Self-reported physical activity and sleep quality is associated with working memory function in middle-aged and older adults during the COVID-19 pandemic

Tiago Guardia 1 - tg17ba@brocku.ca *
Kimberly A. Cote 1 - kcote@brocku.ca
M. Karl Healey 2 - khealey@msu.edu
Kimberley Lyn Gammage 3 - kgammage@brocku.ca
Karen Lucia Campbell 1 - karen.campbell@brocku.ca *

1. Department of Psychology, Brock University, St. Catharines, ON, Canada
2. Department of Psychology, Michigan State University, East Lansing, MI, United States of America
3. Department of Kinesiology, Brock University, St. Catharines, ON, Canada

Corresponding Authors:
Tiago Guardia (PhD)
Department of Psychology, Brock University
1812 Sir Isaac Brock Way
St. Catharines, ON - L2S 3A1
tg17ba@brocku.ca

Word count of main text: 4778

Number of references: 48

Number of data elements (tables and/or figures): 6

ABSTRACT

While previous work has consistently shown a positive relationship between cognitive performance and various lifestyle factors (including sleep quality and physical activity) in younger adults, evidence for this relationship among middle-aged and older adults has been mixed. The current study aimed to further test the relationship among self-reported measures of physical activity, sleep quality, and memory performance in middle-aged and older adults (n = 302; age range = 45 - 75 years old), and to test whether this relationship holds up during a period of unprecedented stress and reduced physical activity caused by the COVID-19 pandemic. Our results showed that self-reported physical activity was associated with better subjective sleep quality and better working memory performance, and better subjective sleep quality was associated with better working memory and self-perceptions of everyday memory abilities. Additionally, we found that the effects of physical activity on working memory were partially mediated by sleep quality, suggesting that physical activity may contribute to improved cognitive performance via improved sleep. Participants reported that the pandemic was affecting their sleep quality and mental health, and pandemic-related stress and sleep disturbances were negatively associated with physical activity, memory, and mental health. While these effects were small and only correlational in nature, they lend further support to the notion that sleep quality and physical activity are beneficial to memory later in life, even (or maybe especially) during a global pandemic that negatively affected people's ability to sleep and exercise.

KEYWORS: sleep; physical activity; memory; aging; COVID-19 pandemic

INTRODUCTION

As life expectancy of the world's population increases, neurodegenerative diseases are becoming increasingly widespread, and lifestyle interventions have been explored as key components in preserving brain health and delaying cognitive decline (Klaming et al., 2017; Toman et al., 2018). Although multidomain lifestyle interventions have been shown to preserve cognitive functioning among older adults, more research is needed to identify the extent to which specific lifestyle factors are associated with brain and cognitive health (Rosenberg et al., 2020).

Sleep is essential for health and well-being throughout the lifespan, and the neural mechanisms involved in sleep-wake regulation are important for optimal cognitive function (Wright et al., 2012). Sleep disturbances and cognitive impairment are common in older adults (Mander et al., 2017), and studies suggest that good sleep quality might serve as a protective factor against subsequent age-related cognitive decline (Bah et al., 2019; Yaffe et al., 2014). Nevertheless, the relationship between sleep quality and cognitive performance has been less consistently demonstrated in older adults, and more research is required to confirm the connection between sleep quality and cognition from middle-age onwards (Dzierzewski et al., 2018).

Another lifestyle factor that benefits cognition is physical activity (Gomes-Osman et al., 2018). While previous studies suggest that higher intensity physical activity helps to maintain cognitive function in older age, more information is needed about the relationship between self-reported daily physical activity (including lower intensity activities, such as vacuuming or light yard work) and cognition in older adults (Gomes-Osman et al., 2018). Additionally, physical activity interventions have also been shown to improve sleep quality and well-being in older adults (Bullock et al., 2020). Indeed, improved sleep efficiency (which is defined as the percentage of time spent sleeping while in bed) may be one of the pathways by which physical activity benefits neurocognitive function in young and older adults. For instance, Wilckens et al. (2018) showed that improved sleep efficiency mediates the positive relationship between physical activity and executive control, including working memory, in young and older adults.

Although several studies suggest that good sleep quality and physical activity relate to better cognitive performance, these effects tend to be most consistent in young adults, and more evidence is needed to support this connection in middle-age and older adults (Stillman et al., 2020; Yaffe et al., 2014). For example, some studies conducted in middle-aged adults linked short sleep duration to poorer executive control, working memory, episodic memory, attention, and frequency of cognitive complaints, while other studies suggest that the association between sleep and cognition weakens as people get older (Scullin and Bliwise, 2015). Further, recent meta-analyses suggest that physical activity in midlife may contribute to the maintenance of cognitive function later in life (Engeroff et al., 2018; Zhidong et al., 2021), including working memory and associative memory which are known to be particularly affected by aging (Matysiak et al., 2019; Nyberg, 2017). However, a recent 5-year moderate-intensity and high-intensity exercise intervention study did not find a significant effect of exercise on global cognitive function in older adults (Zotcheva et al., 2022), illustrating the inconsistency of these effects in older samples. Thus, the current study aimed to further investigate the relationship among self-reported measures of physical activity and sleep quality, and memory in middle-aged and older adults.

A second goal of the current study was to assess the impact of the COVID-19 pandemic on participants' mental health and subjective sleep quality, and to see if the relationship among sleep quality, physical activity, and memory performance holds up despite unprecedented levels of stress and inactivity caused by the pandemic and related restrictions. Recent studies have started to confirm what may have seemed obvious when the current study was conceived (i.e., September

2020) – the COVID-19 pandemic had a negative impact on mental health and sleep quality of the general population as well as among older adults in particular, and the prevalence of major depressive disorders, anxiety disorders and sleep problems increased worldwide due to the pandemic (Del Brutto et al., 2021; Jahrami et al., 2021; Santomauro et al., 2021). Further, government-mandated lockdowns also affected people's ability to exercise and their overall mobility (Stockwell et al., 2021; Wilke et al., 2022). The effect of pandemic-related lockdowns on people's level of physical activity are mixed, and seem to depend on country, sample, type/intensity of physical activity, and how researchers defined (and measured) physical activity and exercise (Larson et al., 2021; Morrison et al., 2022; Visser et al., 2020). Although some studies have reported maintained or even increased activity during the pandemic, most studies report that people on average showed a decrease in daily physical activity and an increase in sedentary time during the COVID-19 pandemic (Park et al., 2022). The same observation was also reported for older adults (Baughn et al., 2022; Oliveira et al., 2022). Thus, we thought it important to ask participants about the effects of COVID-19 on their sleep quality, stress, anxiety, and depression. To this end, we adapted a questionnaire originally designed to measure stress and mental health following the September 11th terrorist attacks (i.e., another major world incident; Swenson and Henkel-Johnson, 2003), but changed the wording to focus on stress/mental health changes related to the pandemic[1].

We recruited 302 participants aged 45 to 75 to participate in an online experiment. Working memory was assessed using the operation span task (OSPAN; Oswald et al., 2014; Unsworth et al., 2005) and associative memory was assessed using the Verbal Paired Associates (VPA) subtest from the Wechsler Memory Scale-III (Uttl et al., 2002). We also measured participants' self-

[1] It should be noted that at the time of planning this study, no other COVID-related questionnaires were available. This was our attempt to make use of an existing scale but adapt it for our purposes.

perceptions of their everyday memory abilities using the Memory Ability Scale of the Multifactorial Memory Questionnaire (MMQ-Ability) (Troyer and Rich, 2002). This scale asks participants to estimate the frequency of everyday memory errors over the past two weeks (e.g., how often have you misplaced your keys or forgotten someone's name). Self-reported physical activity was measured using the Rapid Assessment of Physical Activity (RAPA) questionnaire (Topolski et al., 2006), overall subjective sleep quality using the Pittsburgh Sleep Quality Index (PSQI; Buysse et al., 1989), and general anxiety and depression using the Hospital Anxiety and Depression Scale (HADS). Finally, participants completed our adapted COVID stress and sleep questionnaire.

We hypothesized that higher self-reported levels of physical activity would be associated with better subjective sleep quality, better memory performance, and better self-perceptions of memory abilities in everyday life in middle-aged and older adults. Similarly, we predicted that better subjective sleep quality would correlate with better memory performance and self-perceptions of memory abilities. Additionally, we hypothesized that subjective sleep quality would partially mediate the relationship between physical activity and cognition (Wilckens et al., 2018). We also expected that increasing age would be associated with poorer sleep quality and lower memory performance. Finally, we anticipated that both middle-aged and older adults would report that the COVID-19 pandemic was negatively affecting their mental health and subjective sleep quality.

METHODS

Participants

Participants were recruited from the online platform Prolific (https://www.prolific.co/). The following eligibility criteria were used: age between 45 and 75 years old, residents of the

United Kingdom, English as a first language, and had a Prolific approval rating of 90% or above (meaning that 90% of the time or more they complete experiments with acceptable quality data – i.e., not gibberish or responses that are impossibly fast or slow). Data were collected between December 2020 and February 2021, with the timing of testing set between 6am-6pm. Of the 317 participants who completed the study, 15 were excluded due to: taking more than twice as long to complete the study than expected (i.e., more than 90 minutes, n = 11) or being outside the specified age range (n = 4). No participants failed the attention check questions, which are described below. Exclusion criteria included self-reported neurological conditions such as epilepsy or head injury, sleep disorders (e.g., sleep apnea, restless legs syndrome), and use of psychoactive medications. The final sample consisted of 302 participants (45–75 years old; mean 59.2; SD 8.3; 150 men and 152 women). This sample size was based on the common heuristic of obtaining at least five observations per variable of interest when performing multiple regression analysis (Hair et al., 2014). Demographic information of the current sample is provided in Table 1. All cognitive tasks and questionnaires were given to participants through the online platform Testable (https://www.testable.org/). Three attention check questions were distributed throughout the tasks to make sure that participants were paying attention.

Measures

Physical Activity. The Rapid Assessment of Physical Activity (RAPA) questionnaire was used to determine participants' typical level of physical activity. The RAPA is a self-report questionnaire that has been well validated for use with older adults (Topolski et al., 2006). It includes two sections – one that measures typical aerobic activity levels and one that measures strength and flexibility. In our analyses, we focused on the aerobic portion as previous work has emphasized the importance of aerobic activity in the maintenance of cognitive performance with age (Gomes-Osman et al., 2018). The RAPA starts by explaining what physical activities are ("activities where you move and increase your heart rate above its resting rate, whether you do them for pleasure, work, or transportation."). It then explains what is meant by the different intensity levels of physical activity that will be assessed in the questionnaire and gives some concrete examples (e.g., light activities: walking leisurely, stretching, vacuuming or light yard work; moderate activities: fast walking, aerobics class, strength training, swimming gently; vigorous activities: stair machine, jogging or running, tennis, racquetball, pickleball or badminton). Following these instructions, participants respond yes/no to seven questions that assess the extent to which they engage in activities at each intensity level (e.g., 1. "I rarely or never do any physical activities"; 2. "I do some light or moderate physical activities, but not every week."; 3. "I do some light physical activity every week."; … 7. "I do 20 minutes or more a day of vigorous physical activities, 3 or more days a week."). A score of 1 to 7 is given based on the highest question number with an affirmative response (e.g., if someone responded "yes" to question 7 above, they would receive a score of 7). Scores are classified as sedentary (1), under-active (2-3), under-active regular (4-5), and active (6-7).

Sleep Quality. Subjective sleep quality was assessed using the Pittsburgh Sleep Quality Index (PSQI) questionnaire (Buysse et al., 1989). The PSQI is a widely used, multidimensional self-report measure of sleep quality that produces a global sleep quality score, as well as seven components representing subjective sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbance, use of sleep medications, and daytime dysfunction. Participants rate their sleep quality over the past month. We focused on the global sleep score, which is a sum of the seven components. The PSQI global score ranges from 0 to 21, with higher scores reflecting greater sleep dysfunction. Scores greater than 5 indicate poor sleep quality (REFERENCE NEEDED).

Paired associate learning. Paired-associate learning (PAL) is often used to assess episodic memory performance, and the Verbal Paired Associates (VPA) subtest from the Wechsler Memory Scale is one of the most widely used tests of PAL (Scorpio et al., 2018). In this task, participants were required to memorize pairs of words (e.g., frog-neck; fruit-apple), which were then tested across three study-test trials. At test, participants were provided with the first word in each pair and asked to recall the response word that went with it. In this study we used the VPA-15, which is an adapted version of the VPA from the Wechsler Memory Scale-III (Uttl et al., 2002). The VPA-15 includes the original eight pairs (four related/easy and four unrelated/difficult) from the VPA- Wechsler Memory Scale-III, plus seven new unrelated/difficult word pairs, making a total of 15 word-pairs in the sequence. In the first encoding phase, each word-pair was presented on screen for 2000ms, followed by a 500ms interstimulus interval (ISI). The test phase immediately followed, in which participants had up to 20 seconds to finish typing their response to each cue word. In the first (PAL1) and second (PAL2) test trials, participants were given another chance to study the word pairs. That is, immediately following the input of their response, the original word-pair was shown again regardless of whether their preceding response was correct or not. The final test trial (PAL3) was given after a ~15 minutes delay (during which participants performed the working memory task, described below). Performance on the PAL task was measured as the total number of correctly recalled responses on each test trial (PAL1, PAL2 and PAL3).

Working Memory. Working memory was assessed using the Operation Span Task (OSPAN, (Oswald et al., 2014; Unsworth et al., 2005). The OSPAN task is one of the most widely used tasks for measuring working memory capacity and has been shown to have both good reliability and validity (Oswald et al., 2014; Unsworth et al., 2005). In this task, participants were given a series of simple math problems to solve (e.g., (8 / 2) + 9 = ?). Participants pressed a key once they felt they had solved the equation and then a number was shown on the screen. Participants had to indicate whether the number was the correct solution to the math problem or not. After responding to each math problem, participants were given a letter to remember. At the end of each set (which included 4 to 6 math problems to solve and letters to remember), participants were asked to recall the letters in order. A series of boxes were provided on the screen and participants were asked to type the letters in the correct serial position and to leave a blank space if they could not remember the corresponding letter. In total, the task included four trials of set sizes 4 and 6 and two trials of set size 5, making for a total of 50 letters to be recalled. Participants had up to 10 seconds to solve each math problem and up to 3 seconds to answer whether the following number was a correct answer to the operation or not. There was no time limit to answer the sequence of letters. Performance on the OSPAN task was measured by the total number of letters recalled in the correct position.

Self-perceptions of everyday memory ability. Participants' perceptions of their everyday memory abilities were assessed using the Memory Ability Scale of the Multifactorial Memory Questionnaire (MMQ-Ability) (Troyer and Rich, 2002). The MMQ assesses multiple dimensions of metamemory, and it is focused on memory abilities and strategies that are applicable to everyday life (e.g., remembering names, misplacing belongings) rather than to laboratory situations (e.g., remembering word pairs). The MMQ-ability subscale measures one's self-perception of everyday memory ability. Respondents rate how often they experienced 20 common memory mistakes over the previous two weeks (e.g., not recalling the name of someone you just met; forgetting an appointment). Scores range from 0 to 80, and individuals with higher scores on this scale have a better subjective impression of their memory capabilities than those with lower scores.

Impact of COVID-19 on Sleep, Stress, Anxiety and Depression. We adapted the Stress Symptoms Following September 11th Terrorism Survey (Swenson and Henkel-Johnson, 2003) to assess the impact of the pandemic on sleep, stress, anxiety, and depression. It included 5 questions that measure the impact of COVID-19 on: 1) Sleep due to worries related to the pandemic (score range 1-4); 2) Sleep due to bad dreams about the pandemic (score range 1-4); 3) Stress (score range 1-7); 4) Anxiety (score range 1-7); 5) Depression (score range 1-7).

Mental Health. Finally, we also included the Hospital Anxiety and Depression Scale (HADS) to measure general anxiety and depression in the current sample (Snaith, 2003). The HADS is a well-validated tool for measuring anxiety and depression in both clinical practice and non-clinical research (Stern, 2014). It includes seven questions related to anxiety and seven related to depression and takes 2–5 min to complete. For both the anxiety and depression scales, scores are classified as 'non-case' (0-7), Mild (8-10), Moderate (11-14), and Severe (15-21). We related scores on the HADS to responses on our COVID-related stress questionnaire.

Procedure

Participants first completed a consent form and then a demographics questionnaire in which they were asked about their age, sex, highest level of education, ethnic origin, marital status, major occupation and if they were retired or not. Then, participants completed the first two trials of the paired associate learning task (PAL1 and PAL2), followed by the operation span task (OSPAN) and finally, the last trial of the paired associate learning task (PAL3). After the cognitive tasks were concluded, participants answered the following sequence of questionnaires: Rapid Assessment of Physical Activity (RAPA), Pittsburgh Sleep Quality Index (PSQI), Hospital

Anxiety and Depression Scale (HADS), Impact of COVID-19 on Sleep, Stress, Anxiety and Depression, and the Memory Ability Scale of the Multifactorial Memory Questionnaire (MMQ-Ability).

Data Analysis

Statistical analyses were conducted using IBM SPSS - version 28.0. Pearson correlation analyses were performed to examine the correlations of age, physical activity (RAPA aerobic score), sleep quality (PSQI global score), working memory (composite OSPAN score), associative memory (composite PAL score), and self-perceptions of memory ability (MMQ-Ability score). The level of significance was set at alpha level of $p < 0.05$, and we used the Benjamini–Hochberg correction method for multiple comparisons (Benjamini and Hochberg, 1995)

We followed up on these simple correlations with a series of multiple regression analyses to evaluate the effects of age, physical activity, and sleep quality on working memory, associative learning, and self-perceptions of memory ability while controlling for sex and education level. All independent variables were entered into the equation in one step (forced entry). Additionally, we also tested the mediating effect of sleep quality on the relationship between physical activity and memory by using Hayes' Process v3.5 macro in SPSS.

RESULTS

Descriptive Statistics

Means and standard deviations for the physical activity, sleep, and cognitive measures are provided in Table 2, divided by age subgroups for illustrative purposes but age was treated as a continuous variable for all analyses. Distributions of all the variables are shown in Supplementary Figure S1. In terms of physical activity, most participants would be classified as "under-active regular” ($M = 4.13$ $SD = 1.69$) according to the metrics of the RAPA (Topolski et al., 2006). Regarding sleep quality, participants’ mean global PSQI score was greater than 5 ($M = 6.29$ $SD = 3.69$; Median = 6), indicating that participants were experiencing poor sleep quality on average.

On the OSPAN task, participants remembered an average of 82.94% of the 50 letters in the correct position across trials ($M = 41.47$, $SD = 9.14$). Performance on the math portion of the task was also satisfactory, with participants solving 88.17% ($SD = 10.61$) of the equations correctly in 4.05 seconds (1.26) on average. Given the skewed distribution of the OSPAN scores (see Figure S1), a logarithm transformation (-log10) was applied to these data prior to linear modelling (West, 2022). The accuracy of the math portion of the task was not used as a filtering criterion for further analysis since it has been demonstrated that omitting the accuracy criteria does not cause any changes in the psychometric indicator of the task (Dokić et al., 2018).

For the paired associate learning task, performance got progressively better across trials (PAL1: $M = 5.01$, $SD = 3.28$; PAL2: $M = 7.04$, $SD = 3.61$; PAL3: $M = 8.43$, $SD = 3.61$). A univariate repeated measures ANOVA using the Greenhouse-Geisser correction indicated there was a significant improvement in PAL scores over trials, $F(1.75, 1021.14) = 318.64$, $p < 0.001$, partial $\eta^2 = .51$. For subsequent analyses, we also created a composite score for the paired associate learning task, as the mean z-score of PAL1 and PAL2 scores (mean composite score per age group is shown in Table 2). PAL3 was not included in the composite score because there was a large degree of variability in the amount of time participants took to complete the OSPAN Task (and hence, a variable delay between PAL2 and PAL3 across participants; mean delay = 10.03 minutes, $SD = 3.25$; MIN = 4.36; MAX = 35.51). Further, lag time correlated with PAL3 recall ($r = -0.17$, $p = 0.003$) and thus, we decided to exclude this test trial from the PAL composite score (however, it should be noted that including PAL3 in the composite score does not change the conclusions drawn for any of the subsequent analyses).

Finally, on the MMQ – Ability questionnaire, participants' perceptions of their own memory would be classified as "average" (see Table 2) when compared to normative data from the Professional Manual of the Multifactorial Memory Questionnaire (Troyer and Rich, 2002).

Correlation Analysis

Contrary to our predictions, performance on the cognitive measures did not decline significantly with age, though the different metrics of memory were correlated with each other (see Figure 1). Also unexpectedly, sleep quality improved with age [$r (300) = -0.12$, $p = 0.034$; higher PSQI scores reflect worse sleep], though it should be noted that this correlation does not survive FDR correction for multiple comparisons. Subjective sleep scores were also correlated with working memory [$r (300) = - 0.17$, $p = 0.004$] and self-perceptions of memory ability [$r (300) = - 0.43$, $p < 0.001$], with greater level of sleep dysfunction relating to worse working memory performance and poorer perceptions of everyday memory abilities. Physical activity was associated with reduced levels of sleep dysfunction [$r (300) = - 0.16$, $p = 0.004$] and better working memory performance [$r (300) = 0.14$, $p = 0.012$].

Regression Analyses

A series of multiple regression analyses were performed to evaluate the predictive effects of age, physical activity, and sleep quality (controlling for education and sex) on working memory, associative memory, and self-perceptions of memory (all predictors entered in a single step). We summarize the key findings here (see Table 3 for detailed results). The model predicting working memory was significant [$R2 = 0.05$, $F (5, 296) = 2.92$, $p = 0.014$]. Physical activity ($\beta = 0.13$, $p = 0.034$) and sleep score ($\beta = -0.15$, $p = 0.009$) were significant predictors, but age was not (β = -

0.01, $p = 0.840$). The model predicting associative memory was significant [$R2 = 0.13$, $F (5, 296) = 8.60$, $p < 0.001$]. Physical activity ($\beta = 0.08$, $p = 0.177$), sleep score ($\beta = -0.09$, $p = 0.107$), and age ($\beta = -0.02$, $p = 0.726$) were not significant predictors. The model predicting perceptions of everyday memory ability (MMQ-Ability) was significant [$R2 = 0.18$, $F (5, 296) = 13.39$, $p < 0.001$], with sleep score the only significant predictor ($\beta = -0.42$, $p < 0.001$). For each model, we also ran separate analyses for both men and women and found the same pattern of results for both sexes as reported above.

Mediation Analysis

We assessed the mediating effect of subjective sleep quality on the relationship between physical activity and working memory (controlling for age, education, and sex). Given that working memory was the only significant factor that correlated with both physical activity and sleep, this was the only mediation model evaluated in this study. Our results show that sleep score partially mediates the relationship between physical activity and working memory performance (mediation effect: $ab = 0.06$, 95% CI [0.003, 0.159]), but the direct effect of physical activity on working memory remained significant after accounting for sleep ($c' = 0.03$, 95% CI [0.003, 0.015], $t = 2.13$, $p = 0.034$).

Impact of the COVID-19 Pandemic

Participants' responses to our adapted Stress Symptoms questionnaire are shown in Figure 2. Increasing age was associated with a decreased effect of the pandemic on subjective measures of sleep, stress, anxiety, and depression (see Figure 3 for correlation values). We also found that poor sleep, stress, anxiety, and depression related to the pandemic were associated with poorer performance on our cognitive measures and as would be expected, worse sleep quality on the PSQI and mental health scores on the HADS (see Figure 3). Interestingly, greater levels of physical activity related to lower levels of pandemic-related stress and sleep disturbances.

DISCUSSION

We evaluated the relationship among self-reported measures of physical activity and sleep quality, and memory in middle-aged and older adults, in addition to assessing the impact of the COVID-19 pandemic on participants' well-being and sleep quality. Our results show that participants overall had poor subjective sleep quality and were classified as physically underactive. People who were more active reported better sleep quality and better working memory performance, and better sleep quality was associated with working memory and self-perceptions of memory in everyday life. Additionally, subjective sleep quality partially mediated the relationship between physical activity and working memory performance, suggesting that physical activity may improve cognition via improved sleep. Finally, participants reported that the COVID-19 pandemic was negatively affecting their sleep quality and mental health, with older adults reporting less of an impact than middle-aged adults. Further, greater stress and sleep disturbances related to the pandemic were associated with levels of physical activity, memory, and mental health.

Contrary to our predictions, we did not observe an age-related decline in working or associative memory, but this may have been due to the restricted age range tested here (i.e., we did not include younger adults aged 18-44 years) or the relatively high performance of online samples of older adults (Merz et al., 2020). Nevertheless, we found that working memory performance was predicted by both self-reported physical activity and sleep quality, and that better self-perceptions of everyday memory abilities were predicted by better subjective sleep quality. Although studies have already demonstrated that better sleepers and more active individuals at middle-age and later life demonstrate better cognitive performance and well-being, this relationship is not as consistent as it is among younger adults (Dzierzewski et al., 2018; Zotcheva et al., 2022). Several factors may be contributing to the inconsistency of these findings in older adults, including variations in study design and cohort differences (Quigley et al., 2020; Young et al., 2015). Unexpectedly, we also observed a slight improvement in subjective sleep quality with increasing age. One possible reason for the lack of age-related decline in sleep quality may be that we only tested participants from middle age onwards. According to the literature, age-related changes in sleep patterns start to occur in middle age (Li et al., 2018), and by not including younger adults, who likely would have shown better sleep quality than our sample (which on average showed poor sleep quality), we failed to detect a decline in sleep quality with age.

It is also possible that the pandemic contributed to the slight improvement in subjective sleep quality from middle- to older age. On our adapted pandemic stress questionnaire, middle-aged adults reported a greater effect of the pandemic on their mental health and sleep than older adults, and these pandemic-related effects were also associated with lower levels of subjective sleep quality (see Figure 3). Overall, the current study contributes to the literature by providing further evidence of the cognitive benefits of being a good sleeper and engaging in physical activity from midlife onwards. While the current results are only correlational and quite small in magnitude (i.e., for every one-unit increase in physical activity, we only see a 3% increase in working memory and for every one-unit increase on the PSQI, we only see a 2% decrease in working memory), they point the way towards future interventions that should use random assignment to determine causation. It is also important to mention that in this study we used self-reported measures of sleep quality and physical activity, which can be less accurate that objective measures taken with polysomnography and actigraphy, and especially vulnerable to discrepancies when working with older adults (Landry et al., 2015; Zilli et al., 2009). Future work would also benefit from using more objective measures which were not available to us during the pandemic.

Regarding the effects of physical activity, our findings are in line with recent work with late middle-aged adults showing that those who regularly engage in moderate intensity physical activity demonstrate better working performance than those who only engaged in irregular or low-intensity activities (Chen et al., 2019). Further, several studies show that physical activity helps to preserve grey and white matter volume in older adults (Koblinsky et al., 2021; Strömmer et al., 2020). Additionally, research also demonstrates that larger volume and higher activation in prefrontal and hippocampal regions are associated with the effects of physical activity on cognitive performance (e.g., executive functions and memory; (Erickson et al., 2011; Stillman et al., 2016). Thus, a growing body of literature suggests that physical activity is beneficially associated with brain and cognitive health.

As predicted, we found that subjective sleep quality mediated the effects of physical activity on working memory. Although our analysis does not allow us to infer causality, several studies have shown that physical activity interventions promote better sleep quality (Dolezal et al., 2017). Moreover, the mediating effect of sleep quality in the relationship between physical activity and cognitive function has been show previously (Li et al., 2021; Wilckens et al., 2018). The current results lend further support to the idea that physical activity may benefit cognitive performance via improved sleep quality (though again, our results are correlational here). Physical activity has been shown to promote both acute and chronic benefits to sleep quality via endocrinological, metabolic, and autonomic changes (Uchida et al., 2012). Furthermore, physical activity has been shown to benefit sleep quality in both young and old populations (Wang and Boros, 2021).

In our study, we observed no effect of physical activity and subjective sleep quality on our measure of associative memory. Although physical activity and sleep quality have been positively related to episodic memory in aging there are inconsistencies across studies (Dzierzewski et al., 2018; Engeroff et al., 2018; Mander et al., 2017). The effects of sleep on cognition tend to be more consistent in young and middle-aged adults and age may be a modifier of this association (Scullin and Bliwise, 2015). Further, the effects of physical activity varied depending on the nature, intensity, and frequency of the activity (Engeroff et al., 2018). Another potential reason for the lack of an association in our study is the fact that older adults who participate in online platforms (like Prolific) have been shown to be quite high performing relative to in-lab samples (Merz et al., 2020). If we had a more representative sample, we would presumably have more individual variability in associative memory performance and be better able to detect a relationship to other variables (such as physical activity and sleep). Finally, as discussed further below, stress and sleep disturbances caused by the COVID-19 pandemic may have affected the relationship between these factors.

We explored the impact of the COVID-19 pandemic on participants' self-reported levels of stress, anxiety, depression, and sleep quality. Overall, some participants reported that the pandemic was having a negative effect on their sleep and mental health, though interestingly, the percent of participants reporting these negative outcomes declined with age. This is in line with some other recent studies which have shown that older adults, despite being at greater physical risk, seemed to be relatively resilient to the effects of the pandemic on measures of stress and anxiety (Birditt et al., 2021; Fields et al., 2021; Wilson et al., 2021). Further, our results indicated that self-reported poor sleep, stress, anxiety and depression related to the pandemic were associated with poorer performance on all of our cognitive measures, worse sleep quality on the PSQI, and poorer mental health scores on the HADS. Interestingly, greater levels of physical activity related to lower levels of pandemic-related stress and sleep disturbances, suggesting a protective role of physical activity.

The negative impact of the COVID-19 pandemic on subjective sleep quality and mental health has also been consistently reported (Jahrami et al., 2021). The prevalence and burden of depressive and anxiety disorders have drastically increased globally in the general population (Santomauro et al., 2021). The positive effects of physical exercise on mental health and well-being during the pandemic have also been observed by other researchers, with greater physical activity associated with enhanced happiness, and reduced anxiety, sadness, and depression (Ai et al., 2021). The older population that remained physically active during the pandemic also reported better mental health conditions (Callow et al., 2020). Taken together, our results contribute to the growing literature showing that the COVID-19 pandemic has substantially affected subjective sleep quality and well-being worldwide, and that remaining physically active during the COVID-19 pandemic may have helped alleviate some of the negative mental health effects that the population has experienced during the pandemic.

FINAL CONSIDERATIONS

In this study we showed that self-reported measures of sleep and physical activity are associated with cognitive functioning in middle- and older age. However, this study is not without limitations. First, we recognize that our cross-sectional, correlational design is not ideal for capturing the effects of causality; thus, our results should be interpreted with caution. Additionally, our investigation of pandemic-related effects relies on data collected during the pandemic exclusively, with no equivalent control sample obtained before or after the pandemic. Therefore, our observations in that regard should also be interpreted with caution. Online surveys and cognitive tasks may not yield the best quality data (e.g., due to lack of attention, "professional" participants who take part in many online studies, etc.). Further, we had to rely on self-report measures of sleep quality and physical activity, which may be less accurate that objective measures taken in person (Landry et al., 2015; Wright, 2005). In our sample we observed a ceiling effect in the OSPAN task. Despite appropriate logarithm transformation being applied to reduce the skewness of the data, further replication of our results using a more challenging version of the task is required. Additionally, some of the observed correlations between metrics used in our study could have been caused by shared method variance instead of genuine association between variables (e.g., our measures of sleep quality and self-perceptions of memory both rely on subjective, self-report questionnaires). Despite these limitations, the current results suggest a link between physical activity, sleep, and cognition in middle-aged and older adults that should be followed up with an in-person, intervention-style study.

As age-related neurodegenerative diseases become more prevalent, multidomain lifestyle interventions could be considered a cost-effective strategy to delay and/or prevent cognitive impairment in older individuals. Future translational studies should evaluate the effects of lifestyle interventions by integrating longitudinal research with clinical services (e.g., Cognitive Behavioral Therapy for insomnia, fitness training programs, etc.) to not only generate scientific knowledge but also to have a positive impact on society and people's lives.

ACKNOWLEDGEMENTS

Tiago Guardia was supported by an Ontario Trillium Scholarship; M. Karl Healey by The National Science Foundation under Grant 1848972; and Karen L. Campbell by the Natural Sciences and Engineering Research Council of Canada (Grant RGPIN-2017-03804) and the.

AUTHOR CONTRIBUTIONS

All the authors contributed equally to the work.

COMPETING INTERESTS

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding authors.

PRE-REGISTRATION

This study was not pre-registered.

REFERENCES

Ai, X., Yang, J., Lin, Z., Wan, X., 2021. Mental Health and the Role of Physical Activity During the COVID-19 Pandemic. Front Psychol 12, 4596.

Bah, T.M., Goodman, J., Iliff, J.J., 2019. Sleep as a Therapeutic Target in the Aging Brain. Neurotherapeutics. https://doi.org/10.1007/s13311-019-00769-6

Baughn, M., Grimes, A., Kachadoorian, C., 2022. Changes to Physical Activity Levels in Adults Aged 50+ in the First Six Months of the COVID-19 Pandemic. Gerontol Geriatr Med 8. https://doi.org/10.1177/23337214221106848

Benjamini, Y., Hochberg, Y., 1995. Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing. Journal of the Royal Statistical Society. Series B (Methodological) 57, 289–300.

Birditt, K.S., Turkelson, A., Fingerman, K.L., Polenick, C.A., Oya, A., 2021. Age Differences in Stress, Life Changes, and Social Ties During the COVID-19 Pandemic: Implications for Psychological Well-Being. Gerontologist 61, 205–216. https://doi.org/10.1093/geront/gnaa204

Bullock, A., Kovacevic, A., Kuhn, T., Heisz, J.J., 2020. Optimizing Sleep in Older Adults: Where Does High-Intensity Interval Training Fit? Front Psychol 11. https://doi.org/10.3389/fpsyg.2020.576316

Buysse, D.J., Reynolds, C.F., Monk, T.H., Berman, S.R., Kupfer, D.J., 1989. The Pittsburgh sleep quality index: A new instrument for psychiatric practice and research. Psychiatry Res 28, 193–213. https://doi.org/https://doi.org/10.1016/0165-1781(89)90047-4

Callow, D.D., Arnold-Nedimala, N.A., Jordan, L.S., Pena, G.S., Won, J., Woodard, J.L., Smith, J.C., 2020. The Mental Health Benefits of Physical Activity in Older Adults Survive the COVID-19 Pandemic. American Journal of Geriatric Psychiatry 28, 1046–1057. https://doi.org/10.1016/j.jagp.2020.06.024

Chen, F.-T., Chen, Y.-P., Schneider, S., Kao, S.-C., Huang, C.-M., Chang, Y.-K., 2019. Effects of Exercise Modes on Neural Processing of Working Memory in Late Middle-Aged Adults: An fMRI Study. Front Aging Neurosci 11, 224.

Del Brutto, O.H., Mera, R.M., Costa, A.F., Recalde, B.Y., Castillo, P.R., 2021. Sleep quality deterioration in middle-aged and older adults living in a rural Ecuadorian village severely struck by the SARS-CoV-2 pandemic. A population-based longitudinal prospective study. Sleep 44. https://doi.org/10.1093/sleep/zsab041

Dokić, R., Koso-Drljević, M., Apo, N., 2018. Working memory span tasks: Group administration and omitting accuracy criterion do not change metric characteristics. PLoS One 13. https://doi.org/10.1371/journal.pone.0205169

Dolezal, B.A., Neufeld, E. V, Boland, D.M., Martin, J.L., Cooper, C.B., 2017. Interrelationship between Sleep and Exercise: A Systematic Review. Adv Prev Med 2017, 1364387. https://doi.org/10.1155/2017/1364387

Dzierzewski, J.M., Dautovich, N., Ravyts, S., 2018. Sleep and Cognition in Older Adults. Sleep Med Clin. https://doi.org/10.1016/j.jsmc.2017.09.009

Engeroff, T., Ingmann, T., Banzer, W., 2018. Physical Activity Throughout the Adult Life Span and Domain-Specific Cognitive Function in Old Age: A Systematic Review of Cross-Sectional and Longitudinal Data. Sports Medicine. https://doi.org/10.1007/s40279-018-0920-6

Erickson, K.I., W, V.M., Shaurya, P.R., Chandramallika, B., Amanda, S., Laura, C., S, K.J., Susie, H., Heloisa, A., M, W.S., R, W.T., Emily, M., J, V.V., A, M.S., D, P.B., A, W.J., Edward, M., F, K.A., 2011. Exercise training increases size of hippocampus and improves memory. Proceedings of the National Academy of Sciences 108, 3017–3022. https://doi.org/10.1073/pnas.1015950108

Fields, E.C., Kensinger, E.A., Garcia, S.M., Ford, J.H., Cunningham, T.J., 2021. With age comes well-being: older age associated with lower stress, negative affect, and depression throughout the COVID-19 pandemic. Aging Ment Health. https://doi.org/10.1080/13607863.2021.2010183

Gomes-Osman, J., Cabral, D.F., Morris, T.P., McInerney, K., Cahalin, L.P., Rundek, T., Oliveira, A., Pascual-Leone, A., 2018. Exercise for cognitive brain health in aging: A systematic review for an evaluation of dose. Neurol Clin Pract 8, 257–265. https://doi.org/10.1212/CPJ.0000000000000460

Hair, J.F., Black, W.C., Babin, B.J., Anderson, R.E., 2014. Multivariate data analysis. Pearson Education Limited.

Jahrami, H., BaHammam, A.S., Bragazzi, N.L., Saif, Z., Faris, M., Vitiello, M. V., 2021. Sleep problems during the COVID-19 pandemic by population: A systematic review and meta-analysis. Journal of Clinical Sleep Medicine. https://doi.org/10.5664/JCSM.8930

Klaming, R., Annese, J., Veltman, D.J., Comijs, H.C., 2017. Episodic memory function is affected by lifestyle factors: a 14-year follow-up study in an elderly population. Aging, Neuropsychology, and Cognition 24, 528–542. https://doi.org/10.1080/13825585.2016.1226746

Koblinsky, N.D., Meusel, L.-A.C., Greenwood, C.E., Anderson, N.D., 2021. Household physical activity is positively associated with gray matter volume in older adults. BMC Geriatr 21, 104. https://doi.org/10.1186/s12877-021-02054-8

Landry, G.J., Best, J.R., Liu-Ambrose, T., 2015. Measuring sleep quality in older adults: A comparison using subjective and objective methods. Front Aging Neurosci 7. https://doi.org/10.3389/fnagi.2015.00166

Larson, E.A., Bader-Larsen, K.S., Magkos, F., 2021. The Effect of COVID-19-related Lockdowns on Diet and Physical Activity in Older Adults: A Systematic Review. Aging Dis. https://doi.org/10.14336/AD.2021.0606

Li, J., Vitiello, M. V., Gooneratne, N.S., 2018. Sleep in Normal Aging. Sleep Med Clin. https://doi.org/10.1016/j.jsmc.2017.09.001

Li, L., Yu, Q., Zhao, W., Herold, F., Cheval, B., Kong, Z., Li, J., Mueller, N., Kramer, A.F., Cui, J., Pan, H., Zhan, Z., Hui, M., Zou, L., 2021. Physical Activity and Inhibitory Control: The Mediating Role of Sleep Quality and Sleep Efficiency. Brain Sci 11, 664. https://doi.org/10.3390/brainsci11050664

Mander, Winer, J.R., Walker, M.P., 2017. Sleep and Human Aging. Neuron 94, 19–36. https://doi.org/10.1016/j.neuron.2017.02.004

Merz, Z.C., Lace, J.W., Eisenstein, A.M., 2020. Examining broad intellectual abilities obtained within an mTurk internet sample. Current Psychology. https://doi.org/10.1007/s12144-020-00741-0

Morrison, L., McDonough, M., Won, S., Matsune, A.J., Hewson, J., 2022. Older Adults' Physical Activity and Social Participation During COVID-19. Act Adapt Aging 46, 320–342. https://doi.org/10.1080/01924788.2022.2094658

Oliveira, M.R., Sudati, I.P., Konzen, V.D.M., de Campos, A.C., Wibelinger, L.M., Correa, C., Miguel, F.M., Silva, R.N., Borghi-Silva, A., 2022. Covid-19 and the impact on the physical activity level of elderly people: A systematic review. Exp Gerontol. https://doi.org/10.1016/j.exger.2021.111675

Oswald, F.L., McAbee, S.T., Redick, T.S., Hambrick, D.Z., 2014. The development of a short domain-general measure of working memory capacity. Behav Res Methods 47, 1343–1355. https://doi.org/10.3758/s13428-014-0543-2

Park, A.H., Zhong, S., Yang, H., Jeong, J., Lee, C., 2022. Impact of COVID-19 on physical activity: A rapid review. J Glob Health 12. https://doi.org/10.7189/JOGH.12.05003

Quigley, A., MacKay-Lyons, M., Eskes, G., 2020. Effects of Exercise on Cognitive Performance in Older Adults: A Narrative Review of the Evidence, Possible Biological Mechanisms, and Recommendations for Exercise Prescription. J Aging Res 2020, 1407896. https://doi.org/10.1155/2020/1407896

Rosenberg, A., Mangialasche, F., Ngandu, T., Solomon, A., Kivipelto, M., 2020. Multidomain Interventions to Prevent Cognitive Impairment, Alzheimer's Disease, and Dementia: From FINGER to World-Wide FINGERS. Journal of Prevention of Alzheimer's Disease 7, 29–36. https://doi.org/10.14283/jpad.2019.41

Santomauro, D.F., Mantilla Herrera, A.M., Shadid, J., Zheng, P., Ashbaugh, C., Pigott, D.M., Abbafati, C., Adolph, C., Amlag, J.O., Aravkin, A.Y., Bang-Jensen, B.L., Bertolacci, G.J., Bloom, S.S., Castellano, R., Castro, E., Chakrabarti, S., Chattopadhyay, J., Cogen, R.M., Collins, J.K., Dai, X., Dangel, W.J., Dapper, C., Deen, A., Erickson, M., Ewald, S.B., Flaxman, A.D., Frostad, J.J., Fullman, N., Giles, J.R., Giref, A.Z., Guo, G., He, J., Helak, M., Hulland, E.N., Idrisov, B., Lindstrom, A., Linebarger, E., Lotufo, P.A., Lozano, R., Magistro, B., Malta, D.C., Månsson, J.C., Marinho, F., Mokdad, A.H., Monasta, L., Naik, P., Nomura, S., O'Halloran, J.K., Ostroff, S.M., Pasovic, M., Penberthy, L., Reiner Jr, R.C., Reinke, G., Ribeiro, A.L.P., Sholokhov, A., Sorensen, R.J.D., Varavikova, E., Vo, A.T., Walcott, R., Watson, S., Wiysonge, C.S., Zigler, B., Hay, S.I., Vos, T., Murray, C.J.L., Whiteford, H.A., Ferrari, A.J., 2021. Global prevalence and burden of depressive and anxiety disorders in 204 countries and territories in 2020 due to the COVID-19 pandemic. The Lancet 398, 1700–1712. https://doi.org/10.1016/s0140-6736(21)02143-7

Scorpio, K.A., Islam, R., Kim, S.M., Bind, R., Borod, J.C., Bender, H.A., 2018. Paired-Associate Learning, in: Kreutzer, J.S., DeLuca, J., Caplan, B. (Eds.), Encyclopedia of Clinical Neuropsychology. Springer International Publishing, Cham, pp. 2554–2558. https://doi.org/10.1007/978-3-319-57111-9_1137

Scullin, M.K., Bliwise, D.L., 2015. Sleep, cognition, and normal aging: integrating a half century of multidisciplinary research. Perspect Psychol Sci 10, 97–137. https://doi.org/10.1177/1745691614556680

Snaith, R.P., 2003. The Hospital Anxiety And Depression Scale. Health Qual Life Outcomes 1, 29. https://doi.org/10.1186/1477-7525-1-29

Stern, A.F., 2014. The Hospital Anxiety and Depression Scale. Occup Med (Chic Ill). https://doi.org/10.1093/occmed/kqu024

Stillman, C.M., Cohen, J., Lehman, M.E., Erickson, K.I., 2016. Mediators of Physical Activity on Neurocognitive Function: A Review at Multiple Levels of Analysis. Front Hum Neurosci 10, 626. https://doi.org/10.3389/fnhum.2016.00626

Stillman, C.M., Esteban-Cornejo, I., Brown, B., Bender, C.M., Erickson, K.I., 2020. Effects of Exercise on Brain and Cognition Across Age Groups and Health States. Trends Neurosci 43, 533–543. https://doi.org/https://doi.org/10.1016/j.tins.2020.04.010

Stockwell, S., Trott, M., Tully, M., Shin, J., Barnett, Y., Butler, L., McDermott, D., Schuch, F., Smith, L., 2021. Changes in physical activity and sedentary behaviours from before to during the COVID-19 pandemic lockdown: a systematic review. BMJ Open Sport & Exercise Medicine 7, e000960. https://doi.org/10.1136/bmjsem-2020-000960

Strömmer, J.M., Davis, S.W., Henson, R.N., Tyler, L.K., Cam-CAN, Campbell, K.L., 2020. Physical Activity Predicts Population-Level Age-Related Differences in Frontal White Matter. The Journals of Gerontology: Series A 75, 236–243. https://doi.org/10.1093/gerona/gly220

Swenson, D.X., Henkel-Johnson, G., 2003. A College Community's Vicarious Stress Reaction to September 11th Terrorism. Traumatology (Tallahass Fla) 9, 93–105. https://doi.org/10.1177/153476560300900203

Toman, J., Klímová, B., Vališ, M., 2018. Multidomain lifestyle intervention strategies for the delay of cognitive impairment in healthy aging. Nutrients. https://doi.org/10.3390/nu10101560

Topolski, T.D., LoGerfo, J., Patrick, D.L., Williams, B., Walwick, J., Marsha Patrick, M.B., 2006. The Rapid Assessment of Physical Activity (RAPA) Among Older Adults. Preventing Chronic Disease .

Troyer, A.K., Rich, J.B., 2002. Psychometric Properties of a New Metamemory Questionnaire for Older Adults. The Journals of Gerontology: Series B 57, P19–P27. https://doi.org/10.1093/geronb/57.1.P19

Uchida, S., Shioda, K., Morita, Y., Kubota, C., Ganeko, M., Takeda, N., 2012. Exercise Effects on Sleep Physiology. Front Neurol 3, 48. https://doi.org/10.3389/fneur.2012.00048

Unsworth, N., Heitz, R.P., Schrock, J.C., Engle, R.W., 2005. An automated version of the operation span task. Behav Res Methods 37, 498–505. https://doi.org/10.3758/BF03192720

Uttl, B., Graf, P., Richter, L.K., 2002. Verbal Paired Associates tests limits on validity and reliability. Archives of Clinical Neuropsychology 17, 567–581. https://doi.org/https://doi.org/10.1016/S0887-6177(01)00135-4

Visser, M., Schaap, L.A., Wijnhoven, H.A.H., 2020. Self-reported impact of the covid-19 pandemic on nutrition and physical activity behaviour in dutch older adults living independently. Nutrients 12, 1–11. https://doi.org/10.3390/nu12123708

Wang, F., Boros, S., 2021. The effect of physical activity on sleep quality: a systematic review. Eur J Physiother 23, 11–18. https://doi.org/10.1080/21679169.2019.1623314

West, R.M., 2022. Best practice in statistics: The use of log transformation. Ann Clin Biochem 59, 162–165. https://doi.org/10.1177/00045632211050531

Wilckens, K.A., Erickson, K.I., Wheeler, M.E., 2018. Physical Activity and Cognition: A Mediating Role of Efficient Sleep. Behavioral sleep medicine 16, 569–586. https://doi.org/10.1080/15402002.2016.1253013

Wilke, J., Rahlf, A.L., Füzéki, E., Groneberg, D.A., Hespanhol, L., Mai, P., de Oliveira, G.M., Robbin, J., Tan, B., Willwacher, S., Hollander, K., Pillay, J.D., 2022. Physical Activity During Lockdowns Associated with the COVID-19 Pandemic: A Systematic Review and Multilevel Meta-analysis of 173 Studies with 320,636 Participants. Sports Med Open 8, 125. https://doi.org/10.1186/s40798-022-00515-x

Wilson, J.M., Lee, J., Shook, N.J., 2021. COVID-19 worries and mental health: the moderating effect of age. Aging Ment Health 25, 1289–1296. https://doi.org/10.1080/13607863.2020.1856778

Wright, K.B., 2005. Researching Internet-Based Populations: Advantages and Disadvantages of Online Survey Research, Online Questionnaire Authoring Software Packages, and Web Survey Services. Journal of Computer-Mediated Communication 10, JCMC1034. https://doi.org/10.1111/j.1083-6101.2005.tb00259.x

Wright, K.P., Lowry, C.A., leBourgeois, M.K., 2012. Circadian and wakefulness-sleep modulation of cognition in humans. Front Mol Neurosci. https://doi.org/10.3389/fnmol.2012.00050

Yaffe, K., Falvey, C., Hoang, T., 2014. Connections between sleep and cognition in older adults. Lancet Neurol 13, 1017–1028. https://doi.org/10.1016/S1474-4422(14)70172-3

Young, J., Angevaren, M., Rusted, J., Tabet, N., 2015. Aerobic exercise to improve cognitive function in older people without known cognitive impairment. Cochrane Database of Systematic Reviews. https://doi.org/10.1002/14651858.CD005381.pub4

Zhidong, C., Wang, X., Yin, J., Song, D., Chen, Z., 2021. Effects of physical exercise on working memory in older adults: a systematic and meta-analytic review. European Review of Aging and Physical Activity. https://doi.org/10.1186/s11556-021-00272-y

Zilli, I., Ficca, G., Salzarulo, P., 2009. Factors involved in sleep satisfaction in the elderly. Sleep Med 10, 233–239. https://doi.org/https://doi.org/10.1016/j.sleep.2008.01.004

Zotcheva, E., Håberg, A.K., Wisløff, U., Salvesen, Ø., Selbæk, G., Stensvold, D., Ernstsen, L., 2022. Effects of 5 Years Aerobic Exercise on Cognition in Older Adults: The Generation 100 Study: A Randomized Controlled Trial. Sports Medicine 52, 1689–1699. https://doi.org/10.1007/s40279-021-01608-5

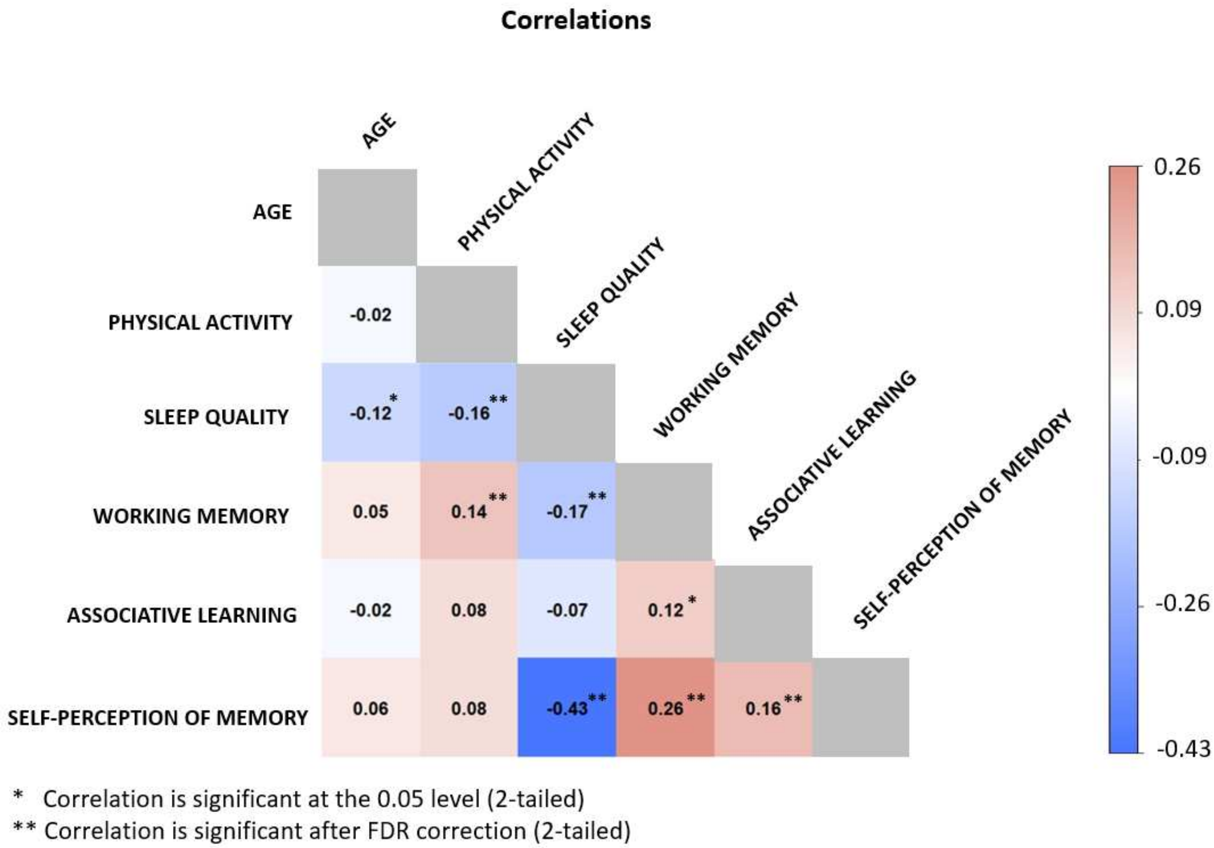

Figure 1 – Pearson's correlation coefficients between variables of interest. Physical activity = RAPA Aerobic Score; Sleep Quality = PSQI Global Score (higher scores reflect greater sleep dysfunction); Working Memory = OSPAN Score; Associative Learning – Composite PAL score; Self-perception of memory = MMQ Score-Ability

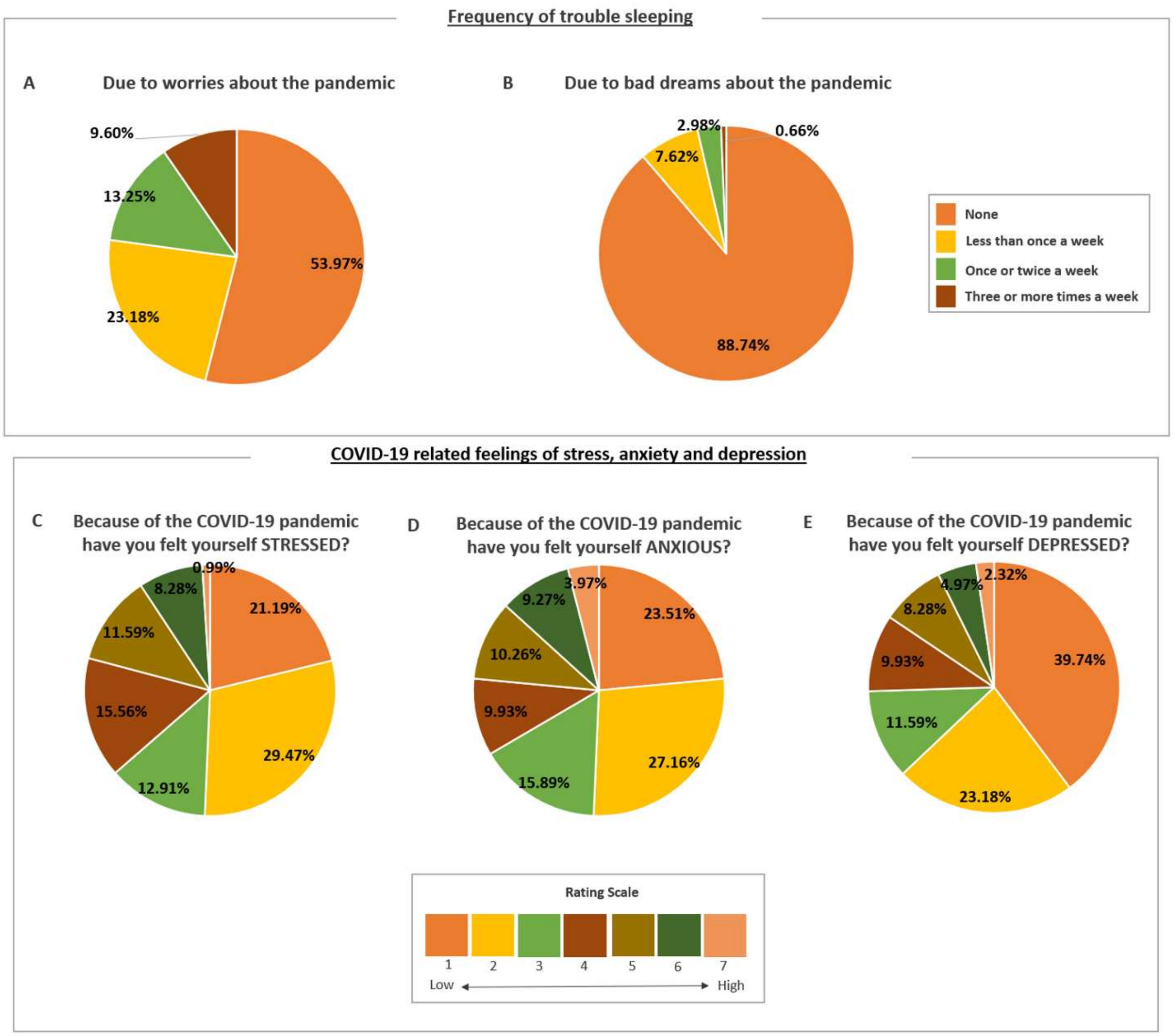

Figure 2 – Frequency of trouble sleeping & Covid related feelings of stress, anxiety, and depression in the whole sample (see Supplementary Figure S2 for the proportions in different age groups). Upper panel: Percentage of participants reporting that they were having trouble sleeping because of A) Worries about the pandemic and B) Bad dreams about the pandemic. Lower panel: Percentage of participants reporting each level of C) Stress, D) Anxiety, and E) Depression related to the pandemic.

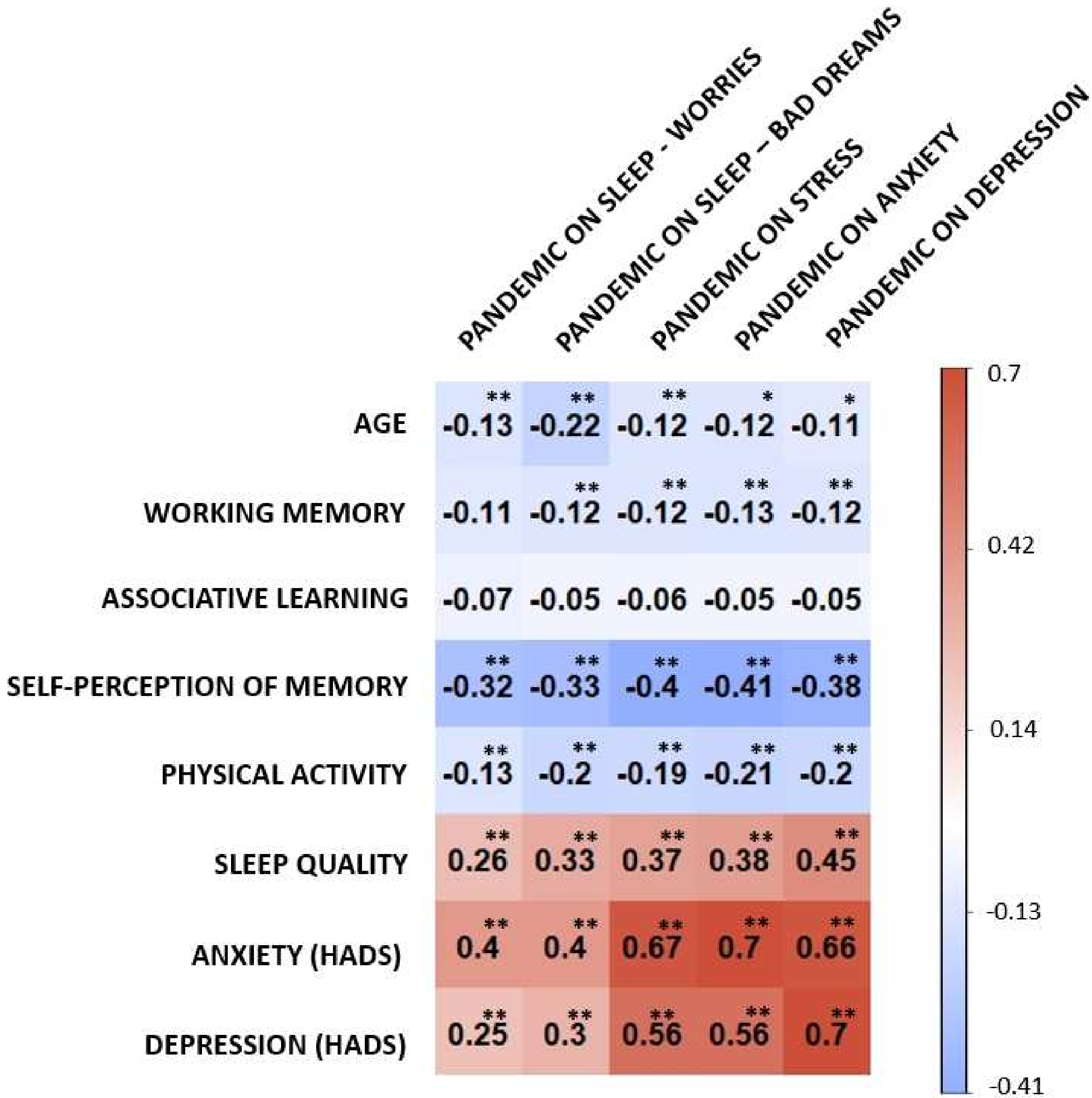

Figure 3 – Pearson's correlation coefficients between variables of interest and impact of COVID-19 pandemic scores. Physical activity = RAPA Aerobic Score; Sleep Quality = PSQI Global Score (higher scores reflect greater sleep dysfunction); Working Memory = OSPAN Score; Associative Memory – Composite score of PAL1 and PAL2; Self-perception of memory = MMQ Score-Ability; HADS = Hospital Anxiety and Depression Scale.

Table 1 - Participant demographics

Age group	1	2	3	All
n	100	101	101	302
Age range (years)	45-54	55-64	65-75	45-75
Age average	49.7 (2.6)	59.2 (3.0)	68.3 (3.3)	59.2 (8.3)
Sex (male/female)	50/50	50/51	50/51	150/152
Highest education				
Master's / Doctorate	12	16	16	44
Bachelor's Degree	44	36	30	110
High school or equivalent	40	42	50	132
Less than High school	4	7	5	16
Retired (no/yes) *	93/6	69/30	15/86	177/122

Note. Participants are divided into age groups for descriptive purposes, but all analyses used age as a continuous variable. **Retired data missing for three participants.*

Table 2 – Mean (SD) physical activity, sleep quality, and cognitive scores

Age group	1 (45-54)	2 (55-64)	3 (65-75)	All
Physical Activity Score (RAPA aerobic)	4.13 (1.77)	4.17 (1.72)	4.08 (1.59)	4.13 (1.69)
Sleep Quality Score (PSQI Global Score)	6.85 (4.04)	6.04 (3.72)	6.00 (3.26)	6.29 (3.69)
PSQI Median	6	5	5	6
PSQI % below 6 / 6 and above (i.e., with poor sleep)	43% / 57%	50.5% / 49.5%	50.5% / 49.5%	48% / 52%
Cognitive Scores				
Working Memory - OSPAN	40.16 (10.39)	42.88 (7.32)	41.37 (9.35)	41.47 (9.14)
Working Memory – OSPAN - Log10	-0.82 (0.47)	-0.73 (0.43)	- 0.79 (0.44)	-0.781 (0.44)
Episodic Memory - PAL1	4.99 (3.37)	4.99 (3.25)	5.05 (3.24)	5.01 (3.28)
Episodic Memory - PAL2	7.01 (3.82)	6.65 (3.56)	7.47 (3.43)	7.04 (3.61)
Episodic Memory - PAL3	8.64 (3.86)	8.27 (3.62)	8.40 (3.37)	8.43 (3.61)
Episodic Memory - PAL Composite Score	0.01 (0.99)	-0.06 (0.93)	0.07 (0.90)	0.00 (0.94)
Self-perception of memory - MMQ-Ability (Raw Score)	57.39 (15.30)	61.40 (12.03)	59.26 (10.06)	59.35 (12.70)

Note: Standard deviations are provided in parentheses. PSQI = Pittsburgh Sleep Quality Index. PSQI Global Score (higher scores reflect greater sleep dysfunction).

Table 3: Regression models predicting our three memory measures from age, physical activity, and sleep

Model	Outcome	Predictors	Coefficients							
			Unstandardized Coefficients			Standardized Coefficients	t	Sig.	95.0% CI	
			B	Exp(B)	Std. Error	Beta			L	U
1	Working Memory	Age	0.00	1.00	0.00	-0.01	-0.20	0.840	-0.01	0.01
		Physical Activity	0.03	1.03	0.02	0.13	2.13	0.034	0.00	0.06
		Sleep Quality (PSQI)	-0.02	0.98	0.01	-0.15	-2.65	0.009	-0.03	-0.01
		Education	0.00	1.00	0.03	0.01	0.11	0.913	-0.06	0.07
		Sex	0.07	1.07	0.05	0.07	1.28	0.203	-0.04	0.17
2	Associative Memory	Age	0.00		0.01	-0.02	-0.35	0.726	-0.01	0.01
		Physical Activity	0.04		0.03	0.08	1.35	0.177	-0.02	0.10
		Sleep Quality (PSQI)	-0.02		0.01	-0.09	-1.62	0.107	-0.05	0.01
		Education	0.17		0.07	0.14	2.52	0.012	0.04	0.29
		Sex	0.56		0.10	0.30	5.46	<0.001	0.36	0.77
3	Self-Perception of Memory	Age	0.02		0.08	0.13	0.24	0.813	-0.14	0.18
		Physical Activity	0.01		0.41	0.00	0.03	0.975	-0.79	0.82
		Sleep Quality (PSQI)	-1.45		0.19	-0.42	-7.85	0.000	-1.82	-1.09
		Education	0.15		0.86	0.01	0.18	0.858	-1.53	1.84
		Sex	-0.80		1.35	-0.03	-0.59	0.553	-3.47	1.86

Note: The working memory outcome variable was log transformed prior to analysis. For ease of interpretation, we also report the exponentiated regression coefficients (exp[B]) for the working memory analysis. Thus, for every one-unit increase in physical activity, our dependent variable (working memory) is multiplied by a factor of 1.03 (i.e., we see a 3% increase in working memory). For every one-unit increase in Pittsburg Sleep Quality Index (PSQI) score (recall that higher scores reflect worse sleep), working memory is multiplied by a factor of 0.98 (i.e., we see a 2% decrease in working memory).