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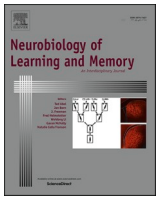

Acute exercise increases BDNF and short-term memory in healthy adults

Ester Tommasini [a,b,1], Elena Turco [b,1], Alice Cancer [b], Laura Colautti [b], Paola Iannello [b], Alessandro Antonietti [b], Sara Missaglia [a,b], Andrea Bosio [c], Daniela Tavian [a,b,*]

[a] Laboratory of Cellular Biochemistry and Molecular Biology, CRIBENS, Università Cattolica del Sacro Cuore, Piazza Michelangelo Buonarroti, 30, 20145 Milan, Italy
[b] Department of Psychology, Università Cattolica del Sacro Cuore, Largo Fra' Agostino Gemelli, 1, 20123 Milan, Italy
[c] Human Performance Laboratory, MAPEI Sport Research Centre, Via Busto Fagnano, 38, 21057 Olgiate Olona, Italy

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ABSTRACT

Acute physical exercise (PE) is known to influence the expression of many neurobiological markers and cognitive functions, but the time course and domain-specificity of such effects remain under debate. This study investigated whether a single bout of maximal incremental exercise can increase serum brain-derived neurotrophic factor (BDNF) levels, improving cognitive performance in healthy adults. Twenty-eight physically active males underwent a maximal incremental cycling test. BDNF serum concentrations were measured at three timepoints: before exercise, 15 min after, and 24 h post-exercise. Cognitive performance in verbal and visuo-spatial memory and convergent creative thinking was assessed before and 24 h post-exercise. Results showed a significant increase in serum BDNF 24 h after exercise, while no significant change was observed 15 min post-exercise. Cognitive assessments revealed improvements in verbal immediate recall and visuo-spatial working memory, but not in long-term verbal memory, visuo-spatial short-term memory, and convergent creative thinking. No significant correlations emerged between BDNF changes and cognitive performance changes. The dissociation between BDNF and behavior points to complex and likely time-dependent mechanisms underlying exercise-induced cognitive enhancements. These results support the effectiveness of acute PE as stimulus for BDNF neurotrophin production and as a non-pharmacological tool to boost specific cognitive functions, with implications for optimizing learning and cognitive performance in healthy populations.

1. Introduction

Physical exercise (PE) is one of the most powerful non-pharmacological interventions for promoting both physical and mental health. Regular engagement in PE reduces the risk of major health disorders, including cardiovascular disease and cancer, throughout the lifespan (ACSM, 2021). Beyond its physical benefits, PE has also been shown to alleviate negative affect, enhance neurocognitive functioning, and promote neuronal plasticity (ACSM, 2021; Caponnetto et al., 2021). Moreover, PE improves performance across several cognitive domains, including novel object recognition memory (Hopkins et al., 2012), cognitive flexibility (Pesce & Audiffren, 2011; Audiffren & André, 2014), vocabulary learning (Winter et al., 2007), and executive functions such as planning, working memory, multitasking, and managing ambiguity (Hillman et al., 2008).

Although numerous studies have explored the cognitive benefits of PE, its effectiveness appears to be influenced by several moderating factors. These include individual characteristics such as age (Smith et al., 2010), as well as exercise-related variables such as type (aerobic, anaerobic, or combined; Smith et al., 2010), duration (single-session vs. long-term programs; Hopkins et al., 2012), and intensity (light, moderate, or vigorous; Kashihara et al., 2009). Moreover, the timing of cognitive task administration relative to the exercise session (i.e., during or after; Schmidt-Kassow et al., 2013), along with the type of tasks employed (Lambourne & Tomporowski, 2010), also appears to play a key role in determining the cognitive outcomes of PE.

Some studies point to age-related differences in the effects of PE (Ludyga et al., 2016). Aerobic training appears to enhance working

* Corresponding author at: Laboratory of Cellular Biochemistry and Molecular Biology, CRIBENS, Department of Psychology, Università Cattolica del Sacro Cuore, 20145 Milan, Italy.
E-mail addresses: ester.tommasini@unicatt.it (E. Tommasini), elena.turco@unicatt.it (E. Turco), alice.cancer@unicatt.it (A. Cancer), laura.colautti1@unicatt.it (L. Colautti), paola.iannello@unicatt.it (P. Iannello), alessandro.antonietti@unicatt.it (A. Antonietti), sara.missaglia@unicatt.it (S. Missaglia), andrea.bosio@mapeisport.it (A. Bosio), daniela.tavian@unicatt.it (D. Tavian).
[1] These authors contributed equally to this work.

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memory in older adults more than in younger adults (Smith et al., 2010). However, the evidence on the cognitive benefits of PE in young adults remains limited, as most studies have focused primarily on older populations. Nonetheless, PE is widely recognized as a key lifestyle factor in maintaining cognitive functions and reducing the risk of age-related neurodegenerative diseases (Karp et al., 2005; Wilson et al., 2002; Festa et al., 2023).

Converging evidence suggests that the cognitive effects of acute PE depend on the interaction between exercise intensity and duration. High-intensity or prolonged exercise may impair cognitive performance by redirecting cognitive resources toward physical effort (Browne et al., 2017; Eich & Metcalfe, 2009), whereas short, moderate-intensity exercise is more consistently associated with cognitive benefits, likely mediated by increased arousal, improved mood, and neurotransmitters release (Audiffren & André, 2014; Fernandes et al., 2018). Conversely, long-term exercise has consistently been shown to have positive effects on memory and executive functions (e.g., cognitive flexibility and working memory) by promoting neuroplasticity, enhancing cognitive resource regulation, and strengthening self-regulatory capacity, ultimately supporting cognitive health across the lifespan (Audiffren & André, 2014; Cotman et al., 2007; Festa et al., 2023).

It is also worth mentioning that the timing of PE relative to a cognitive task appears to modulate its effects (Schmidt-Kassow et al., 2013). This may be attributed to physiological and neurochemical changes occurring during and after exercise that influence cognitive processes. These temporal effects highlight the importance of considering the underlying neurobiological mechanisms linking PE to cognition, with particular emphasis on brain-derived neurotrophic factor (BDNF), one of the most extensively studied molecular mediators in this field (Lu et al., 2023). BDNF is a neurotrophin widely distributed throughout the central nervous system (Binder & Scharfman, 2004; Park & Poo, 2013), with high expression in some regions relevant for cognitive processes, including the hippocampus and the cortex (Yan et al., 1997; Leal et al., 2017). In the peripheral circulation, BDNF is present both freely in plasma and, in much greater proportion, stored in platelets (Walsh & Tschakovsky, 2018). The mature form of BDNF (mBDNF) is produced through the proteolytic cleavage of its precursor, proBDNF (Wang et al., 2021). Notably, proBDNF and mBDNF exert distinct and opposite effects by binding to p75 neurotrophin receptor (p75NTR) and tyrosine kinase receptor B (TkB) receptors, respectively (Woo et al., 2005).

An increasing body of research suggests that circulating BDNF levels are correlated with cognitive processes, particularly memory (Bekinschtein et al., 2011; Laing et al., 2012) and memory-related hippocampal activity (Hariri et al., 2003). Interestingly, while some studies have shown that increased BDNF levels following acute PE are associated with enhanced cognitive outcomes (Winter et al., 2007; Griffin et al., 2011), this association is not consistently reported, possibly due to insufficient exercise intensity, as hypothesized by Schmidt-Kassow et al. (2013). These inconsistencies highlight the importance of providing exercise stimuli capable of inducing sustained increases in basal BDNF levels and of identifying the temporal window in which such changes may translate into cognitive benefits.

Acute PE represents a potent and effective stimulus for elevating circulating BDNF levels (Walsh & Tschakovsky, 2018). Acute exercise interventions in rodents showed increased BDNF levels in the hippocampus and parahippocampal structures, resulting in improvements in memory and learning tasks (Loprinzi, 2019; Vaynman et al., 2003). In humans, BDNF levels also increase following acute exercise programs with beneficial effects on cognitive functioning and neuroprotection in young adults (Ferris et al., 2007). However, the specific exercise aspects that modulate the BDNF response are not completely clear, with some evidence suggesting an intensity-dependent effect (Knaepen et al., 2010) while other studies highlight exercise duration as the primary driver (Dinoff et al., 2017).

Several tissues - including the brain, skeletal muscle, peripheral blood mononuclear cells, vascular endothelial cells, and platelets - contribute to the increase in circulating BDNF in response to exercise (Walsh & Tschakovsky, 2018). A recent study by Tarassova et al. (2025) suggested that exercise-induced increases in serum mBDNF may largely reflect the mobilization of mBDNF stored in platelets, rather than net release from the brain. Moreover, they reported that proBDNF may be released from skeletal muscle after exercise, highlighting the role of muscle tissue as a relevant peripheral source of BDNF. Emerging evidence also suggests that peripheral BDNF may cross the blood–brain barrier and exert central effects, further supporting the potential relevance of circulating mBDNF in cognitive modulation (Chen & Nakagawa, 2023). Given that proBDNF-to-mBDNF conversion involves intracellular and extracellular proteolytic processes (Wang et al., 2021), circulating mBDNF levels may follow distinct temporal dynamics, making it relevant to assess mBDNF levels beyond the immediate post-exercise period.

Lastly, although the primary focus of the study was to examine memory performance and the BDNF response to exercise, we also conducted an exploratory assessment of convergent creative thinking. According to recent evidence, hippocampal processes related to episodic memory are pivotal for creative cognition. More specifically Cabeza et al. (2020) suggested that the hippocampus may also contribute to convergent creative thinking through its associative functions, facilitating the integration of disparate information and supporting the experience of insight, as previously indicated by Luo and Niki (2003), Kizilirmak et al. (2016), and Becker et al. (2020). Therefore, assessing both creativity and memory performance should allow us to explore whether the cognitive benefits of exercise, potentially mediated by BDNF, extend beyond memory to other hippocampal-related functions.

Effectively, recent interest has focused on the relationship between PE and creative thinking, defined as a complex and highly functional ability in everyday life, enabling the generation of ideas that are both novel and useful for a given situation (Runco & Jaeger, 2012; Shamay-Tsoory et al., 2011). Producing creative ideas is thought to rely on key cognitive abilities such as cognitive control and flexibility, working memory, and long-term memory (Colautti et al., 2023), all of which have been shown to benefit from PE. Accordingly, recent reviews support the presence of a link between PE and creative performance. However, it is still not entirely clear which specific type of PE is most beneficial for enhancing creative performance (Chen, 2024; Frith et al., 2019). Creative thinking consists of divergent thinking (generating multiple ideas) and convergent thinking (finding one correct solution) (Zhang et al., 2020). Regarding divergent thinking, low-intensity exercise shows no clear effects, whereas moderate to vigorous activity is associated with improved performance (Aga et al., 2021). In contrast, maximal intensity may hinder flexibility (Colzato et al., 2013). For instance, a 15-minute light-to-moderate cycling session was found to enhance both fluency and flexibility (Aga et al., 2021). Evidence for convergent thinking remains limited, with improvements observed only after moderate-intensity exercise (Chen, 2024; Frith et al., 2019). Importantly, the literature on PE and creative thinking is characterized by heterogeneous protocols, subjective intensity measures, and a scarcity of neurobiological data, limiting comparisons across studies (Chen, 2024).

Given these gaps, the present study aims to explore the effects of a maximal incremental PE bout on BDNF levels and cognitive performance, with a specific focus on memory and convergent creative thinking in healthy adults. To capture both immediate and delayed BDNF responses, blood samples were collected at baseline, 15 min, and 24 h post-exercise. We further investigated whether exercise-induced changes in mBDNF concentrations were accompanied by concurrent changes in cognitive performance.

2. Materials and Methods

2.1. Participants

Twenty-eight male subjects (aged 21-–63 yrs, body mass index, 22.9 ± 2.1 kg/m^2) were recruited via notices and participated in this study. The experimental protocol was conducted in accordance with the Declaration of Helsinki (World Medical Association, 2013) and was approved by the Ethics Commission of the Università Cattolica del Sacro Cuore of Milan (N° of protocol 28–22). Written informed consent for study participation and permission for personal data treatment and biochemical analysis was obtained from all participants upon enrolment. The Italian version of the International Physical Activity Questionnaire was used to assess the physical activity levels of the participants (Mannocci et al., 2010). Inclusion criteria were: age between 20 and 65; body mass index (BMI) ≤ 30 kg/m^2; moderate or high physical activity level (> 600 MET-minutes/week); being healthy. Participants were considered healthy based on self-report. Exclusion criteria included a specific learning disorder, history of neurological disorders, musculoskeletal impairment, other motor restrictions which could influence the regular outcome of the study, and current pharmacotherapy, which could alter the results. Participants were required to maintain the same dietary habits during the study length, as well as to refrain from (i) smoking and drinking coffee or alcohol at least 2 h before the test and (ii) doing exercise, from moderate and vigorous intensity, and long-duration training in the previous 48 h and throughout the study period following the exercise. Participants completed all the assessments over two consecutive days, occurring at the same time each day from 10:00 a.m. to 1:00 p.m., to account for the circadian effects.

2.2. Anthropometric and body composition parameters

Weight and height were measured to the nearest 0.1 cm and 0.1 kg, respectively, using a calibrated mechanical scale (761, SECA GmbH & Co. KG, Hamburg, Germany) and a stadiometer (213, SECA GmbH & Co. KG Hamburg, Germany), following the procedures described by Gordon et al. (1988). Fat mass (FM), expressed in percentage, was determined by skinfold thickness using a calibrated skinfold caliper (Harpenden; Baty International, UK), in accordance with the American College of Sports Medicine guidelines (Wagner & Gibson, 2021). All skinfold measurements were performed by the same experienced operator to ensure consistency. Body density was estimated utilizing the 3-site Jackson & Pollock skinfold thickness equation (Jackson & Pollock, 1978), and the Siri equation was subsequently applied to convert estimated body density into the percentage of fat mass (Siri, 1993).

2.3. Cognitive measures

Memory and creativity performances were assessed at two timepoints: baseline (t_0) and 24 h after exercise (t_2). All cognitive tests were administered by a trained examiner across both sessions to ensure consistency.

Learning and verbal memory were assessed with the Italian version of Rey Auditory Verbal Learning Test (RAVLT) (Carlesimo et al., 1996), which includes two indices:

i) immediate recall (IR), consisting of five trials in which the researcher read a list of 15 unrelated words; Immediately after each repetition, the respondent had to recall as many words as possible. The score represented the total number of words remembered over the five trials;
ii) delayed recall (DR), in which, after a 15-minute delay, the respondent was asked to recall the words from the previously presented list. The score represented the number of correctly remembered words in the trial. A parallel version of the list was administered at t_2 to reduce practice effect. To control for order-related biases, the two lists were counterbalanced and randomly assigned across participants.

Visuo-spatial short-term memory (vsSTM) and working memory (vsWM) were assessed using the Corsi Block-Tapping Test (Monaco et al., 2013). In the forward version (vsSTM), the examiner tapped a sequence of blocks which the participant had to repeat in the same order. In the backward version (vsWM), the participant had to reproduce the sequence in reverse order. The outcome score in both cases corresponded to the longest correctly reproduced sequence.

Convergent creative thinking (CT) was measured using the Italian version of the Compound Remote Associates (CRA) Test (Salvi et al., 2016). Participants were presented with triads of words (e.g., *crab*, *pine*, *sauce*) and asked to identify a fourth word (e.g., *apple*) that forms a compound with each. The task was self-administered on a computer. CT performance was calculated as follows: (correct responses – incorrect responses)/40 |namely, the total number of items|).

2.4. Exercise protocol

All participants performed a maximal incremental test on a cycle ergometer (LC6 Monark; Vansbro, Sweden, and Excalibur Sport, Lode BV, Groningen, Netherlands). The exercise test took place in a room with controlled environmental conditions, maintaining a relative humidity below 60% and a temperature between 18°C and 22°C. After a 2-minute basal oxygen consumption assessment on the cycle ergometer and a 3-minute warm-up at 80 W, the workload was increased by 20 W every minute until volitional exhaustion. Subjects were instructed to maintain a cadence between 85 and 90 revolutions per minute throughout the test. The exercise protocol included a 5-minute cooldown phase at 50 W and a subsequent 10-minute passive recovery in a seated position. The incremental phase lasted on average 10 ± 2 min. Heart rate was recorded with an ANT + heart rate monitor (Garmin, Olathe, USA), whereas gas-exchange data were collected breath-by-breath during the tests with a metabolic cart (Quark CPET, COSMED, Rome, Italy, and Vyntus CPX, Vyaire GmbH, Hochberg, Germany). According to the operating manufacturer's instructions, the turbine flowmeter was calibrated using a 3-liter syringe. In addition, the gas analysis system was calibrated using room air – 21% O_2, 0,03% CO_2, and a certified gas mixture: 16% O_2, 5% CO_2 (Scott Medical ProductsTM, Plumsteadville, PA, USA) – prior to each exercise test, along with the delay and scrubber calibration. The maximal oxygen uptake and heart rate value reached during the exercise test was considered as peak oxygen uptake (VO_{2peak}) and peak heart rate (HR_{peak}). The peak power (PP) was determined according to Kuipers et al. (2003).

2.5. Blood sampling and analysis

Participants arrived at the laboratory following a 2-hour fast. Three samples (3 ml each one) of peripheral venous blood were drawn using a vacutainer system at the following timepoints: i) baseline (t_0); ii) 15 min after reaching maximal exhaustion during the incremental test (t_1); iii) approximately 24 h post-exercise (t_2) (Fig. 1). Vacutainers were immediately centrifuged at 10,000 rpm for 10 min and serum was separated and stored at –80°C for subsequent analysis. Samples were not diluted and were evaluated in duplicate in 40-well plates. Serum mature BDNF was detected by ELISA kit (Cat. EK-033–22, *Phoenix* Pharmaceuticals, Burlingame, CA, USA) according to the manufacturer's instructions, using the Victor Nivo multimode plate reader (PerkinElmer, Waltham, Massachusetts, USA). Inter- and intra-assay variation for BDNF were < 15% and < 10%, respectively. All samples fell within the provided standard curve.

2.6. Statistical analysis

Statistical analysis was conducted using Jamovi software, version 2.6

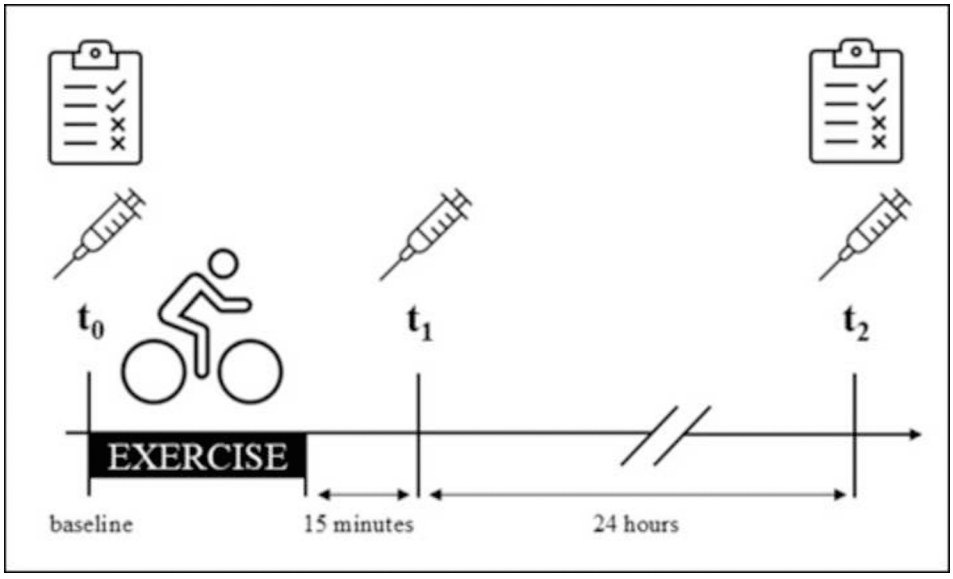

Fig. 1. Schematic flowchart of the experimental protocol. Syringes indicate timing of blood sample collection, at baseline (prior to the incremental exercise test), 15 min after exhaustion, and 24 h post-exercise. Sheets represent the timepoints at which cognitive tests were administered.

(The jamovi project, 2024). A priori power analysis ($\alpha = 0.05$) based on the planned one-tailed paired *t*-test assessing pre-post changes in cognitive performance indicated that, assuming a moderate effect size ($dz = 0.5$), a sample size of 28 participants was required to achieve adequate power (0.82). First, to test if age was associated with baseline BDNF levels and cognitive performance, bivariate correlations were conducted between age and all baseline measures. Then, assumptions of normality of the distribution for all variables were checked using the Shapiro-Wilk's normality test. Given that the BDNF measures did not meet the assumption of normality (Shapiro-Wilk's $p < 0.001$), non-parametric tests were used to compare BDNF concentrations across the three timepoints (t_0, t_1, t_2). Specifically, the Friedman test was used to perform a one-way repeated measures analysis of variance by ranks, and pairwise comparisons were conducted using the Durbin-Conover test.

For the cognitive measures – namely IR, DR, vsSTM, vsWM, CT – parametric paired-sample t-tests were used to compare pre- (t_0) and 24 h post-exercise (t_2) performances, as they met the assumption of normality (Shapiro-Wilk's $p > 0.05$). Given the limited number of planned comparisons, no adjustment for multiple testing was applied. Effect sizes were calculated using Cohen's *d*. Cohen's *d* values of 0.2, 0.5, and 0.8 were considered small, medium, and large effects, respectively.

Subsequently, difference scores (DS) between baseline (t_0) and 24 h (t_2) after exercise were calculated ($t_2 - t_0$) to test the associations between changes in BDNF concentration and changes in all cognitive measures using Spearman's rho correlation.

3. Results

3.1. Participants' characteristics

A total of 28 healthy male individuals, with ages ranging from 20 to 65 years, were included in the study. The details of the sample's characteristics are shown in Table 1.

Age was not associated with either pre-exercise BDNF concentration levels or baseline memory and creative performance (Table 2). Therefore, age was not included as a covariate in the following analyses.

3.2. Cognitive measures

As for the effect of exercise on memory and CT performance, paired comparisons showed significant improvements in IR ($t_{(24)} = -2.72$, $p = 0.012$, $d = 0.54$) and vsWM ($t_{(25)} = -2.93$, $p = 0.007$, $d = 0.57$) at t_2 compared to t_0. No significant differences emerged for DR ($t_{(24)} = 0.06$, $p = 0.095$), vsSTM ($t_{(25)} = 0.98$, $p = 0.34$), and CT ($t_{(25)} = 0.09$, $p = 0.92$). Descriptive statistics for all cognitive scores are reported in Table 3.

Table 1
Participants anthropometric characteristics, education, body composition, and physical exercise parameters.

Measures	Mean, SD
Age, yrs	37.5, 15.6
Education, yrs	15.1, 3.5
Height, m	1.79, 0.06
Weight, kg	73.6, 9.0
BMI, kg/m^2	22.9, 2.1
FM, %	13.2, 6.2
HR_{peak}, bpm	179, 15
VO_{2peak}, ml/kg/min	48.37, 9.03
PP, W	301, 54

BMI, body mass index; *FM,* fat mass; VO_{2peak}, peak oxygen uptake; HR_{peak}, peak heart rate; *PP*, peak power, yrs, years.

Table 2
Bivariate correlations amongst participants' age, pre-exercise (t_0) BDNF concentration, and cognitive test scores.

Measures	1	2	3	4	5	6
1. Age, yrs	–					
2. t_0 BDNF	−0.29	–				
3. t_0 immediate recall	0.12	−0.11	–			
4. t_0 delayed recall	−0.13	0.06	0.76***	–		
5. t_0 visuo-spatial short-term memory	0.06	0.08	0.27	0.17	–	
6. t_0 visuo-spatial working memory	−0.08	−0.12	0.30	0.07	0.45*	–
7. t_0 convergent creative thinking	0.05	0.04	0.10	0.03	0.13	0.28

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. *BDNF*, brain-derived neurotrophic factor.

Table 3
Descriptive statistics and comparisons of memory measures at baseline (t_0) and 24 h after exercise (t_2).

Measures	Phase	Mean, SD	p
immediate recall	t_0	38.45, 8.16	0.012*
	t_2	41.77, 7.59	
delayed recall	t_0	7.20, 2.58	0.095
	t_2	7.16, 3.24	
visuo-spatial short-term memory	t_0	5.48, 1.28	0.980
	t_2	5.75, 0.96	
visuo-spatial working memory	t_0	4.81, 1.09	0.007**
	t_2	5.42, 0.99	
convergent creative thinking	t_0	0.24, 0.16	0.924
	t_2	0.24, 0.18	

*p < 0.05, **p < 0.01, ***p < 0.001.

3.3. Biochemical analysis

The comparison of BDNF concentrations across the three sampling timepoints (t_0, t_1, t_2) revealed a significant main effect of phase ($\chi^2(2) = 22.3$, $p < 0.001$). Post-hoc pairwise comparisons indicated significant increases in BDNF concentrations between t_0 and t_2 ($p < 0.001$) and between t_1 and t_2 ($p < 0.001$) (Fig. 2), with BDNF levels showing a 14% increase from t_0 to t_2.

3.4. Correlations between BDNF concentration and memory test difference scores

Finally, changes in BDNF concentrations from baseline (t_0) to 24 h after exercise (t_2) were not associated with improvements in memory performance and convergent creativity, as indicated by the nonsignificant correlations between BDNF DS and cognitive test DS (Table 4 and Fig. 3).

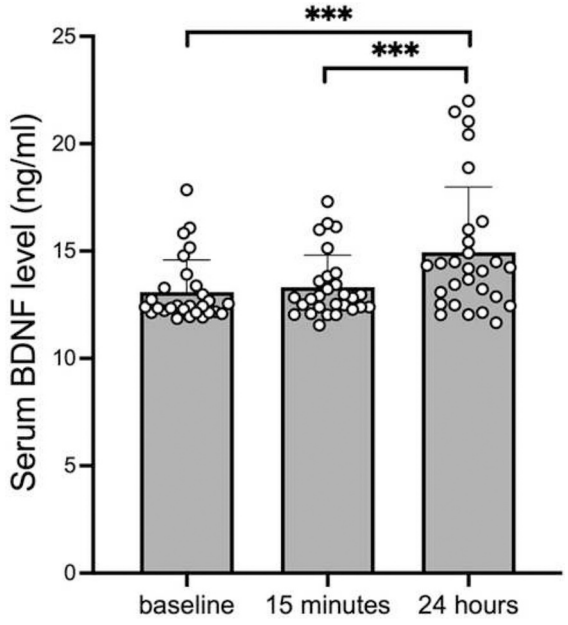

Fig. 2. Estimated marginal means of BDNF concentration variations across three sampling timepoints, namely baseline, 15 min and 24 h post-exercise. ***p < 0.001.

Table 4
Bivariate correlations between BDNF concentration and cognitive test difference scores.

Measures	1	2	3	4	5
1. BDNF DS	–				
2. immediate recall DS	0.10	–			
3. delayed recall DS	0.001	0.54**	–		
4. visuo-spatial short-term memory DS	−0.20	0.11	0.04	–	
5. visuo-spatial working memory DS	0.10	−0.05	0.07	0.19	–
6. convergent creative thinking DS	0.11	−0.28	−0.14	0.13	−0.09

*p < 0.05, **p < 0.01, ***p < 0.001. *BDNF*, brain-derived neurotrophic factor; *DS,* difference scores.

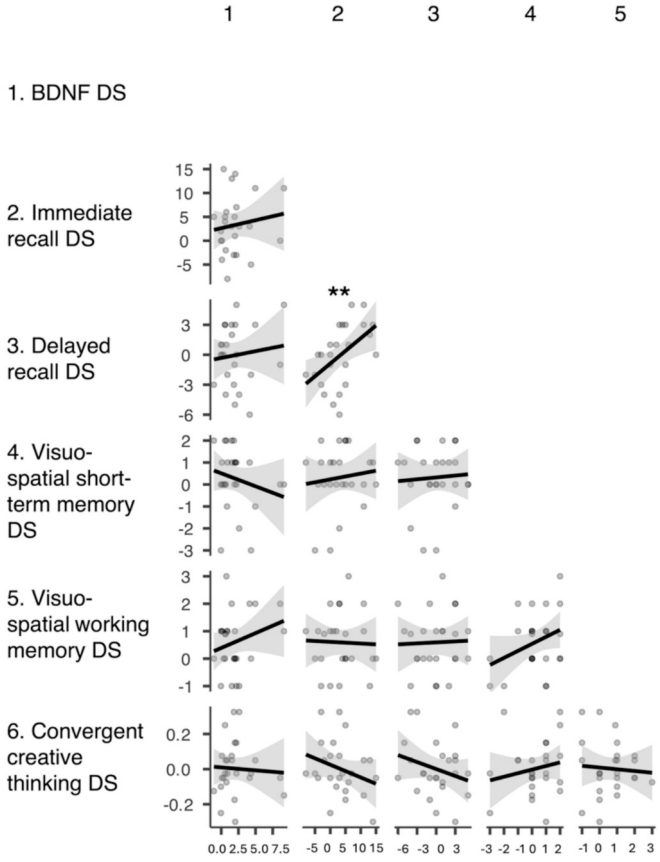

Fig. 3. Scatter plots illustrate bivariate associations between changes in BDNF concentration and changes in cognitive performance (difference scores). *p < 0.05, **p < 0.01, ***p < 0.001. *BDNF*, brain-derived neurotrophic factor; *DS,* difference scores.

4. Discussion

The present study aimed to explore the effects of a single session of maximal incremental PE on peripheral mBDNF levels and cognitive performance in healthy adults. We assessed mBDNF concentrations at baseline and both immediately and 24 h post-exercise and evaluated verbal and visuo-spatial memory, as well as convergent creative thinking, before and 24 h following the exercise session. Furthermore, we investigated whether exercise-induced changes in mBDNF concentrations were associated with concomitant changes in cognitive performance.

The main findings of the present study were that the highest levels of serum mBDNF were observed 24 h after PE. Some improvements in cognitive performance were also found, specifically in IR and vsWM,

compared to baseline. However, increased levels of serum mBDNF following exercise were not associated with concurrent improvements in memory tasks.

The delayed increase in serum mBDNF following acute PE suggests that BDNF response may not be exclusively rapid and transient, as previously proposed (Knaepen et al., 2010; Dinoff et al., 2017). Instead, our findings point to the possibility of a delayed mBDNF increase after acute exercise. Although serum mBDNF levels were significantly elevated at 24 h post-exercise, individual responses were highly heterogeneous. A subset of participants showed larger increases; however, these individuals did not share a common profile in terms of age, fitness level, or body composition. The majority of the literature has focused on the early post-exercise period, reporting a return to baseline levels within approximately 1 h after exercise cessation (Knaepen et al., 2010; Szuhany et al., 2015; Dinoff et al., 2017). Few studies, however, have investigated mBDNF responses at later timepoints (Knaepen et al., 2010). The percentage change in serum BDNF observed in our study is consistent with previous reports, which have documented exercise-induced increases in serum or plasma BDNF ranging from 12% to 410% following acute exercise (Knaepen et al., 2010), with larger increases generally reported in plasma compared to serum (Dinoff et al., 2017). However, to our knowledge, this is the first study to report a significant 14% increase in serum BDNF 24 h after exercise.

To our knowledge, only two studies to date have investigated circulating BDNF levels 24 h after an acute bout of exercise in healthy individuals, as in the present study. Reichel et al. (2022) examined the effects of a prolonged endurance protocol (running for 40 min at 95% of the individual anaerobic threshold followed by 20 min at 110%). They reported a significant increase in plasma BDNF immediately post-exercise, followed by a decrease at both 3 and 24 h post-exercise. However, it is important to note that this study measured mBDNF in plasma and previous research has shown that serum and plasma BDNF concentrations are poorly correlated (Gejl et al., 2019; Tsuchimine et al., 2014). Therefore, the absence of a delayed increase in plasma BDNF in those studies does not necessarily contradict our findings in serum. Moreover, Żebrowska et al. (2020) assessed serum BDNF responses following 40 min of continuous cycling at moderate intensity and observed a significant elevation only immediately post-exercise. Although BDNF levels at 24 h remained elevated, they did not differ significantly from baseline. It is likely that the lower intensity of the exercise stimulus used in that study elicited a less pronounced delayed BDNF response compared to our protocol. Based on recent evidence indicating that pro-BDNF is highly expressed in human skeletal muscle (Edman et al., 2024) and that its circulating levels increase following exercise (Edman et al., 2024; Tarassova et al., 2025), it is plausible that the elevated mBDNF levels observed 24 h post-exercise may be related to an exercise-induced release of pro-BDNF from skeletal muscle. This effect could be further affected by increased proteolytic activity triggered by PE, which has been suggested to promote the enzymatic cleavage of proBDNF into its mature form (Ding et al, 2011). Although these mechanisms were not directly assessed in the present study, measuring mBDNF concentrations at later time points, such as 24 h post-exercise, might have captured a delayed elevation in peripheral mBDNF. Further research is necessary to directly investigate these mechanisms and confirm the delayed elevation of peripheral mBDNF.

Regarding the characteristics of the exercise stimulus, our findings align with previous research indicating that high-intensity protocols are generally effective in eliciting significant increases in mBDNF concentrations (Knaepen et al., 2010; Dinoff et al., 2017). However, it is important to note that although our protocol was brief, it involved maximal exertion and therefore may not represent a feasible or sustainable form of daily exercise. This highlights the importance of investigating moderate-intensity protocols and alternative stimuli (as suggested by Leaney et al., 2025) to determine whether they can induce comparable immediate and delayed mBDNF responses. Such approaches could be more suitable for everyday practice, even among people with reduced mobility or lower levels of physical fitness.

Concerning cognitive assessment, improvements in specific memory components following acute PE further support the conceptualization of memory not as a unitary process but as involving different phases (e.g., acquisition, consolidation, storage, retrieval) or distinctions between short- and long-term memory processes, each mediated by distinct structures and molecular mechanisms (Bekinschtein et al., 2014; Berchtold et al., 2010). Accordingly, previous studies suggested that PE benefits are more frequently found in working-memory processes than in long-term memory retrieval (Tomporowski, 2003). One possible hypothesis is that the benefits of PE were observed only in the task that was more demanding for participants, namely, the one requiring them to recall specific sequences of blocks in reverse rather than forward order. This is consistent with prior evidence showing that vsWM performance is typically lower than vsSTM (Berch et al., 1998; Vandierendonck et al., 2004), especially in the presence of visuo-spatial difficulties (Cornoldi & Mammarella, 2008; Donolato et al., 2017). These two memory processes are believed to rely on distinct cognitive and neuroanatomical mechanisms. In particular, vsWM involves greater cognitive load and additional processing during encoding and retrieval, requiring the engagement of the central executive (Carlesimo et al., 1994; Gerton et al., 2004). Although few studies have directly compared the forward and backward Corsi tasks, the test is widely recognized for evaluating visuo-spatial memory (Donolato et al., 2017). Evidence from the Digit Span task similarly supports that backward recall tasks impose greater cognitive demands and activate prefrontal executive control regions (Gerton et al., 2004; Yang et al., 2015; see Donolato et al., 2017 for a review). Finally, verbal memory was assessed using the RAVLT, a widely validated test of verbal episodic memory (Lezak et al., 2012). While improvements were noted in IR, DR remained unaffected. This pattern suggests that verbal learning and retrieval processes may rely on distinct temporal dynamics and neurobiological mechanisms (Saury & Emanuelson, 2017). IR may depend more on attention and working memory, while DR involves consolidation and access from long-term memory (Huo et al., 2018). The improvement in working memory aligns with the literature showing a link between exercise and enhanced executive control (Hillman et al., 2008; Audiffren & André, 2014).

The lack of improvement in convergent creative thinking following a maximal incremental PE aligns with increasing evidence that a single session of high-intensity exercise does not directly enhance convergent thinking performance (Aga et al., 2021; Colzato et al., 2013), nor does regular vigorous-intensity PE (Chen et al., 2021). Together, these findings may support the existence of an inverted U-shaped relationship between PE intensity and creative thinking (Chen, 2024). Further analyses conducted by Aga and collaborators (2021) revealed that the PE effect on convergent-thinking performance depended on subjects' mood after exercise, a variable that deserves attention in further studies. Our findings could also be framed under the ego-depletion theory (Baumeister et al., 1998). Since convergent thinking relies on top-down executive control (e.g., Colzato et al., 2013), engaging in tasks that demand high levels of self-regulation, such as sustained physical effort, may temporarily deplete the cognitive resources necessary for such control, thereby impairing subsequent performance. It is plausible that PE redirects attentional focus and cognitive resources away from demanding cognitive processes, influencing creative convergent thinking. These results underline the importance of considering task demands and individual resource availability when evaluating the cognitive effects of acute PE.

The absence of associations between changes in mBDNF levels and cognitive performance suggests that the relationship between BDNF and cognition may follow a complex, time-dependent trajectory, with differential implications for encoding, consolidation, and retrieval, as previously proposed (Berchtold et al., 2005). Further studies are needed to clarify these dynamics and determine optimal timepoints for cognitive assessment after exercise. Indeed, some findings suggest that memory consolidation benefits may emerge or peak at timepoints

beyond 24 h (Berchtold, et al., 2010). To our knowledge, this is the first study examining the potential association between BDNF levels and convergent creative thinking. While the exploratory analysis did not reveal a significant relationship, further research is needed to clarify this preliminary observation.

These results also carry relevant practical implications. The observation that even a single session of PE can yield cognitive enhancements in healthy adults supports the versatility of exercise as a low-cost, accessible, and non-pharmacological cognitive enhancer. This is particularly promising from a preventive perspective, especially when considering cognitive aging and the potential for early interventions to sustain cognitive reserve across the lifespan (Colombo et al., 2018; Fusi et al., 2024; Colombo et al., 2025; Garau et al., 2025).

In occupational contexts where cognitive efficiency is crucial (e.g., education, healthcare, decision-making roles), promoting structured PE may prove beneficial for optimizing performance and well-being. Encouraging the integration of PE into daily routines, including in workplace wellness programs, may thus result in both enhancing physical health and promoting cognitive function. Overall, this study contributes to the growing evidence base supporting acute PE as a modifiable behavioral factor capable of influencing neurocognitive functioning. However, more research is warranted to clarify the underlying mechanisms, investigate the role of moderators such as mood or motivation, and determine how to tailor exercise programs for maximal cognitive benefit across different populations and cognitive domains.

From a methodological perspective, the use of a standardized incremental protocol and a delayed assessment of both peripheral mBDNF and cognition represent important strengths. The detection of higher BDNF levels at 24 h highlights the critical role of timing in post-exercise biomarker measurement. However, the present study also presents limitations. First, no control condition was included, which limits causal inferences. Second, the sample size, although adequate for medium effects, restricts generalizability. In particular, given the relatively small sample size, the study was adequately powered to detect moderate-to-large correlations ($r \geq 0.45$) but underpowered to detect small-to-moderate effects. Therefore, non-significant findings from correlation analyses should be interpreted with caution. Third, we did not assess platelet count in the present study. However, it is known that measuring both serum BDNF and BDNF/platelet ratios provides a more comprehensive understanding of the BDNF system, accounting for both tissue-derived sources and platelet storage and release. Psychological variables such as arousal or mood, which are known to interact with both BDNF and cognition (Mandolesi et al., 2018), were not assessed. Maximal effort during the exercise protocol was assessed solely via volitional exhaustion; no objective physiological markers (e.g., HR, respiratory quotient, VO_2 plateau) were checked. Lastly, this study included only male participants, which limits the generalizability of the findings, especially considering evidence that females seem to exhibit lower BDNF responses to exercise compared to males (Szuhany et al., 2015). Therefore, future research should investigate the delayed BDNF response to exercise in both sexes.

In conclusion, this study demonstrates that a single session of maximal incremental exercise can significantly increase peripheral BDNF levels, with a delayed increase observed 24 h post-exercise. Importantly, this effect was accompanied by selective improvements in cognitive performance, specifically in verbal immediate recall and visuo-spatial working memory, while no changes were detected in long-term verbal memory, visuo-spatial short-term memory, and convergent creative thinking. Although no direct correlation between BDNF increases and cognitive gains emerged, the results support the hypothesis that acute PE may selectively enhance executive-related cognitive functions, potentially through delayed neurobiological mechanisms, including BDNF-related plasticity. Furthermore, our findings reinforce the notion that cognitive benefits of exercise are domain-specific, depending on the type of memory involved and the cognitive demands of the task. Future research should address these aspects by including control or comparison groups and expanding the range of cognitive domains and neurobiological mediators considered. Assessing mood, motivation, and arousal in parallel with cognitive tasks and BDNF sampling could also help disentangle the mechanisms behind PE-induced cognitive enhancement.

CRediT authorship contribution statement

Ester Tommasini: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Elena Turco:** Writing – review & editing, Writing – original draft, Investigation. **Alice Cancer:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Laura Colautti:** Writing – review & editing, Writing – original draft, Methodology. **Paola Iannello:** Writing – review & editing, Supervision, Conceptualization. **Alessandro Antonietti:** Writing – review & editing, Supervision. **Sara Missaglia:** Writing – review & editing, Methodology, Data curation. **Andrea Bosio:** Writing – review & editing, Methodology. **Daniela Tavian:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization.

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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.

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Data availability

Data will be made available on request.

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