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The effects of a short exercise bout on executive functions in healthy older adults

Matteo Martini[1,5], Jamie Enoch[1,2] & Arthur F. Kramer[3,4]

Regular physical activity is associated with healthier brains and improved cognition among older adults. Yet, the impact of a short bout of exercise on older adults' cognition still is not fully clarified. The present study explored the effects of 20 min of moderate-intensity aerobic exercise (on a cycle ergometer) on cognition. Forty-eight healthy older adults were randomly assigned to an exercise or a control group and completed four cognitive tests: Affective Go/No-Go (AGN), Simple Reaction Time (SRT), Spatial Working Memory (SWM) and a Backward Counting task. Tests were administered prior to and immediately after 20 min of cycling (exercise group) or rest (control group). Mixed-design 2 × 2 ANOVAs indicated a significant interaction of Group x Session, for commission errors on the positive valence of the Affective Go/No-go task, indicating that the exercise group performed better on one aspect of this inhibition test after cycling ($p = 0.004$), while the control group's performance declined after rest. A similar pattern was found for the SWM, with the exercise group showing a significantly better performance after the exercise both for total error ($p = 0.027$) and the strategy ($p = 0.002$), while no improvement was observed after rest (controls). The study suggests that inhibitory control functions and working memory may be improved by a single relatively short bout of moderate exercise. However, the null effects of exercise on the other cognitive measures indicate that the neurocognitive benefits of acute exercise for older adults may be selectively sensitive to exercise parameters and to specific aspects of cognition.

Keywords Physical activity, Executive functions, Cognition, Healthy ageing, Fitness

Worldwide, the percentage of the general population represented by older adults is rapidly rising[1]. Demographic projections suggest that two billion people will be aged 60 or over by 2050[2], making healthy aging an urgent healthcare priority. Biological ageing is associated with structural and functional brain changes, characterized by altered cognition[3] and declining executive functions (EFs)[4]. Certain lifestyle factors, like engaging in regular physical activity, can help prevent cognitive decline and may even boost cognition in healthy older adults[5–8].

The psychobiological mechanisms behind such benefits are manifold. Aerobic fitness has been associated with increased hippocampal volume, and neurogenesis[7,9] and increased grey matter in older adults' prefrontal and temporal cortices[5,7,9] that typically decline with age[10]. Exercise can also boost cerebral blood flow and affect patterns of neural activation[11–16]. As a result, short bouts of physical activity (or 'acute exercise') may temporarily boost cognitive function in older adults[16]. In particular, such activity may have a positive impact on EFs[17]. EFs are a class of top-down mental effortful processes (i.e. shifting attention, working memory and inhibitory control functions)[18] that are recruited when automatic processes are not sufficient or possible, as when presented with novel, unexpected challenges[19]. Since, as anticipated earlier, EFs' efficiency generally declines with age, finding a way to contrast such detrimental effect of ageing can be crucial in an ageing world[20]. Of importance, however, acute exercise will likely have different effects on specific EFs. For instance, moderate-intensity acute exercise has significantly enhanced working memory without significantly benefiting inhibitory control[21]. Improvements in working memory following moderate exercise may be limited to faster response time, while working memory accuracy may deteriorate[22]. Therefore, moderate exercise may have selective effects that depend on the neurocognitive outcome measure used. Yet, acute exercise has had a small, positive effect on overall cognitive function across various age groups[23]. Basso and Suzuki[23] suggested that these effects are most pronounced on tasks that are mediated by brain activity in the prefrontal cortex (PFC), although acute exercise can activate

[1]Department of Psychology, University of East London, Water Lane, London E15 4LZ, UK. [2]School of Health & Psychological Sciences, City, University of London, Northampton Square, London EC1V 0HB, UK. [3]Center for Cognitive & Brain Health, Northeastern University, Boston, MA, USA. [4]Beckman Institute, University of IL at Urbana-Champaign, Urbana, IL, USA. [5]Present address: Department of Humanities, Letters, Cultural Heritage and Educational Studies, Via Arpi, 71121 Foggia, Italy. email: matteo.martini@unifg.it

widespread changes across numerous additional brain structures and circuits. While acute exercise seems to have a small, positive effect on older adults' cognitive function[16,24], conflicting findings have complicated the picture. For example, the effects have varied even when the same cognitive task was used[25,26]. This uncertainty provides the rationale for our attempt to test whether a single bout of moderate aerobic exercise (20 min cycling) would improve cognitive function in a sample of healthy older adults.

The exercise dosage used in this study has practical relevance: if just 20 min of exercise can benefit cognitive function, older adults may be more motivated to engage in physical activity. Indeed, lack of motivation is a common barrier found to limit older adults' engagement in physical activity[27]. Hyodo et al.[28] showed positive effects from as little as 10 min of cycling, although Chang et al.[24] suggested that positive significant effects of exercise were generally found when the exercise lasted longer than 20 min. In this study, we opted for 20 min of exercise to ensure sufficient duration while avoiding excessive exertion. Regarding exercise intensity, Davey[29], drawing on Yerkes and Dodson's[30], suggested an 'inverted-U' relationship between performance and arousal, predicting that the effect of acute exercise on cognitive function would be smallest when exertion levels are either very low or very high, with the largest effects associated with moderate intensity exercise. Building on this idea and based on findings that moderate intensity should be sufficient to benefit cognitive function[31,32], a moderate intensity exercise (around 60% of maximum heart rate) was considered for the current study. Type of cognitive task can also be a significant moderator of the effects of acute exercise[24]. Weng et al.[21] found that acute exercise may positively affect one executive function (e,g. working memory) while not affecting or possibly negatively affecting others (e.g., inhibitory control). Therefore, we employed four neurocognitive tasks associated with brain activity in the PFC. Also, we chose to test participants as soon as participants felt comfortable and ready after the exercise finished (~ 1 min. after). Finally, participants' baseline fitness levels may moderate exercise effects in older participants, with higher fitness levels associated with greater cognitive gains from acute exercise than lower fitness levels[33,34]. However, since Ludyga et al.'s[35] meta-analysis suggested that across studies, fitness level did not significantly influence the effect of exercise on cognitive function, we chose to maximize the recruitment of healthy older adults, choosing not to be confined by the participants' baseline levels of cardiovascular fitness.

Against this background of prior research, we investigated the effect of exercise on a sample of older adults, using a single, relatively short, moderately intensive exercise bout, as measured by four neurocognitive tests assessing different aspects of EF (see "Measures" below). To control for mere learning effects, we compared an exercise group and control group who did not perform any acute physical activity. We hypothesized that there would be a positive, small, significant effect of exercise on cognitive test performance, and made no specific hypotheses at the level of each individual test.

Method

Participants

Forty-eight English-speaking older adult participants, ranging in age from 55 to 75 years (*M* age = 62.1, *SD* = 5.4), were recruited. They were mainly recruited from nearby older adult leisure centres and from friends of the experimenter's parents. Participants' demographic characteristics are shown in Table 1. The experimental and control groups were matched with respect to age, gender, years of education, scores on the Beck Depression Inventory (BDI, Beck et al., 1961), and scores on the Mini-Mental State Exam (MMSE[36]).

Participants were excluded if they reported on screening questionnaire that any of the following conditions were present at the time of the experiment or previously: mobility impairments, diabetes, cardiovascular disease, neurological or psychiatric conditions. Participants were also excluded if they displayed potential signs of cognitive impairment (cut-off at 23 on the MMSE[37,38]), and/or a score of > 14 on the BDI[39–41] since depression can adversely impact aspects of cognitive function such as attention, information processing, and working memory[42]. Participants were also asked about their last meal time, and were excluded if this was less than two hours before the start of the experimental procedure, as cognitive performance can be acutely affected by meals, particularly in the one hour following lunch[43]. Moreover, participants were excluded if they had consumed tea or coffee two hours or less before the start of the experiment, since caffeine intake can positively impact cognitive function in older adult groups, for example in terms of attention or psychomotor performance[44]. All participants were offered water before the start of the procedure. Due to limited participant availability, we were unable to control for the time of day when the experiment was conducted, even though some evidence suggests that older adults' cognitive functions (and attention, in particular) peak in the morning[45]. Participants were required to be right-handed, as measured using the Edinburgh Handedness Inventory (EHI[46]), as handedness provides an indication of cerebral hemispheric dominance, which can differentially influence cognitive performance.

	All participants (n = 48)	EG (n = 24)	CG (n = 24)	*P*[1]
Age—mean (SD)	62.16 (5.43)	61.33 (4.73)	63 (6.04)	.29
Age—range	55–75	55–71	55–75	n/a
Female gender (%)	29 (60.41)	14 (58.33)	15 (62.5)	n/a
Years of education—mean (SD)	15.65 (2.6)	15.58 (3.02)	15.76 (2.13)	.87
BDI score—mean (SD)	4.02 (3.74)	3.88 (4.16)	4.28 (3.34)	.79
MMSE score—mean (SD)	28.17 (1.51)	28.17 (1.61)	28.04 (1.54)	1

Table 1. Socio-demographic characteristics of study participants. [1]p-value from independent samples t-tests comparing the exercise (EG) and control group (CG).

Ethical considerations

We undertook the study in accordance with the ethical code of the British Psychological Society (BPS), and the research protocol complied with the BPS 2018 Code of Ethics and Conduct. We adapted a standardized ethics form provided by the University of East London (UEL) for this experiment, and we received approval for this study from UEL's Research Ethics Committee before recruiting any participants. All participants signed an informed written consent before beginning the study.

Measures

Screening questionnaires

We used screening questionnaires to ensure participants met the inclusion criteria discussed above. A general screening questionnaire was used to record participants' demographics (age, gender, education). For the abovementioned reasons, the BDI was used to screen for symptoms of depression[47], the MMSE o screen for cognitive impairment[36], and the Veale Edinburgh Handedness Inventory to ascertain right-handed dominance[46]. Questionnaires were administered by one of the authors (JE) with the help of the experimenters reported in the Acknowledgment section.

CANTAB research suite

Three of the four tests used to assess cognitive function were from the CANTAB Research Suite, version 6.0 (Cambridge Cognition, 2014): (i) the Affective-Go/No-go (AGN) test, (ii) the Simple Reaction Time (SRT) test and (iii) the Spatial Working Memory (SWM) test. These tasks were administered on a Gigabyte personal computer tablet specifically designed for running the CANTAB tasks. The Gigabyte tablet was connected to a press-pad with two clickable buttons, with one button used to register a response during the AGN and SRT tests. We used the Gigabyte tablet's touch screen during the SWM test. For each participant, tests were set up in a random order, with a first round undertaken before the exercise/rest intervention. For the second round of tests, conducted after the intervention (or rest), the tests were randomized into a different order. This randomization was intended to minimize order effects, such as the effect of fatigue which can lead to a decrement in performance towards the end of a round of testing[48]. The tasks were chosen on the basis that they test a range of EFs. For example, the AGN tests response inhibition[49], the SWM tests manipulate spatial information by working memory[50], Backward Counting is associated with working memory and the ability to focus and sustain attention[51], and the SRT tests processing speed, which is correlated with working memory[52]. Before the start of each task, participants were given the necessary instructions by the experimenter, reading from the CANTAB test administration scripts (Cambridge Cognition, 2014). They were guided through practice rounds of each task, and they were provided with encouragement to complete the tasks as quickly and accurately/carefully as possible. Specifically, they were told at the start of the procedure to "please complete the tasks as quickly and accurately as possible," and in light of the length of the SWM task, these instructions we repeated each time they were three blocks away from the end of the task. Specific aspects of each task are discussed in turn below. The list of outcome measures derived from each test are reported at the beginning of the Results section.

Affective Go/No-go (AGN)

The AGN tests inhibitory control, with participants required to respond to one target valence (e.g. positive) of words, and to ignore distractor words of the opposite (e.g. negative) valence. It also tests for whether there is a bias for processing positive or negative stimuli. Since acute exercise may modulate emotional processing and the activity in related brain structures both in younger[53] and in older adults[54], we preferred this "Affective" version of the classic Go/No-go task[55].

In this experiment, positive or negative stimuli were presented, in 10 blocks, each containing 18 words (with targets, i.e. 'go trials', being positive for blocks 3, 4, 7 and 8, and negative being 'go' trials for blocks 1, 2, 5, 6, 9 and 10). Blocks 1 and 2 were practice blocks by default (CANTAB Research Suite, version 6.0—Cambridge Cognition, 2014). In total 180 words were presented, 90 negative and 90 positive with 90 'go' trials (half positive, half negative). Words were presented on the tablet screen for 300 ms, followed by an interval between words of 900 ms. Examples of positive words include "pleasant" or "success," and examples of negative words include "burden" or "inferior." Participants were instructed to click as quickly and accurately as possible on the press-pad button when they registered a word from the target valence, and to ignore words of the distractor valence. The experimenter clarified with the participant at the start of each block which valence was the target. The AGN generally took around 5–6 min to complete.

Spatial working memory (SWM)

The SWM tests the retention and manipulation of spatial information by working memory. Participants were read the administration script, which asked them to search an array of boxes for a hidden blue token by touching the boxes using the tablet touch-screen. Once the hidden token was found in a given box, the token would not be present in that box again and so participants should thereafter avoid revisiting those locations by remembering where tokens have been found. The test was run in 'high-functioning shortened mode,' which included two practice blocks (with 3 boxes each) followed by 1 block of 6 boxes, 1 block of 8 boxes, 3 blocks of 10 boxes, and 3 blocks of 12 boxes. During the practice blocks, the experimenter guided the participant through the task with verbal instructions and hands-on demonstration to ensure their understanding. This task was the longest of the four, frequently taking over 10 min to complete.

Simple reaction time (SRT)

The SRT was designed to assess participants' reaction time to click the press-pad as soon as they saw a white square appear against a black background, which appeared at varying intervals. The SRT was administered in 'clinical mode'[56], consisting of a practice block of 24 trials, followed by two assessed rounds each consisting of 50 trials. Generally, it took around 5 min for participants to complete this task.

Backward counting
Randomly interspersed among the CANTAB tests, participants undertook a fourth task, requiring them to count backwards verbally from 100 in sets of 3 (e.g. 100, 97, 94…). In the event of an error, the experimenter would correct participants and make a note of the error.

This task is based on the more established 'Serial Sevens' task, which can be considered a measure of concentration and is typically used in an alternative version of the MMSE[57].

Outcome measures
AGN—latencies (time for a correct response), commission errors (participant pressing the button during distractor words) and omission errors (missed responses), separated into those for positive valence stimuli and those for negative valence stimuli. Finally, 'bias', i.e. the difference between the mean of correct response times during positive targets and the mean of correct response times during negative targets, was also included;

SWM—between errors (number of times the participant revisited a box in which a token was previously found), within errors (number of times the participant revisited an empty box), total errors, strategy scores (the number of distinct boxes used by the subject to begin a new search for a token—to be noted that for this measure the lower the score the better the performance), mean time to first response and mean time to last response.

SRT—mean latencies, accuracy (measured by % correct responses), commission errors (participant pressing the button too soon), omission errors (missed responses);

Backward Counting—time in seconds and number of errors;

Cycle ergometer
In the Exercise Group (EG), participants undertook 20 min of exercise on a stationary bike, or ergometer (manufactured by TEKKNA 250, JK Fitness, Piove di Sacco, Italy). There were eight resistance settings which were adjusted depending on the participant's preference to ensure that the physical activity was sufficiently aerobic (see next sub-section). The saddle height of the ergometer was adjusted to ensure the participant's safety, comfort and full range of leg motion.

Heart rate measurement
Participants assigned to the experimental group (EG) had their heart rate measured at the start of their exercise session to establish their baseline heart rate, and this was subsequently measured each minute during the 20-min cycling session. Measurement was carried out with an AliveCore Heart Monitor which was fixed to a smartphone using adhesive tape. The Kardia application was installed on the smartphone in order to measure the heart rate in conjunction with the exercise. The AliveCor/Kardia system is recommended by the UK National Institute for Health and Care Excellence (NICE, 2015), and has been found in a randomised controlled trial to reduce rates of atrial fibrillation in an older adult sample relative to routine care[58]. It is also been recently used to diagnose arrhythmias during exercise in athletes[59]. This validation demonstrates the accuracy and reliability of the heart rate measurement provided concurrently by the AliveCore Heart Monitor and Kardia application. In this experiment, the heart rate measurement was used to ensure that exercising participants remained within thresholds for moderate intensity activity. The appropriate heart rate for each participant was determined, firstly by calculating the maximum heart rate (HRmax) using a formula specifically tailored to cycling that takes individuals' age into account: $[160 - (0.5\times \text{age}) \pm 5]$[60]. Given the target population, the choice was oriented toward the Knoepfli-Lenzin's heart rate formula as it is optimised for sedentary to moderately trained individuals[55]. Secondly, using Loprinzi and Kane's definition of moderate exercise as 51–70% of HRmax (giving a midpoint of 60%)[61], the target heart rate of each participant was set to 60% of their maximum heart rate. Thus combining these two calculations, a 60-year-old participant was instructed to speed up or slow down to a level of around $[160\text{-}(0.5*60)]*0.6 = 78 \pm 5$ beats per minute (bpm). Participants' heart rate was measured at baseline before cycling, i.e. at rest, and if this was found to be high (exceeding 75 bpm), participants were encouraged to maintain a heart rate at the upper end of the margin (thus 83 bpm in the case of a 60-year old). In order to keep the HR level within the 'moderate' PA boundaries, during the exercise participants were asked to cycle faster (if their HR was too low) or slower (if HR was too high). HR values were only monitored (not recorded) during the physical activity performed by the EG, to make sure that they were within the adequate HR range. As the controls did not engage with any physical activity during the experiment, their HR was not monitored.

Procedure
Upon arrival, participants provided their informed consent and completed the screening questionnaires discussed above. They were initially randomly assigned to either the exercise group (EG, n = 24) or control group (CG, n = 24), with care taken to match the two groups by age, gender, years of education, and their BDI and MMSE scores. After completing the screening questionnaires, participants were offered water before commencing the experiment. Participants then carried out the four neurocognitive tests in a randomized order, with instructions provided before each task. They were given a chance to ask questions during the practice round to ensure full understanding of the task. When the first round of tests was completed, EG participants cycled for 20 min, while CG participants rested, remaining seated, for 20 min. No activity was assigned during this time to the CG to avoid any possible emotional/cognitive influence that this could have had on the performance at the second round of tests.

As discussed in Materials, the target heart rate for the EG was measured each minute, and the experimenter consequently provided feedback to participants to maintain their speed, slow down, or increase speed as necessary. The experimenter also made sure that participants' subjective exertion was not exceeding a moderate level. Following the 20 min of exercise or rest, the four neurocognitive tests were completed in a different order from the first round. Chang et al.[24] suggested, in their meta-analysis, that administering tests 0–10 min after exercise might reveal negative effects. Conversely, when tests are administered 11–20 min after the exercise period, positive effects can be uncovered[24]. Yet, other investigators have shown that acute exercise can improve performance on cognitive tasks administered immediately after the exercise[62], including improved working memory for older adult participants[63], improved reaction time and attention[64], and improved inhibitory control[26]. Thus, in the present study, we chose to test participants as soon as participants felt comfortable and ready after the exercise (~ 1 min.).

Data analysis

Given the inter-participant variability, we performed an outliers check on data values, with values beyond two standard deviations from the group's mean replaced by the group's mean for the same measure[65]. Out of 2016 values, 97 (i.e. 4.8%) values were found to be outliers and were therefore replaced. Even after the replacement of the outliers the variables obtained were not normally distributed according to the Shapiro–Wilk test (all $ps < 0.01$) and given that some distributions were negatively skewed, with values between − 1 and − 2, we considered a logarithmic transformation [Log10 (K-X), where K is = 1+ the highest number in the distribution][65]. Nonetheless, the logarithmic transformation did not sufficiently improve the distribution. Therefore, since the F-test had proven to be robust even to great departures from normality[66], we proceeded with an analysis of the original data.

We described data in terms of means (and standard deviations). Table 2 shows scores (means and standard deviations) for each task, by group (EG or CG) before (pre) and after the intervention (post). Initial t-test group comparisons were conducted to determine whether participants in EG and CG groups differed on initial demographic and screening variables. We analyzed the neurocognitive task scores were using a 2 × 2 mixed-design analysis of variance (ANOVA), with 'Session' (pre and post) as the within participants factor and 'Group' (EG or CG) as the between-participants factor. As explained above, ANOVA is considered to be robust and not significantly affected by distribution deviations from normality[66]. Bonferroni post-hoc tests were used to better understand details of any significant interaction effects. The statistical significance was set at an alpha level of 0.05. Partial eta-squared were computed for effect sizes with the indicative threshold values of 0.0099, 0.0588, and 0.1379, regarded as small, medium, and large effects respectively[67]. The software considered for the analysis was JASP (JASP Team (2023)—JASP (Version 0.17.2) [Computer software]).

Results

Independent samples t-tests showed no significant differences between the EG and CG in terms of socio-demographic factors, BDI or MMSE scores (see Table 1). The results relative to the neurocognitive tests are presented below for each measure.

AGN

On the Affective Go/No-Go test, for AGN 'positive' outcome measures involving mean correct latencies, both groups did slightly better during the 'post' session but at the statistical level these variations in the performance were not substantial: indeed there were no significant main effect for Session, $F_{(1,46)} = 1.20$, $p = 0.28$, $\eta^2_p = 0.025$ nor was there any main effect for Group, $F_{(1,46)} = 2.14$, $p = 0.15$, $\eta^2_p = 0.044$ or for the interaction effect between Session * Group, $F_{(1,46)} = 0.04$, $p = 0.84$, $\eta^2_p = 0.0008$. Conversely, for omission scores, while there were no significant main effects of the two factors (Session, $F_{(1,46)} = 1.11$, $p = 0.30$, $\eta^2_p = 0.024$ or Group, $F_{(1,46)} = 0.04$, $p = 0.83$, $\eta^2_p = 0.0009$) the two groups behaved in the opposite way, with the EG doing better during the 'post' session while the CG did worse (significant Session * Group interaction effect, $F_{(1,46)} = 5.10$, $p = 0.029$, $\eta^2_p = 0.10$). However, subsequent, post-hoc analysis, using Bonferroni post-hoc test, revealed no specific significant findings in pairwise testing. For Commission scores too the EG did much better during the 'post' session, and this time this difference passed the statistical threshold: indeed while there was no main effect of Group, $F_{(1,46)} = 0.39$, $p = 0.53$, $\eta^2_p = 0.008$, there was a main effect of Session, $F_{(1,46)} = 7.07$, $p = 0.011$, $\eta^2_p = 0.13$, and there was a significant interaction effect of Group x Session, $F_{(1,46)} = 6.38$, $p = 0.015$, $\eta^2_p = 0.12$. Bonferroni-corrected post-hoc tests showed that only the EG showed a significant improvement across pre and post-testing sessions, with this group more successfully inhibiting their responses during distractor words at testing after exercise than before exercise ($p = 0.004$; see Fig. 1). For the Bias scores both groups did better during the 'post' session and overall the CG had a better bias score but no difference was significant: the ANOVA revealed a trend toward significance for the main effect of Session, $F_{(1,46)} = 4.03$, $p = 0.05$, $\eta^2_p = 0.08$ with both groups increasing their scores in the post-testing session, and there was a non-significant trend in the main for Group as well, $F_{(1,46)} = 3.72$, $p = 0.06$, $\eta^2_p = 0.075$ with the CG trending toward higher scores. However, there was no significant interaction effect, $F_{(1,46)} = 0.004$, $p = 0.94$, $\eta^2_p = 0.00009$.

For AGN 'negative' outcome measures involving mean correct latencies, there were no statistically-relevant differences in terms of performance of the two groups, with no significant main effects (but a trend) for Session, $F_{(1,46)} = 3.46$, $p = 0.07$, $\eta^2_p = 0.07$ or Group, $F_{(1,46)} = 0.24$, $p = 0.62$, $\eta^2_p = 0.005$. There was also no significant interaction effect for Session * Group, $F_{(1,46)} = 0.82$, $p = 0.37$, $\eta^2_p = 0.018$. Similarly, there were no significant main effects for Omission—Session: $F_{(1,46)} = 1.62$, $p = 0.20$, $\eta^2_p = 0.034$; Group: $F_{(1,46)} = 0.04$, $p = 0.83$, $\eta^2_p = 0.0009$; Session * Group: $F_{(1,46)} = 1.28$, $p = 0.26$, $\eta^2_p = 0.027$ or Commission – Session: $F_{(1,46)} = 0.80$, $p = 0.37$, $\eta^2_p = 0.017$; Group: $F_{(1,46)} = 0.05$, $p = 0.82$, $\eta^2_p = 0.001$; Session * Group: $F_{(1,46)} = 2.88$, $p = 0.59$, $\eta^2_p = 0.006$.

Measure	Group	Pre	Post	Mean delta
AGN+ latency (ms)	EG	526.8 (56.2)	518.9 (47.5)	**7.9** ↑
	CG	547.8 (65)	542.3 (56.7)	5.5 ↑
AGN+ omission	EG	2.96 (4)	1.48 (2)	**1.48** ↑
	CG	1.81 (1.9)	2.35 (2.5)	− 0.54 ↓
AGN+ commission	EG	4.09 (1.91)	2.39 (1.4)	**1.7** ↑
	CG	3.61 (2.8)	3.57 (2.5)	0.04 ↑
AGN bias	EG	− 17.43 (28.5)	− 7.69 (25.7)	**− 9.74** ↑
	CG	− 6.22 (26)	2.89 (20.9)	− 9.11 ↑
AGN− latency (ms)	EG	542.91 (77.3)	519.19 (50.1)	**23.72** ↑
	CG	542.64 (58.2)	534.46 (50.4)	8.18 ↑
AGN− omission	EG	2.26 (2.9)	1.5 (2.7)	**0.86** ↑
	CG	2.05 (1.9)	2 (2.6)	0.5 ↑
AGN− commission	EG	2.38 (1.9)	2.26 (1.6)	0.12 ↑
	CG	2.45 (1.7)	2 (1.8)	**0.45** ↑
SWM between error	EG	92.08 (50)	80.21 (50.9)	**11.87** ↑
	CG	90.74 (48.5)	87.6 (54.3)	3.14 ↑
SWM within error	EG	5.27 (5.4)	5.55 (5.6)	**− 0.28** ↓
	CG	5.61 (5.4)	6 (8.5)	− 0.39 ↓
SWM total error	EG	94.29 (50.7)	77.26 (47.8)	**17.03** ↑
	CG	90.26 (50)	88.25 (55.3)	2.01 ↑
SWM strategy	EG	51.65 (10)	45.75 (12.8)	**5.9** ↑
	CG	48.13 (12.1)	47.78 (12.8)	0.35 ↑
SWM mean time to first response (ms)	EG	2513.84 (1047.97)	2071.3 (832.4)	442.54 ↑
	CG	3206.59 (1314.4)	2252.08 (837.7)	**954.51** ↑
SWM mean time to last response (ms)	EG	55,645.84 (24,622.5)	49,153.84 (21,832.2)	6492 ↑
	CG	55,556.63 (24,798.3)	47,679.4 (30,911.7)	**7877.23** ↑
SRT latency (ms)	EG	294.15 (51.9)	294.98 (53.1)	**− 0.83** ↓
	CG	306.36 (58.6)	314.25 (72.2)	− 7.89 ↓
SRT correct	EG	99.04 (1.1)	99.29 (0.9)	− 0.25 ↑
	CG	99.3 (0.9)	99.55 (0.7)	− 0.25 ↑
SRT omission	EG	0 (0)	0 (0)	–
	CG	0 (0)	0 (0)	–
SRT commission	EG	0.96 (1.2)	0.54 (0.8)	0.42 ↑
	CG	0.57 (0.8)	0.61 (1)	0.42 ↑
Backward counting errors	EG	1.26 (1.2)	0.59 (0.8)	**0.67** ↑
	CG	1.16 (1.3)	0.9 (0.8)	0.26 ↑
Backward counting time (s)	EG	70 (17.7)	59.58 (15.3)	10.42 ↑
	CG	88.9 (37)	77.2 (33.4)	**11.7** ↑

Table 2. Means (and SDs) for neurocognitive task outcome measures, per each group (Exercise—EG/Control—CG) and Session (Pre/Post). Mean deltas are calculated as a difference between Pre and Post: Pre—Post. Differences denoting an improvement in the Post compared to the Pre are signalled with an arrow pointing up. Conversely, differences indicating a worse performance have a downward arrow. Values in bold reveal which one, between the two groups, performed better (or less worse) for each outcome measure across sessions.

SWM

On Spatial Working Memory (SWM) between error scores, collectively, both groups of participants made fewer mistakes during the 'post' session, but there was no significant difference between the two groups: indeed there was a main effect of Session, $F_{(1,46)} = 4.63$, $p = 0.037$, $\eta^2_p = 0.092$ but no main effect of Group, $F_{(1,46)} = 0.04$, $p = 0.83$, $\eta^2_p = 0.0009$, and no significant interaction effect, $F_{(1,46)} = 1.56$, $p = 0.22$, $\eta^2_p = 0.033$. Regarding within errors, the performance of both groups basically did not vary between sessions: indeed there was no significant main effects for Session, $F_{(1,46)} = 0.12$, $p = 0.73$, $\eta^2_p = 0.003$ or Group, $F_{(1,46)} = 0.06$, $p = 0.80$, $\eta^2_p = 0.001$, and there was no significant Session * Group interaction effect, $F_{(1,46)} = 0.004$, $p = 0.95$, $\eta^2_p = 0.00005$. For total errors, EG showed a much more pronounced better performance during the 'post' session: indeed, while there was no significant main effect of Group if Session was not considered: ($F_{(1,46)} = 0.060$, $p = 0.80$, $\eta^2_p = 0.001$), there was a significant main effect of Session, ($F_{(1,46)} = 5.56$, $p = 0.023$, $\eta^2_p = 0.11$) and a trend toward an interaction effect between Session and Group was found: $F_{(1,46)} = 3.46$, $p = 0.07$, $\eta^2_p = 0.07$. Explorative Bonferroni-corrected

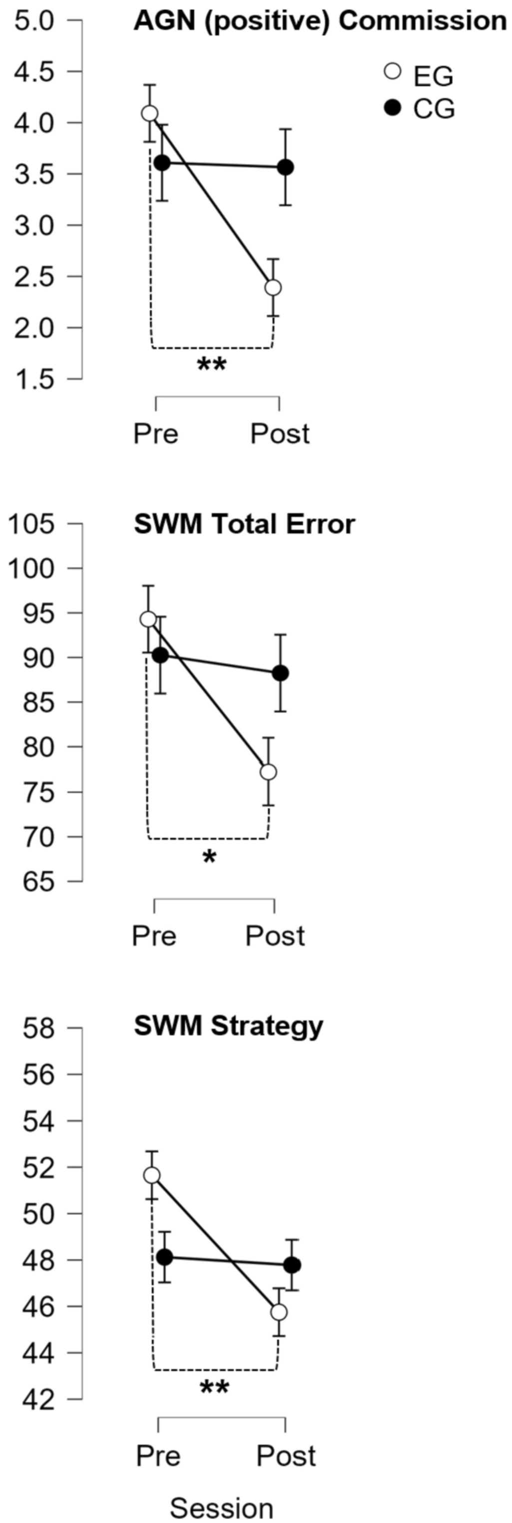

Fig. 1. Means and SEs for each Group (EG: experimental group, CG: control group) and Session (Pre, Post) relative to the three outcome measures for which significant results were found. Scores levels are reported on the Y axis and asterisks denote significant differences (*p < 0.05, **p < 0.01).

post-hoc effects showed that this trend was in the direction of fewer total errors on post-testing from the EG participants ($p = 0.027$).

Also for SWM strategy scores the two groups behaved significantly different, with the EG showing a better strategy score during the 'post' session: in particular, there was no main effect of Group, $F_{(1,46)} = 0.05$, $p = 0.8$, $\eta^2_p = 0.001$, but there was a significant main effect of Session ($F_{(1,46)} = 8.67$, $p = 0.005$, $\eta^2_p = 0.16$) and there was a significant interaction effect of Session * Group: $F_{(1,46)} = 6.87$, $p = 0.01$, $\eta^2_p = 0.13$. Bonferroni-corrected post-hoc effects showed that only the EG made significantly less errors in the post-test compared to the pre-test ($p = 0.002$).

Time to first and last response both showed a similar strong effect of time (Session), with both groups showing a strong reduction of reaction times during the 'post' session, but no other significant effects (respectively, Session: $F_{(1,46)} = 17.99$, $p < 0.001$, $\eta^2_p = 0.28$; Group: $F_{(1,46)} = 3.13$ $p = 0.08$, $\eta^2_p = 0.06$; Session * Group: $F_{(1,46)} = 2.41$, $p = 0.12$, $\eta^2_p = 0.050$. Session: $F_{(1,46)} = 19.09$, $p < 0.001$, $\eta^2_p = 0.29$; Group: $F_{(1,46)} = 0.01$, $p = 0.91$, $\eta^2_p = 0.0002$; Session * Group: $F_{(1,46)} = 0.17$, $p = 0.67$, $\eta^2_p = 0.004$.

SRT

Omission scores could not enter the ANOVA because they were all zeros (no missed responses). Beside a trend to significance for the 'Session' factor of the accuracy scores, likely due to a mere learning effect, no actual statistical differences were found at this task as in all other measures of SRT: mean latencies—Session: $F_{(1,46)} = 0.41$, $p = 0.52$, $\eta^2_p = 0.009$; Group: $F_{(1,46)} = 0.99$, $p = 0.32$, $\eta^2_p = 0.021$; Session * Group: $F_{(1,46)} = 0.26$, $p = 0.60$, $\eta^2_p = 0.006$. Accuracy—Session: $F_{(1,46)} = 3.63$, $p = 0.06$, $\eta^2_p = 0.07$; Group: $F_{(1,46)} = 1.27$, $p = 0.26$, $\eta^2_p = 0.02$; Session * Group: $F_{(1,46)} = 0.001$, $p = 0.97$, $\eta^2_p = 0.00002$. Commission—Session: $F_{(1,46)} = 1.64$, $p = 0.20$, $\eta^2_p = 0.03$; Group: $F_{(1,46)} = 0.47$, $p = 0.50$, $\eta^2_p = 0.01$; Session * Group: $F_{(1,46)} = 2.49$, $p = 0.12$, $\eta^2_p = 0.05$.

Backward counting

Participants from both groups made fewer errors at the backward counting during the 'post' session compared to 'pre', but there was no difference between the two groups: the ANOVA on the errors made during the backward counting showed a main effect of Session ($F_{(1,46)} = 5.69$, $p = 0.02$, $\eta^2_p = 0.11$) but no Group or interaction effects (respectively: $F_{(1,46)} = 0.21$, $p = 0.65$, $\eta^2_p = 0.005$; $F_{(1,46)} = 1.12$, $p = 0.29$, $\eta^2_p = 0.02$). Both groups were faster at responding during the 'post' session and the EG was overall faster in responding, regardless of the session: the analysis of the time taken to complete the task revealed a main effect of both Session and Group (respectively: $F_{(1,46)} = 29.15$, $p < 0.001$, $\eta^2_p = 0.39$; $F_{(1,46)} = 5.66$, $p = 0.02$, $\eta^2_p = 0.11$) but no interaction effect: $F_{(1,46)} = 0.10$, $p = 0.75$, $\eta^2_p = 0.002$.

Discussion

We explored the effects of acute exercise on the cognitive performance of a group of healthy older adults. Our results revealed a clear effect of exercise in three of the measures considered. In particular, a significant interaction effect was found for AGN + commission errors, with the EG making, on average, fewer errors after exercise than before exercise. Conversely, the CG made almost the same amount of errors during the 'post' session. The AGN tests response inhibition, and commission errors in particular may be viewed as an inhibition failure[68]. Thus, the improvement in the EG's performance relative to the CG in AGN commission errors supports previous findings that acute exercise can enhance younger, middle-aged and older adults' performance on tasks requiring inhibitory control[16,69–73]. Furthermore, research on longer-term, rather than acute, exercise suggests that inhibitory control is particularly strongly impacted relative to other cognitive functions. For example, Boucard et al.[74] found that physical activity level among older adults positively influences inhibitory function, but not task shifting and updating functions. Yet, aerobic fitness training has been shown to have a positive effect on task switching in older adults[75]. To our knowledge, the present study is the first to investigate the effects of physical activity on an affective go/no-go task, thus making inferences about why an effect was found only for positive words may prove hazardous. Yet, it is known that affective processes trigger the representation of approach-avoidance behaviour[76] and that stimuli with opposite valence have a differential effect on psychophysics, with response times generally slower for negative stimuli[77]. This said, further evidence is needed to prove that exercise has a different effect depending on the valence of the stimuli. Also, while it is well known that exercise improves inhibitory control, the mechanisms behind such cognitive improvement remain unclear. A study on the effects of an acute bout of moderate-intensity exercise on executive control (including inhibitory control) in older adults, reported a significantly greater functional activation (incongruent > congruent) in the left inferior frontal gyrus and inferior parietal lobule after exercise compared to rest[78]. A recent activation-likelihood-estimation (ALE) meta-analysis[79], on both acute and chronic exercise, suggests a hyper-connectivity in the default mode network (DMN) regions with an improved coupling between the DMN and the frontal-parietal network, and activations of the dorsolateral prefrontal cortex-caudate circuit and of the pathway extending from the left anterior middle temporal gyrus and the left anterior insula to the lateral orbitofrontal cortex[79].

The other two outcome measures where a clear effect was found were both in the remit of SWM: errors and strategy. These results are in line with several studies showing how working memory is frequently enhanced directly after acute and chronic exercise. For example, Tsujii and coworkers found that acute exercise improved performance in a working memory task among healthy older adults compared to when these same participants rested between test sessions[80]. A similar improvement in working memory was also found in a sample of post-stroke patients after 15 min exercise on a cycling ergometer[81]. A greater preservation of hippocampal volume, associated with a better accuracy and RTs during spatial working memory tasks have been shown in older adults with higher levels of fitness[82]. Nonetheless, a meta-analysis of 15 studies across age groups found that unlike chronic exercise, which is reliably associated with working memory improvements, acute exercise does not have a significant positive impact on working memory task performance[83]. However, as the same authors of the review acknowledge, several factors may have limited the generalizability of the results[83]. Additionally, there is evidence that SWM task difficulty may mediate the effect of acute exercise on performance: in a young adult sample, Yamazaki and colleagues[84] found that light cycling for 10 min improved SWM performance in the low difficulty condition (remembering the location of 1 black dot), but exercise did not significantly improve SWM performance in the high difficulty condition (remembering the location of 3 black dots). In the present study the SWM task involved remembering between six and twelve token locations in a round, thus the difficulty level was higher than in Yamazaki's study. Yet, our EG did significantly better after the acute exercise. Therefore, it is possible that only 10 min of light exercise as in Yamizaki's study, may not be sufficient to get the full beneficial effect of physical activity on SWM tasks when the complexity of these becomes more cognitively demanding. We are inclined to think that the length of exercise could have actually contributed to this disparity between our and Yamizaki's finding: in a study run on twenty-six healthy young adults, a Stroop test was administered after either 10, 20 or 45 min. of moderate exercise. A curvilinear dose–response relation was found, with 20 min exercise improving cognition while 10 or 45 min had negligible effects[85]. Hence, our decision to have a 20 min exercise session for our EG may have led to the maximum expression of the benefits of physical activity on cognition. Yet, out of all the measures considered in the present experiment, only three of them showed a significant improvement. Chang et al.'s meta-analysis suggests that in the case of light—especially very light—exercise, facilitatory effects on cognitive function may dissipate more quickly than with more intense exercise[24]. This would align with the neurophysiological theory that light intensity exercise may not be sufficient to activate the underlying molecular mechanisms (such as upregulation of BDNF) which can contribute to improved cognitive function[86]. Therefore, possible shortcomings linked to the Knoepfli-Lenzin et al.'s target heart rate formula[60] could be addressed by pairing heart rate monitoring with use of the Borg Rating of Perceived Exertion (RPE) Scale[87,88], which seems to be a practical tool for monitoring and prescribing exercise intensity, independent of gender, age, exercise modality, physical activity level and coronary artery disease status[89]. One further explanation for the lack of effect of acute exercise on cognitive task performance may be linked to the pre-test/post-test design. Indeed, practice effects on neuropsychological tests of cognitive function may be at their strongest between the first and second round of tests for older adults, and thereby risk obscuring the effects of the intervention[90].

At last, it should be noted that the various tasks considered in our and in similar studies rely on different brain networks. For instance, tasks like the SWM are known to rely on a broad range of neuroanatomical structures such as the hippocampus, the parietal and the prefrontal cortex[91,92], which may be sensitive to the beneficial effects of exercise. Indeed, a single session of acute exercise has been linked to glial, synaptic and dendritic processes which yield beneficial microstructural alterations in the hippocampus of healthy older adults[93]. Thus, it is plausible to think that certain specific parameters adopted during acute exercise interventions may lead to a measurable effect because some brain networks have benefitted, for a limited time, more from them than others. Along this line, Kennedy and colleagues[94] investigated whether greater fitness and lower aortic stiffness predicted better cognitive performance in a cohort of healthy older adults. Both higher fitness and lower central arterial stiffness significantly, and independently, explained better SWM performance, even after adjusting for the effects of age, sex, and BMI. Importantly however, no such relationships were found for the other measures of cognition like Simple and Choice Reaction Time, Immediate Recognition, Stroop, Contextual Memory and Delayed Recognition[94]. The fMRI results of a study on middle-aged adults further suggest that the neural basis for a better performance at a SWM task may reside in a greater activation, while carrying out such task, of a specific neural network. In those individuals regularly practicing open-skill exercises (e.g., tennis, table tennis, badminton) this network includes the left inferior frontal gyrus (IFG), the left anterior cingulate cortex (ACC)/supplementary motor area (SMA), the left thalamus, and the right hippocampus[95].

Our study has practical implications for promoting cognitive health as well as cardiovascular health. Reduced physical activity in adults aged 60 or over has been associated with lower quality-of-life[96] and yet it has been shown that few older adults are able to meet the recommended physical activity guidelines[97]. Sparling and colleagues argue that it is important for healthcare practitioners to encourage a realistic level of physical activity, involving reduced sedentary time and incorporating brief bouts of exercise into everyday life[98]. In keeping with this perspective, our study suggests that even a short amount of exercise can positively affect certain EFs such as inhibition control and working memory; and this could provide an additional motivation for older adults to integrate brief periods of exercise into their daily routines. Furthermore, since acute exercise is the building block of a long-term, more regular form of exercise (i.e. "chronic exercise"), understanding the effects that a singular bout of exercise may have on cognition can offer new insights into how to interpret and approach the study of the effects of chronic increases in physical exercise on cognitive function[23]. Also, acute exercise effects can predict chronic exercise effects in cognition and functional brain measures[99].

Before we conclude, we should also acknowledge some limitations of our study. For instance, while we did keep track of the socio-demographic characteristics of our participants, along with BDI and MMSE scores, we did not control for the time of the day each participant had been tested. Indeed, even though the time of the day may not affect all cognitive functions equally[100], circadian variations can still occur for attentional capacities, executive functioning, and memory[101]. Another factor we did not consider is the level of fitness of our participants, or if they engaged with physical activity just before the study. Although Ludyga et al.'s meta-analysis[35] suggested that across studies, fitness level does not significantly influence the effect of exercise on cognitive function, and considering that our pre-post design allowed, to some extent, for a control of each participant's baseline, their previous engagement with physical activity may still have affected the results. After all, not only is a regular engagement with physical activity associated with a greater ability to allocate attentional resources toward the environment and to more efficiently process information[102], but also the post-exercise recovery duration can interact with the fitness level to influence the effect of acute exercise on cognitive functions like memory, so that individuals with higher levels of aerobic endurance, compared to their less fit counterparts, have greater memory performance after exercise[103]. Furthermore, while we monitored the HR of our participants (in the EG) throughout their physical exercise to make sure it stayed within the 'moderate' boundaries for their age, we did not actually record it. Keeping a record of the HR in both groups could have added useful information regarding this physiological parameter as it is linked to cognitive performance[104,105]. Finally, while the level of activity was monitored via such physiological parameter, it would have been interesting to keep track of the perceived exertion too (for instance via a Borg scale[106]), given its potential role in modulating cognitive performance[107].

Conclusion

In conclusion, the present study corroborated and extended previous findings that a moderate intensity bout of acute exercise can improve inhibitory control functions and aspects of working memory.

In particular, the measures that showed a significant improvement were the CANTAB's AGN (positive) Commission, the SWM total errors and SWM strategy. While an amelioration in the performance of other tests could be recorded after the intervention, only in the aforementioned tests could the facilitatory effect of acute exercise be statistically ascertained. Since we could only focus our attention on a restricted range of EFs, future studies could test the effects of a single bout of exercise on other aspects like planning or set shifting[52]. Also, future endeavours could check if and how the results change after controlling for factors such as level of fitness and time of the day when the test occurs.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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References

1. OECD. *Preventing Ageing Unequally*. (OECD, 2017). https://doi.org/10.1787/9789264279087-en.
2. Harper, S. Economic and social implications of aging societies. *Science* **1979**(346), 587–591 (2014).
3. Hedden, T. & Gabrieli, J. D. E. Insights into the ageing mind: a view from cognitive neuroscience. *Nat. Rev. Neurosci.* **5**, 87–96 (2004).
4. Ferguson, H. J., Brunsdon, V. E. A. & Bradford, E. E. F. The developmental trajectories of executive function from adolescence to old age. *Sci. Rep.* https://doi.org/10.1038/s41598-020-80866-1 (2021).
5. Colcombe, S. J. et al. Aerobic exercise training increases brain volume in aging humans. *J. Gerontol. A Biol. Sci. Med. Sci.* **61**, 1166–1170 (2006).
6. Colcombe, S. & Kramer, A. F. Fitness effects on the cognitive function of older adults: a meta-analytic study. *Psychol. Sci.* **14**, 125–130 (2003).
7. Erickson, K. I. et al. Aerobic fitness is associated with hippocampal volume in elderly humans. *Hippocampus* **19**, 1030–1039 (2009).
8. Hamer, M., Terrera, G. M. & Demakakos, P. Physical activity and trajectories in cognitive function: English Longitudinal Study of Ageing. *J. Epidemiol. Community Health* **1978**(72), 477–483 (2018).
9. Erickson, K. I., Gildengers, A. G. & Butters, M. A. Physical activity and brain plasticity in late adulthood. *Dialogues Clin. Neurosci.* **15**, 99–108 (2013).
10. Burke, S. N. & Barnes, C. A. Neural plasticity in the ageing brain. *Nat. Rev. Neurosci.* **7**, 30–40 (2006).
11. Marques-Aleixo, I., Oliveira, P. J., Moreira, P. I., Magalhães, J. & Ascensão, A. Physical exercise as a possible strategy for brain protection: evidence from mitochondrial-mediated mechanisms. *Prog. Neurobiol.* **99**, 149–162 (2012).
12. Erickson, K. I., Donofry, S. D., Sewell, K. R., Brown, B. M. & Stillman, C. M. Cognitive aging and the promise of physical activity. *Annu. Rev. Clin. Psychol.* **18**, 417–442 (2022).
13. Szuhany, K. L., Bugatti, M. & Otto, M. W. A meta-analytic review of the effects of exercise on brain-derived neurotrophic factor. *J. Psychiatr. Res.* **60**, 56–64 (2015).
14. Patten, A. R. et al. Long-term exercise is needed to enhance synaptic plasticity in the hippocampus. *Learn. Mem.* **20**, 642–647 (2013).
15. Fernandes, J., Arida, R. M. & Gomez-Pinilla, F. Physical exercise as an epigenetic modulator of brain plasticity and cognition. *Neurosci. Biobehav. Rev.* **80**, 443-456. (2017).
16. Kamijo, K. et al. Acute effects of aerobic exercise on cognitive function in older adults. *J. Gerontol. B Psychol. Sci. Soc. Sci.* **64**, 356–363 (2009).
17. MacDonald, E. et al. Moderate intensity intermittent lifestyle physical activity is associated with better executive function in older adults. *Front. Sports Act. Living* https://doi.org/10.3389/fspor.2024.1393214 (2024).
18. Miyake, A. et al. The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: a latent variable analysis. *Cogn. Psychol.* **41**, 49–100 (2000).
19. Diamond, A. Executive functions. *Handb. Clin. Neurol.* **173**, 225–240 (2020).
20. Beard, J. R. et al. The world report on ageing and health: a policy framework for healthy ageing. *Lancet* **387**, 2145–2154 (2016).
21. Weng, T. B., Pierce, G. L., Darling, W. G. & Voss, M. W. Differential effects of acute exercise on distinct aspects of executive function. *Med. Sci. Sports Exerc.* **47**, 1460–1469 (2015).
22. McMorris, T., Sproule, J., Turner, A. & Hale, B. J. Acute, intermediate intensity exercise, and speed and accuracy in working memory tasks: a meta-analytical comparison of effects. *Physiol. Behav.* **102**, 421–428 (2011).
23. Basso, J. C. & Suzuki, W. A. The effects of acute exercise on mood, cognition, neurophysiology, and neurochemical pathways: a review. *Brain Plast.* **2**, 127–152 (2017).
24. Chang, Y. K., Labban, J. D., Gapin, J. I. & Etnier, J. L. The effects of acute exercise on cognitive performance: a meta-analysis. *Brain Res.* **1453**, 87–101 (2012).
25. Barella, L. A., Etnier, J. L. & Chang, Y. K. The immediate and delayed effects of an acute bout of exercise on cognitive performance of healthy older adults. *J. Aging Phys. Act.* **18**, 87–98 (2010).
26. Johnson, L. et al. An acute bout of exercise improves the cognitive performance of older adults. *J. Aging Phys. Act.* **24**, 591–598 (2016).
27. Justine, M., Azizan, A., Hassan, V., Salleh, Z. & Manaf, H. Barriers to participation in physical activity and exercise among middle-aged and elderly individuals. *Singapore Med. J.* **54**, 581–586 (2013).
28. Hyodo, K. et al. Acute moderate exercise enhances compensatory brain activation in older adults. *Neurobiol. Aging* **33**, 2621–2632 (2012).
29. Davey, C. P. Physical exertion and mental performance. Vol. 16, 595–599 https://doi.org/10.1080/00140137308924455016 (2007).
30. Yerkes, R. M. & Dodson, J. D. The relation of strength of stimulus to rapidity of habit-formation. *J. Compar. Neurol. Psychol.* **18**, 459–482 (1908).

31. Damrongthai, C. et al. Benefit of human moderate running boosting mood and executive function coinciding with bilateral prefrontal activation. *Sci. Rep.* **11**(1), 1–12 (2021).
32. Donahue, E. K. et al. Physical activity intensity is associated with cognition and functional connectivity in Parkinson's disease. *Parkinsonism Relat. Disord.* **104**, 7–14 (2022).
33. Chang, Y. K., Chu, C. H., Wang, C. C., Song, T. F. & Wei, G. X. Effect of acute exercise and cardiovascular fitness on cognitive function: an event-related cortical desynchronization study. *Psychophysiology* **52**, 342–351 (2015).
34. Chu, C. H., Chen, A. G., Hung, T. M., Wang, C. C. & Chang, Y. K. Exercise and fitness modulate cognitive function in older adults. *Psychol. Aging* **30**, 842–848 (2015).
35. Ludyga, S., Gerber, M., Brand, S., Holsboer-Trachsler, E. & Pühse, U. Acute effects of moderate aerobic exercise on specific aspects of executive function in different age and fitness groups: A meta-analysis. *Psychophysiology* **53**, 1611–1626 (2016).
36. Folstein, M. F., Folstein, S. E. & McHugh, P. R. 'Mini-mental state' A practical method for grading the cognitive state of patients for the clinician. *J. Psychiatr. Res.* **12**, 189–198 (1975).
37. Kochhann, R., Varela, J. S., de Macedo Lisboa, C. S. & Chaves, M. L. F. The Mini Mental State Examination: Review of cutoff points adjusted for schooling in a large Southern Brazilian sample. *Dement. Neuropsychol.* **4**, 35–41 (2010).
38. Di Carlo, A. et al. Incidence of dementia, Alzheimer's disease, and vascular dementia in Italy. The ILSA study. *J. Am. Geriatr. Soc.* **50**, 41–48 (2002).
39. Giordano, M. et al. Screening of depressive symptoms in young-old hemodialysis patients: relationship between Beck Depression Inventory and 15-item Geriatric Depression Scale. *Nephron Clin. Pract.* **106**, c187–c192 (2007).
40. Zhou, J. et al. Optimal cut-offs of depression screening tools during the COVID-19 pandemic: a systematic review. *BMC Psychiatry* https://doi.org/10.1186/s12888-023-05455-8 (2023).
41. Carney, C. E., Ulmer, C., Edinger, J. D., Krystal, A. D. & Knauss, F. Assessing depression symptoms in those with insomnia: an examination of the beck depression inventory second edition (BDI-II). *J. Psychiatr. Res.* **43**, 576–582 (2009).
42. Lam, R. W., Kennedy, S. H., McIntyre, R. S. & Khullar, A. Cognitive dysfunction in major depressive disorder: effects on psychosocial functioning and implications for treatment. *Can. J. Psychiatry* **59**, 649–654 (2014).
43. Mahoney, C. R., Taylor, H. A., Kanarek, R. B. & Samuel, P. Effect of breakfast composition on cognitive processes in elementary school children. *Physiol. Behav.* **85**, 635–645 (2005).
44. Nehlig, A. Is caffeine a cognitive enhancer?. *J. Alzheimers Dis.* **20**(Suppl 1), S85–S94 (2010).
45. Knight, M. & Mather, M. Look out-it's your off-peak time of day! Time of day matters more for alerting than for orienting or executive attention. *Exp. Aging Res.* **39**, 305–321 (2013).
46. Veale, J. F. Edingburgh Handedness Inventory—Short Form: A revised version based on confirmatory factor analysis. *Laterality Asymmetries Body Brain Cogn.* **19**, 164–177 (2014).
47. Beck, A., Ward, C., Mendelson, M., Mock, J. & Erbaugh, J. An inventory for measuring depression. *Arch. Gen. Psychiatry* **4**, 561–571 (1961).
48. Smith, M. F. Research methods in sport [2nd Edition]. 208 (2017).
49. Meule, A. Reporting and interpreting task performance in Go/no-go affective shifting tasks. *Front. Psychol.* **8**, 261225 (2017).
50. Piskulic, D., Olver, J. S., Norman, T. R. & Maruff, P. Behavioural studies of spatial working memory dysfunction in schizophrenia: A quantitative literature review. *Psychiatry Res.* **150**, 111–121 (2007).
51. Lezak, ꞓm. D., Howieson, D. B., Loring, D. W., Hannay, H. J. & Fischer, J. S. Neuropsychological asessment 4 Ed. 1016 (2004).
52. Diamond, A. Executive functions. *Annu. Rev. Psychol.* **64**, 135–168 (2013).
53. Schmitt, A. et al. Effects of low- and high-intensity exercise on emotional face processing: an fMRI face-matching study. *Soc. Cogn. Affect. Neurosci.* **14**, 657–667 (2019).
54. Kommula, Y. et al. Emotional processing and positive affect after acute exercise in healthy older adults. *Psychophysiology* https://doi.org/10.1111/psyp.14357 (2023).
55. Drewe, E. A. Go - no go learning after frontal lobe lesions in humans. *Cortex* **11**, 8–16 (1975).
56. Karlsen, R. H. et al. Examining 3-month test-retest reliability and reliable change using the Cambridge Neuropsychological Test Automated Battery. *Appl. Neuropsychol. Adult.* **29**, 146–154 (2022).
57. Hawkins, K. A., Cromer, J. R., Piotrowski, A. S. & Pearlson, G. D. Mini-Mental State Exam performance of older African Americans: effect of age, gender, education, hypertension, diabetes, and the inclusion of serial 7s subtraction versus 'world' backward on score. *Arch. Clin. Neuropsychol.* **26**, 645–652 (2011).
58. Halcox, J. P. J. et al. Assessment of remote heart rhythm sampling using the AliveCor heart monitor to screen for atrial fibrillation: The REHEARSE-AF Study. *Circulation* **136**, 1784–1794 (2017).
59. Jewson, J. L. et al. Use of a smartphone electrocardiogram to diagnose arrhythmias during exercise in athletes: a case series. *Eur. Heart J. Case Rep.* https://doi.org/10.1093/ehjcr/ytac126 (2022).
60. Knoepfli-Lenzin, C., Haenggli, B. & Boutellier, U. Optimised heart rate formulae to monitor endurance training in sedentary individuals. *J. Sports Sci.* **32**, 557–562 (2014).
61. Loprinzi, P. D. & Kane, C. J. Exercise and cognitive function: a randomized controlled trial examining acute exercise and free-living physical activity and sedentary effects. *Mayo Clin. Proc.* **90**, 450–460 (2015).
62. Hung, T. M., Tsai, C. L., Chen, F. T., Wang, C. C. & Chang, Y. K. The immediate and sustained effects of acute exercise on planning aspect of executive function. *Psychol. Sport Exerc.* **14**, 728–736 (2013).
63. Hogan, C. L., Mata, J. & Carstensen, L. L. Exercise holds immediate benefits for affect and cognition in younger and older adults. *Psychol. Aging* **28**, 587–594 (2013).
64. Peiffer, R., Darby, L. A., Fullenkamp, A. & Morgan, A. L. Effects of acute aerobic exercise on executive function in older women. *J. Sports Sci. Med.* **14**, 574 (2015).
65. Barbaranelli, C. *Analisi Dei Dati. Tecniche Multivariate per La Ricerca Psicologica e Sociale*. Vol. 8 (2003).
66. Blanca, M. J., Alarcón, R., Arnau, J., Bono, R. & Bendayan, R. Non-normal data: Is ANOVA still a valid option?. *Psicothema* **29**, 552–557 (2017).
67. Richardson, J. T. E. Eta squared and partial eta squared as measures of effect size in educational research. *Educ. Res. Rev.* **6**, 135–147 (2011).
68. Congdon, E. et al. Measurement and reliability of response inhibition. *Front. Psychol.* https://doi.org/10.3389/fpsyg.2012.00037 (2012).
69. Shigeta, T. T. et al. Acute exercise effects on inhibitory control and the pupillary response in young adults. *Int. J. Psychophysiol.* **170**, 218–228 (2021).
70. Aguirre-Loaiza, H. et al. Effect of acute physical exercise on inhibitory control in young adults: High-intensity indoor cycling session. *Physiol. Behav.* **254**, 113902 (2022).
71. Silveira-Rodrigues, J. G. et al. Acute bouts of aerobic and resistance exercise similarly alter inhibitory control and response time while inversely modifying plasma BDNF concentrations in middle-aged and older adults with type 2 diabetes. *Exp. Brain Res.* **241**, 1173–1183 (2023).
72. Fujihara, H., Megumi, A. & Yasumura, A. The acute effect of moderate-intensity exercise on inhibitory control and activation of prefrontal cortex in younger and older adults. *Exp. Brain Res.* **239**, 1765–1778 (2021).
73. Netz, Y. et al. Acute aerobic activity enhances response inhibition for less than 30min. *Brain Cogn.* **109**, 59–65 (2016).
74. Boucard, G. K. et al. Impact of physical activity on executive functions in aging: a selective effect on inhibition among old adults. *J. Sport Exerc. Psychol.* **34**, 808–827 (2012).

75. Kramer, A. F. et al. Ageing, fitness and neurocognitive function. *Nature* **400**, 418–419 (1999).
76. Krieglmeyer, R., Deutsch, R., de Houwer, J. & de Raedt, R. Being moved: valence activates approach-avoidance behavior independently of evaluation and approach-avoidance intentions. *Psychol. Sci.* **21**, 607–613 (2010).
77. Bendall, R. C. A., Eachus, P. & Thompson, C. The influence of stimuli valence, extraversion, and emotion regulation on visual search within real-world scenes. *Sci. Rep.* **12**(1), 1–10 (2022).
78. Won, J., Alfini, A. J., Weiss, L. R., Callow, D. D. & Smith, J. C. Brain activation during executive control after acute exercise in older adults. *Int. J. Psychophysiol.* **146**, 240–248 (2019).
79. Wu, J. et al. Effects of exercise on neural changes in inhibitory control: an ALE meta-analysis of fMRI studies. *Front. Hum. Neurosci.* **16**, 891095 (2022).
80. Tsujii, T., Komatsu, K. & Sakatani, K. Acute effects of physical exercise on prefrontal cortex activity in older adults: a functional near-infrared spectroscopy study. *Adv. Exp. Med. Biol.* **765**, 293–298 (2013).
81. Moriya, M., Aoki, C. & Sakatani, K. Effects of physical exercise on working memory and prefrontal cortex function in post-stroke patients. *Adv. Exp. Med. Biol.* **923**, 203–208 (2016).
82. Szabo, A. N. et al. Cardiorespiratory fitness, hippocampal volume, and frequency of forgetting in older adults. *Neuropsychology* **25**, 545–553 (2011).
83. Rathore, A. & Lom, B. The effects of chronic and acute physical activity on working memory performance in healthy participants: a systematic review with meta-analysis of randomized controlled trials. *Syst. Rev.* https://doi.org/10.1186/s13643-017-0514-7 (2017).
84. Yamazaki, Y. et al. Inter-individual differences in exercise-induced spatial working memory improvement: a near-infrared spectroscopy study. *Adv. Exp. Med. Biol.* **977**, 81–88 (2017).
85. Chang, Y. K. et al. Dose-response relation between exercise duration and cognition. *Med. Sci. Sports Exerc.* **47**, 159–165 (2015).
86. Ratey, J. J. & Loehr, J. E. The positive impact of physical activity on cognition during adulthood: a review of underlying mechanisms, evidence and recommendations. *Rev. Neurosci.* **22**, 171–185 (2011).
87. Borg, G. A. V. Psychophysical bases of perceived exertion. *Med. Sci. Sports Exerc.* **14**, 377–381 (1982).
88. Borg, G., Hassmén, P. & Lagerström, M. Perceived exertion related to heart rate and blood lactate during arm and leg exercise. *Eur. J. Appl. Physiol. Occup. Physiol.* **56**, 679–685 (1987).
89. Scherr, J. et al. Associations between Borg's rating of perceived exertion and physiological measures of exercise intensity. *Eur. J. Appl. Physiol.* **113**, 147–155 (2013).
90. Collie, A., Maruff, P., Darby, D. G. & McStephen, M. The effects of practice on the cognitive test performance of neurologically normal individuals assessed at brief test–retest intervals. *J. Int. Neuropsychol. Soc.* **9**, 419–428 (2003).
91. Constantinidis, C. & Wang, X. J. A neural circuit basis for spatial working memory. *Neuroscientist* **10**, 553–565 (2004).
92. van Asselen, M. et al. Brain areas involved in spatial working memory. *Neuropsychologia* **44**, 1185–1194 (2006).
93. Callow, D. D. et al. Microstructural plasticity in the hippocampus of healthy older adults after acute exercise. *Med. Sci. Sports Exerc.* **53**, 1928–1936 (2021).
94. Kennedy, G. et al. Physical fitness and aortic stiffness explain the reduced cognitive performance associated with increasing age in older people. *J. Alzheimers Dis.* **63**, 1307–1316 (2018).
95. Chen, F. T. et al. Effects of exercise modes on neural processing of working memory in late middle-aged adults: an fMRI study. *Front. Aging Neurosci.* https://doi.org/10.3389/fnagi.2019.00224 (2019).
96. Yerrakalva, D. et al. Associations between change in physical activity and sedentary time and health-related quality of life in older English adults: the EPIC-Norfolk cohort study. *Health Qual. Life Outcomes* https://doi.org/10.1186/s12955-023-02137-7 (2023).
97. Jefferis, B. J. et al. Adherence to physical activity guidelines in older adults, using objectively measured physical activity in a population-based study. *BMC Public Health* https://doi.org/10.1186/1471-2458-14-382 (2014).
98. Sparling, P. B., Howard, B. J., Dunstan, D. W. & Owen, N. Recommendations for physical activity in older adults. *BMJ* **350**, h100 (2015).
99. Voss, M. W. et al. Acute exercise effects predict training change in cognition and connectivity. *Med. Sci. Sports Exerc.* **52**, 131–140 (2020).
100. Knight, M. & Mather, M. Look out—it's your off-peak time of day! Time of day matters more for alerting than for orienting or executive attention. *Exp. Aging Res.* **39**, 305 (2013).
101. Schmidt, C., Collette, F., Cajochen, C. & Peigneux, P. A time to think: circadian rhythms in human cognition. *Cogn. Neuropsychol.* **24**, 755–789 (2007).
102. Gomez-Pinilla, F. & Hillman, C. The influence of exercise on cognitive abilities. *Compr. Physiol.* **3**, 403 (2013).
103. Loprinzi, P. D., Roig, M., Tomporowski, P. D., Javadi, A. H. & Kelemen, W. L. Effects of acute exercise on memory: Considerations of exercise intensity, post-exercise recovery period and aerobic endurance. *Mem. Cogn.* **51**, 1011–1026 (2023).
104. Gonnelli, F. et al. Physical capacities and leisure activities are related with cognitive functions in older adults. *J. Sports Med. Phys. Fitness* **62**, 131–138 (2022).
105. Ma, Z. et al. Associations between resting heart rate and cognitive decline in Chinese oldest old individuals: a longitudinal cohort study. *BMC Geriatr.* https://doi.org/10.1186/s12877-023-04600-y (2024).
106. Borg, G. Borg's perceived exertion and pain scales. (1998).
107. Hogg, J. A. et al. Changes in dual-task cognitive performance elicited by physical exertion vary with motor task. *Front. Sports Act Living* https://doi.org/10.3389/fspor.2022.989799 (2022).

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Author contributions

M.M. and A.F.K. conceptualized the study and the experimental design. J.E. collected the data. M.M. run the analysis and made the figure and tables. A.F.K. supervised the analytic process and provided insights on the results. J.E. and M.M drafted a first version of the manuscript. A.F.K., J.E. and M.M. revised the manuscript until its last version.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to M.M.