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Reduction in physical activity during Covid-19 lockdowns predicts individual differences in cognitive performance several months after the end of the safety measures

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ABSTRACT

Prior studies suggest that the reductions in physical activity during Covid-19-related lockdowns impacted physical and mental health. Whether reductions in physical activity that occurred during lockdowns also relate to cognitive functions such as memory and attention is less explored. Here, we investigated whether changes in physical activity (PA) that occurred during and following Covid-19-related lockdowns could predict a variety of measures of cognitive performance in 318 young adults. Participants were assessed on their engagement in PA before, during, and after lockdowns. They also completed tests of cognitive control, working memory, and short-term memory following lockdown(s). As expected, engagement in PA decreased during lockdown and returned to near baseline levels thereafter. Decreases in PA during lockdown predicted individual differences in cognitive performance following lockdown. Greater reductions in PA during lockdown were associated with lower scores on the go/no-go task, a measure of cognitive control ability, and the n-back task, a measure of working memory performance. Larger post-lockdown increases in PA were associated with higher scores on the same tasks. Individual differences in pandemic-related stress and insomnia also predicted cognitive outcomes. These findings suggest that reductions of PA can predict cognitive performance, and underscore the importance of maintaining PA for cognitive health, especially in situations such as lockdowns.

1. Introduction

Physical activity has been defined as bodily movement produced by skeletal muscles that results in energy expenditure (Caspersen et al., 1985). Evidence pointing toward the positive effects of PA on general health has accumulated for decades (Blair & Brodney, 1999; Marquez et al., 2020; Warburton et al., 2006) and the WHO recommends that individuals engage in PA on a regular basis (WHO, 2010). Importantly, PA plays a major role in the prevention of chronic disease by opposing obesity (Anderson & Durstine, 2019; Booth et al., 2012; Celik & Yildiz, 2021). In fact, overweight and obese conditions are emerging as global epidemics. They affect not only adults but also increasingly children and adolescents (Shirvani Shiri et al., 2023). These conditions are significant risk factors for a range of morbidities (Aghili et al., 2021; Pi-Sunyer, 2009). Among the most concerning health implications are the heightened risks of cardiovascular disease (Elagizi et al., 2020; Lavie et al., 2019), type 2 diabetes (Boutari et al., 2023), cancer (Pati et al., 2023), hypertension (El Meouchy et al., 2022), osteoporosis (Gkastaris et al., 2020), and osteoarthritis (Oliveira et al., 2020). The cumulative impact of obesity and related chronic diseases substantially diminishes the quality of life and can lead to premature mortality (Abdelaal et al., 2017). Additionally, there is longstanding evidence linking insufficient levels of PA to adverse mental health outcomes (Weyerer & Kupfer, 1994), including anxiety (Kandola et al., 2018) and depression (Ströhle,

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2009).

Of particular relevance to the current study, PA is considered a gene modulator capable of inducing positive changes in the brain structure and function. These structural changes are connected with neuroplasticity, i.e. with changes of the brain on the cellular and the molecular level. PA is related with higher brain volumes and their neural efficiency, especially if performed as physical exercise (PE) (Mandolesi et al., 2018). The latter has been described as planned, structured, repetitive, and has as a final or an intermediate objective the improvement or maintenance of one or more components of physical fitness" (WHO, 2010). Both PA and PE trigger the release of brain-derived neurotropic factor (BDNF). This neurotrophin supports the growth of neurons, enhances the growth of dendrites, the density of spines and consequently of synapses (Mrówczyński, 2019; Sleiman et al., 2016). BDNF further impacts the voluminal growth of two key memory structures, the hippocampus (Killgore et al., 2013) and the entorhinal cortex (Whiteman et al., 2016), in which the neurotrophin is highly expressed. As a consequence, BDNF plays a major role in memory performance (Miranda et al., 2019). A number of studies show that higher levels of exercise and cardiorespiratory fitness are associated with improved hippocampal structure and function (Hendrikse et al., 2022; Voss et al., 2019). Also the viscoelasticity of the hippocampus, a measure determining its memory performance is connected with PA (Schwarb et al., 2017).

Exercise also stimulates neurogenesis (Ben-Zeev et al., 2022), a self-regeneration mechanism of the brain. Starting from the hippocampus, neural stem cells migrate to other brain areas where they differentiate and integrate within pre-existing cell assemblies. Neurogenesis is a major factor related to grey matter density (Augusto-Oliveira et al., 2023). Relevant to our investigation are the orbitofrontal cortex, the dorsolateral prefrontal cortex (Friedman & Robbins, 2022) and the anterior cingulate cortex are connected with better cognitive control (Menon & D'Esposito, 2022): these regions mediate executive functions among which is attention. Altogether, PA impacts cognitive functions (Mitchell et al., 2023; van Praag, 2009), specifically memory (Erickson et al., 2011b) and attention (de Sousa et al., 2019). For reviews, please see Erickson et al. (2019) and Sewell et al. (2021).

In December 2019, an acute respiratory syndrome emerged in China, initially named SARS-CoV-2. It was later reclassified as Covid-19, an acronym for Corona Virus Disease 19 (Zou et al., 2020). The rapid spread and severity of this illness led to its characterization as a global pandemic. To curb infections and hospitalizations, governments worldwide implemented unprecedented safety measures, including lockdowns and social distancing. These measures varied in intensity across different countries, but uniformly led to widespread closures of schools, pauses in business activities, and significant alterations in public life. The restrictions, while necessary for public health, instigated considerable distress (Di Blasi et al., 2021) and disrupted regular health habits, particularly in nutrition and PA (Rico-Bordera et al., 2023). In Western countries, there was a noticeable shift in dietary patterns toward sweeter, highly-processed foods, and an uptick in alcohol consumption (González-Monroy et al., 2021). Additionally, the enforced social distancing and subsequent weight gain led to a widespread reduction in PA across all demographic groups (Caputo & Reichert, 2020; Wunsch et al., 2022). This reduction in PA was particularly evident among children and adolescents, with decreases ranging between 10.8 and 91 min per day; factors influencing this decline included age, gender, socioeconomic status, and access to outdoor spaces (Rossi et al., 2021). Similarly, adults adhered to government advice, leading to a reduction in their PA levels (Oliveira et al., 2022; Park et al., 2022; Runacres et al., 2021). It is noteworthy that the World Health Organization recommends individuals over 65 to engage in 150 to 300 min of moderate-intensity PA weekly, including functional balance and strength training three times a week (Izquierdo et al., 2021). This recommendation underscores the potential health implications of these lifestyle changes.

1.1. Decline in mental health

The unforeseen mental and physical health repercussions of government-imposed Covid-19 safety measures, particularly on sleep disturbances, have emerged as a significant concern. A comprehensive meta-analysis involving 250 studies and nearly half a million participants from 49 countries revealed a global prevalence of sleep disturbances from March 2020 until July 2021 of approximately 41 %. This issue was more pronounced among Covid-19 patients (46 %) and was also high in children and adolescents (43 %) (Jahrami et al., 2022). Sleep disturbances were higher during lockdown (43 %) compared to times without lockdowns (38 %). Altogether, four in every ten individuals reported a sleep problem during the Covid-19 pandemic, as reported by Jahrami et al. (2022).

The bidirectional relationship between insomnia and psychiatric disorders is well studied (Rosenberg, 2021). Poor sleep can contribute to the occurrence of mental health disorders, and psychiatric conditions often manifest with disrupted sleep patterns. Treating insomnia can mitigate mental health issues and, in some cases, effective sleep management can prevent these problems from developing (Freeman et al., 2020). The pandemic's restrictions led to significant lifestyle changes for various age groups. Children and adolescents, deprived of social interactions and PA, faced a heightened risk of developing psychiatric conditions (Pfefferbaum & Van Horn, 2022). Adults were confronted with job insecurity and financial concerns (Blomqvist et al., 2023) in addition to a lack of social contact and PA. For the elderly, the isolation during this period exacerbated feelings of loneliness, which is linked not only with emotional disturbances like anxiety and anger, but also with increased stress hormone levels and with the potential onset of psychiatric illnesses (Webb & Chen, 2022).

Anxiety rates notably increased during the pandemic. A meta-analysis summarizing 29 studies with over 80,000 children and adolescents worldwide indicated a doubling of anxiety rates compared to pre-pandemic levels, with an estimated 21 % of this group affected by anxiety symptoms (Racine et al., 2021). A study including over 57,000 adults living in England found a correlation between strict policy measures and heightened anxiety. This study, which employed the Generalized Anxiety Disorder assessment (Spitzer et al., 2006), highlighted the influence of both contextual (e.g., stringency index of the policy, Covid-19 cases) and individual factors (e.g., Covid-19 knowledge and social support) on anxiety levels (Bu et al., 2023). Similarly, anxiety significantly impacted the elderly, especially those above 60, who exhibited more pronounced emotional responses (Bafail, 2022).

1.2. Decline in cognitive functions

In a review of 62 studies, Manfredini et al. (2023) revealed a general decline in cognitive performance in both healthy individuals and patients with neurological conditions due to Covid-19 lockdown measures. This decline predominantly affected memory, executive functions, and attention. Notably, the lockdown measures expedited cognitive decline, particularly in clinical populations. For patients with pre-existing conditions, such as those attending the Alzheimer Center Amsterdam, pre- and post-lockdown data were available that included assessments such as the Mini-Mental State Examination, Trail Making Test, and Rey-Auditory Verbal Learning Test (RAVLT) of immediate and delayed recall (Bakker et al., 2023). Compared to a matched control group, these patients exhibited accelerated memory decline, particularly in pre-dementia stages. The additional stress from lockdown measures, including loss of routine, loneliness, and depression, were considered contributing factors (Bakker et al., 2023). Similar patterns were observed in individuals with intellectual and developmental disabilities (Braga & Felipe-Castaño, 2022). This study, which included pre- and post-lockdown data, showed a decline in attention, language, and the ability to perform complex tasks (Braga & Felipe-Castaño, 2022).

Bzdok and Dunbar (2020) highlighted the neurocognitive impact of social isolation, linking social deprivation to compromised reasoning and memory performance. A study conducted in Italy with 1215 non-clinical individuals responding to a Qualtrics-based online survey found cognitive functioning severely altered. This decline impacting attention, temporal orientation, and executive functions was due to the seven to ten week lockdown that occurred from April to May 2020 (Fiorenzato et al., 2021). Further studies, including one by Favieri et al. (2021) using a Stroop test and a Go/No-Go task as indicators of executive functions, identified executive deficits across diverse demographics, suggesting isolation as a primary factor (Favieri et al., 2021). Ingram et al. (2021) studied the effects of social isolation across various cognitive domains in a diverse sample. Participants completed tests measuring attention, memory, decision-making, time-estimation, and learning. The authors predicted and found that cognitive performance was lowest under the most isolating conditions, improving with increased social interaction post-lockdown.

The literature's focus on the impact of Covid-19 restrictions on mental health has overshadowed studies on cognitive effects, as noted by Favieri et al. (2021). This disparity might be due to the more immediate and urgent nature of mental health symptoms compared to the gradual onset of cognitive decline. Nevertheless, the long-term impact of reduced cognitive capacities can significantly affect academic achievement, career progression, and overall quality of life. In the most severe cases, a decline in cognitive abilities could impair individuals' capacity to earn a living and support their families over the long term.

It is crucial to recognize that the Covid-19 pandemic and related governmental measures created an extraordinary situation with multiple overlapping factors affecting cognition. These include stress due to social distancing, co-occurrence of health conditions, and psychological and psychiatric issues. These factors collectively contribute to reduced PA and to disentangle them is a challenging task. Additionally, research often does not differentiate between people who contracted Covid-19 and those who did not. Notably, a study involving over 1000 patients found memory, attention and executive impairment as a consequence of the illness (Daroische et al., 2021). Another review highlighted various types of neurological damage caused by Covid-19 (Bhola et al., 2022). The literature examining the cognitive effects of social isolation does not always account for vaccination status, despite some risks of cerebrovascular and neurological disorders associated with vaccines (Hosseini & Askari, 2023), which could contribute to cognitive decline. While the lack of PA due to the closure of gyms and recreational facilities may have impacted cognitive functions, the overall cognitive decline experienced by the population cannot be attributed solely to PA reduction. It may also stem from Covid-19 infection or vaccine effects.

1.3. Lack of physical activity during lockdowns and its possible impact on cognitive functions

In recent years, numerous studies have scrutinized the increase in sedentary lifestyles during home confinements, highlighting a global shift in PA behaviors (see for reviews Rubio-Tomás et al., 2022; Stockwell et al., 2021). These studies, encompassing diverse populations and regions from New Zealand (Hargreaves et al., 2021) to China (Zhou et al., 2021) and European countries (Constandt et al., 2020; Deschasaux-Tanguy et al., 2021; Maugeri et al., 2020; Robinson et al., 2021; Srivastav et al., 2021; Trabelsi et al., 2021), uniformly reveal that people became more sedentary during lockdowns. Despite online offerings for indoor PA, most people did not adequately compensate for reduced physical exercise (Stockwell et al., 2021).

The impact of this diminished PA on both physical health (Bentlage et al., 2020; Kaur et al., 2020; Woods et al., 2020), and mental health (Meyer et al., 2020; Sang et al., 2021) are well-documented. In fact, studies measuring health parameters before lockdowns show a statistical link between reduced physical exercise, body weight changes, and associated eating habits (Bakaloudi et al., 2021; Jimenez et al., 2021). However, unlike body health, measuring the impact of lockdowns on cognitive capacities such as memory is more complex, particularly in healthy populations where baseline data on memory performance was not acquired on a large scale before lockdowns.

Our study aims to explore the potential impact of prolonged inactivity on cognitive functions, particularly memory and attention. Working memory (WM), a core cognitive function, enables us to keep information in mind and to mentally work with it for a certain amount of time. WM is integral to higher-order processes such as language, thinking, and problem solving (Nęcka et al., 2021) and it is linked to academic performance (Bull et al., 2008; Cowan, 2014; Gathercole et al., 2004; Jarrold, 2017; Nutley & Söderqvist, 2017). Working memory capacity (WMC) differs between individuals (D'Esposito & Postle, 2015) and is thought to contribute to human intelligence (Hagemann et al., 2023). The lack of PA adversely affects memory (Vivar et al., 2023).

PA improves cardiorespiratory fitness, which is crucial for maintaining the hippocampus (Knierim, 2015), the brain region primarily responsible for short-term memory (Maguire et al., 2016; Squire, 2004). The hippocampus is particularly vulnerable to early and rapid deterioration, especially in clinical populations (Nauer et al., 2020). Erickson et al. (2011a) suggest that aerobic exercise, a form of PA requiring oxygen, is highly effective in enhancing the hippocampus's structure and function. In humans, regular PA has been shown to prevent age-related hippocampal atrophy and functional decline, especially in older adults (Firth et al., 2018). Moreover, children with higher PA levels exhibit improved hippocampal connectivity, white matter volume, and overall functionality (Valkenborghs et al., 2019). Even moderate-intensity PA can improve cardiovascular health and consequently benefit the hippocampus. Research in rodents demonstrates that PA supports hippocampal angiogenesis, neurogenesis, cell proliferation and survival (van Praag et al., 1999).

WM plays a critical role in multitasking by retaining information for processing and task switching. Multitasking has been defined as the capacity to shift one's focus of attention from one task to another and back whenever necessary (Garner & Dux, 2023). This skill is particularly crucial given our limited attentional resources. In the brain, attention is thought to be managed through a network comprising three distinct domains: alerting, orienting, and executive attention. Alerting involves maintaining a state of heightened sensitivity to incoming stimuli, while orienting focuses on selecting specific information from sensory input. Executive attention, on the other hand, plays a critical role in monitoring and resolving conflicts among information being processed, including thoughts, feelings, and behaviors necessary for task completion (Posner & Rothbart, 2007). To manage multitasking effectively, the brain establishes a hierarchy of goals and sub-goals, often referred to as "goal trees", based on their relative importance (Rothbart & Posner, 2015). This hierarchical structure is evidenced in everyday activities like driving a car, where multiple tasks must be balanced simultaneously. For instance, when a phone call interrupts the driving process, a new goal tree involving answering the call and conversing is activated. This process necessitates a partial shift of attention while still maintaining the core aspects of driving.

PA plays also a vital role in attention. Research has shown a positive correlation between physical fitness and attention, especially in teenagers. A study involving 210 teenagers found that higher levels of physical fitness, as indicated by increased oxygen consumption, were predictive of better attentional performance (Reigal et al., 2020). Another study with 187 teenagers linked maximal oxygen uptake with improved attention and concentration, as measured by the D2 attention test (González-Fernández et al., 2023). Furthermore, PA has been found to benefit children with ADHD symptoms, improving their inhibitory control and attentional capacities (Dastamooz et al., 2023). These findings underscore the importance of physical fitness in enhancing cognitive functions like attention and multitasking.

1.4. The current study

Considering the impact that PA has on mental health and cognitive functions, the present study aimed to better understand the effects of reduced PA during Covid-19 restrictions, particularly in relation to attention and memory. We had three research objectives. First, we aimed to monitor the changes in physical activity before, during and after lockdown periods. We expected to observe lower levels of PA during lockdown relative to pre- and post-lockdown periods. Second, we sought to investigate whether baseline (pre-lockdown) levels of PA or the change in PA during and following lockdown could predict measures of cognitive performance. We expected higher baseline levels of PA to positively predict cognitive outcomes. Third, we investigated whether levels of stress and insomnia severity were also predictive of cognitive performance. We expected higher levels of stress and greater insomnia severity to negatively predict cognitive outcomes. Performance on the go/no-go task, a measure of cognitive control ability, n-back task, a measure of working memory performance, and Rey Auditory Verbal Learning Test (RAVLT), a measure of short- and long-term verbal memory, was assessed following lockdown.

2. Methods

2.1. Participants

A sample size calculation conducted prior to data collection aimed to determine the required number of participants for a linear multiple regression model with five predictors. The calculation was based on an effect size (f^2) of 0.1, a desired power of 0.8, and a significance threshold (alpha) of 0.05. The analysis indicated that a sample size of 81 participants per country was needed to adequately power the study. The study was completed by 372 participants living in Austria (n = 85), Germany (n = 103), Iran (n = 93), and Italy (n = 91), of whom 61.3 % were females, 38.4 % males, 0.3 % diverse. The mean age was 26.9 years (SD = 7.4 years). The only inclusion criterion required participants to be between 18 and 40 years old. More than half of the participants (57.3 %) were students with an h-degree or higher education. Of all participants, 38.7 % experienced weight gain following lockdown compared to before lockdown, 19.9 % experienced weight loss, and 40.9 % remained stable post- versus pre-lockdown. Participants living in Italy and Austria were recruited using the online platform Prolific (https://prolific.co/) and were reimbursed 8.50€ per hour. Participants in Germany were current students at the University of Leipzig and University of Potsdam. They were offered 15€ for their participation. In Iran, students enrolled at the University of Yasouj volunteered to complete the study without compensation. The participants in Germany and Iran were recruited in the context of university classes through a convenience sampling strategy. All participants provided their consent to participate in the study through the online form. The study was approved by the Ethics Committee at the Catholic University of the Sacred Heart of Milan, Italy.

2.2. Materials

2.2.1. Survey on physical activity during the Covid-19 pandemic

To investigate the impact of pandemic-related restrictions on PA, we developed a comprehensive questionnaire addressing PA before, during, and after the lockdown period. The questionnaire was structured into three distinct sections, each focusing on a different timeframe: pre-lockdown, during lockdowns, and post-lockdown, when regular daily routines presumably resumed. Participants were asked to detail the physical activities they carried out in each section by choosing between a categorized list of activities based on intensity levels: low, medium, and high. For each selected activity, participants indicated the average number hours per week and which activity they performed. This approach enabled a thorough assessment of participants' physical activity levels across the three distinct periods. The complete questionnaire is included in the supplementary materials.

2.2.2. Go/no-go and n-back tasks

Standard go/no-go and n-back tasks provided measures of cognitive control and working memory abilities, respectively (Owen et al., 2005; Steele et al., 2013). In the ***go/no-go task***, participants saw the number "1" or the letter "l", characters that differ slightly in terms of their visual perceptual features. Participants were asked to press the spacebar with their right index finger as fast as possible anytime they recognized the number "1" in two of the four total blocks or the letter "l" in the other two blocks. In each trial, a fixation cross appeared for 1000 ms, followed by the visual stimulus ("1" or "l") for 500 ms. The visual stimulus was followed by an inter-trial interval of 500 ms. There were 30 trials per block. Targets were shown in 20 out of the 30 trials in each block.

In the ***n-back task***, participants were shown letters. They appeared one by one in the center of the screen for 1000 ms and were separated by an interstimulus interval of 500 ms. Participants were instructed to press the spacebar with their right index finger as fast as possible if the currently presented letter had been presented two letters before. After two brief practice blocks with 10 stimuli in which participants received accuracy feedback after each trial, participants completed two blocks of this task without receiving feedback. Each block contained 100 letters, and targets (letters that matched those two letters before) occurred in 25 of the 100 trials in each block.

2.2.3. Rey memory test

The Rey Auditory Verbal Learning Test (RAVLT) is a neuropsychological test designed to evaluate verbal memory in adult participants (Bean, 2011). In its original version, a list of 15 words is read aloud by an experimenter with an interstimulus interval of 3 s (Caltagirone et al., 1979). The participants are asked to repeat as many words as they can remember. This process is repeated 5 times (Caltagirone et al., 1979). We adapted the Rey test to allow for online data collection. The 15 words were translated into German, Italian, and Persian. Participants were shown the list of words in their native language; the words appeared in the center of the screen one by one for a duration of 3 s each. Thereafter, participants were asked to type all of the words that they could remember, including those already written in the previous recall phases, for a total of 5 times. The 15 words, translated in the three languages (i.e. Italian, German and Persian) were: curtain, drum, coffee, belt, sun, garden, mustache, window, river, villager, color, turkey, school, house, hat. The sum of the words remembered in the 5 repetitions is considered an index of learning capacity. After a delay of about 15 min, the participants were asked to re-type the remembered words again. This performance is considered as an index of long-term memory (Bean, 2011).

2.2.4. Insomnia Severity Index (ISI)

The Insomnia Severity Index (ISI) is a self-report instrument that evaluates an individual's perception of their insomnia symptoms (Bastien et al., 2001). It comprises seven items that assess various aspects of insomnia: difficulties in falling asleep and maintaining sleep (including nocturnal and early morning awakenings), satisfaction with current sleep patterns, interference with daily functioning, noticeable impairment attributable to sleep issues, and the level of distress or concern brought on by sleep disturbances. Scores range from 0 to 28, with each item rated on a scale from 0 (no problem) to 4 (severe problem). A higher total score indicates more severe insomnia symptoms. The ISI has been validated in multiple languages, including German (Gerber et al., 2016), Italian (Castronovo et al., 2016), and Persian (Sadeghniiat-Haghighi et al., 2014). As noted earlier, poor sleep quality can significantly impact cognitive functions, making the ISI a crucial tool in understanding the broader impacts of insomnia. By assessing the sleep of our subjects, our aim was to determine the impact of their sleep quality on their memory and attention.

2.2.5. Pandemic-related perceived stress scale of Covid-19 (PSS-10C)

The PSS-10C scale, developed during the Covid-19 pandemic, consists of 10 items designed to assess the psychological effects of Covid-19 and related governmental measures on individuals (Campo-Arias et al., 2020). The scale explores a range of emotional responses, including feelings of stress, anxiety levels, and perceived coping abilities in the context of both the illness itself and the measures implemented to control it. For instance, one of the items is, "I have felt that I am unable to control the important things in my life because of the epidemic". Respondents are given five options to indicate the frequency of their experiences: never, almost never, occasionally, almost always, and always. This nuanced approach enables a comprehensive assessment of the emotional impact of the pandemic on individuals' lives. Considering that psychic issues also influence cognitive resources, we wanted to assess how much the stress perceived by our subjects would have an impact on their memory and attention.

2.3. Procedure and design

The data acquisition procedure was carried out entirely online, utilizing Qualtrics survey software (https://www.qualtrics.com) and the Gorilla Experiment Builder (https://gorilla.sc). Participants began by reviewing an information sheet and providing informed consent for their participation and data processing. The experiment started with (1) the Rey memory test. Next, participants were asked to complete (2) a sociodemographic information form, (3) the questionnaire on physical activity during the Covid-19 pandemic, (4) the Insomnia Severity Index (ISI), and (5) the Pandemic-Related Perceived Stress Scale of Covid-19 (PSS-10C). This was followed by (6) the n-back task and go/no-go task. The session concluded with (7) a delayed recall Rey test, in which participants were asked to recall the list of words learned at the start of the session. The entire procedure is shown in Fig. 1.

2.4. Data analysis

2.4.1. Measures of physical activity, cognitive test performance, and outlier data

PA was operationalized as the total number of hours per week participants reported engaging in each of their physical activities, weighted by the intensity of each activity (low, medium, or high). The total number of hours per week, weighted by activity intensity, prior to lockdown was used as a baseline measure of PA. Changes in PA during lockdown relative to baseline were computed by subtracting this baseline measure of PA from the total number of hours per week weighted by activity intensity reported by participants for the period during lockdown. Finally, changes in post-lockdown PA relative to lockdown PA were computed by subtracting lockdown PA weighted by activity intensity from the total post-lockdown number of hours per week of PA weighted by activity intensity. Cognitive performance on the go/no-go and n-back tasks was assessed using *d*-prime scores and mean response times on correct response trials.

We first checked the PA and cognitive test measures for outliers, defined as individual participant values >3 *SDs* above or below the group mean for a given measure. Participants displaying one or more outlying measure were excluded from all analyses. Partial datasets from individuals who did not complete the study were also excluded. Thus, a total of 318 participants were included in the analyses. Table 1 reports the participants' sociodemographic characteristics.

2.4.2. Mixed effects modeling of physical activity levels before, during, and after Covid-19 lockdown

Linear mixed effects models were used to examine the fixed effect of time point (before, during, and after Covid-19-related lockdowns) on self-reported hours of PA per week weighted by activity intensity, as well as on the overall number of different activities in which participants were engaged. The models were generated in R version 3.6.3 (R Core

Table 1
Sociodemographic characteristics of the participants included in the analyses. M = male, F = female, NB = non-binary.

Country	*N*	Age (years)		Sex	Education	Occupation
		M	*SD*			
Austria	77	29.2	9.9	**M** (45.5 %) **F** (54.5 %)	**1** (0.0 %); **2** (0.0 %); **3** (2.6 %); **4** (42.9 %); **5** (29.9 %); **6** (16.9 %); **7** (7.8 %)	**1** (27.3 %); **2** (5.2 %); **3** (14.3 %); **4** (39.0 %); **5** (5.2 %); **6** (2.6 %); **7** (6.5 %)
Germany	95	22.2	3.4	**M** (30.5 %) **F** (69.5 %)	**1** (0.0 %); **2** (1.1 %); **3** (1.1 %); **4** (81.1 %); **5** (9.5 %); **6** (4.2 %); **7** (3.2 %)	**1** (94.7 %); **2** (0.0 %); **3** (2.1 %); **4** (2.1 %); **5** (0.0 %); **6** (0.0 %); **7** (1.1 %)
Iran	65	28.4	7.3	**M** (43.1 %) **F** (55.4 %) **NB** (1.5 %)	**1** (0.0 %); **2** (4.6 %); **3** (7.7 %); **4** (40.0 %); **5** (41.5 %); **6** (6.2 %); **7** (0.0 %)	**1** (53.8 %); **2** (1.5 %); **3** (13.8 %); **4** (24.6 %); **5** (0.0 %); **6** (1.5 %); **7** (4.6 %)
Italy	81	26.9	6.8	**M** (39.5 %) **F** (60.5 %)	**1** (0.0 %); **2** (0.0 %); **3** (0.0 %); **4** (46.9 %); **5** (16.0 %); **6** (22.2 %); **7** (14.8 %)	**1** (37.0 %); **2** (3.7 %); **3** (8.6 %); **4** (29.6 %); **5** (13.6 %); **6** (0.0 %); **7** (7.4 %)
All	318	26.4	7.6	**M** (39.0 %) **F** (60.7 %) **NB** (0.3 %)	**1** (0.0 %); **2** (1.3 %); **3** (2.5 %); **4** (54.7 %); **5** (22.6 %); **6** (12.3 %); **7** (6.6 %)	**1** (55.3 %); **2** (2.5 %); **3** (9.1 %); **4** (22.6 %); **5** (4.7 %); **6** (0.9 %); **7** (4.7 %)

Education:
1 = lower secondary school
2 = professional school
3 = upper secondary school
4 = bachelor degree
5 = master degree
6 = postgraduate school
7 = PhD

Occupation:
1 = student
2 = unemployed
3 = part-time employee
4 = full-time employee
5 = freelance
6 = prefer not to answer
7 = other

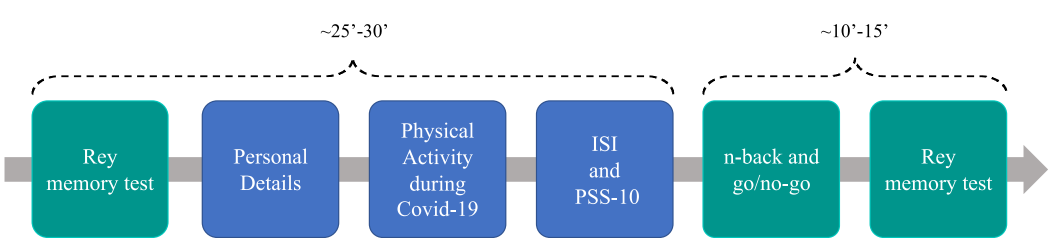

Fig. 1. Overview of tasks and questionnaires included in the experiment.

Team, 2020) using the 'lme4' package (Bates et al., 2015). The random effects structure of both models included a random intercept by participant. Statistical contrasts between time points were performed using *t*-tests in the 'emmeans' package in R (Lenth, 2020).

2.4.3. Predicting cognitive performance based on physical activity levels, Covid-19-related stress levels, and insomnia severity

We performed multiple linear regression analyses using the 'stats' package in R version 3.6.3 (R Core Team, 2020) to examine whether PA levels, pandemic-related stress levels, and insomnia severity predicted individual differences in measures of cognitive performance. To address our hypotheses regarding the predictive effects of baseline PA levels, change in PA levels during and following lockdown, stress levels, and insomnia severity on cognitive performance, five predictors were included in each model: (i) self-reported hours of PA in which participants engaged per week prior to Covid-19 related lockdowns weighted by activity intensity, (ii) the difference in hours of PA per week during lockdown relative to before lockdown weighted by activity intensity, (iii) the difference in hours of PA per week following lockdown relative to during lockdown weighted by activity intensity, (iv) self-reported pandemic-related stress levels assessed using the PSS-10C, and (v) self-reported insomnia severity assessed using the ISI. The variance inflation factor (VIF) was close to 1 for all model predictors (M VIF = 1.35, SE = 0.12), indicating that the predictors were not highly correlated with each other, and that the variance of the estimated regression coefficients was not inflated due to multicollinearity.

Effects of predictors on go/no-go task accuracy (*d*-prime scores) and response times, n-back task accuracy (*d*-prime scores) and response times, and total scores on the Rey test (sum of immediate and delayed recall) were modeled. The five predictors were able to explain a small but significant proportion of the variability in go/no-go accuracy (Adjusted R^2 = 0.11, F (5, 312) = 9.00, p < .001), n-back accuracy (Adjusted R^2 = 0.04, F (5, 312) = 3.71, p = .003), and n-back response time (Adjusted R^2 = 0.08, F (5, 312) = 6.49, p < .001), but not in go/no-go response time (Adjusted R^2 = 0.01, F (5, 312) = 1.87, p = .10) or Rey test scores (Adjusted R^2 < 0.001, F (5, 312) = 0.69, p = .63). The Rey test score model's residuals—differences between the observed and predicted Rey test scores—were non-normally distributed (w = 0.85, p < .001). To address this, we applied various transformations to the Rey test variable, including log, square root, and Box-Cox transformations, but these did not normalize the distribution of the residuals. We therefore used robust regression for modeling the Rey test scores, which provides estimates that are less sensitive to violations of the multivariate normality assumption, using the 'MASS' package in R (Ripley et al., 2020). For completeness, we report the statistical significance of predictors for all models (Table 2). The statistical significance of each predictor was determined using *t*-tests and associated false-discovery rate (FDR) corrected *p*-values. An alpha level of α = 0.05 was used for all statistical tests.

3. Results

3.1. Reduced engagement in physical activities during Covid-19 lockdowns

We first examined influences of lockdown on the total number of PA hours engaged in per week weighted by activity intensity, shown in Fig. 2. A mixed effects model on the hours per week spent engaging in physical activities reveals that activity time significantly decreased during lockdown (M = 14.6 h, SE = 1.0 h) compared to pre-lockdown (M = 18.7 h, SE = 1.1 h), β = 4.06, t = 4.45, p < .001. Following lockdown, activity time significantly increased (M = 18.0 h, SE = 1.1 h) relative to time spent during lockdown (M = 14.6 h, SE = 1.0 h), β = −3.34, t = −3.67, p < .001. Hours engaged in PA did not significantly differ pre-lockdown versus post-lockdown, β = 0.72, t = 0.79, p = .71. Thus, Covid-19-related lockdowns had a significant impact on the

Table 2
Multiple regression models predicting cognitive performance.

Predictor	β	*SE*	*t*	*p*	*95 % CI*
Go/no-go task accuracy (*d*-prime)					
Physical activity before lockdown	0.01	0.004	2.77	**0.006****	0.003, 0.019
Physical activity during − before lockdown	−0.02	0.005	−2.90	**0.004****	−0.026, −0.005
Physical activity after − during lockdown	0.02	0.008	2.86	**0.005****	0.007, 0.036
Pandemic-related stress	0.01	0.01	1.09	0.28	−0.01, 0.03
Insomnia severity	−0.30	0.08	−3.62	**<0.001****	1.61, 2.54
Go/no-go task response time (ms)					
Physical activity before lockdown	−0.39	0.17	−2.34	0.019	−0.72, −0.06
Physical activity during − before lockdown	0.09	0.23	0.41	0.69	−0.36, 0.55
Physical activity after − during lockdown	−0.33	0.32	−1.03	0.30	−0.97, 0.30
Pandemic-related stress	−0.51	0.44	−1.17	0.24	−1.37, 0.35
Insomnia severity	−0.26	3.58	−0.07	0.94	−7.31, 6.78
N-back task accuracy (*d*-prime)					
Physical activity before lockdown	0.005	0.003	1.93	0.054	−0.001, 0.01
Physical activity during − before lockdown	−0.009	0.004	−2.35	**0.019***	−0.02, −0.001
Physical activity after − during lockdown	0.01	0.005	2.64	**0.009***	0.003, 0.02
Pandemic-related stress	−0.002	0.007	−0.26	0.80	−0.02, 0.01
Insomnia severity	−0.09	0.06	−1.55	0.12	−0.20, 0.02
N-back task response time (ms)					
Physical activity before lockdown	−1.44	0.35	−4.11	**<0.001*****	−2.1, −0.75
Physical activity during − before lockdown	−0.52	0.49	−1.06	0.29	−1.5, 0.4
Physical activity after − during lockdown	−0.33	0.67	−0.49	0.62	−1.7, 1.0
Pandemic-related stress	−3.23	0.91	−3.55	**<0.001*****	−5.0, −1.4
Insomnia severity	3.23	7.49	0.43	0.67	−11.5, 18.0
Rey test accuracy (score)					
Physical activity before lockdown	−0.003	0.006	−0.46	0.60	−0.01, 0.01
Physical activity during − before lockdown	0.002	0.008	0.22	0.83	−0.01, 0.02
Physical activity after − during lockdown	0.007	0.01	0.61	0.53	−0.01, 0.03
Pandemic-related stress	0.003	0.02	0.24	0.82	−0.09, 0.03
Insomnia severity	0.15	0.13	1.20	0.24	−0.02, 0.03

Measures of performance on three cognitive tasks (the go/no-go task, n-back task, and Rey test) were predicted from baseline physical activity levels, changes in physical activity during and following lockdowns, pandemic-related stress, and insomnia severity. Physical activity was reported in hours per week and was weighted by task intensity. Pandemic-related stress was measured using the Pandemic-Related Perceived Stress Scale of Covid-19 (PSS-10C). Self-reported insomnia was measured using the Insomnia Severity Index (ISI).
*p < .05, **p < .01, ***p < .001 following false discovery rate (FDR) correction.

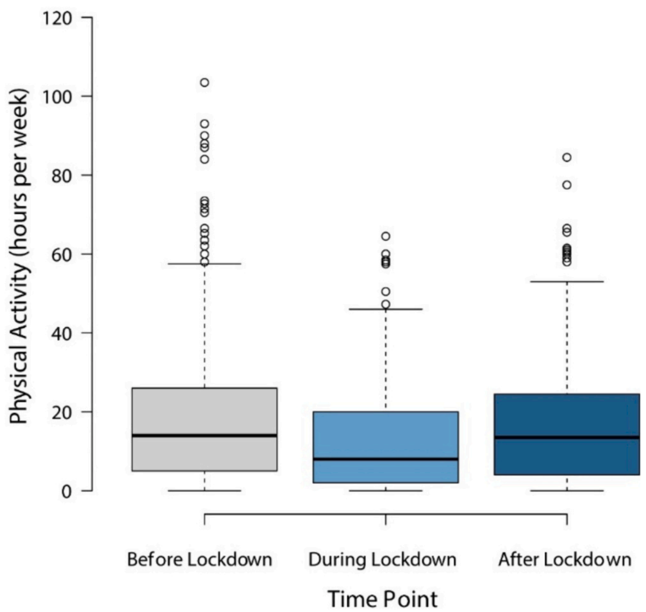

Fig. 2. Physical activity before, during, and after lockdown.
Physical activity is shown in total hours per week weighted by activity intensity. Physical activity decreased significantly during lockdown compared to before lockdown, and increased significantly following lockdown compared to during lockdown.

number of hours participants spent engaging in PA, namely a decrease in activity levels during lockdown compared to both pre- and post-lockdown periods.

We also examined influences of lockdown on the overall number of different physical activities in which participants were engaged, shown in Fig. 3. A mixed effects model on the number of different activities performed per week showed that participants engaged in a reduced number of activities during lockdown (*M* = 3.3 activities, *SE* = 0.2 activities) compared to prior to lockdown (*M* = 5.2 activities, *SE* = 0.2 activities), β = 1.91, *t* = 11.01, $p < .001$. Following lockdown, the number of activities in which participants were engaged significantly increased (*M* = 4.0 activities, *SE* = 0.2 activities) relative to during lockdown (*M* = 3.3 activities, *SE* = 0.2 activities), β = −0.71, *t* = −4.21, $p < .001$. The number of activities in which participants were engaged was also significantly reduced post-lockdown compared to pre-lockdown, β = 1.18, *t* = 6.80, $p < .001$. Therefore, lockdowns significantly reduced not only the number of hours spent engaging in physical activity but also the overall number of physical activities in which participants were engaged.

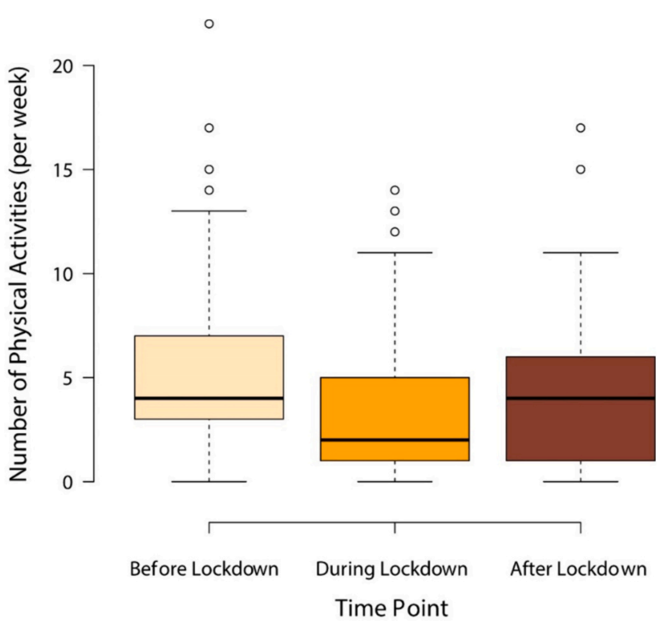

Fig. 3. Number of physical activities per week.
The overall number of unique physical activities in which participants were engaged per week saw a significant decrease during compared to before lockdown. This number also increased significantly following lockdown compared to during lockdown.

3.2. *Greater baseline physical activity levels associated with enhanced cognitive performance*

We next analyzed the relationship between baseline PA levels, i.e., the total hours of physical activity per week in which participants were engaged prior to lockdown weighted by activity intensity, and performance on the three cognitive tasks: the go/no-go task, a measure of cognitive control and flexibility, the n-back task, a measure of working memory, and the Rey test, a measure of verbal learning and long-term memory ability. A regression model of *d*-prime scores on the go/no-go task indicated that the number of hours spent engaged in physical activity per week prior to lockdown, weighted by activity intensity, significantly predicted task performance, β = 1.18, *SE* = 0.004, *t* = 6.80, *p* = .005, as shown in Fig. 4. Individuals who engaged in a greater amount of PA tended to score more highly on the go/no-go task.

There was also a significant relationship between PA per week prior to lockdown and response times on the n-back task, β = −1.44, *SE* = 0.35, *t* = −4.11, $p < .001$, shown in Fig. 4. Higher activity levels predicted faster n-back response times. A similar relationship between PA prior to lockdown and response times on the go/no-go task was found, but did not survive FDR correction, β = −0.39, *SE* = 0.17, *t* = −2.34, *p* = .019. Activity levels prior to lockdown did not significantly predict *d*-prime scores on the n-back task, β = 0.005, *SE* = 0.003, *t* = 1.93, *p* = .054, or scores on the Rey test, β = −0.003, *SE* = 0.006, *t* = −0.46, *p* = .60. The full set of regression results for all models is shown in Table 2.

3.3. *Changes in physical activity during and following lockdown predict cognitive control and working memory performance*

The extent to which an individual's PA changed during Covid-19-related lockdown compared to prior to lockdown was also a significant predictor of *d*-prime scores on the go/no-go task, β = −0.02, *SE* = 0.005, *t* = −2.90, *p* = .004, and the n-back task, β = −0.009, *SE* = 0.004, *t* = −2.35, *p* = .019. A greater reduction in PA levels during lockdown relative to pre-lockdown was associated with lower go/no-go performance and n-back performance, as shown in Fig. 5.

Further, the extent to which engagement in PA changed following lockdown compared to during lockdown also predicted go/no-go *d*-prime scores, β = 0.02, *SE* = 0.008, *t* = 2.86, *p* = .005, and n-back *d*-prime scores, β = −0.01, *SE* = 0.005, *t* = 2.64, *p* = .009. Larger post-lockdown increases in PA were associated with higher scores, shown in Fig. 5.

Changes in PA during or following Covid-19 lockdowns did not significantly predict changes in response times in either the go/no-go task (during lockdown: β = 0.09, *SE* = 0.23, *t* = 0.41, *p* = .69; post-lockdown: β = −0.33, *SE* = 0.32, *t* = −1.93, *p* = .30), or the n-back task (during lockdown: β = −0.52, *SE* = 0.49, *t* = −1.06, *p* = .29; post-lockdown: β = −0.33, *SE* = 0.68, *t* = −0.49, *p* = .62), or scores on the Rey test (during lockdown: β = 0.002, *SE* = 0.008, *t* = 0.22, *p* = .83; post-lockdown: β = 0.007, *SE* = 0.01, *t* = 0.61, *p* = .53).

3.4. *Individual differences in insomnia and pandemic-related stress associated with cognitive outcomes*

Scores on the Pandemic-Related Perceived Stress Scale of Covid-19

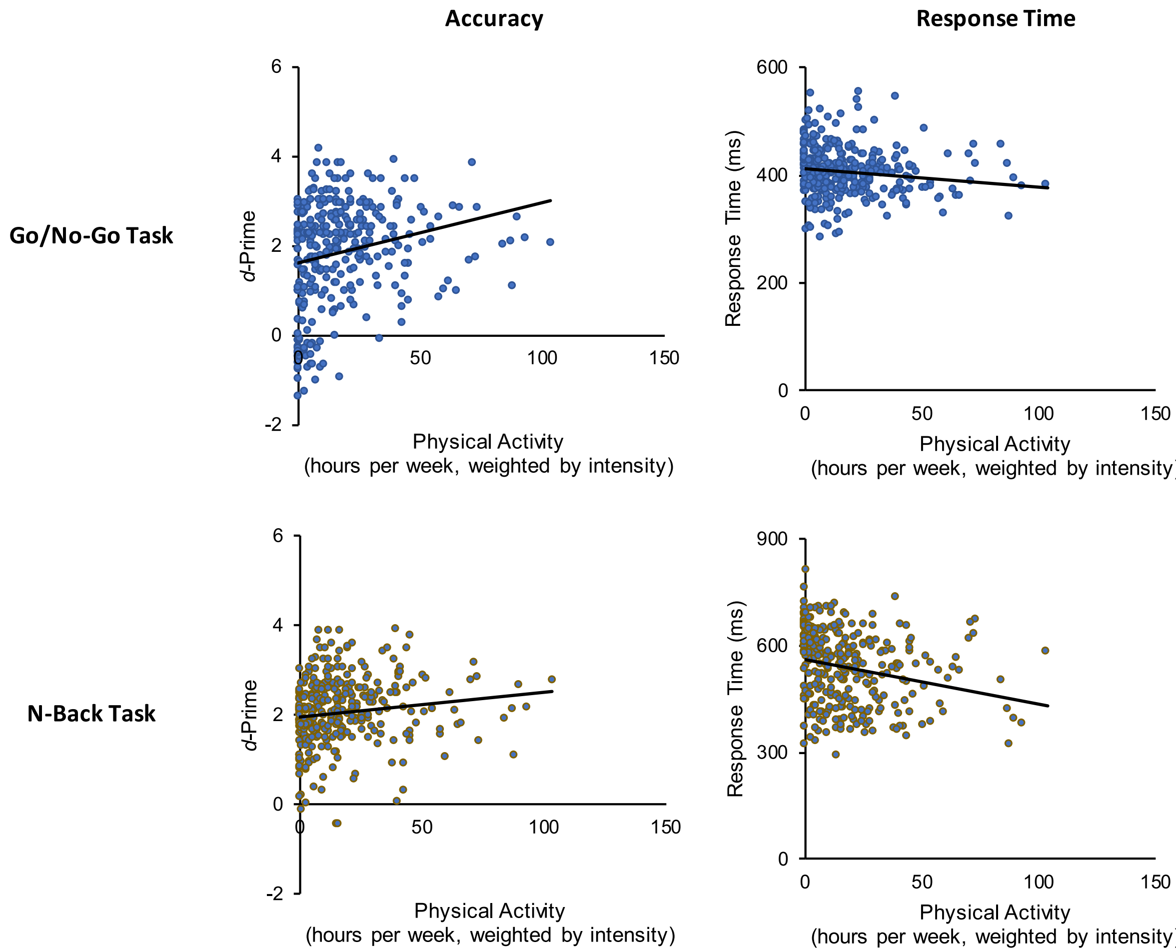

Fig. 4. Relationship between baseline physical activity levels and cognitive performance.
Relationship between physical activity (hours per week, weighted by intensity) prior to Covid-19-related lockdowns and performance in the go/no-go task (top) and n-back task (bottom). Individuals engaged in a greater amount of physical activity showed significantly higher performance in the go/no-go task ($\beta = 1.18$, $SE = 0.004$, $t = 6.80$, $p = .005$; top left) and responded significantly faster in the n-back task ($\beta = -1.44$, $SE = 0.35$, $t = -4.11$, $p < .001$; bottom right).

and the Insomnia Severity Index were included as predictors in the regression models of performance on the go/no-go task, n-back task, and Rey test. Pandemic-related stress was a significant predictor of response speed in the n-back task, $\beta = -3.23$, $SE = 0.91$, $t = -3.55$, $p < .001$. Participants reporting higher pandemic-related stress tended to respond more quickly when completing the n-back task. However, pandemic-related stress did not predict *d*-prime scores on the n-back task, $\beta = -0.001$, $SE = 0.007$, $t = -0.26$, $p = .79$, *d*-prime the go/no-go task, $\beta = 0.01$, $SE = 0.01$, $t = 1.09$, $p = .28$, or scores on the Rey test, $\beta = 0.003$, $SE = 0.02$, $t = 0.24$, $p = .82$. Pandemic-related stress also did not predict go/no-go response time, $\beta = -0.51$, $SE = 0.44$, $t = 1.17$, $p = .24$.

Insomnia severity significantly predicted performance on the go/no-go task, $\beta = -0.30$, $SE = 0.08$, $t = -3.62$, $p < .001$. Individuals who reported higher levels of insomnia also demonstrated significantly lower *d*-prime scores on the go/no-go task. Insomnia severity did not predict *d*-prime scores on the n-back task, $\beta = -0.09$, $SE = 0.06$, $t = -1.55$, $p = .12$, or performance on the Rey test, $\beta = 0.15$, $SE = 0.13$, $t = 1.20$, $p = .24$.

4. Discussion

We investigated the relationship between Covid-19 lockdowns, physical activity (PA), and cognitive performance. There were four main findings. First, there was a decrease in the hours spent engaging in physical activities and in the variety of physical activities undertaken during lockdown compared to pre-lockdown, as well as a subsequent post-lockdown increase in these measures. Second, baseline PA levels, prior to lockdown, predicted cognitive task performance, such that individuals with higher pre-lockdown PA levels demonstrated greater cognitive control and flexibility. Third, changes in PA levels during and after lockdown also predicted cognitive performance: Greater reductions in physical activity during lockdown was associated with lower performance on both the go/no-go and n-back tasks, and increased PA post-lockdown correlated with improved performance. Fourth, higher levels of pandemic-related stress and more severe insomnia symptoms were also associated with lower cognitive performance. Taken together, these findings support our three hypotheses. Our study shows that lockdown measures across various countries significantly reduced engagement in PA, leading to more sedentary lifestyles. In our sample, this sedentary behavior led to weight gains between 35 and 40 %. These behavioral changes were associated with changes in cognitive functions, such as attention and memory. Altogether, the findings underscore the importance of maintaining PA for cognitive health, especially in situations such as lockdowns.

In tasks assessing attention, such as the *go/no-go task*, we found that higher PA levels were associated with better performance. Similarly, a greater reduction in physical activity levels during lockdown was related to lower go/no-go performance. Higher levels of insomnia affected the subject's performance with lower *d*-prime scores in the go/no-go task. This pattern suggests that lockdown-induced changes in lifestyle negatively affected attention in our diverse sample from four different countries. Favieri et al. (2021) noted a similar decline in cognitive

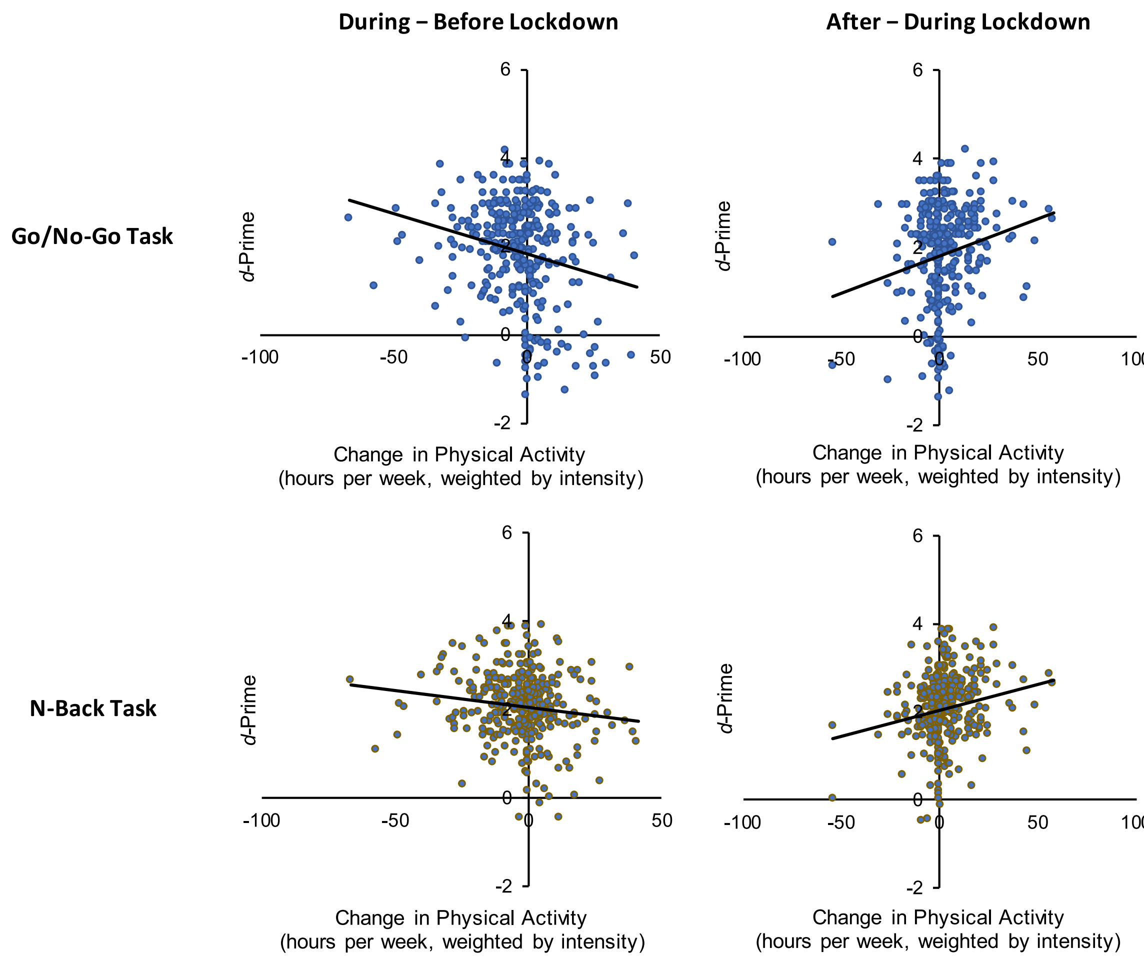

Fig. 5. Relationship between changes in physical activity during and following lockdown and cognitive performance.
Greater reductions in physical activity levels during lockdown relative to pre-lockdown were associated with lower go/no-go performance (β = −0.02, *SE* = 0.005, *t* = −2.90, *p* = .004; top left) and n-back performance (β = −0.009, *SE* = 0.004, *t* = −2.35, *p* = .019; bottom left). Similarly, larger increases in post-lockdown physical activity relative to activity during lockdown were associated with higher go/no-go performance (β = 0.02, *SE* = 0.008, *t* = 2.86, *p* = .005; top right) and n-back performance (β = −0.01, *SE* = 0.005, *t* = 2.64, *p* = .009; bottom right).

functions in Italian participants due to lockdown-related distress based on go/no-go task performance. Like our study, their participants experienced a drop in PA and exhibited post-traumatic stress symptoms. The authors suggested that the decline of cognitive functions had to do with distress connected to the possible contagion for oneself or others. Our findings align with this, as our participants reported pandemic-related stress and poor sleep. In the n-back test, individual stress levels were significant predictors of response speed.

These co-occurring conditions, resulting from lockdowns are complex and intertwined, making it challenging to isolate their individual effects. Previous pre-pandemic studies provide insights into how PA enhances cognition. For example, Reigal et al. (2020) found a significant relationship between 210 teenagers' physical fitness levels, attention, and concentration, with oxygen consumption emerging as a key predictor of attention. In another study focusing on pre-adolescents (Páez-Maldonado et al., 2020), a relationship emerged between physical fitness, cognitive functioning, and academic performance. The study found that participants with higher fitness levels exhibited higher attention and concentration performance. This correlation was attributed to cardiorespiratory fitness. Physical activities can be categorized as either endurance exercises (EE), such as running or cycling, or resistance exercises (RE), which involve strength training in which muscles work against a weight or a force. Although our study could not directly link these exercise types to specific aspects of cognitive performance due to the loss of statistical power, both EE and RE are recognized for their comprehensive benefits to brain health (Di Liegro et al., 2019).

Our study's reliance on online questionnaires precluded us from conducting in-person experimental activities. Therefore, our conclusions about the impact of PA on cognition are derived from existing literature and remain speculative. One key factor known to be influenced by PA is the secretion of brain-derived neurotrophic factors (BDNFs) (Szuhany et al., 2015). BDNFs not only regulate the survival, growth, and differentiation of neurons during the early development of the brain (Oppenheim et al., 1991), they also contribute to synaptogenesis (Kowiański et al., 2018) and synaptic plasticity (Leal et al., 2017). This could partially explain, the correlation we observed between PA and improved memory. Additionally, the results from the n-back task in our study were impacted by the significant reduction in physical activity during lockdown. BDNFs are also known to support neuroplasticity (Chakrapani et al., 2020), particularly in the hippocampal (Leal et al., 2017; von Bohlen Und Halbach & von Bohlen Und Halbach, 2018) function (Egan et al., 2003) and structure (Puhlmann et al., 2021). Clearly, our study faces limitations in establishing causality, and we acknowledge that several uncontrolled factors coincided with the lockdowns. We recognize the complexity of disentangling these variables and their collective impact on the findings reported here.

5. Conclusion

In conclusion, the lockdown measures implemented in countries like Austria, Germany, Italy, and Iran contributed to a marked decrease in physical activity, adversely affecting cognitive control and memory. During the years 2020 to 2022, gym closures and restrictions on outdoor exercise activities at various times significantly limited PA opportunities for people. Cognitive performance, i.e., cognitive control and memory processes, were affected by the decreases in PA. Additionally, pandemic-related stress and sleep disturbances compounded these cognitive challenges. However, with the easing of lockdowns, PA increased again, and this was related to higher cognitive outcomes. Our findings suggest that reductions in physical activity due to safety measures can detrimentally affect cognitive functions as memory and attention. Despite the limitations we addressed, our results suggest that the use of lockdowns as a pandemic intervention can have negative outcomes on cognitive health.

CRediT authorship contribution statement

Manuela Macedonia: Writing – original draft, Validation, Conceptualization. **Brian Mathias:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Christian Andrä:** Writing – review & editing, Data curation. **Nasrin Sedaghatgoftar:** Data curation. **Claudia Repetto:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.actpsy.2024.104472.

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