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Original Article

The differential effect of strength, cognitive and aerobic training combinations on cognitive performance and functional abilities in elderly with cognitive decline: The Fit4Alz project

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ABSTRACT

Background: Despite the global impact of neurodegenerative diseases and ongoing research efforts, pharmacological therapies have shown limited benefits. In contrast, physical exercise, with no side effects, has emerged as a non-pharmacological alternative that can enhance brain structure and function, promoting a healthier neurological phenotype.
Objectives: This study aimed to explore the effects of aerobic and strength training methods, both with and without cognitive training, on mitigating or reversing cognitive decline in older adults.
Design, Setting, Participants: In a randomized controlled trial, a total of 350 participants (average age 72.9 ± 6.0 years, 79 % female), with signs of decline (MoCA score below 26), were assigned to one of five groups: i) strength plus cognitive training (STCT, $n = 92$); ii) strength training (ST, $n = 41$); iii) aerobic training (AT, $n = 97$); iv) aerobic plus cognitive training (ATCT, $n = 91$); v) control (CG, $n = 29$).
Intervention: For 12 weeks, all groups followed a 60 min training session three times a week, tailored to their specific group, with half of the sample adding 20 min of cognitive stimulation after the physical exercise.
Measurements: Cognitive and physical assessments were conducted at the start and end of the intervention using the MoCA and the Senior Fitness test. A mixed ANCOVA analysis revealed significant interactions between time and group for all tests.
Results: After the intervention, the CG showed significantly lower scores compared to all experimental groups. The CG also performed significantly worse than the ATCT group ($p < 0.001$). Additionally, the ATCT outperformed the STCT in the 6-min walk test ($p < 0.05$), while the STCT showed superior performance in the flexibility tests (sit and reach, back scratch) compared to the CG ($p < 0.05$).

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Conclusions: Results showed that 12-weeks of aerobic and strength training, with or without cognitive components, improved cognitive performance in older adults with cognitive decline, highlighting the importance of maintaining functional abilities for preserving skills, autonomy, independence, and quality of life in aging.

1. Introduction

Aging is characterized by a progressive decline in physiological, cognitive, and functional capacities[1], which can lead to reduced mobility, loss of autonomy, and diminished independence [2–4]. When this decline in functional capacity is compounded by physical inactivity, the risk of developing neurodegenerative conditions increases. These conditions initially manifest as mild impairments in executive skills [5], but progress to severe cognitive decline, ultimately compromising quality of life throughout the aging process [6–8]. Today, physical inactivity represents more than 20 % of the risk for development of dementia in European older adults [9]. Therefore, physical exercise is a high-efficient low-cost strategy for retarding functional disability and neurodegenerative conditions in aging. In fact, our previous study demonstrated that aerobic and strength training, or their combination with cognitive training improve executive function and functional abilities in elderly with cognitive decline [10]. However, how different training components influence these gains still need to be elucidated.

Cognitive training has shown to be effective for improving perceptual skills, working memory, inhibitory control and general cognition in elderly [11–13]. However, its benefits appear to have some limitations in older individuals [14,15]. Aerobic exercise, instead, physiologically regulates the expression of a trophic factors and cellular mechanisms that drive memory formation, consolidation and retrieval [16,17]. It also promotes angiogenesis and neurogenesis [18], and supports the maintenance of cortical thickness and volume [19]. Studies consistently report that regular aerobic exercise can improve executive function even in aging individuals in the course of cognitive decline [20]. Martini et al. [19] have recently shown that a single 20-min of cycling at a moderate-intensity was sufficient to improve inhibitory control and working memory in health older adults. Further, the same authors reported that exercising three times per week during the course of 2 years was able to improve cognition and executive function in older adults with cognitive frailty. Studies show that low to moderate intensity aerobic exercise has a positive effect on domains of executive function and memory in aging individuals with and without neurodegenerative condition [21,22].

Studies have shown that integrating aerobic, strength, and cognitive exercises enhances dual-task performance, gait speed, and balance compared to single-domain interventions [23,24]. A 9-week program combining aerobic and strength training was more effective than aerobic training alone in slowing cognitive and motor decline in dementia patients [25]. Simultaneous exercise-cognitive training appears particularly beneficial for improving gait speed, balance, and functional mobility in cognitively healthy older adults[26]. These combined interventions may help reduce fall risk and enhance daily functioning by improving the ability to divide attention between motor and cognitive tasks (Fraser et al., 2017; van het Reve & de Bruin, 2014). While the exact mechanisms remain unclear, the evidence suggests that integrating cognitive and physical training can yield greater functional benefits than either approach alone.

With cognitive and aerobic training eligibly modify cognitive processes, reports of cognitive improvements in response to strength training are less present and might occur in a smaller scale. The meta-analysis performed by [27] reported that, in older adults, concurrent training with aerobic and resistance exercises had no effect on their global cognition when compared to active controls but revealed a positive effect when compared to sedentary controls. Conversely, a recent study by Ding et al. [28] demonstrated that combining resistance training with a cognitive task incremented the cognitive improvement in older adults, an effect that was not achieved by those in resistance training alone.

Combining cognitive tasks with aerobic and strength training may induce neurobiological changes that stimulate neuroplasticity via additive effects and provide a more consistent results [29,30]. However, the neurobiological changes evoked by the exercise component potentially play a major role in such stimulus-response. For instance, the study by Castellote-Caballero et al. [31] compared cognitive stimulation alone with a program that combined cognitive stimulation and psychomotor sessions including chair exercises, walks, wall exercises, stretches, ball passing and agility circuits. Their results showed improvements in physical and cognitive aspects only in the combined program group, and not in that of cognitive stimulation alone.

In our previous study, 12 weeks of traditional aerobic or strength training or their combination with cognitive training resulted in improvements in cognitive performance of elderly individuals [10]. However, any control group was analyzed. To address this limitation, the current study incorporated a control group to better investigate how distinct components of training might influence specific cognitive and functional outcomes. The main objectives of this study were to assess the impact of aerobic and resistance training, both with and without cognitive training, on cognitive and functional parameters in elderly individuals with cognitive decline. Specifically, we aimed to evaluate (i) whether aerobic and resistance training, with or without cognitive training, would lead to improvements in cognitive function; and (ii) whether the combination of physical and cognitive training would result in greater enhancements in cognitive function. Based on these objectives, we hypothesized that (i) aerobic and resistance training with or without cognitive training would improve the cognitive parameters in elderly with cognitive decline; (ii) combination of physical and cognitive training can enhance the improvements in cognitive function in elderly with cognitive decline.

2. Methods

2.1. Participants

Recruitment was conducted by directly reaching out to elderly individuals through project partners, using a convenience sampling method that facilitated easy access to the target population. The partners involved municipalities, sports associations, and universities. Potential participants were invited to join through municipalities or sports associations, and those who expressed interest in volunteering were added to the participant list. The sample size was determined in the previous study conducted with similar conditions. Through the G*Power v.3.1.9.7 software (Kiel University, Kiel, Germany) [32], it was suggested a minimum of 124 participants. A total of 360 older adults of both sexes were invited to participate in the study, but 6 were excluded for failing to complete at least 80 % of the training sessions, and 4 were excluded due to a lack of autonomy and understanding, which indicated they were not suitable for inclusion in the study. As a result, 350 participants were included in the study. Of the total participants, 76 were male (mean age 75.4 $\pm$ 7.1 years), and 280 were female (mean age 72.3 $\pm$ 5.5 years). Of the total participants, 321 were assigned to the four experimental groups, while 29 comprised the control group. The inclusion criteria for the study were: i) age 65 or older; ii) no physical limitations hindering participation; iii) a Montreal Cognitive Assessment (MoCA) score of 26 or lower, indicating cognitive decline; iv) attendance of at least 80 % of training sessions; and v) participation in all evaluation moments. Those who did not meet these criteria were excluded from the study.

The MoCA is a reliable and validated screening tool for cognitive assessment, showing high sensitivity compared to other measures like the Mini-Mental State Examination (MMSE) [33,34]. Only participants scoring below 26 on the MoCA were included in the study, as this score is widely recognized as the threshold indicating mild cognitive impairment (MCI) or early signs of cognitive decline [33]. While a MoCA score below 26 alone does not serve as a formal clinical diagnosis of MCI, this criterion was chosen to target individuals in the early stages of cognitive decline, particularly those in the second phase of dementia progression, such as the "confusion" stage or mild Alzheimer's disease. This is the stage where interventions have shown the greatest promise in slowing cognitive deterioration. Participants were recruited from community settings, and individuals with diagnosed deep dementia or those exhibiting signs of moderate to severe cognitive impairment were excluded. Although no formal clinical diagnosis of MCI was made, the capacity to consent was ensured through a structured process led by trained researchers. Only participants who demonstrated an understanding of the study procedures and voluntarily agreed to participate were included. If there was any doubt regarding a participant's ability to provide informed consent, they were not enrolled in the study.

The study lasted 16 weeks, with 12 weeks dedicated to the intervention, two weeks for baseline assessments, and two weeks for post-intervention evaluations. The study was conducted following the principles of the Declaration of Helsinki and approved by the Ethics Committee of the Instituto Politécnico de Viana do Castelo (protocol code: CECSVS2024/02/vi).

2.2. Study design

The present study utilized a randomized controlled design involving older adults, who were divided into five groups: i) strength plus cognitive training (STCT), ii) strength training (ST), iii) aerobic training (AT), iv) aerobic plus cognitive training (ATCT), and v) control group. Participants were recruited on a voluntary basis, and within each group, a random selection process determined who would receive cognitive training and who would only undergo physical training. The study followed CONSORT guidelines to ensure thorough and transparent reporting of the results [35]. The research was conducted following approval from the Ethics Committee of the Instituto Politécnico de Viana do Castelo, reference: CECSVS2024/02/vi.

Before participation, the older adults were informed about the study design, the associated risks, and the potential benefits. After voluntarily consenting to participate, they signed informed consent forms. The study adhered to the ethical principles outlined in the Declaration of Helsinki.

2.3. Programs of physical exercise

The interventions were carried out over 12 consecutive weeks, with participants attending 60 min sessions three times per week, allowing for a 48 h rest period between sessions. The sessions took place at partner facilities in Portugal, Serbia, Italy, and Poland, and were led by the research team, who designed and prescribed both the aerobic and strength training programs. Detailed training protocols for the interventions are provided in Tables 1 and 2.

Participants followed identical aerobic and strength training sessions in both experimental groups, with the intensity monitored using the rate of perceived exertion (RPE) scale (0-10), allowing adjustments based on individual needs. Each exercise in the aerobic training plan had three variations (based on exercise intensity) to allow instructors to tailor the exercises to each individual's needs. Additionally, the rate of perceived exertion (RPE) was used in every session and for each exercise to gauge the intensity of the workload. This tool, initially developed by Borg [36] and later adapted to a 0-to-10 scale [37], is widely validated for monitoring internal load, reflecting participants' perceived exertion in response to the external exercise load. The intensity and load of both strength and aerobic exercises were continuously adjusted throughout the intervention based on participants' RPE scores, with strength exercise weights progressively increased and aerobic training variables modified as required.

2.3.1. Sessions of cognitive training

Cognitive training sessions used the Fit4Alz software (https://fit4alz.wixsite.com/fit4alz), which targets memory, attention, and executive functions through two games per function, each with five levels of difficulty. This software was inspired by a previous scoping review [38], which found that cognitive training software typically focuses on enhancing memory (Make pairs and Play the sequence), attention (Find the differences and Face to face), and executive functions (Stroop and Tap or avoid). The participants could only progress to higher difficulty levels based on the score achieved at the end of each game. Therefore, if they were unable to complete the task within the allotted time (2 min), they would not advance to the next difficulty level. However, if they successfully completed the task, they would move on to the next level. After completing each game, participants receive a score based on the time taken to finish the task. All these sessions were supervised by the project team and conducted in person, immediately after the physical training, using touch-screen tablets. A prior pilot study had shown that using a mouse could cause difficulties (primarily in terms of speed) for this population. Each cognitive training session lasted 20 min and was conducted after the physical training session. During each session, a different cognitive function was targeted, ensuring that participants received an equal number of sessions for each cognitive domain.

Table 1
Description of plan A and B of aerobic training sessions.

	Time	Phase	Exercise	Methodology	Intensity	HR
Plan A	5′	Warm-up	Single-joint and multi-joint exercises that allow for the gradual increase of body temperature. If possible, activities that individuals enjoy and promote group participation.	Continuous	5/6 RPE	60 %
	42-44′	Fundamental	**Two times:** 1. Jumping jacks 3. Walk out 9. High knee 10. Lunge 4. Kipping 8. Plank knee	6 × 2′ 1′ rest between each repetition 4-6′ walk between sets	7/8 RPE	75-85 %
	3′	Cool down	Walking or some low activity	Continuous	3/4 RPE	40 %
	Time	Phase	Exercise	Methodology	Intensity	HR
Plan B	5′	Warm-up	Single-joint and multi-joint exercises that allow for the gradual increase of body temperature. If possible, activities that individuals enjoy and promote group participation.	Continuous	5/6 RPE	60 %
	42-44′	Fundamental	**Two times:** 2. Burpees 6. Squat 7. Lunge with kick 11. Butt kicks 5. Running 12. Step up and down	6 × 2′ 1′ rest between each repetition 4-6′ walk between sets	7/8 RPE	75-85 %
	3′	Cool down	Walking or some low activity	Continuous	3/4 RPE	40 %

Legend: RPE: rate of perceive exertion; HR: heart rate.

Table 2
Description of the strength training plan.

	Time	Phase	Exercise	Methodology	Intensity	HR
Weeks 1 to 12	5′	Warm-up	Single-joint and multi-joint exercises that allow for the gradual increase of body temperature. If possible, activities that individuals enjoy and promote group participation.	Continuous	5/6 RPE	60 %
	42-44′	Fundamental	**Two blocks of tri-sets 1st block:** 1 hip-dominant exercise 1 anti-core exercise 1 upper pull exercise **2nd block:** 1 knee-dominant exercise 1 anti-core exercise 1 upper push exercise	**Hip- and knee-dominant exercises** **1st week:** 2 × 5 reps **2nd week:** 2 × 8 reps **3rd week:** 2 × 10 reps **4th week:** 3 × 8 reps **5th week:** 3 × 10 reps **Weeks 6-8:** 3 × 12 reps **Weeks 9-12:** 3 × 15 reps **Anti-core holds** **1st week:** 2 × 10s **2nd week:** 2 × 20s **3rd week:** 2 × 25s **Weeks 4-12:** 3 × 30s	4/5 RIR	75-85 %
	3′	Cool down	Walking or some low activity	Continuous	3/4 RPE	40 %

RPE: rate of perceive exertion; RIR: repetitions in reserve; reps: repetitions; HR: heart rate.

2.4. Outcomes

Data collection took place both before and at the end of the intervention, involving two separate sessions: one for cognitive assessment and another for physical fitness assessment. All assessments were conducted indoors in a controlled environment, always during morning hours. In the first session, the MoCA test was administered by a team of four professionals. Participants who scored above 26 points on the MoCA were excluded from the study. Those who scored below this threshold were invited to participate in the second session. During the second session, a team of five trained evaluators conducted all assessments. Participants were divided into small groups of 4 to 5 individuals, following a predefined sequence of activities. The session began with anthropometric measurements, followed by a warm-up, before proceeding with the six tests from the Senior Fitness Test [39]: i) chair stand; ii) arm curl; iii) chair sit-and-reach; iv) back scratch; v) 8-foot up-and-go; and vi) six-minute walk or 2 min step-in-place test.

2.5. Anthropometric Measurements

All measurements were taken in a suitable room with participants dressed in light clothing and barefoot. Standing height was measured to the nearest 0.1 cm using a portable stadiometer (Seca 213, Hamburg, Germany). Body mass was recorded to the nearest 0.1 kg using a standard scale. Each measurement was performed twice, and the average of the two readings was used for analysis.

2.6. Chair stand

This assessment aimed to measure the strength and endurance of the lower limbs. A stopwatch and a chair with a backrest, set at an approximate seat height of 43 cm, were used for the test. For safety, the chair was secured against a wall or otherwise stabilized to prevent any movement during the procedure. The participant sat with their back supported and feet flat on the floor, while the evaluator stood nearby to hold the chair for added stability. The participant crossed their arms, placing their middle fingers on their shoulders. Upon the evaluator's signal, they were instructed to stand fully and then sit back down, repeating the action as many times as possible within 30 s. The evaluator demonstrated the test once to ensure understanding before conducting the official test.

2.7. Arm curl

To assess upper limb strength and endurance, a stopwatch, a chair without armrests, and hand weights (2.3 kg for women and 3.6 kg for men) were used. The participant sat upright with their dominant arm positioned near the edge of the chair, gripping the weight in a handshake hold, with their arm extended perpendicular to the floor. The evaluator ensured proper form by stabilizing the participant's upper arm during the test. On the evaluator's signal, the participant rotated their palm upward, fully flexed the arm, and then returned to the extended position. They aimed to complete as many repetitions as possible within 30 s. After a brief demonstration and practice repetitions, the official test was performed once.

2.8. Chair sit and reach

To assess lower limb flexibility, a chair without armrests (approximately 43 cm high) and a 45 cm ruler were used. For safety, the chair was placed against a wall to keep it stable. The participant sat so that their inguinal line was parallel to the seat of the chair, with one leg bent and the foot off the ground, while the other leg was extended in front. The evaluator remained close to assist. The participant then leaned forward and attempted to touch their toes by sliding their hands down the extended leg, keeping their back straight. The position was held for two seconds, and if the knee bent, the participant was asked to straighten it before continuing. Two trials were performed, and the best result was recorded.

2.9. Back Scratch

For this test, the participant stood near the evaluator, who was positioned behind them. The participant placed their dominant hand on the opposite shoulder, reaching down their back, while the other arm reached upward from behind to try to touch or overlap the extended fingers. The evaluator ensured that the middle fingers aligned but did not touch. Two practice trials were followed by two official test attempts. The score was determined by measuring the distance between the tips of the middle fingers or by the degree of overlap, recorded to the nearest centimeter. Negative results (-) indicated the shortest distance, while positive results (+) signified overlap. The best result was used for performance assessment, with any signs of overlap or distance noted on the scoring sheet.

2.10. Foot up and go

This test measures physical mobility, focusing on speed, agility, and dynamic balance. The required equipment included a stopwatch, measuring tape, a cone (or marker), and a chair approximately 43 cm high, positioned against a wall for stability. The cone was placed 2.44 meters from the chair, with at least 1.22 meters of clear space around it. The participant began seated with their posture upright, one foot slightly ahead of the other. The evaluator stood nearby to assist if necessary. Upon the signal, the participant stood up, walked briskly around the cone, and returned to sit down. The timer started at the signal and stopped when the participant was seated. After a demonstration, the participant practiced once before completing two official attempts. The score was based on the time taken, with the fastest (shortest) time used for evaluation. Participants were reminded to walk quickly (without running) around the cone and back to the chair.

2.11. Six-minute walk

This test assesses aerobic endurance and used a stopwatch, measuring tape, cones, poles, chalk, and markers. For safety, chairs were positioned at various points along the circuit. The course covered a total distance of 45 meters, marked in 5-meter segments with chalk or tape, in a well-lit and level area. Participants started at the beginning of the course, with the evaluator nearby to record the time. Upon the signal, participants walked as fast as possible (without running) around the course, completing as many laps as they could within the 6 min time limit. Participants were allowed to stop and rest as needed before resuming. The evaluator joined the course after all participants had started, providing updates on the time elapsed. The course was marked in 5-meter segments for the 6 min walk test.

2.12. 2-Minute step-in-place test

This test was used as an alternative to the six-minute walk test for participants who relied on orthopedic devices while walking or those who had balance difficulties. It was designed to assess aerobic endurance. The required equipment included tape for marking the wall, a stopwatch, and a wall. The participant stood upright next to the wall, with the tape positioned at the midpoint between the knee and the hip bone. The participant then performed a marching motion in place for two minutes, aiming to raise their knees to the height of the tape. Rest breaks were allowed, and participants could hold onto the wall or a stable chair for support if needed. The test concluded after two minutes.

2.13. Statistical procedures

Statistical analyses were conducted using SPSS Statistics (version 28.0. Armonk, NY: IBM Corp, USA), with data visualization performed in JASP (version 0.19.3, Amsterdam, The Netherlands). Prior to main analyses, data were screened for normality using the Shapiro-Wilk test, homogeneity of variance using Levene's test, and sphericity using Mauchly's test, where applicable, with outliers examined using boxplots and standardized residuals. A mixed ANCOVA was employed to assess the effects of time (pre-intervention, post-intervention) and group (experimental groups, control) on senior fitness test outcomes and MoCA scores, using baseline (pre-intervention) scores as covariates. Partial eta-squared (η_p^2) was used to report effect sizes, and Bonferroni-corrected pairwise comparisons with Cohen's d effect sizes were conducted for significant interaction effects. Cohen's d values were interpreted as trivial (d<0.2), small (d = 0.2-0.6), medium (d = 0.6-1.2), large (d = 1.2-2.0), and very large (d>2.0). Additionally, mean difference scores (post-intervention minus pre-intervention) were calculated for each outcome measure, and a univariate ANCOVA, with baseline scores as covariates, was used to compare the magnitude of change between groups. The statistics were conducted for a significance level of $p < 0.05$.

3. Results

Table 3 present the descriptive statistics of the anthropometric data for the participants, categorized by group.

Table 4 exhibits the descriptive statistics of outcomes across the five groups and within-group comparisons. Mixed ANCOVA, using baseline values as a covariate, revealed significant interactions between time and group for the following tests: MoCA ($F = 22.022$; $p < 0.001$; η_p^2=0.204), chair stand test ($F = 16.948$; $p < 0.001$; η_p^2=0.165), arm curl test ($F = 23.716$; $p < 0.001$; η_p^2=0.215), 2-min step test ($F = 17.780$; $p < 0.001$; η_p^2=0.223), sit and reach right leg ($F = 4.322$; $p = 0.002$; η_p^2=0.047), sit and reach left leg ($F = 4.474$; $p = 0.002$; η_p^2=0.052), back scratch right arm ($F = 6.215$; $p < 0.001$; η_p^2=0.068), back scratch left arm ($F = 9.874$; $p < 0.001$; η_p^2=0.109), 8-foot up and go test ($F = 30.301$; $p < 0.001$; η_p^2=0.262) and 6-min walk test ($F = 6.053$; $p < 0.001$; η_p^2=0.082).

Regarding the MoCA, after the intervention, the CG showed significantly lower scores compared to the ST ($p < 0.001$; d = -1.012; moderate ES), STCT ($p < 0.001$; d = -0.979; moderate ES), AT ($p < 0.001$; d = -1.571; large ES), and ATCT ($p < 0.001$; d = -1.710; large ES). No other significant differences were observed between groups in the MoCA ($p >$ 0.05). In the pre-test, the values regarding this test ranged between 15 and 26, 14 and 26, 16 and 26, 15 and 26 and 15 and 26, for group ST, STCT, AT, ATCT and control group, respectively. In the post-test moment they ranged between 17 and 30, 17 and 30, 20 and 30, 18 and 30 and 13 and 30, for group ST, STCT, AT, ATCT and control group, respectively.

Considering the chair stand test, after the intervention, the CG showed significantly lower scores compared to the ST ($p < 0.001$; d = -1.685; large ES), STCT ($p < 0.001$; d = -1.880; large ES), AT ($p < 0.001$; d = -1.333; large ES), and ATCT ($p < 0.001$; d = -1.043; moderate ES). Additionally, the STCT ($p = 0.033$; d = 1.000; moderate ES) and AT ($p = 0.030$; d = 0.442; small ES) groups performed significantly better than the ATCT. No other significant differences were observed between groups in the chair stand test ($p > 0.05$).

Regarding the arm curl test, after the intervention, the CG showed significantly lower scores compared to the ST ($p < 0.001$; d = -0.918; moderate ES), STCT ($p < 0.001$; d = -0.783; moderate ES), and AT ($p <$ 0.001; d = -0.977; moderate ES). Additionally, the ST ($p < 0.001$; d = 0.565; small ES), STCT ($p = 0.033$; d = 0.486; small ES) and AT ($p = 0.030$; d = 0.733; moderate ES) groups performed significantly better than the ATCT. No other significant differences were observed between groups in the arm curl test ($p > 0.05$).

Considering the 2-min step test, after the intervention, the CG

Table 3
Descriptive statistics (mean ± standard deviation) of the anthropometric information of the included participants.

	ST (n = 42)	STCT (n = 97)	AT (n = 97)	ATCT (n = 91)	CT (n = 29)
Men (n)	12	36	10	9	9
Women (n)	30	61	87	82	20
Age (years)	74.07 ± 3.76	74.07 ± 6.45	71.94 ± 5.30	71.19 ± 4.88	76.45 ± 9.70
Height (m)	1.60 ± 0.10	1.64 ± 0.09	1.63 ± 0.07	1.64 ± 0.08	1.62 ± 0.08
Body mass (kg)	65.29 ± 11.36	69.81 ± 12.02	69.44 ± 10.42	71.10 ± 11.77	66.71 ± 9.50
Body mass index (kg/m^2)	25.28 ± 2.98	25.85 ± 3.74	25.81 ± 3.65	27.09 ± 5.78	25.29 ± 3.49

STCT: strength and cognitive training; ST: strength training; AT: aerobic training; ATCT: aerobic and cognitive training.

Table 4
Descriptive statistics (mean ± standard deviation) of outcomes across the five groups and within-group comparisons.

	ST (n = 42)	STCT (n = 97)	AT (n = 97)	ATCT (n = 91)	Control (n = 29)
MoCA (A.U.)					
Pre	21.1 ± 3.0	21.4 ± 4.6	23.7 ± 2.3	24.0 ± 2.7	21.4 ± 4.6
Post	24.7 ± 3.4	25.2 ± 4.7	26.1 ± 2.3	26.5 ± 2.2	20.6 ± 4.7
Post-pre comparison	$p < 0.001$ | d = 1.125 | ⇑	$p < 0.001$ | d = 0.817 | ⇑	$p < 0.001$ | d = 1.043 | ⇑	$p < 0.001$ | d = 1.020 | ⇑	$p = 0.009$ | d = -0.172 | ⇓
2-min step test (n)					
Pre	n.a.	75.6 ± 13.7	90.7 ± 27.4	113.8 ± 23.3	56.0 ± 31.1
Post	n.a.	79.4 ± 12.9	106.0 ± 30.9	121.2 ± 18.5	55.7 ± 31.2
Post-pre comparison	n.a.	$p = 0.136$ | d = 0.286 | ⇒	$p < 0.001$ | d = 0.525 | ⇑	$p < 0.001$ | d = 0.354 | ⇑	$p = 0.171$ | d = -0.110 | ⇒
6-min walk test (m)					
Pre	518.4 ± 67.2	530.0 ± 70.5	550.1 ± 63.0	483.0 ± 73.3	n.a.
Post	529.7 ± 56.3	551.7 ± 60.9	563.8 ± 59.5	543.5 ± 88.6	n.a.
Post-pre comparison	$p = 0.110$ | d = 0.183 | ⇒	$p < 0.001$ | d = 0.330 | ⇑	$p = 0.015$ | d = 0.224 | ⇑	$p < 0.001$ | d = 0.747 | ⇑	n.a.
8-foot up and go test (s)					
Pre	5.25 ± 0.84	6.44 ± 2.31	5.34 ± 0.96	5.40 ± 0.94	10.26 ± 7.78
Post	4.73 ± 0.59	5.47 ± 1.73	5.00 ± 1.01	4.84 ± 0.93	10.91 ± 8.22
Post-pre comparison	$p < 0.001$ | d = -0.727 | ⇑	$p < 0.001$ | d = -0.480 | ⇑	$p < 0.001$ | d = -0.345 | ⇑	$p < 0.001$ | d = -0.599 | ⇑	$p < 0.001$ | d = -0.081 | ⇓
Arm curl test (n)					
Pre	18.4 ± 4.1	19.8 ± 5.6	20.5 ± 5.7	19.7 ± 4.5	19.4 ± 6.2
Post	22.9 ± 3.5	23.1 ± 5.7	24.9 ± 7.0	20.5 ± 5.0	18.4 ± 6.3
Post-pre comparison	$p < 0.001$ | d = 1.184 | ⇑	$p < 0.001$ | d = 0.536 | ⇑	$p < 0.001$ | d = 0.577 | ⇑	$p = 0.022$ | d = 0.474 | ⇑	$p = 0.109$ | d = -0.283 | ⇒
Chair stand test (n)					
Pre	18.2 ± 3.9	19.9 ± 4.9	17.1 ± 5.1	16.2 ± 3.4	14.5 ± 4.7
Post	20.6 ± 3.7	22.5 ± 4.8	20.1 ± 5.3	18.0 ± 4.2	13.1 ± 5.2
Post-pre comparison	$p < 0.001$ | d = 0.632 | ⇑	$p < 0.001$ | d = 0.536 | ⇑	$p < 0.001$ | d = 0.577 | ⇑	$p < 0.001$ | d = 0.474 | ⇑	$p < 0.001$ | d = -0.283 | ⇓
Sit and reach test – right (cm)					
Pre	2.8 ± 12.6	12.8 ± 12.7	2.8 ± 11.2	3.1 ± 9.7	-5.2 ± 17.2
Post	4.4 ± 11.2	14.5 ± 12.9	3.8 ± 10.8	2.6 ± 10.8	-5.3 ± 16.9
Post-pre comparison	$p = 0.177$ | d = 0.134 | ⇒	$p < 0.001$ | d = 0.133 | ⇑	$p = 0.320$ | d = 0.091 | ⇒	$p = 0.219$ | d = -0.049 | ⇒	$p = 0.194$ | d = -0.006 | ⇒
Sit and reach test – left (cm)					
Pre	2.4 ± 12.7	12.9 ± 12.5	1.7 ± 11.6	2.6 ± 9.1	-6.7 ± 15.7
Post	4.1 ± 11.4	14.9 ± 12.8	2.5 ± 10.7	3.3 ± 10.2	-7.0 ± 15.3
Post-pre comparison	$p = 0.095$ | d = 0.141 | ⇒	$p < 0.001$ | d = 0.158 | ⇑	$p = 0.371$ | d = 0.072 | ⇒	$p = 0.462$ | d = 0.073 | ⇒	$p = 0.111$ | d = -0.019 | ⇒
Back scratch – right (cm)					
Pre	-6.1 ± 9.8	-4.0 ± 10.3	-4.8 ± 9.2	-3.8 ± 7.6	-17.4 ± 20.5
Post	-4.9 ± 9.0	-1.9 ± 10.4	-4.1 ± 9.0	-1.4 ± 7.4	-18.2 ± 21.4
Post-pre comparison	$p = 0.105$ | d = 0.128 | ⇒	$p < 0.001$ | d = 0.203 | ⇑	$p = 0.072$ | d = 0.077 | ⇒	$p < 0.001$ | d = 0.320 | ⇑	$p = 0.027$ | d = -0.038 | ⇓
Back scratch – left (cm)					
Pre	-11.3 ± 9.2	-5.3 ± 11.3	-7.5 ± 10.5	-6.0 ± 8.1	-20.0 ± 20.1
Post	-10.5 ± 8.6	-3.5 ± 11.3	-7.8 ± 9.8	-3.7 ± 8.1	-21.0 ± 20.5
Post-pre comparison	$p = 0.379$ | d = 0.090 | ⇒	$p < 0.001$ | d = 0.159 | ⇑	$p = 0.663$ | d = -0.030 | ⇒	$p < 0.001$ | d = 0.284 | ⇑	$p = 0.013$ | d = -0.049 | ⇓

p: p-value; d: standardized effect size of Cohen; ⇑: significant improvements after intervention period; ⇓: significant decline after intervention period; ⇒: non-significant differences between pre and post-interventions; n.a.: not applicable.

showed significantly lower scores compared to the AT ($p < 0.001$; d = -1.620; large ES), and ATCT ($p < 0.001$; d = -2.636; very large ES). Additionally, the STCT performed significantly worse than both the AT ($p < 0.001$; d = -1.215; large ES) and ATCT ($p = 0.041$; d = -2.662; very large ES). No other significant differences were observed between groups in the 2-min step test ($p > 0.05$).

Regarding the sit and reach test – right leg, after the intervention, the CG showed significantly lower scores compared to the STCT ($p = 0.025$; d = -1.329; large ES). Additionally, the ATCT performed significantly worse than STCT ($p = 0.002$; d = -1.004; moderate ES). No other significant differences were observed between groups in the sit and reach test – right leg ($p > 0.05$).

Considering the sit and reach test – left leg, after the intervention, the CG showed significantly lower scores compared to the STCT ($p = 0.002$; d = -1.559; large ES). Additionally, the STCT performed significantly better than AT ($p = 0.023$; d = -1.055; moderate ES) and ATCT ($p = 0.042$; d = -1.009; moderate ES). No other significant differences were observed between groups in the sit and reach test – left leg ($p > 0.05$).

Regarding the back scratch test – right arm, after the intervention, the CG showed significantly lower scores compared to the STCT ($p < 0.001$; d = -1.025; moderate ES) and ATCT ($p < 0.001$; d = -1.167; moderate ES). No other significant differences were observed between groups in the back scratch test – right arm ($p > 0.05$).

Regarding the back scratch test – left arm, after the intervention, the CG showed significantly lower scores compared to the STCT ($p < 0.001$; d = -1.101; moderate ES) and ATCT ($p < 0.001$; d = -1.210; large ES). Additionally, the STCT performed significantly better than AT ($p < 0.001$; d = -1.055; moderate ES). No other significant differences were observed between groups in the back scratch test – left arm ($p > 0.05$; d = 0.408).

Considering the 8-foot up and go test, after the intervention, the CG showed significantly lower scores compared to the SG ($p < 0.001$; d = 1.403; large ES), STCT ($p < 0.001$; d = 1.093; moderate ES), AT ($p < 0.001$; d = 1.281; moderate ES), and ATCT ($p < 0.001$; d = 1.327; moderate ES). Additionally, the STCT performed significantly better than the AT ($p < 0.001$; d = -1.343; moderate ES) and ATCT ($p = 0.011$; d = -0.474; small ES). No other significant differences were observed between groups in the 8-foot up and go test ($p > 0.05$).

Considering the 6-min walk test, after the intervention, the ATCT showed significantly greater scores compared to the ST ($p < 0.001$; d =

0.190; trivial ES), and STCT ($p = 0.011$; $d = 0.110$; trivial ES). No other significant differences were observed between groups in the 6-min walk test ($p > 0.05$).

Fig. 1 exhibits the delta mean difference (post-intervention vs. baseline) for the MOCA, 6 min walk test, 2 min step test, and 8-foot up-and-go test (U&G) across five groups. The ANCOVA comparing the mean differences between groups, using baseline values as covariable revealed significant differences in MoCA ($F = 22.022$; $p < 0.001$; η_p^2=0.204), 2-min step test ($F = 17.780$; $p < 0.001$; η_p^2=0.223), 6-min walk test ($F = 6.053$; $p < 0.001$; η_p^2=0.082), and 8-foot up and go test ($F = 26.479$; $p < 0.001$; η_p^2=0.237). The significant post-hoc comparisons are shown in Fig. 1.

Fig. 2 exhibits the delta mean difference (post-intervention vs. baseline) for the arm curl test and chair stand test across five groups. The ANCOVA comparing the mean differences between groups, using baseline values as covariable revealed significant differences in the arm curl test ($F = 23.716$; $p < 0.001$; η_p^2=0.215), and chair stand test ($F = 16.948$; $p < 0.001$; η_p^2=0.165). The significant post-hoc comparisons are shown in Fig. 2.

Fig. 3 exhibits the delta mean difference (post-intervention vs. baseline) for the sit and reach test and back scratch test across five groups. The ANCOVA comparing the mean differences between groups, using baseline values as covariable revealed significant differences in the sit and reach test – right leg ($F = 4.322$; $p = 0.002$; η_p^2=0.047), and left leg ($F = 4.474$; $p = 0.002$; η_p^2=0.052), and chair and stand test – right leg ($F = 6.215$; $p < 0.001$; η_p^2=0.068) and left leg ($F = 9.695$; $p < 0.001$; η_p^2=0.107). The significant post-hoc comparisons are shown in Fig. 3.

4. Discussion

The aim of the current study was to examine the impact of aerobic and strength training approaches, both with and without cognitive training, on delaying cognitive decline. Results showed that twelve weeks of aerobic and strength training with and without the cognitive components improved the MoCA test results in older individuals with cognitive decline. These findings support the notion that maintaining functional abilities is crucial for preserving essential skills, autonomy, independence, and overall quality of life in aging [40]. After the 12-week training program, participants in all training groups showed improvements in functional abilities, in opposition to the control group that showed declines in MoCA test and also physical performance. However, the different training components had varying effects on their physical and cognitive gains. The subjects' strength was improved in all training groups, but more pronouncedly in the ST. Similarly, agility was enhanced in participants from all training groups, but a higher effect was observed for those in the ST. Agility, by concept, is the ability to move quickly and easily and to respond to change effectively. It is deeply connected to strength, speed and power, which respond to strength training as a cluster [15]. Alternatively, data from the upper and lower limbs flexibility indicates that flexibility might have benefited from cognitive training. Our results showed that ATCT improved flexibility only in participants' lower limbs flexibility, and STCT promoted a global flexibility improvement. Interestingly, flexibility was improved only in the groups that included cognitive training suggesting that cognitive training might be relevant for the acquisition of flexibility in the present sample. Although the link between cognitive training and flexibility may seem unexpected, cognitive exercises involving motor planning, attention, and coordination can improve body awareness and neuromuscular control, facilitating better movement and flexibility. Cognitive training may also enhance brain-muscle communication, aiding stretching and postural control. Previous studies combining cognitive and physical training support broader improvements in mobility and flexibility, especially in older adults [41,42]. Concerning to the cardiorespiratory fitness, as expected, the 2-min step test showed that all participants in aerobic training groups had significant improvements in their fitness condition, with no distinction for the presence or absence of cognitive training. Importantly, a decline found in the cardiorespiratory fitness of participants in the STCT group implies that aerobic training is essential

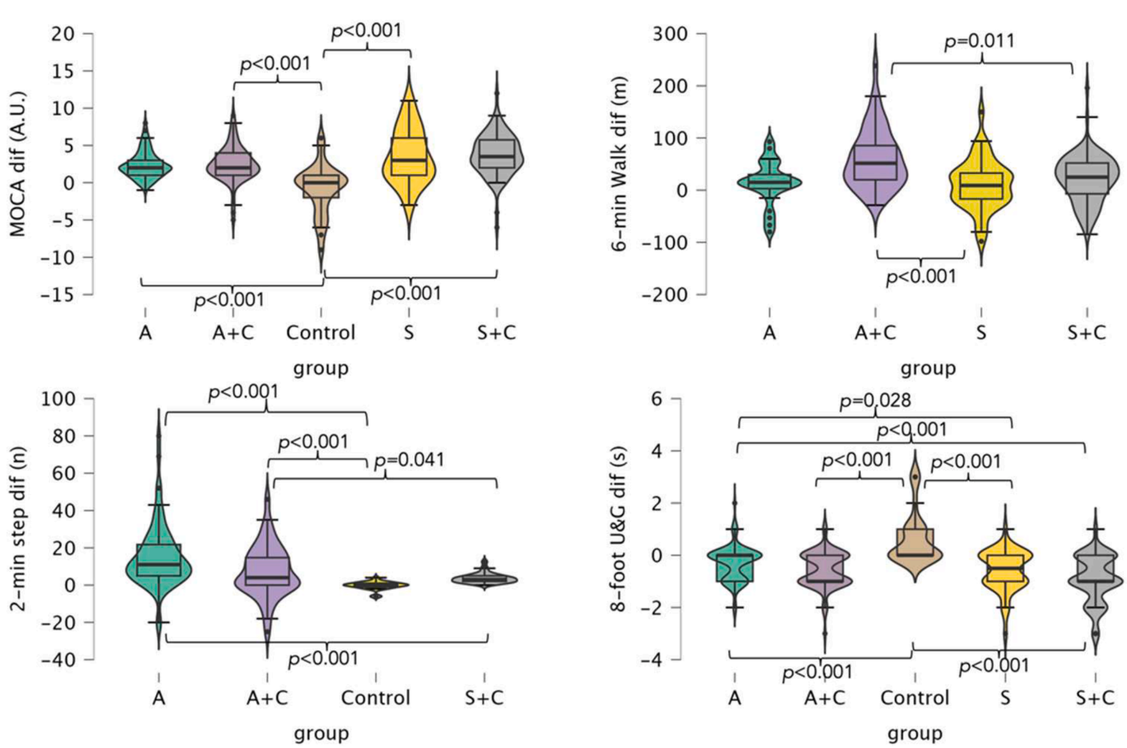

Fig. 1. Violin and box plots illustrating the delta differences (post-intervention vs. baseline) for the MoCA, 6 min walk test, 2 min step test, and 8-foot up-and-go test (U&G) across five groups: aerobic (A), aerobic + cognitive (A+C), control, strength (S), and strength + cognitive (S+C).

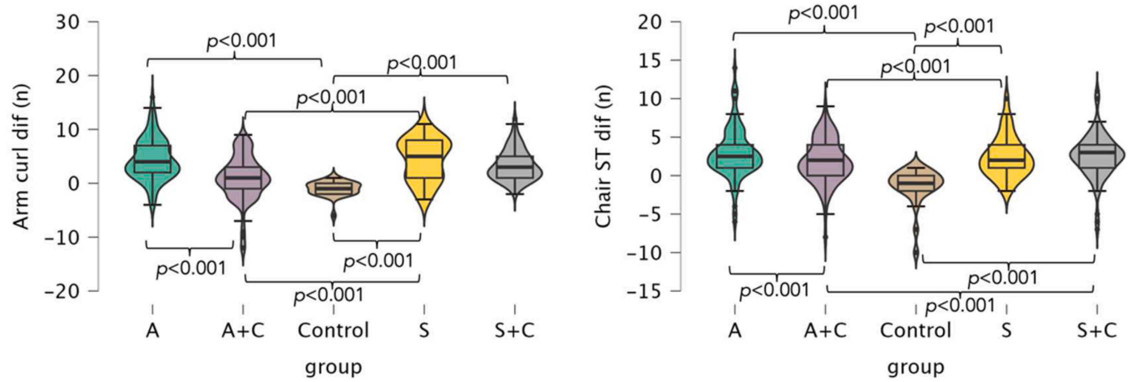

Fig. 2. Violin and box plots illustrating the delta differences (post-intervention vs. baseline) for the arm curl test and chair stand test across five groups: aerobic (A), aerobic + cognitive (A+C), control, strength (S), and strength + cognitive (S+C).

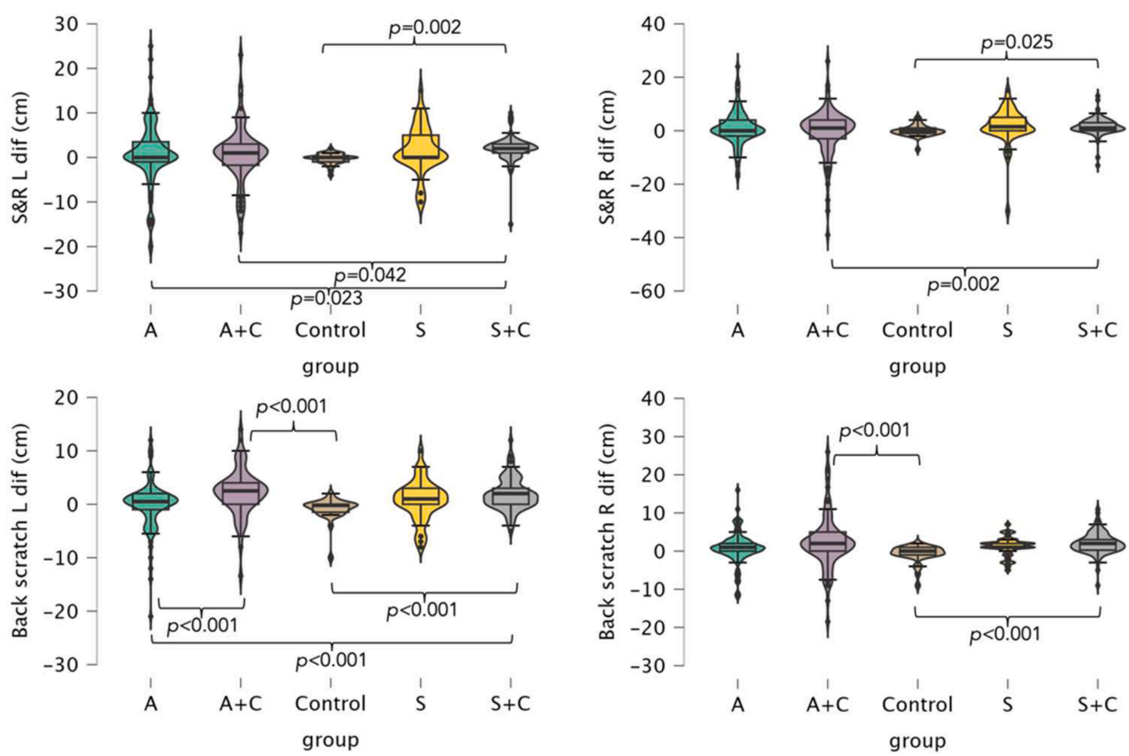

Fig. 3. Violin and box plots illustrating the delta differences (post-intervention vs. baseline) for the sit and reach test (R: right; L: left) and back scratch test across five groups: aerobic (A), aerobic + cognitive (A+C), control, strength (S), and strength + cognitive (S+C).

for the maintenance of fitness condition and protection against several frailty related conditions [6].

Regarding the cognitive domain, results confirmed that regular physical exercise allow to improve the executive function in older adults with cognitive decline. This aligns with evidence showing that physical activity promotes neuroplastic adaptations such as neurogenesis, synaptogenesis, angiogenesis, and increased release of neurotrophic factors, all of which contribute to improved cognitive functioning [43,44]. In particular, exercise appears to benefit executive functions and information processing speed [45].In the study by Castellote-Caballero et al. [31], 12 weeks engagement in systematic sessions of psychomotor and cognitive stimuli improved the functional abilities and cognitive performance in older adults with cognitive decline. These findings reinforce the importance of integrating physical and cognitive training for enhancing cognitive parameters. The positive effects may be mediated not only by physiological mechanisms – such as enhanced cardiovascular fitness, cerebral blood flow, and neurotransmitter function – but also by psychological factors including mood improvement and increased self-perceived competence [45,46]. Therefore, multimodal interventions that address both physical and cognitive domains appear to be especially promising for promoting cognitive health in aging populations.

Our results suggest that the cognitive component had a less significant effect on cognitive performance compared to the aerobic training component. In our study, the aging individuals with cognitive decline who participated in training programs including the aerobic component exhibited greater improvements in their MoCA results. The metabolic demands of exercise increase the activity of transcription factors that regulate core proteins to cells structure and function [47,48]. So, the physiological changes induced by the aerobic exercise regulate cytokines with a critical role in adaptive mechanisms that contribute to the plasticity of neural circuits and specific gains in cognitive processes [49–51]. For instance, acute exercise induces an increase in plasma levels of several cytokines, including IL-6, TNF-α, and BDNF [26], which play important roles in muscle growth, metabolic regulation, and the modulation of inflammation [52]. In addition, this helps to counteract the anabolic resistance present in older adults with high inflammatory status cooperating for gains in strength, as presented by individuals in the aerobic training programs [53].

The regularity, intensity and volume of the exercise or training are also relevant to elicit neurobiological mechanisms related to these gains [50,54]. Similarly to our study, the study by Leckie et al. [55] showed that 1-year walking at a moderate intensity was able to improve the cognitive flexibility domains of executive function in individuals over the age of 71 years. Compiling our results with the scientific evidence it is possible to assume that the regularity was a relevant for the gains in the cognitive performance elicited by all of the training groups in older adults with cognitive decline.

In general, the combination of training components did not determinate the improvement in cognitive performance in older adults with cognitive decline. From the perspective of specificity, different training combinations provided selective adaptions and might be used to address subpopulations with more specific demands. For example, the strength training program was not effective to improve flexibility or fitness condition in the participants but was more effective to improve their agility. It might be worthwhile to investigate how different training combinations affect specific functional abilities to help establishing precise recommendations.

It should be highlighted that the Montreal Cognitive Assessment (MoCA) was used primarily as a screening tool to identify early signs of cognitive decline, rather than as a diagnostic instrument for dementia. In line with the original validation by Nasreddine et al. [56], cognitive decline was considered for scores up to 26 points, which is commonly used to indicate potential MCI. A cut-off of 17/30, while relevant in diagnostic contexts for specific dementias, was not applicable here, as it would exclude individuals with milder cognitive deficits – the target population of this intervention. Moreover, no formal diagnosis of MCI or confirmation of the absence of dementia was conducted before inclusion. While the MoCA is widely recognized and validated for detecting cognitive impairment, future studies should consider employing more sensitive and domain-specific assessments, such as those targeting working memory or executive functions, to provide a deeper understanding of cognitive changes. Additionally, one of the study groups had a smaller sample size compared to the others, which may limit the generalizability of the findings. However, this imbalance was accounted for in the statistical analysis. Finally, the intervention duration was limited to 12 weeks, which may not have been sufficient to observe longer-term cognitive or functional changes. Evidence from previous meta-analyses (e.g., [57]) suggests that longer and more intensive cognitive training protocols, especially when supervised, are more likely to yield measurable benefits, particularly in populations with cognitive impairment. While cognitive training shows potential benefits, researchers emphasize the need for well-controlled, large-scale randomized trials with long-term follow-ups and functional outcome measures to fully assess its efficacy in MCI and address issues of generalization [58].

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Consent statement

All participants provided written informed consent prior to their inclusion in the study. The study procedures were explained in detail, and participants were informed of their right to withdraw at any time without penalty.

CRediT authorship contribution statement

Ana Filipa Silva: Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Investigation, Funding acquisition, Conceptualization. **Gilmara Assis:** Writing – original draft, Conceptualization. **Rui Miguel Silva:** Methodology. **Eugenia Murawska-Ciałowicz:** Project administration, Methodology. **Grzegorz Zurek:** Project administration, Methodology. **José Carvalho:** Validation, Project administration, Methodology. **Mafalda Sofia Roriz:** Project administration. **José Alberto Azevedo:** Resources, Project administration, Methodology. **António Sampaio:** Project administration, Methodology. **Telmo Bento:** Software. **Olivera Jovanovic:** Project administration, Methodology. **Marko Adamovic:** Project administration, Methodology. **Spartaco Grieco:** Project administration, Methodology. **Roberta Germini:** Methodology. **Filipe Manuel Clemente:** Supervision, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ana Filipa Silva (but from the project not personally) reports financial support was provided by European Union. If there are other authors, they 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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