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SYSTEMATIC REVIEW

Acute Effects of Resistance Exercise on Cognitive Function in Healthy Adults: A Systematic Review with Multilevel Meta-Analysis

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Abstract

Background Recent research has revealed a beneficial impact of chronic resistance exercise (RE) on brain function. However, it is unclear as to whether RE is also effective in an acute setting.

Objective To investigate the immediate effects of a single RE session on cognitive performance in healthy adults.

Methods A multilevel meta-analysis with random effects meta-regression model was used to pool the standardized mean differences (SMD) between RE and no-exercise (NEX) as well as between RE and aerobic exercise (AE). In addition to global cognitive function, effects on reported sub-domains (inhibitory control, cognitive flexibility, working memory, attention) were examined.

Results Twelve trials with fair methodological quality (PEDro scale) were identified. Compared to NEX, RE had a positive effect on global cognition (SMD: 0.56, 95% CI 0.22–0.90, $p = 0.004$), but was not superior to AE (SMD: − 0.10, 95% CI 0.01 to − 0.20, $p = 0.06$). Regarding cognitive sub-domains, RE, compared to NEX, improved inhibitory control (SMD: 0.73, 95% CI 0.21–1.26, $p = 0.01$) and cognitive flexibility (SMD: 0.36, 95% CI 0.17–0.55, $p = 0.004$). In contrast, working memory (SMD: 0.35, 95% CI − 0.05 to 0.75, $p = 0.07$) and attention (SMD: 0.79, 95% CI − 0.42 to 2.00, $p = 0.16$) remained unaffected. No significant differences in sub-domains were found between RE and AE ($p > 0.05$).

Conclusion RE appears to be an appropriate method to immediately enhance cognitive function in healthy adults. Further studies clearly elucidating the impact of effect modifiers such as age, training intensity, or training duration are warranted.

Key Points

Previous literature shows that several weeks of resistance training induces moderate improvements in cognitive function.

A single bout of resistance exercise leads to moderate improvements in cognitive function when compared to a no-exercise control.

The acute effects of resistance exercise are not superior to those occurring after aerobic exercise.

The impact of effect modifiers such as age, training duration, or training intensity needs to be further elucidated.

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1 Introduction

Engagement in physical activity represents a well-established method to elicit health-beneficial effects in a variety of peripheral organs such as the skeletal muscles, the heart, or the lungs [1]. Over recent decades, the potential impact of regular movement on brain morphology and function has evolved as another focus of research. Accumulating evidence suggests the occurrence of training-induced cerebral adaptations that may help to prevent or delay cognitive decline and neurodegenerative diseases; according to data from animal experiments, chronic exercise promotes synaptic plasticity, angiogenesis, and neurogenesis [2–4]. Human studies have, furthermore, demonstrated the expression of brain-derived neurotrophic factor (BDNF), as well as increases in hippocampal brain volume, in response to several weeks of training [5]. It has been hypothesized that the described exercise-induced changes in the brain, functionally, result in enhanced cognitive performance. This seems plausible as, for instance, angiogenesis allows enhanced perfusion

and the hippocampus is related to learning and long-term memory [6].

To date, most studies examining the effects of physical activity on brain function have used aerobic-type exercise. Several meta-analyses, which included both acute and chronic interventions, detected small to moderate training-induced improvements in domains such as processing speed, attention, executive function, and memory [7–17]. In view of the positive effects observed, recent research has also been dedicated to the potential impact of resistance exercise. Compared to endurance training, which typically consists of the repetitive execution of one specific movement pattern (e.g., running or cycling), resistance training often involves a series of different exercises in both the upper and lower limbs. It may, therefore, be speculated that strength training, with its higher variability, may stimulate the brain at least to a similar degree as aerobic exercise does.

Existing systematic reviews found mixed, but mainly small, positive effects of resistance exercise on different measures of cognition [18–21]. Their findings are in line with data reported by two meta-analyses of trials recruiting healthy older adults for chronic training interventions. Kelly et al. [22] did not detect an effect of resistance exercise on working memory or attention, but did observe a large improvement in reasoning. However, their sample was relatively small as they identified only a maximum of three studies per cognitive dimension. Northey et al. [15] were able to pool the results of 13 trials; the authors reported moderate effects of resistance exercise on executive function (standardised mean difference [SMD]: 0.49), memory (SMD: 0.54), and working memory (SMD: 0.49).

In contrast to the data available for chronic regimes, evidence is scarce with regard to the immediate effects of one training session. The only existing systematic analysis of the literature examining this issue [23] is rather old, did not provide a quantitative data synthesis, and was focussed on children. The present meta-analysis, therefore, aimed to investigate the acute effects of a single resistance exercise bout on cognitive function in healthy adults.

2 Methods

A systematic review with multilevel meta-analysis and a random effect meta-regression model was performed according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [24]. It followed the recommendations for ethical publishing of systematic reviews proposed by Wager and Wiffen [25]. The study was registered in the PROSPERO database (CRD42018089914).

2.1 Search Strategy

Two independent investigators (JW, FG) performed a systematic literature search between February and April 2018. Relevant articles were identified using the online databases MEDLINE (PubMed), ScienceDirect, Web of Science, Cochrane Central, and Google Scholar. For Google Scholar, an approach described in previous systematic reviews of our work group was used [26, 27]. In addition to the database search, the reference lists of all included studies were checked in order to identify other eligible papers [28].

2.2 Inclusion Criteria

Randomized controlled trials (crossover or parallel-group design) with accessible full text were considered for inclusion. Further criteria were (1) enrolment of healthy adults, (2) performance of resistance exercise, (3) testing of acute effects on cognitive function (measurement starting within 5 min post-exercise), and (4) publication in the English language and in a peer-reviewed journal. All studies investigating chronic effects, other training methods, or persons with diseases were excluded.

2.3 Data Extraction

Using a standardized assessment sheet, two investigators (KK, FG) independently performed the data extraction. They retrieved the following information: study design, sample size, participant characteristics, interventions, measured outcomes (tests and related cognitive sub-dimension; Table 1) and results (pre-post changes plus standard deviations of each intervention arm). The primary outcome of the meta-analysis was global cognition, which included pooling of all clinically validated measures of cognitive function. If a study performed more than one cognitive test, or had more sub-domains in one test, all effect sizes (ES) were extracted.

2.4 Data Synthesis and Statistics

For each intervention arm of the parallel-group studies, the mean pre to post changes plus standard deviations (SDs) were retrieved. If reporting was incomplete (i.e., missing SDs of the changes from baseline), the corresponding authors of the trials were contacted to request the missing information. If no values could be obtained, missing data were determined from figures or imputed according to the recommendations in the Cochrane handbook, using the formula $SD_{change} = \sqrt{\left(SD^2_{baseline} + SD^2_{postintervention}\right) - \left(2 \times Corr \times SD_{baseline} \times SD_{postintervention}\right)}$, where Corr = 0.7. The value chosen for Corr has previously been

Table 1 Cognitive subdimensions and related tests

Dimension	Tests
Attention	Stroop Color, Stroop Word, Trail Making Test A
Working memory	Sternberg-Test, Paced Auditory Serial Addition Test
Cognitive flexibility	Trail Making Test B
Inhibitory control	Stroop Incongruent, Stroop Interference, Go/No-Go Test

recommended as a conservative estimate of the correlation between the baseline and post-treatment SDs [32]. For crossover trials, the SD of the difference between the two relevant conditions' pre-post changes, the correlation of the respective pre-post changes, and the standard error were calculated. If the correlation coefficient could not be extracted from publications or raw data, a conservative value of 0.5 was assumed, which also fits with the known correlations of the other included studies. When combining the results from parallel-group and crossover studies, we used appropriate formulae for standardized mean ES and standard errors [33].

The following potential moderators of the treatment effect were coded as numerical data: cognitive domain (inhibitory control, cognitive flexibility, working memory, attention), study design (parallel-group, crossover trial), training duration (short: ≤ 30 min, long: > 30 min), training intensity (light: $< 50\%$ of the 1-repetition maximum (1 RM), moderate: 50–75% 1 RM, high: 75–100% 1 RM) and age (young: ≤ 40 years, old > 40 years).

A multilevel meta-analysis with a robust random effects meta-regression model was used to pool the SMD and 95% confidence intervals (CIs) between resistance exercise (RE) and aerobic exercise (AE), as well as between RE and no-exercise control (NEX [34]). Dependency of ES was taken into account by nesting the term "study" as a random factor in the model. Potential moderators were identified with separate models: (1) estimating the significance of each level by means of the 95% CI and (2) testing for differences between the respective levels [15]. The between-study variance component was determined by means of Tau^2, using the method-of-moments estimate; for within-study variance (more than one dependent effect size), $omega^2$ (ω^2) was calculated [34]. p values < 0.05 were considered significant. The software employed was R (R Foundation for Statistical Computing, Vienna, Austria), packages meta (G Schwarzer), and robumeta (version 2.0, [35]).

2.5 Sensitivity Analyses and Risk of Bias

To test the robustness of imputed values, sensitivity analyses were performed for each outcome; this was achieved by means of comparing the result of the primary meta-analyses (studies with fully available data plus studies with imputed SDs) against a secondary analysis including only trials with fully available data. If the conclusions drawn, based on the ES and confidence intervals, were identical, then the findings of the primary meta-analysis were deemed robust [36]. Publication bias was examined by means of visual inspection of funnel plots (ES against standard errors) and optional sensitivity analyses excluding potential outliers.

The methodological quality of the included trials was rated by means of the PEDro scale [29], which has been demonstrated to represent a reliable and valid assessment tool [29–31]. The sum score of the instrument is based on the rating of 10 items assessing potential sources of bias. Two independent examiners (JW, FG) performed the quality scoring. In case of disagreement, a third investigator (KK) provided the decisive vote.

3 Results

3.1 Search Results

A flow diagram of the literature search is displayed in Fig. 1. The algorithms used returned a total of 1611 records. Twelve studies [34–45] met the eligibility criteria and were included in the review.

3.2 Characteristics of the Studies

All included papers collectively evaluated 447 participants (239 men and 208 women) with mean ages ranging from 20.4 to 72.3 years (Table 2). Eleven studies [37–44, 46–48] compared the acute effects of RE and CON, whereas five studies [39, 40, 45–47] compared the impact of RE and AE on brain function. Complete data were available or obtained from figures for seven studies [40, 42–44, 46–48], whilst imputation was needed for five trials [37–41, 45].

3.3 Methodological Quality

The two reviewers agreed on 116 (96.3%) of the 120 criteria scored by means of the PEDro scale. All disagreements were resolved by discussion without consulting the third investigator. The methodological quality of the 12 trials included ranged from 2 to 5 out of 10 and the mean score (3.7 ± 1) was classified as fair. Most studies reported randomization,

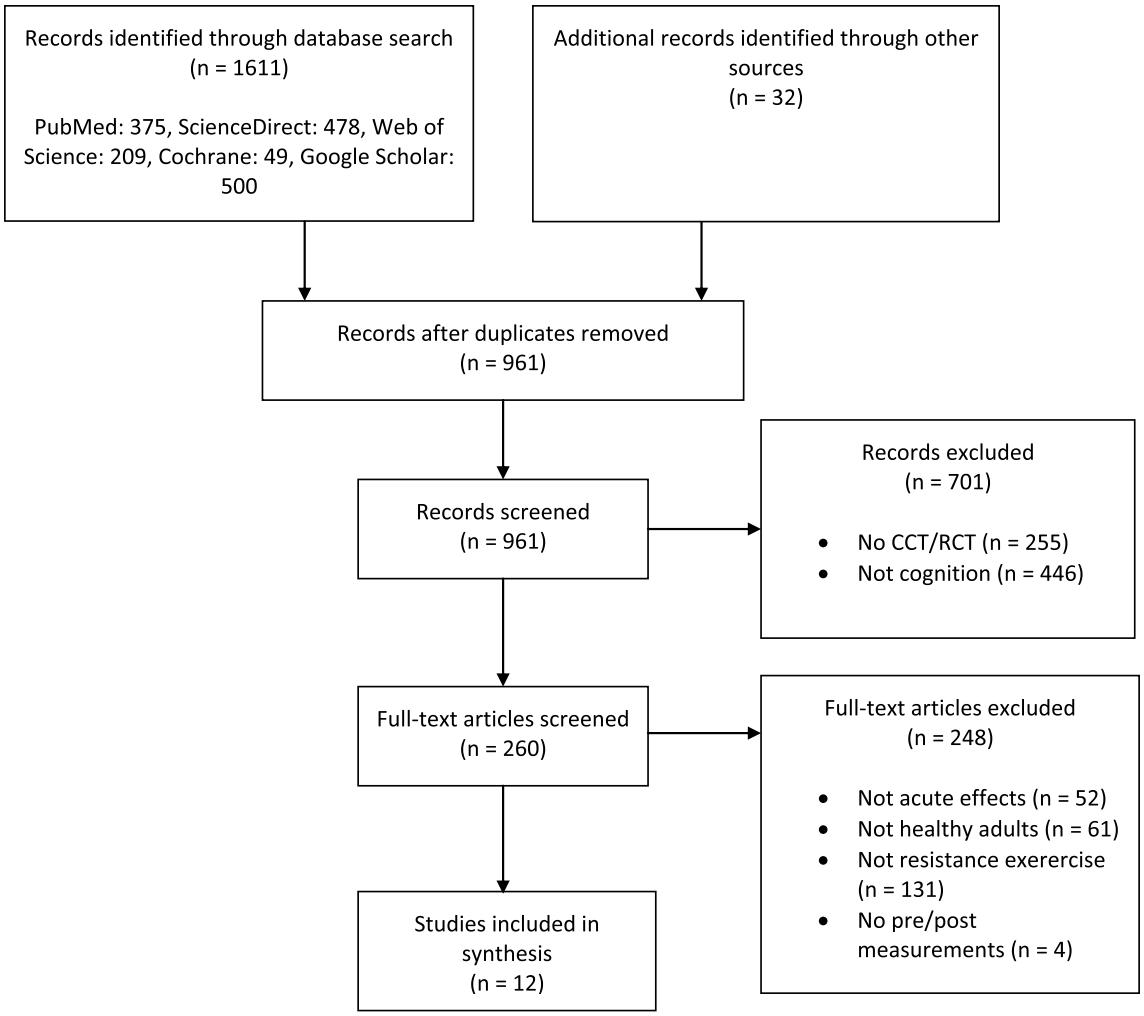

Fig. 1 PRISMA chart of the study flow. *CCT* controlled clinical trial, *RCT* randomized controlled trial

had comparable baseline values between conditions or groups, analyzed group differences, and included point and variability measures (Table 3). Since some studies used a crossover design, a substantial share of the sample was not able to satisfy the criterion of concealed allocation because it was a priori evident that all participants would receive each intervention.

3.4 Resistance Exercise versus No Exercise

A medium ES favouring RE over NEX was found ($n = 86$ ES, SMD: 0.56, 95% CI 0.22–0.90, $p = 0.004$, Tau^2: 0.38, ω^2: 0). According to the moderator analysis (Table 4), RE was more effective in some of the sub-domains, improving inhibitory control (SMD: 0.73, 95% CI 0.21–1.26, $p = 0.01$, Fig. 2) and cognitive flexibility (SMD: 0.36, 95% CI 0.17–0.55, $p = 0.004$, Fig. 3). A tendency approaching but failing statistical significance was found in working memory (SMD: 0.35, 95% CI − 0.05 to 0.75, $p = 0.07$, Fig. 4). For attention, no difference between RE and NEX was found (SMD: 0.79, 95% CI − 0.42 to 2.00, $p = 0.16$). With regard to the other moderators, factors statistically associated with a superiority of RE were parallel-group study design, a higher treatment duration, younger age, and a low and high (but not moderate) exercise intensity ($p < 0.05$). However, the ES and p values of the other levels of these variables were mostly similar, which implies a rather marginal impact (Table 4). This was confirmed by the fact that no between-level differences were found in any of the potential moderators.

3.5 Resistance Exercise versus Aerobic Exercise

Although the position of the confidence interval almost suggested a trend for the slight superiority of AE, there was no significant difference between RE and AE (SMD: − 0.10, 95% CI 0.01 to − 0.20, $p = 0.06$, Tau^2: 0.03, ω^2: 0, $n = 26$ ES). Similarly, no condition was more effective in the investigated sub-domains. Further moderator analyses were

Table 2 Characteristics of the studies included in the meta-analysis

Study	Participants	Design	Intervention	Control	Cognitive outcomes
Alves et al. [40]	$n=42$ (all women); 52 ± 7 y	Crossover	1: strength exercise (30 min, six exercises with 2×15 repetitions) 2: aerobic exercise (30 min walking, 50–60% HRR)	15 min instructions about health benefits of regular exercise training and 15 min low-intensity active stretching exercise	Stroop Test, Trail Making Test A/B
Chang and Etnier [37]	$n=41$ (14 men, 27 women); 49 ± 9 y Resistance group: $n=22$ (52 ± 9 y) Control group: $n=19$ (46 ± 9 y)	Parallel-group	1: resistance exercise (45 min, six exercises with 2×10 repetitions, 75% 1 RM)	45 min reading about resistance exercise	Stroop Test, Trail Making Test A/B
Chang and Etnier [38]	$n=65$ (33 men, 32 women); 26 ± 3 y High-intensity resistance group: $n=17$ (26 ± 3 y) Moderate-intensity resistance group: $n=16$ (26 ± 3 y) Low-intensity resistance group: $n=16$ (26 ± 4 y) Control group: $n=16$ (26 ± 3 y)	Parallel-group	1: high-intensity resistance exercise (45 min, six exercises with 2×10 repetitions, 100% 10 RM) 2: moderate-intensity resistance exercise (45 min, six exercises with 2×10 repetitions, 70% 10 RM) 3: low-intensity resistance exercise (45 min, six exercises with 2×10 repetitions, 40% 10 RM)	45 min watching a video about resistance exercise training	Stroop Test, PASAT (Trials 1–4)
Chang et al. [41]	$n=30$ (14 men, 16 women); 57 ± 3 y	Crossover	1: resistance exercise (20 min, seven exercises with 2×10, 70% 10 RM)	20 min reading about physical activity and mental health	Tower of London Task
Chang et al. [42]	$n=30$ (15 men, 15 women); 58 ± 3 y	Crossover	1: resistance exercise (30 min, seven exercises with 2×10 repetitions, 70% 10 RM)	30 min reading about physical activity and mental health	Stroop Test
Chang et al. [46]	$n=36$ (sex unknown) High-intensity resistance group: $n=9$ (21 ± 2 y) High-intensity aerobic group: $n=9$ (22 ± 1 y) Combined moderate-intensity group: $n=9$ (20 ± 2 y) Control group: $n=9$ (22 ± 1 y)	Parallel-group	1: high-intensity resistance exercise (seven exercises with 3×8–10 repetitions, 80% 1 RM) 2: moderate-intensity exercise (seven exercises with 3×12 repetitions, 30% 1 RM and 50–60% HRR walking) 3: high-intensity aerobic exercise (30 min running, 30% HRR)	No exercise	Stroop Test
Dunsky et al. [47]	$n=39$ (29 men, 10 women); 52 ± 8 y	Crossover	1: resistance exercise (25 min, six exercises with 3×10 repetitions, 75% 1 RM) 2: aerobic exercise (25 min, walking, 60% HRR)	25 min watching a video in seated position	Go/No-Go Task, Stroop Test
Hsieh et al. [44]	Study 1: $n=20$ men; 24 ± 2 y Study 2: $n=20$ men; 67 ± 2 y	Crossover	1: resistance exercise (30 min, eight exercise with 2×10 repetitions, 70% 10 RM)	30 min reading information about physical activity and mental health	Modified Sternberg Test

Table 2 (continued)

Study	Participants	Design	Intervention	Control	Cognitive outcomes
Johnson et al. [45]	$n=31$ (10 men, 21 women); 72 ± 2 y Resistance group: $n=14$ (71 ± 10 y) Aerobic group: $n=17$ (72 ± 7 y)	Parallel-group	1: resistance exercise (two sessions: 10- and 30-min circuit of five exercises, 60% 1 RM) 2: aerobic exercise (two sessions: 10- and 30-min cycle ergometer, 13 to 14 on RPE scale)	-	Stroop Test
Pontifex et al. [39]	$n=21$ (12 men, 9 women); 20 ± 0.3 y	Crossover	1: resistance exercise (30 min, seven exercises with 3 × 8–12 repetitions, 80% 1 RM) 2: aerobic exercise (30 min, treadmill running, 60–70% VO_{2max})	30 min seated rest	Modified Sternberg Test
Tsai et al. [43]	$n=60$ (all men) High-intensity resistance group: $n=20$ (22 ± 2 y) Moderate-intensity resistance group: $n=20$ (23 ± 3 y) Control group: $n=20$ (23 ± 2 y)	Parallel-group	1: high-intensity resistance exercise (40 min, six exercises with 2 × 10 repetitions, 80% 1 RM) 2: moderate-intensity resistance exercise (40 min, six exercises with 2 × 10 repetitions, 50% 1 RM)	45 min reading magazines	Erikson Flanker (Go/No-Go)
Tsukamoto et al. [48]	$n=12$ (all men); 23 ± 1 y	Crossover	1: high-intensity resistance exercise (17 min, 6 × 10 repetitions bilateral knee extension, 80% 1 RM) 2: moderate-intensity resistance exercise (17 min, 6 × 10 repetitions bilateral knee extension, 40% 1 RM)	17 min rest	Stroop Test

Age data are mean ± standard deviation

RM repetition maximum, *HRR* heart rate reserve, *VO2max* maximal oxygen uptake, *PASAT* Paced Auditory Serial Addition Test, *RPE* rate of perceived exertion, *1 RM* 1 one repetition maximum, *no.* number, *CI* confidence interval

Asterisks indicate statistical significance ($p < 0.05$)

Table 3 Methodological quality of the studies included (ratings on the PEDro scale)

	Alves et al. [40]	Chang and Etnier [37]	Chang and Etnier [38]	Chang at al. [41]	Chang et al. [42]	Chang et al. [46]	Dunsky et al. [47]	Hsieh et al. [44]	Johnson et al. [45]	Pontifex et al. [39]	Tsai et al. [43]	Tsukamoto et al. [48]
Eligibility criteria[a]	−	+	+	+	+	+	+	+	+	−	−	+
Random allocation	+	+	+	−	−	+	+	−	+	−	+	+
Concealed allocation	−	+	−	−	−	−	−	−	−	−	−	−
Similarity at baseline	+	+	−	+	−	−	+	+	+	+	−	+
Subject blinding	−	−	+	−	−	−	−	−	−	−	−	−
Therapist blinding	−	−	−	−	−	−	−	−	−	−	−	−
Assessor blinding	−	−	−	−	−	−	−	−	−	−	−	−
>85% follow-up	−	−	+	−	−	−	+	−	−	−	−	−
Intention-to-treat analysis	−	−	−	−	−	−	−	−	−	−	−	−
Between-group comparison	+	+	+	+	+	+	+	+	+	+	+	+
Point estimates and variability	+	+	+	+	+	+	+	+	+	+	+	+
Total (points)	4	5	5	3	2	3	5	3	4	3	3	4

+ point awarded, − no point awarded

[a]External validity, not counted for score

possible for the variables study design and participants' age (Table 4). While there were no differences between levels, the factors crossover-design and old age of participants were significant ($p < 0.05$).

3.6 Risk of Bias

Sensitivity analyses for imputed data did not yield any indication of bias. Visual inspection of the funnel plot (Fig. 5) suggested a potential publication bias due to the large effects and standard errors in one study [42]. A sensitivity analysis without this study, however, showed that the results were robust; only the effect of RE on attention became significant (SMD 0.39, 95% CI 0.16–0.62, $p = 0.008$). The findings including this trial (which was kept in the model) are therefore a conservative estimate of the treatment effects.

4 Discussion

This systematic review is the first to summarize the available evidence for the acute effects of RE on cognitive function. Our results demonstrate that a single training session can induce moderate improvements in performance. Previous meta-analyses investigating the long-term effects following chronic RE interventions mostly reported smaller ES [11, 18–21]. The hypothesized mechanisms by which exercise may affect cognitive function could explain this difference. Acute AE has been shown to enhance the blood flow in the brain [49, 50]. A similar effect may occur following RE. However, while the main modulators of cerebral perfusion after AE are neuronal demand, cardiac output, and partial pressure of arterial carbon dioxide, RE can be speculated to rather cause blood flow variations through oscillations and/or peaks in blood pressure [50]. Another potential factor relates to alterations in serum cortisol level. In their study, Tsai et al. [43] measured higher concentrations of the stress hormone after RE. Interestingly, these increases were associated with higher arousal, a psycho-physiological state of being awake and attentive, which, in turn, could influence brain function.

While circulatory processes (blood flow, hormones) appear to moderate acute exercise-induced changes in cognitive performance, the long-term response may rather be explained by structural adaptations. It has been speculated that chronic RE triggers adult neurogenesis, which is supported by recent data. For example, when Yarrow et al. [51] examined the association between RE and expression of BDNF they detected elevated serum concentrations of the substance immediately post-training. Furthermore, following a 5-week intervention period, the exercise-induced increases in BDNF were even more pronounced, suggesting the importance of repeated stimuli [51]. In another study by

Table 4 Results of the moderator analysis

Comparison	Moderator	No. of effect sizes	Mean estimate (95% CI)	Tau^2/$omega^2$
Resistance vs. control	Cognitive dimension			0.47/0
	Attention	30	0.79 (− 0.42 to 2.00)	
	Working memory	24	0.35 (− 0.05 to 0.75)	
	Cognitive flexibility	3	0.36 (0.17–0.55)*	
	Inhibitory control	21	0.73 (0.21–1.26)*	
	Duration			0.43/0
	Short (≤ 30 min)	48	0.58 (− 0.11 to 1.27)	
	Long (> 30 min)	34	0.51 (0.44–0.58)*	
	Intensity			0.61/0
	Low (≤ 50% 1 RM)	13	0.41 (0.41–0.41)*	
	Moderate (50–75% 1 RM)	31	0.92 (− 0.53 to 2.37)	
	High (75–100% 1 RM)	32	0.48 (0.12–0.85)*	
	Age			0.44/0
	Young (≤ 40 years)	53	0.49 (0.30–0.68)*	
	Old (> 40 years)	33	0.70 (− 0.27 to 1.67)	
	Study design			0.43/0
	Crossover	48	0.58 (− 0.09 to 1.24)	
	Parallel-group	38	0.56 (0.39–0.73)*	
Resistance vs. aerobic exercise	Age			0.04/0
	Young (≤ 40 years)	8	− 0.04 (− 0.81 to 0.74)	
	Old (> 40 years)	18	− 0.11 (− 0.19 to − 0.04)*	
	Study design			0.05/0
	Crossover	16	− 0.12 (− 0.24 to − 0.01)*	
	Parallel-group	10	0.02 (− 0.75 to 0.78)	

1 RM 1 one repetition maximum, *no.* number, *CI* confidence interval

Asterisks indicate statistical significance ($p < 0.05$)

Tsai et al. [52], higher serum levels of insulin growth factor 1 (IGF-1), which is related to neurogenesis and synaptogenesis [53], were measured after a 12-month RE intervention. Finally, Best et al. [54] demonstrated that 52 weeks of RE reduced age-related white matter atrophy in older women [54].

Our review detected no difference between RE and AE in acute effects on brain function. This result is in line with the meta-analysis of Northey et al. [15], who investigated the effects of chronic exercise on cognition in adults aged 50 years and older. Pooling data from 39 studies, these authors calculated comparable SMDs for RE (0.29) and AE (0.25). Notwithstanding, our result of the similar effectiveness of RE and AE in an acute setting should be interpreted with caution. The lower limit of the comparison's confidence interval (− 0.01 to 0.20, SMD of 0.10 in favour of AE) was very close to zero and, hence, one additional study favouring AE may have been sufficient to alter the meta-analytic outcome. Additional research is necessary in order to answer the question of whether AE could be slightly more effective.

Acute enhancements of cognitive function may be of value in different contexts. The use of resistance exercises during warm-up could play a role in the prevention of sports injuries because, in most situations potentially causing trauma, athletes are required to rapidly integrate and process a multitude of sensory information on a supraspinal level, developing and adjusting motor plans under high time constraints. The tested cognitive domains (particularly inhibitory control and cognitive flexibility) represent key factors within this framing [55]. Moreover, although data from prospective trials are still sparse, a study by Wilkerson [56] found that neurocognitive reaction time could be used to predict lower extremity injuries (relative risk: 2.2). Besides helping to prevent musculoskeletal injury, cognitive improvements induced by RE could also aid game-related decision-making by athletes and, with this, increase sports performance. In a cross-sectional study, Huijgen et al. [57] demonstrated that elite youth football players display superior cognitive flexibility and inhibitory control when compared to sub-elite players. Outside the sports setting, acute RE sessions can be of use

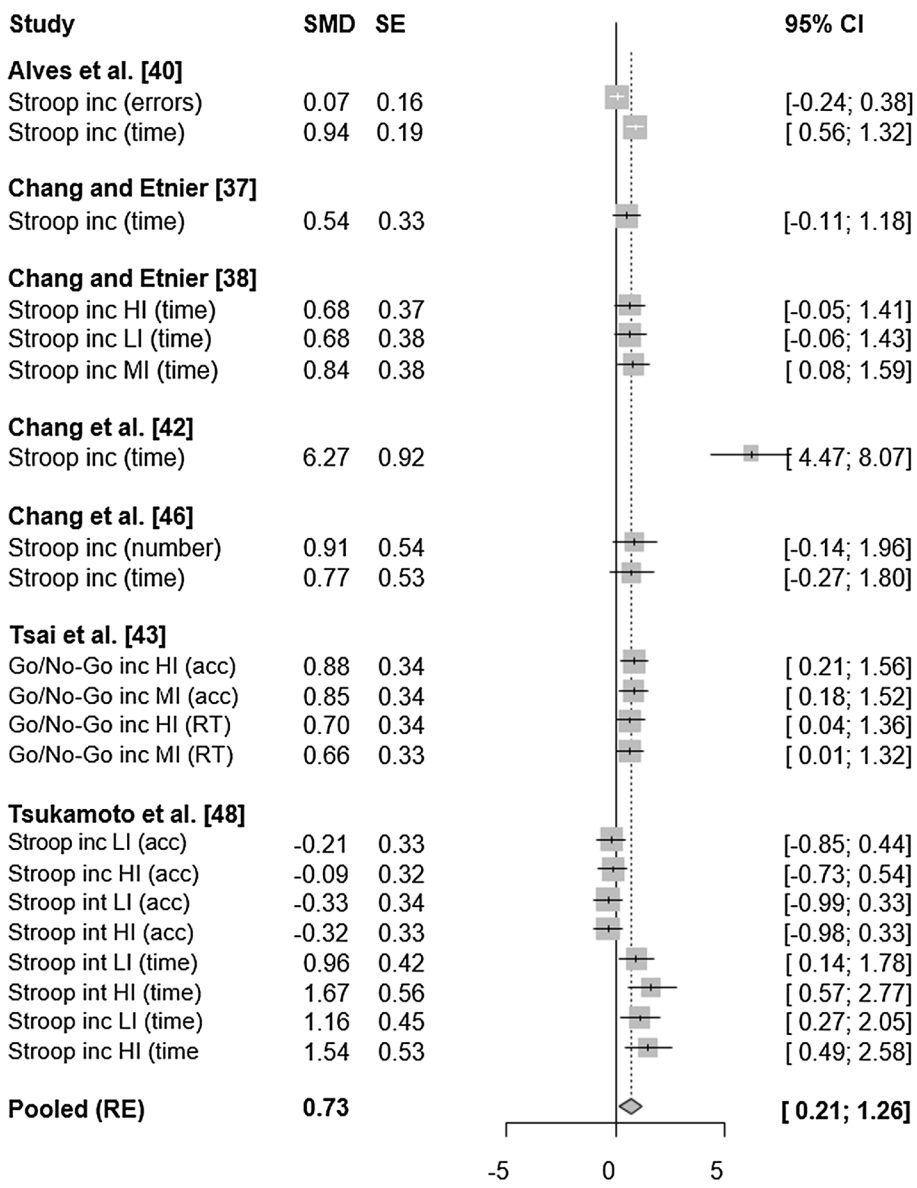

Fig. 2 Effects of resistance exercise vs. no-exercise control in the domain of inhibitory control. Forest plots with pooled standardized mean differences (SMD), standard errors (SEs), and 95% confidence intervals (CIs) are displayed. *Inc* incongruent condition, *int* interference score, *LI* low intensity, *MI* moderate intensity, *HI* high intensity, *RT* reaction time, *acc* accuracy, *RE* random effects

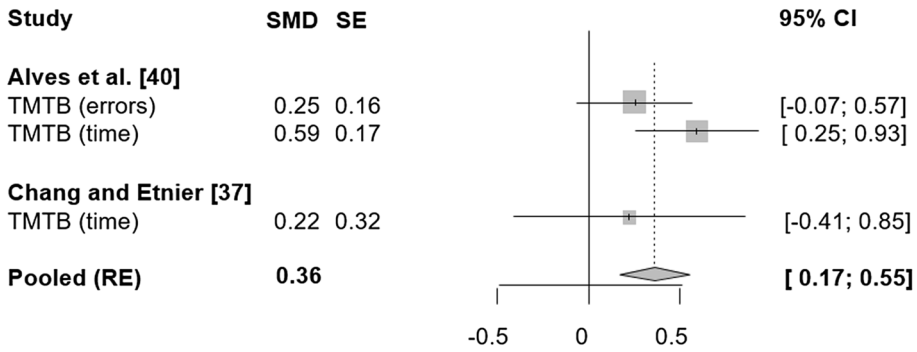

Fig. 3 Effects of resistance exercise vs. no-exercise control in the domain of cognitive flexibility. Forest plots with pooled standardized mean differences (SMDs), standard errors (SEs), and 95% confidence intervals (CIs) are displayed. *TMTB* Trail Making Test B, *RE* random effects

in occupational or academic settings, as work- and study-related abilities, such as cognitive flexibility and working memory, may be increased by active breaks, i.e., during lunchtime.

Despite the promising fields of application, several aspects call for further research. The studies included mainly focused on the effects of RE on different aspects of executive function. However, it would be intriguing to

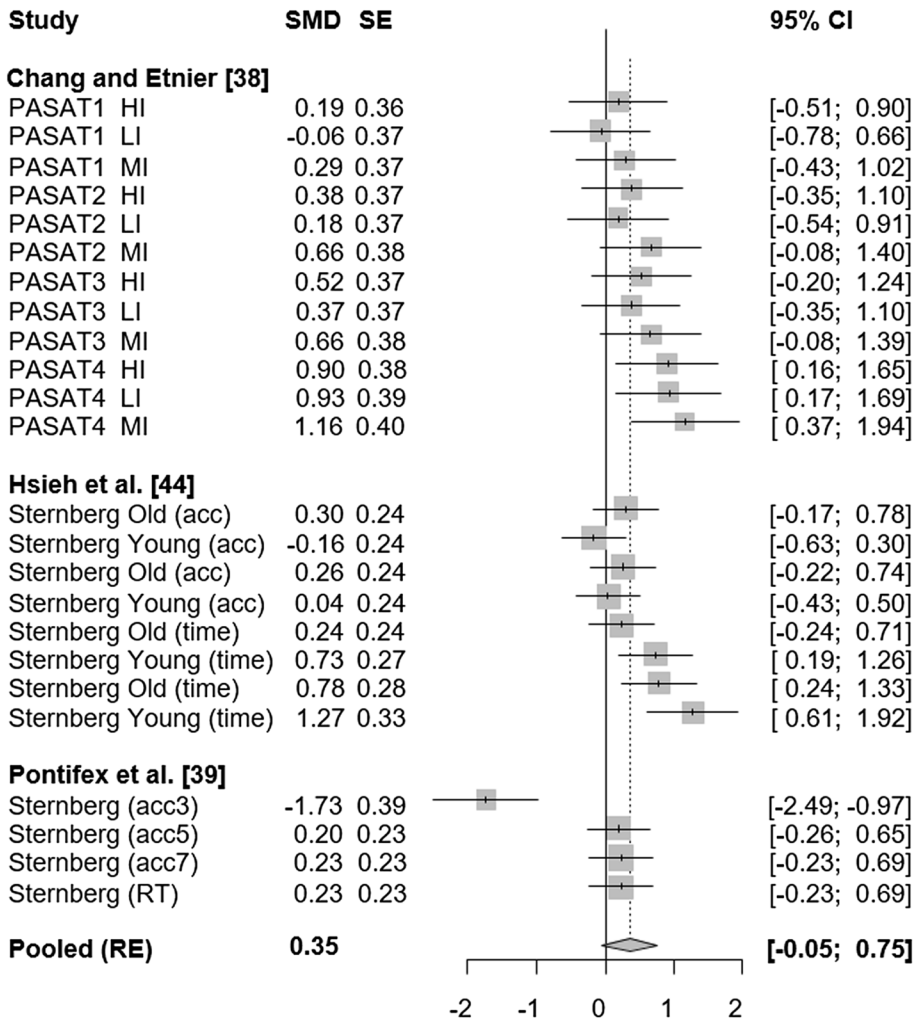

Fig. 4 Effects of resistance exercise vs. no-exercise control in the domain of working memory. Forest plots with pooled standardized mean differences (SMDs), standard errors (SEs), and 95% confidence intervals (CIs) are displayed. *PASAT* Paced Auditory Serial Addition Test, *LI* low intensity, *MI* moderate intensity, *HI* high intensity, *acc* accuracy, *RT* reaction time, *RE* random effects

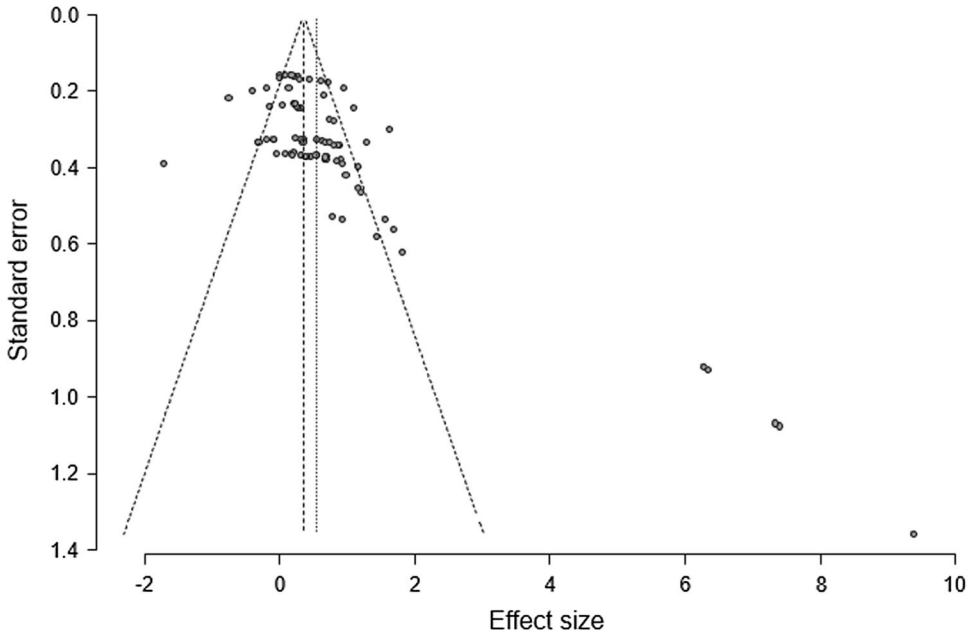

Fig. 5 Funnel plot of the overall effect of resistance exercise on measures of cognitive function (effect sizes against standard error). Note the outliers on the right. Sensitivity analyses without these data from Chang et al. [42] showed that the result was robust

elucidate its impact on other domains such as episodic memory. Furthermore, while our systematic review provides compelling evidence for the occurrence of acute RE-induced increases in cognitive performance, little is known about the sustainability of the effects. Only two of the 12 included studies performed a follow-up measurement. In the first of these, Pontifex et al. [39] did not find enhancements of cognitive function at 30 min post-RE. The second trial by Johnson et al. [45] found persisting, but non-significant, increases at 30 and 60 min in some outcomes, which were ascribed to high data variability. The most important aspect warranting additional investigation relates to the impact of effect modifiers. We made a strong effort to include a series of potentially relevant variables in the moderator analysis. However, the value of the conclusions to be drawn is limited. With regard to training parameters and participant characteristics, there was little variability, often only allowing a binary classification. For instance, in the majority of the included trials, the participants exercised for around 30 min. Only one study used a very short duration (10 min [45]), and none of the trials performed sessions longer than 45 min. The same (small between-study variation) applied to the factor age. It is, hence, not surprising that the ES and *p* values of the different levels were similar even if one of them was significant. Another issue that needs to be noted became evident for training intensity. Whilst some trials used percentages of 1 RM, others used 10RM. Due to this and because of the large CI in the effects of RE on cognitive function at moderate intensity, the suggested *U*-shaped relationship (superiority of low- and high-intensity exercise) should be considered with great care.

In sum, contrary to the general effects of RE on cognitive function and related sub-domains, the optimal training parameters (intensity, duration, repetitions) and conditions (age, sex) are still unclear and are yet to be elucidated.

5 Conclusions

Based on the available evidence, resistance exercise appears to represent an adequate method to acutely improve cognitive function. This finding may be of value for athletes aiming to prevent injury and to improve performance in team sports, or employees seeking to advance job performance. Future research should examine dose-response relationships and the sustainability of the effects of RE on cognitive function.

Compliance with Ethical Standards

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