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ORIGINAL ARTICLE

Acute and Long-term Effects of Resistance Training on Executive Function

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Abstract
The current body of evidence suggests that both acute and chronic exercise have a positive impact on executive function (i.e., top-down mental processes for achieving internal goals). Previous reviews have mainly focused on the effects of aerobic exercise, whereas possible benefits following resistance training have received far less attention. Therefore, the present review examines both the acute and long-term effects of resistance training on the three core facets of executive function (inhibitory control, working memory, and cognitive flexibility). Comparing the effects of resistance training on different subcomponents, benefits were most pronounced for inhibitory control in both the acute and long-term exercise paradigms. Although some studies also reported positive effects of resistance training on working memory and cognitive flexibility, the interpretation of these improvements is limited due to heterogeneous findings and a small number of studies. Thus, it is premature to conclude that resistance training selectively benefits the inhibitory aspect of executive function. Further, it remains unclear how frequency, duration, and intensity of resistance training influence such cognitive enhancements. Consequently, future studies are encouraged to address possible influences of exercise characteristics on the subcomponents of executive function, and to further examine the effects of resistance training across all age groups.

Keywords Inhibitory control · Working memory · Cognitive flexibility · Physical activity · Healthy participants

Introduction

Higher order cognition and executive functioning in particular are associated with numerous health-related outcomes across all ages. For example, executive functions are related to academic achievement (Best et al. 2011), instrumental activities in daily living (e.g., traveling, shopping and cleaning; Vaughan and Giovanello 2010) and mental health (Royall et al. 2002). The executive function domain refers to a family of top-down mental processes needed for achieving internal goals and orchestrating thoughts and plans (Diamond 2013). Its core components include (a) inhibitory control (override a prepotent response or suppress irrelevant stimuli); (b) working memory (maintain and manipulate information to guide response); and (c) cognitive flexibility (flexibly shift between mental sets; Miyake et al. 2000).

Among different interventions that are considered to be efficient for the elicitation of cognitive benefits, physical activity has attracted increasing attention within the last decade. The majority of studies have examined the effects of aerobic exercise, defined as rhythmic contractions of large muscle groups over a prolonged time, which utilize oxygen to meet the energy demands (Fletcher et al. 2013; Howley 2001), on executive function. In this respect, meta-analytical findings support that a single session of aerobic exercise elicits temporary benefits for this cognitive domain across age (Chang et al. 2012b; Ludyga et al. 2016). Similarly, reviews of longitudinal findings in children and older adults support long-term effects of aerobic exercise on executive function (Chaddock et al. 2011; Erickson et al. 2013, 2014). These benefits have been attributed to a cascade of neurobiological mechanisms elicited by physical exercise, including increased expression of brain-derived neurotrophic factor (BDNF) and insulin-like growth factor-1 (IGF-1), as well as structural changes of the cortical and subcortical regions (Lubans et al. 2016). Additionally,

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favorable changes in the allocation of attentional resources, speed of stimulus evaluation, and conflict monitoring have also been considered as processes that contribute to enhanced cognitive performance after both a single session and a period of regular exercise training (Alderman et al. 2016; Hillman et al. 2011).

Although the majority of studies have focused on the effects of aerobic exercise on executive function, other types of training, such as resistance training, have received far less attention. Resistance training is categorized into anaerobic exercise, in which a muscle contraction is opposed by force, leading to increased lactate levels, blood pressure, and oxygen consumption (Fletcher et al. 2013; Spurway 1992). In comparison to aerobic exercise, resistance exercise is therefore characterized by different physiological (i.e., cardiovascular, musculoskeletal, metabolic, etc.) demands, which may have an impact on its cognitive effects. With regard to neurotransmitters, aerobic exercise has been found to increase BDNF levels (Huang et al. 2014), whereas resistance exercise rather elicits an elevated IGF-1 expression (Cassilhas et al. 2007; Chang et al. 2012c; Tsai et al. 2014). Given this distinct response profile, it is likely that executive function benefits following resistance exercise are triggered by a different pathway.

However, acute and long-term effects of this specific exercise modality have not been summarized in a review. So far, literature overviews have been provided on the long-term effects of different exercise types on various cognitive functions in healthy older adults (Barha et al. 2017; Chang et al. 2012a, b, c; Levin et al. 2017). Although these reviews provide some indications for a positive influence of resistance training on executive function, it should be noted that findings are to some extent based on studies investigating effects of resistance exercise combined with other modalities. Consequently, it is difficult to draw conclusions on cognitive benefits following a period of pure resistance exercise. Additionally, possible acute effects of this exercise modality have not been summarized yet. Therefore, the purpose of this review is to examine both acute and long-term effects of pure resistance training on executive function. To provide insights into possible benefits of resistance training across all ages, studies with healthy older adults and other age groups (e.g., young adults) are included.

Long-term Effects of Resistance Training on Executive Function

Any changes in executive function following a period of regular engagement in resistance training are referred to as long-term effects in the present review. The improvements in this cognitive domain induced by such an exercise paradigm are of high practical relevance, because the benefits may last longer than those elicited by a single exercise session (Best et al. 2015; Perrig-Chiello et al. 1998). However, it remains unclear how many resistance training sessions are required and how they should be designed to provoke a durable improvement in different core facets of executive function. In this respect, an overview of findings from longitudinal studies is provided in Table 1.

Focusing on quantitative aspects of resistance training, Liu-Ambrose et al. (2010) examined the influence of its frequency on the three fundamental components of executive function and whole brain volume in senior women. Participants were randomly assigned to either once-weekly training, twice-weekly training, or twice-weekly balance training and toning over a period of 12 months. Regardless of exercise frequency, resistance training resulted in greater improvements of inhibitory control compared to balance training and toning, whereas changes in working memory and cognitive flexibility were not significantly different between groups. Interestingly, only twice-weekly training elicited benefits for peak muscle power, so that improvements in inhibitory control in the once-weekly training group were independent of changes in muscular fitness. With regard to MRI assessments, both training interventions led to decreased whole brain volume (0.32–0.43%), probably due to changes in cerebral fluid. Based on an examination of further outcomes of the same study, Liu-Ambrose et al. (2012) reported improved inhibitory control along with increased cortical activity in prefrontal regions associated with executive functions.

Further support for beneficial effects of resistance training on inhibitory control in older adults was provided by Forte et al. (2013). The authors found similar improvements of inhibitory control after 3 months of multimodal and resistance training. Mediation analyses further revealed that multimodal training directly affected this core facet of executive control, whereas resistance training elicited benefits through increased muscular fitness. Using a slightly longer intervention period (4 months), Coetsee and Terblanche (2017) examined the effects of resistance exercise and aerobic exercise in comparison to no exercise training in older adults. The findings further support improvements of inhibitory control after resistance training as well as aerobic training.

In addition to inhibitory control, the current evidence provides some indications that other components of executive function are also sensitive to resistance training. Anderson-Hanley et al. (2010) found that older adults assigned to 1 month of resistance training improved both inhibitory control and working memory compared to a wait list control group. Investigating neurotransmitter levels, Cassilhas et al. (2007) have gained insights into the mechanisms by which exercise benefits working memory. In their study, older adults were randomly assigned to moderate- or high-intensity resistance training or no intervention. Independent of intensity levels, the resistance training groups showed improved working memory performance, peak muscle power, and higher

Table 1 Overview of studies investigating the chronic effects of resistance training on executive functions

Authors	Participants' characteristics	Study design	Groups	Resistance training program	Executive function assessment	Primary outcomes
Anderson-Hanley et al. (2010)	*N* = 4 f/28 m Age = 72.1 ± 10.0 years	RCT	INT: 60 min resistance training, 2–3×/week CON: wait list	1 month: resistance training for osteoporosis prevention	Stroop Color-Word (inhibitory control) Digit Span Backward (working memory) Color Trails (cognitive flexibility)	Improvement in inhibitory control and working memory: INT vs. CON
Cassilhas et al. (2007)	*N* = 62 m Age = 68.3 ± 0.8 years BMI = 26.9 ± 0.7 kg/m^2	RCT	INT1: 60 min moderate resistance training, 3×/week INT2: 60 min intense resistance training, 3×/week CON: 60 min stretching and mild resistance training, 3×/week	6 months: 8 repetitions at 50% (INT1) or 80% (INT2) of 1 RM	Digit Span Forward/Backward (working memory)	Improvement in working memory: INT1 vs. CON INT2 vs. CON
Liu-Ambrose et al. (2010)	*N* = 155 f Age = 69.6 ± 2.9 years BMI = 26.8 ± 3.5 kg/m^2 PAS-E = 121.0 ± 57.7	RCT	INT1: 60 min resistance training, 1×/week INT2: 60 min resistance training, 2×/week CON: 60 min balance and toning, 1×/week	12 months: 7 exercises, 6–8 repetitions at 7 RM	Stroop Color-Word (inhibitory control) Verbal Digits Forward/ Backward (working memory) Trail Making Test (cognitive flexibility)	Improvement in inhibitory control: INT1 vs. CON INT2 vs. CON
Liu-Ambrose et al. (2012)	*N* = 52 f Age = 69.3 ± 3 years	RCT	INT1: 60 min resistance training, 1×/week INT2: 60 min resistance training, 2×/week CON: 60 min balance and toning, 1×/week	12 months: 7 exercises, 6–8 repetitions at 7 RM	Flanker task (inhibitory control)	Improvement in inhibitory control: INT1 vs. CON
Forte et al. (2013)	*N* = 26 f/16 m Age = 69.8 ± 3.4 years BMI = 25.9 ± 3.3 kg/m^2	RT	INT1: 60 min resistance training, 2×/week INT2: 60 min multicomponent training, 2×/week	3 months: 12 exercises, 8 repetitions at 60–80% of 1 RM	Random number generation (inhibitory control) Trail Making Test (cognitive flexibility)	Improvement in inhibitory control: post vs. baseline (INT1,2)
Iuliano et al. (2015)	*N* = 48 f/32 m Age = 67.0 ± 11.7 years	RCT	INT1: 30 min resistance training, 1×/week INT2: 30 min high intensity cardiovascular exercise INT3: 20 min postural and balance exercise CON: no training	12 weeks: 6 exercises, 6–12 repetitions at 60–85% of 1 RM	Stroop Color-Word (inhibitory control) Trail Making Test (cognitive flexibility)	No significant improvements in inhibitory control and cognitive flexibility
Coetsee and Terblanche (2017)	*N* = 46 f/ 21 m Age = 62.7 ± 5.7 years BMI =26.4 ± 4.0 kg/m^2	RCT	INT1: 30 min resistance training, 3×/week INT2: 30 min high intensity aerobic training (90–95% HRmax) INT3: 47 min moderate intensity aerobic training (70–75% HRmax) CON: no training	16 weeks: 10 repetitions at 50–100% of 10 RM	Stroop Color-Word (inhibitory control)	Improvement in inhibitory control: INT1 and INT3 vs. INT2 and CON

RCT, randomized controlled trial; *RT*, randomized trial; *BMI*, body mass index; *INT*, intervention group; *CON*, control group; *RM*, repetition maximum; *PAS-E*, Physical Activity Scale for the Elderly; *HRmax* maximal heart rate

IGF-1 serum levels compared to the control group after 24 weeks. Because IGF-1 is involved in neurogenesis and angiogenesis, adaptations of brain structure might have contributed to enhanced working memory performance (Voss et al. 2011). However, it should be noted that other studies failed to find increased IGF-1 levels (Goekint et al. 2010) and improvements in executive function (Iuliano et al. 2015) following resistance training.

In summary, most of the experimental findings (from older adults) support beneficial effects of resistance training (performed at least 2–3×/week over 1 month) on inhibitory control. Less is known on the effect of long-term resistance training on other facets of executive function, although some studies also reported improved working memory performance following a period of regular engagement in resistance training.

Acute Effects of Resistance Training on Executive Function

Acute effects of resistance training differ from long-term effects as changes are considered to be transient in nature. Although the maintenance of cognitive benefits over an extended period of time may have a higher practical relevance, the fact that a single session may provoke (temporary) improvements of executive control is a crucial advantage of the acute resistance training paradigm. Probably due to this advantage, much more research is available on the acute effects compared to the long-term effects of resistance training. An overview of studies investigating core facets of executive control following a single session of resistance training is provided in Table 2.

Using a controlled crossover design, Pontifex et al. (2009) examined the effects of moderate aerobic exercise and intense resistance training on working memory in young adults. The behavioral performance on the working memory task was improved after aerobic exercise compared to baseline, whereas no such effect was observed for resistance training. In contrast, Hsieh et al. (2016) found greater enhancements of working memory in both young and older adults after resistance training, but no change following the control condition. However, it should be noted that participants completed moderately intense resistance training, so that the intensity was lower than the one used in the study by Pontifex et al. (2009). Thus, it is possible that quantitative aspects of this exercise modality influence the facilitation of working memory.

With regard to the other core facets of executive function, Alves et al. (2012) compared the acute effects of aerobic exercise, resistance training and stretching on inhibitory control and cognitive flexibility in healthy older women. Although aerobic and resistance training sessions both elicited greater improvements for inhibitory control than stretching, changes in cognitive flexibility did not differ across conditions. In contrast, Dunsky et al. (2017) only found a non-significant trend towards improved inhibitory control following both aerobic and resistance training relative to a physically inactive control condition in middle-aged adults. Nonetheless, further evidence corroborates the notion that this core component of executive function is sensitive to resistance training. Chang and Etnier (2009) examined how intensity influences exercise-induced benefits for behavioral performance on an inhibitory control task. Young adults were therefore assigned to 40, 70, and 100% of the 10-repetition maximum or an inactive control group. Their findings showed that the effect of resistance training intensity on inhibitory control resembled an inverted-U curve, suggesting that moderately intense resistance training leads to greater improvements than resistance training at low or high intensity. Similar acute benefits of moderately intense resistance training for inhibitory control have been observed in older adults (Chang et al. 2014). However, it should be noted that the effects of resistance training were compared to those of reading, which constitutes a cognitively demanding task. Based on the examination of another outcome from the same study, Chang et al. (2012a) also reported improved planning abilities following moderately intense resistance training. This indicates that resistance exercise may also have a positive influence on more complex executive functions.

Possible neurophysiological and endocrinological mechanisms underlying the exercise-induced benefits for executive functions have been investigated by Tsai et al. (2014). In their study, young adults were randomly assigned to high intensity resistance training, low intensity resistance training or reading, which can be regarded a cognitively challenging control condition. Inhibitory control, neurotrophic factors, cortisol, and event-related potentials measured via electroencephalography were assessed before and after the experimental conditions. Comparing both measurement time points, there were increased allocation of attentional resources, improved inhibitory control, and increased growth hormone and IGF-1, whereas serum cortisol levels were decreased. Only the changes of cortisol levels were associated with an exercise-induced improvement for inhibitory control. These results suggest that a reduction of cortisol levels rather than an increased expression of neurotrophic factors contributes to enhanced inhibitory control after 40 min of low and high intensity resistance training.

Whereas there is accumulating evidence for temporary benefits of resistance training for some aspects of executive function, only few insights have been gained regarding the duration of these effects. In this respect, Brush et al. (2016) examined how resistance training intensity influences the time course of the facilitation of the three core executive functions. Using a crossover design, young adults completed resistance training at 40, 70, and 100% of 10 repetitions maximum and watched a video while seated. Executive functions were

Table 2 Overview of studies investigating the acute effects of resistance training on executive functions

Authors	Participants' characteristics	Study design	Groups	Resistance training program	Executive function assessment	Primary outcomes
Alves et al. (2012)	$N = 42$ f Age = 52.0 ± 7.3 years BMI = 26.2 ± 3.8 kg/m^2	CO	INT1: 30 min resistance training INT2: 30 min aerobic exercise CON: 30 min stretching	6 exercises, 15 repetitions at 15 RM (INT1)	Stroop Color-Word (inhibitory control) Trail Making Test (cognitive flexibility)	Improvement in inhibitory control: INT1 vs. CON INT2 vs. CON
Brush et al. (2016)	$N = 14$ f/14 m Age = 20.5 ± 2.1 years BMI = 23.7 ± 3.1 kg/m^2 VO_{2MAX} = 44.5 ± 9.6 ml/min/kg	CO	INT1: 45 min mild resistance training INT2: 45 min moderate resistance training INT3: 45 min intense resistance training CON: 45 min watching a video	7 exercises, 10 repetitions at 40% (INT1), 70% (INT2) or 100% INT3) RM of 10 RM	Stroop Task, Simon Task (inhibitory control) 2-Back Task, Verbal Span Task (working memory) Dimension-Switching, Plus-Minus Task (cognitive flexibility)	Improvement in inhibitory control: INT3 vs. CON Delayed Improvement in cognitive flexibility: INT1 vs. CON INT2 vs. CON
Chang and Etnier (2009)	$N = 32$ f/33 m Age = 26.0 ± 3.2 years BMI = 23.8 ± 4.5 kg/m^2 ACLSPAQ = 28.8 ± 19.0	RCT	INT1: mild resistance training INT2: moderate resistance training INT3: intense resistance training CON: watching a video	6 exercises, 10 repetitions at 40% (INT1), 70% (INT2) or 100% (INT3) RM of 10 RM	Stroop Color-Word (inhibitory control)	Improvement in inhibitory control: Quadratic trend for exercise intensity
Chang et al. (2012a, b, c)*	$N = 16$ f/14 m Age = 57.2 ± 2.9 years BMI = 24.0 ± 3.0 kg/m^2 IPAQ = 857.0 ± 609.8 MET-min/week	CO	INT: 20–25 min resistance training CON: 30 min reading	7 exercises, 10 repetitions at 70% of 10 RM	Tower of London (planning)	Improvement in planning: INT vs. CON
Chang et al. (2014)*	N = 15 f/15 m Age = 58.1 ± 3.0 years BMI = 24.0 ± 3.0 kg/m^2 IPAQ = 845.7 ± 606.3 MET-min/week	CO	INT: 20–25 min resistance training CON: 30 min reading	7 exercises, 10 repetitions at 70% of 10 RM	Stroop Color-Word (inhibitory control)	Improvement in inhibitory control: INT vs. CON
Dunsky et al. (2017)	$N = 10$ f/29 m Age = 52.0 ± 7.8 years BMI = 25.6 ± 3.5 kg/m^2 VO_{2MAX} = 39.8 ± 7.7 ml/min/kg	CO	INT1: 25 min aerobic exercise INT2: 25 min resistance training CON: 25 min watching a show	10 repetitions at 75% of 1 RM (INT2)	Stroop and Go/No Go task (inhibitory control)	Marginal improvement: INT1 vs. CON INT2 vs CON
Hsieh et al. (2016)	$N = 20$ m (young), 20 m (older) Age = 24.0 ± 2.2 years, 67.2 ± 1.8 years BMI = 23.4 ± 3.1, 23.0 ± 2.5 kg/m^2 IPAQ = 1740.2 ± 905.9, 1984.6 ± 1267.2 MET-min/week	CO	INT: 30 min resistance training CON: 30 min reading	8 exercises, 10 repetitions at 70% of 10-RM	Sternberg task (working memory)	Improvement in working memory: INT vs. CON
Pontifex et al. (2009)	$N = 9$ f/12 m Age = 20.2 ± 0.3 years BMI = 22.9 ± 0.7 kg/m^2 VO_{2MAX} = 54.6 ± 2.3 ml/min/kg	CO	INT1: 30 min resistance training INT2: 30 min aerobic exercise CON: 30 min seated rest	7 exercises, 8–12 repetitions at 80% of 1 RM (INT1)	Sternberg Task (working memory)	Improvement in working memory: Post vs. baseline (INT2)
Tsai et al. (2014)	$N = 60$ m Age = 22.9 ± 2.4 years BMI = 21.4 ± 2.0 kg/m^2 IPAQ = 2912 ± 330.3 MET-min/week	RCT	INT1: 40 min moderate resistance training INT2: 40 min intense resistance training CON: 45 min reading	6 exercises, 10 repetitions at 50% (INT1) or 80% (INT2) of 1-RM	Go-/NoGo Task combined with Flanker paradigm (inhibitory control)	Improvement in inhibitory control: Post vs. baseline (INT1 and INT2)

RCT, randomized controlled trial; *CO*, crossover study; *BMI*, body mass index; *INT*, intervention group; *CON*, control group; *RM*, repetition maximum; VO_{2MAX}, maximum oxygen consumption; *IPAQ*, International Physical Activity Questionnaire; *ACLSPAQ*, Aerobics Center Longitudinal Study Physical Activity Questionnaire

*Part of the same study

assessed at 15 and 180 min after each experimental condition. The findings revealed that compared to the control condition, highly intense resistance training improved inhibitory control at 15 min post-exercise. In contrast, resistance training at low and moderate intensities elicited greater benefits for cognitive flexibility than the control condition at 180 min post-exercise. In line with Pontifex et al. (2009), working memory seemed to be unaffected by resistance training. Consequently, these findings point towards intensity- and component-specific effects of resistance training on executive functions.

Similar to experimental studies investigating long-term effects of resistance training, findings of the acute exercise paradigm support the view that inhibitory control is more sensitive to resistance training than other aspects of executive function. Benefits for this executive function component were predominantly found in young and older adults following moderately intense resistance training, although some studies also reported similar effects after exercise at higher intensity. With regard to working memory and cognitive flexibility, the few studies that have investigated effects of resistance training on these aspects of executive function have produced heterogeneous findings.

Limitations and Future Directions

Although evidence is limited, the current state of research supports positive acute and long-term effects of resistance training on the inhibitory aspect of executive function. However, knowledge on the efficiency of specific resistance training programs in different populations and age groups is still lacking, so that potential moderators and mediators should be addressed in future studies.

First, it remains unclear how resistance training affects executive function in children and adolescents. The findings on possible long-term effects of resistance training are based on experimental studies with older adults only. Similarly, the acute effects of resistance training on executive function should not be generalized across age groups, because there is a paucity of studies with children. Considering the growing body of research that indicates positive effects of aerobic exercise on children's cognitive performance (Álvarez-Bueno et al. 2017; Ludyga et al. 2016), it is likely that resistance training may also have a favorable impact on executive function in this age group.

Second, the current literature does not allow conclusions on whether possible executive function gains following acute or regular resistance training are subject to ceiling effects. For other exercise modalities, previous studies have provided evidence that individuals with low compared to high cognitive performance can expect greater benefits for executive function following exercise (Budde et al. 2010; Drollette et al. 2014; Sibley and Beilock 2007). Thus, baseline cognitive performance might mediate the cognitive benefits of resistance exercise.

Third, intensity- and dose-dependent effects of resistance training on executive function should be examined further. For long-term effects, the limited number of studies does not allow conclusions on how quantitative aspects of resistance training influence executive function. Regarding the acute effects, some findings suggest that intensity has an impact on improvements observed following a single session of resistance training (Brush et al. 2016; Chang and Etnier 2009). The few experimental findings support the notion that acute moderately intense resistance training in particular leads to improved inhibitory control (Alves et al. 2012; Brush et al. 2016; Chang and Etnier 2009; Chang et al. 2014; Tsai et al. 2014). Moreover, it is possible that the beneficial effects of moderate and high exercise intensities for the elicitation of improvements in executive function differ between studies investigating acute and long-term effects. Therefore, experimentally manipulating exercise intensity and other quantitative characteristics in future intervention studies may be necessary to gain further insights.

Fourth, investigating the beneficial effects of resistance training (alone or in combination with other exercise types) compared to other interventions that target cognitive performance seems worthwhile. So far, possible differential effects of aerobic exercise and resistance training on executive function have been compared in long-term exercise (Coetsee and Terblanche 2017; Iuliano et al. 2015) and in the acute exercise paradigm (Alves et al. 2012; Dunsky et al. 2017; Pontifex et al. 2009). Due to heterogeneous findings, more research is necessary to evaluate which exercise type elicits the greatest benefits for the different components of executive function. Given that aerobic exercise and resistance training seem to affect executive functions by different pathways (Huang et al. 2014; Cassilhas et al. 2007; Tsai et al. 2014), it should be elucidated whether or not a combination of both results in further enhancements of cognitive performance. In this respect, Levin et al. (2017) implied that combined aerobic and resistance exercise compared to a single exercise modality elicits improvements across different cognitive domains. Thus, further examination of the acute and long-term effects of mixed exercise types is fundamental for developing exercise programs that efficiently improve executive function.

Lastly, although the present review summarized acute and long-term effects of resistance training on executive function, it did not address possible benefits for other cognitive domains. However, some studies have already reported improvements of memory function following resistance training (Lachman et al. 2006; Perrig-Chiello et al. 1998; Weinberg et al. 2014). Thus, it is possible that this exercise type elicits similar or even greater performance enhancements for tasks capturing other cognitive domains.

Conclusion

Evidence, albeit limited, suggests that resistance training has beneficial effects on the inhibitory component of executive function. For working memory and cognitive flexibility, results are inconsistent from both the acute and long-term exercise paradigms. So far, researchers were not yet able to draw general conclusions in terms of the impact of resistance training on executive function, although it should be noted that there is no evidence for any detrimental effects on this cognitive domain. To further elucidate the potential benefits of resistance training on executive function, possible moderators and mediators (such as age of participants, intensity, duration, and type of resistance training) need to be examined in future studies.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

References

Alderman, B. L., Olson, R. L., & Brush, C. J. (2016). Using event-related potentials to study the effects of chronic exercise on cognitive function. *International Journal of Sport and Exercise Psychology*, 1–11 (ePub ahead of print).

Álvarez-Bueno, C., Pesce, C., Cavero-Redondo, I., Sánchez-López, M., Martínez-Hortelano, J. A., & Martínez-Vizcaíno, V. (2017). The effect of physical activity interventions on children's cognition and metacognition: a systematic review and meta-analysis. *Journal of the American Academy of Child & Adolescent Psychiatry, 56*(9), 729–738.

Alves, C. R., Gualano, B., Takao, P. P., Avakian, P., Fernandes, R. M., Morine, D., & Takito, M. Y. (2012). Effects of acute physical exercise on executive functions: a comparison between aerobic and strength exercise. *Journal of Sport and Exercise Psychology, 34*(4), 539–549.

Anderson-Hanley, C., Nimon, J. P., & Westen, S. C. (2010). Cognitive health benefits of strengthening exercise for community-dwelling older adults. *Journal of Clinical and Experimental Neuropsychology, 32*(9), 996–1001. https://doi.org/10.1080/13803391003662702.

Barha, C. K., Galea, L. A., Nagamatsu, L. S., Erickson, K. I., & Liu-Ambrose, T. (2017). Personalising exercise recommendations for brain health: considerations and future directions. *British Journal of Sports Medicine, 51*(8), 636–639.

Best, J. R., Miller, P. H., & Naglieri, J. A. (2011). Relations between executive function and academic achievement from ages 5 to 17 in a large, representative national sample. *Learning and Individual Differences, 21*(4), 327–336.

Best, J. R., Chiu, B. K., Hsu, C. L., Nagamatsu, L. S., & Liu-Ambrose, T. (2015). Long-term effects of resistance exercise training on cognition and brain volume in older women: results from a randomized controlled trial. *Journal of the International Neuropsychological Society, 21*(10), 745–756. https://doi.org/10.1017/s1355617715000673.

Brush, C. J., Olson, R. L., Ehmann, P. J., Osovsky, S., & Alderman, B. L. (2016). Dose-response and time course effects of acute resistance exercise on executive function. *Journal of Sport and Exercise Psychology, 38*(4), 396–408. https://doi.org/10.1123/jsep.2016-0027.

Budde, H., Voelcker-Rehage, C., Pietrassyk-Kendziorra, S., Machado, S., Ribeiro, P., & Arafat, A. M. (2010). Steroid hormones in the saliva of adolescents after different exercise intensities and their influence on working memory in a school setting. *Psychoneuroendocrinology, 35*(3), 382–391.

Cassilhas, R. C., Viana, V. A., Grassmann, V., Santos, R. T., Santos, R. F., Tufik, S., & Mello, M. T. (2007). The impact of resistance exercise on the cognitive function of the elderly. *Medicine and Science in Sports and Exercise, 39*(8), 1401–1407. https://doi.org/10.1249/mss.0b013e318060111f.

Chaddock, L., Pontifex, M. B., Hillman, C. H., & Kramer, A. F. (2011). A review of the relation of aerobic fitness and physical activity to brain structure and function in children. *Journal of the International Neuropsychological Society, 17*(6), 975–985. https://doi.org/10.1017/S1355617711000567.

Chang, Y. K., & Etnier, J. L. (2009). Exploring the dose-response relationship between resistance exercise intensity and cognitive function. *Journal of Sport and Exercise Psychology, 31*(5), 640–656.

Chang, Y. K., Ku, P. W., Tomporowski, P. D., Chen, F. T., & Huang, C. C. (2012a). Effects of acute resistance exercise on late-middle-age adults' goal planning. *Medicine and Science in Sports and Exercise, 44*(9), 1773–1779. https://doi.org/10.1249/MSS.0b013e3182574e0b.

Chang, Y. K., Labban, J. D., Gapin, J. I., & Etnier, J. L. (2012b). The effects of acute exercise on cognitive performance: a meta-analysis. *Brain Research, 1453*, 87–101. https://doi.org/10.1016/j.brainres.2012.02.068.

Chang, Y. K., Pan, C. Y., Chen, F. T., Tsai, C. L., & Huang, C. C. (2012c). Effect of resistance-exercise training on cognitive function in healthy older adults: a review. *Journal of Aging and Physical Activity, 20*(4), 497–517.

Chang, Y. K., Tsai, C. L., Huang, C. C., Wang, C. C., & Chu, I. H. (2014). Effects of acute resistance exercise on cognition in late middle-aged adults: general or specific cognitive improvement? *Journal of Science and Medicine in Sport, 17*(1), 51–55. https://doi.org/10.1016/j.jsams.2013.02.007.

Coetsee, C., & Terblanche, E. (2017). The effect of three different exercise training modalities on cognitive and physical function in a healthy older population. *European Review of Aging and Physical Activity, 14*(1), 13.

Diamond, A. (2013). Executive functions. *Annual Review of Psychology, 64*, 135–168. https://doi.org/10.1146/annurev-psych-113011-143750.

Drollette, E. S., Scudder, M. R., Raine, L. B., Moore, R. D., Saliba, B. J., Pontifex, M. B., & Hillman, C. H. (2014). Acute exercise facilitates brain function and cognition in children who need it most: an ERP study of individual differences in inhibitory control capacity. *Developmental Cognitive Neuroscience, 7*, 53–64. https://doi.org/10.1016/j.dcn.2013.11.001.

Dunsky, A., Abu-Rukun, M., Tsuk, S., Dwolatzky, T., Carasso, R., & Netz, Y. (2017). The effects of a resistance vs. an aerobic single session on attention and executive functioning in adults. *PLoS One, 12*(4), e0176092. https://doi.org/10.1371/journal.pone.0176092.

Erickson, K. I., Gildengers, A. G., & Butters, M. A. (2013). Physical activity and brain plasticity in late adulthood. *Dialogues in Clinical Neuroscience, 15*(1), 99–108.

Erickson, K. I., Leckie, R. L., & Weinstein, A. M. (2014). Physical activity, fitness, and gray matter volume. *Neurobiology of Aging, 35*(Suppl 2), S20–S28. https://doi.org/10.1016/j.neurobiolaging.2014.03.034.

Fletcher, G. F., Ades, P. A., Kligfield, P., Arena, R., Balady, G. J., Bittner, V. A., ... & Gulati, M. (2013). Exercise standards for testing and training: a scientific statement from the American Heart Association. *Circulation, 128*(8), 873–934.

Forte, R., Boreham, C. A., Leite, J. C., De Vito, G., Brennan, L., Gibney, E. R., & Pesce, C. (2013). Enhancing cognitive functioning in the elderly: multicomponent vs resistance training. *Clinical Interventions in Aging, 8*, 19–27. https://doi.org/10.2147/cia.s36514.

Goekint, M., De Pauw, K., Roelands, B., Njemini, R., Bautmans, I., Mets, T., & Meeusen, R. (2010). Strength training does not influence serum brain-derived neurotrophic factor. *European Journal of Applied Physiology, 110*(2), 285–293. https://doi.org/10.1007/s00421-010-1461-3.

Hillman, C. H., Kamijo, K., & Scudder, M. (2011). A review of chronic and acute physical activity participation on neuroelectric measures of brain health and cognition during childhood. *Preventive Medicine, 52*, S21–S28.

Howley, E. T. (2001). Type of activity: resistance, aerobic and leisure versus occupational physical activity. *Medicine & Science in Sports & Exercise, 33*(6), S364–S369.

Hsieh, S. S., Chang, Y. K., Hung, T. M., & Fang, C. L. (2016). The effects of acute resistance exercise on young and older males' working memory. *Psychology of Sport and Exercise, 22*, 286–293.

Huang, T., Larsen, K. T., Ried-Larsen, M., Møller, N. C., & Andersen, L. B. (2014). The effects of physical activity and exercise on brain-derived neurotrophic factor in healthy humans: a review. *Scandinavian Journal of Medicine & Science in Sports, 24*(1), 1–10.

Iuliano, E., di Cagno, A., Aquino, G., Fiorilli, G., Mignogna, P., Calcagno, G., & Di Costanzo, A. (2015). Effects of different types of physical activity on the cognitive functions and attention in older people: a randomized controlled study. *Experimental Gerontology, 70*, 105–110.

Lachman, M. E., Neupert, S. D., Bertrand, R., & Jette, A. M. (2006). The effects of strength training on memory in older adults. *Journal of Aging and Physical Activity, 14*(1), 59–73.

Levin, O., Netz, Y., & Ziv, G. (2017). The beneficial effects of different types of exercise interventions on motor and cognitive functions in older age: a systematic review. *European Review of Aging and Physical Activity, 14*(1), 20.

Liu-Ambrose, T., Nagamatsu, L. S., Graf, P., Beattie, B. L., Ashe, M. C., & Handy, T. C. (2010). Resistance training and executive functions: a 12-month randomized controlled trial. *Archives of Internal Medicine, 170*(2), 170–178. https://doi.org/10.1001/archinternmed.2009.494.

Liu-Ambrose, T., Nagamatsu, L. S., Voss, M. W., Khan, K. M., & Handy, T. C. (2012). Resistance training and functional plasticity of the aging brain: a 12-month randomized controlled trial. *Neurobiology of Aging, 33*(8), 1690–1698.

Lubans, D., Richards, J., Hillman, C., Faulkner, G., Beauchamp, M., Nilsson, M., ... Biddle, S. (2016). Physical activity for cognitive and mental health in youth: a systematic review of mechanisms. *Pediatrics, 138*(3). doi:https://doi.org/10.1542/peds.2016-1642.

Ludyga, S., Gerber, M., Brand, S., Holsboer-Trachsler, E., & Puhse, U. (2016). Acute effects of moderate aerobic exercise on specific aspects of executive function in different age and fitness groups: a meta-analysis. *Psychophysiology.* https://doi.org/10.1111/psyp.12736.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: a latent variable analysis. *Cognitive Psychology, 41*(1), 49–100. https://doi.org/10.1006/cogp.1999.0734.

Perrig-Chiello, P., Perrig, W. J., Ehrsam, R., Staehelin, H. B., & Krings, F. (1998). The effects of resistance training on well-being and memory in elderly volunteers. *Age and Ageing, 27*(4), 469–475.

Pontifex, M. B., Hillman, C. H., Fernhall, B., Thompson, K. M., & Valentini, T. A. (2009). The effect of acute aerobic and resistance exercise on working memory. *Medicine and Science in Sports and Exercise, 41*(4), 927–934. https://doi.org/10.1249/MSS.0b013e3181907d69.

Royall, D. R., Lauterbach, E. C., Cummings, J. L., Reeve, A., Rummans, T. A., Kaufer, D. I., et al. (2002). Executive control function: a review of its promise and challenges for clinical research. A report from the Committee on Research of the American Neuropsychiatric Association. *The Journal of Neuropsychiatry and Clinical Neurosciences, 14*(4), 377–405.

Sibley, B. A., & Beilock, S. L. (2007). Exercise and working memory: an individual differences investigation. *Journal of Sport and Exercise Psychology, 29*(6), 783–791.

Spurway, N. C. (1992). Aerobic exercise, anaerobic exercise and the lactate threshold. *British Medical Bulletin, 48*(3), 569–591.

Tsai, C. L., Wang, C. H., Pan, C. Y., Chen, F. C., Huang, T. H., & Chou, F. Y. (2014). Executive function and endocrinological responses to acute resistance exercise. *Frontiers in Behavioral Neuroscience, 8*, 262.

Vaughan, L., & Giovanello, K. (2010). Executive function in daily life: age-related influences of executive processes on instrumental activities of daily living. *Psychology and Aging, 25*(2), 343.

Voss, M. W., Nagamatsu, L. S., Liu-Ambrose, T., & Kramer, A. F. (2011). Exercise, brain, and cognition across the life span. *Journal of Applied Physiology, 111*(5), 1505–1513. https://doi.org/10.1152/japplphysiol.00210.2011.

Weinberg, L., Hasni, A., Shinohara, M., & Duarte, A. (2014). A single bout of resistance exercise can enhance episodic memory performance. *Acta Psychologica, 153*, 13–19. https://doi.org/10.1016/j.actpsy.2014.06.011.