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Acute Aerobic Exercise Intensity on Working Memory and Vigilance After Nap Deprivation: Effects of Low-Intensity Deserve Attention

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Background: Napping deprivation in habitual nappers leads to cognitive impairment. The ameliorative effect of acute aerobic exercise has been demonstrated for this post-cognitive impairment. However, it is still unclear which intensity of aerobic exercise is the most effective and how long this improvement can be sustained.

Methods: Fifty-eight healthy adults with a chronic napping habit were randomly assigned to four intervention groups after undergoing nap deprivation: a sedentary control group, a low-intensity exercise group (50–59% maximum heart rate, HR_{max}), a moderate-intensity exercise group (60–69% HR_{max}), and a high-intensity exercise group (70–79% HR_{max}). Working memory (N-back task), vigilance (Psychomotor Vigilance Task, PVT), and response inhibitory capacity (Go/NoGo task) were measured.

Results: Regression analyses showed a quadratic trend between exercise intensity and working memory reaction time and accuracy (F =3.297–5.769, $p < 0.05$, R^2 =10.7–18.9%). The effects of exercise were optimal at low-intensity. There was a significant quadratic trend between exercise intensity and PVT lapse (F =4.314, p =0.042, R^2 =7.2%). The effect of exercise increased with higher intensity. Prolonged observation found that the effect of low-intensity exercise on working memory was maintained for 2 hours.

Conclusion: The effect of low-intensity exercise might be underestimated. Low-intensity exercise significantly improved working memory performance, and the effects could be maintained throughout the afternoon. In contrast, the effects of high-intensity exercise were unlikely to be maintained and might even have negative effects. Future researchers can broaden the categories of participants to enhance the external validity and collect diverse physiological indicators to explore related physiological mechanisms.

Keywords: exercise intensity, executive function, habitual nappers, nap deprivation, working memory

Introduction

Sleep condition is closely related to people's daily performance and mental health.[1] As an important part of one's sleep during daytime, napping is insufficiently studied. Previous studies have mostly focused on nighttime sleep, while less attention has been paid to napping.[2,3] Napping is very common among Chinese people. More than 80% of Chinese university students take naps regularly and believe that napping helps them to work and study.[4] Napping is used as an important way to relieve daytime drowsiness and nighttime sleep deprivation.[5–7] However, the need for a nap is sometimes not met due to daily work schedules and unforeseen circumstances. This may be due, on the one hand, to the lack of a favorable environment for napping and, on the other hand, to the fact that the stress brought about by unexpected life events makes it difficult for people to fall asleep. These lead to nap deprivation in habitual nappers, which interrupts the habitual biorhythms and causes cognitive impairment.[8,9] Therefore, exploring scientific, convenient,

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and effective interventions to alleviate or eliminate cognitive impairment after nap deprivation carries great practical value.

Napping has a positive impact on cognitive function and is considered one of the measures to enhance it. For instance, research by Cai et al[7] has shown that napping is associated with better cognitive function, including orientation, language, and memory. Many scientists recommend napping to improve alertness, stimulate creativity, enhance memory, and boost performance in complex tasks such as executive functions.[10,11] Previous studies indicate that habitual nappers tend to derive more benefits from napping compared to non-habitual nappers.[12] Recent evidence confirms that napping habits play a pivotal role in the relationship between napping and cognitive function.[13] Habitual nappers exhibit better cognitive performance than non-habitual nappers. However, while enjoying the benefits of napping, habitual nappers should also consider the adverse effects of nap deprivation caused by urgent tasks or unexpected situations.

Current research on the higher cognitive effects of napping has focused on memory[10] and learning,[14] and relatively few studies have investigated the effects of napping on executive functions (ie, inhibition, working memory, and cognitive flexibility). Working memory temporarily stores and processes information vital for complex tasks like reasoning and decision-making,[15] often assessed through tasks like N-back, spatial working memory, and Wisconsin card sorting.[16] Inhibitory function focuses cognitive resources on a task, suppressing dominant responses and reducing the influence of habits or distractions, enhancing task efficiency. Inhibitory control disorders may lead to behavioral impulsivity, assessed through tasks like Go/NoGo, Stop Signal, and Stroop Color Word.[17]

Several studies have indicated that napping is beneficial to executive function. For instance, daytime naps can enhance the accuracy of preschoolers in Flanker tasks,[6] while nocturnal naps can improve adults' performance in Go/NoGo tasks.[18] Research by Ru et al[19] revealed that brief napping can elevate sustained attention but has no effect on working memory. Chen et al[9] conducted a study on habitual nappers subjected to nap deprivation, which showed that nap deprivation significantly reduced participants' accuracy and reaction speed in Go/NoGo tasks. Another study by Ru et al[20] demonstrated that nap deprivation noticeably impacts participants' performance in the Psychomotor Vigilance Task (PVT) and accuracy in Go/NoGo tasks, yet it does not affect reaction speed. Under conditions of nap deprivation, both accuracy and reaction speed decrease in N-back tasks.[20] These findings suggest that the impact of napping on task performance depends on the cognitive domain and task difficulty. On the other hand, Zhou et al[21] found that nap deprivation significantly increased subjective sleepiness and negative emotions, impairing performance in PVT tasks and tasks measuring working memory. However, a minority of studies indicate that napping has no effect on executive function. For example, inhibitory function assessed by Go/NoGo tasks remained unaffected by nap deprivation.[22] Some studies have even reported detrimental effects of napping on inhibitory function. Lam et al[23] discovered that compared to preschoolers with normal naps, those deprived of naps showed significant improvement in Go/NoGo tasks. In terms of cognitive flexibility, Slama et al's research[24] showed that napping significantly improves the switching speed of cognitive flexibility, and the increase in switching task accuracy is related to the augmentation of N1 phase during NREM sleep. Golkashani et al[25] recently found that sleep schedules incorporating daytime nap opportunities facilitate the establishment of robust and flexible schemas, thereby enhancing cognitive flexibility. In conclusion, previous studies on the effects of nap deprivation on working memory and inhibitory function yield mixed results, while those on cognitive flexibility present more consistent findings.

Existing measures to improve executive functions include meditation, aerobic exercise, medication, and napping.[15] Among them, inappropriate use of meditation may lead to addiction or mental disorders, and frequent use of drugs has more severe side effects, whereas the realization of positive thinking meditation and napping requires a quiet and comfortable environment, which is difficult to obtain in urgent conditions. Therefore, aerobic exercise is a potential intervention worthy of further investigation.

Many studies have demonstrated the benefits of acute aerobic exercise on executive functions.[26–28] Acute aerobic exercise, also commonly referred to short-duration aerobic exercise or one-time aerobic exercise, is a single session of exercise lasting approximately 10–60 minutes in which oxygen is involved in metabolism and provides energy, primarily involving cardiorespiratory function and mitochondrial biosynthesis.[29] The implementation of acute aerobic exercise is not easily affected by external environment, which is convenient and simple, suitable for all ages and has good application prospects.[30–33] A systematic review by Dinoff found that acute or chronic aerobic exercise significantly increased BDNF concentrations, and both in healthy and cognitively impaired populations.[34] Acute exercise interventions have been shown to be effective in coping with cognitive impairment following nocturnal sleep deprivation, and 5-HT may be one of the possible mechanisms by which aerobic exercise alleviates the cognitive control impairment caused by sleep deprivation.[35] A recent study on planning ability and alertness after nap deprivation also indicated that acute aerobic exercise significantly improved participants' planning ability and alertness relative to shut-eye.[36] However, the effects of different exercise intensities and their sustained effects have not been elucidated through research.

Exercise intensity is a moderator often considered in acute exercise research. Although meta-analysis results indicate that exercise has a small positive effect on executive function, not all findings are consistent.[37] Focus on exercise intensity can help to understand the mechanisms by which interventions produce their effects. Meta-analytic evidence demonstrated that light to moderate-intensity exercise had a small but beneficial effect on executive functions, however, this positive effect only occurred immediately after acute exercise.[38] In contrast, moderate-intensity exercise showed a similarly small but long-lasting positive effect on executive functions. A generalized review conducted by Erickson et al[39] found strong evidence that acute exercise at moderate-intensity had a transient benefit on cognitive performance during the recovery period after exercise. Both the "inverted U" hypothesis and drive theory suggest that exercise intensity will influence the magnitude of the effect.[38] Specifically, the "inverted U" hypothesis predicts that exercise at moderate-intensity will have the greatest benefit, whereas the drive theory suggests that the greatest benefit occurs at higher intensities.[40] Research suggested that this benefit might be related to activation of the prefrontal cortex.[41] While other studies suggest that very low to moderate intensity exercise is beneficial for cognition, high to very high intensity exercise does not confer cognitive benefits.[42] In summary, the effect of exercise intensity on cognition is still controversial, and the differences in these findings may be due to different types of exercise, participants, and the degree of cognitive impairment. The intensity of exercise may have different effects on subsequent executive functions and the duration of the effect, and the dose effect of exercise on cognitive recovery after nap deprivation remains unclear. Moreover, the continuity of effects after a period of intervention is also a factor of interest. Exploring the long-term effects of exercise on executive functions can help to schedule the frequency of interventions more scientifically to achieve optimal intervention outcomes. Whether acute aerobic exercise interventions can help habitual nappers after nap deprivation maintain executive function to cope with learning and training tasks throughout the afternoon is one of the questions that still need to be explored.

Therefore, drawing upon previous research, the study aims to investigate the influence of varying intensities of acute aerobic exercise on the executive functions of habitual nappers. Specifically, it selects habitual nappers as participants, employs low, moderate, and high intensities of acute aerobic exercise as interventions, and utilizes computerized behavioral tasks to assess executive function. By meticulously analyzing cognitive performance indices across different observation time points, the study endeavors to uncover the most effective intensity for cognitive recovery after nap deprivation. In this study, rope jumping was chosen as the aerobic exercise intervention primarily due to prior evidence suggesting that moderate-intensity rope jumping can positively improve cognitive function, particularly in habitual nappers after nap deprivation.[36] Additionally, the uniformity and ease of standardization in rope jumping's workload allow researchers to meticulously control the exercise intensity, which is essential for investigating the effects of varying intensities on executive function. It is hypothesized that a moderate-intensity exercise intervention will be the most effective in recovering from executive function impairment among habitual nappers after nap deprivation. This hypothesis is based on previous findings that moderate-intensity exercise can enhance cognitive performance by eliminating the expression of posterior-contralateral negativity to interfering stimuli.[43] No hypothesis is made about the results after a certain amount of time, as it is open to be explored.

Methods

Recruitment and Screening of Participants

Participants were recruited through online posters. Potential participants were required to complete an initial questionnaire to screen for their eligibilities. Sample sizes were pre-calculated using the G*power software and referenced to similar previous research paradigms.[44,45] The probability of both Type I ($p \leq 0.05$) and Type II ($1-\beta \geq 0.8$) errors was fixed.

Based on an earlier study with a similar paradigm,[46] the effect size (η_p^2 =0.27) for the primary outcome (ie, reaction time) was retained. The G*power software indicated that the minimum sample size required to achieve a test efficacy of 0.8 was 44 participants, and taking into account a dropout rate of 20%, 60 subjects were recruited for this study.

Eligibility criteria included (1) male habitual nappers (≥3 naps per week, 30 min-120 min/day); (2) not in the habit of taking substances that affect sleep (including caffeine, alcohol, tea, tranquilizers, etc.) and have not taken them in the 7 days before coming to the lab and (3) aged between 18 and 25 years old. Exclusion criteria included (1) personal or family history of psychiatric illness; (2) neurological disorders; (3) smoking, alcohol, caffeine/tea habits; (4) shift work, jet lag, or all-night sleeplessness in the last month; (5) scores of >7 on the Pittsburgh Sleep Quality Index;[47] (6) scores of > 7 on the Fatigue Scale-14;[48] (7) scores of >11 on the Epworth Sleepiness Scale;[49] and (8) excessive differences between subjectively reported nap duration and recorded by accelerometers (Actigraph type wGT3X-BT).

Two participants dropped out halfway during the study and were thus excluded from the subsequent analyses. As a result, a total of 58 habitual napping college students completed the study and were included in statistical analyses.

Experimental Protocol

One week before the experiment, eligible participants visited the lab and familiarized themselves with the experimental procedures. They were asked to complete an online questionnaire for baseline measurements, in which they reported demographic information, nap and exercise-related information, and the Morning and Evening Questionnaire-5 (MEQ-5). After that, they were required to perform a standardized Burpee beep test to measure their maximum heart rate[50] (HR_{max}), which was recorded and utilized to define exercise intensity. This standardized test was based on a multi-stage exercise beep test using a 20-meter shuttle run. A Burpee consists of a deep squat, a backward jump to a plank position, a forward jump to a deep squat position, and a hands up and vertical jump. This sequence was equivalent to one repetition. A track of multiple levels of beeps in progressively increasing speed is played through the speakers. The first round consisted of 1 beep every 6 seconds for 30 seconds, requiring a total of 5 Burpee repetitions. Each round, the number of burpee repetitions increases with faster beeps. Participants were required to keep performing the Burpee exercise until they missed 2 consecutive beeps, which was considered to be the maximum heart rate.

During the interview, participants were asked to maintain regular sleep-wake schedules as well as physical activity levels that were not intentionally increased or decreased. Participants were also asked to wear an Actigraph and to complete a sleep diary to ensure the reliability of the routine for 7 consecutive days. Accelerometer (Actigraph type wGT3X-BT, Actigraph Corp, Pensacola, FL, USA) was used to measure the objective sleep outcomes. It is a wrist-worn accelerometer that measures and records physical movements associated with wake and sleep. All participants were asked to wear the Actigraph on their non-dominant wrist at all times for 7 days prior to the experiment to ensure that their napping and exercise habits were in line with the experiment. Through the sleep diary participants can record their own sleep behavior patterns and daytime functions affected by sleep, so that it is easy for the researcher to obtain first-hand sleep information from participants directly. The sleep diary used in this study was adapted from The Consensus Sleep Diary.[51] Caffeine, alcohol, and other substances that might impact their physical activity and sleep were prohibited.

Once recruited, the participants were randomized using computer software[52] and allocated to one of four separate groups: (1) sedentary control group; (2) low-intensity exercise group (50–59% HR_{max}); (3) moderate-intensity exercise group (60–69% HR_{max}), and (4) high-intensity exercise group (70–79% HR_{max}). The experimental procedure is illustrated in Figure 1. Polar H10 sensor chest strap device (Polar Electro Oy, Kempele, Finland; sampling rate: 1000 Hz) was used to record and monitor heart rate. The heart rate of the control group was also recorded at the same time to ensure differentiation from the intervention groups.

On the experiment day, participants got up following their regular routine and ate the same standard breakfast and lunch at 08:00 and 11:00 AM. They arrived at the lab at 12:00 and familiarized themselves with the experimental tasks. Trained lab assistants were responsible for answering questions to ensure that participants fully understood the rules of the experiment. In addition, each of them needed to wear the Polar H10 chest transmitter in preparation for the subsequent intervention phase. At 12:30 PM, Test 1 was administered to measure participants' baseline level of cognitive functions, followed by one hour of nap deprivation. During nap deprivation, participants were only allowed to sit still and read pre-prepared neutral materials and were prohibited from using electronic devices. Test 2 was executed at 2:00 PM to

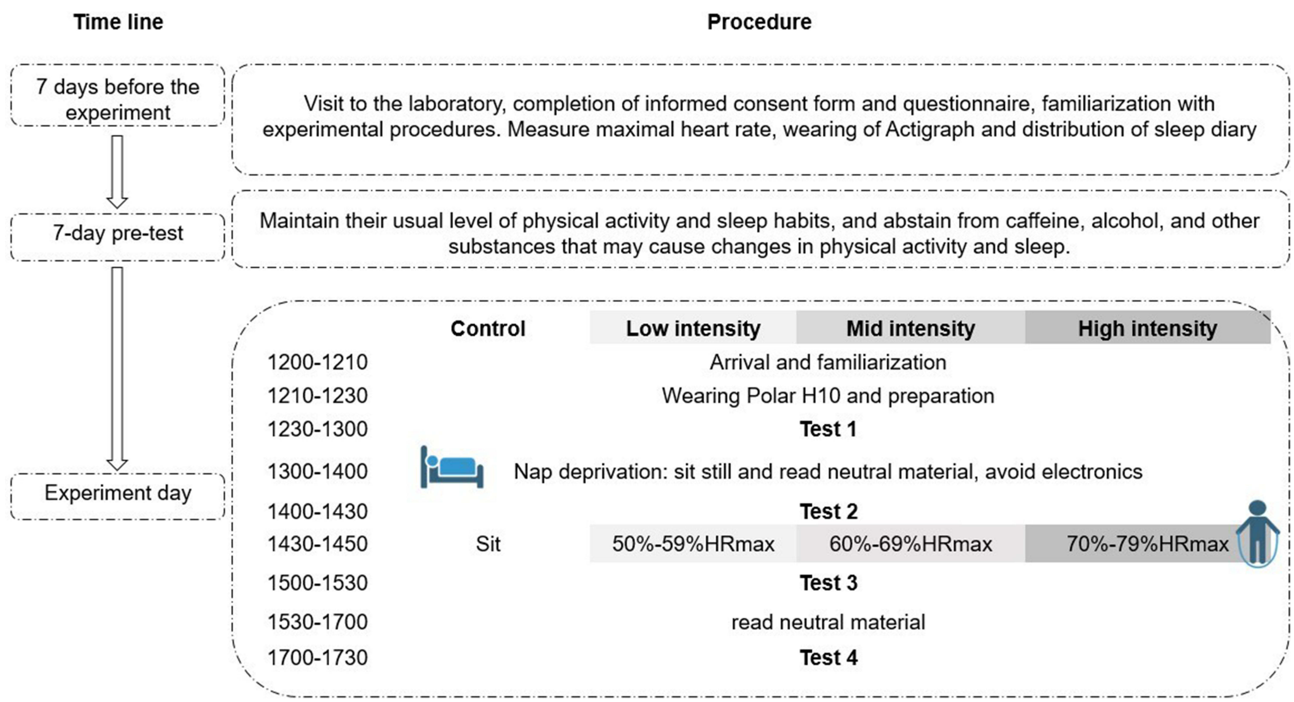

Figure 1 Schematic diagram of the overall research program. The content and sequence of the cognitive test were the same in each test, including a subjective questionnaire section and a computerized task section which consisted of 1-back, 3-back, PVT, and Go/NoGo tasks.

measure the effects that nap deprivation brought on participants' cognitive functions. After Test 2 was completed, at approximately 14:30, the participants were randomly grouped for intervention or control.

During exercise, participants performed rope jumping at a specific percentage of their HR_{max} measured 7 days before: low-intensity exercise group (50–59% HR_{max}), moderate-intensity exercise group (60–69% HR_{max}), and high-intensity exercise group (70–79% HR_{max}). Intensity was prescribed directly based on the participant's measured maximal capacity. During the first 5 minutes of exercise, participants gradually increased the exercise intensity until they reached the specified percentage of HR_{max}, and were instructed to maintain this intensity for the remainder of the exercise time (15 min). The total exercise lasted 20 minutes. In the sedentary control group, participants sat in comfortable chairs while continuing to read neutral materials. Two experimental assistants would supervise the entire process to ensure that all participants did not fall asleep during nap deprivation, that the heart rates of participants in the exercise group met the requirements during the intervention, and at the same time, monitored the participants in the control group to ensure they remain awake. All groups wore heart rate transmitters throughout the phase.

After the intervention was completed, participants were allowed to rest and adjust briefly for 10 minutes and Test 3 was performed at 15:00. In order to measure whether the intervention remained effective after a period of time, participants were also required to continue reading neutral material in the laboratory from 15:30–17:00 and to perform Test 4 at 17:00.

The cognitive tasks for each test are identical, including a computerized task section consisting of 1-back, 3-back, Psychomotor Vigilance Task (PVT), and Go/NoGo tasks. The order of the tasks is balanced using a Latin square method. Prior to each computerized task, all participants were instructed to practice so they understood the task correctly; and a hit rate of 80% or better was required during practice to proceed.

Blinding

The assistants during the experiment and the evaluators of the cognitive ability tests were completely unaware of the group allocation until the intervention was implemented. Participants were blinded by informing them that this study was designed to evaluate an exercise intervention, but they did not know what intensity of exercise or control they needed to follow until the intervention was implemented.

Ethics Approval and Consent to Participate

This study was approved by the Medical Research Ethics Committee of the Naval Medical University, with the protocol number 20210310041 and the approval number NMUMREC-2021-041. All participants signed a written informed consent prior to study commencement and were financially compensated for the completion of all study visits. The study was conducted in accordance with the Declaration of Helsinki and considered as not causing any other economic burden or injury.

Study Measures

Questionnaire

Demographic information was collected through a questionnaire, including gender, age, height, weight, body mass index (BMI), frequency and intensity of regular physical activity, psycho/neurological disorders or family history, habit of smoking, alcohol consumption, caffeine/tea consumption, etc. The nap-related questionnaire asked about nap frequency, average duration, and typical nap time. Participants were first asked: "How often do you usually nap?". There were four possible responses: "not in the past month", "less than once a week", "once or twice a week", "three or four times a week", and "five or more times a week". Those who answered other than "not in the past month" were asked to be specific: "What is the average duration of your naps?" (0.5 hours or less, 1 hour, 1.5 hours, 2 hours, 2 hours or more) and "What time do you usually nap?" (in the morning, 12:00–15:00, 15:00–18:00 and 18:00–21:00). MEQ-5[53] was utilized to assess how active and awake participants were at specific times in the morning and evening The scale was a self-rating scale, consisting of 5 entries. Participants were categorized into three groups based on their total scores: night-type type (4–11 points), neutral type (12–17 points), and early morning type (18–25 points). Sleep quality was measured using Pittsburgh Sleep Quality Index (PSQI),[47] a 19-item self-scoring questionnaire designed to assess sleep quality over one month through seven factors: subjective sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disorders, use of sleep medications, and daytime dysfunction. The sum of the component scores produces a total score ranging from 0 to 21. The Epworth Sleepiness Scale (ESS)[49] is a very simple, easy-to-administer scale that can evaluate sleepiness, essentially asking participants to consider sleepiness in eight scenarios in their lives, scoring them on a scale of 0–3, with higher scores representing a higher likelihood of sleepiness occurring.

N-Back Task

Separate blocks of 1-back and 3-back tasks were performed as part of each test.[54] In this task, a letter appeared in the central area of the screen for 1000 ms, followed by a blank screen of 3000 ms before the presentation of the next letter. For the 1-back task, participants were instructed to respond with a button press to indicate whether the current stimulus presented to them matched (F) or did not match (J) the letter from the previous trial. For the 3-back task, they had to do the same, except to determine whether the current stimulus matched the letter that was presented three trials ago. The match-to-mismatch ratio was 20:30. There were four indicators of performance: reaction time (RTs) indicating reaction times for correct responses, the omission rate being the ratio of incorrect responses to the total number of target responses, the false alarm rate being the ratio of incorrect responses to the total non-target responses, and the index of discrimination (d') equaled to the Z-score of the hit rate minus the Z-score of the false alarm rate.

Psychomotor Vigilance Task (PVT)

Psychomotor Vigilance task is a widely used behavioral test task to measure participants' attentional state, arousal level, and changes in vigilance. PVT used in the current experiment was the 5-minute version, which was shown to be equivalent to the 10-minute version.[55] During the task, participants were required to stay focused when they saw a "+" appear on the screen and to press the F key as soon as the "+" changed to an "X". Symbol changes were presented at randomized stimulus intervals ranging from 2s to 10s. The indicators included mean RTs, lapses, 10% fastest reaction time, and 10% slowest reaction time. Lapses were defined as trials with a reaction time less than 100ms and/or greater than 500ms.

Go/NoGo Task

During the task, participants were asked to look at the center of the screen, relax, and minimize eye blinking or body movement. The visual stimuli consisted of single and double triangles on a black background presented on a computer screen. After the Go stimulus (even-numbered triangles), participants had to press a key with the index finger of their dominant hand, whereas after the NoGo stimulus (odd-numbered triangles only), participants had to restrain the response as quickly as possible.[56] At the beginning of each trial, a small white cross (+) appeared in the center of the screen against a black background for 100 ms. Then, a 200 ms stimulus was administered in the center of the screen, with stimulus intervals randomized to 1000 ~ 1200 ms. The task instructions emphasized the speed and accuracy of responses. The task contained 200 stimuli (60% Go and 40% NoGo) at random. Behavioral data such as hit rate in Go condition, RTs, false alarm rate, and d' were collected.

All computer tasks performed in this experiment were carried out through Eprime 3.0.

Statistical Analysis

This study used a 4×4 mixed experimental design with two variables of group and time. Statistical analyses were conducted using SPSS 26.0[52] and images were created using GraphPad Prism 9. Measurement data are presented as mean (standard deviation) in the table, and the standard error bar is shown in the figures. The chi-square test or one-way analysis of variance was used to measure the comparability of the baseline data across groups. The normality of the data in each group was tested. For data that obeyed normal distribution, one-way analysis of variance (ANOVA) was used to measure the comparability across groups, while for data that did not obey normal distribution, the Kruskal–Wallis *H*-test was applied.

The data analysis in this study drew on previous similar research,[44] in which regression analysis was conducted on the difference scores between the control group and resistance exercise groups of varying intensities to derive the dose-response relationship between exercise intensity and cognitive function. To test the immediate post-intervention dose-response relationships between exercise intensity and cognitive ability, regression analyses was conducted with linear and quadratic models, using exercise intensity as a predictor of the difference scores after intervention (Test 3) and versus nap deprivation (Test 2). To test the prolonged post-intervention dose-response relationships, the same regression analysis was conducted between exercise intensity and DS between extended observation (Test 4) and nap deprivation (Test 2). Separate regression analyses were performed for each indicator of cognitive ability.

Difference scores were used as a criterion for two reasons. First, there was no guarantee that some of the cognitive metrics differed between groups after nap deprivation. Second, because randomization could not be relied upon to ensure that the groups had the same scores after nap deprivation, it was necessary to consider pre-intervention scores when determining the effect of exercise intensity on cognitive performance.

Results

Demographic Information

The demographic information of different groups is displayed in Table 1. The participants were on average within the intermediate chronotype range. One-way ANOVA or chi-square test showed that there were no statistically significant differences between the groups in terms of demographic information, napping habits, and exercise habits (F =0.092–1.826, χ^2 =12.338–16.286, p > 0.05). Demographic information including age, maximum heart rate and some screening questionnaires. Napping habits include: nap frequency, nap onset time, nap end time and nap duration. Exercise habits include: exercise frequency and daily exercise intensity.

Baseline Data and Nap Deprivation

One-way ANOVA and Kruskal–Wallis *H*-test revealed that there were no significant differences (p > 0.05) among the four groups in baseline N-back performance (1-back RTs: F =1.780, p > 0.05; 1-back Omission Rate: H =6.798, p >

Table 1 Demographic Information of Different Groups

Variable	Control	Low Intensity	Moderate Intensity	High intensity	Total	F/X²	P
N	14	15	15	14	58		
Age (years)	23.13 (2.50)	22.27 (2.82)	23.13 (2.56)	21.71 (2.13)	22.58 (2.53)	1.110	0.353
Nap frequency (day/week)	6.07 (1.03)	6.13 (1.06)	6.20 (1.08)	6.00 (0.78)	6.10 (0.98)	0.108	0.955
Maximum heart rate (beats/minute)	177.43 (15.42)	179.27 (8.75)	177.21 (9.44)	174.79 (6.99)	177.21 (10.44)	0.434	0.729
Fatigue scale	2.73 (2.05)	2.80 (2.21)	3.40 (2.53)	2.86 (2.38)	2.95 (2.26)	0.265	0.850
Epworth sleepiness scale	7.60 (2.67)	6.80 (3.05)	7.87 (1.96)	6.43 (3.06)	7.19 (2.71)	0.895	0.449
Pittsburgh sleep quality index	4.27 (1.58)	4.80 (1.57)	5.00 (1.65)	4.50 (1.79)	4.64 (1.63)	0.578	0.632
Morning and evening questionnaire-5	13.60 (2.97)	14.93 (1.75)	14.13 (2.07)	15.43 (2.24)	14.51 (2.35)	1.826	0.153
Nap onset time	12:49 (19.10)	12:50 (21.71)	12:43 (27.95)	12:56 (23.05)	12:49 (23.02)	0.734	0.536
Nap end time	13:57 (22.43)	13:57 (13.31)	13:57 (27.37)	14:00 (4.99)	13:58 (18.77)	0.092	0.964
Nap duration (hours)	1.139 (0.31)	1.13 (0.32)	1.23 (0.45)	1.07 (0.40)	1.14 (0.37)	0.441	0.725
Exercise frequency							
Almost every day (≥5 times per week)	26.70%	0.00%	13.30%	35.70%	18.60%	16.286	0.061
Frequently (3~4 times per week)	20.00%	53.30%	53.30%	42.90%	42.40%		
Occasionally (1–2 times per week)	40.00%	33.30%	33.30%	14.30%	30.50%		
Hardly (≤3 times per month)	13.30%	13.30%	0.00%	7.10%	8.50%		
Daily exercise intensity							
High	0.00%	6.67%	13.33%	21.43%	10.17%	12.338	0.195
Moderate	66.67%	73.33%	80.00%	71.43%	72.88%		
Low	20.00%	20.00%	6.67%	7.14%	13.56%		
Sedentary	13.33%	0.00%	0.00%	0.00%	3.39%		

0.05; 1-back False Alarm Rate: H =6.408, p > 0.05; 1-back d': H =6.131, p > 0.05; 3-back RTs: H =5.327, p > 0.05; 3-back Omission Rate: H =1.022, p > 0.05; 3-back False Alarm Rate: H =2.606, p > 0.05; 3-back d': H =0.792, p > 0.05), baseline PVT performance (RTs: F =1.261, p > 0.05; Lapse: H =2.520, p > 0.05; 10%FRTs: F=1.195, p > 0.05; 10%SRTs: F =0.382, p > 0.05) and Go/NoGo performance (Go Hit Rate: H =2.487, p > 0.05; Go RTs: F =0.615, p > 0.05; NoGo False Alarm Rate: F =0.159, p > 0.05; GoNoGo d': F =0.333, p > 0.05). Means and standard deviations for participants' baseline scores are presented in Table 2. After nap deprivation, participants produced varying degrees of decreases in cognitive performance, particularly in reaction times on the 1-back and 3-back tasks. Detailed information on performance before and after nap deprivation and the scores at each test can be found in the Supplementary Files.

Immediate Post-Intervention Dose-Response Relationships

Working Memory

The heart rate of the control group was 35 to 45% of the maximum heart rate and is therefore replaced by 40% in the graph. Table 3 shows the immediate intervention effect of excise across different intensity One-way ANOVA revealed that there were significant differences (p < 0.05) among the four groups in 1-back rts, 1-back omission rate, 3-back omission rate and 3-back d'. Table S1 lists the means and standard deviations for each group on T2, T3, and T4, as well as the difference scores.

Figure 2 illustrates the immediate post-intervention dose-response relationships in 1-back difference scores. Regression analysis revealed a significant quadratic trend between exercise intensity and 1-back reaction time difference scores (F =5.769, p =0.005, R^2 =18.9%). A close quadratic trend was found between 1-back omission rate difference scores and exercise intensity, however it did not reach statistical significance (F =2.414, p =0.099, R^2 =8.1%). Regarding

Table 2 Baseline Data of Different Groups

Variable	Control	Low Intensity	Moderate Intensity	High Intensity	Total	*F/H*	*P*
N	14	15	15	14	58		
1-back reaction time (RTs, ms)	533.76 (31.91)	566.96 (88.71)	586.75 (88.36)	539.39 (57.89)	556.94 (73.39)	1.780[a]	0.162
1-back Omission Rate	0.1 (0.11)	0.13 (0.11)	0.2 (0.13)	0.22 (0.26)	0.16 (0.16)	6.798	0.079
1-back False Alarm Rate	0.05 (0.04)	0.1 (0.09)	0.13 (0.16)	0.18 (0.25)	0.12 (0.16)	6.408	0.093
1-back Index of discrimination (d’)	3.24 (0.82)	2.65 (0.97)	2.23 (1.05)	2.22 (1.82)	2.58 (1.26)	6.131	0.105
3-back RTs (ms)	1601.20 (424.10)	1349.71 (672.31)	1365.87 (493.50)	1403.86 (400.23)	1432.00 (504.14)	5.327	0.149
3-back Omission Rate	0.15 (0.17)	0.24 (0.25)	0.16 (0.2)	0.16 (0.13)	0.18 (0.19)	1.022	0.796
3-back False Alarm Rate	0.04 (0.03)	0.08 (0.19)	0.03 (0)	0.03 (0.01)	0.04 (0.10)	2.606	0.456
3-back d’	3.07 (0.86)	2.72 (1.45)	3.2 (0.84)	3.03 (0.71)	3.01 (1.00)	0.792	0.851
PVT RTs (ms)	331.64 (46.59)	353.67 (56.22)	322.36 (32.08)	345.86 (54.34)	338.37 (48.49)	1.261[a]	0.297
PVT Lapse	3.57 (5.10)	4.40 (3.96)	2.20 (2.48)	3.14 (3.86)	3.33 (3.92)	2.520	0.472
PVT 10%FRTs (ms)	234.41 (54.35)	254.38 (31.39)	230.88 (31.50)	245.64 (29.23)	241.37 (38)	1.195[a]	0.321
PVT 10%SRTs (ms)	494.73 (99.19)	513.46 (119.31)	470.03 (82.41)	503.06 (152.62)	495.20 (113.98)	0.382[a]	0.767
Go Hit Rate	0.99 (0.01)	0.98 (0.02)	0.97 (0.05)	0.98 (0.05)	0.98 (0.04)	2.487	0.478
Go RTs (ms)	325.5 (31.01)	342.27 (33.02)	333.52 (24.92)	340.63 (53.47)	335.56 (36.55)	0.615[a]	0.608
NoGo False Alarm Rate	0.24 (0.12)	0.25 (0.15)	0.24 (0.15)	0.27 (0.13)	0.25 (0.14)	0.159[a]	0.924
GoNoGo d’	3.28 (0.61)	3.09 (0.74)	3.05 (0.91)	3.03 (0.71)	3.11 (0.74)	0.333[a]	0.801

Notes: [a]The data in each group followed a normal distribution and were compared between groups using analysis of variance (ANOVA).
Abbreviations: 10%FRTs, 10% fastest reaction time; 10%SRTs, 10% slowest reaction time.

Table 3 The Immediate and Prolonged Intervention Effect of Excise Across Different Intensity

Variables	Control		Low Intensity		Moderate Intensity		High Intensity		F		P	
	DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2
1-back reaction time (RTs, ms)	−30.81 (36.85)	−67.12 (42.92)	−70.98 (47.45)	−68.36 (64.44)	−44.54 (37.01)	−32.21 (40.79)	−13.73 (52.76)	−69.91 (56.41)	4.658	1.272	0.006	0.293
1-back Omission Rate	−0.01 (0.06)	0.03 (0.07)	−0.09 (0.15)	−0.13 (0.2)	−0.05 (0.16)	−0.01 (0.14)	−0.02 (0.09)	0 (0.11)	1.462	3.025	0.045	0.037
1-back False Alarm Rate	−0.01 (0.05)	−0.02 (0.05)	−0.02 (0.08)	−0.07 (0.1)	−0.04 (0.14)	−0.03 (0.07)	−0.05 (0.09)	−0.07 (0.1)	0.568	1.537	0.638	0.215
1-back Index of discrimination (d')	0.15 (0.49)	−0.17 (0.68)	0.5 (0.85)	0.43 (0.81)	0.5 (1.15)	−0.12 (1.68)	0.39 (0.76)	−0.02 (0.79)	0.787	2.232	0.506	0.095
3-back RTs (ms)	−407.6 (405.03)	−533.16 (519.2)	−66.78 (943.35)	−405.29 (314.97)	−148.39 (864.94)	−525.33 (743.57)	−382.57 (480.2)	−783.08 (974.26)	0.819	0.759	0.489	0.522
3-back Omission Rate	0 (0.08)	0 (0.12)	−0.08 (0.11)	−0.08 (0.1)	−0.06 (0.09)	−0.02 (0.13)	−0.01 (0.1)	−0.02 (0.13)	2.401	1.202	0.048	0.318
3-back False Alarm Rate	0 (0.03)	0.01 (0.04)	−0.01 (0.02)	−0.01 (0.01)	−0.02 (0.04)	−0.02 (0.04)	0 (0.02)	0.04 (0.07)	1.727	4.394	0.172	0.008
3-back d'	−0.03 (0.61)	0.07 (0.59)	0.56 (0.63)	−0.14 (0.37)	0.43 (0.52)	−0.18 (0.7)	0.09 (0.68)	−0.24 (0.99)	2.975	0.542	0.040	0.655
PVT RTs (ms)	8.07 (30.71)	−13.93 (23.29)	−11.07 (67.16)	−8.2 (51.78)	0.53 (26.76)	7.2 (45.94)	−24.64 (80.58)	−15.93 (57.92)	0.915	0.737	0.440	0.535
PVT Lapse	1.64 (4.22)	1.07 (3.17)	1.73 (4.11)	0.93 (3.94)	−0.53 (2.1)	0.53 (4.39)	−1.36 (5.79)	0.29 (4.81)	1.950	0.109	0.052	0.954
PVT 10%FRTs (ms)	−4.5 (39.31)	−19.43 (46.14)	−27.33 (62.13)	−4.27 (45.4)	1.87 (14.15)	−4.6 (54.33)	−7.64 (29.35)	−20.86 (47.99)	1.452	0.506	0.238	0.680
PVT 10%SRTs (ms)	−5.79 (68.21)	−11 (69.9)	32.73 (101.7)	6.87 (81.31)	13.07 (69.91)	18.53 (105.8)	−54.43 (187.42)	−24.79 (132)	1.483	0.531	0.230	0.663
Go Hit Rate	0 (0.02)	0 (0.02)	−0.01 (0.05)	0 (0.03)	0 (0.01)	0 (0.02)	0 (0.03)	0 (0.03)	0.743	0.109	0.531	0.954
Go RTs (ms)	−7.36 (25.6)	−9.79 (14.94)	−12.67 (22.91)	−24.07 (39.63)	−8.33 (16.03)	−6.67 (18.46)	−7.29 (17)	−10.5 (25.12)	0.223	1.269	0.880	0.294
NoGo False Alarm Rate	0.03 (0.09)	0.04 (0.1)	0.01 (0.1)	0 (0.16)	0 (0.09)	−0.01 (0.11)	0 (0.09)	0.04 (0.12)	0.308	0.625	0.820	0.602
GoNoGo d'	−0.12 (0.68)	−0.17 (0.42)	−0.17 (0.89)	−0.11 (0.95)	0.03 (0.5)	0 (0.72)	−0.03 (0.66)	−0.28 (0.91)	0.246	0.340	0.864	0.796

Abbreviations: 10%FRTs, 10% fastest reaction time. 10%SRTs, 10% slowest reaction time.

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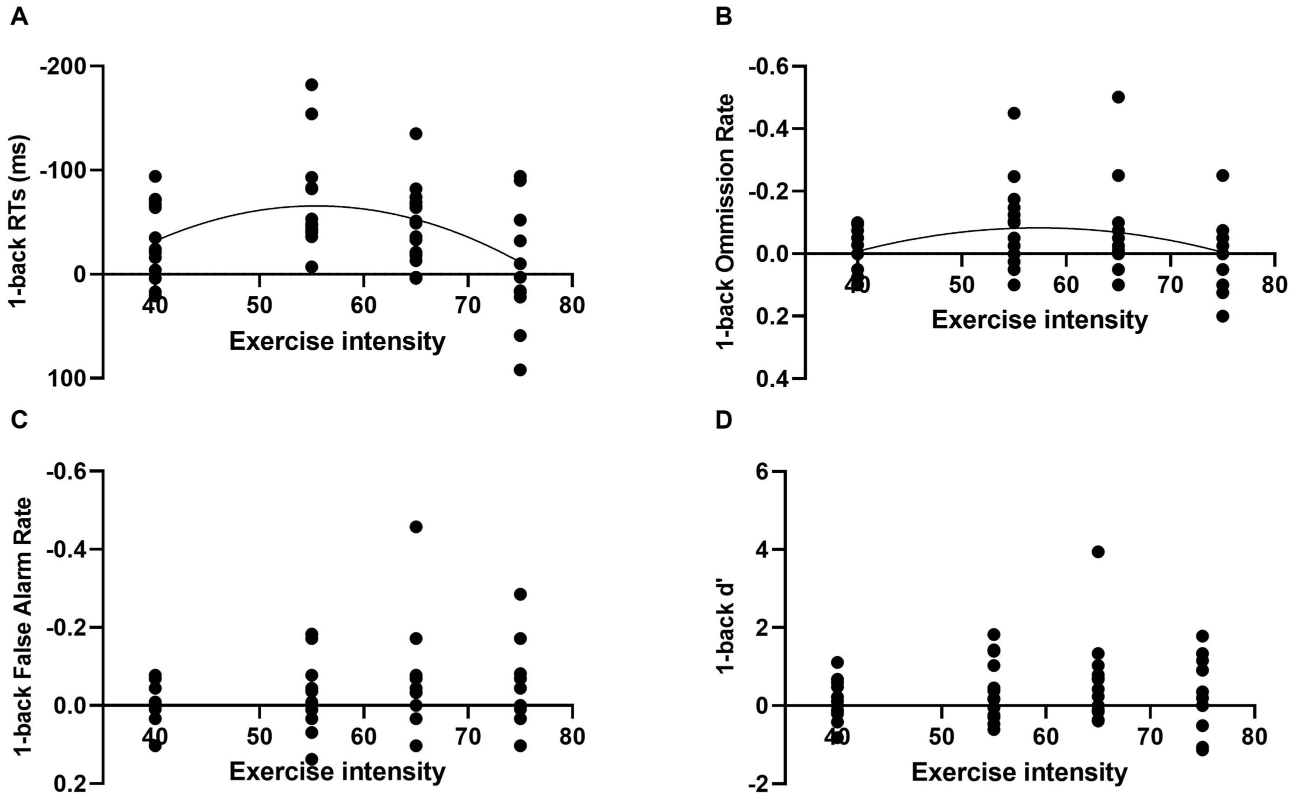

Figure 2 (**A**–**D**) Immediate post-intervention dose-response relationships in 1-back difference scores. The x-axis represents the exercise intensity group (control, 55%, 65% and 75% HR_{max}). The line represents the line of best fit for each distribution.
Abbreviations: RTs, reaction times for correct responses; d', Index of discrimination.

the false alarm rates and d' for the 1-back task, no significant linear or quadratic trends were found between their difference scores and exercise intensity (see Figure 2).

For the 3-back task, the results were different (see Figure 3). There was a significant quadratic trend between exercise intensity and 3-back omission rate difference scores (F =3.297, p =0.044, R^2 =10.7%), as well as a significant quadratic trend between exercise intensity and 3-back d' difference scores (F =4.263, p =0.019, R^2 =13.4%). A quadratic trend approaching significance was demonstrated between exercise intensity and 3-back false alarm rate difference scores (F =2.530, p =0.089, R^2 =8.4%). However, significant trends between exercise intensity and 3-back reaction time ware not demonstrated.

Psychomotor Vigilance

The results of the regression analyses for the PVT task indicated that there was a quadratic trend between exercise intensity and lapse (F =4.314, p =0.042, R^2 =7.2%). However, no statistically significant trends were found in the fitting results for the other variables (see Figure 4). One-way ANOVA revealed that there was an nearly significant differences (p = 0.052) among the four groups in PVT lapse (See Table 3).

Response Inhibition

Similar statistical analysis methods were applied to the Go/NoGo task. However, one-way ANOVA revealed that there were no significant differences (p > 0.05) among the four groups in Go/NoGo performance. Besides, significant trends influenced by exercise intensity were not found in any variable of this task.

Prolonged Dose-Response Relationships After Intervention

To explore whether the effects of the exercise were immediate or long-lasting, we conducted another extended test (Test 4) at 5:00 PM. The results show that PVT performance and Go/NoGo performance during the extended observation

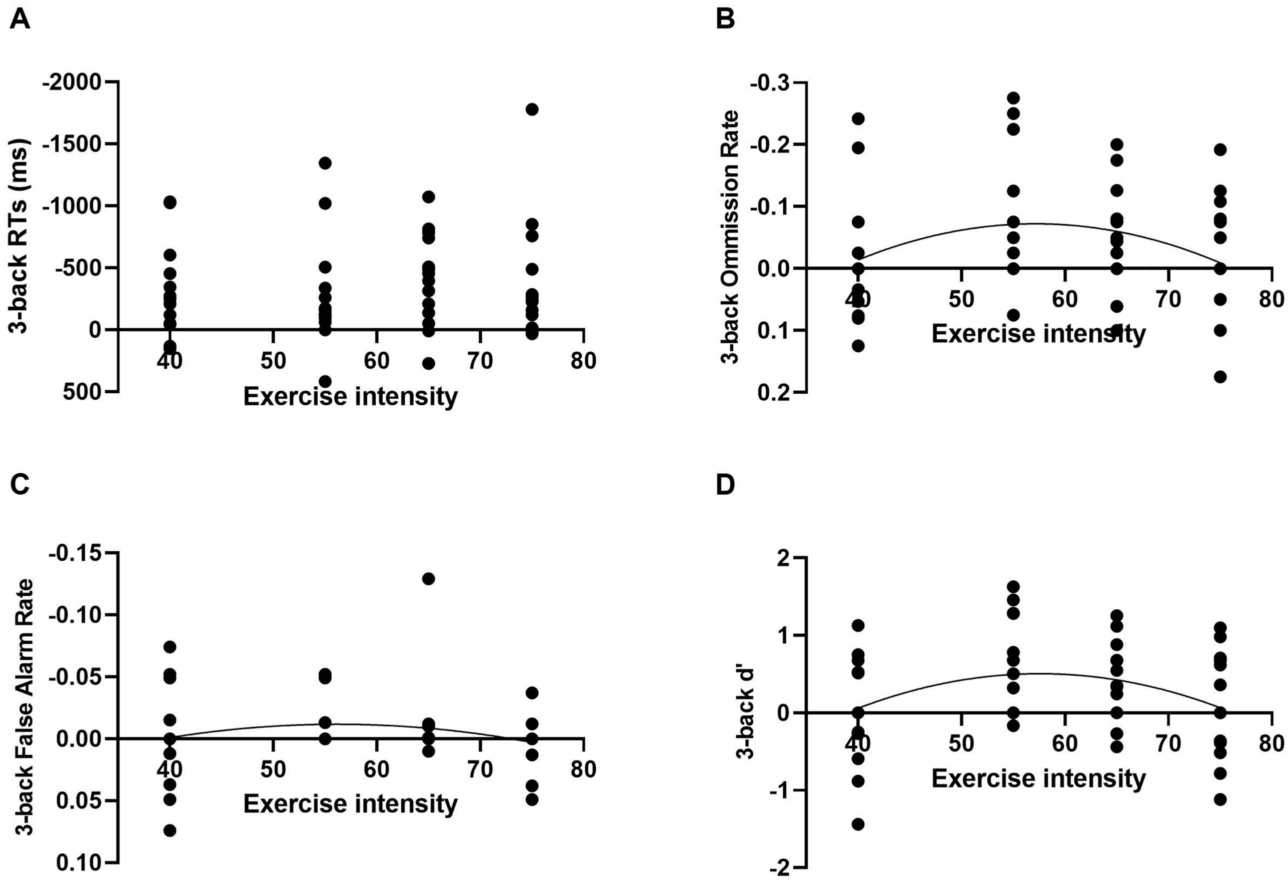

Figure 3 (**A**–**D**) Immediate post-intervention dose-response relationships in 3-back difference scores. The x-axis represents the exercise intensity group (control, 55%, 65% and 75% HR_{max}). The line represents the line of best fit for each distribution.
Abbreviations: RTs, reaction times for correct responses; d', Index of discrimination.

phase did not change much compared with those after nap deprivation, and no significant linear or quadratic trends influenced by exercise intensity were found. Table 3 shows the prolonged intervention effect of excise across different intensity. ANOVA revealed that there were significant differences ($p < 0.05$) among the four groups in 1-back omission rate and 3-back false alarm rate.

In the 1-back task, a significant quadratic relationship was observed between exercise intensity and omission rate (F =5.894, p =0.018, R^2 =10.4%), with the best continuation effect following low-intensity exercise, whereas high-intensity exercise negatively impacted omission rate on the 1-back task instead. As for the other variables, although no significant trend was found, the moderate-intensity group performed relatively poorly in terms of prolonged improvement between exercise groups, while the prolongation effect was still present in the low- and high-intensity groups (see Figure 5A–D). In terms of the 3-back task, there was a significant quadratic relationship between exercise intensity and false alarm rate difference scores (F =4.066, p =0.023, R^2 =12.9%), with the best continuation effect following low-intensity exercise, while high-intensity exercise negatively impacted false alarm rates in the 3-back task No statistically significant trends were found among other variables on the 3-back task. (see Figure 5E).

Discussion

The intervention effects of different exercise intensities on executive functions after nap deprivation remained ambiguous in previous research. In the current study, there were significant anti-disturbance effects of different intensities of exercise on the decrease in working memory and vigilance, as well as significant quadratic trends between exercise intensity and some indicators of cognitive function. High-intensity exercise resulted in the best immediate benefits on PVT lapse;

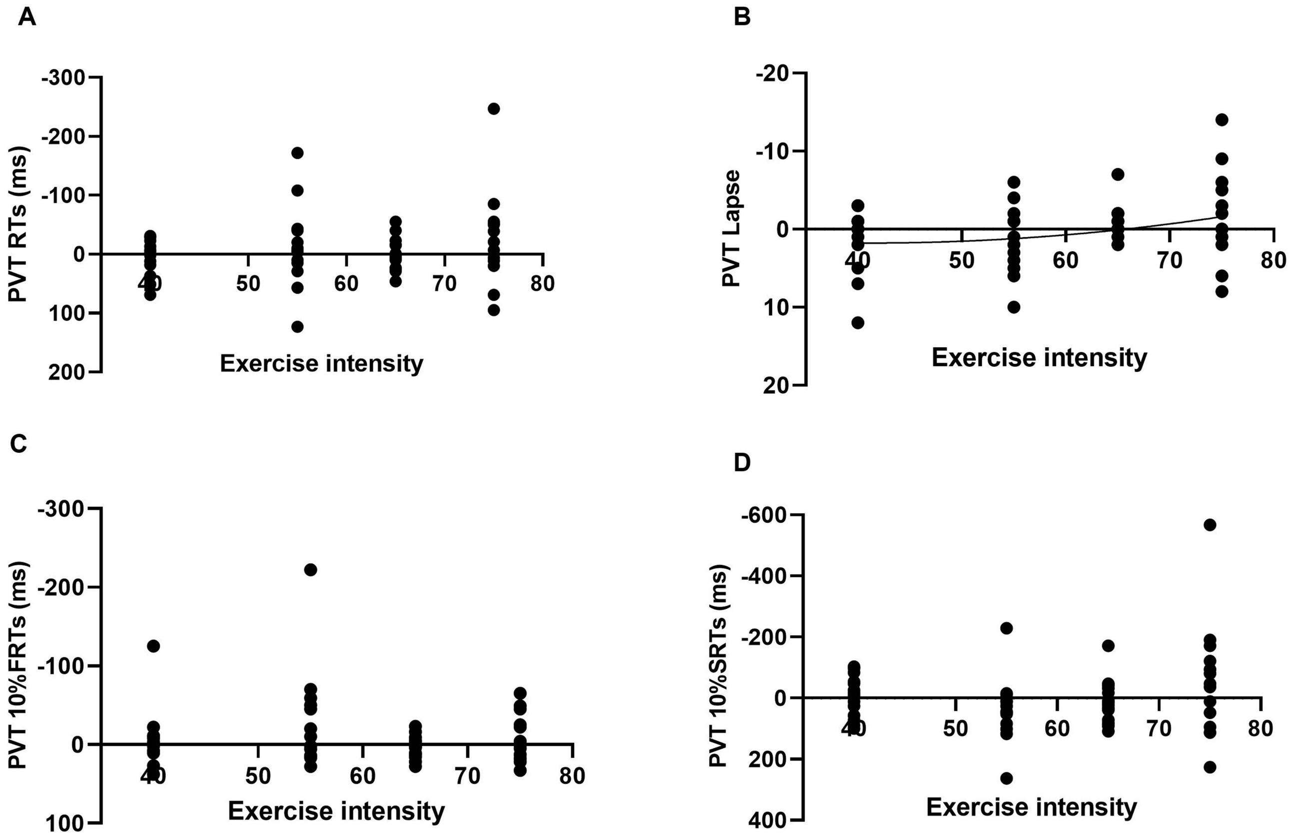

Figure 4 (**A**–**D**) Immediate post-intervention dose-response relationships in PVT difference scores. The x-axis represents the exercise intensity group (control, 55%, 65% and 75% HR_{max}). The line represents the line of best fit for each distribution.
Abbreviations: 10%FRTs, 10%fastest reaction time; 10%SRTs, 10% slowest reaction time.

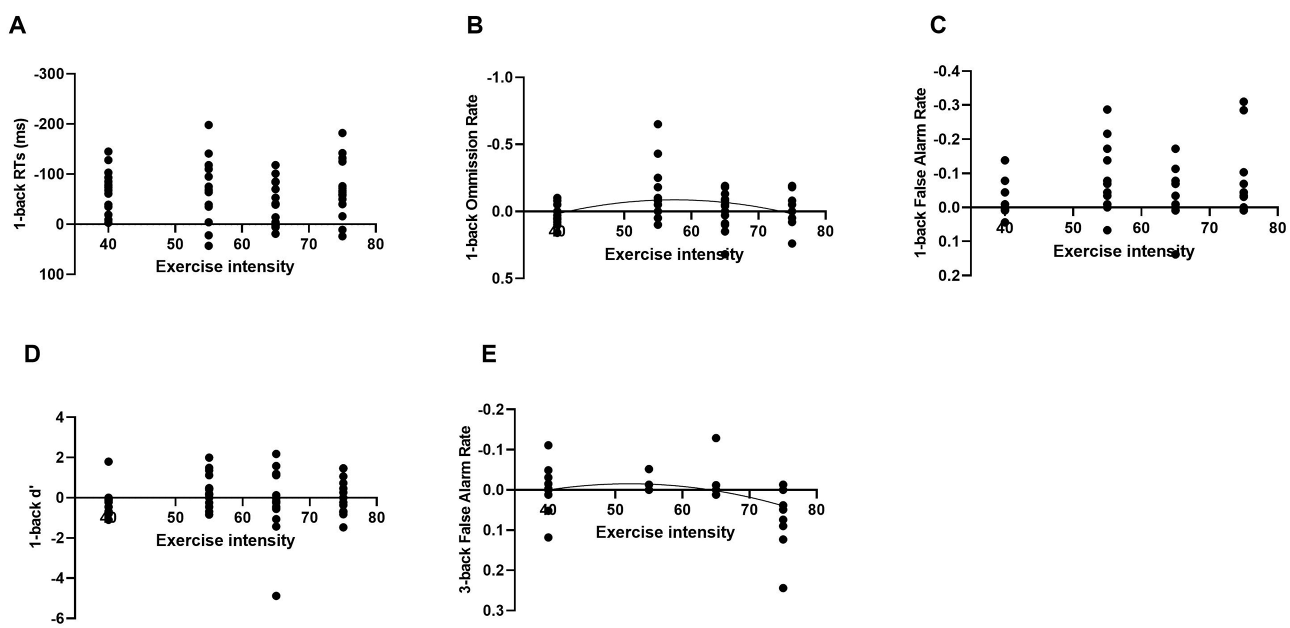

Figure 5 (**A**–**E**) Prolonged post-intervention dose-response relationships in 1-back and 3-back difference scores. The x-axis represents the exercise intensity group (control, 55%, 65% and 75% HRmax). The line represents the line of best fit for each distribution.
Abbreviations: RTs, reaction times for correct responses; d', Index of discrimination.

while low-intensity exercise was better for working memory. To the best of our knowledge, this study investigated for the first time the intervention effect of different intensities of exercise on cognitive impairment after nap deprivation and further observed the prolonged effect of this effect. Extended observation analysis suggested that the effects of low-intensity exercise were sustained, while the effects of high-intensity exercise were difficult to maintain and were likely to yield negative effects.

Effects of Nap Deprivation

Several previous studies have shown that nap deprivation reduces participants' alertness[9] and working memory,[57] increases fatigue,[58] and disrupts mood,[59] which is consistent with our findings. A study exploring the impact of nap duration on working memory and alertness found that napping for 40 and 60 minutes extended the benefits for 1.5 to 6 hours after the nap compared to not napping at all.[60] Considering that the participants included in this study had a habit of taking longer naps (more than 60 minutes), the impact of nap deprivation on this group may be more significant and longer-lasting. However, some studies have also presented a different view. A within-subjects study of 18 young adults with a napping habit showed that nap deprivation led to reduced performance on sustained attention tasks, but had little effect on working memory.[19] Researchers believed this might be related to the fact that napping could lead to lower physiological arousal as well as relatively higher δ and lower β activity. Another study showed that sleep deprivation adversely affected working memory accuracy and omission rates but not reaction time,[61] which contradicts our findings. It is possible that differences in sleep restriction duration and task paradigms could partly explain these contradictory findings between previous studies and those from the current one. For example, studies using tasks that require the processing of more complex stimuli (eg, emotional stimuli) have not shown consistent effects of sleep deprivation on RT.[57] In addition, nap deprivation and nocturnal sleep deprivation may impact cognitive performance differentially. There are far more studies on nighttime sleep deprivation than nap deprivation,[62] and more high-quality randomized controlled trials as well as meta-analyses are necessary to support the results. The effects of nap deprivation on cognitive task accuracy were not significant. The possible reason is that there is a ceiling effect on the tasks measured. It can be argued that different cognitive measures need to be used if the effects of nap deprivation on cognitive accuracy are to be truly tested.[63]

Immediate Post-Intervention Dose-Response Relationships

The results of this study showed that low-intensity exercise tended to have the most significant effect on working memory, both in the 1-back and 3-back tasks. The analysis indicated an inverted U-shaped curve that seemed to be similar to the "inverted U" hypothesis.[38] However, this traditional hypothesis assumed that moderate-intensity interventions worked best[64] rather than low-intensity, suggesting that the peak of the curve was shifted forward in the current study. Yerkes-Dodson Law stated that there was a curvilinear relationship between performance and arousal, ie, performance increased with arousal, but decreased after a certain level of increase.[37] The present study pointed out that this decline occurred earlier than previously expected in the exercise intervention following nap deprivation. The efficacy of exercise in improving working memory peaked at low-intensity and then declined as the intensity of exercise increased. Furthermore, a number of recent studies found that the traditional "inverted U" hypothesis might not be reliable. Although there was no previous study in the field of nap deprivation as a reference, studies in other areas of cognitive impairment found results consistent with the current study, such as in patients with depression[65] or among the aged population. A previous meta-analysis of long-term exercise interventions on executive function in older adults showed no significant difference in the amount of effect produced by moderate- or high-intensity exercise interventions.[16] In addition, studies of physiologic markers also showed that exercise reduced systolic blood pressure, but the reduction was comparable between lower and higher intensity exercise.[66] A meta-analysis of 29 randomized controlled trials by Smith et al showed that physical activity increased the expression of brain-derived neurotrophic factor(BDNF) in the hippocampus and perihippocampal structures.[67] Pereira et al found that increases in BDNF in the dentate gyrus of the brain were associated with dose-response improvements in memory performance in young adults participating in an exercise intervention.[68] These findings suggest that exercise interventions after nap deprivation may lead to an increase in BDNF, which brought about an improvement in working memory. However, the differences in physiologic changes associated with different intensities of exercise are unclear. Additional studies are much needed to further explore the differences in cognitive-related EEG, BDNF, and neurotransmitters after different intensities of exercise.

In contrast, the present study found that the exercise intervention significantly improved PVT lapse, while the improvement increased with increasing exercise intensity. In other words, high-intensity exercise showed the most significant improvement in PVT lapse, which was consistent with the drive theory.[40] A previous study on the effects of resistance training on a PVT task showed that between 80% and 90% of maximal oxygen uptake, participants had faster reaction times.[69] Although the current study did not find a relationship between aerobic exercise intensity and PVT reaction time, it was able to find that high-intensity exercise had an optimal effect on performance on the vigilance in conjunction with previous research. Physical fitness levels are associated with higher cognitive functions such as decision-making,[70] and exploring the role of exercise interventions for nap deprivation-induced cognitive impairments can help to develop scientifically based measures to cope with more complex task demands.

In addition, previous research suggests that the processes involved in maintaining vigilant attention may be complex, encompassing both top-down and bottom-up processes.[71] And because of the long duration of the attention task, performance on the Go/NoGo task may have been influenced to some extent by the previous PVT task.The effect of the PVT on executive functioning may also be one of the reasons why we did not find significant changes in Go/NoGo results.

Prolonged Dose-Response Relationships After Intervention

Further statistical analysis of the results suggested that the efficacy of low-intensity exercise might be underestimated. After low-intensity exercise, participants demonstrated sustained improvements (maintained for 2 hours) in low-level working memory omission rate and high-level working memory false alarm rate. However, in the moderate-or high-intensity groups, participants' behavioral performance rebounded to varying degrees after 2 hours. This could be explained by neural noise.[72] Previous research supports the hypothesis that if cognitive effort can allocate sufficient resources to the task, performance at low arousal is likely to be as good as performance at medium arousal.[73] At high arousal levels, adrenocorticotropic hormone-releasing factor, ACTH, and cortisol interact with norepinephrine and dopamine in the brain, leading to an increase in the synthesis and release of catecholamine neurotransmitters, which increases the potential for neural noise.[54,74] These can hinder cognitive efforts to allocate sufficient resources to the task, resulting in the effects of the intervention not being sustained over time.[75] The 2-hour duration setting is based on the usual work schedule. The work-day usually tends to end around 5:30 p.m. Therefore, this study aims to explore the question of which intensity of exercise intervention would be most effective in securing the whole afternoon work. It was found that improvements in cognitive performance with moderate and high-intensity exercise were not sustainable, with even a decline in accuracy after high-intensity exercise at the prolonged test, which is consistent with previous findings.[76] In addition, a pilot study on sub-extreme exercise also found that physiologic markers (including significant elevations in heart rate and cortisol) change immediately after exercise but were not sustained, which may explain the lack of a significant prolonged effect.[77] The unexpected but gratifying results of low-intensity exercise imply that more satisfying outcomes might be achieved with easier exercise. However, limited by the number of participants, more studies need to be conducted to further explore the credibility and mechanism of this result.

Strengths and Limitation

This study is the first to use an acute aerobic exercise program of varying intensities in habitual nappers experiencing nap deprivation to investigate what intensity of exercise minimizes the impairment of cognitive functioning after nap deprivation. In addition, this study focuses on the sustained effects of an acute exercise intervention by adding a 2-hour interval test beyond the immediate post-intervention test. A valuable extension of the existing literature is provided by the rigorous napping criteria as well as the randomized controlled study.

However, some potential limitations of the current study should also be mentioned. First, there may be a ceiling effect in the choice of experimental paradigm and the accuracy of the task may not be objectively measured. Second, although the current experiment was preceded by a requirement that participants familiarize themselves with and practice the experimental task, and that they achieve a standard rate of correctness to avoid a practice effect. The results, especially the Go/NoGo task, were still affected by the practice effect. In subsequent experiments, multiple practice sessions in the days before the experiment should be considered to minimize the interference of the practice effect. Moreover, the potential effect of low-intensity exercise was only found at the behavioral level, this study did not detect or control for physiological indicators such as melatonin levels across the different groups and further explore its physiological mechanisms, which needs to be strengthened in future studies. By collecting diverse physiological indicators, they can delve into the physiological mechanisms (such as BDNF, neurotransmitters, etc.) underlying the effects of exercise intervention following nap deprivation. Finally, it is noteworthy that the participants included in this study were highly habitual nappers, men who napped more frequently and for a longer duration, so the interpretation of results needs to be handled with caution when generalizing the results to other populations. Researchers can broaden the categories of participants to enhance the external validity in future studies.

Conclusion

In the present study, we found that exercise of varying intensities had a significant ameliorative effect on nap deprivation-induced decreases in executive functioning (eg, working memory) and alertness. There were significant quadratic or linear relationships between exercise intensity and executive function indicators. Low-intensity exercise had the best improvement in working memory, whereas high-intensity exercise had the best immediate effect on vigilance. The effects of low-intensity exercise were maintained after 2 hours, whereas the effects of high-intensity exercise were difficult to maintain and may even negatively affect working memory. The effects of low-intensity exercise deserve further attention. The present study provides insight into understanding the effects of exercise intensity on executive function after nap deprivation. Future research can broaden the categories of participants to enhance external validity and collect diverse physiological indicators to explore the physiological mechanisms underlying the effects of exercise interventions following nap deprivation.

Abbreviations

d', Index of discrimination; DS, Difference scores; ESS, The Epworth Sleepiness Scale; HR_{max}, Maximum heart rate; MEQ-5, Morning and Evening Questionnaire-5; PSQI, Pittsburgh Sleep Quality Index; PVT, Psychomotor Vigilance task; RTs, reaction time.

Data Sharing Statement

The datasets generated and analyzed during the current study are not publicly available due to the specificity of the participants in this survey, but are available from the corresponding author on reasonable request.

Ethics Approval and Informed Consent

This study was approved by the Medical Research Ethics Committee of the Naval Medical University, with the protocol number 20210310041 and the approval number NMUMREC-2021-041. All participants signed a written informed consent prior to study commencement and were financially compensated for the completion of all study visits. The study was carried out in accordance with relevant guidelines and regulations and considered as not causing any other economic burden or injury.

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Author Contributions

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

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Disclosure

The authors declare that they have no competing interest in this work.

References

1. Arora T, Grey I, Östlundh L, et al. A systematic review and meta-analysis to assess the relationship between sleep duration/quality, mental toughness and resilience amongst healthy individuals. *Sleep Medicine Reviews*. 2022;62:101593. doi:10.1016/j.smrv.2022.101593
2. Mograss M, Crosetta M, Abi-Jaoude J, et al. Exercising before a nap benefits memory better than napping or exercising alone. *Sleep: Journal of Sleep and Sleep Disorders Research*. 2020;43(9):1–9. doi:10.1093/sleep/zsaa062
3. Häusler N, Marques-Vidal P, Haba-Rubio J, Heinzer R. Does sleep predict next-day napping or does napping influence same-day nocturnal sleep? Results of a population-based ecological momentary assessment study. *Sleep Medicine*. 2019;61:31–36. doi:10.1016/j.sleep.2019.04.014
4. He R, Yang Y, Li X, et al. 大学生午睡情况调查 [A survey on napping among college students]. 中国临床康复 *[China Clinical Rehabilitation]*. 2006;22:43–45.
5. Dutheil F, Bessonnat B, Pereira B, et al. Napping and cognitive performance during night shifts: a systematic review and meta-analysis. *Sleep*. 2020;43(12):zsaa109. doi:10.1093/sleep/zsaa109
6. Cremone A, McDermott JM, Spencer RMC. Naps enhance executive attention in preschool-aged children. *J Pediatr Psychol*. 2017;42(8):837–845. doi:10.1093/jpepsy/jsx048
7. Cai H, Su N, Li W, Li X, Xiao S, Sun L. Relationship between afternoon napping and cognitive function in the ageing Chinese population. *Gen Psychiatr*. 2021;34(1):e100361. doi:10.1136/gpsych-2020-100361
8. Miller NL, Shattuck LG, Matsangas P. Sleep and fatigue issues in continuous operations: a survey of U.S. Army officers. *Behav Sleep Med*. 2011;9(1):53–65. doi:10.1080/15402002.2011.533994
9. Chen Q, Ru T, Yang M, et al. Effects of afternoon nap deprivation on adult habitual nappers' inhibition functions. *Biomed Res Int*. 2018;2018:5702646. doi:10.1155/2018/5702646
10. Igloi K, Gaggioni G, Sterpenich V, Schwartz S. A nap to recap or how reward regulates hippocampal-prefrontal memory networks during daytime sleep in humans. *Elife*. 2015;4:e07903. doi:10.7554/eLife.07903
11. Lahl O, Wispel C, Willigens B, Pietrowsky R. An ultra short episode of sleep is sufficient to promote declarative memory performance. *J Sleep Res*. 2008;17(1):3–10. doi:10.1111/j.1365-2869.2008.00622.x
12. Evans FJ, Cook MR, Cohen HD, Orne EC, Orne MT. Appetitive and replacement naps: EEG and behavior. *Science*. 1977;197(4304):687–689. doi:10.1126/science.17922
13. Milner CE, Fogel SM, Cote KA. Habitual napping moderates motor performance improvements following a short daytime nap. *Biol Psychol*. 2006;73(2):141–156. doi:10.1016/j.biopsycho.2006.01.015
14. DeMasi A, Horger MN, Allia AM, Scher A, Berger SE. Nap timing makes a difference: sleeping sooner rather than later after learning improves infants' locomotor problem solving. *Infant Behavior & Development*. 2021;65. doi:10.1016/j.infbeh.2021.101652
15. Diamond A. Executive functions. *Annu Rev Psychol*. 2013;64:135–168. doi:10.1146/annurev-psych-113011-143750
16. Chen FT, Etnier JL, Chan KH, Chiu PK, Hung TM, Chang YK. Effects of exercise training interventions on executive function in older adults: a systematic review and meta-analysis. *Sports Med*. 2020;50(8):1451–1467. doi:10.1007/s40279-020-01292-x
17. Randall WM, Smith JL. Conflict and inhibition in the cued-Go/NoGo task. *Clin Neurophysiol*. 2011;122(12):2400–2407. doi:10.1016/j.clinph.2011.05.012
18. Tempesta D, Cipolli C, Desideri G, De Gennaro L, Ferrara M. Can taking a nap during a night shift counteract the impairment of executive skills in residents? *Med Educ*. 2013;47(10):1013–1021. doi:10.1111/medu.12256
19. Ru T, Qian L, Chen Q, Sun H, Zhou G. Effects of an afternoon nap on sustained attention and working memory: the role of physiological arousal and sleep variables. *Int J Psychophysiol*. 2022;179:21–29. doi:10.1016/j.ijpsycho.2022.06.013
20. Ru T, Chen Q, You J, Zhou G. Effects of a short midday nap on habitual nappers' alertness, mood and mental performance across cognitive domains. *J Sleep Res*. 2019;28(3):e12638. doi:10.1111/jsr.12638
21. Zhou Y, Chen Q, Luo X, Li L, Ru T, Zhou G. Does bright light counteract the post-lunch dip in subjective states and cognitive performance among undergraduate students? *Front Public Health*. 2021;9:652849. doi:10.3389/fpubh.2021.652849
22. Schumacher AM, Miller AL, Watamura SE, Kurth S, Lassonde JM, LeBourgeois MK. Sleep moderates the association between response inhibition and self-regulation in early childhood. *J Clin Child Adolesc Psychol*. 2017;46(2):222–235. doi:10.1080/15374416.2016.1204921
23. Lam JC, Koriakin TA, Scharf SM, Mason TBA, Mahone EM. Does increased consolidated nighttime sleep facilitate attentional control? A pilot study of nap restriction in preschoolers. *J Atten Disord*. 2019;23(4):333–340. doi:10.1177/1087054715569281

24. Slama H, Deliens G, Schmitz R, Peigneux P, Leproult R. Afternoon nap and bright light exposure improve cognitive flexibility post lunch. *PLoS One*. 2015;10(5):e0125359. doi:10.1371/journal.pone.0125359
25. Aghayan Golkashani H, Leong RLF, Ghorbani S, Ong JL, Fernández G, Chee MWL. A sleep schedule incorporating naps benefits the transformation of hierarchical knowledge. *Sleep*. 2022;45(4):zsac025. doi:10.1093/sleep/zsac025
26. Kojima S, Abe T, Morishita S, et al. Acute moderate-intensity exercise improves 24-h sleep deprivation-induced cognitive decline and cerebral oxygenation: a near-infrared spectroscopy study. *Respir Physiol Neurobiol*. 2020;274:103354. doi:10.1016/j.resp.2019.103354
27. Papadakis Z, Forsse JS, Peterson MN. Acute partial sleep deprivation and high-intensity interval exercise effects on postprandial endothelial function. *Eur J Appl Physiol*. 2020;120(11):2431–2444. doi:10.1007/s00421-020-04468-5
28. Reid KJ, Baron KG, Lu B, Naylor E, Wolfe L, Zee PC. Aerobic exercise improves self-reported sleep and quality of life in older adults with insomnia. *Sleep Med*. 2010;11(9):934–940. doi:10.1016/j.sleep.2010.04.014
29. Pellegrino JK, Anthony TG, Gillies P, Arent SM. The exercise metabolome: acute aerobic and anaerobic signatures. *J Int Soc Sports Nutr*. 2022;19(1):603–622. doi:10.1080/15502783.2022.2115858
30. Saunders TJ, Gray CE, Poitras VJ, et al. Combinations of physical activity, sedentary behaviour and sleep: relationships with health indicators in school-aged children and youth. *Appl Physiol Nutr Metab*. 2016;41(6 Suppl 3):S283–293. doi:10.1139/apnm-2015-0626
31. Seol J, Park I, Kokudo C, et al. Distinct effects of low-intensity physical activity in the evening on sleep quality in older women: a comparison of exercise and housework. *Exp Gerontol*. 2021;143:111165. doi:10.1016/j.exger.2020.111165
32. Stutz J, Eiholzer R, Spengler CM. Effects of evening exercise on sleep in healthy participants: a systematic review and meta-analysis. *Sports Med*. 2019;49(2):269–287. doi:10.1007/s40279-018-1015-0
33. Vanderlinden J, Boen F, van Uffelen JGZ. Effects of physical activity programs on sleep outcomes in older adults: a systematic review. *Int J Behav Nutr Phys Act*. 2020;17(1):11. doi:10.1186/s12966-020-0913-3
34. Dinoff A, Herrmann N, Swardfager W, et al. The effect of exercise training on resting concentrations of peripheral brain-derived neurotrophic factor (BDNF): a meta-analysis. *PLoS One*. 2016;11(9):e0163037. doi:10.1371/journal.pone.0163037
35. Liu S, Zhang R. Aerobic exercise alleviates the impairment of cognitive control ability induced by sleep deprivation in college students: research based on go/nogo task. *Front Psychol*. 2022;13:914568. doi:10.3389/fpsyg.2022.914568
36. Du J, Huang Y, Zhao Z, et al. Planning ability and alertness after nap deprivation: beneficial effects of acute moderate-intensity aerobic exercise greater than sitting naps. *Front Public Health*. 2022;10:861923. doi:10.3389/fpubh.2022.861923
37. Lambourne K, Tomporowski P. The effect of exercise-induced arousal on cognitive task performance: a meta-regression analysis. *Brain Res*. 2010;1341:12–24. doi:10.1016/j.brainres.2010.03.091
38. Chang YK, Labban JD, Gapin JI, Etnier JL. The effects of acute exercise on cognitive performance: a meta-analysis. *Brain Res*. 2012;1453:87–101. doi:10.1016/j.brainres.2012.02.068
39. Erickson KI, Hillman C, Stillman CM, et al. Physical activity, cognition, and brain outcomes: a review of the 2018 physical activity guidelines. *Med Sci Sports Exerc*. 2019;51(6):1242–1251. doi:10.1249/MSS.0000000000001936
40. McMorris T, Hale BJ. Differential effects of differing intensities of acute exercise on speed and accuracy of cognition: a meta-analytical investigation. *Brain Cogn*. 2012;80(3):338–351. doi:10.1016/j.bandc.2012.09.001
41. Chacko SC, Quinzi F, De Fano A, et al. A single bout of vigorous-intensity aerobic exercise affects reactive, but not proactive cognitive brain functions. *Int J Psychophysiol*. 2020;147:233–243. doi:10.1016/j.ijpsycho.2019.12.003
42. Brown BM, Rainey-Smith SR, Castalanelli N, et al. Study protocol of the intense physical activity and cognition study: the effect of high-intensity exercise training on cognitive function in older adults. *Alzheimers Dement (N Y)*. 2017;3(4):562–570. doi:10.1016/j.trci.2017.09.003
43. Dodwell G, Liesefeld HR, Conci M, Müller HJ, Töllner T. EEG evidence for enhanced attentional performance during moderate-intensity exercise. *Psychophysiology*. 2021;58(12):e13923. doi:10.1111/psyp.13923
44. Chang YK, Etnier JL. Exploring the dose-response relationship between resistance exercise intensity and cognitive function. *J Sport Exerc Psychol*. 2009;31(5):640–656. doi:10.1123/jsep.31.5.640
45. Brown DMY, Bray SR. Isometric exercise and cognitive function: an investigation of acute dose-response effects during submaximal fatiguing contractions. *J Sports Sci*. 2015;33(5):487–497. doi:10.1080/02640414.2014.947524
46. Wu CH, Karageorghis CI, Wang CC, et al. Effects of acute aerobic and resistance exercise on executive function: an ERP study. *J Sci Med Sport*. 2019;22(12):1367–1372. doi:10.1016/j.jsams.2019.07.009
47. Buysse DJ, Reynolds CF, Monk TH, Berman SR, Kupfer DJ. The Pittsburgh Sleep Quality Index: a new instrument for psychiatric practice and research. *Psychiatry Res*. 1989;28(2):193–213. doi:10.1016/0165-1781(89)90047-4
48. Chalder T, Berelowitz G, Pawlikowska T, et al. Development of a fatigue scale. *J Psychosom Res*. 1993;37(2):147–153. doi:10.1016/0022-3999(93)90081-p
49. Johns MW. Reliability and factor analysis of the Epworth Sleepiness Scale. *Sleep*. 1992;15(4):376–381. doi:10.1093/sleep/15.4.376
50. Gottschall JS, Davis JJ, Hastings B, Porter HJ. Exercise time and intensity: how much is too much? *Internat J Sports Physiol Perform*. 2020;15(6):808–815. doi:10.1123/ijspp.2019-0208
51. Carney CE, Buysse DJ, Ancoli-Israel S, et al. The consensus sleep diary: standardizing prospective sleep self-monitoring. *Sleep*. 2012;35(2):287–302. doi:10.5665/sleep.1642
52. M Corp. *IBM SPSS Statistics for Windows, Version 25.0*. Armonk, NY: IBM Corp; 2019.
53. Horne JA, Ostberg O. A self-assessment questionnaire to determine morningness-eveningness in human circadian rhythms. *Int J Chronobiol*. 1976;4(2):97–110.
54. Ren M, Xu J, Li Y, et al. Neural signatures for the n-back task with different loads: an event-related potential study. *Biolog Psychol*. 2023;177:108485. doi:10.1016/j.biopsycho.2023.108485
55. Basner M, Mollicone D, Dinges DF. Validity and sensitivity of a brief psychomotor vigilance Test (PVT-B) to total and partial sleep deprivation. *Acta Astronaut*. 2011;69(11–12):949–959. doi:10.1016/j.actaastro.2011.07.015
56. Fang Z, Liu X, Wang C, Cao J, Peng Y, Lv Y. Insomnia attenuates response inhibition: evidence from Go/NoGo research. *Sleep Medicine*. 2022;100:518–533. doi:10.1016/j.sleep.2022.09.007
57. MacDonald KJ, Lockhart HA, Storace AC, Emrich SM, Cote KA. A daytime nap enhances visual working memory performance and alters event-related delay activity. *Cogn Affect Behav Neurosci*. 2018;18(6):1105–1120. doi:10.3758/s13415-018-0625-1

58. Caldwell JA, Caldwell JL, Thompson LA, Lieberman HR. Fatigue and its management in the workplace. *Neurosci Biobehav Rev*. 2019;96:272–289. doi:10.1016/j.neubiorev.2018.10.024
59. Souissi M, Souissi Y, Bayoudh A, Knechtle B, Nikolaidis PT, Chtourou H. Effects of a 30 min nap opportunity on cognitive and short-duration high-intensity performances and mood states after a partial sleep deprivation night. *Journal of Sports Sciences*. 2020;38(22):2553–2561. doi:10.1080/02640414.2020.1793651
60. Mulrine HM, Signal TL, van den Berg MJ, Gander PH. Post-sleep inertia performance benefits of longer naps in simulated nightwork and extended operations. *Chronobiol Int*. 2012;29(9):1249–1257. doi:10.3109/07420528.2012.719957
61. Gerhardsson A, Åkerstedt T, Axelsson J, Fischer H, Lekander M, Schwarz J. Effect of sleep deprivation on emotional working memory. *J Sleep Res*. 2019;28(1):e12744. doi:10.1111/jsr.12744
62. Dutheil F, Danini B, Bagheri R, et al. Effects of a short daytime nap on the cognitive performance: a systematic review and meta-analysis. *Int J Environ Res Public Health*. 2021;18(19):10212. doi:10.3390/ijerph181910212
63. Etnier JL, Chang YK. The effect of physical activity on executive function: a brief commentary on definitions, measurement issues, and the current state of the literature. *J Sport Exerc Psychol*. 2009;31(4):469–483. doi:10.1123/jsep.31.4.469
64. Davey CP. Physical exertion and mental performance. *Ergonomics*. 1973;16(5):595–599. doi:10.1080/00140137308924550
65. Meyer JD, Koltyn KF, Stegner AJ, Kim JS, Cook DB. Influence of exercise intensity for improving depressed mood in depression: a dose-response study. *Behav Ther*. 2016;47(4):527–537. doi:10.1016/j.beth.2016.04.003
66. Cornelissen VA, Verheyden B, Aubert AE, Fagard RH. Effects of aerobic training intensity on resting, exercise and post-exercise blood pressure, heart rate and heart-rate variability. *J Hum Hypertens*. 2010;24(3):175–182. doi:10.1038/jhh.2009.51
67. Smith PJ, Blumenthal JA, Hoffman BM, et al. Aerobic exercise and neurocognitive performance: a meta-analytic review of randomized controlled trials. *Psychosom Med*. 2010;72(3):239–252. doi:10.1097/PSY.0b013e3181d14633
68. Pereira AC, Huddleston DE, Brickman AM, et al. An in vivo correlate of exercise-induced neurogenesis in the adult dentate gyrus. *Proc Natl Acad Sci U S A*. 2007;104(13):5638–5643. doi:10.1073/pnas.0611721104
69. González-Fernández FT, Latorre-Román PÁ, Parraga-Montilla J, Castillo-Rodriguez A, Clemente FM. Effect of exercise intensity on psychomotor vigilance during an incremental endurance exercise in under-19 soccer players. *Motor Control*. 2022;26(4):661–676. doi:10.1123/mc.2022-0033
70. Castillo-Rodríguez A, Alejo-Moya EJ, Figueiredo A, Onetti-Onetti W, González-Fernández FT. Influence of physical fitness on decision-making of soccer referees throughout the match. *Heliyon*. 2023;9(9):e19702. doi:10.1016/j.heliyon.2023.e19702
71. Langner R, Eickhoff SB. Sustaining attention to simple tasks: a meta-analytic review of the neural mechanisms of vigilant attention. *Psychol Bull*. 2013;139(4):870–900. doi:10.1037/a0030694
72. Bays PM. Noise in neural populations accounts for errors in working memory. *J Neurosci*. 2014;34(10):3632–3645. doi:10.1523/JNEUROSCI.3204-13.2014
73. Kashihara K, Nakahara Y. Short-term effect of physical exercise at lactate threshold on choice reaction time. *Percept Mot Skills*. 2005;100(2):275–291. doi:10.2466/pms.100.2.275-291
74. Xie L, Ren M, Cao B, Li F. Distinct brain responses to different inhibitions: evidence from a modified Flanker Task. *Sci Rep*. 2017;7(1):6657. doi:10.1038/s41598-017-04907-y
75. Yanagita S, Amemiya S, Suzuki S, et al. Effects of spontaneous and forced running on activation of hypothalamic corticotropin-releasing hormone neurons in rats. *Life Sciences*. 2007;80(4). doi:10.1016/j.lfs.2006.09.027
76. Frimpong E, Mograss M, Zvionow T, et al. Acute evening high-intensity interval training may attenuate the detrimental effects of sleep restriction on long-term declarative memory. *SLEEP*. 2023;46:zsad119. doi:10.1093/sleep/zsad119
77. Souissi A, Farjallah MA, Chortane OG, et al. The effects of daytime melatonin ingestion on arousal and vigilance vanish after sub-maximal exercise: a pilot study. *Europ Rev Med Pharmacol Sci*. 2022;26:17.