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Kelsey R. Sewell

Stephanie R. Rainey-Smith
Edith Cowan University

Jeremiah Peiffer

Hamid R. Sohrabi
Edith Cowan University

James Doecke

See next page for additional authors

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RESEARCH ARTICLE

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The influence of baseline sleep on exercise-induced cognitive change in cognitively unimpaired older adults: A randomised clinical trial

Kelsey R. Sewell[1] | Stephanie R. Rainey-Smith[1,2,3,4] | Jeremiah Peiffer[1] | Hamid R. Sohrabi[1,2,3,5] | James Doecke[6] | Natalie J. Frost[1,3,4] | Shaun J. Markovic[1,3] | Kirk Erickson[7,8] | Belinda M. Brown[1,2,3]

[1]Centre for Healthy Ageing, Health Futures Institute, Murdoch University, Murdoch, Western Australia, Australia

[2]School of Medical and Health Sciences, Edith Cowan University, Joondalup, Western Australia, Australia

[3]Australian Alzheimer's Research Foundation, Sarich Neuroscience Research Institute, Nedlands, Western Australia, Australia

[4]School of Psychological Science, University of Western Australia, Crawley, Western Australia, Australia

[5]Department of Biomedical Sciences, Macquarie University, Sydney, New South Wales, Australia

[6]Royal Brisbane and Women's Hospital, CSIRO Health and Biosecurity/Australian E-Health Research Centre, Brisbane, Queensland, Australia

[7]Department of Psychiatry, University of Pittsburgh, Pittsburgh, Pennsylvania, USA

[8]AdventHealth Research Institute, Orlando, Florida, USA

Correspondence

Kelsey R. Sewell, Discipline of Exercise Science, Murdoch University, 90 South Street, Murdoch, Western Australia 6150, Australia.
Email: Kelsey.sewell@murdoch.edu.au

Abstract

Objectives: Observational studies consistently demonstrate that physical activity is associated with elevated cognitive function, however, there remains significant heterogeneity in cognitive outcomes from randomized exercise interventions. Individual variation in sleep behaviours may be a source of variability in the effectiveness of exercise-induced cognitive change, however this has not yet been investigated. The current study aimed to (1) investigate the influence of a 6-month exercise intervention on sleep, assessed pre- and post-intervention and, (2) investigate whether baseline sleep measures moderate exercise-induced cognitive changes.

Methods: We utilised data from the Intense Physical Activity and Cognition (IPAC) study (n = 89), a 6-month moderate intensity and high intensity exercise intervention, in cognitively unimpaired community-dwelling older adults aged 60–80 (68.76 ± 5.32). Exercise was supervised and completed on a stationary exercise bicycle, and cognitive function was measured using a comprehensive neuropsychological battery administered pre- and post-intervention. Sleep was measured using the Pittsburgh sleep quality index. There was no effect of the exercise intervention on any sleep outcomes from pre- to post-intervention.

Results: There was a significant moderating effect of baseline sleep efficiency on both episodic memory and global cognition within the moderate intensity exercise group, such that those with poorer sleep efficiency at baseline showed greater exercise-induced improvements in episodic memory.

Conclusions: These results suggest that those with poorer sleep may have the greatest exercise-induced cognitive benefits and that baseline sleep behaviours may be an important source of heterogeneity in previous exercise interventions targeting cognitive outcomes.

KEYWORDS
cognition, exercise, intervention, older adults, sleep

Key points

- Cognitive improvements due to exercise may be influenced by other lifestyle factors, such as sleep
- Poor sleepers showed the greatest exercise-induced improvement in episodic memory and global cognition
- Exercise may aid in compensating for negative effects of poor sleep on cognition

1 | INTRODUCTION

Physical inactivity is a significant modifiable risk factor for dementia.[1] Consistent evidence from observational research demonstrates that a higher volume of habitual physical activity (any bodily movement resulting in energy expenditure) is associated with better cognitive function and reduced dementia risk.[2,3] Exercise is a structured or planned form of physical activity,[4] the evidence for exercise interventions to modify cognitive function has been inconclusive and less consistent, compared to the observational physical activity literature.[5] Reviews of randomized clinical trials for exercise-induced cognitive change produce varying levels of support.[6,7] There are many factors which likely moderate the efficacy and effectiveness for exercise interventions to improve cognition, and thus contribute to some of the inconsistencies in the literature, for example, brain-derived neurotrophic factor genotype.[8,9] One additional factor highlighted in prior studies is the impact of sleep on physical activity-cognition associations.[10,11] Although acknowledged as having a possible moderating influence, intervention studies have not considered whether sleep moderates the magnitude of exercise-induced cognitive changes.

Sleep is associated with cognitive function across the lifespan.[12] Age-related cognitive declines are mirrored by changes in sleep with increasing age, including declines in overall sleep quality, changes in sleep duration, and increases in sleep fragmentation.[13] Observational research demonstrates that poor sleep is associated with poorer cognitive function in older adults,[14,15] and that poorer sleepers are at a higher risk for cognitive decline and Alzheimer's disease.[16] Thus, both sleep and exercise are associated with cognitive function independently, however exercise and sleep are also associated. Both acute and chronic exercise interventions improve subjective and objective sleep quality at a similar efficacy to sleep medication[17]; making it likely that variation in sleep may contribute to the individual variability observed in the exercise-cognition association.

Observational research indicates that sleep might moderate the association between physical activity and cognitive function.[18,19] Specifically, poor sleep may strengthen the association between physical activity and cognition.[20,21] However, randomised clinical trials with supervised exercise interventions have not yet reported whether sleep influences the efficacy of exercise-induced cognitive change, or whether exercise influences the association between sleep and cognitive function.[11] Thus, the primary aim of the current paper was to determine whether baseline sleep moderates the ability of an exercise intervention to affect cognition.

Although the effects of exercise on sleep are well-established,[22–24] the optimal type and dose of exercise needed to maximally improve sleep is yet to be determined. Namely, the frequency, duration, intensity, and type of exercise needed to elicit the greatest benefit for cognition remains unclear, and whether the parameters needed to modify cognition differ from those needed to maximise sleep has not yet been tested. One meta-analysis has indicated that variation in exercise intensity does not significantly impact the association with sleep outcomes,[17] whilst other reviews have concluded that moderate intensity exercise may be more beneficial for sleep compared to high intensity exercise.[25] Thus, the secondary aim of the current study was to investigate whether a dose-response manipulation of exercise intensity for 6-months differentially impacts sleep characteristics.

The current research is a secondary analysis of a randomised clinical trial designed to examine the effect of a moderate intensity and high intensity six-month exercise intervention on cognitive function in cognitively unimpaired older adults. For the current analysis, we examined whether baseline sleep moderated the magnitude of exercise-induced changes to cognition, and how the exercise intensity dose manipulation affected sleep pre- to post-intervention. Based on Lambiase[20] and Sewell,[21] we hypothesised that poorer sleepers at baseline would show greater cognitive improvement from pre- to post-intervention, compared to better sleepers. Moreover, given that exercise can improve sleep in older adults, but the dose parameters of this association are unclear, we aimed to compare the impact of moderate intensity and high intensity exercise on changes in subjective sleep from pre- to post-intervention. We hypothesised that both exercise groups would show sleep improvements post-intervention, compared to the control group, but that the moderate intensity group demonstrate the greatest benefit.[25]

2 | METHOD

2.1 | Participants

Participants of the Intense Physical Activity and Cognition (IPAC) study were 99 cognitively unimpaired community-dwelling older

adults aged 60–80. Data were collected from 1st February, 2017 to 25th September, 2019. Full inclusion and exclusion criteria have been described previously.[26] A block randomisation protocol was used to randomise participants into either 6-months of high intensity exercise, moderate intensity exercise, or an inactive control group. For the current analyses, participants with incomplete baseline sleep data or cognitive data pre- to post-intervention were excluded ($n = 3$ from the high intensity group; $n = 4$ from the moderate intensity group; $n = 3$ from the control group), resulting in a final sample of $n = 89$. See Brown et al.[27] for the Consolidated Standards Of Reporting Trials (CONSORT) diagram and for additional participant information.

The IPAC study is registered with the Australian New Zealand Clinical Trials Registry (ACTRN12617000643370). The human research ethics committees at Murdoch University and Edith Cowan University approved the conduct of this study, and individuals provided written informed consent prior to participation.

2.2 | Intervention protocol

A detailed description of the intervention protocol can be found in Brown et al.[27] Briefly, participants in the exercise groups engaged in supervised exercised twice a week for 6 months. Exercise was conducted on a cycle ergometer (Wattbike Pro; Wattbike, Australia) and each session lasted 50 min, with intensity being set using the Borg scale of perceived exertion.[28] Those in the high intensity exercise group completed a 10-min warm up, 11 intervals of 1 min cycling at hard exertion at 18.0 Borg Scale, 80% aerobic capacity (VO_2peak, determined at baseline, 3 and 6 months by cycling based graded exercise test), interspersed with 2 min of active recovery, and a 9-min cool down. The moderate intensity group cycled at a constant intensity for 50 min (50%–60% aerobic capacity; 13.0 Borg Scale). Participants in the control group attended one information session regarding the benefits of exercise to overall health and the brain.

2.3 | Pittsburgh sleep quality index

The Pittsburgh Sleep Quality Index (PSQI) was administered at baseline and 6-months (immediately post-intervention) to measure subjective sleep quality. The PSQI is a self-reported measure of sleep behaviours over the past month[29] that consists of 19 self-rated items, is widely used to measure subjective sleep quality, and has good internal consistency.[30] A self-report measure of sleep was selected as it is widely applicable, provides important information about sleep self-perception which may not be available via objective measures, and is associated with important health outcomes.[31,32] For the current study, we selected specific outcomes from the PSQI *a*-priori with the aim of maximising statistical power. Thus, the PSQI was scored to yield measurements of: sleep duration, sleep efficiency, and sleep onset latency, as these parameters of sleep are most consistently associated with exercise and cognitive function.[10,17,33]

There is a hypothesised U-shaped association between sleep duration and cognitive function, such that both too much and too little sleep may be detrimental to cognition.[34] Specifically, those sleeping ≥9 h or ≤5 h per night show greater cognitive declines and higher dementia risk, compared to those sleeping 7 h per night.[35,36] In the current sample, however, there was limited variation in sleep duration within each exercise group, meaning we were unable to compare groups at these cut off points. Instead, we used recommendations from the US National Sleep Foundation to inform our group classifications, drawing comparisons between those with 'optimal' sleep duration (7–8 h inclusive), and those with 'suboptimal' sleep duration <7 h or >8 h.[37] Thus, sleep duration was treated as a categorical variable in all analyses. For the purposes of data visualisation only, sleep efficiency was separated into the following groups: <65%, 65%–74%, 75%–84%, and ≥85% based on categorisation from the PSQI.

2.4 | Cognitive assessment

At baseline and 6-month follow-up (immediately post-intervention), a comprehensive cognitive battery was administered to all participants. The cognitive battery was comprised of the California Verbal Learning Test second edition (CVLT-II), Montreal Cognitive Assessment (MoCA), Brief Visual Memory Test (BVMT), Wechsler Adult Intelligence Scale-III Digit Span, Trail Making Test A and B, and the National Institutes of Health - Executive Abilities: Measures and Instruments for Neurobehavioral Evaluation and Research (NIH-EXAMINER) verbal fluency task, Flanker, and Set-shifting. The Cogstate battery, a computerised cognitive assessment (www.cogstate.com), was also delivered including Groton Maze learning and recall, identification, detection, one-card learning, and one-back tasks. We calculated composite scores for global cognitive function, attention, episodic memory, and executive function, as defined below.

Individual performances across all timepoints were used to create *z*-scores to form cognitive composite scores. For tasks where a lower score indicates better functioning (i.e., reaction time), the score was inversed ([score]*-1). The global cognitive composite was formed from the Digit Span, Cogstate one-back, Cogstate identification task, CVLT-II (learning, short delay recall, long delay recall, and recognition d'), BVMT (learning and long delay recall), Cogstate Groton Maze recall, Trail Making Test B, Phonemic fluency, Flanker, and Set-shifting tasks. The attention composite score consisted of the Digit Span (Forward only) and Cogstate identification task. The episodic memory composite score was formed from the CVLT-II (short delay recall, long delay recall, and recognition d'), BVMT long delay recall, and Groton Maze recall. The executive function composite score included the Trail Making Test B, Phonemic fluency, Flanker, and Set-shifting tasks.

2.5 | Covariates

All analyses included age, sex, education level, and Apolipoprotein E (*APOE*) ε4 allele carriage status as covariates, as these factors are known to impact the variables of interest.[38–40] Age, sex and years of

education were determined via demographic questionnaire, *APOE* genotype was established as previously described.[27] An interaction term for age*sex was added to the linear mixed models to account for baseline differences per participant.

2.6 | Statistical analyses

All analyses were conducted using R statistical computing packages version 4.0.3.[41] Descriptive statistics were calculated to compare clinical and demographic variables across control, moderate and high intensity exercise groups. For continuous variables, analyses of variance were conducted whilst chi-square tests were conducted for categorical variables. For all analyses which examined change from pre- to post-intervention, intention-to-treat analyses were performed, such that all participants with complete baseline sleep data ($n = 89$) were included in analyses, regardless of session adherence or study withdrawal.

To examine whether baseline sleep variables influenced exercise-associated cognitive improvement, we conducted a series of linear mixed effects models (LMMs). Firstly, the data were subset by exercise group, namely moderate intensity and high intensity. The control group was excluded from these within-group analyses because our aim was to examine the effect of baseline sleep on exercise-induced cognitive change, and these individuals did not complete an exercise intervention. A paired samples *t*-test was considered for this analysis, however to account for covariates and baseline cognition whilst considering possible random effects, LMMs were selected. Within the moderate and high intensity groups, cognitive composite scores were entered as the dependent variable (either episodic memory, executive function, attention, or global cognition), with covariates and the time*sleep variable (either onset latency, duration, or sleep efficiency) interaction entered as the fixed factors, and participant identification number (ID) as a random intercept. Random slope models were tested but did not improve model performance, thus only the random intercept for participant ID was used. Time (calculated as days from baseline) was used as opposed to the categorical timepoint variable to account for any slight variation in visit schedules (e.g., if a participant had their follow-up one-week post intervention). LMMs were conducted for baseline and 6-month data only. Although there was an 18-month follow-up period for the IPAC study, our research aimed to examine how baseline sleep moderates the effect of exercise on cognition immediately post-intervention. This is the first study to investigate whether baseline sleep influences the effect of an exercise intervention on cognition, and thus correction for multiple comparisons was not applied as these were intended as exploratory analyses to warrant further investigation.[42]

To examine whether the exercise intervention improved sleep, and whether this varied due to exercise intensity, a series of LMMs were conducted. The respective sleep outcome was entered as the dependent variable (either onset latency, duration, or sleep efficiency), with covariates and time*group (control, moderate intensity, high intensity) entered as the fixed factors, and participant ID number as a random effect. The false discovery rate correction for multiple comparisons was applied for this analysis.[43]

3 | RESULTS

One hundred and eight participants were enrolled, and 99 participants were subsequently randomised. Seven participants withdrew during the six-month intervention, and an additional six participants did not complete the 18-month follow-up (for full details of participant flow see Brown et al., 2021). For the current analyses, participants with incomplete baseline sleep or cognitive data were excluded, resulting in a sample of $n = 89$. Descriptive data for this sample, including baseline sleep characteristic data, are presented in Table 1. The mean age of the current sample was 68.76 ± 5.32, majority (54%) of the sample were female, and the mean score on the MoCA was 26.4 ± 2.28.

3.1 | Effect of the exercise intervention on cognition, moderated by baseline sleep

The primary aim of the current study was to determine whether baseline sleep characteristics influenced the ability of the exercise intervention to impact cognitive function. The overall effect of the exercise intervention on cognitive function in the IPAC study cohort has been previously reported, such that there was no effect of the exercise intervention on cognition.[27] Nevertheless, in the current analyses, after controlling for covariates, there was a time*sleep efficiency interaction in the moderate intensity group on both episodic memory and global cognition from baseline to post-intervention, but not for executive function or attention (Table 2). Specifically, those in the moderate intensity exercise group reporting <75% sleep efficiency at baseline showed improvements in episodic memory over the course of the exercise intervention (<65%: $\beta = 0.703$, SE = 0.316, $p = 0.026$; 65%–74%: $\beta = 1.064$, SE = 0.395, $p = 0.007$; Figure 1), whereas those reporting ≥75% sleep efficiency showed no exercise-induced changes in episodic memory (75%–84%: $\beta = 0.366$, SE = 0.243, $p = 0.131$; >85%: $\beta = 0.126$, SE = 0.121, $p = 0.300$; Figure 1).

We found similar effects for global cognition, such that the moderate intensity exercise intervention improved global cognition in all sleep efficiency categories except for those with 75%–84% sleep efficiency (<65%: $\beta = 0.602$, SE = 0.194, $p = 0.002$; 65%–74%: $\beta = 0.585$, SE = 0.242, $p = 0.016$; 75%–84%: $\beta = 0.132$, SE = 0.171, $p = 0.440$; >85%: $\beta = 0.266$, SE = 0.077, $p = 0.001$; Figure 2). There were no time*sleep efficiency interactions in the high intensity exercise group for any cognitive outcome (Table 2). Finally, there was no effect of baseline sleep duration or sleep onset latency on cognitive change in either the moderate or high intensity groups (Table 2).

TABLE 1 Descriptive statistics of the included sample from the IPAC study cohort, presented by exercise group.

	Control (n = 30)	Moderate intensity (n = 30)	High intensity (n = 29)	Test statistic
Age, years	70.1 (5.6)	68.0 (4.2)	68.2 (6.0)	F = 1.77
Gender, % female (n)	53.3 (16)	50 (15)	58.6 (17)	χ^2 = 0.55
APOE ε4 allele carriers, % (n)	26.7 (8)	20.0 (6)	27.6 (8)	χ^2 = 0.55
Years of education	13.4 (2.3)	14.5 (2.4)	14.3 (2.1)	F = 1.98
Global cognition, MoCA score	26.2 (2.1)	26.3 (2.8)	26.7 (2.1)	F = 0.67
Baseline VO_2peak (mL/kg/min)	22.2 (6.5)	25.1 (5.6)	23.2 (6.1)	F = 0.45
Alcohol, units per week	5.9 (6.0)	5.7 (5.6)	5.7 (5.5)	F = 0.01
Time from baseline to 6-mo assessment (wks)	33.1 (3.9)	34.3 (4.5)	34.1 (2.4)	F = 0.95
DASS depression score	3.9 (2.1)	3.33 (2.6)	3.6 (2.7)	F = 0.18
BMI (kg/m^2)	26.0 (3.7)	25.9 (3.6)	25.3 (3.6)	F = 0.39
Poor sleepers, % (n)[a]	60.0 (18)	40.0 (12)	55.2 (16)	χ^2 = 2.93
Sleep efficiency (%)[b]	83.7 (10.7)	84.3 (14.1)	79.8 (16.0)	F = 1.16
Sleep duration (hrs)	7.2 (0.9)	7.1 (1.2)	6.8 (1.4)	F = 1.53
Sleep onset latency (mins)[c]	17.4 (16.4)	17.6 (15.4)	21.2 (13.8)	F = 0.85

Note: Unless otherwise described, data are presented as mean (standard deviation). Differences between groups were calculated using independent samples t-tests for continuous variables and chi-square for categorial variables. All presented sleep data were collected at baseline.

Abbreviations: *APOE*, Apolipoprotein E gene; BMI, Body Mass Index; DASS, Depression, Anxiety Stress Scale; IPAC, Intense Physical Activity and Cognition; MoCA, Montreal Cognitive Assessment; VO_2peak, volume of oxygen uptake during peak exercise.

[a]Poor sleepers are defined as those scoring ≥5 on the Pittsburgh Sleep Quality Index total score.

[b]Time in bed spent asleep.

[c]Time taken to fall asleep.

*$p < 0.05$, **$p < 0.001$.

3.2 | Effect of the exercise intervention on sleep

The secondary aim of the current study was to investigate whether the exercise intervention improved subjective sleep, and whether this varied by exercise intensity. After controlling for covariates, there were no differences between the high intensity and moderate intensity groups compared to the control group for any sleep variables (duration, sleep efficiency, sleep onset latency) from baseline to 6-months (immediately post intervention; Table 3). Additionally, we examined whether there was a main effect of time on sleep outcomes collapsed across all groups. There was no change in any sleep variable (duration, sleep efficiency, sleep onset latency) from baseline to 6-months (β = 0.01, SE = 0.12, p = 0.934; β = −0.02, SE = 1.60, p = 0.890; β = −3.86, SE = 2.06, p = 0.061, respectively).

4 | DISCUSSION

This study aimed to investigate whether baseline sleep influenced the effect of a 6-month exercise intervention on cognitive improvements in community-dwelling cognitively unimpaired older adults, and whether the exercise intervention improved sleep outcomes. Here, we found that: 1. Baseline sleep efficiency influenced change in episodic memory and global cognition over time in those completing a moderate intensity exercise intervention; and 2. Six-months of moderate or high intensity exercise did not affect sleep duration, sleep onset latency or sleep efficiency, compared to an inactive control.

The current findings show that baseline sleep efficiency influenced the effect of moderate intensity exercise on both episodic memory and global cognition. Specifically, those with poorer sleep efficiency showed improvement in episodic memory from pre- to post-intervention. Similarly, both those with poorer sleep efficiency (<74%) and better sleep efficiency (>85%) showed improvements in global cognition from pre- to post-intervention. These results are consistent with previous research showing that physical activity may attenuate some of the negative impact of poor sleep on cognitive function.[11,20,21] Importantly, the current research extends previous findings by illustrating that despite a lack of exercise induced change in sleep efficiency (Table 2), exercise still had a positive influence on cognition in those with poorer baseline sleep efficiency. These results may indicate that exercise-induced sleep improvement is not a *necessary* requirement for exercise-induced cognitive improvement in poor sleepers, and that there may be other mechanisms influencing these associations.[11] For example, suboptimal glymphatic clearance in poor sleep may be attenuated by exercise-induced increases in cerebral blood flow.[44,45] Further research is required to elucidate these mechanisms; however, the current results suggest that

TABLE 2 Effect of the exercise intervention and baseline sleep on cognitive function.

	Time*sleep unstandardised B (standard error)	
	Baseline to 6-months	
	Moderate intensity	High intensity
Episodic memory composite		
Sleep efficiency	**−0.02 (0.01)****	0.01 (0.02)
Sleep duration [suboptimal versus optimal]	0.24 (0.22)	−0.12 (0.38)
Sleep onset latency	0.00 (0.01)	0.01 (0.01)
Executive function composite		
Sleep efficiency	−0.01 (0.01)	0.01 (0.01)
Sleep duration [suboptimal versus optimal]	−0.04 (0.27)	−0.12 (0.25)
Sleep onset latency	−0.00 (0.01)	−0.00 (0.01)
Attention composite		
Sleep efficiency	0.02 (0.02)	0.01 (0.03)
Sleep duration [suboptimal versus optimal]	−0.03 (0.39)	0.06 (0.50)
Sleep onset latency	0.01 (0.01)	−0.00 (0.01)
Global cognition composite		
Sleep efficiency	**−0.01 (0.01)***	0.01 (0.01)
Sleep duration [suboptimal versus optimal]	0.22 (0.14)	−0.08 (0.20)
Sleep onset latency	0.00 (0.00)	0.03 (0.01)

Note: Linear mixed models examining the influence of baseline sleep on cognitive change from pre- to post-intervention, by exercise group. Age, sex, education level, and Apolipoprotein E (*APOE*) ε4 allele carriage status were included as covariates for all models. Sleep was assessed at baseline using the Pittsburgh Sleep Quality Index. Sleep Efficiency is the time in bed spent asleep (%). Sleep Onset Latency is the time taken to fall asleep (minutes). Sleep Duration (hours) was categorised as suboptimal (<7 h or >8 h) and optimal (7–8 h inclusive). Bolded values indicate significance.
*$p < 0.05$, **$p < 0.01$.

moderate intensity exercise may yield the greatest cognitive benefit, particularly in episodic memory, for those with poorer sleep efficiency, potentially by exercise attenuating some of the negative cognitive effects of poor sleep efficiency.

The current study did not find an effect of baseline sleep on exercise-induced changes in executive function composite score in either the moderate or high intensity exercise groups. This is somewhat surprising given that previous research shows associations between physical activity, sleep efficiency and executive function.[10,20] However, the current study examined the effect of an exercise intervention, whereas previous research has examined these associations with observational physical activity.[10,20] Indeed, associations may differ between physical activity and exercise for different sleep parameters (sleep duration, sleep efficiency or sleep onset latency) and across cognitive domains.[11] Additionally, both Lambiase (2014)[20] and Wilckens (2018)[10] measured sleep efficiency objectively, as opposed to via a subjective measure per the current study. This may account for the disparate findings as subjective and objective tools may measure different components of sleep, for example, perceptions of sleep and physiological sleep parameters, respectively.[46]

Our results are inconsistent with previous research which shows that regular exercise induces small to medium improvements in various sleep parameters.[17] Here, we observed no effect of six-months of moderate or high-intensity exercise on sleep, compared to an inactive control group. Previous research showing that regular moderate intensity exercise improves sleep in middle aged and older adults has been specific to those with self-reported reported poor sleep.[47,48] However, sleep categorisation (i.e., stratifying participants into good/poor sleepers, such as the categorisation of sleep efficiency applied in the current study) has not been considered as a moderator of the exercise-sleep association in previous reviews, and may explain the null results in the current study. Further research is needed to examine the effect of exercise on sleep in older adults and specifically those with and without poor sleep.

Here, we found that those with poorer sleep efficiency in the moderate intensity group showed greater cognitive improvements post-intervention, particularly in episodic memory, but such an association did not exist in those in the high intensity exercise group. Previous research shows that a lack of sleep may impair post-exercise recovery and modify inflammatory and hormonal responses to exercise,[49,50] and animal models show that sleep

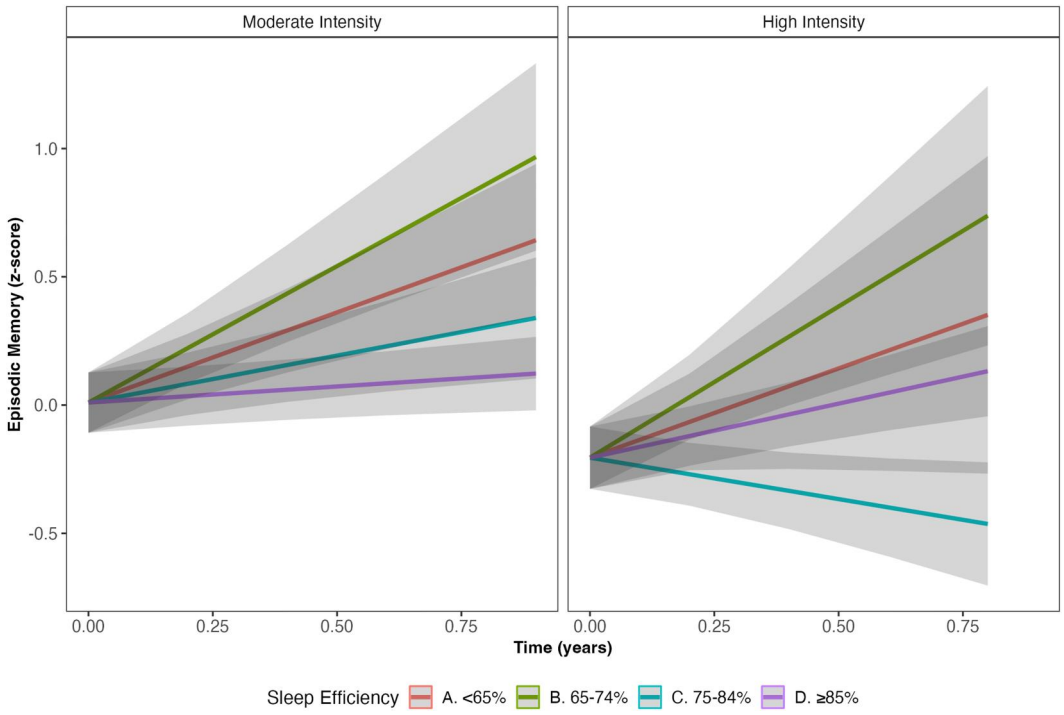

FIGURE 1 The effect of exercise group and sleep efficiency at baseline on episodic memory from baseline (indicated by time 0) to post-intervention (indicated by time 0.75). A sleep efficiency*time interaction exists within the moderate intensity group only (left panel; $\beta = -0.024$, SE = 0.008, $p = 0.004$); such that only those with <65% sleep efficiency and those with 65%–74% sleep efficiency showed significant increases in episodic memory from baseline to post-intervention ($\beta = 0.703$, SE = 0.316, $p = 0.026$; $\beta = 1.064$, SE = 0.395, $p = 0.007$, respectively).

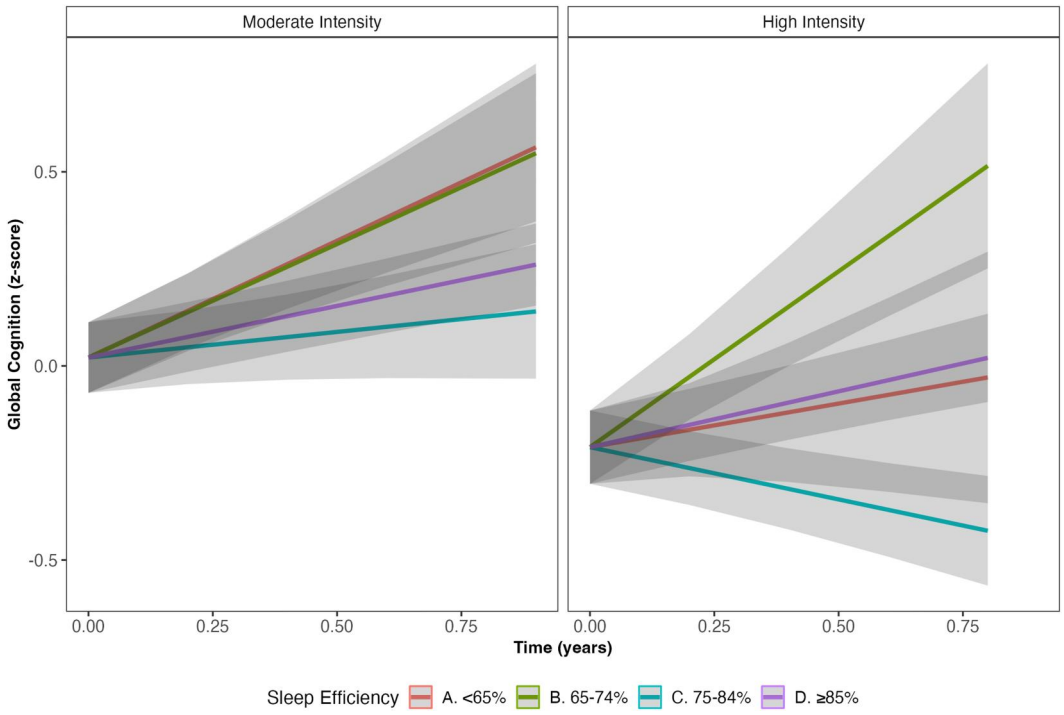

FIGURE 2 Effect of exercise group and sleep efficiency at baseline on global cognition from baseline (indicated by time 0) to post-intervention (indicated by time 0.75). A sleep efficiency*time interaction exists within the moderate intensity group only (left panel; $\beta = -0.011$, SE = 0.005, $p = 0.036$), such that all sleep efficiency categories increased global cognition from baseline to post-intervention, except for those with 75%–84% sleep efficiency (<65%: $\beta = 0.602$, SE = 0.194, $p = 0.002$; 65%–74%: $\beta = 0.585$, SE = 0.242, $p = 0.016$; 75%–84%: $\beta = 0.132$, SE = 0.171, $p = 0.440$; ≥85%: $\beta = 0.266$, SE = 0.077, $p = 0.001$).

TABLE 3 Effect of the exercise intervention on sleep outcomes.

	Raw mean change from baseline (95% CI)			Group*time interaction unstandardised B (standard error)
	Control	Moderate intensity	High intensity	
Sleep efficiency (%)	2.35 (−3.0, 4.7)	0.37 (−2.8, 6.8)	−0.30 (−1.8, 4.0)	−0.89 (2.03)
Sleep duration (hours)	0.34 (−0.4, 0.2)	−0.11 (−0.3, 0.6)	−0.02 (−0.2, 0.3)	−0.17 (0.15)
Sleep onset latency (minutes)	−4.09 (−4.0, 6.0)	−4.74 (−0.7, 10.3)	1.11 (−4.0, 3.0)	2.44 (2.62)

Note: Linear mixed models examining the influence of the 6-month exercise intervention on sleep outcomes. Age, sex, education level, and Apolipoprotein E (*APOE*) ε4 allele carriage status were included as covariates for all models. Sleep was assessed using the Pittsburgh Sleep Quality Index. Sleep Efficiency (%) is the time in bed spent asleep. Sleep Onset Latency (minutes) is the time taken to fall asleep.
Abbreviation: CI, confidence interval.

deprivation reduces protein synthesis, decreasing post exercise recovery.[51] Although the mechanisms between exercise and cognition remain to be fully elucidated, impaired recovery may, in turn, influence cognitive processes resulting in a lack of improvement such as that observed for those with poorer sleep efficiency in the high intensity exercise group. Further research is required to characterise the mechanisms between exercise, sleep and cognitive function; however, what is clear from the current study is that sleep efficiency may influence the effectiveness of exercise-induced cognitive improvement, highlighting the need for future research in this area.

The current study utilised a self-report measure for sleep, the PSQI, which may be subject to recall bias, and limited our ability to measure other sleep architecture, such as slow wave sleep. However, the PSQI is well-validated and has been associated with important health outcomes, such as hypertension and mortality.[31,32,52] Additionally, the current cohort was relatively homogenous, including highly motivated, educated individuals, and future studies should consider examining the associations between sleep and exercise in other populations. We also acknowledge that lifetime sleep and physical activity behaviours may have influenced the current results. Nevertheless, the strengths of this study include a randomised clinical trial design with a fully supervised exercise intervention at varying intensities, use of comprehensive cognitive assessments, and our analysis controlled for confounding variables.

Here, we demonstrate that sleep characteristics may influence exercise-induced cognitive change in older adults. Future exercise intervention trials aiming to improve cognitive function should consider the impact of sleep on this association. Our results show that those with poorer sleep may demonstrate the greatest cognitive benefit from a moderate intensity exercise intervention, however, further research is required to confirm these findings. Such research should utilise objective sleep measurements implemented across multiple study timepoints. Ultimately, further research in this area may inform the development of effective multi-modal lifestyle interventions, improving cognitive function, and thereby potentially delaying the onset of cognitive decline and dementia.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The datasets generated and/or analysed during the current study are not publicly available due to additional secondary analyses currently being conducted but are available from the corresponding author on reasonable request.

ETHICS APPROVAL AND CLINICAL TRIAL REGISTRATION

The IPAC study is registered with the Australian New Zealand Clinical Trials Registry (ACTRN12617000643370). The human research ethics committees at Murdoch University and Edith Cowan University approved the conduct of this study, and all participants provided written informed consent.

ORCID

Kelsey R. Sewell https://orcid.org/0000-0002-3859-5017

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