being recorded during HIIT session (n = 3). In addition, eligible participants were lost to follow-up due to loss of contact (i.e., stopped responding to emails and calls). In total, 103 eligible participants completed the study. From this sample, a total of 88 participants were included in our final analysis. The other 15 participants were excluded from the analysis due to non-adherence to protocol, technical issues, and low accuracy (outliers: accuracy less than 50% of the learned stimuli).

The exercise protocol was completed with no injury or adverse effects by 95.5% of participants (n = 42). Two participants reported feeling lightheaded (3-5 seconds). Forty-two participants (95.5%) achieved an RPE rating corresponding to 85-95% of age-predicted heart rate. At the end of the exercise all participants answered questions regarding the enjoyability level, difficulty of the exercise, and whether they would include HIIT as a part of their routine. About 41%, 45% and 7% reported having highly, moderately, and lightly enjoyed the HIIT, respectively. In regard to difficult of the HIIT, about 23%, 52%, 11% and 7% reported that the HIIT intervention was highly, moderately, lightly and not difficult, respectively. Most of the participants who completed the HIIT (68%) reported wanting to add HIIT to their daily routine.

In order to assess the feasibility of the memory task for this population, participants rated their performance during the task, the difficulty of the task and their motivation to do well during the task. The average self-reported rating of performance was halfway between extremely poor to excellent during the immediate [M = 4.92, SD = 1.56] and delayed [M = 4.72, SD = 1.60] recall tasks. The mean self-reported rating for the difficulty of the task was moderately difficult for both immediate [M = 6.30, SD = 1.60] and delayed [M = 6.09, SD = 1.68] tasks. The mean rating of self-reported motivation was moderate for both immediate [M = 6.50, SD = 2.25] and delayed [M = 6.43, SD = 1.99] tasks. In the exercise groups, 45% were highly motivated (rating between 7-10), 48% were moderately motivated (rating between 4-6) and 7% were not motivated (rating between 0-3) to complete the delayed recall task well. In the non-exercise groups, 63% were highly motivated, 23% were moderately motivated and 14% were not motivated to complete the task well.

Lastly, 96% (n = 99 out of 103) of all participants followed the sleep protocol of the experimental night. A total of four participants were excluded due to non-adherence to the sleep protocol (Figure 4).

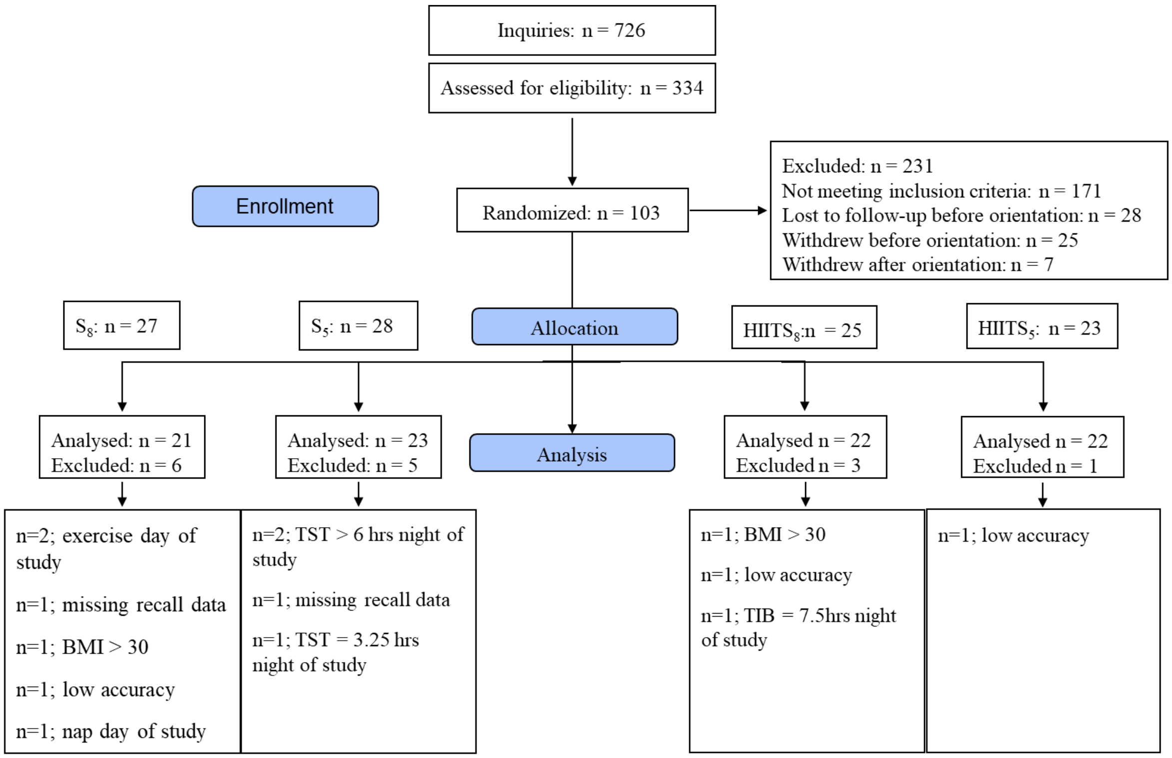


Figure 4: Flow diagram. Average sleep group (S_8), Sleep restricted group (S_5), HIIT with average sleep ($HIITS_8$), HIIT with sleep restriction ($HIITS_5$). Body mass index (BMI), total sleep time (TST), time in bed (TIB).

5.2 Performance accuracy and Reaction time during Immediate and Delayed Retrievals

5.2.1 Correct responses of the recall tasks

Table 3 shows a two-way ANOVA with analyses of the interaction of exercise (HIIT or no-HIIT) and sleep (average sleepers and restricted sleepers) on accuracy during the immediate and the delayed retrieval tasks and the differences between the two tasks. There were no significant main effects for exercise (HIIT or no-HIIT) during the immediate accuracy, delayed accuracy, and the difference between the two accuracies ($p > 0.05$). Additionally, there were no significant main effects for sleep (restricted sleepers or average sleepers) during the immediate accuracy, delayed accuracy, and the difference between the two accuracies ($p > 0.05$). There was a trend interaction between HIIT and sleep on immediate retrieval accuracy [$F(1,88) = 3.298$, $p = 0.073$, $\eta_p^2 = 0.038$]. In contrast, there was a significant interaction effect with a small-to-moderate effect size between HIIT and sleep on the delayed retrieval accuracy [$F(1,87) = 4.277$, $p = 0.042$, $\eta_p^2 = 0.049$]. Pairwise comparisons analysis results with Bonferroni corrections revealed that S_8 had significantly higher delayed accuracy compared with $HIITS_8$ ($p = 0.013$) and compared with S_5 ($p = 0.023$) (figure 5). However, there were no significant differences in delayed accuracy between the sleep restricted groups ($HIITS_5$ versus S_5; $p > 0.05$) and between the HIIT groups ($HIITS_5$ versus $HIITS_8$; $p > 0.05$). There were no significant interactions for the differences between the accuracies of the tasks ($p > 0.05$).

5.2.2 Correct responses RT of the recall tasks

Table 4 shows a two-way ANOVA with analyses of the interaction of exercise (HIIT or no-HIIT) and sleep (average sleepers and restricted sleepers) on reaction times of the immediate and the delayed retrieval tasks and the differences between the two tasks. There were no significant main effects of the exercise and sleep conditions and their interactions on reaction time during the immediate and delayed retrieval tasks and the differences between the two tasks ($p > 0.05$).

Table 3: 2x2 ANOVA with Interaction Analysis of Exercise & Sleep on Accuracy

Variables	Source	*SS*	*df*	*MS*	*F*	*P*	η_p^2
Immediate Retrieval Accuracy	S_8 & S_5	136.223	1	136.223	0.678	0.413	0.008
	HIIT & No HIIT	127.500	1	127.500	0.635	0.428	0.008
	Interaction	662.312	1	662.312	3.298	0.073	0.038
	Error	16870.904	84	200.844			
	Total	587718.0	88				
Delayed Retrieval Accuracy	S_8 & S_5	618.973	1	618.973	2.510	0.117	0.029
	HIIT & No HIIT	366.163	1	366.163	1.485	0.226	0.018
	Interaction	1054.504	1	1054.504	4.277	0.042*	0.049
	Error	20464.150	83	246.556			
	Total	658650.0	87				
Difference between Delayed & Immediate Retrieval Accuracy	S_8 & S_5	13.598	1	13.598	0.284	0.596	0.003
	HIIT & No HIIT	96.997	1	96.997	2.023	0.159	0.024
	Interaction	9.292	1	9.292	0.194	0.661	0.002
	Error	4028.019	84	47.953			
	Total	6121.0	88				

η_p^2 = partial eta-squared, SS = Type III Sum of Squares, df = degree of freedom, MS = Mean Square, F= F-value, P= p-value

N = 88; Groups: Sleep restriction & HIIT ($HIITS_5$, n=22); Average sleepers & HIIT ($HIITS_8$, n=22); Average Sleep (S_8, n=21); Restricted Sleep (S_5, n=23).

$p < 0.05$: 2 x 2 ANOVA

One data point of the delayed accuracy in the S_8 group was removed (> 2 SD).

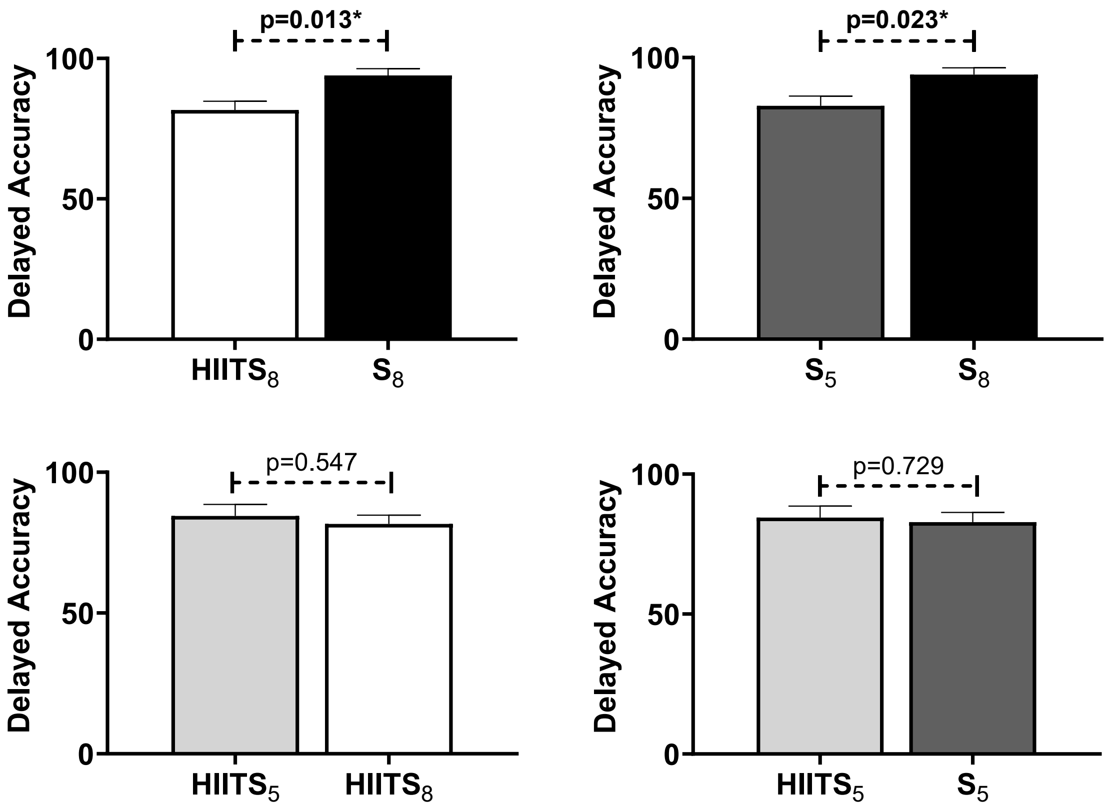


Figure 5: Post hoc Pairwise comparison adjusted for Bonferroni corrections of the delayed accuracy between groups.
N = 87; Groups: Sleep restriction & HIIT ($HIITS_5$, n=22); Average sleepers & HIIT ($HIITS_8$, n=22); Average Sleep (S_8, n=20); Restricted Sleep (S_5, n=23).

Table 4: 2 x 2 ANOVA on Exercise & Sleep on RT

Variables	Source	*SS*	*df*	*MS*	*F*	*P*	η_p^2
Immediate Retrieval RT	S_8 & S_5	0.001	1	0.001	0.006	0.941	0.000
	HIIT & No HIIT	0.113	1	0.113	0.871	0.353	0.010
	Interaction	0.066	1	0.066	0.504	0.480	0.006
	Error	10.922	84	0.130			
	Total	453.372	88				
Delayed Retrieval RT	S_8 & S_5	0.012	1	0.012	0.068	0.794	0.001
	HIIT & No HIIT	0.309	1	0.309	1.717	0.194	0.020
	Interaction	0.061	1	0.061	0.339	0.562	0.004
	Error	15.115	84	0.180			
	Total	387.825	88				
Difference between Delayed & Immediate Retrieval RT	S_8 & S_5	0.019	1	0.019	0.222	0.639	0.003
	HIIT & No HIIT	0.048	1	0.048	0.563	0.455	0.007
	Interaction	$8.169e^{-5}$	1	8.169E-5	0.001	0.975	0.000
	Error	7.178	84	0.085			
	Total	10.251	88				

2 x 2 ANOVA: *$*p < 0.05$, η_p^2 = partial eta-squared, SS = Type III Sum of Squares, df = degree of freedom, MS = Mean Square, F= F-value, P= p-value, RT = Reaction Time*
N = 88; Groups: Sleep restriction & HIIT ($HIITS_5$, n=22); Average sleepers & HIIT ($HIITS_8$, n=22); Average Sleep (S_8, n=21); Restricted Sleep (S_5, n=23).

5.3 Changes in performance from retrieval 1 to retrieval 2 within the groups

Furthermore, table 5 outlines a paired samples t-test that was conducted to determine the effects on performance difference within each group. The results indicated significant increase in accuracy and shorter reaction time from immediate to delayed retrieval. Performance accuracy was significantly higher during the delayed retrieval compared with the immediate retrieval ($HIITS_5$: $p = 0.02$; $HIITS_8$: $p = 0.015$; S_5: $p = 0.002$; S_8: $p < 0.001$). On the other hand, reaction time was significantly faster during the delayed retrieval compared with the immediate retrieval ($HIITS_5$: $p = 0.01$; $HIITS_8$: $p = 0.012$; S_5: $p = 0.012$; S_8: $p < 0.001$).

Table 5: Paired t-test Performance metrics

Groups (N)	Variables	*M*	*SD*	*t*	*P*	*d*
HIITS$_5$ (n=22)	ICor - DCor	-3.64	6.77	-2.52	0.02*	-0.54
	IRT - DRT	0.15	0.24	2.85	0.01*	0.61
HIITS$_8$ (n=22)	ICor - DCor	-3.77	6.70	-2.64	0.015*	-0.56
	IRT - DRT	0.18	0.30	2.74	0.012*	0.58
S$_5$ (n=23)	ICor - DCor	-5.09	7.38	-3.31	0.002*	-0.69
	IRT - DRT	0.19	0.39	2.42	0.012*	0.51
S$_8$ (n=21)	ICor - DCor	-7.30	5.94	-5.50	< 0.001**	-1.23
	IRT - DRT	0.22	0.19	5.28	< 0.001**	1.15

d = cohen's d, SD = standard deviation, M = Mean, t = t-value, P= p-value

n=88, Groups: Sleep restriction & HIIT (HIITS5); Average sleepers & HIIT (HIITS8); Average Sleep (S8); Restricted Sleep (S5).

ICOR: Immediate recall accuracy, DCOR: Delayed recall accuracy, IRT: Immediate reaction time, DRT: Delayed reaction time.

$p < 0.05$*, $p < 0.01$**

Paired t-test

5.4 Self-reported Performance, Difficulty, Motivation, KSS during the tasks

Table XVII shows self-reported performance, difficulty, motivation and sleepiness (KSS) ratings during the tasks and the differences between the immediate and delayed tasks (Appendix C, Supplementary tables). There were main effect significant differences for motivation ($p = 0.046$) and for KSS ($p < 0.001$) scores during the delayed retrieval tasks between groups. Pairwise comparisons revealed that S_8 had higher delayed motivation compared with S_5 ($p = 0.01$) and $HIITS_5$ ($p = 0.019$). Pairwise comparisons also revealed that S_5 was significantly more sleepy than S_8 ($p < 0.001$), $HIITS_5$ ($p = 0.018$) and $HIITS_8$ ($p < 0.001$). Similarly, $HIITS_5$ was more sleepy than $HIITS_8$ ($p = 0.031$). There were no other differences in immediate self-reported performance, difficulty, motivation and KSS scales ($p > 0.05$).

5.5 Sleep quality prior to and following the experimental procedure

Sleep variables were assessed using a consensus sleep diary four days prior to and following the night of the experimental procedure. To assess whether there were differences between groups with respect to the baseline and/or experimental night sleep variables, we conducted a one-way ANOVA analysis. Table 6 represents the baseline sleep variables results, while Table 7 shows the results for the experimental night. Four days prior to the experimental night, there were no significant differences between groups regarding their quality of sleep. As for the experimental night, Kruskal Wallis analysis revealed significant differences between groups for time in bed ($p < 0.001$), total sleep time ($p < 0.001$) and sleep onset latency ($p = 0.016$). As expected, pairwise comparisons revealed time in bed and total sleep time for the average sleep groups ($HIITS_8$ and S_8) were higher than the sleep restricted groups ($HIITS_5$ and S_5) ($p < 0.001$). Additionally, sleep onset latency was shorter for S_5 compared with S_8 ($p = 0.03$) and $HIITS_8$ ($p = 0.012$). Furthermore, figure 6 showed the sleep variables of the experimental night, comparing the average sleepers together ($HIITS_8$ versus S_8) and the sleep restricted groups together ($HIITS_5$ versus S_5) using an independent t-test. We found no significant comparisons between groups ($p > 0.05$), except for total sleep time was slightly higher in S_5 compared with $HIITS_5$ [(*M* = 5.19, *SD* = 0.20 versus *M* = 5.31, *SD* = 0.19) hours, $p = 0.037$], respectively.

Table 6: Sleep Diary Variables 4-days prior to the Experimental Procedure (mean ± SD)

Variable	S_8 (N = 21)	S_5 (N = 23)	$HIITS_8$ (N = 22)	$HIITS_5$ (N = 22)	Main effect p-value
TIB (hr)	9.26 (0.72)	9.27 (0.97)	8.84 (0.57)	9.14 (1.01)	0.300
TST (hr)	8.08 (0.58)	8.11 (0.68)	7.93 (0.59)	8.13 (0.60)	0.677
AWK (number)	0.89 (0.75)	1.03 (1.17)	0.66 (0.62)	0.48 (0.57)	0.126
TA (min)	22.96 (13.74)	18.41 (13.87)	19.13 (10.90)	16.22 (6.96)	0.507
SOL (min)	15.88 (8.80)	11.69 (7.60)	14.27 (6.86)	13.57 (6.72)	0.187
SE (%)	87.17 (5.42)	88.44 (6.48)	89.70 (3.54)	89.59 (5.68)	0.383
WASO (min)	7.08 (6.94)	6.72 (10.02)	4.85 (6.24)	2.66 (3.16)	0.099

N=88; Groups: Sleep restriction & HIIT (HIITS5); Average sleepers & HIIT (HIITS8); Average Sleep (S8); Restricted Sleep (S5).
TST, total sleep time; TIB, time in bed; AWK, number of wake periods during time in bed; TA, time awake, SOL, sleep onset latency; SE, sleep efficiency; WASO, wake after sleep onset.
$p > 0.05$
One-Way ANOVA (TIB, TST, SE) & Kruskal Wallis Test (AWK, TA, SOL & WASO)

Table 7: Study Night Sleep Diary Variables (mean ± SD)

Variable	S_8 (N = 21)	S_5 (N = 23)	$HIITS_8$ (N = 22)	$HIITS_5$ (N = 22)	Main effect p-value
TIB (hr)	8.73 (0.40)[a]	5.93 (0.43)	8.66 (0.53)	5.94 (0.69)	< 0.001**
TST (hr)	8.07 (0.30)[b]	5.31 (0.19)	7.90 (0.47)	5.19 (0.20)	< 0.001**
AWK (number)	1.14 (1.46)	0.87 (1.06)	0.73 (0.99)	0.36 (0.73)	0.118
TA (min)	19.67 (12.60)	11.48 (7.58)	19.91 (15.60)	14.25 (8.62)	0.133
SOL (min)	14.62 (7.21)[c]	8.22 (5.89)	15.82 (12.11)	12.05 (7.31)	0.016*
SE (%)	92.49 (3.78)	89.89 (6.01)	91.21 (5.29)	88.25 (7.92)	0.189
WASO (min)	5.05 (7.19)	3.26 (5.09)	4.09 (7.77)	2.21 (5.47)	0.142

N=88; Groups: Sleep restriction & HIIT (HIITS5); Average sleepers & HIIT (HIITS8); Average Sleep (S8); Restricted Sleep (S5).
TST, total sleep time; TIB, time in bed; AWK, number of wake periods during time in bed; TA, time awake, SOL, sleep onset latency; SE, sleep efficiency; WASO, wake after sleep onset.
* $p < 0.05$; ** $p < 0.001$
Kruskal Wallis (TIB, TST, AWK, TA, SOL, SE, WASO)
Pairwise comparison:
[a] TIB: Significantly different between S_5 & S_8 ($p<0.001$)
[b] TST: Significantly different between S_5 & S_8 ($p<0.001$)
[d] SOL: Significantly different between S_5 & S_8 ($p=0.003$) and $HIITS_8$ & S_5 ($p=0.012$)

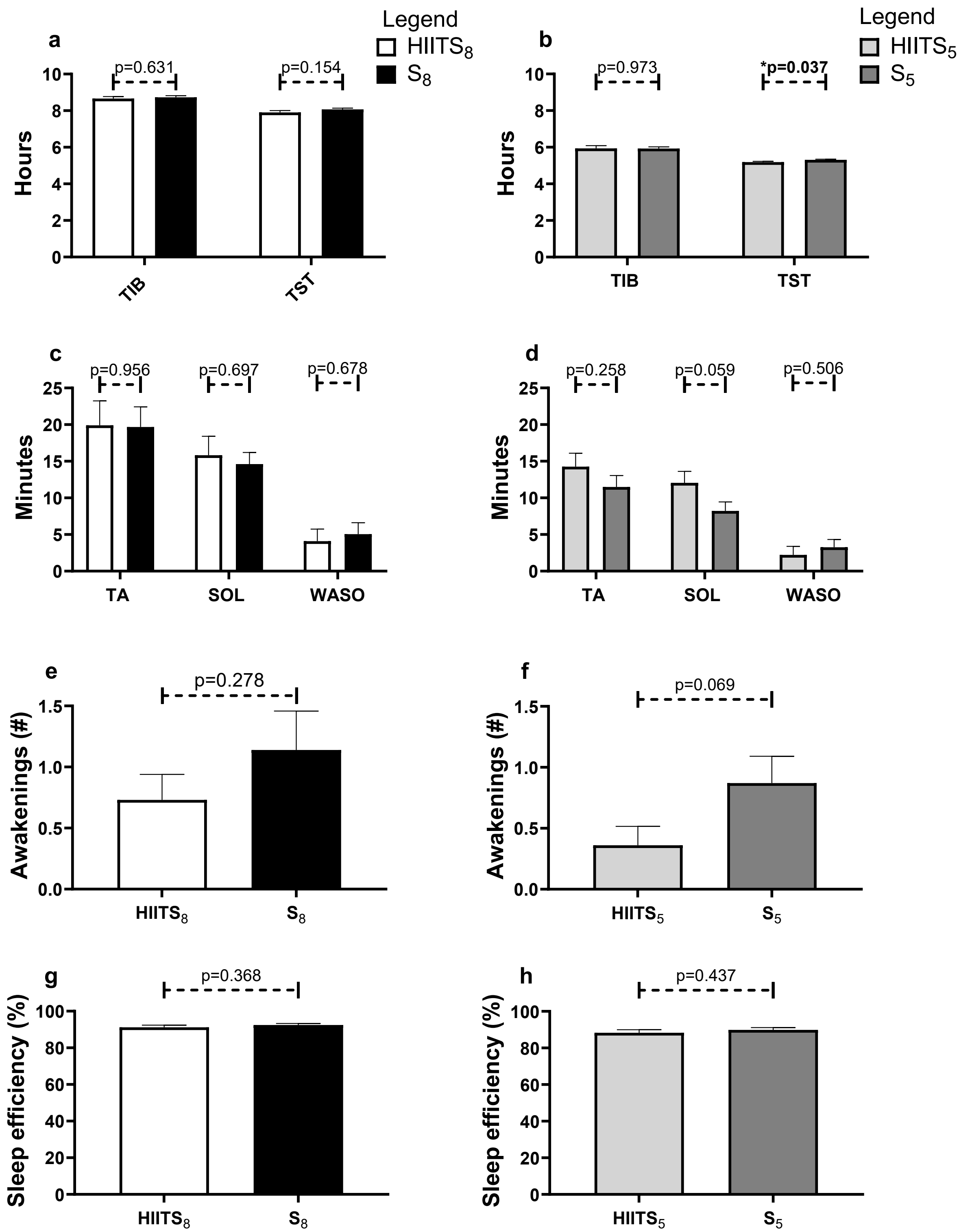


Figure 6. Experimental night sleep quality between groups.1 a & b) Time in bed (TIB) and total sleep time (TST) in hours. 1 c & d) Time awake (TA); Sleep Onset Latency (SOL); Wake after sleep onset (WASO). 1 e & f) Number of awakenings. 1 g & h) Sleep efficiency (%). *N = 88; Groups: Restricted sleepers & HIIT (HIITS$_5$, n=22); Average sleepers & HIIT (HIITS$_8$, n =22); Restricted Sleepers (S$_5$, n=23); Average Sleepers (S$_8$, n=21).*

5.6 Correlations between sleep and memory performance metrics

5.6.1 Correlations between baseline sleep and Accuracy

There were negative correlations between the following: total sleep time and delayed accuracy ($r = -0.285$, $p = 0.007$), sleep efficiency (%) and immediate accuracy ($r = -0.223$, $p = 0.037$), sleep efficiency (%) and delayed accuracy ($r = -0.229$, $p = 0.033$). And positive associations between sleep onset latency and immediate accuracy ($r_s = 0.232$, $p = 0.029$), sleep onset latency and delayed accuracy ($r_s = 0.257$, $p = 0.016$). There were no other correlations between baseline sleep variables and accuracy (Appendix C, Supplementary Table 8).

Pearson correlations were performed for the exercise groups separately. Within $HIITS_5$, there was a positive correlation between time awake (in minutes) and immediate recall ($r = 0.467$, $p = 0.028$) (Appendix C, Table 9). For $HIITS_8$, there were negative correlations between the following: total sleep time and delayed accuracy ($r = -0.431$, $p = 0.045$), sleep efficiency (%) and immediate accuracy ($r = -0.445$, $p = 0.038$), sleep efficiency (%) and delayed accuracy ($r = -0.548$, $p = 0.008$) (Appendix C, Table 10). Likewise, Pearson correlations were performed for the each of the non-exercise groups. There were negative correlations for S_5 between the following: time in bed and the difference between immediate and delayed accuracy ($r = -0.648$, $p < 0.001$); total sleep time and the difference between immediate and delayed accuracy ($r = -0.419$, $p = 0.047$) (Appendix C, Table 11). There were no significant correlations between the baseline sleep variables and accuracy for S_8 (Appendix C, Table 12).

5.6.2 Correlations between baseline sleep and RT

For the total sample size (Appendix C, Supplementary Table 8), there were positive and negative correlations between the following: sleep efficiency and delayed RT ($r = 0.253$, $p = 0.017$), time in bed and difference between immediate and delayed RT ($r = -0.285$, $p = 0.007$), sleep onset latency and immediate RT ($r_s = -0.218$, $p = 0.041$). There were no other correlations between the baseline sleep variables and RT.

There were negative correlations for $HIITS_5$ between the following: time in bed and delayed RT ($r = -0.451$, $p = 0.035$), sleep onset latency and immediate RT ($r_s = -0.490$, $p = 0.021$), sleep onset latency and delayed RT ($r_s = -0.425$, $p = 0.049$) (Appendix C, Table 9). There was a positive correlation for $HIITS_8$ between sleep efficiency (%) and immediate RT ($r = 0.458$; $p = 0.032$) (Appendix C, Table 10).

For S_5, there was a negative correlation between time in bed and the difference between immediate and delayed RT ($r = -0.432$, $p = 0.039$) (Appendix C, Table 11). There were negative correlations for S_8 between the following: number of awakenings and difference between delayed and immediate RT ($r = -0.462$, $p = 0.035$), sleep onset latency and difference between delayed and immediate RT ($r = -0.622$, $p = 0.003$), time awake and difference between delayed and immediate RT ($r_s = -0.784$, $p < 0.001$), WASO and difference between delayed and immediate RT ($r_s = -0.711$, $p < 0.001$) (Appendix C, Table 12). There were no other associations between baseline sleep and RT within groups.

5.6.3 Correlations between experimental sleep and accuracy

Table XII represents the associations between experimental night sleep and accuracy for the total sample size (Appendix C, Supplementary). There were positive correlations between: sleep onset latency and immediate accuracy ($r_s = 0.218$, $p = 0.041$) as well as sleep onset latency and delayed accuracy ($r_s = 0.224$, $p = 0.037$). There were no other significant correlations observed. In addition, there were no significant correlations ($p > 0.05$) between the experimental night sleep variables and accuracy in $HIITS_5$, $HIITS_8$, S_5 and S_8 individually as seen in tables 14, 15, 16 and 17, respectively (Appendix C, Supplementary Tables).

5.6.4 Correlations between experimental sleep and RT

When looking at the total sample size ($n = 88$), there were no correlations ($p > 0.05$) between the experimental night sleep variables and RT (Appendix C, Supplementary Table 13). Similarly, there were no correlations ($p > 0.05$) between the study night sleep variables and reaction time in $HIITS_5$, $HIITS_8$ and S_5, as shown in tables 14, 15 and 16 (Appendix C, Supplementary tables), respectively. In contrast, there were positive and negative correlations for S_8 between the following: sleep efficiency and difference between immediate and delayed RT ($r = 0.501$, $p = 0.021$), wake after sleep onset and immediate reaction time ($r_s = 0.623$, $p = 0.003$), wake after sleep onset and difference between immediate and delayed reaction time ($r_s = -0.479$, $p = 0.028$) (Appendix C, table 17). There were no other significant correlations.

6. Discussion:

In line with the hypothesis, the main findings of this thesis show that the protocol was feasible, however there were several technical issues due to the on-line, remote set-up. As expected, the sleep restricted group performed worse compared to the average sleep alone. In contrast with our hypothesis, the average sleep HIIT group had worse performance compared with the average sleep group alone on the associative face-name task. Acute evening HIIT does not appear to negatively impact subsequent self-reported nighttime sleep.

6.0 Adherence and feasibility of the study

A little over a third of our participants dropped out of the study due to various reasons. We had a 36.8% drop out rate (17.2% loss to follow up, 19.6% withdrew). This is not dissimilar to other studies of HIIT exercise interventions in young adults. For example, Roy et al. (2018) investigated a home-based HIIT intervention (21 to 24 minutes a week) for 12 months, reporting a 31.5% drop out and loss to follow-up rate (Roy et al., 2018). In our study, computer issues, not being comfortable being recorded during the HIIT session and low compensation accounted for a quarter of the total dropout rate.

We ensured high adherence to our study procedures. We ensured participants followed the study sleep schedule by reviewing their sleep diaries on a daily basis. We also ensured intervention fidelity, or how similarly participants performed the exercise during the study compared to the exercise designed in our protocol, by observing their performance of the exercises during the orientation and study night and assessing it with a custom checklist. We also recorded participants' exercise session during the study night and assessed them to ensure the participants completed the exercises as intended in the protocol. We also monitored and recorded the participants' perceived exertion (Borg RPE) at every session to ensure adherence to the prescribed exercise intensity, achieving a 95.5% adherence rate. This is a higher adherence rate than reported in similar studies. Roy et al reported 60.8% adherence to the exercise protocol at baseline, dropping to 23% by the end of the protocol (Roy et al., 2018). Eather et al. (2019) reported a 55% adherence rate in their study of the efficacy and feasibility of an 8-week, 8-12-minute HIIT intervention with a 1:1 work to rest ratio in university students (18-25 years old).

The exercise protocol was feasible because most of the participants in the exercise groups were able to complete the HIIT training safely and exert themselves with the required RPE equivalent (85-95% of age-related HRmax). Only two participants felt lightheaded, but the symptom subsided within five seconds with no further complications. Participants felt lightheaded during the cool down, possibly due to the abrupt changes in body position from the last HIIT exercise (mountain climbers) to standing position (during cool down). Overall, participants in the exercise groups were burdened with the greater amount of information compared to the non-exercise groups (see limitation section below). However, we got positive feedback from participants who completed the HIIT intervention. Most of the participants fairly enjoyed the workout, found it moderately difficult, and would adopt the HIIT workout to their daily routine.

Taken as a whole, the memory task was cognitively challenging since none of the participants matched all the face-name pairs correctly and the average score for delayed accuracy was 71%.

However, it was not extremely difficult either, because only three participants got a score below 50% of the learned stimuli (excluded as mentioned above). The non-exercise group appeared to be more motivated than the exercise groups during the delayed retrieval. This may be due to the fact that participants in the HIIT groups may have been more burdened than the non-exercise groups. On average participants rated their performance moderate, scored the difficulty of the task as moderate and they were moderately motivated to complete the tasks well. Lastly, most of the participants followed the sleep protocol of the experimental night.

Overall, we deem this protocol feasible, because each of the portion of the protocol were successfully executed by almost all of the participants (over 80%). Similarly, Shepherd et al.'s (2015) adherence rate to HIIT intervention was 83.1%, while Moholdt et al.'s (2012) adherence rate was 85.7% to the aerobic interval training (Moholdt et al., 2012; Shepherd et al., 2015). This criteria for judging the protocol feasible was set after the results were in. However, we did decide to monitor fidelity (did they do exercise right during the orientation and going through their recording HIIT protocol) and adherence (sleep schedule, refraining from drinking of alcohol, caffeine, coffee, smoking and/or exercise) a priori (before study began).

6.1 Average sleep and HIIT on memory

This pilot study was based on Mograss et al.'s (2020) study, which examined the combined effect of a single bout of moderate intensity cycling and a nap on declarative memory in a population of young healthy adults (Mograss et al., 2020). They recruited 115 participants and randomized them into four groups: exercise and nap, nap only, exercise only, and the control (no exercise/no nap). In the morning (11:00 a.m.), the exercising groups completed a 40-minute cycling at 60% of their HRmax, while the non-exercising groups rested (seated position). Then, at 1:30 p.m., all groups studied a series of 45 neutral photographs taken from the International Affective Pictures System, IAPS. At 2:30 p.m., half of the groups had a 60-minute nap opportunity while the other half did not. At 5:00 p.m., all groups completed a recognition memory task, where they were shown 90 photographs (half of which were presented during the learning session and the other half were new). Participants were asked to identify each photograph as old or new. They found that the combined effects of acute moderate-intensity exercise and nap improved declarative memory more than exercise or nap alone. While they found a positive effect of exercise and sleep on memory, we found that the combined effects of average sleep and HIIT negatively impacted memory. This difference in findings may be due to a few key differences between their study and our pilot study: 1) daytime nap versus overnight sleep; 2) 40-minute moderate intensity training on a cycle ergometer in the morning versus 15-minute evening HIIT intervention using body weight alone; 3) objective sleep versus subjective sleep; 4) 90 photographs of scenes to recognize (learning early afternoon and testing later that day in the afternoon/early evening) which is easier than 120 face-name pairs (learning evening and testing immediately afterwards and the following morning); 5) in-lab versus home-based, respectively.

The results of this study may be influenced by several factors. One may be that this study was underpowered. We conducted a post hoc sample size calculation powered at 55.8% with 88 participants far below the 80% threshold. In order for us to have achieved 80% power, we need to recruit 143 participants. Therefore, this may not be a true effect. Another explanation could be based on the transient hypofrontality hypothesis.

The transient hypofrontality hypothesis predicts that, as a result of high intensity interval training, metabolic and cognitive demand increases toward sustaining the movement, and since there are limited metabolic resources in the brain, this leads to a decline in one's ability to perform optimally during cognitive tasks (i.e. prefrontal cortex function impaired) (Loprinzi et al., 2019). During maximal physical output, the brain receives four times less blood flow per heart beat compared to resting states due to the fact that blood is being shunted from areas that do not require it (e.g., prefrontal cortex, frontal cortex, etc.) (Dietrich, 2006). Since the brain cannot activate all brain regions at once, the activation of some structures (e.g., motor cortex, premotor cortex, cerebellum, etc.) come at the expense of others (e.g., prefrontal cortex, frontal cortex, etc.).

This effect is influenced by exercise intensity and fitness level (Burma et al., 2020; P. D. Loprinzi et al., 2019). In one experiment, researchers found that compared to resting conditions, both working and episodic memory were impaired during a twenty-minute HIIT (70% HRR) when the exercise was performed simultaneously with the memory task (Loprinzi et al., 2019). However, in another experiment, light and moderate intensity exercise did not impair working memory function (Loprinzi et al., 2019). Furthermore, Burma et al. (2020) studied nine fit young adults in three conditions: moderate intensity, HIIT and control (quiet rest). They found that there were alterations in cerebrovascular metrics after HIIT, but not after moderate intensity. Cerebrovascular recovery after HIIT occurred between one to two hours post-exercise. Similarly, a cross-over within subject design showed that 18 healthy young males (23.03 ± 0.92 years) had the better performance on a hippocampal-dependent associative memory task (11:30 A.M.) 1-hour after moderate intensity compared to resting conditions, while having no improvements after an acute bout of 15-minute high intensity cycling (10:00 A.M.) (Bosch et al., 2021). To our knowledge, there are no studies that researched the influence on the time of day of transient hypofrontality hypothesis. It could be speculated that the positive impact of sleep on memory was dampened in the HIITS$_8$ group compared with S$_8$ probably due to the transient hypofrontality hypothesis and HIITS$_8$ may not have fully recovered from the circulatory and neural activity changes in the brain by the time of encoding and/or during sleep. Future studies should research the duration of transient hypofrontality hypothesis post-exercise to see how long it would take for sedentary individuals to recover and whether transient hypofrontality is influenced by time of day.

Although we did not see a positive effect of high intensity exercise on memory after average sleep, reviews have shown that daytime high intensity exercises have positive effects on memory (Loprinzi et al., 2018; Loprinzi et al., 2019). The effect is influenced by factors such as timing of the exercise relative to the memory task, exercise intensity and age (Loprinzi et al., 2018; Loprinzi et al., 2019). According to a systemic review with meta-analysis by Loprinzi et al (2019), the timing of acute exercise, in relation to episodic memory, may generate different results on memory performances. For example, acute exercise after a cognitive task improves episodic memory (medium to large effects). However, it was not significantly different when acute exercise was completed before the memory task. Contrary to our own findings, young adults performed better on the memory tasks compared to older adults and vigorous intensity improved memory more than other exercise intensities (Loprinzi et al., 2019). Another review by Loprizi et al. (2018) that evaluated the effects of daytime acute exercise intensity on memory function in young adults showed three out of nine studies found that high-intensity exercise prior to a memory task had the best effect on episodic memory compared with other exercise intensity groups (Etnier et al., 2016; Keyan and Bryant, 2017; Winter et al., 2007), but one study showed no differences between exercise intensities (Loprinzi & Kane, 2015). These were daytime studies, starting with the exercise interventions or seated rest controls, followed by learning and immediate recall sessions and ended with long-term recall sessions one day (Etnier et al., 2016), two days (Keyan & Bryant, 2017), one week and/or eight months later (Loprinzi & Kane, 2015; Winter et al., 2007). Briefly, daytime high intensity exercise before and after a memory task tend to have positive effects on memory however, there are inconsistent findings.

6.2 Effects of sleep restriction on memory

As expected, participants in the S_5 group had a worse performance compared to the S_8 group. The reason for the difference in performance between these two groups may be attributed to a reduced hippocampal function, downregulation of BDNF and/or a reduced long term potentiation capacity as a result of sleep loss (Mohammadipoor-ghasemabad et al., 2019; Sahin et al., 2021; Zagaar et al., 2013). Synaptic homeostasis hypothesis states that after a day of wakefulness the synaptic potentiation in the brain becomes saturated, leading to a decreased learning capacity or consolidating long-term memory (Tononi & Cirelli, 2006). However, good quality and quantity sleep, with enough SWS, decreases synaptic saturation, which then can make room for increased learning capacity and memory performances (Tononi & Cirelli, 2006). On the other hand, the system consolidation hypothesis states that the same synapses that were activated during encoding are reactivated during SWS, which results in the transfer of memory from the hippocampus to the neocortical areas of the brain where it is stored as long-term memory (Gais et al., 2007; McClelland et al., 1995; Roig et al., 2022). Therefore, we can assume that the S_8 group, compared to S_5 group, had a greater synaptic saturation downscaling and/or greater synapses reactivations during SWS, which was beneficial for long-term memory.

Even though there were performance differences during the delayed recall task between groups, all groups had significantly greater accuracy and faster reaction times in the recall tasks the following morning compared to the evening before the study night. This may be the result of overnight declarative memory retention related to post-learning sleep that depend on NREM sleep (Clemens et al., 2005). In addition, this is likely due to the fact that participants had relatively intact SWS hence overnight memory consolidation occurred, as was seen in one study which subjected 88 healthy teenagers to five different sleep protocols (five-hour, six-hour, seven-hour, eight-hour and nine-hour sleep) for four consecutive nights (Voderholzer et al., 2011). Participants were given a word-pair encoding session prior to the sleep restriction protocol and recall occurred two days after the sleep restriction. They found no significant differences in recall between the groups, and they also found that SWS was preserved in the sleep restricted conditions (bedtime: between 10:30 p.m. and 1:30 a.m. / wakeup time: 6:30 a.m.).

6.3 HIIT, sleep restriction and declarative memory

In this study, contrary to our hypothesis, acute evening HIIT did not compensate for the negative effect of sleep restriction on declarative memory. As seen in our results, participants in the HIIT sleep restricted group had similar delayed memory performance compared with the sleep restricted group. Furthermore, sleep was not disturbed by one bout of evening HIIT (see section 7.6). Surprisingly, long-term memory for $HIITS_8$ was worse than S_8, suggesting that acute evening HIIT hindered the positive effects of having enough sleep quantity (between eight-to-nine hours) on memory. This may be due to the fact that we had an acute exercise intervention, while some animal studies have found positive improvement on memory post chronic exercise intervention and total sleep deprivation (Mohammadipoor-ghasemabad et al., 2019; Sahin et al., 2021; Zagaar et al., 2013). A recent review found that chronic exercise has been shown to have a protective effect on neuroplasticity and memory after acute sleep deprivation in animal studies (Roig et al., 2022). For example, forcing rodents into a chronic treadmill intervention protected them from performing poorly in a wide range memory tasks (e.g., Morris water maze) after an acute total sleep deprivation (Mohammadipoor-ghasemabad et al., 2019; Sahin et al., 2021; Zagaar et al., 2013). Some studies have found that chronic exercise prevented sleep-deprived induced downregulation of neuroplasticity signaling molecules (e.g., BDNF) and reduced the inhibition of early as well as late long term potentiation important for learning and memory in the hippocampus (Mohammadipoor-ghasemabad et al., 2019; Zagaar et al., 2012, 2013). Additionally, exercise has an antioxidant effect as it reduces the amount of sleep-deprived oxidative stress enzymes released in the hippocampus and cortex (Vollert et al., 2011). Only one study did not find that chronic exercise had a protective effect on memory after chronic sleep restriction (Zielinski et al., 2013). Originally, rodents did experience improvement in recall after 11 weeks of exercise training. However, after sleep depriving the animals for four hours per day for 11 weeks following the exercise training, their Morris water maze task performance declined. Overall, chronic exercise intervention seems to improve brain physiology important for learning and memory performances. Future studies should also consider the effects of chronic exercise intervention and light to moderate intensities on memory after acute and/or chronic sleep restriction.

In human study, we did not find any studies that research the combined effects of sleep restriction on declarative memory. However, Sauvet et al. (2020) studied chronic exercise training and total sleep deprivation on executive function. After seven weeks of exercise training (a mixture of HIIT and moderate intensity exercise, three times a week) impaired executive process (e.g., working memory) did not improve after a 40-hour sleep deprivation protocol compared with the baseline pre-exercise training (Sauvet et al., 2020). Although this study aimed to determine the effects of chronic exercise protocol and total sleep deprivation on working memory, our pilot study also did not result in a bout of HIIT improving episodic memory after one night of sleep restriction. On the other hand, they found that training decreased the deleterious effects on vigilance post-sleep deprivation during the recovery day (Sauvet et al., 2020), while reaction time in our study was not significantly different.

6.4 Self-reported difficulty, performance, motivation and sleepiness during the tasks

Self-reported difficulty and performance did not differ between groups during the tasks. In contrast, delayed motivation was significantly different between groups. S_8 was the most motivated group and as mentioned earlier they also had the best performance out of the groups. Similar to our findings, according to a Tucker et al. (2018) exploratory analysis revealed that intrinsic motivation, which is defined as the drive to do well on a task simply by desiring to do so, without having any external reward, improved declarative memory acquisition and consolidation

(Tucker et al., 2018). A study by Robinson et al., 2012 showed that young adult males tend to perform better with an external reward, and they are not likely to be distracted by incongruent stimuli. However, participants with high intrinsic motivation were not influenced by extrinsic motivation (Robinson et al., 2012). In summary, subjects that have higher intrinsic motivation during a task tend to have better accuracy compared with lower intrinsic motivation, as was seen in the S_8 group.

HIITS$_8$, HIITS$_5$ and S_8 were not as sleepy the following morning compared to S_5. According Sauvet et al. (2020), following a seven-week exercise training session KSS did not change at baseline, during total sleep deprivation and during recovery. However, sleep pressure (assessed with multiple sleep onset latency test) was reduced post-training at baseline and after recovery night, but not during the total sleep deprivation compared to pre-exercise intervention. As expected, the HIITS$_5$ was more sleepy compared to the HIITS$_8$ the following morning. To conclude, both of the restricted groups were sleepier than the average sleep groups which is to be expected.

6.5 Correlations between sleep quality and performance metrics

Poor sleep quality during the baseline and experimental nights was associated with better performance metrics. When considering the average four nights, longer sleep onset latency and lower sleep efficiency was correlated with a higher accuracy for immediate and delayed recall tasks. In addition, delayed accuracy was greater with shorter total sleep time. This means participants experiencing a worse sleep efficiency, taking longer time to fall asleep, and having a reduced total sleep time at baseline, had a more accurate memory performance during the tasks. Likewise, baseline sleep efficiency was positively correlated with delayed reaction time. This suggests an increase in sleep efficiency was associated with slower time answering the task questions. As was seen with baseline nights, longer sleep onset latency during the experimental night was positively correlated with immediate and delayed recall accuracy. Although, they were weak correlations, poorer subjective sleep quality was associated with better declarative memory performance.

We find similar findings when investigating these correlations amongst individual groups. There were moderate correlations for HIITS$_5$ between baseline nights sleep variables and performance metrics. Longer time spent awake at baseline was correlated with better immediate recall. However, as expected, the more time spent in bed, the faster the delayed reaction time was. For HIITS$_8$, baseline sleep quality measures and performance metrics were moderately correlated. Specifically, as expected, total sleep time was positively related to delayed correct responses, and lower sleep efficiency was related to slower immediate reaction time. Similarly, Clemens et al. (2005) observed significant moderately positive correlations between the correct responses of a face-name association task and objective total sleep time (EEG measurements) (Clemens et al., 2005). Likewise, Eiman et al. (2019) showed a negative correlation between reaction time during the Stroop test[14] and sleep efficiency (Eiman & Weinstein, 2019). Unexpectedly, participants with

[14] Stroop test: On the top half of a computer screen, the words "red", "green" or "blue" were displayed but the color in which they were written did not necessary match (e.g., "blue" was written in red). The bottom half of the screen contained the words "red", "green" and "blue". Participants had to match the color of the word on the top half with the word on the bottom half (e.g., participants chose "red" from the bottom half, if the word "blue" was written in the color red on the top half).

lower sleep efficiency had better immediate and delayed accuracy, indicating that less efficient sleep quality was correlated with better memory performance. For S_5, the greater time spent in bed and asleep, the lower the accuracy differences were between the two tasks. During baseline sleep for S_8, when there was a greater number of awakenings, longer time awake, longer sleep onset latency and longer wake after sleep onset, the lower the differences in accuracy between the immediate and delayed recall tasks. For S_8 experimental night sleep variables, longer wake after sleep onset was correlated with slower immediate reaction time. In brief, when looking at individual groups, the correlations ranged between moderate to strong and often in an unexpected direction. However, in a few instances good sleep quality was associated with better performance metrics and vice versa. Surprisingly, there were almost no correlations between the experimental night sleep variables and the performance metrics within individual groups.

These unexpected correlations may have been the result of our pilot study being underpowered. Another possible explanation for these unexpected findings can be that we did not collect any objective sleep measures and therefore may have missed underlying issues. For example, participants filled out screening questionnaires and sleep diary to screen for sleep disorders and to calculate sleep variables. However, polysomnography (PSG) is the gold standard to screen for sleep disorders and can directly determine sleep characteristics such as micro-arousals (sleep disruptions without waking up). Sleep fragmentation and sleep disorders such as insomnia, obstructive sleep apnea or narcolepsy can impair sleep dependent memory consolidation (Pace-Schott & Spencer, 2015). On the other hand, if our finding is a true effect, then there are other factors to consider. For example, the HIIT intervention and other external factors such as genetics may have influenced the results memory (Bearden et al., 2011). Therefore, more studies are needed to measure sleep objectively in conjunction with exercise and memory.

6.6 HIIT effects on subsequent nighttime sleep

In support with a systemic review and meta-analysis on evening high intensity exercise by Frimpong et al. (2021), our results showed that one bout of early evening HIIT may not negatively impact nighttime sleep compared to their counterpart, the non-exercising groups. They found that sleep duration increased and sleep onset latency decreased when participants engaged in high intensity exercise close to bedtime, however REM sleep was shorter (Frimpong et al., 2021). Another meta-analysis by Stutz et al. (2019) showed that evening light to moderate exercise increased REM sleep and slow wave sleep (deep sleep), while decreasing stage 1 sleep (light sleep) in healthy young adult good sleepers. They did not find that exercise impaired sleep, but rather improved sleep quality unless the exercise was vigorous intensity within one hour of bedtime (i.e., increased slightly sleep onset latency and decreased total sleep time and sleep efficiency) (Stutz et al., 2019). Additionally, another study by Robey and colleagues showed that regular early evening high intensity interval training in athletes did not disrupt subjective sleep variables nor actigraphy sleep (Robey et al., 2013). Similarly, we did not find that early evening HIIT disrupts following nighttime subjective sleep quality.

According to our results, sleep onset latency during the experimental night was the only sleep variable that was different between the four groups. Sleep onset latency was shorter in the sleep restricted group alone compared to both average sleep groups. According to Sleep Foundation (2022), sleep pressure (i.e., need for sleep as the day progresses) is increased when participants go to sleep later than usual, hence they tend to fall asleep faster (sleep onset latency is shorter) compared to participants who go to sleep earlier than usual (sleep onset latency is longer) (Pacheco, 2022). Therefore, participants in the sleep restricted groups may have had a higher sleep pressure at bedtime, while participants in the average sleep groups may have had a lower sleep pressure.

6.6 Strengths and Limitations

This pilot study had a few strengths. First, this study was the first of its kind. It gives us insight on whether young healthy sedentary adults would benefit from one bout of evening HIIT during an exam period for example. Second, there were two comparator groups and a control group. Third, we were able to have similar number of participants ($HIITS_5$: n = 22; $HIITS_8$: n = 22; S_5: n = 23; S_8: n = 21) with a similar number of males and females within each group. The demographics and pre-screening questionnaire scores of participants were similar between groups: no mental illness (within cut-off BAI and BDI), good sleepers, neutral chronotype, sedentary, normal BMI, young adults and with no reported physical disorder or disease. Fourth, this study was home-based, this allowed us to study participants in their habitual environment. Fifth, this protocol did not require additional materials (such as weights, ergometer etc.). All that the participants needed was their body weight, enough space to safely perform each exercise, water, proper attire, and a computer.

This pilot study had a few limitations. The first limitation was related to the pandemic regarding sample size. Our study was underpowered based on the previous study (Mograss et al., 2020). Although, we did find significant interactions between HIIT and sleep conditions for the delayed recall. We originally set out to recruit eighty participants in one year; the time it would take to complete my thesis. However, we only managed to recruit this many participants over a period of two years of active recruitment. We started recruiting participants in August 2020 and our last participant completed the protocol in May of 2022. The university and the lab were shut down and therefore the study had to be adapted to a remote protocol.

This led to the second limitation, we had to forgo all objective measures in a controlled lab environment such as polysomnography data (sleep variables) and actigraphy data (sleep/wake cycles and heart rate). These data were replaced by subjective measures such as sleep diary, screening questionnaires and RPE scores. Due to the pandemic forcing the closure of the facility, the third limitation was that we started recruiting for the two non-exercising groups first (S_8 & S_5), believing the research lab would be open by the time we had to recruit participants for the two exercising groups ($HIITS_8$ & $HIITS_5$). When it was clear the lab would not resume its pre-pandemic activities, we created a remote online version of the exercise protocol, and we received an amendment for it.

Once all the non-exercising groups were complete and randomized amongst themselves, we began randomizing eligible participants into the two exercising groups. This is when we encountered our fourth limitation, where half of the eligible participants (i.e., twelve in four months) would withdraw from the study before or after the orientation session. We had to rethink our protocol and make a few minor changes. The following issues were addressed: With the addition of the HIIT component, we sent participants very dense emails that contained all the necessary information for the HIIT intervention along with the memory task. Additionally, we attached extra documents for the participants to go through before attending the orientation session. Additionally, all participants had to download the memory tasks and Psycho.Py on their personal computer, which came with a forty-five-page step-by-step instruction document. Often, participants were unable to download Psycho.Py to their personal computers without running into software issues and fixing those problems was time consuming. Based on our experiences in this study, we would reduce the number of documents to sent out to participants in future studies (including the larger study this served as a pilot for). For example, I would not be sending participants a guideline on how to install Psycho.Py on their computers, instead I would show them how it's done during the orientation session.

To address these issues in the pilot study, we increased the compensation upon completion of the study from 30$ to 50$. Then, we had participants download team viewer on their personal computers, which allowed them remote access to the research assistant's computer, already containing Psycho.Py and the memory tasks. This alone drastically reduced the email length and the number of documents we sent participants. With all these changes, the number of participants dropping out of the study decreased. The fifth limitation was that we did not standardize the time of the memory tasks (10:00 p.m. versus 11:00 p.m. and 7:00 a.m. versus 8:30 a.m.) and the wake time (6:00 a.m. versus 7:00 a.m.), perhaps this is why we did not find any significant differences between groups when taking into consideration the difference between the immediate and delayed performance metrics of the tasks. The sixth limitation concerned the gender of our sample. Most of the participants were females and therefore our pilot may not be generalizable to males.

7. Conclusion

While we originally predicted that acute exercise and average sleep would benefit memory performance, we found that acute evening HIIT in the average sleep group hindered long-term memory compared to the average sleep group alone. We also predicted that HIIT would alleviate the effects of sleep loss on memory, however we found that acute bout of HIIT did not compensate the negative sleep loss effects on memory. In contrast, supporting our hypothesis, sleep restriction alone had a negative impact on long-term declarative memory compared to the average sleep group alone. Surprisingly, we did not find positive associations between memory and sleep quality. Furthermore, as expected, the following morning the sleep restricted groups were more subjectively sleepy compared to the average sleep groups. Whereas the average sleep group had the highest intrinsic motivation compared to the other groups. In line with previous work, our findings also showed that an evening bout of HIIT may not disrupt subsequent self-reported nighttime sleep. Nevertheless, given that this pilot study was underpowered and was conducted online, future studies should aim to confirm these findings in a well-controlled lab environment with a larger sample size and objective PSG measures.

This pilot study provided significant and important insights for the design and conduct of the upcoming in-lab study. First, we realized that we may need to account for higher potential dropout and incorporate that amount into our sample size and power calculations for the in-lab study. Furthermore, we determined that HIIT may not be an effective intervention to improve memory for this population group, and a decision was made to investigate the effects of moderate intensity exercise (supported by literature) instead. However, in future studies investigating the effects of HIIT, we would space out the HIIT and the memory task more, keeping them more than 3 hours apart. In addition, we will continue to use the face-name association memory task as it is challenging for this population. Lastly, we will standardize the wake-up times and the time of the memory tasks for all groups in a laboratory setting.

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Appendix A: Scales

Figure 7: Borg's Rating of Perceived Exertion Scale

Borg's Rating of Perceived Exertion (RPE) Scale	
Perceived Exertion Rating	**Description of Exertion**
6	No exertion; sitting and resting
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion

Figure 8: Karolinska Sleepiness Scale (KSS)

Please indicate your sleepiness during the previous 5 minutes using the corresponding number keys:

1. Extremely alert
2. Very alert
3. Alert
4. Rather alert
5. Neither alert nor sleepy
6. Some signs of sleepiness
7. Sleepy, no effort to stay awake
8. Sleepy, some effort to stay awake
9. Very sleepy, fighting sleep

Appendix B: HIIT Checklist and Feedback

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** ☐

Appendix C: Supplementary tables

Table 8: Correlations between baseline sleep and performance metrics (accuracy and RT) for n=88

Variable	Immediate Accuracy	Immediate RT	Delayed accuracy	Delayed RT	Differences in Accuracy	Differences in RT
TIB (hr)	-0.27	0.004	-0.124	-0.192	-0.082	-0.285**
TST (hr)	-0.188	0.107	-0.285**	0.031	-0.103	-0.087
AWK (number)	-0.007	0.079	-0.004	0.049	-0.046	0.000
TA (min)	0.203	-0.154	0.206	-0.120	0.061	0.001
SOL (min)	0.232*	-0.218	0.257*	-0.202	0.115	-0.072
SE (%)	-0.223*	0.181	-0.229*	0.253*	-0.053	0.146
WASO (min)	0.069	0.093	0.051	0.031	-0.026	-0.022

TST, total sleep time; TIB, time in bed; AWK, number of wake periods during time in bed; TA, time awake, SOL, sleep onset latency; SE, sleep efficiency; WASO, wake after sleep onset.
N=88; Groups: Sleep restriction & HIIT (HIITS5); Average sleepers & HIIT (HIITS8); Average Sleep (S8); Restricted Sleep (S5).
*$p < 0.05$, ** $p < 0.01$
Pearson Correlation (Accuracies, RTs, TIB, TST, SE) and Spearman Correlations (AWK#, TA, SOL, WASO)

Table 9: Correlations between baseline sleep and performance metrics (accuracy and RT) for HIITS5

Variable	Immediate Accuracy	Immediate RT	Delayed accuracy	Delayed RT	Differences in Accuracy	Differences in RT
TIB (hr)	-0.036	-0.307	-0.075	-0.451*	0.017	-0.293
TST (hr)	-0.348	-0.168	-0.397	-0.135	-0.246	0.031
AWK (number)	-0.220	-0.091	0.246	0.038	-0.037	-0.017
TA (min)	0.467*	-0.349	0.364	-0.361	0.041	-0.074
SOL (min)	0.256	-0.490	0.270	-0.425	0.036	-0.071
SE (%)	-0.352	0.155	-0.416	0.397	-0.325	0.388
WASO (min)	0.128	0.067	0.093	0.201	-0.178	0.131

TST, total sleep time; TIB, time in bed; AWK, number of wake periods during time in bed; TA, time awake, SOL, sleep onset latency; SE, sleep efficiency; WASO, wake after sleep onset.
N=22; Group: Sleep restriction & HIIT (HIITS5).
*p < 0.05, ** p < 0.01
Pearson Correlation (TIB, TST, TA, immediate accuracy and RT, Delayed RT, differences in accuracy and RT) and Spearman Correlations (AWK#, SOL, SE, WASO, delayed accuracy)

Table 10: Correlations between baseline sleep and performance metrics (accuracy and RT) for HIITS8

Variable	Immediate Accuracy	Immediate RT	Delayed accuracy	Delayed RT	Differences in Accuracy	Differences in RT
TIB (hr)	-0.157	-0.015	-0.154	0.055	-0.061	0.082
TST (hr)	-0.377	0.232	-0.431*	-0.217	-0.278	0.040
AWK (number)	-0.096	-0.044	-0.111	0.067	0.062	0.163
TA (min)	0.116	-0.330	0.135	-0.045	0.254	0.345
SOL (min)	0.053	-0.368	0.163	-0.186	0.332	0.203
SE (%)	-0.445*	0.458*	-0.548**	0.293	-0.414	-0.089
WASO (min)	0.037	0.011	0.046	0.026	0.218	0.092

TST, total sleep time; TIB, time in bed; AWK, number of wake periods during time in bed; TA, time awake, SOL, sleep onset latency; SE, sleep efficiency; WASO, wake after sleep onset.
N=22; Group: Average Sleep & HIIT (HIITS8).
*p < 0.05, ** p < 0.01
Pearson Correlation (TIB, TST, SE, accuracies, and RTs) and Spearman Correlations (AWK#, SOL, TA, WASO)

Table 11: Correlations between baseline sleep and performance metrics (accuracy and RT) for S_5

Variable	Immediate Accuracy	Immediate RT	Delayed accuracy	Delayed RT	Differences in Accuracy	Differences in RT
TIB (hr)	-0.084	0.224	-0.363	-0.209	-0.648**	-0.041
TST (hr)	0.000	0.070	-0.185	-0.156	-0.419*	-0.330
AWK (number)	-0.026	0.114	-0.087	0.225	-0.127	0.300
TA (min)	-0.022	0.019	-0.067	0.203	-0.120	0.198
SOL (min)	0.133	0.000	0.095	0.137	-0.213	0.182
SE (%)	0.014	-0.137	0.106	-0.115	0.210	-0.277
WASO (min)	-0.137	0.244	-0.211	0.148	-0.126	0.062

TST, total sleep time; TIB, time in bed; AWK, number of wake periods during time in bed; TA, time awake; SOL, sleep onset latency; SE, sleep efficiency; WASO, wake after sleep onset.
N=23; Group: Sleep Restriction (S5).
*$p < 0.05$, ** $p < 0.01$
Pearson Correlation (TIB, TST, SE, accuracies, and RTs) and Spearman Correlations (AWK#, SOL, TA, WASO)

Table 12: Correlations between baseline sleep and performance metrics (accuracy and RT) for S_8

Variable	Immediate Accuracy	Immediate RT	Delayed accuracy	Delayed RT	Differences in Accuracy	Differences in RT
TIB (hr)	0.056	0.264	-0.168	0.092	0.153	-0.398
TST (hr)	-0.152	0.356	-0.326	0.322	0.161	-0.082
AWK (number)	-0.223	0.204	-0.234	0.004	-0.191	-0.462*
TA (min)	0.378	0.076	0.276	-0.222	0.037	-0.784**
SOL (min)	0.248	-0.039	0.288	-0.311	0.317	-0.622**
SE (%)	-0.245	0.192	-0.190	0.339	-0.024	0.332
WASO (min)	0.218	0.217	0.080	-0.114	-0.296	-0.711**

TST, total sleep time; TIB, time in bed; AWK, number of wake periods during time in bed; TA, time awake, SOL, sleep onset latency; SE, sleep efficiency; WASO, wake after sleep onset.
N=21; Group: Average Sleep (S8).
*p < 0.05, ** p < 0.01
Pearson Correlation (TIB, TST, Awk#, SOL, SE, accuracies, and RTs) and Spearman Correlations (TA, WASO)

Table 13: Correlations between experimental sleep and performance metrics (accuracy and RT) for n=88

Variable	Immediate Accuracy	Immediate RT	Delayed accuracy	Delayed RT	Differences in Accuracy	Differences in RT
TIB (hr)	0.086	-0.004	0.080	-0.075	0.050	-0.109
TST (hr)	0.075	-0.006	0.115	-0.054	-0.024	-0.071
AWK (number)	-0.011	0.113	0.030	0.105	0.040	-0.058
TA (min)	0.105	0.021	0.130	0.064	0.085	-0.013
SOL (min)	0.218*	-0.067	0.224*	-0.040	0.091	-0.043
SE (%)	0.033	-0.044	0.050	0.002	0.071	0.021
WASO (min)	-0.071	0.086	0.007	0.146	0.031	-0.105

TST, total sleep time; TIB, time in bed; AWK, number of wake periods during time in bed; TA, time awake, SOL, sleep onset latency; SE, sleep efficiency; WASO, wake after sleep onset.
N=88; Groups: Sleep restriction & HIIT (HIITS5); Average sleepers & HIIT (HIITS8); Average Sleep (S8); Restricted Sleep (S5).
*p < 0.05, ** p < 0.01
Pearson Correlation (Accuracies, RTs, TST) and Spearman Correlations (TIB, AWK#, TA, SOL, SE, WASO)

Table 14: Correlations between experimental sleep and performance metrics (accuracy and RT) for HIITS5

Variable	Immediate Accuracy	Immediate RT	Delayed accuracy	Delayed RT	Differences in Accuracy	Differences in RT
TIB (hr)	0.155	0.074	0.128	-0.192	-0.011	-0.346
TST (hr)	0.319	0.070	0.309	0.052	0.095	-0.021
AWK (number)	-0.094	0.177	0.028	0.099	0.126	-0.119
TA (min)	-0.117	-0.090	-0.091	-0.096	-0.116	-0.015
SOL (min)	0.041	-0.337	0.056	-0.269	0.016	0.033
SE (%)	0.079	0.009	0.062	0.228	-0.034	0.244
WASO (min)	-0.149	0.270	-0.039	0.190	0.057	-0.108

TST, total sleep time; TIB, time in bed; AWK, number of wake periods during time in bed; TA, time awake, SOL, sleep onset latency; SE, sleep efficiency; WASO, wake after sleep onset.
N=22; Group: Sleep restriction & HIIT (HIITS5).
*p < 0.05, ** p < 0.01
Pearson Correlation (TST, immediate accuracy and RT, Delayed RT, differences in accuracy and RT) and Spearman Correlations (TIB, AWK#, TA, SOL, SE, WASO, delayed accuracy)

Table 15: Correlations between experimental sleep and performance metrics (accuracy and RT) for $HIITS_8$

Variable	Immediate Accuracy	Immediate RT	Delayed accuracy	Delayed RT	Differences in Accuracy	Differences in RT
TIB (hr)	0.246	-0.123	0.063	0.171	-0.096	0.249
TST (hr)	0.046	0.118	-0.048	0.103	-0.110	-0.090
AWK (number)	-0.162	0.134	-0.043	0.130	0.100	-0.056
TA (min)	0.003	-0.030	0.090	0.009	0.139	0.050
SOL (min)	0.162	-0.047	0.176	-0.040	0.068	0.068
SE (%)	-0.187	0.108	-0.102	-0.134	-0.022	-0.294
WASO (min)	-0.172	0.088	-0.063	0.028	0.111	-0.149

*p < 0.05, ** p < 0.01
N=22; Group: Average Sleep & HIIT (HIITS8).
Spearman Correlations (TIB, TST, SE, AWK#, SOL, TA, WASO)
TST, total sleep time; TIB, time in bed; AWK, number of wake periods during time in bed; TA, time awake, SOL, sleep onset latency; SE, sleep efficiency; WASO, wake after sleep onset.

Table 16: Correlations between experimental sleep and performance metrics (accuracy and RT) for S_5

Variable	Immediate Accuracy	Immediate RT	Delayed accuracy	Delayed RT	Differences in Accuracy	Differences in RT
TIB (hr)	-0.152	0.150	-0.271	-0.079	-0.326	-0.039
TST (hr)	-0.287	-0.117	-0.281	-0.289	-0.050	-0.252
AWK (number)	0.221	-0.309	0.321	0.043	0.173	0..205
TA (min)	0.226	0.017	0.256	0.199	0.120	0.225
SOL (min)	0.303	-0.069	0.297	0.137	-0.096	0.093
SE (%)	0.155	-0.221	0.175	-0.037	0.079	0.134
WASO (min)	-0.222	-0.242	0.321	0.105	0.153	0.253

TST, total sleep time; TIB, time in bed; AWK, number of wake periods during time in bed; TA, time awake, SOL, sleep onset latency; SE, sleep efficiency; WASO, wake after sleep onset.
N=23; Group: Sleep Restriction (S5).
*p < 0.05, ** p < 0.01
Pearson Correlation (TST, TA, SE, accuracies, and immediate and delayed RTs) and Spearman Correlations (TIB, AWK#, SOL, WASO, Differences in RT)

Table 17: Correlations between experimental sleep and performance metrics (accuracy and RT) for S_8

Variable	Immediate Accuracy	Immediate RT	Delayed accuracy	Delayed RT	Differences in Accuracy	Differences in RT
TIB (hr)	-0.142	-0.243	-0.012	-0.226	0.141	-0.171
TST (hr)	0.217	-0.387	-0.142	-0.292	0.125	0.224
AWK (number)	-0.201	0.424	-0.376	0.210	-0.401	-0.209
TA (min)	0.223	0.419	0.064	0.238	0.088	-0.384
SOL (min)	0.318	0.284	0.243	0.177	0.167	-0.304
SE (%)	-0.068	-0.067	-0.104	0.152	-0.048	0.501*
WASO (min)	-0.033	0.623**	-0.279	0.349	-0.230	-0.479*

TST, total sleep time; TIB, time in bed; AWK, number of wake periods during time in bed; TA, time awake, SOL, sleep onset latency; SE, sleep efficiency; WASO, wake after sleep onset.
N=21; Group: Average Sleep (S8).
*$p < 0.05$, ** $p < 0.01$
Pearson Correlation (TST, SE, accuracies, and RTs) and Spearman Correlations (TIB, Awk#, SOL, TA, WASO)

Table 18: One-Way ANOVA analysis with Bonferonni corrections for Performance, Difficulty, Motivation and KSS during the immediate and delayed recall tasks and the differences between the two

Variables	S_8 (N = 21 - Immediate N= 20 - Delayed)	S_5 (N = 23)	$HIITS_8$ (N = 22)	$HIITS_5$ (N = 22)	Main effect p-value
		Immediate			
Performance	5.24 (1.26)	4.74 (2.01)	4.64 (1.22)	5.09 (1.60)	0.577
Difficulty	6.24 (1.38)	5.96 (1.82)	7.0 (1.20)	6.0 (1.77)	0.106
Motivation	7.29 (1.82)	6.13 (2.83)	5.82 (2.32)	6.82 (1.62)	0.126
KSS	5.95 (1.28)	6.57 (1.85)	5.18 (2.06)	5.41 (1.84)	0.100
		Delayed			
Performance	5.05 (1.19)	4.57 (1.81)	4.32 (1.39)	5.0 (1.85)	0.504
Difficulty	6.10 (1.48)	6.0 (2.0)	6.27 (1.49)	6.0 (1.75)	0.944
Motivation	7.40 (1.54) [a]	5.74 (2.47)	6.45 (2.11)	6.23 (1.34)	0.046*
KSS	4.25 (1.65) [b]	6.52 (1.62)	3.95 (1.56)	5.18 (1.59)	< 0.001**

N=88; Groups: Sleep restriction & HIIT (HIITS5); Average sleepers & HIIT (HIITS8); Average Sleep (S8); Restricted Sleep (S5).

Performance: subjective rating of how well one performed in the face-name task from 0 to 10 (Extremely poorly to Excellent); Difficulty: Subjective rating of difficulty in completing the face-name task from 0 to 10 (Extremely easy to Extremely difficult); Motivation: Subjective rating of motivation to complete the face-name task from 0 to 10 (Not motivated to Extremely motivated); KSS: Subjective rating of sleepiness using Karolinska Sleepiness Scale (KSS) from 1-9 (1-Extremely alert; 2-Very alert; 3-Alert; 4-Rather alert; 5- Neither alert not sleepy; 6-Some signs of sleepiness; 7-Sleepy, no effort to stay awake; 8- Sleepy, some effort to stay awake; 9- Very sleepy, fighting sleep.

*$p < 0.05$; **$p < 0.01$

One Way ANOVA (immediate & delayed difficulty); Kruskal Wallis (immediate, delayed & difference between the two: performance, motivation and KSS; difference between the two difficulty)

Pairwise comparison with Bonferonni corrections:

[a] Delayed motivation: Significantly different between S_5 & S_8 (p = 0.01) and $HIITS_5$ & S_8 (p = 0.019)

[b] Delayed KSS: Significantly different between S_5 & S_8 (p<0.001); S_5 & $HIITS_5$ (p=0.018); S_5 & $HIITS_8$ (p<0.001); $HIITS_8$ & $HIITS_5$ (p=0.031).