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The impact of regular activity and exercise intensity on the acute effects of resistance exercise on cognitive function

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Beneficial acute effects of resistance exercise on cognitive functions may be modified by exercise intensity or by habitual physical activity. Twenty-six participants (9 female and 17 male; 25.5 ± 3.4 years) completed four resistance exercise interventions in a randomized order on separate days (≥48 h washout). The intensities were set at 60%, 75%, and 90% of the one repetition maximum (1RM). Three interventions had matched workloads (equal resistance*$n_{repetitions}$). One intervention applied 75% of the 1RM and a 50% reduced workload (resistance*$n_{repetitions}$ = 50%). Cognitive attention (Trail Making Test A—TMTA), task switching (Trail Making Test B—TMTB), and working memory (Digit Reading Spans Backward) were assessed before and immediately after exercise. Habitual activity was assessed as MET hours per week using the International Physical Activity Questionnaire. TMTB time to completion was significantly shorter after exercise with an intensity of 60% 1RM and 75% 1RM and 100% workload. Friedman test indicated a significant effect of exercise intensity in favor of 60% 1RM. TMTA performance was significantly shorter after exercise with an intensity of 60% 1RM, 90% 1RM, and 75% 1RM (50% workload). Habitual activity with vigorous intensity correlated positively with the baseline TMTB and Digit Span Forward performance but not with pre- to post-intervention changes. Task switching, based on working memory, mental flexibility, and inhibition, was beneficially influenced by acute exercise with moderate intensity whereas attention performance was increased after exercise with moderate and vigorous intensity. The effect of regular activity had no impact on acute exercise effects.

KEYWORDS
executive function, neurocognitive, strength training

1 | INTRODUCTION

Since the 1990s, a growing number of studies have reported the effects of physical activity and structured exercise on cognitive health and performance.[17] Based on these data, it can be hypothesized that just a single bout of exercise may be feasible to induce beneficial cognitive effects but that these effects may vary based on the exercise conditions such as the intensity, duration, and type.

Up-do-date reviews and meta-analyses still debate this and other hypotheses concerning dose-response relationships and the accumulation of evidence for the beneficial impacts of endurance[31] and resistance exercises.[45] Compared to the convincing evidence for the beneficial effects of endurance exercise[31] there is still insufficient knowledge concerning dose-response relationships and the mechanisms of how resistance exercise might affect the higher or lower cognitive functions. Some executively controlled higher cognitive functions, such as cognitive flexibility and inhibitory control, have been reported to benefit from acute resistance exercise in a recent meta-analysis based on 12 experimental designs,[45] while memory storage and retrieval or lower cognitive functions were not affected. Wilke and colleagues further concluded that exercise durations of longer than 30 min may have superior effects to shorter ones. Intensity, on the contrary, may follow a U-shaped dose-response relationship, with a higher impact of low (≤50% one repetition maximum (1RM)) and vigorous intensity (75%–100% 1RM) exercise compared to moderate intensity (50%–75% 1RM).[45] It should be noted, however, that most experiments included in this review do not compare multiple exercise interventions with different durations or intensities within one study design.

At the study level, however, RCTs comparing different exercise intensities (in crossover or parallel group designs) have reported significant effects on the lower cognitive functions, assessed via the Stroop Test´s congruent conditions (*Stroop Test Word and Color condition to assess* attention and processing speed)[10,14,44] and the Go/No-Go Task´s Go-condition (attention and processing speed)[43] although no clear impact of exercise intensity was reported by these studies. Only one study reported a linear trend, indicating a greater response of lower cognitive function after higher intensity exercise bouts.[10] For the higher cognitive functions, which rely on executive control (*Stroop Test Interference Condition to assess interference control*), two studies have found a dose-response relationship favoring moderate-intensity exercise (70% ten repetition maximum (10RM)[10] or 60% 1RM[14] compared to vigorous (100% 10RM[10] or 90% 1RM[14] or low intensity (40% 10RM[10]) exercise. Another experiment has indicated a superior effect of moderate-intensity (100% 10RM) exercise on the Stroop Test performance compared to exercise bouts within the range of low to moderate intensity (40% and 70% 1RM).[6] However, the design also detected a delayed effect of lower intensity exercise (70% 10RM) on the Simon Task performance (inhibitory control).[6] Brush et al.[6] interpreted both the applied Stroop and Simon Tasks as being higher functions relying on an executive control. In a fourth experiment, Tsai et al.[43] reported comparable effects of moderate and vigorous intensity (50% and 80% 1RM) exercise bouts on the No-Go Task performance (inhibitory control)[43], the authors also defined this task as a higher and executively controlled cognitive function. Lastly, an intervention study on the effects of a lower extremity exercise (bilateral knee extension) reported greater effects from vigorous intensity exercise (80% 1RM) compared to low intensity (40% 1RM) on the reaction time but not on the accuracy of performance of the incongruent condition of a Stroop Test.[44] Taken together, these studies accumulate preliminary evidence for the superior effects of moderate and vigorous intensity resistance exercise compared to exercise with lower intensity. It remains unclear if vigorous or moderate intensity exercise is more feasible to induce beneficial cognitive effects. Since moderate exercise may be more suited as a break during occupational time and carries a lower risk for injuries, future studies need to investigate further the differences in the effects of moderate and vigorous intensity resistance exercise.

One explanation for the inconsistencies between the meta-analytic and experimental findings can be found in the categorization of exercise intensity. Wilke and colleagues[45] reported the 75% 1RM intensity to represent both the upper end of moderate intensity and the lower end of vigorous intensity. Thus, experiments with an intervention intensity of 75% 1RM (which equals 100% 10RM[7]) could, potentially, be reported in both spectra. With a view on the feasibility and injury risk, it is of great relevance to address the intensity range above and below 75% 1RM in future studies in order to specify whether the resulting recommendations should promote vigorous or moderate intensity resistance exercise.

Another explanation for discrepancies between the intervention studies is the lack of control of other mechanobiological exercise determinants, such as the duration and type (i.e., free weights vs. machine exercises) or workload (resistance*$n_{\text{repetitions}}$) accumulated during the exercises.[40] These limitations need to be addressed by controlling the confounding influence of other exercise determinants while analyzing the impact of the intensity.

Although earlier studies have suggested that both regular activities and acute exercise may impact cognitive performance[17,] only one of the RCTs which studied the impact of exercise intensity on the effects of resistance exercise controlled the influence of physical fitness (VO2max) as a marker for long term physical activity on acute exercise effects.[6] Likewise, some studies on endurance exercise have analyzed the impact of physical fitness on the effect of acute exercise.[9,21,27,39,42] Although some of these experiments were able to detect differences in the electrophysiological outcomes between fit and unfit individuals[27,39,42] or fitness-related differences in baseline cognitive performance[9] none of these studies found a direct relationship between physical fitness and the effect of acute aerobic exercise on cognitive performance. Future research should, consequently, assess the influences of the habitual activities themselves.

Other factors which need to be addressed are the underlying mechanisms behind the acute effects of exercise on cognitive performance. Current literature has focused on exercise-induced positive thinking and a more positive psychological state[23] as well as changes in neurotransmitters and hormones associated with stress.[29] As reported by earlier studies, such adaptations are not only influenced by acute exercise but also show significant associations with beneficial changes in cognitive performance.[43] On a self-reported level, a direct relation between cognitive function and affective response seems plausible.[14] With a view on mechano-biological exercise determinants, this association might be influenced by exercise intensity as well as by the number of repetitions and the duration of rest intervals.[43] These assumptions are in line with already described functional links between the perceived exertion and enhanced neuronal activity, which have been reported in experiments on isometric muscle contraction (Berchicci et al., 2013).[3] Future studies should, thus, assess both the affective response or psychological state after exercise and the level of exertion.

This study had three aims. Firstly, we compared the effects of a resistance exercise intervention with an intensity of 75% 1RM to the effects of exercise with higher (90% 1RM; vigorous intensity) and lower intensity (60% 1RM; moderate intensity) on the cognitive functions. Secondly, we analyzed the impact of workload on the effect of 75% 1RM resistance exercise by applying an intervention with 50% reduced workload. Thirdly, we analyzed the effect of habitual physical activity on cognitive performance and the potential influences of habitual physical activity and sedentary behavior on the acute effects of resistance exercise. We hypothesize that (1) resistance exercise intensity has no impact on the effects of exercise on domain-specific cognitive functions (attention, executive control, memory, and working memory), (2) resistance exercise workload has no impact on the effects of exercise on domain-specific cognitive functions, and (3) habitual physical activity or sedentary behavior is not associated with cognitive performance or the magnitude of cognitive performance changes after acute exercise.

2 | METHODS

2.1 | Study design

This is a four-armed randomized, controlled crossover experimental design. Previous results of this study design have already been published elsewhere[14] while the present analysis contains no duplicate data from the aforementioned publication. The local ethics commission approved the study (reference number: 2017-36). The design and realization of the study were in accordance with the Declaration of Helsinki (Version Fortaleza 2012).

2.2 | Participants

A sample size of 24 participants in a crossover design was calculated a priori based on an earlier intervention study[6] using G*power (Version 3.1.9.2, Germany).[18] We applied an effect size of $\text{eta}^2 = .1$ and a Bonferroni adjusted alpha of .025. We considered a dropout rate of 10% and recruited 26 healthy, regularly active adults (assessed using the International Physical Activity Questionnaire—IPAQ[22]) through advertisements and flyers. Exclusion criteria were acute, or chronic, physical and psychological diseases and drug abuse (assessed by a questionnaire and anamnesis). Participants refrained from alcohol, caffeine, and strenuous physical activity 24 h before all intervention appointments and maintained habitual physical activity and regular diet during study participation. Participants were excluded from the analysis if they did not complete all appointments. We informed the participants about the benefits and risks of participating in the study. Afterward, they signed an institutionally approved informed consent document.

2.3 | Study flow and appointments

Five appointments were necessary for each participant. During the first appointment, we assessed the anthropometric data, physical activity behavior, fluid intelligence (Wiener Matrices test), and educational status (school and study years). Participants were familiarized with the cognitive testing procedures, and the baseline values for the cognitive performance outcomes were assessed (Trail Making Test A and B, Digit Span Forward and Backward).

After the baseline assessments, the participants were familiarized with the resistance exercises and the one repetition maximums (1RM) were assessed. During the 1RM assessment, the participants were familiarized with the scales for perceived exertion and affective response.

Subsequently, during the four following appointments, the participants completed four different resistance exercise interventions. Each appointment started with the testing of the pre-values (before exercise) of cognitive performance, after which the participants executed a 2-minute warm-up (Jumping Jacks) followed by the resistance exercises. Immediately after cessation of the last exercise of the intervention (sitting on the bench of the last exercise), the affective response and perceived exertion were documented. Afterwards, participants performed a post-exercise intervention assessment of cognitive performance within a time frame of 15 min after exercise cessation. Interventions took place in the mornings between eight and noon. Participants executed all of their individual appointments at the same time of day, and the data were assessed in the same standardized setting during the appointments (room size, workplace, temperature, and lighting) to minimize distracting stimuli.

2.4 | Resistance exercise interventions

The resistance exercise intervention included six exercises (chest press, leg press, latissimus pull down, seated rowing, seated squat, and shoulder press). One repetition maximum (1RM) was calculated based on the following validated equation: 1RM = 100*weight lifted/(102.78–2.78 *number of repetitions performed).[7] Using this equation, 100% of ten repetition maximum (10RM) matches 75% of 1RM. The approach has been validated and is reported to be strongly associated with directly assessed 1RM.[34] In order to minimize the risks of overuse and injuries for participants with limited training experience, this approach has been found to be successful.[12,14]

During the four different resistance exercise interventions, the participants executed the following number of sets and repetitions for the aforementioned exercises, respectively: (1) three sets of 10 repetitions with 75% of 1RM, (2) two sets of 19 repetitions with 60% of 1RM, (3) five sets of five repetitions with 90% 1RM, and (4) three sets of five repetitions with 75% of 1RM. Intervention 1 was based on earlier studies, which had already reported significant effects on cognitive function using an intensity of 75% 1RM in randomized and controlled designs[6,10] Interventions 2 and 3 applied lower and higher intensities but had matched workloads meaning that both resulted in a comparable amount of physical work (workload-matched, equal resistance*$n_{\text{repetitions}}$). Exercise intervention 4 was applied to control the impact of the workload. We applied a 50% reduced amount of physical work (compared to interventions 1–3) by using half the repetitions but the same number of sets and the same intensity (resistance) as in intervention 2 (workload-reduced). Participants executed the movements during all the interventions with a comparable pace and range of motion and we adapted the resting intervals in order to reach a comparable overall duration of approximately 1 h for all four interventions. The interventions were applied in a randomized balanced order. In line with the findings of a systematic review on neurophysiological and cognitive effects of exercise,[2] we included a washout time of ≥48 h between each arm to limit the carry-over effects. Randomization (block-randomization, two blocks, each block $n = 24$, permutated order, one complete block, one with $n = 2$ participants) was undertaken by using a randomization software (https://www.randomizer.org/)).

2.5 | Baseline assessment

Participants reported both anthropometrical and educational data and performed the Wiener Matrices Test to assess their fluid intelligence.[19] We applied the International Physical Activity Questionnaire (IPAQ) as an assessment tool for physical activity and sedentary behavior.[22] The questionnaire deduces the amount of physical activity with moderate and vigorous intensity, as well as the time spent walking, during a time period of one week. Furthermore, time spent with sedentary behavior is documented. Based on the guidelines for the data processing analysis of the International Physical Activity Questionnaire[38] we calculated the metabolic equivalent of task (MET) hours per week (MET h/wk) for physical activity. Sedentary behavior was analyzed as hours per week (h/wk).

Participants were categorized into three groups based on their habitual physical activity: inactive (<10 MET h/wk), minimally active (10–49 MET h/wk), and health-enhancing physical activity (HEPA) (≥50 MET h/wk).[38]

2.6 | Cognitive performance assessment

Figure 1 gives an overview of the cognitive assessments applied in our study.

We used the Trail Making Tests to deduce visuospatial lower and higher cognitive functions. Trail Making Test part A (TMT A) was applied as a task to measure attention and processing speed, which are categorized as lower cognitive functions. Trail Making Test part B (TMT B) was used as a task-switching paradigm; this can be defined as an executive function and, thus, as a higher cognitive function. We applied a pen and paper version of the TMT A and B. For the TMTA, participants connected a row of ascending numbers (1 – 25), which were randomly allocated on a sheet of paper by drawing a continuous line. For the TMT B, participants connected a row of ascending numbers (1 – 13) and letters (A - M) beginning with number one and alternating between numbers and letters (1 – A – 2 – B – 3 – C, etc.) by drawing a continuous line. Test validity for executive function and attention, as well as their reliabilities, are reported elsewhere.[36]

In order to measure the higher cognitive functions based on auditory perception and to compare the performances in automatically processed memory tasks with

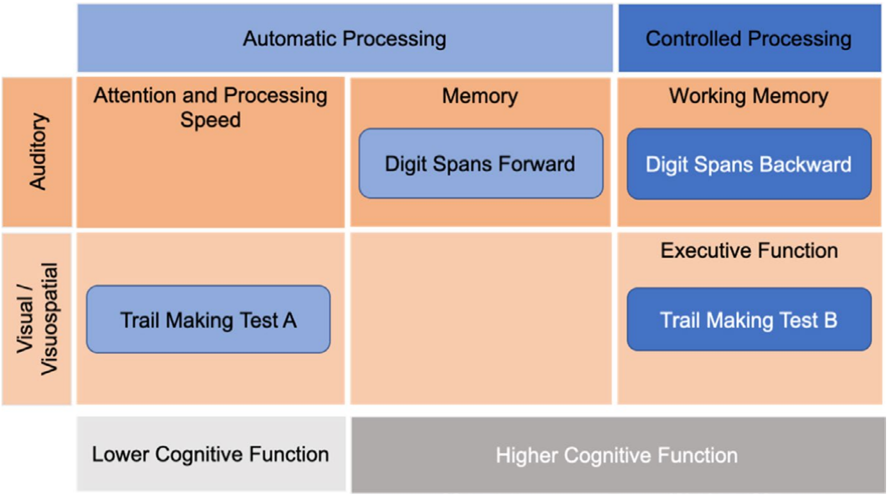

FIGURE 1 Overview of the cognitive testing paradigms, outcomes, and tests analyzed in our study. Test paradigms were categorized as follows: (1) higher and lower cognitive functions, (2) functions that need to be controlled by a central executor and tasks that are executed via automatic processing, and (3) visual and visuospatial tasks or tasks based on verbally provided information (auditory)

those in tasks which are controlled by a central executor, we applied verbal versions of the Digit Span Test paradigms. Automatically processed memory or short-term memory performance was assessed using a Digit Span Forward paradigm (DSFwd). Cognitive performance controlled by a central executor was analyzed using a Digit Span Backward paradigm (DSRew). During the DSFwd testing, the participants were instructed to memorize and verbally report digit spans beginning with three digits (e.g., 385), and, in cases of successful task execution, one digit was added for the next run. The maximal number of digits used in the span was eight (e.g., 74628431). During the DSRew testing, the participants were instructed to memorize a digit span (e.g., 581) and verbally report it in reverse order (i.e., 185). Again, if the task was executed correctly, then one digit was added for the subsequent run. Test validity for memory and working memory, as well as their reliabilities, are reported elsewhere.[20]

In order to avoid learning effects for the Trail Making Tests and Digit Span Tests, we applied a different test variation for each assessment of cognitive performance.

2.7 | Perceived exertion and affect after exercise

We assessed the perceived exertion by using a 15-point Borg Scale ranging from 6 (<very, very light) to 20 (>very, very hard).[4] The validity and reliability for perceived exertion are provided by Borg.[4] The affective response was documented using a 11-point Feeling Scale.[24] The validity and reliability for the affective response to exercise are given by Haile et al.[23] We asked the participants, immediately after cessation of the resistance exercise, to indicate their perceived exertion and affective response to the exercise intervention verbally or by finger pointing on the scale. Scales were presented visually for every assessment.

2.8 | Statistics

We applied Microsoft Excel 2010 and SPSS Version 24 (IBM Corp) for data analysis. Descriptive data were reported as means and standard deviations.

Friedman tests were applied to detect differences between the interventions. All change scores (pre- to post-intervention differences) were compared between groups. In case of significant omnibus Friedman tests, multiple Durbin-Conover comparisons were performed for post hoc analysis.

In each intervention arm, potential exercise effects were indicated by 95% confidence intervals for pre-intervention to post-intervention differences (change scores) of each cognitive outcome. The exercise intervention reached a significant impact on cognitive outcomes if the 95% confidence interval of the pre- to post-intervention changes did not include the value zero.[1,33,37] Spearman correlations were used to control the association between the habitual activity and cognitive performance and to detect potential moderators of acute exercise effects by analyzing the associations of habitual physical activity, sedentary behavior, and affective response with pre- to post-exercise changes of cognitive performance. In cases where significant correlations between one of these factors and the change scores of cognitive performance in multiple intervention arms occurred, analysis of covariance was applied to control for the influence of this moderator. Furthermore, we compared the cognitive performances between the IPAQ-based physical activity groups by using the Kruskal–Wallis test.

3 | RESULTS

3.1 | Descriptive data

Twenty-six full data sets of participants were included in the analyses; no participant was excluded, and no one withdrew consent. Descriptive statistics are included in Table 1. Male participants ($n = 17$) were taller ($T = -3.9$; $p = 0.001$) and heavier ($T = -2.6$; $p = 0.015$) than the females ($n = 9$). All other data, including the cognitive performance and subjective response to exercise, showed no significant differences between the sexes.

3.2 | Acute effects of resistance exercise and dose-response effects of exercise intensity

Descriptive data of the cognitive testing, the 95% confidence intervals of the pre- to post-intervention changes of cognitive performance for each intervention and results of the between-group comparisons for repeated measures are given in Table 2.

The Friedman test showed significant differences in the pre- to post-intervention changes of the Trail Making Test B performance between the interventions. The Durbin-Conover tests for pairwise comparisons indicated that resistance exercise with lower intensity (60% 1RM) led to significantly greater performance benefits compared to exercise with vigorous intensity (90% 1RM) ($F = 1.996$; $p = 0.0495$) or exercise with 75% 1RM intensity and reduced workload ($F = 2.852$; $p = 0.0056$). The change scores of the Trail Making Test A, Digit Span Forward, or Digit Span Backward performances did not show a significant impact of exercise intensity or workload.

The 95% confidence intervals indicated a significant exercise effect on the Trail Making Test A performance for all intervention protocols except for the intervention with 75% 1RM and full workload.

The Trail Making Test B performance was beneficially altered by the 60% 1RM and 75% 1RM intensity resistance exercises but not by exercise with vigorous intensity (90% 1RM) or the intervention with75% 1RM intensity and reduced workload. The test results for all cognitive outcomes are displayed in Table 2.

3.3 | Perceived exertion and affective response to exercise

The descriptive data and details for the omnibus and post hoc tests for perceived exertion and affective response to resistance exercise are indicated in Table 3. The durations of all the interventions are also indicated in Table 3.

The affective response to exercise (11-point Feeling Scale) and overall duration (in minutes) of resistance exercise did not differ significantly between interventions. As indicated in Table 3, the Friedman test for effects of intervention intensity and workload on perceived exertion (Borg Scale) showed an impact of exercise intensity and workload. The Durbin-Conover Tests for pairwise comparisons indicated that participants had the highest rating of perceived exertion after exercise with 60% 1RM intensity (vs. 75% 1RM: $F = 2.432$, $p = 0.0174$; vs. 90% 1RM $F = 2.084$, $p = 0.0405$; vs. 75% 1RM 50% work $F = 9.379$, $p < 0.0001$), whereas reports of exertion after exercise with 75% 1RM and 90% 1RM intensity were not different to each other ($F = 0.347$, $p = 0.7293$) and exercise with 75% 1RM intensity but 50% reduced workload led to the lowest exertion (vs. 75% 1RM $F = 6.948$, $p < 0.0001$; vs. 90% 1RM $F = 7.295$, $p < 0.0001$). Correlation analysis revealed an association between the TMT B change scores and perceived exertion ($r = 0.609$; $p = 0.0010$) of the 60% 1RM resistance exercise intervention. Change scores of the TMT B performance after 75% 1RM exercise and the perceived exertion showed no significant correlation. The pre- to post-intervention changes of the TMT A performance reported for exercise with 60% 1RM exercise, 90% 1RM, and 75% 1RM with 50% workload were also not associated with perceived exertion after exercise.

TABLE 1 Anthropometrics of the participants

Outcome	Mean and standard deviation	Range
Age in years	25.5 ± 3.4	18 – 32
Height in centimeters	174.5 ± 8.5	151 – 185
Weight in kilograms	75.7 ± 15.1	51 – 101
Fluid Intelligence in WMT points	12.2 ± 3.2	6 – 18
Education level group	3.2 ± 1.0	1 – 4
Physical Activity in MET h/wk	71.8 ± 60.5	0 – 221
Sedentary Behavior in hours per week	45.0 ± 25.6	1 – 14

Note: Fluid intelligence testing rated according to the Wiener Matrices Test (WMT), educational level allocated values of 1= lower school certificate, 2= apprenticeship or technical baccalaureate, 3= high school degree, and 4 = university degree, while habitual physical activity was obtained using the IPAQ questionnaire (MET h/wk = metabolic equivalent of task hours per week); n = number; Values are mean and standard deviation (first column) and range (second column).

TABLE 2 Descriptive data (mean ± standard deviation and range), 95% confidence intervals (in parentheses) and details for Friedman tests and post hoc analysis for the pre- to post-intervention differences in cognitive performance markers (Trail Making Test A—TMT A; Trail Making Test B—TMT B; Digit Span Forward—DSFwd; and Digit Span Backward—DSRew)

	Resistance Exercise Characteristics				
Cognitive outcome	**60% 1RM**	**75% 1RM**	**90% 1RM**	**75% 1RM 50% work**	**Friedman test results**
TMT A	−3.32 ± 7.86 −25.0 – 13.0 (−6.34 - −0.296)*	−2.75 ± 11.4 −42.0 – 14.0 (−7.12 – 1.62)	−4.65 ± 8.29 −18.7 – 18.0 (−7.84 - −1.47)*	−4.29 ± 9.01 −25.0 – 10.0 (−7.75 - −0.824)*	$\chi^2 = 2.07$; df = 3; $p = 0.5574$
TMT B	−7.47 ± 10.4 −29.6 – 10.8 (−11.48 - −3.47)*	−5.72 ± 8.34 −26.0 – 6.00 (−8.93 - −2.51)*	−1.35 ± 11.3 −21.0 – 31.6 (−5.68 – 2.97)	−1.37 ± 8.26 −11.0 – 18.1 (−4.54 – 1.81)	$\chi^2 = 8.00$; df = 3; $p = 0.0459^{\#}$
DSFwd	0.385 ± 1.30 −2.00 – 3.00 (−0.115 – 0.884)	0.154 ± 1.78 −4.00 – 3.00 (−0.531 – 0.839)	0.346 ± 1.62 −3.00 – 3.00 (−0.278 – 0.970)	0.385 ± 1.39 −3.00 – 3.00 (−0.149 – 0.918)	$\chi^2 = 1.39$; df = 3; $p = 0.7079$
DSRew	0.231 ± 1.73 −3.00 – 4.00 (−0.433 – 0.895)	0.577 ± 1.65 −2.00 – 4.00 (−0.059 – 1.212)	0.346 ± 1.55 −4.00 – 3.00 (−0.249 – 0.941)	0.538 ± 1.50 −2.00 – 3.00 (−0.0392 – 1.12)	$\chi^2 = 0.409$; df = 3; $p = 0.9385$

Note: The Friedman test results are indicated as chi-square (χ^2), degrees of freedom (df), and *p*-value (*p*). #indicates significant effects of intervention characteristics and *indicates significant intervention effects based on 95% confidence intervals.

TABLE 3 Descriptive data (mean ± standard deviation, range) and details for the Friedman and post hoc tests for exercise duration (in minutes) and the subjective response to exercise (11-point Feeling Scale) and exercise-induced perceived exertion (15- point Borg Scale)

Intervention outcome	**60% 1RM**	**75% 1RM**	**90% 1RM**	**75% 1RM 50% work**	**Friedman test results**
Duration in minutes	58.3 ± 2.90 50.0 – 60.0	59.4 ± 1.21 56.0 – 62.0	60.7 ± 3.10 58.0 – 70.0	57.3 ± 3.84 50.0 – 60.0	$\chi^2 = 7.08$; df = 3; $p = 0.0695$
Borg scale	$16.2 \pm 2.01^{\#}$ 10.0 – 19.0	$15.8 \pm 1.54^{*\#}$ 13.0 – 19.0	$15.8 \pm 1.88^{*\#}$ 11.0 – 18.0	$13.2 \pm 2.17^{*}$ 8.0 – 17.0	$\chi^2 = 44.6$; df = 3; $p < 0.0001$
Feeling scale	3.88 ± 2.36 1.00 – 10.0	3.62 ± 2.94 −1.0 – 10.0	4.19 ± 2.95 0.0 – 10.0	4.23 ± 2.85 0.0 – 10.0	$\chi^2 = 7.18$; df = 3; $p = 0.0665$

*Indicates significant differences to 60% 1RM exercise. #Indicates significant difference to 75% 1RM 50% work exercise; $p < 0.05$.

3.4 | The impact of habitual physical activity and sedentary behavior

Participants showed a broad range of physical activity participation and sedentary behavior duration during daily living (Table 1). Just 7.7% of participants were classified as inactive (<10 MET h/wk) whereas 42.3% were minimally active (10–49 MET h/wk) and half of the participants were categorized as HEPA active (≥50 MET h/wk). Group comparisons (Table 4) showed no differences in the performance of specific cognitive functions between the habitual physical activity categories during baseline testing. However, while moderate-intensity habitual activity level (mean ± SD: 8.7 ± 11.4; range: 0 – 40 MET h/wk) was not associated with cognitive performance, vigorous intensity habitual activity (mean ± SD: 33.1 ± 35.3; range: 0 – 144 MET h/wk) was correlated with the Trail Making Test B ($r = -0.391$; $p = 0.0486$) and the Digit Span Forward ($r = 0.457$; $p = 0.0190$) performances.

For cognitive performance change scores which did show a significant acute effect of resistance exercise (TMT A and TMT B), overall habitual physical activity level, vigorous intensity physical activities or sedentary behavior during the weekly routine, did not show a significant correlation with the magnitude of pre- to post-intervention changes in cognitive performance.

4 | DISCUSSION

Exercise with the lowest intensity (60% 1RM), but, consequently, having the highest number of repetitions, led

TABLE 4 Descriptive data (mean ± standard deviation and range) for the baseline performance of cognitive test outcomes (Trail Making Test results in seconds, Digit Span Test results as number of digits) indicated as overall values for the whole sample and physical activity subgroups, based on the metabolic equivalent of task hours per week (MET h/wk)

Cognitive test	Trail Making Test A	Trail Making Test B	Digit Span Forward	Digit Span Backward
Overall	22.8 ± 5.59	49.0 ± 16.9	7.96 ± 1.73	6.27 ± 1.80
	15.0 – 35.6	26.0 – 94.0	4 – 13	2 – 10
<10 MET h/wk ($n = 2$)	21.0 ± 4.24	49.0 ± 7.07	8.00 ± 1.41	6.00 ± 1.41
	18.0 – 24.0	44.0 – 54.0	7 – 9	5 – 7
10–49 MET h/wk ($n = 11$)	23.9 ± 6.51	57.1 ± 19.3	7.36 ± 2.38	5.64 ± 2.11
	15 – 35.6	39.1 – 94.0	4 – 13	2 – 10
≥50 MET h/wk ($n = 13$)	22.1 ± 5.10	42.2 ± 13.1	8.46 ± 0.877	6.85 ± 1.46
	15 – 33.1	26.0 – 69.0	7 – 10	5 – 10
Kruskal–Wallis test	$\chi^2 = 0.599$; df = 2; $p = 0.7412$	$\chi^2 = 4.644$; df = 2; $p = 0.0981$	$\chi^2 = 4.566$; df = 2; $p = 0.1020$	$\chi^2 = 3.388$; df = 2; $p = 0.1838$

Note: The Kruskal–Wallis test results for differences between subgroups are indicated as chi-square (χ^2), degrees of freedom (df), and p-value (p).

to the highest subjective exertion and the greatest performance enhancement in task-switching performance (executive function). Furthermore, our data indicated that perceived exertion and changes in task-switching performance were associated with each other. In line with earlier studies,[6,10] exercise with 75% 1RM also led to a significantly increased task-switching performance. However, no significant association with perceived exertion was found within this intervention arm. Exercise with vigorous intensity (90% 1RM) or exercise with moderate intensity but reduced workload (75% 1RM 50% workload) did not induce significant effects on executive function (task switching).

Attention operationalized by Trail Making Test A, as a lower cognitive function, was stimulated by three exercise interventions but not by the standard intervention with 75% 1RM resistance exercise and full workload. These effects showed neither a trend for a dose-response relationship nor an association with perceived exertion. Furthermore, memory performance was not at all influenced by acute resistance exercise.

Vigorous physical activity during daily living was associated with executive function (task switching) and memory or short-term memory performance during baseline testing. However, habitual physical activity outcomes and sedentary behavior based on IPAQ showed no impact on the acute effect of resistance exercise. These findings are in line with earlier studies which also did not find an influence of fitness on the acute beneficial effects of exercise on cognitive performance[9,27,39,42]. Consequently, we confirm the assumption of Etnier et al.[17] that acute exercise and regular physical activity patterns need to be discussed as separate, influencing factors for cognitive performance.

4.1 | Higher cognitive functions demanding controlled processing by a central executor

Taking into consideration our data and earlier crossover or parallel group designs regarding the different intensities, beneficial effects on executive control can be confirmed for an intensity range of between 40% 1RM[44] and 90% 1RM.[14] The majority of studies so far have applied Stroop Test paradigms to test higher cognitive functions demanding controlled processing by a central executor[6,10,14,44]. Based on this paradigm, a potential threshold range for optimal effects can be deciphered between 70% 10RM (~53% 1RM)[10] and 80% 1RM.[44]

Findings on other test paradigms for executive functions are in line with this hypothesis. For the Go/No-Go task performance (Inhibitory Control), comparable effects of 50% and 80% 1RM intensity resistance exercise have been reported.[43] We detected beneficial effects on task-switching performance for an intensity range from 60% 1RM to 75% 1RM with a trend for higher effects of 60% 1RM. Figure 2 shows a simplified dose-response curve for optimal intensity indicated by our data and available RCT studies comparing different intensities[6,10,14,43,44]

Although one study reported significant effects of light intensity resistance exercise (40% 1RM)[44] and one study reported significant effects of vigorous intensity exercise (90% 1RM),[14] all evidence consistently indicates that the optimal effects lay in the range of moderate intensity (50% – 75% 1RM). The effects of vigorous intensity exercise (90% 1RM) on the Stroop Test[14] and TMT B performance suggest that the impact of vigorous intensity exercise may be related to specific task requirements rather than to

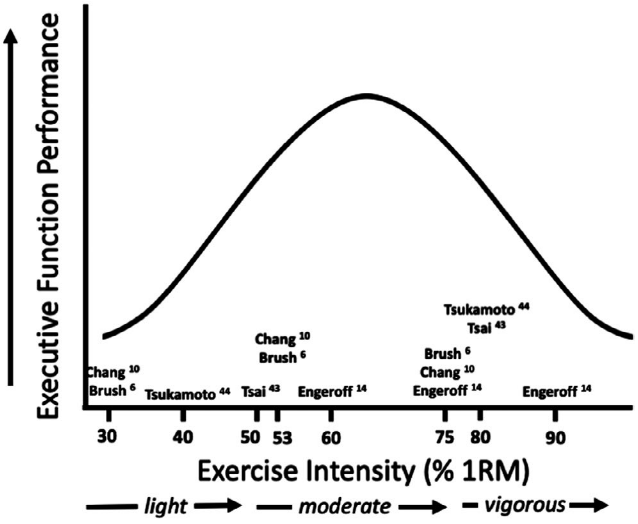

FIGURE 2 Illustration of the currently available data on the dose-response relationship of resistance exercise intensity and executive function performance. This schematic is based on our findings and the available RCT designs comparing the different intensities[6,10,14,43,44]

executive functions in general. The assumption that inhibition and interference control may be more prone to exercise effects is in line with the findings of Brush and colleagues.[6] The workgroup applied a cognitive testing battery and reported significant effects for the Stroop Test and Simon Task performance[6] but no effects for one other paradigm which demanded controlled processing (the Dimension Switching Task) and three more automatically processed tasks (Two Back Task, Verbal Running Span Task and Plus-Minus Task).[6] Current evidence, thus, supports the executive control hypothesis of Colcombe and Kramer which stated that the higher the relevance of executive control processes, such as coordination, inhibition, or interference control, the more sensitive a cognitive function might be to activity- and fitness-induced alteration.[11]

4.2 | Lower cognitive functions and automatically processed tasks

In line with the earlier published RCTs,[6,14,43,44] our analysis showed no impact of the different exercise intensities on the exercise effects on lower cognitive functions. Only one experiment with multiple stuy arms has discussed a trend for a linear dose-response relationship in favor of a larger effect on post-exercise outcomes by higher intensity exercise (75% 1RM) compared to lower intensity (30% 1RM).[10]

Overall, the experiments confirm an effect on low-level central nervous system function uncontaminated by subjective strategies or high-level cognition, as stated in the speed hypothesis of Colcombe and Kramer.[11] However, no clear and positive evidence on significant dose-response relationships following a maximal trend, as described in one experiment[10] and early meta-analyses[17,] or an optimal trend (inverted U-shaped) in favor of moderate intensity, as reported for endurance exercise,[5,31,32] can be confirmed.

So far only Brush and colleagues have applied multiple cognitive tests within one study design in order to analyze the effect of exercise intensity on different cognitive functions including measures for memory and working memory.[6] In line with our findings, the study reported effects on some executive functions but not on cognitive domains relying mainly on information storage and manipulation. Although evidence on resistance exercise effects is sparse, a study on endurance effects, which compared memory tasks that rely on different levels of executive control, reported significant exercise effects, mainly on tasks requiring constant mediation by a central executor.[35] We, thus, hypothesize that memory storage and provision performance are neither beneficially nor detrimentally altered by acute resistance exercise.

4.3 | The relevance of habitual physical activity or perceived exertion and affective response to resistance exercise as effect modifiers

Physiological effects of and affective response to exercise are discussed as underlying mechanisms for acute and chronic exercise effects on cognitive performance. The alteration of cardiorespiratory fitness or associated changes in angiogenesis or efficiency of aerobic metabolism[16] and the supply of nutrients and oxygen[30] are potential key mechanisms for the effects of exercise on cognition. The responses of neurometabolic factors, such as N-acetylaspartate[15,16,] brain-derived neurotrophic factor (BDNF)[28,] and growth hormones[43], have been discovered in clinical studies and have also been discussed as mediators for exercise effects on cognitive health and performance.[13,43] In line with these findings on long-term exercise effects, our data indicate an association between habitual physical activity of vigorous intensity and cognitive performance.

For the further comparison of acute and chronic exercise effects it is important to note that, according to the IPAQ, all resistance exercise regimes applied in our study would be categorized as vigorous intensity activities[38]. However, habitual activities showed no influence on acute exercise effects. Therefore, the question arises of whether acute and chronic exercise effects are induced by different mechanisms.

Focusing on acute effects, the alteration of neuronal tissue oxygenation has been discussed as one of the key mechanisms behind the comparative superiority effects of low- to moderate-intensity exercise.[8] Chang and colleagues had detected a detrimental association between decreased oxygenation in the prefrontal cortex and worse cognitive performance during high-intensity exercise when compared with moderate-intensity exercise.[8] Moderate exercise intensity may, thus, induce better oxygen and nutrient distribution by increased blood flow and oxygen saturation.[8] In addition to metabolic adaptations, increased cognitive performance might be stimulated by an affective response to exercise and changes in related neurotransmitters and stress-associated hormones such as adrenalin and cortisol.[29] Such adaptations are not only influenced by acute exercise but also show significant associations with beneficial changes in cognitive performance[14,43]. In our study, the highest values for exertion were accompanied by the strongest effects on executive function performance. This association is significant for exercise with lower objective intensity but having higher numbers of repetition and shorter rest intervals. In line with these observations in subjective outcomes, lower serum cortisol, higher levels of arousal and associated adaptations of electroencephalographic measures are described as a response to single bouts of moderate-intensity resistance exercise.[43] Our findings thus validate the previously suggested functional links between perceived exertion and enhanced neuronal activity during isometric muscle contraction[3] for more complex resistance exercises.

As studies on aerobic exercise reported comparable findings,[25,26,41] moderate-intensity resistance exercise and strenuous endurance exercise may trigger comparable mechanisms. Overall, moderate-intensity exercise might shift the brain from a stimulus-driven response mode to a more controlled mode which could enhance the ability to perform tasks relying on constant moderation by a central executor.[11,14,43]

Earlier theories have focused on exercise-induced positive thinking and a more positive psychological state[23] as key mechanisms for beneficial adaptations of higher cognitive functions.[14] Our data on perceived exertion and affective response indicate that an exercise effect, such as physical exertion, does not necessarily need to be associated with a positive or pleasant emotional reaction to induce beneficial cognitive adaptations. Future studies need to assess hormone levels and the affective response in order to analyze whether higher exertion might be accompanied by decreased or increased cortisol or adrenaline after exercise.

4.4 | Strengths and Limitations

Since most of the currently available studies compared interventions with varying intensity without controlling the influence of workload[6,10,43,44] this is one of the first studies that is able to deduce the impacts of exercise intensity and workload. Furthermore, this is one of the first studies, which has applied tests for different cognitive domains including the working memory and memory. A limitation of our study is the number of repeated measures based on the pre- and post-intervention tests and multiple study arms. However, we applied multiple versions of all tests in a randomized sequence in order to minimize learning and repetition effects.

5 | CONCLUSION

Based on our experiments and earlier RCTs, we conclude that cognitive processes demanding controlled processing (executive functions) are beneficially altered by one-hour resistance exercise with moderate intensity (50%–75% 1RM). Vigorous and low intensity resistance exercise seems not to lead to decreased cognitive performance but is likely to induce less pronounced beneficial effects. We, therefore, adopted an inverted U-shaped dose-response for resistance exercise intensity. Reaching a certain level of exertion and perceiving the exercise as “hard” to “very hard” seem to be relevant in order to induce significant beneficial cognitive effects. The Feeling Scale data indicated that well-being or mood, however, seem to be of minor relevance and we found no detrimental influence of higher discomfort during exercise on cognitive performance.

Future studies should assess the impact on cognitive performance in setting specific approaches and could also evaluate the influence of mood or well-being under different conditions. Such designs could address occupational activities in order to analyze alterations in productivity and well-being. Another field of application could be the coping of concentration disorders in educational settings.

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DATA AVAILABILITY STATEMENT

The data set will be made available via direct contact with investigator after approval of a written proposal and a signed data access agreement.

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