Experimental Gerontology 206 (2025) 112768

Contents lists available at ScienceDirect

Experimental Gerontology

journal homepage: www.elsevier.com/locate/expgero

Review article

Comparative efficacy of exercise interventions for cognitive health in older adults: A network meta-analysis

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ARTICLE INFO

Section Editor: Chang won Won

Keywords:
Cognitive function
Older adults
Exercise interventions
Resistance training
Network meta-analysis

ABSTRACT

Background: Previous studies have consistently demonstrated that exercise mitigates cognitive decline in older adults. However, the most effective types of exercise, along with optimal frequency and duration of interventions, remain inadequately defined. To address these gaps, we conducted a network meta-analysis synthesizing direct and indirect evidence from existing literature to identify the most effective exercise interventions for enhancing cognitive function in older adults.

Methods: We conducted a systematic search across databases including PubMed and Web of Science to identify randomized controlled trials (RCTs) evaluating the impact of various exercise interventions on cognitive function in older adults. We assessed the quality of included studies and performed a traditional meta-analysis with Review Manager 5.3. Subsequently, a network meta-analysis was conducted using Stata 17.0 to evaluate the effects of different exercise modalities on cognitive outcomes, specifically memory, inhibitory control, and task-switching abilities.

Results: A total of 37 studies encompassing 2585 older adults met the inclusion criteria. The network meta-analysis revealed that resistance training exerted the strongest effect on overall cognitive improvement. Aerobic exercise, multimodal exercise, and physical-mental training followed in effectiveness. Specifically, resistance training significantly enhanced inhibitory control compared to high-intensity interval training (HIIT), aerobic exercise, and other modalities. Physical-mental training emerged as the most effective intervention for improving task-switching ability and demonstrated superior efficacy in enhancing working memory compared to aerobic exercise. Conversely, aerobic exercise showed the strongest effect on memory function, outperforming resistance training, multimodal exercise, and physical-mental training.

Conclusion: Resistance training is the most effective exercise modality for enhancing overall cognitive function and inhibitory control in older adults. Physical-mental training offers the greatest benefits for improving working memory and task-switching ability, while aerobic exercise is most beneficial for enhancing memory function. Based on these findings, the recommended exercise protocols are: Resistance Training: 12 weeks, 2–3 times per week, 45 min per session. Aerobic Exercise: 21 weeks, twice per week, 60 min per session. These tailored exercise interventions can inform public health strategies and clinical practices aimed at optimizing cognitive health in the aging population.

Registration: The protocol for this review was registered in PROSPERO (CRD42024597545).

1. Background

As the global population ages rapidly, dementia has emerged as the third-largest health threat, following cardiovascular diseases and cancer (Colcombe and Kramer, 2003). By 2050, the number of people living with dementia worldwide is expected to exceed 110 million, creating significant challenges for individual health, healthcare systems, and the economy (Wimo et al., 2017). The financial costs of dementia care are expected to rise sharply, potentially reaching $1.89 trillion by 2050 (Bai and Dong, 2021). In China, the large elderly population exacerbates the dementia crisis, further straining healthcare and economic resources (Wu et al., 2017).

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https://doi.org/10.1016/j.exger.2025.112768
Received 23 January 2025; Received in revised form 6 April 2025; Accepted 30 April 2025
Available online 2 May 2025

Despite the limited efficacy of pharmacological treatments in preventing and treating dementia, non-pharmacological interventions, particularly physical exercise, have gained recognition as effective strategies for delaying cognitive decline and preventing dementia (Colcombe and Kramer, 2003). Studies consistently show that physical activity improves cognitive function in older adults, regardless of existing cognitive impairment (Huang et al., 2022). While aerobic exercise, resistance training, and mind-body practices (such as Tai Chi) offer distinct cognitive benefits, their effectiveness depends on the type, intensity, and frequency of the exercise (Northey et al., 2018). However, research still lacks clear guidance on the optimal types, frequencies, and durations of these interventions (Gallardo-Gomez et al., 2022; Gavelin et al., 2021), and most studies do not compare the effects of different exercise interventions or optimize the intervention parameters (Guo et al., 2024).

This study integrates direct and indirect evidence from existing literature through a network meta-analysis to compare the relative effects of various exercise modalities on cognitive function in older adults. By exploring how different exercise types impact cognitive functions—particularly memory and executive functions—this study provides evidence-based recommendations for exercise prescriptions tailored to enhance cognitive health in aging populations.

2. Methods

This study followed the guidelines outlined in the Cochrane Handbook for Systematic Reviews of Interventions and adhered to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement to ensure transparent and comprehensive reporting (Moher et al., 2009).

2.1. Literature search

A systematic literature search was conducted across multiple databases, including PubMed, Web of Science, ScienceDirect, CNKI (China National Knowledge Infrastructure), and Wanfang Data, to identify relevant randomized controlled trials (RCTs) evaluating the effects of exercise on cognitive function in healthy older adults. The search strategy incorporated both English and Chinese terms to ensure comprehensive coverage. Key search terms included "older adults," "healthy older adults," "cognitive function," "executive function," "memory," "exercise," "aerobic exercise," "resistance training," "high-intensity interval training," and "physical and mental training." The search period encompassed all records up until **May 1, 2024**. Additionally, reference lists of relevant systematic reviews and meta-analyses were manually reviewed to identify any additional studies (Gallardo-Gomez et al., 2022; Gavelin et al., 2021).

2.2. Inclusion and exclusion criteria

2.2.1. Inclusion criteria

2.2.1.1. Participants. Healthy older adults aged **55 years and above**, irrespective of gender or nationality, without diagnosed cognitive impairment or dementia.

2.2.1.2. Interventions. Experimental groups engaged in interventions such as resistance training, aerobic exercise, high-intensity interval training (HIIT), physical and mental training (e.g., Tai Chi, Baduanjin), or multi-modal exercise.

2.2.1.3. Control groups. Participants in control groups received either health education or continued their usual activities.

2.2.1.4. Outcome measures. **Primary Outcome:** Cognitive function. **Secondary Outcomes:** Specific executive functions (e.g., inhibitory control, task-switching) and memory. **Cognitive Assessments:** Included the Montreal Cognitive Assessment (MoCA), Mini-Mental State Examination (MMSE), Stroop Test, Trail Making Test (TMT), N-back Test, and the Wechsler Memory Scale.

2.2.1.5. Study design. Only randomized controlled trials (RCTs) were included to ensure the highest quality of evidence.

2.2.1.6. Exclusion criteria. Duplicate publications. Studies lacking extractable outcome measures or reporting incomplete data. Non-RCTs or trials with inadequate control group comparisons.

2.3. Quality assessment

Two reviewers independently assessed the risk of bias in the included studies using the Cochrane Collaboration's Risk of Bias Tool (Courel-Ibanez et al., 2019). This tool evaluates potential biases across seven domains: Random sequence generation, Allocation concealment, Blinding of participants and personnel, Blinding of outcome assessment, Incomplete outcome data, Selective reporting, Other biases. Studies were categorized based on their risk of bias: **Low Risk:** Four or more domains with low risk. **Moderate Risk:** Two to three domains with low risk. **High Risk:** One or fewer domains with low risk. Additionally, publication bias was assessed using funnel plots and Egger's test, with statistical significance set at $p < 0.05$ (Egger et al., 1997).

2.4. Data extraction

Following the initial search, all identified articles were imported into **Note Express** reference management software to remove duplicates. Two independent reviewers screened the titles and abstracts based on the predefined inclusion and exclusion criteria. Studies that did not meet the criteria were excluded, and any disagreements between reviewers were resolved through consensus with a third reviewer (Markov et al., 2023). Full-text articles of the remaining studies were retrieved and subjected to a second screening for eligibility.

Two independent reviewers extracted data using a standardized form based on the **Cochrane Handbook for Systematic Reviews** guidelines (Lim et al., 2024). Extracted data included: **Study Characteristics:** Title, first author, publication year, study design. **Participant Characteristics:** Sample size, mean age, gender distribution. **Intervention Details:** Type, duration, frequency, intensity of exercise intervention, and control group details. **Outcome Measures:** Pre- and post-intervention data for cognitive function and specific executive functions. To ensure data accuracy, all extracted data were cross-verified by the two reviewers, with discrepancies resolved through consensus or consultation with a third reviewer.

2.5. Statistical analysis

All statistical analyses were performed using Review Manager 5.3 and Stata 17.0 software. For continuous outcomes, the standardized mean difference (SMD) and 95 % confidence intervals (CI) were calculated. For studies reporting data in non-standard formats, appropriate formulas were applied to convert the data to means and standard deviations (SD) (Loprinzi et al., 2019).

To evaluate network transitivity, we compared the clinical and methodological characteristics of studies to ensure that the multiple treatment comparisons were adequately comparable. The inconsistency and consistency models were tested using both the design-by-treatment interaction model (a global approach) and the node-splitting test (a local approach). The node-splitting test was used to identify any substantial discrepancies between direct and indirect comparisons for each treatment, evaluating the consistency of the results. The probability values were compiled and presented as the surface under the cumulative ranking curve. The exercise interventions were ranked by using the surface under the cumulative ranking curve and mean rank. Model fit was assessed using the Deviance Information Criterion (DIC), where a lower DIC value indicated a better model fit. To evaluate consistency in the network, node-splitting analysis was conducted to compare direct and indirect estimates, with a *p*-value >0.05 indicating no significant inconsistency. Additionally, heterogeneity across studies was assessed using the I^2 statistic, with $I^2 > 50$ % considered indicative of substantial heterogeneity. To determine the ranking of exercise interventions, we used Surface Under the Cumulative Ranking Curve (SUCRA) values. A SUCRA value close to 100 % indicates a high probability of being the most effective intervention, whereas a value close to 0 % suggests the least effective intervention. Interventions were ranked based on their mean SUCRA scores, allowing a probabilistic ranking of effectiveness across cognitive domains.

The analysis focused on five key indicators of cognitive function: Overall Cognitive Function, Inhibitory Control, Task-Switching Ability, Working Memory, Memory. Heterogeneity among studies was assessed using the I^2 statistic. An I^2 value above 50 % indicated substantial heterogeneity, warranting the use of a random-effects model; otherwise, a fixed-effects model was employed (Talar et al., 2022). A network meta-analysis was conducted to compare the relative effectiveness of different exercise modalities, allowing for both direct and indirect comparisons across studies (Wei et al., 2022).

2.6. Ethical considerations

All included studies had obtained approval from their respective ethics committees, and informed consent was obtained from all participants. No additional ethical approval was required for this meta-analysis, as it involved the secondary analysis of published data.

3. Results

3.1. Study selection

The systematic search across multiple databases yielded 2569 articles. After removing duplicates and conducting an initial title and abstract screening, 145 studies were deemed potentially eligible. Following a full-text review, 37 randomized controlled trials (RCTs) (Albinet et al., 2016; Anderson-Hanley et al., 2010; Ansai and Rebelatto, 2015; Cancela and Ayan, 2007; Cassilhas et al., 2007; Coelho-Junior et al., 2020; Coetsee and Terblanche, 2017; Fabre et al., 2002; Farinha et al., 2021; Gothe et al., 2017; Iuliano et al., 2015; Jonasson et al., 2016; Lachman et al., 2006; Legault et al., 2011; Liu-Ambrose et al., 2010; Maki et al., 2012; Moreira et al., 2018; Mortimer et al., 2012; Muscari et al., 2010; Nguyen and Kruse, 2012; Nishiguchi et al., 2015; Oken et al., 2006; Predovan et al., 2012; Sun et al., 2015; Timmons et al., 2018; Vaughan et al., 2014; Venturelli et al., 2010; Williamson et al., 2009; Chen, 2020;Jiang, 2020; Li, 2019; Liu et al., 2018; Liu, 2021; Peng, 2021; Sun, 2011; Sun, 2021; Xu, 2022) involving a total of 2585 older adults were included in the final analysis. The PRISMA flow diagram illustrating the study selection process is presented in Fig. 1.

3.2. Characteristics of included studies

The characteristics of the included studies are summarized in Table 1. A total of 37 studies were conducted across 13 countries, including China, the United States, Australia, and Italy. The average age

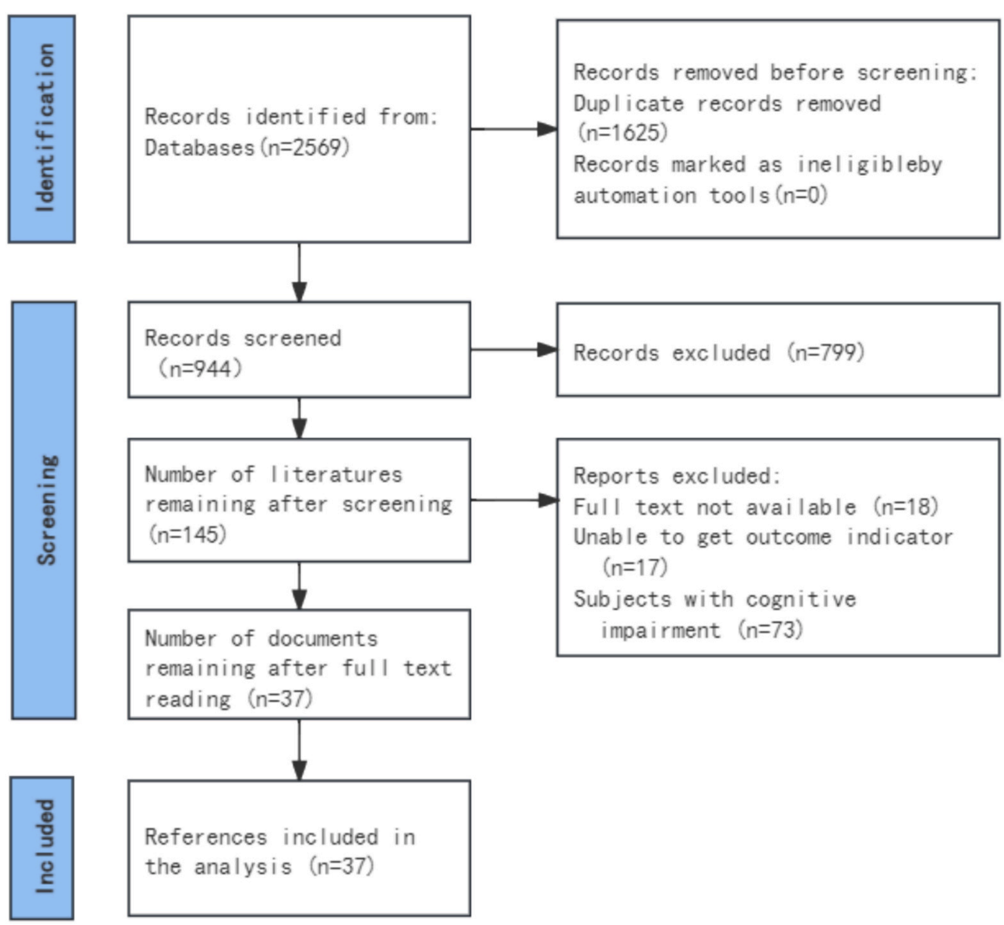

Fig. 1. Study selection.

Table 1
Included in the study characteristics table.

First author	Year	Country	Total sample	Age/year	Experimental group intervention				Control group	Outcome measures
					Type of exercise	Time (mins)	Frequency	Weeks		
Jiao Sun	2015	China	138	69.2 ± 5.9	PMT	60	2/w	25	No intervention	①
Hélio J	2020	Brazil	26	66.7 ± 4.7	RES	60	2/w	24	No intervention	①⑤
Shu N	2015	Japan	48	73.3 ± 5.1	CEX	90	1/w	12	No intervention	①③⑤
Juliana H A	2015	Brazil	69	82.4 ± 2.4	CEX/RES	60	3/w	16	No intervention	①
Moreira N B	2018	Brazil	45	83.6 ± 3.9	CEX	50	3/w	16	No intervention	①
J.M. C C	2007	Spain	62	68.4 ± 3.4	CEX	90	2/w	21	Health education	①
Muscari A	2010	Italy	120	69.2 ± 2.7	AER	60	3/w	52	Health education	①
Jeff D. W	2009	America	102	77.4 ± 4.3	CEX	50	3/w	52	Health education	①②⑤
Massimo V	2010	Italy	23	83.7 ± 6.2	RES	45	3/w	12	No intervention	①
James F	2018	Ireland	84	69.3 ± 3.5	AER/RES/CEX	40	3/w	12	No intervention	①
Li Shaohua	2019	China	74	66.3 ± 4.5	PMT	60	1/w	40	No intervention	①②④
Sun Rifang	2021	China	30	61.4 ± 1.9	PMT	60	3/w	12	No intervention	①②⑤
Liu Jin-yan	2018	China	73	63.1 ± 3.3	PMT	60–90	5/w	12	No intervention	①
Sun Jiao	2011	China	138	69.2 ± 5.9	PMT	60	2/w	12	No intervention	①
Carlos F	2021	Portugal	74	72.4 ± 5.1	AER/CEX	45	2/w	28	No intervention	①
Cay A-H	2010	America	32	72.9 ± 9.3	RES	60	2/w	4	No intervention	②⑤
David P	2012	Canada	50	67.9 ± 6.2	AER	60	3/w	12	No intervention	②
Carla C	2017	S.Africa	67	62.7 ± 5.7	RES/HIIT/AER	45	3/w	16	No intervention	②
Teresa L-A	2010	Canada	88	69.6 ± 2.9	RES	60	2/w	52	Muscle stretching	②③
Barry S	2006	America	135	72.1 ± 4.9	PMT/AER	90	1/w	26	No intervention	②⑤
Sue V	2014	Australia	49	68.8 ± 3.3	CEX	60	2/w	16	No intervention	②③⑤
James A.	2012	America	90	67.8 ± 5.6	PMT/AER	50	3/w	40	No intervention	②③⑤
Cédric, T.	2016	France	36	60–75	AER	60	2/w	21	Muscle stretching	②④⑤
Enzo I	2015	Italy	60	66.9 ± 11.7	RES/HIIT	30	1/w	12	No intervention	②③
Jiang Yijun	2020	China	30	64.0 ± 3.7	PMT	60	3/w	12	No intervention	②④
Xu Weihao	2022	China	30	62.3 ± 1.8	AER	60	3/w	12	No intervention	②
Liu Tongtong	2021	China	34	64.5 ± 4.3	PMT	60	5/w	12	No intervention	②③④
Neha P.	2017	America	108	62.1 ± 5.6	PMT	60	3/w	8	Muscle stretching	③
Claudine L	2011	America	36	76.5 ± 4.9	AER	75	2/w	16	No intervention	④⑤
Manh H N	2012	Germany	96	68.9 ± 5.1	PMT	60	2/w	26	No intervention	③
Yohko M	2012	Japan	150	72.0 ± 4.0	AER	90	1/w	13	Health education	③
Lars S. Jon	2016	Sweden	58	68.7 ± 2.7	AER	45	3/w	26	Muscle stretching	③④⑤
Peng Xiaoqin	2021	China	32	67.3 ± 3.7	PMT	60	3/w	13	Health education	③④
Ricardo C.	2007	Brazil	43	67.7 ± 0.9	RES	60	3/w	24	No intervention	⑤
Fabre C	2002	France	16	65.6 ± 1.8	AER	60	2/w	8	No intervention	⑤
Margie E	2006	America	210	74.9 ± 6.9	RES	35	3/w	26	No intervention	⑤
Chen Shuang	2020	China	29	62.4 ± 3.1	PMT	90	5/w	24	Health education	③

Annotation:RES:Resistance training;AER:Aerobic exercises;HIIT:High-intensity interval training;PMT:Physical and mental training;CEX:Multi-modal exercise interventions;CON:Control group.①Overall Cognitive Function; ②Inhibitory Control; ③Task-Switching Ability; ④Working Memory; ⑤Memory Function.

of the participants was 69.4 years, with the combined sample size comprising 2585 individuals. Of the included studies: 10 trials (comprising 585 participants) assessed the effects of resistance training. 13 trials (768 participants) examined aerobic exercises. 2 trials (75 participants) focused on high-intensity interval training (HIIT). 13 trials (932 participants) evaluated physical and mental training interventions, such as Tai Chi or yoga. 8 trials (443 participants) investigated multi-modal exercise interventions. These studies utilized a variety of exercise modalities to explore their impacts on cognitive functions among healthy older adults. The diversity in intervention types and participant demographics across different geographic regions provides a comprehensive overview of the current landscape in exercise-based cognitive health research. Table 1 provides detailed information on each study, including the authors, publication year, country, sample size, participant characteristics, type of intervention, duration, frequency, intensity, and primary outcomes measured.

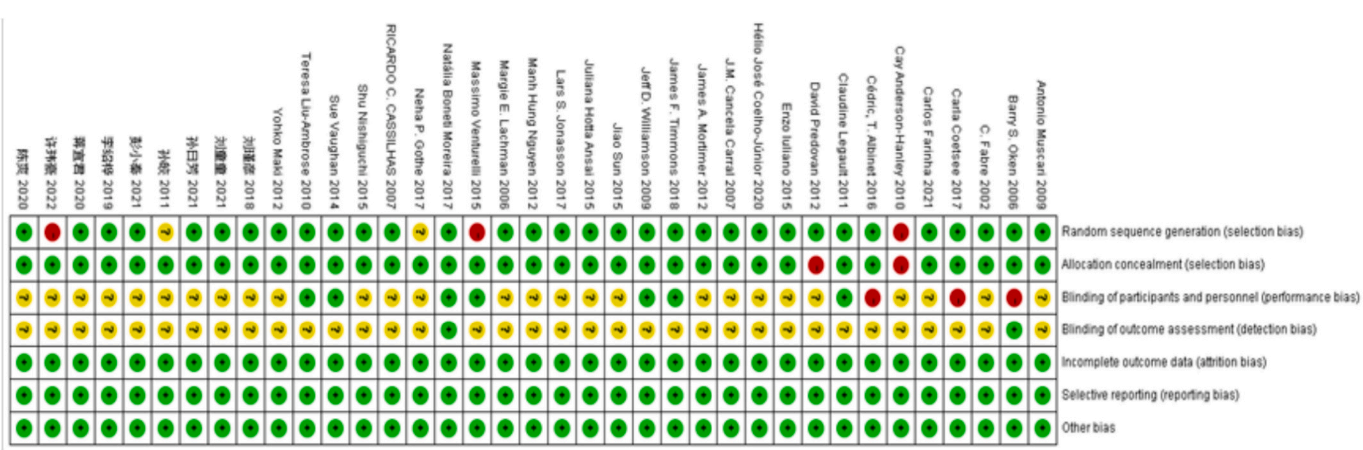

Fig. 2. Figure of risk of bias assessment.

3.3. Risk of bias assessment

The risk of bias in the included studies was systematically evaluated using the Cochrane Collaboration's Risk of Bias Tool. The assessment categorized studies into three grades based on their overall risk of bias: Grade A (Low Risk): 1 study. Grade B (Moderate Risk): 29 studies. Grade C (High Risk): 7 studies. No studies were excluded from the analysis based on their risk of bias. Fig. 2 provides a detailed breakdown of the risk of bias across all included studies, illustrating the distribution of bias domains such as random sequence generation, allocation concealment, blinding, incomplete outcome data, selective reporting, and other potential biases. Additionally, publication bias was assessed using Egger's test, which revealed no significant bias ($p > 0.05$). This suggests that the results of the meta-analysis are unlikely to be substantially influenced by selective publication of studies.

3.4. Meta-analysis results

Fig. 3 presents the network plot for the different outcome measures, while Fig. 4 illustrates the SUCRA rankings. Table 2 shows the results for SUCRA values. SUCRA values represent the probability (0–100 %) that an intervention will be the most optimal choice. For example, resistance training had an SUCRA value of 83.3 %, indicating an 83.3 % probability that it would be the most effective intervention for improving overall cognitive function. However, it is important to note that confidence intervals (e.g., SMD = 0.88, 95 % CI: 0.30–1.46) should be used to assess the stability of the results and the uncertainty surrounding the SUCRA values. The results of the pairwise comparisons are detailed in Fig. 5.

3.5. Overall cognitive function

Fifteen studies (n = 958) were included in the analysis of overall cognitive function. The network meta-analysis revealed that all exercise modalities—**mind-body exercise** (SMD = 0.53, 95 % CI: 0.08–0.98), **multimodal exercise** (SMD = 0.56, 95 % CI: 0.15–0.97), **aerobic exercise** (SMD = 0.71, 95 % CI: 0.19–1.22), and **resistance training** (SMD = 0.88, 95 % CI: 0.30–1.46)—significantly improved cognitive function compared to the control group. The ranking of different exercise interventions based on cumulative probability plots and SUCRAs are shown in Fig. 4 and Table 2, among these interventions, resistance training demonstrated the highest effectiveness, achieving the highest surface under the cumulative ranking curve (**SUCRA = 83.3**), followed by aerobic exercise (**SUCRA = 68.5**), multimodal exercise (**SUCRA = 49.3**), and mind-body exercise (**SUCRA = 48.4**).

3.6. Inhibitory control

Fifteen studies (n = 907) were included in the analysis of inhibitory control. Resistance training significantly enhanced inhibitory control compared to the control group (SMD = 0.31, 95 % CI: 0.04–0.58). The ranking of different exercise interventions based on cumulative probability plots and SUCRA values are presented in Fig. 4 and Table 2. These rankings highlight the effectiveness of various interventions, with resistance training emerging as the most effective intervention, possessing both the highest probability of being the optimal treatment (39.9 %) and the highest SUCRA value **(SUCRA = 82.1)**. Other exercise modalities, including high-intensity interval training (**HIIT**), aerobic exercise, and mind-body exercise, showed improvements; however, these effects were not statistically significant.

3.7. Task-switching ability

Twelve studies (n = 842) investigated the effects of different exercise modalities on task-switching ability. The network meta-analysis indicated that mind-body exercise had the most significant effect on task-switching ability (SMD = 0.72, 95 % CI: 0.24–1.19). Multimodal exercise, resistance training, and aerobic exercise also demonstrated improvements, albeit to a lesser extent. The SUCRA rankings for task-switching ability placed mind-body exercise at the top (**SUCRA = 85.1**), followed by multimodal exercise (**SUCRA = 66.0**), resistance training (**SUCRA = 51.4**), and aerobic exercise (**SUCRA = 40.3**).

3.8. Working memory

Seven studies (n = 297) explored the impact of exercise on working memory. Both mind-body exercise and aerobic exercise showed improvements in working memory; however, these results were not statistically significant compared to the control group. As shown in Table 2,

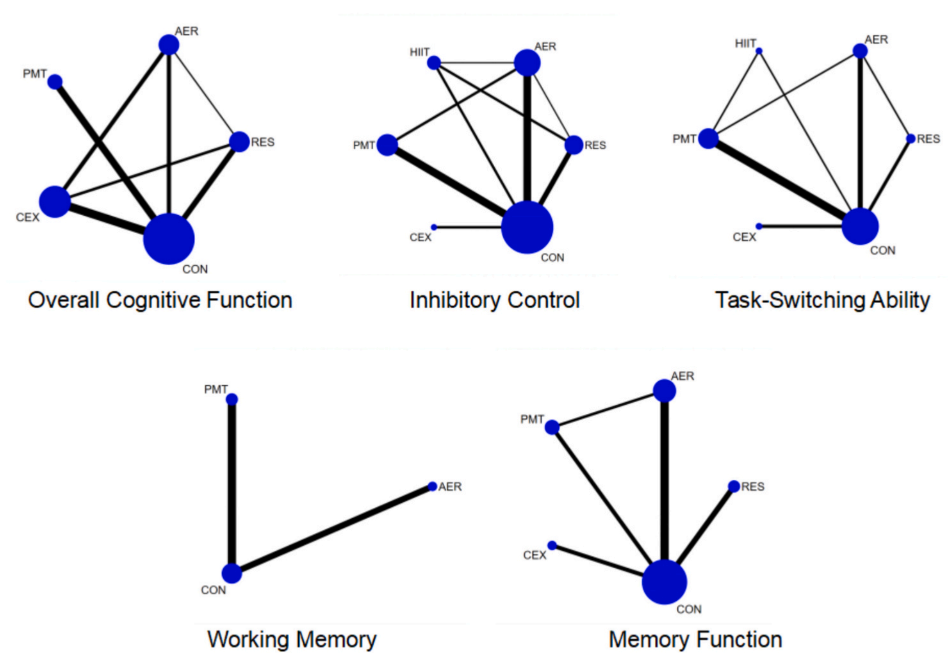

Fig. 3. Network plot. RES resistance training, AER aerobic exercises, HIIT high-intensity interval training, PMT physical and mental training,CEX multi-modal exercise interventions,CON control group.

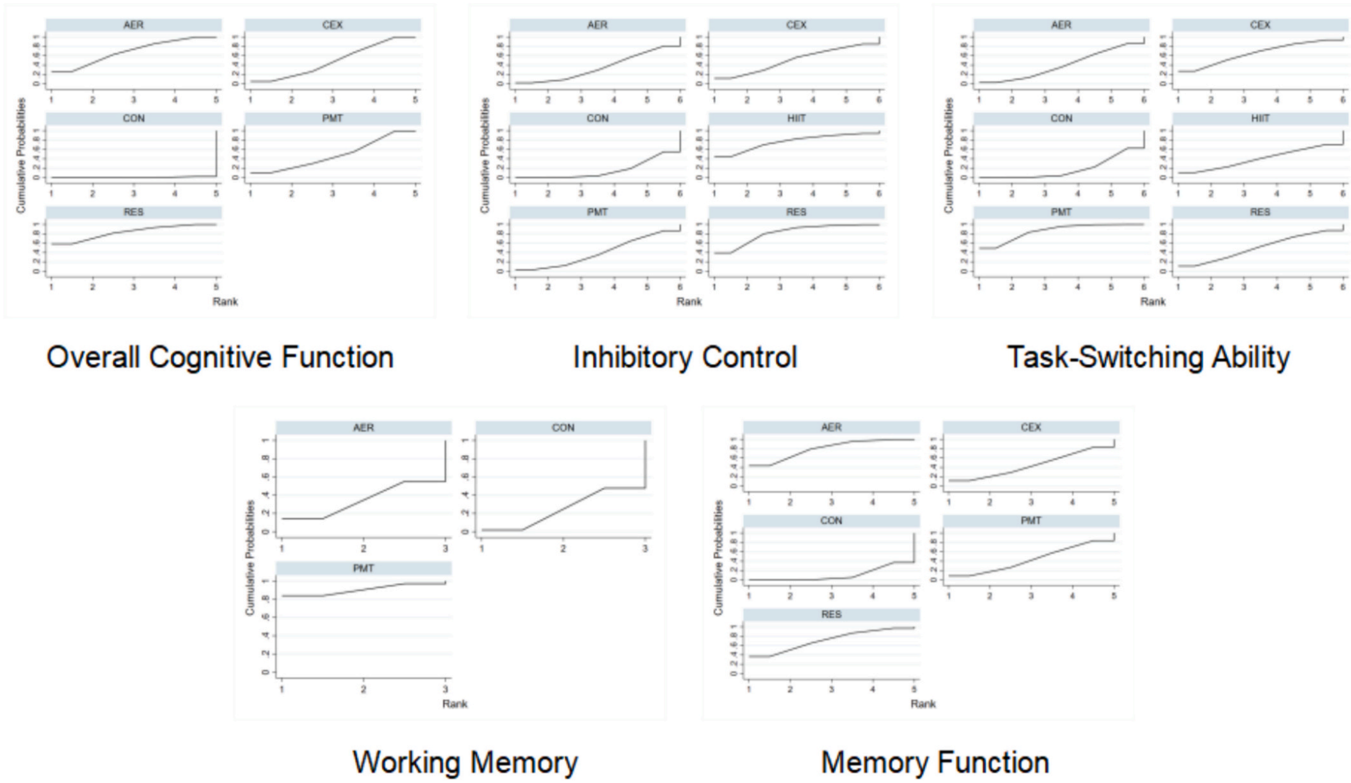

Fig. 4. Surface under the cumulative ranking area.

Table 2
Summary of SUCRA ranking.

Experimental group	Overall Cognitive Function			Inhibitory Control			Task-switching Ability			Working Memory			Memory		
	SUCRA	Mean rank	P (%)	SUCRA	Mean rank	P (%)	SUCRA	Mean rank	P (%)	SUCRA	Mean rank	P (%)	SUCRA	Mean rank	P (%)
RES	83.3	1.7	58.4	82.1	1.9	39.9	51.4	3.4	12.7	–	–	–	70.7	2.2	36.1
AER	68.5	2.3	26.2	35.1	4.2	1.9	40.3	4	2.6	35.1	2.3	14	80	1.8	44.6
HIIT	–	–	–	76.1	2.2	43.3	39.2	4	9.3	–	–	–	–	–	–
PMT	48.4	3.1	10.2	40.7	4	2.8	85.1	1.7	48	90.6	1.2	84	43.8	3.2	7.9
CEX	49.3	3	5.2	50.7	3.5	12	66	2.7	27.4	–	–	–	45	3.2	11.5
CON	0.5	5	0	15.4	5.2	0	18	5.1	0	24.3	2.5	2	10.6	4.6	0

Mind-body exercise had the highest probability (84.0 %) of being the most effective exercise type in protecting working memory, with a SUCRA value of 90.6, followed by aerobic exercise (**SUCRA = 35.1**).

3.9. Memory function

Fourteen studies (n = 907) assessed the effects of exercise interventions on memory function. Aerobic exercise had the most significant effect on memory (SMD = 0.50, 95 % CI: 0.10–0.90) compared to the control group. Resistance training, mind-body exercise, and multimodal exercise also exhibited positive effects, although these were not statistically significant. Aerobic exercise achieved the highest SUCRA ranking (**SUCRA = 80.0**), followed by resistance training (**SUCRA = 70.7**), multimodal exercise (**SUCRA = 45.0**), and mind-body exercise (**SUCRA = 43.8**).

3.10. Subgroup analyses

Subgroup analyses were conducted based on the **duration**, **frequency**, and **intensity** of exercise interventions. The results indicated that: **Resistance Training:** Programs lasting **12 weeks**, with sessions performed **twice per week** for **45** min, had the most significant effect on cognitive function. **Aerobic Exercise:** Interventions lasting **21 weeks**, with sessions conducted **twice per week** for **60 min**, were the most effective for memory enhancement. Table 3 summarizes the findings from the subgroup analyses, providing detailed insights into the optimal parameters for exercise interventions aimed at improving cognitive health in older adults. Meta-regression analysis showed that the heterogeneity ($I^2 > 50$ %) was mainly due to the duration of the intervention ($\beta = 0.21$, $p = 0.03$) and the difference in cognitive assessment tools (e.g., MoCA vs. MMSE). After excluding studies with high risk of bias in sensitivity analysis, the heterogeneity was significantly reduced ($I^2 = 35$ %), but the direction of effect remained consistent.

4. Discussion

Cognitive decline, encompassing mild cognitive impairment, memory loss, and dementia, is a significant concern among older adults (Petersen et al., 2014). This study is the first to integrate direct and indirect evidence to quantify the relative effects of different exercise patterns on specific cognitive functions and to suggest targeted intervention parameters through a network meta-analysis. Our network meta-analysis findings complement the lack of cross-intervention comparisons and parameter optimization in the existing literature. The

Overall Cognitive Function

RES				
0.17 (-0.52,0.86)	AER			
0.32 (-0.29,0.93)	0.15 (-0.37,0.67)	CEX		
0.35 (-0.38,1.08)	0.18 (-0.50,0.86)	0.03 (-0.58,0.64)	PMT	
0.88 (0.30,1.46)	**0.71 (0.19,1.22)**	**0.56 (0.15,0.97)**	**0.53 (0.08,0.98)**	CON

Inhibitory Control

RES					
-0.00 (-0.44,0.44)	HIIT				
-0.17 (-0.59,0.25)	-0.17 (-0.71,0.37)	CEX			
-0.22 (-0.57,0.12)	-0.22 (-0.70,0.26)	-0.05 (-0.44,0.33)	PMT		
-0.24 (-0.58,0.09)	-0.24 (-0.71,0.23)	-0.07 (-0.46,0.31)	-0.02 (-0.28,0.24)	AER	
-0.31 (-0.58,-0.04)	-0.31 (-0.75,0.12)	-0.14 (-0.46,0.18)	-0.09 (-0.30,0.13)	-0.07 (-0.29,0.15)	CON

Task-Switching Ability

PMT					
-0.20 (-1.13,0.73)	CEX				
-0.38 (-1.25,0.48)	-0.18 (-1.27,0.91)	RES			
-0.51 (-1.17,0.16)	-0.30 (-1.28,0.67)	-0.12 (-0.95,0.71)	AER		
-0.53 (-1.50,0.45)	-0.33 (-1.59,0.94)	-0.14 (-1.36,1.08)	-0.02 (-1.12,1.08)	HIIT	
-0.72 (-1.19,-0.24)	-0.51 (-1.31,0.28)	-0.33 (-1.07,0.41)	-0.21 (-0.77,0.35)	-0.19 (-1.17,0.79)	CON

Working Memory

PMT		
0.90 (-0.78,2.59)	AER	
0.98 (-0.14,2.10)	0.08 (-1.18,1.34)	CON

Memory Function

AER				
0.05 (-0.56,0.66)	RES			
0.26 (-0.39,0.91)	0.21 (-0.50,0.92)	CEX		
0.27 (-0.26,0.79)	0.22 (-0.47,0.90)	0.00 (-0.71,0.72)	PMT	
0.50 (0.10,0.90)	0.44 (-0.04,0.93)	0.23 (-0.28,0.75)	0.23 (-0.27,0.72)	CON

Fig. 5. League table of outcome measures.

findings indicate that resistance training, mind-body exercises, and aerobic exercise each confer distinct benefits across different cognitive domains. Our findings highlight the necessity of customizing exercise interventions to address specific aspects of cognitive health in the aging population.

4.1. Impact of resistance training on cognitive function

Our analysis revealed that resistance training exerts the most substantial effect on overall cognitive function, particularly enhancing inhibitory control. This aligns with existing literature suggesting that resistance training improves executive functions and working memory through several neurobiological mechanisms (Loprinzi et al., 2019). Notably, resistance training increases brain-derived neurotrophic factor (BDNF) levels, promoting synaptic plasticity and neural growth in the hippocampus, a critical region for memory and learning (Schley et al., 2006). Additionally, it stimulates the release of insulin-like growth factor 1 (IGF-1), which enhances neural connectivity and protects against age-related cognitive decline (Engeroff et al., 2022). Resistance training also exhibits anti-inflammatory properties by reducing pro-inflammatory cytokines such as TNF-α and IL-6, which are implicated in cognitive deterioration (Schley et al., 2006).

The optimal resistance training protocol identified—**12 weeks**, with sessions conducted **twice weekly** for **45** min—is consistent with the World Health Organization's (WHO) physical activity guidelines for older adults. This regimen not only bolsters physical strength but also supports cognitive health, presenting a cost-effective and accessible non-pharmacological intervention to mitigate cognitive decline (Ahlskog et al., 2011).

4.2. Efficacy of physical and mental training on executive function

Physical and mental training modalities, such as Tai Chi and yoga, demonstrated significant improvements in task-switching ability and working memory. These exercises involve complex motor sequences, sustained mental focus, and continuous adaptation, thereby imposing high cognitive demands on participants. This heightened engagement is believed to enhance executive functions, particularly cognitive flexibility (Gu et al., 2019). Research indicates that such training activates the prefrontal cortex, a brain region integral to executive control, facilitating more efficient task-switching and working memory updating (Colcombe and Kramer, 2003b; Kramer and Colcombe, 2018). In line with our findings, the SUCRA rankings indicate that mind-body exercises, like Tai Chi, ranked highly for improving cognitive flexibility and working memory, with a 90.6 % probability of being the most effective modality for enhancing working memory. However, while the rankings suggest mind-body exercises may be the best intervention in this specific domain, it is crucial to assess the uncertainty of these findings by considering the confidence intervals, such as SMD = −0.18 (−0.41, 0.05), which demonstrate some variation in effect sizes.

Subgroup analysis identified that engaging in these exercises three times weekly for 12 weeks, with each session lasting 60 min, yields the most significant cognitive benefits. These findings underscore the potential of mind-body exercises as a holistic approach to cognitive health, promoting both mental and physical well-being (Liu et al., 2023).

4.3. Aerobic exercise and memory function enhancement

Aerobic exercise emerged as the most effective modality for enhancing memory function. This corroborates existing studies that demonstrate aerobic exercise's role in increasing hippocampal neurogenesis and improving cerebral blood flow, both of which are essential for memory formation and retention (Tao et al., 2019). Additionally, aerobic exercise stimulates lactate production, which traverses the blood-brain barrier and serves as a metabolic fuel for neurons, thereby enhancing cognitive processes (Riske et al., 2017). The SUCRA value for

Table 3
Subgroup analyses.

Subgroup	Number of documents	Sample size	SMD (95%CI)	Heterogeneity test	
				P	I^2(%)
Overall Cognitive Function(Resistance training)					
Single intervention time	4				
≤45 min	2	65	1.64(−1.10,4.39)	0.000	93.6
>45 min	2	72	0.93(−0.63,2.48)	0.004	87.8
The frequency of intervention per week	4				
<3 times	1	26	1.76(0.84, 2.68)	0.000	0.0
≥3 times	3	111	1.05(−0.25,2.36)	0.000	89.1
Intervention weeks	4				
≤12 weeks	2	65	1.64(−1.10,4.39)	0.000	93.6
>12 weeks	2	72	0.93(−0.63,2.48)	0.004	87.8
Inhibitory Control(Resistance training)					
Single intervention time	4				
≤45 min	2	81	−0.26(−0.70,0.18)	0.882	0.0
>45 min	2	120	−0.27(−0.63,0.09)	0.791	0.0
The frequency of intervention per week	4				
<3 times	3	160	−0.26(−0.57,0.05)	0.959	0.0
≥3 times	1	41	−0.29(−0.91,0.33)	0.000	0.0
Intervention weeks	4				
≤12 weeks	2	72	−0.28(−0.74,0.18)	0.795	0.0
>12 weeks	2	129	−0.26(−0.60,0.09)	0.890	0.0
Task-Switching Ability(Physical and mental training)					
Single intervention time	6				
<60 min	1	60	−0.86(−1.39,-0.33)	0.000	0.0
=60 min	4	247	−0.79(−1.65,0.08)	0.000	89.3
>60 min	1	30	−0.24(−0.96,0.48)	0.000	0.0
The frequency of intervention per week	6				
≤3 times	4	273	−0.98(−1.72,-0.25)	0.000	86.8
>3 times	2	64	−0.14(−0.63,0.35)	0.701	0.0
Intervention weeks	6				
≤12 weeks	3	174	−0.41(−0.71,-0.11)	0.469	0.0
>12 weeks	3	163	−1.09(−2.14,-0.04)	0.000	89.1
Memory Function(Aerobic exercises)					
Single intervention time	6				
≤60 min	4	170	0.41(0.11,0.72)	0.531	0.0
>60 min	2	124	0.81(−0.97,2.60)	0.000	93.5
The frequency of intervention per week	6				
<3 times	4	176	0.75(−0.09,1.59)	0.001	83.1
≥3 times	2	118	0.33(−0.03,0.70)	0.925	0.0
Intervention weeks	6				
≤21 weeks	3	85	1.08(−0.19,1.97)	0.032	70.9
>21 weeks	3	209	0.16(−0.11,0.43)	0.365	0.7

aerobic exercise was 80 %, indicating a high probability that it is among the most effective interventions for memory function. However, the differences between aerobic exercise and other interventions, such as resistance training, should be interpreted with caution. For example, resistance training, with a SUCRA value of 83.3 %, showed a slightly higher probability of being the optimal intervention, but the confidence intervals (e.g., SMD = 0.88, 95 % CI: 0.30–1.46) overlap, suggesting that the true difference may not be statistically significant in some contexts.

The optimal aerobic exercise regimen identified—21 weeks, with sessions conducted twice weekly for 60 min—provides robust evidence for its efficacy in promoting memory function among older adults. Given that memory decline is a hallmark of cognitive aging, aerobic exercise represents a practical intervention that can be readily integrated into public health initiatives aimed at reducing the burden of dementia (Blomstrand et al., 2023).

4.4. Implications for public health and clinical practice

The study's findings offer critical insights for developing personalized exercise prescriptions tailored to the specific cognitive needs of older adults. Resistance training, physical and mental training, and aerobic exercise each target distinct cognitive domains, enabling customized interventions based on individual objectives: Resistance training enhances overall cognitive function and inhibitory control; mind-body exercises improve working memory and task-switching abilities; and aerobic exercise strengthens memory function (See Table 4). Promoting these exercise interventions within aging populations can yield substantial public health benefits. Physical activity not only delays cognitive decline but also reduces healthcare costs and improves overall quality of life. Public health campaigns emphasizing

Table 4
Optimal intervention for cognitive function.

Type of exercise	Optimum duration	Intervention frequency	Single intervention time	Cognitive function domain
RES	12 weeks	2–3 times/week	45 min	Overall Cognitive Function、Inhibitory Control
AER	21 weeks	2 times/week	60 min	Memory Function
PMT	12 weeks	3 times/week	60 min	Task-Switching Ability、Working Memory

the cognitive benefits of exercise could play a pivotal role in alleviating the societal and economic burdens associated with dementia (Blondell et al., 2014). The application of SUCRA rankings in this study allows clinicians and policymakers to consider the most effective interventions for different cognitive functions in older adults, based on both the probability of efficacy and the uncertainty of the results. These rankings can guide decisions on personalized exercise interventions, particularly when the objective is to target specific cognitive domains, such as memory or executive function.

4.5. Study limitations and future directions

Despite its strengths, this study has several limitations. Firstly, the heterogeneity of cognitive assessment tools across included studies may introduce variability in the results. Future research should strive to standardize cognitive outcome measures to enable more consistent comparisons. Secondly, the study primarily focused on cognitive function, executive function, and memory, neglecting other cognitive domains such as attention and language fluency. Future investigations should encompass these additional domains to provide a more comprehensive understanding of how exercise influences cognitive health. Third, although multiple exercise modalities were analyzed, insufficient attention to dose-response relationships (particularly intervention intensity gradients) and feasibility barriers (e.g., time demands, functional capacity disparities in older adults) limits practical applicability–a critical gap given the divergent implementation challenges between low-intensity mind-body practices (e.g., tai Chi) and high-intensity regimens like HIIT, for example, mind-body exercises such as tai Chi may be easier to promote because of their lower intensity and greater safety profile, whereas high-intensity interval training (HIIT) may be limited in feasibility. Finally, because only a few studies reported long-term follow-up data after the end of the intervention, we extracted data on the intervention endpoint only from these studies. Therefore, our study does not provide evidence on the impact of exercise on the duration of the intervention, and future longitudinal studies are needed to verify the sustained effect of the intervention.

5. Conclusion

This study demonstrates that resistance training is the most effective exercise modality for enhancing overall cognitive function and inhibitory control in older adults. Physical and mental training (e.g., Tai Chi, yoga) offers the greatest benefits for improving task-switching ability and working memory, whereas aerobic exercise is most effective for boosting memory function. These findings emphasize the importance of tailoring exercise interventions to target specific cognitive domains, thereby optimizing cognitive health in the aging population. Future research should explore the underlying mechanisms through which each exercise modality influences brain health. Additionally, long-term studies are necessary to assess the sustained benefits of exercise on cognitive function in older adults, further informing public health recommendations and interventions.

CRediT authorship contribution statement

Jinhao Zhang: Formal analysis, Data curation. **Wei Ye:** Formal analysis, Data curation, Conceptualization. **Wang Li:** Methodology, Investigation. **Fan Zhang:** Software, Resources. **Zhijian Wu:** Writing – review & editing, Resources, Funding acquisition.

Consent for publication

Not applicable.

Funding

This work was supported by the National Social Science Foundation of China (No. 23CTY018). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Declaration of competing interest

The authors declare that they have no competing interests.

Acknowledgements

We would like to thank those who supported the project, including the Nanjing Municipal Bureau of Sports of the coordination committee. We would also like to thank Editage [www.editage.cn] for English language editing.

Data availability

The datasets generated and/or analyzed during the current study are not publicly available due to participant privacy and confidentiality requirements but are available from the corresponding author on reasonable request.

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