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ORIGINAL RESEARCH

Exploring Temporal and Intensity Effects of Resistance Exercise on Inhibition: A Four-Arm Crossover Randomized Controlled Trial

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Objective: Given the recognized benefits of resistance exercise on both physical and cognitive domains, elucidating how to maximize its benefit is pivotal. This study aims to evaluate these effects in terms of their timing and intensity on cognitive performance.

Methods: This was a four-arm, crossover randomized controlled trial. Healthy college-aged male adults with recreational resistance training experience participated in this study. Participants completed three separate sessions of circuit barbell resistance exercises, including back squat, press, and deadlift. Each session corresponded to a different intensity level: 65% 1RM, 72% 1RM, and 78% 1RM. Each session consisted of 5 repetitions across 3 sets, with a 3-minute rest between exercises and sets. For the control condition, participants engaged in a reading activity for the same duration. The subjective exercise intensity was measured using the rating of perceived exertion and repetitions in reserve immediately after each set. The primary outcome was the temporal effect of acute resistance exercise on inhibition, measured by the Stroop color-word task. The secondary outcome was the effect of different intensities.

Results: 30 out of 31 recruited participants were randomized, with 28 completing all experiment sessions. Using repeated measures correlation (r_{rm}), a linear temporal effect was observed on accuracy-adjusted congruent reaction time: $r_{rm} = 0.114$, $p = 0.045$, 95% CI [0.002, 0.223]. Participants responded 19.1 ms faster than the control condition approximately 10 minutes post-intervention. This advantage, however, gradually declined at a rate of 4.3 ms every 15 minutes between 10–55 minutes post-intervention. In contrast, no significant effects were detected for incongruent trials or the Stroop effect. When examining the linear relationship across exercise intensities, no significant correlations emerged for congruent trials.

Conclusion: Resistance exercise demonstrates a temporal effect on cognitive performance, particularly in reaction speed for congruent trials, without significant changes in incongruent trials or the overall Stroop effect. The findings highlight the importance of timing in leveraging the cognitive benefits of acute resistance exercise, suggesting a window of enhanced cognitive performance following exercise. However, this study has a limitation regarding Type I error inflation, due to multiple measurements of cognitive performance being undertaken, suggesting caution in interpreting the observed temporal effects. Practically, scheduling crucial, cognitively demanding tasks within 10–60 minutes post-exercise may maximize benefits, as positive effects diminish after this period.

Keywords: executive function, physical exercise, resistance training, cognition, RCT

Introduction

The Stroop task, introduced nearly a century ago by J.R. Stroop, has been a cornerstone in the study of cognitive psychology.[1] This task requires participants to name the color of a word while ignoring its semantic meaning. In the congruent condition, both the color and the word's meaning match. In contrast, in the incongruent condition, they contradict each other, such as the word "RED" displayed in blue. The difference in reaction times between these conditions defines the Stroop effect.[1] This effect is considered to reflect either the ability for response-distractor inhibition[2] or selective attention.[1] In addition to the Stroop effect, the overall reaction time in the Stroop task, categorized as choice reaction tasks, also depends on the response inhibition at the motor level.[3] Given its insights into attention,

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inhibition, and other cognitive processes, the Stroop task is widely recognized as a useful tool for assessing cognitive function.

Resistance exercise is not only renowned for its benefits on physical health and muscular strength but is also suggested to have a positive impact on cognitive capacity.[4] In order to provide an unbiased overview and to avoid cherry-picking, we conducted a systematic search (see Supplement 1) to identify research that employed the Stroop task as a measure of the effects of acute resistance exercise on cognitive performance. This search yielded 30 relevant studies (Figure 1).

Of the studies reviewed, nine conducted multiple cognitive post-tests following interventions, as detailed in Table 1. However, only four of these incorporated a control condition.[5–8] Of these studies, two suggested a possible linear trend indicating a gradual decline in the effects of resistance exercise over time. Performance was better 15–45 minutes post-exercise than 180–215 minutes post-exercise as noted in Brush et al (2016).[5] Similarly, performance was better 10 minutes post-exercise than 30 minutes post-exercise, as reported by Vonk et al (2019).[6] In contrast, the other two studies found no significant difference in Stroop task performance immediately after exercise when compared to 40 minutes[7] and

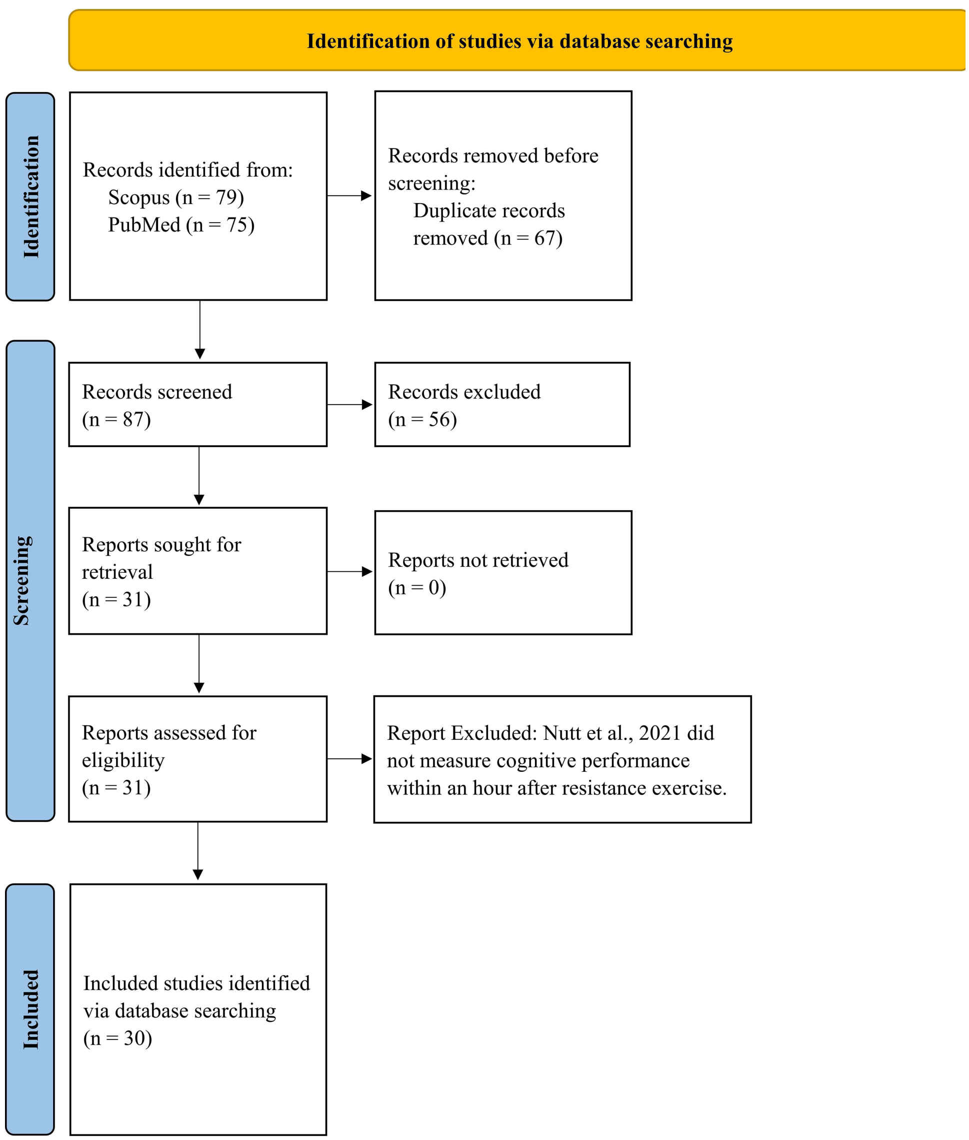

Figure 1 PRISMA 2020 Flow Diagram.

Table 1 Characteristics and Methodological Features of Studies Investigating the Impact of Resistance Exercise on Stroop Task Performance

Study design
1. Non-exercise control group or condition (Y: yes; N: No)
2. Reportedly used randomization
3. Report of random number generation (NA: not applicable; P: partly reported)
4. Report of allocation sequence concealment
5. Use of a crossover design (Y: complete crossover; I: incomplete crossover; N: no crossover)
6. Maximal strength test for determining intervention load
7. Number of familiarization visits for resistance exercise before maximal strength test
8. Number of familiarization visits for cognitive task
9. Cognitive pre-test before intervention
10. Include a warm-up block/trial before each cognitive test (Y: both pre- and post-test; PT: pre-test only; PI: pre-intervention only)

Intervention and measurement
a. Manipulations of different resistance exercise parameters (I: intensity; D: exercise duration; R: repetition; B: blood flow restriction; E: exercise selection; RI: rest interval; S: movement speed)
b. Investigation the temporal effect of resistance exercise on cognitive performance

ID	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	a.	b.
Chang and Etnier (2009)[9]	Y	Y	N	N	N	1	0	0	Y	N	N	N
Alves et al (2012)[10]	Y	Y	N	N	Y	N	NA	1	Y	N	N	N
Chang et al (2014)[11]	Y	N	NA	NA	Y	1	0	0	Y	N	N	N
Brush et al (2016)[5]	Y	N	NA	NA	Y	1	0	1	N	N	I^	Y
Harveson et al (2016)[12]	Y	Y	N	N	Y	N	NA	1	N	N	N	N
Johnson et al (2016)[13]	N	Y	N	N	I*	1	0	2	Y	PT	D	Y
Chang et al (2017)[14]	Y	Y	N	N	N	1	0	1	Y	N	N	N
Tsukamoto et al (2017)[15]	Y	Y	N	N	Y	1	0	1	Y	PT	I^	N
Quintero et al (2018)[16]	Y	Y	P*	N*	N	1	0	1	Y	N	N	N
Sardeli et al (2018)[17]	Y	Y	N	N	Y	2	0	0	Y	N	I#, R & B	N
Engeroff et al (2019)[18]	N	Y	Y	N	Y	1	0	1	Y	N	I# & R	N
Harveson et al (2019)[19]	Y	Y	N	N	Y	N	NA	1	N	N	N	N
Tsuk et al (2019)[20]	Y	N	NA	NA	Y	1*	0	1	Y	N	N	N
Vonk et al (2019)[6]	Y*	Y	N	N	Y	1	0	1	Y	N	N	Y
Wang et al (2019)[21]	Y	N	NA	NA	Y	1	0	0	N	PT	N	N
de Souza et al (2020)[22]	Y	Y	P	N	N	N	NA	0	Y	Y	N	N
Tomoo et al (2020)[23]	N	Y	N	N	Y	1	0	1	Y	PT	I# & R	Y
Wilke et al (2020)[24]	N	Y	N*	N	N	1	0	1	Y	Y	E	N
Chou et al (2021)[7]	Y	Y	N	N	N	1	0	0	Y	Y	N	Y
Coelho-Júnior et al (2021)[8]	Y	Y	N*	N	Y	1	0	0	Y	Y	S	Y
de Almeida et al (2021)[25]	Y	Y	N*	N	Y	2	0	2	Y	N	I?	N
Dora et al (2021)[26]	N	Y	N	N	Y	1	0	1	Y	PT	S	Y
Dora et al (2021)[27]	N	Y	N	N	Y	1	0	1	Y	PT	I# & S	Y
Lin et al (2021)[28]	Y*	Y	P	P	Y	1	1	0	Y	Y	N	N
Tomoo et al (2021)[29]	N	N	NA	NA	Y	1	0	1	Y	PT	RI	Y
Yamada (2021)[30]	Y	Y	N	N	Y	1	0	1	Y	N	B	N
Carbonell-Hernandez et al (2022)[31]	N	N	NA	NA	Y	N	NA	1	Y	N	N	N
Chen et al (2023)[32]	Y	Y	N	N	Y	1	0	1	N	PI	N	N
Silveira-Rodrigues et al (2023)[33]	N	N	NA	NA	Y	1	0	1	Y	N	N	N
Wang et al (2023)[34]	N	N	NA	NA	Y	N*	0	1	N	Y	N	N
This study	Y	Y	Y	Y	Y	1	1	2	Y	Y	Y	Y

Notes: *:[13]: Parallel-group design for exercise mode (aerobic and resistance), and a crossover design for different volumes. [16]: Random number generation was reported in a previous study.[16,35]: Allocation sequence concealment was not reported in either the included article or the referenced ones.[20,35,36]: 15 repetition max (RM) was tested, the repetition-to-failure method for estimating 1RM was less accurate when there were ≥ 10 repetitions. [6]: Active-control (loadless movement). [21]: Included practice trials before intervention, but not a pre-test. [24]: Reported only the software used. [8]: Reported only the allocation ratio. [28]: Active-control (stretching). [34]: The muscle strength test described may not be suitable for measuring maximal strength. ^: Having at least one comparison in which all training parameters were kept constant, with the exception of intensity. (Such training parameters include number of repetitions, sets, and rest intervals.) #: Lacking even a single comparison where all training parameters, with the exception of intensity, were kept constant. ?: de Almeida et al (2021)[25] reported that they "performed 10 sets of 12 maximum repetitions". However, "12 maximum repetitions" describes training intensity (12 RM), which contradicts their earlier statement that one condition was at 50% 1RM and the other was at 70% 1RM.

60 minutes later.[8] In summary, the data suggests that cognitive performance seems to peak at approximately 10 minutes after exercise, then gradually fades thereafter.

While there are some indications of the effects of time on cognitive performance post-exercise, the influence of exercise intensity is less clear. Out of the 30 included studies, 7[5,15,17,18,23,25,27] included comparisons of resistance exercise intensity. However, only two of these[5,15] had at least one comparison where all parameters, except intensity, were kept constant (see Table 1). Comparing exercise intensity, ceteris paribus, is crucial because variations in other factors, such as the rest interval between sets and the number of repetitions, can influence the effects of resistance exercise without altering the absolute intensity. Tsukamoto et al employed a non-exercise control condition alongside two exercise conditions with different intensities, administering the paper-based Stroop task with an oral response both immediately before and after the interventions.[15] Their findings revealed that the "high-intensity" resistance exercise outperformed the control condition in both neutral and incongruent trials as well as in Stroop interference. Moreover, this high-intensity condition showed greater benefits than the "low-intensity" condition in incongruent trial and interference score.[15] Further discussion about the exercise intensity will be provided later.

The study conducted by Brush et al (2016)[5] was the only research included that investigated the influence of exercise intensity on the temporal effects, while keeping all other training parameters constant. The researchers employed one non-exercise control condition and three exercise conditions with different intensities. They administered two cognitive post-tests: the first occurred 15–45 minutes after the intervention, and the second took place 180–210 minutes post-intervention.[5] The findings revealed that, during first post-test, the reaction time in congruent trials was shorter after "moderate intensity" condition compared to the control condition.[5] Brush et al also observed a linear trend for the Stroop effect, where a higher intensity corresponded to a smaller Stroop effect, indicating better inhibition. However, for the second post-test, no significant effect was found for resistance exercise.[5] Our study aims to extend the investigation conducted by Brush et al[5] by assessing cognitive measurements at various time points within 1 hour after the exercise intervention. Additionally, we combined intensity levels while evaluating the temporal effect, and vice versa, to achieve higher degrees of freedom in the analysis (refer to the Statistical Analysis section).

The number of relevant research studies is not only low (k = 2), but there's also concern about the exercise intensities reported by these two studies, an issue we previously highlighted.[28] Specifically, Brush et al (2016)[5] stated that their high-intensity condition consisted three sets of 10 repetitions with 100% 10-RM.[5] This directly contradicts the definition that N-RM represents the intensity at which participants can performed N repetitions based on a single set.[37] Similarly, Tsukamoto et al (2017)[15] reported that their participants perform 6 sets of 10 repetitions with 80% 1RM.[15] However, according to the predicted equations we summarized,[28] a 10RM should range from 74–80% 1RM. As such, it appears challenging to reconcile the reported multiple sets of 10 repetitions at either 100% 10RM or 80% 1RM with these definitions. One possible explanation we have proposed is that their participants' maximal strength might have been underestimated due to the lack of familiarization with the resistance exercise movements.[28] Other limitations on study design were also identified.

In our review of prior research, we systematically examined the methodologies of the aforementioned 30 studies, as detailed in Table 1. Specifically, we assessed whether each study included the following: (1) a non-exercise control group or condition, (2) randomization (3) report of random number generation, (4) documentation of allocation sequence concealment, (5) a crossover design, (6) a maximal strength test, (7) a familiarization visit for resistance exercise before the maximal strength test, (8) a familiarization visit for cognitive tasks, (9), a cognitive pre-test before the intervention, and (10) a warm-up block or trials before each pre- and post-test. This comprehensive examination allowed us to identify recurrent limitations in the existing body of research. In response, we thoroughly designed our study to address these gaps and integrate all these critical aspects. As a result, our methodology offers a comprehensive coverage of key considerations, enhancing the reliability and validity of our findings and providing a foundation for future research in the field (see Table 1).

This study aims to validate the temporal effect of acute resistance exercise and explore the impact of different exercise intensities using Stroop task data from our four-arm crossover randomized controlled trial, which addressed the limitations previously mentioned. In our initial analysis,[38] we combined all three exercise conditions with varying intensities to confirm the primary exercise effect on the first post-test. Findings indicated that acute resistance exercise, performed at an intensity of 65–78% 1RM for 5 repetitions (or 76-91% 5RM/relative intensity) per set, across 3 sets with 3-minute rest intervals, enhanced speed in Stroop congruent trials. However, this analysis neither explored the differential impact of exercise intensities nor incorporated the cognitive outcomes of subsequent post-tests to investigate the temporal effect.

We hypothesized that the cognitive enhancement from acute resistance exercise would be most evident in the first Stroop post-test, centered around 10 minutes post-intervention, and would diminish in subsequent performance measured at 25, 40, and 55 minutes after the intervention. In other words, we expect a linear relationship in the effect of acute resistance exercise on different post-test time points, with the enhancement effect starting from larger to smaller. Regarding the effects of varying intensities, we refrained from setting a directional hypothesis, rendering this aspect of our exploratory analysis.

Methods

The original protocol, encompassing trial design, study environment, participant qualification criteria, outcome metrics, randomization and allocation methods, and the intervention process, has been described in the referenced registered report.[38]

Trial Period

The trial period commenced on June 1, 2022, and concluded on May 31, 2023. The trial status is closed.

Inclusion Criteria

Eligibility for participation was based on the following:

1. Healthy men within the age range of 18–40 years;
2. Regularly participated in resistance training, at least once weekly for the last 6 months;
3. Not having any medical conditions as outlined in the 2014 Physical Activity Readiness Questionnaire update (PAR-Q+);[39]
4. No previous instances of cardiovascular, cerebrovascular, or neurological conditions or other long-term diseases;
5. Having either normal or corrected-to-normal vision;
6. Non-smokers.

Exclusion Criteria

1. They could not perform intervention exercises, ie, barbell squat, press, deadlift;
2. They had color blindness;
3. They were currently undergoing rigorous training for a competitive sports team or exercising for over 20 hours weekly.

Cognitive Tasks

The cognitive tasks were conducted in a laboratory or quiet classroom. Participants were provided with earmuffs (3M Peltor X5A) to minimize external noise. E-prime 3.0 (Psychology Software Tools, Inc., Sharpsburg, PA) was used to administer all tasks. The visual stimuli were presented on a 14-inch Acer A514 laptop, ensuring clear visibility. The participants took short breaks between the different blocks.

In the computer-based Stroop test, participants encountered both congruent and incongruent trials. For congruent trials, participants saw one of the three Chinese color words in its respective color. In contrast, incongruent trials displayed these words in non-matching colors. Participants were required to identify the word's color using an external numeric keyboard (Z-book Z9) rapidly and accurately. They used the "1" key for red, "2" key for green, and "3" key for blue.

Each test consisted of two blocks, each with 63 trials, resulting in a total of 126 trials. The stimulus appeared on the screen for up to 1000 ms, or until the participant pressed a key, whichever came first. The intervals between stimuli varied, ranging from 400 ms to 600 ms. If the participant did not respond within that 1000 ms time frame, their response was considered an error.

Randomization and Allocation Concealment

An experienced graduate student, who was not involved in this study, generated two sequences of random block randomizations utilizing our team's dedicated tool (https://osf.io/6cjt5/). This procedure was undertaken to ensure that participants would not encounter the same exercise intensity with double the chance. The first sequence corresponded to the exercise intervention sessions and had block sizes of "3" and "6". In contrast, the second sequence was designated for the control visits, with block sizes of "4" and "8".

Exercise interventions included low-intensity resistance exercise (LRE), moderate-intensity resistance exercise (MRE), and high-intensity resistance exercise (HRE). To reduce allocation imbalances, a Latin square design was adopted, narrowing down potential sequences from six ($3! = 3 \times 2 \times 1$) to three, namely: 1. LRE → MRE → HRE, 2. MRE → HRE → LRE, and 3. HRE → LRE → MRE. Block randomization method was employed to further prevent pronounced allocation disparities by chance and random block sizes of 3/4 and 6/8 were used to diminish the likelihood of researchers predicting the sequence for the forthcoming participant, thereby reducing potential biases during recruitment. Random numbers were assigned to match the ID of participants, namely the order in which they were recruited. In each block, participants receiving the lowest random number(s) (1 for size "3"/"4" and 2 for size "6"/"8") were allocated to the first sequence; subsequent numbers were associated with the following sequences. This method ensured that the maximum difference between sequences was no more than 2. The CONSORT diagram for participant flow and the randomization outcome can be found in the figures of the referenced article.[38] The generation of all random numbers was accomplished with the use of Excel's RAND and RANDBETWEEN operations. The determined sequences were kept hidden inside non-transparent envelopes, managed by the graduate student who generated them. On the initial day of the intervention, the first author unveiled the designated sequence, reducing potential biases due to allocation non-concealment.

Procedure and Interventions

A total of six visits were required to complete the experiment. On the first visit, after the informed consent form was signed, bodyweight and height were measured, and body mass index (BMI) was calculated (kg/m^2). The health status and physical activity of the participants were assessed using the PAR–Q+ and the International Physical Activity Questionnaire,[40] respectively. The familiarization session for resistance exercise consisted of 4–6 sets of 5 repetitions of each movement, working up to 70–80% of their estimated 1RM. The weight and Rating of Perceived Exertion (RPE)[41] of the last set were recorded to be consulted for choosing the load of the first attempt in the 1RM test on visit 2. To reduce inter–instructor and inter–rater variability, all participants were introduced to the resistance exercise and were tested for 1RM by author TYL.

On both the first and second visits, the participants completed a familiarization session of the cognitive task, which was identical to the test on visits 3–6. The reason for this was that familiarization reduced the noise arising from the practice effect. Furthermore, one meta–analysis found that the effect of acute exercise on inhibition was more prominent when there was familiarization with the cognitive task than when there was none.[42] On the second visit, after the familiarization of the cognitive task, 1RM was tested. The weight started at approximately 50% of 1RM estimated by the record from the familiarization session after warm–up and aimed to find the 1RM within 3 to 5 attempts with adequate rest between each attempt (1–5 minutes, depending on the difficulty of the previous attempt). The participants were asked to refrain from consuming caffeine and alcohol for 12 hours and from vigorous exercise for 48 hours before visits 2–6. To account for the possible impact of circadian rhythm on strength and cognitive performance, all participants were instructed to visit the laboratory at roughly the same time, with a maximum allowable difference of ± 1 hour. The intervals between visits were 4.5 ± 1.7 days, ranging from 3 to 9 days.

There were four conditions (three exercises and one control) on visits 3–6. For the three exercise conditions, all training parameters except intensity were the same. The three different intensities were selected according to the "high", "moderate", and "low" intensity descriptions by Zourdos et al[43] and Haff et al.[44] For the exercise conditions, participants performed 5 repetitions at 78% 1RM (8RM or 91% 5RM/relative intensity) for the high-intensity condition, at 72% 1RM (11RM or 84% 5RM/relative intensity) for the moderate-intensity condition, and at 65% 1RM (16RM or 76% 5RM/relative intensity) for the low-intensity condition. These estimations were derived using Wathen's equation, as cited in LeSuer et al (1997).[45] Details of the resistance exercise intervention procedure were provided in the figure of the cited report.[38] Exercise interventions took about 40 minutes. The subjective exercise intensity was measured using the modified RPE scale, with scores ranging from 0 to 10,[41] and the reported Repetition in Reserve (RIR)[43] immediately after each set. This measurement was taken across a total of nine sets. During the control condition, participants were asked to read a book related to exercise for a duration similar to that of the exercise conditions.

Analytic Metrics

To control for a potential speed-accuracy trade-off and to reduce the number of dependent variables analyzed, the inverse efficiency score was used. This score is calculated as the reaction time divided by accuracy.[46] As a result, there were three dependent variables: Stroop congruent reaction time, Stroop incongruent reaction time, and the Stroop effect. The Stroop effect was calculated as the difference in reaction times between the congruent and incongruent conditions.

The Stroop effect serves as an indicator of one's ability to suppress distractions from unrelated information and is connected to the frontal cortex's function.[2] The congruent condition of the Stroop test, which can be likened to a choice reaction task, offers insights into the specific motor response inhibition occurring in the spinal cord and motor cortex.[3]

The impact of exercise on cognition was determined using the formula (RT is accuracy-adjusted reaction time): $\left[\left(RT_{ij} - RT_{i0}\right) - \left(RT_{0j} - RT_{00}\right)\right]$. In this formula, the first subscript denotes the intensity, with i representing low, moderate, or high intensity and 0 representing control condition. The second subscript labels the timing of the test, where j corresponds to the first, second, third, and the fourth post-tests, and 0 signifies pretest. For instance, to assess the effect of high-intensity resistance exercise on the third post-test, the computation would be: [(third post-test *RT* in the high-intensity condition – pre-test *RT* in the high-intensity condition) – (third post-test *RT* in control condition – pre-test *RT* in control condition)]. The subtraction in the first set of parentheses was accounts for daily variations in participants' cognitive ability, while the second set of parentheses controls for potential biases introduced by the procedure, such as practice effect and fatigue. For a visual representation of the cognitive test flow, refer to the figure in the cited registered report.[38]

Statistical Analysis

Primary Outcome: Temporal Effect

The repeated measures correlation (correlation within subjects) introduced by Bland and Altman (1995)[47] was employed to assess the presence of a linear relationship across various post-test time points. For this purpose, the first to the fourth post-test were assigned dummy variables of 1 through 4, respectively, to serve as the independent variable (x). The dependent variables (y) consisted the analytic metrics specified in preceding section. These metrics were the accuracy-adjusted Stroop congruent and incongruent reaction times, as well as the Stroop effect, after accounting for both the pre-test and control condition.

The data was standardized using the following equation:

$$Sx_{ik} = x_{ik} - \bar{x}_i(Sy_{ik} = y_{ik} - \bar{y}_i) \tag{1}$$

This process centers data around each participant's mean. In this equation, Sx_{ik} and Sy_{ik} indicated the standardized x and y values, respectively. The term y_{ik} denotes value of kth analyzed measurements of ith participant. In this study, there were 12 such values for each participant (3 intensities multiplied by 4 post-tests). The symbol $\bar{y}_i$ indicates the mean of the analyzed measurements for ith participant. Notably, in this trial, each participant underwent a total of 20 measurements (4 conditions multiplied by the sum of 1 pre-test and 4 post-tests). All pre-tests exercise conditions (counting as 3 measurements) aimed to control noise arising from daily cognitive fluctuations. Meanwhile, all tests in control condition (counting as 5 measurements) served to control bias from procedure effect. This resulted in a total of 12 input data points per participant, comprising 3 data points per time point due to a total of three exercise intensities.

Following Equation (1), the total sum of square of Sy_{ik} represented the within-participant variation. This variation can further be split into the variation explained by within-participant correlation (sum of squares due to the regression) and the residual.[47] The variation attributable to within-participant correlation was then computed as:[48]

$$\text{Variation explained by within} - \text{participant correlation} = \left(SS_{SxSy}\right)^2 / SS_{SxSx} \tag{2}$$

$$\text{Sum of products of standardized x and y values } \left(SS_{SxSy}\right) = \sum S_{Sx_i} S_{Sy_i} - \frac{\sum S_{Sx_i} \sum S_{Sy_i}}{\text{total number of analyzed measurements } (n \times k)} \tag{3}$$

$$\text{Sum of squares of standardized x values } (SS_{SxSx}) = \sum S_{Sx_i}{}^2 - \frac{\left(\sum S_{Sx_i}\right)^2}{\text{total number of analyzed measurements } (n \times k)} \tag{4}$$

Due to standardization process, both $\sum S_{Sx_i}$ and $\sum S_{Sy_i}$ equate to zero. Therefore SS_{SxSy} becomes $\sum S_{Sx_i} S_{Sy_i}$, and SS_{SxSx} becomes $\sum S_{Sx_i}{}^2$. The repeated measures correlation coefficient, as described by Bland and Altman[47], is:

$$r_{rm} = \sqrt{\frac{\frac{\left(SS_{SxSy}\right)^2}{SS_{SxSx}} (\text{Variation explained by within} - \text{participant correlation})}{\sum S_{Sy_i}{}^2 (\text{within} - \text{particiapnt sum of squares})}} \tag{5}$$

It is worth noted that the denominator in (5) is the sum of the variation explained by within-participant correlation and the residual.

To determine the p-value, the r_{rm} was converted to t-value, as per Cohen (2013):[49]

$$t = \frac{r}{\sqrt{\frac{1-r^2}{df}}} \tag{6}$$

The degrees of freedom (df) for the t-test are:[47]

$$(n \times k) - df_{particiapnt} - df_{correlation} - 1 \tag{7}$$

In this study, given that $n \times k$ represents the total number of analyzed measurements and n is the number of participants (which was 28 in this study), the participant's degrees of freedom are n – 1, and the df for correlation coefficient is 1, the df equates to 307. The p-value can subsequently be derived from the t-value for his df (307).

As the effect size correlation coefficient is not interval-based, the 95% confidence interval (CI) for r_{rm} was derived by converting it to a z value using Fisher's transformation of the correlation coefficient:[50]

$$z = \frac{1}{2}[\ln(1 + r) - \ln(1 - r)] \tag{8}$$

The standard error of z is approximately:[50]

$$\sigma_z = \frac{1}{\sqrt{df \text{ of } r_{rm} - 1}} \tag{9}$$

In this study, σ_z is 1 ÷ √ (307–1). Subsequent conversion of $z \pm 1.96\sigma_z$ back to the correlation coefficient provides the upper and lower bounds of the 95% CI. For ease of comparison with other studies, we also supplied the effect size $d_{matched}$ derived from the t-value:[49]

$$\mathbf{d} = \frac{t}{\sqrt{\text{total number of analyzed measurements}}} \tag{10}$$

Secondary Outcomes: Intensity Effect

The analysis for the intensity effect followed the same procedure as that for the temporal effect. However, in this case, the dummy variables 1, 2, and 3 were assigned to the low-, moderate-, and high-intensity conditions, respectively. Figures for repeated measures correlation were drawn using RStudio software (version 4.3.1). The code is provided in Supplement 2.

Ancillary Analyses

The one-sample *t*-test was employed to evaluate the effects across different intensities (by combining all four post-tests), specific time points (by merging all three exercise intensities), and each distinct post-test. Notably, the interaction stemming from a 2×2 analysis of variance (ANOVA)—with factors exercise (control vs exercise) and test time (pre-test vs post-test)—produced the exact *p*-value as the paired *t*-test, which compared the difference between post-exercise and pre-exercise with the difference between post-control and pre-control. Moreover, the *p*-value and effect size of this paired *t*-test are also the same as those from conducting one sample *t*-test with the analytic metrics listed in preceding section, which represent the difference of post-exercise minus pre-exercise, subtracted from post-control minus pre-control.

Opting for the *t*-test over the ANOVA prevented unnecessary type I error inflation due to multiple factors, which is referred to as familywise type I error. The choice of the one-sample *t*-test, in particular, was made to facilitate a more direct interpretation of the effect by comparing it to zero, as the computations for the paired *t*-test and one-sample *t*-test were identical in this context. These analyses were performed using the above formulas and basic arithmetic functions in Excel 2019. The line charts were drawn using GraphPad PRISM 10 (GraphPad Software, Inc.).

Sample Size and Statistical Power

Although the sample size was initially determined to capture the overall effect of resistance exercise on cognitive performance on the first post-test,[38] the analysis for linear relationship in this article should be able to detect small to medium correlations. This was achieved through the repeated measure correlation analysis, capitalizing on the strengths of our study's design. Despite using the non-exercise condition and pre-test in all conditions for better control, this study retained a total of 307 degrees of freedom. This df was calculated using the equation (7) in preceding section. In sample size calculation for correlation analysis,[49] the formula was given as $df = \frac{(z_{1-\frac{\alpha}{2}}+z_{1-\beta})^2}{r^2} - 1$. Using the parameters α = 0.05, power = 0.8, and $r = 0.16$, the calculation was as the follows: $df = \frac{(1.96+0.84)^2}{0.16^2} - 1$. This resulted in a required df of approximately 305. As such, this study was expected to have a statistical power ≥ 80% when the absolute value of r is 0.16 or greater.

Blinding (Masking) and Controlling Risk of Bias

Given the specific characteristics of exercise-based interventions, it was not feasible to blind either the participants or the experimenters in our investigation. However, we made certain that all cognitive performance evaluations were computer-driven, avoiding the need for human judgement. Additionally, the individuals responsible for data analysis followed a pre-established analytical approach. Adopting these methods reduce biases that might arise due to the absence of blinding and potential subjective choices by the research team. Since the majority of participants were either graduate or undergraduate students, potential bias from their intention to "help the researchers" was addressed. The first author informed any participant who inquired about the research question and hypothesis that the study would be published, irrespective of whether the results were statistically significant. Participants were assured that their only responsibility was to give their best effort.

Results

Recruitment

The means (standard deviation) for age, height, weight, and BMI were 23.2 (2.2) years, 175.4 (6.8) cm, 76.3 (11.5) kg, and 24.8 (3.4) kg/m², respectively. Complete reporting for drop-outs, anthropometric measurements, and baseline data can be found in the previous report.[38] In summary, out of the 31 participants who were recruited and met the criteria, 30 underwent randomization. The data collection for this trial concluded with 28 participants completing all six visits. This results in a dropout rate of 6.7% (2 out of 30).

Manipulation Check

Both the unadjusted and accuracy-adjusted reaction times were consistently shorter in the congruent trials compared to the incongruent trials across all time points (averaging four conditions at pre- and four post-tests) and intensities (averaging the pre-test and four post-tests). Specifically, the unadjusted reaction times ranged from 447.0 to 461.6 ms for congruent trials and from 506.7 to 520.7 ms for incongruent trials. The accuracy-adjusted reaction times ranged from 467.0 to 481.7 ms for congruent trials and from 580.5 to 613.1 ms for incongruent trials. Additionally, the mean accuracy rates for incongruent trials were consistently lower than those in congruent trials, with the values ranged from 85.9 to 88.0% for incongruent trials and from 95.6 to 96.3% for congruent trials. These data suggested the presence of the Stroop effect. The means and standard deviations for each condition and intensity are provided in Supplement 3. The subjective intensity of the exercise intervention, measured by the RPE, is provided in Table 2.

Stroop Performance Compared to Control Condition

The effects of various acute barbell resistance exercises on accuracy-adjusted congruent and incongruent reaction times, as well as the Stroop effect, are presented in Figure 2. At individual time points for each condition, high-intensity exercise led to a statistically significant improvement in both congruent and incongruent trials at the first post-test (~10 minutes after intervention). Moderate intensity improved only the congruent trials, while the low-intensity condition showed no significant effect at any of the four post-test time points. When combining the three different exercise intensities to assess the overall resistance exercise effect, congruent reaction times significantly improved at three out of four post-tests, while only the first post-test reaction time in the incongruent condition was significantly shortened.

Supplement 4 provides the statistics for every pairwise comparison across the three resistance exercise intensities and four post-test conditions for both congruent and incongruent reaction times, as well as the Stroop effect. It should be noted that, when combining all four post-tests, all three resistance exercises improved performance in congruent trials. The trend indicates that resistance exercise has a more pronounced effect on improving reaction speed in congruent trials than in incongruent ones. Regarding the Stroop effect, no significant changes were observed under any exercise intensity, nor when combining the three intensities.

Table 2 Rating of Perceived Exertion (RPE) and Repetition in Reserve (RIR) of Resistance Exercise (N = 28)

All sets combined	**Set RPE**	**Set RIR**
	Mean ± SD	**Mean ± SD; reported ≥10 RIR (%)**
Low intensity: 5 repetitions at 65% 1RM		
Squat	4.2 ± 1.5	5.7 ± 1.5 (83%); ≥10 (17%)
Press	3.8 ± 1.3	6.1 ± 1.7 (71%); ≥10 (29%)
Deadlift	4.6 ± 1.7	5.7 ± 1.9 (83%); ≥10 (17%)
Moderate intensity: 5 repetitions at 72% 1RM		
Squat	5.0 ± 1.6	4.7 ± 1.8 (87%); ≥10 (13%)
Press	4.8 ± 1.5	5.3 ± 1.7 (89%); ≥10 (11%)
Deadlift	5.5 ± 1.6	4.7 ± 1.7 (98%); ≥10 (2%)
High intensity: 5 repetitions at 78% 1RM		
Squat	5.9 ± 1.4	3.9 ± 1.7 (98%); ≥10 (2%)
Press	5.7 ± 1.4	3.7 ± 1.6 (96%); ≥10 (4%)
Deadlift	6.6 ± 1.5	3.3 ± 1.6 (100%); ≥10 (0%)
All intensity combined		
Squat	5.0 ± 1.7	4.7 ± 1.8 (89%); ≥10 (11%)
Press	4.8 ± 1.6	5.0 ± 1.9 (86%); ≥10 (14%)
Deadlift	5.6 ± 1.8	4.5 ± 2.0 (94%); ≥10 (6%)

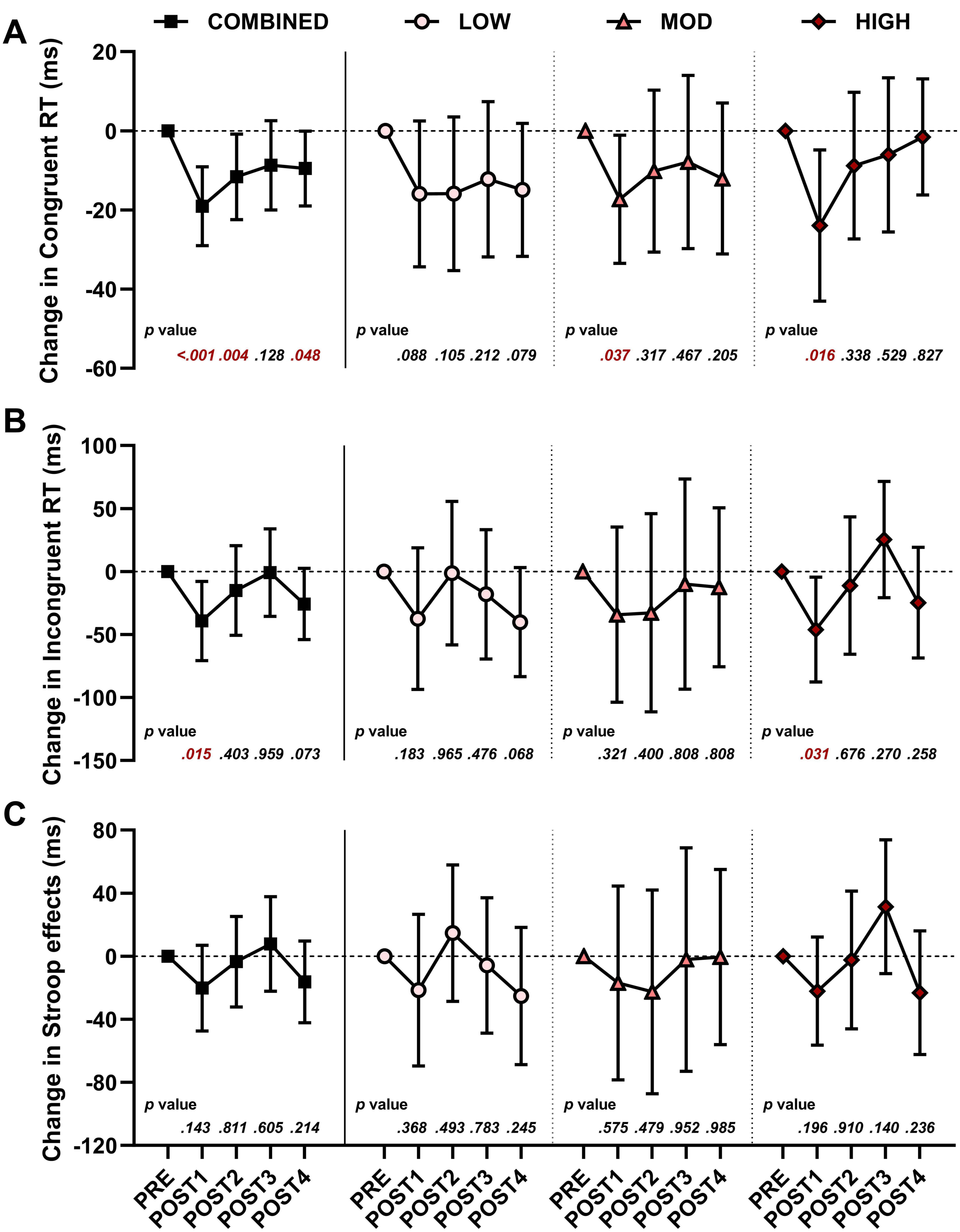

Figure 2 Line charts illustrating (**A**) changes in congruent reaction time (RT), (**B**) changes in incongruent reaction time, and (**C**) changes in the Stroop effect.
Notes: unit: milliseconds; COMBINED: combining all three exercise intensities; The PRE value (set to zero) was added for visualization purposes.
Abbreviations: LOW, low-intensity; MOD, moderate-intensity; HIGH, high-intensity. PRE, pre-test; POST1-4, post-tests 1–4.

Repeated Measures Correlation

Figures 3 and 4 illustrate the repeated measures correlation analyses for temporal and intensity effects of resistance exercise on Stroop task performance, respectively. The analyses suggested a linear temporal effect on accuracy-adjusted congruent reaction time: $r_{rm} = 0.114$, $p = 0.045$, 95% CI [0.002, 0.223]. The repeated measures correlation coefficient (0.114) suggests that, although Figure 2 demonstrates significant improvements at both the first and fourth post-tests when all intensities are combined compared to the same time points in the control condition, the beneficial effects of resistance exercise did not remain constant and began to gradually decline as early as 10 minutes after the intervention. In contrast, the repeated measures correlation for incongruent trials and the Stroop effect were not statistically significant: $r_{rm} = 0.058$, $p = 0.309$, 95% CI [−.054, 0.169] and $r_{rm} = 0.027$, $p = 0.638$, 95% CI [−.085, 0.138], respectively.

Regarding the linear relationship across exercise intensities, no significant correlation was found for congruent trials: $r_{rm} = 0.061$, $p = 0.282$, 95% CI [−.051, 0.172], incongruent trials: 0.039, $p = 0.681$, 95% CI [−.073, 0.145], or the Stroop effect: $r_{rm} = 0.023$, $p = 0.688$, 95% CI [−.089, 0.134]. The statistical values, including t-value converted from r_{rm}, z-value from Fisher's transformation, standard deviation of z-value and its 95% CI, $d_{matched}$ derived from t-value, and slope are detailed in Supplement 4.

Discussion

The present study aimed to investigate the influence of a single session of barbell resistance exercise on cognitive performance, with a specific focus on temporal and intensity factors. As illustrated in Figure 2, the results suggested that this intervention enhanced cognitive performance. This enhancement was especially pronounced in Stroop congruent trials and was limited to the first post-test for incongruent trials. The analysis also revealed a linear relationship between the timing of the post-tests and the effect of resistance exercise on Stroop congruent reaction time. The effect was most pronounced at 10 minutes post-intervention and gradually declined thereafter.

The change in the accuracy-adjusted reaction time in congruent trials at the first post-test was −19.1 ms and slope of the regression line was 4.3 (refer to Supplement 4). This suggests that around 10 minutes after the resistance exercise, participants responded about 19 ms faster than in the control condition. This enhancement effect then gradually decreased at a rate of approximately 4 ms every 15 minutes. Based on these findings, the positive effects of acute resistance exercise can be inferred to last for about 1 to 1.5 hours post-exercise. However, it should be noted that despite the statistical significance of the correlation, its explaining power is relatively low, given the coefficient of only 0.114. Therefore, while the findings are statistically meaningful, their practical significance may be limited.

Regarding the influence of different exercise intensities, this study found no significant difference between training at 65–78% 1RM for five repetitions. Please refer to the figure 2 in the associated article[38] for detailed exercise intervention information. Overall, the results of this study align with the previous findings reviewed in the Introduction. Given the lack of a significant correlation between the three exercise intensities and the changes in cognitive performance at each time point (as shown in Figure 2), this study suggests that the differences in exercise intensities used might be minimal and of limited practical significance.

While one might argue that significant results could be observed with a broader range of exercise intensities, such as prescribing 30% 5RM, 60% 5RM, and 90% 5RM (relative intensity) across three exercise conditions, the outcomes of such studies might not offer substantial contribution to designing resistance training programs, regardless of their statistical significance. One NSCA handbook[44] categorized relative intensity between 65–70% as "very light", and relative intensities < 65% were not even listed, indicating training at such low intensities is not recommended. This was one reason we chose 76% relative intensity as the lowest threshold. Furthermore, a recent meta-analysis has suggested that at least 60% 1RM should be prescribed for improving maximal strength.[51] Additionally, other training literature has recommended a higher and more specific range of intensity.[37] As for the 91% relative intensity, which was the highest one in this study ("HRE"), it is worth noting that this estimated 91% refers to a single set, and this trial encompassed three exercise movements with three sets each. Although most participants did not reach volitional failure, 20 out of 28 reported ≤ 3 repetitions in reserve after the last exercise (3rd set of barbell deadlift). This suggests that, while the training-to-failure method was not employed, the sets in the high-intensity condition were not too far from maximal

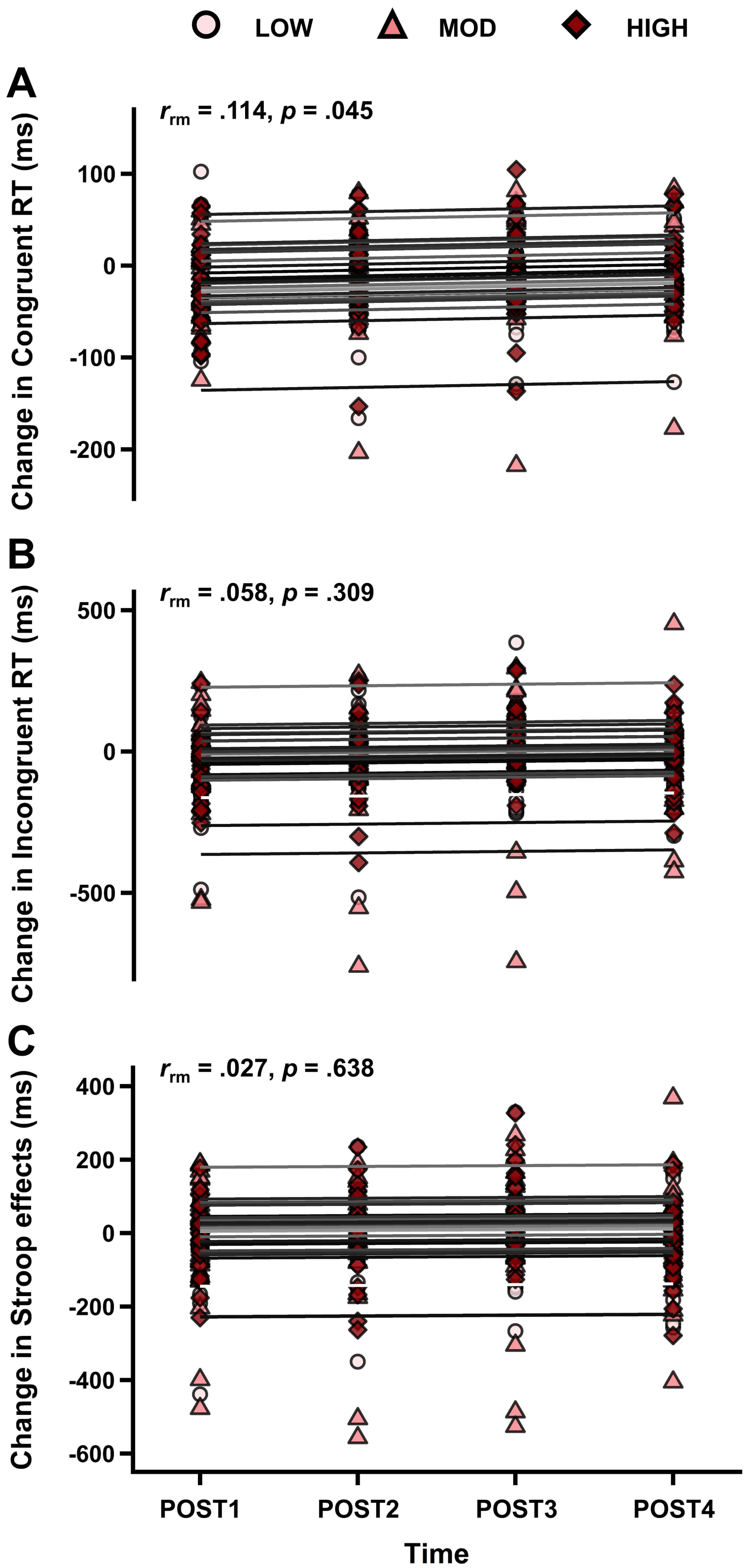

Figure 3 Repeated measures correlations for the temporal effect. The labels POST1-4 on the x-axis correspond to post-tests 1–4, respectively. See the main text for detailed statistics, including correlation coefficients and *p*-values. (**A**) Depicts the change in reaction time (RT) in milliseconds (ms) for congruent trials, (**B**) illustrates the change for incongruent trials, and (**C**) shows the change in Stroop effect.

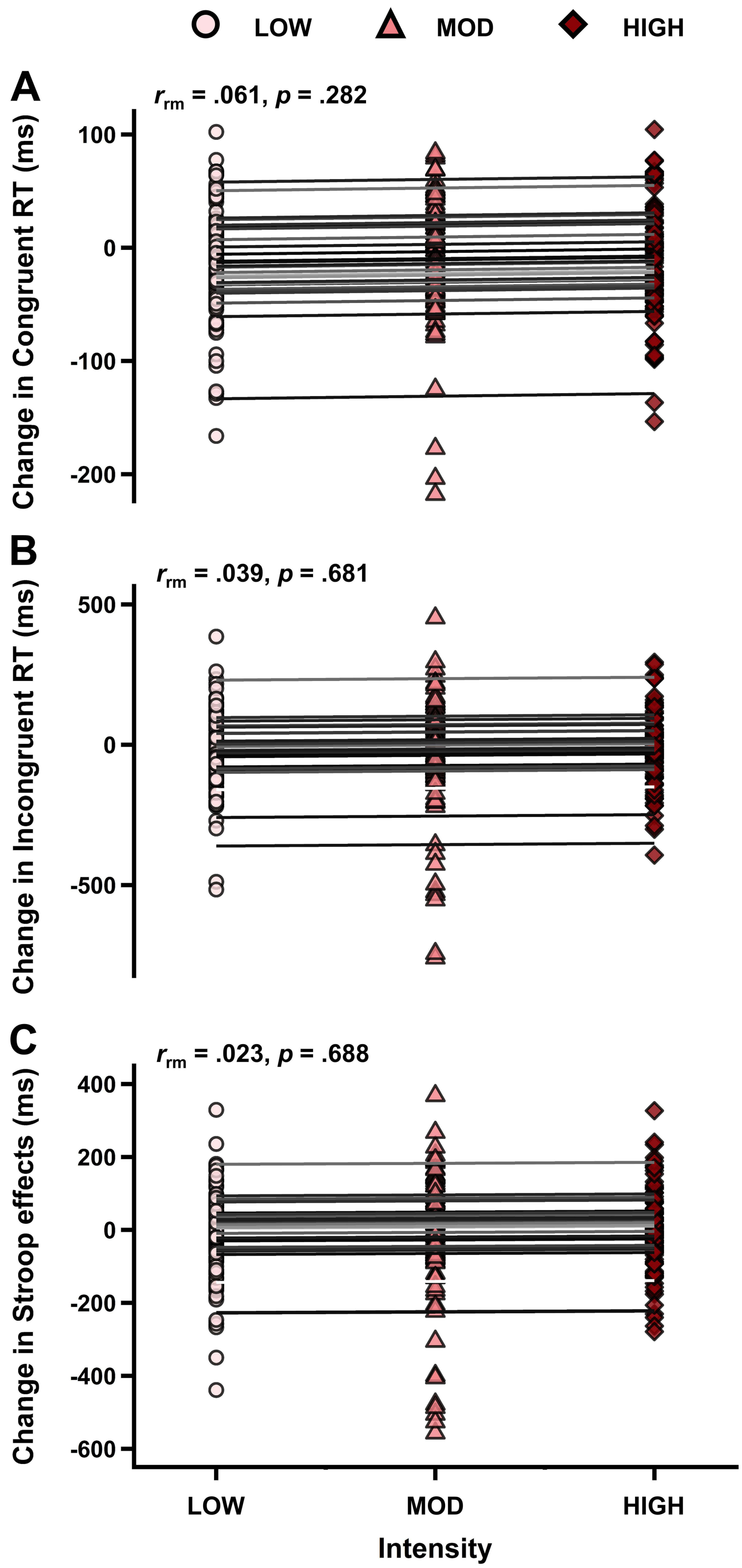

Figure 4 Repeated measures correlations for the intensity effect. The labels LOW, MODERATE, and HIGH on the x-axis correspond to low, moderate, and high intensity conditions, respectively. See the main text for detailed statistics. (**A**) Depicts the change in reaction time (RT) in milliseconds (ms) for congruent trials, (**B**) illustrates the change for incongruent trials, and (**C**) shows the change in Stroop effect.

effort. The raw data on Rate of Perceived Exertion (RPE) and Repetitions in Reserve (RIR) are available at the Open Science Framework (https://osf.io/4fkpc) and are summarized in Table 2.

Practical Application

This research indicates that for maximizing both athletic and cognitive benefits, scheduling cognitively challenging tasks within 1 hour after a training session—especially one focused on muscular strength improvement through free-weight, multiple-joint, structural exercises—may be recommended. Additionally, the study reveals a temporal dimension to this cognitive enhancement, indicating that improvements in cognitive performance may be most pronounced approximately 10 minutes after the exercise session. Therefore, prioritizing cognitively challenging tasks shortly after exercising could potentially maximize these benefits.

Limitation

There are two major limitations to this study that could potentially undermine the reliability of our research findings: type I error inflation and researchers' degrees of freedom.

First, many studies neither adjust for the experimentwise type I error rate nor recognize this concern. However, just because an issue is frequently unrecognized does not mean it is any less problematic.[52] Although we did make efforts to mitigate this risk by reducing the number of analyzed dependent variables (combining reaction time and accuracy) and by using *t*-tests instead of multiple factor ANOVA to avoid unnecessary inferential analyses, our true type I error rate is still above the conventional $\alpha = 0.05$ threshold.

To illustrate the risk of an inflated type I error rate, consider the main result regarding the repeated measures correlation for the temporal effect: Assuming that reaction times in Stroop congruent and incongruent trials are highly correlated, and these two variables are largely independent of the Stroop effect, then the experimentwise type I error rate for this outcome might be closer to 10% (0.1) rather than the expected 5% (0.05).

The other major threat to the reliability is the potential for exercising researchers' degrees of freedom, which encompasses at least two concerns. One concern is hypothesizing after the results are known (HARKing). Unlike the initial report of this trial,[38] which was a registered report, this article was written post-data-collection. Although we conducted a systematic search to prevent cherry-picking the previous studies for discussion, it does not eliminate our intrinsic bias when interpreting these findings to formulate hypotheses consistent with our results. The other concern is selective reporting. While we have provided justifications for our data analysis methods, these decisions were not predetermined or made public prior to the trial's start. This leaves potential discretion regarding which results to report.

Another limitation concerning our research findings pertains to the interpretation of the metric we analyzed. Throughout this article, we referred to the construct we measured simply and conservatively as "inhibition", rather than labeling it as an executive function, which is a common practice in exercise-cognition studies. This framing is influenced by an early, influential study which divided basic executive functions into inhibition and the other two components. Notably, this study considered the Stroop effect—and not the reaction times for either Stroop congruent or incongruent trials—as the indication of this cognitive ability.[53] As a result, while many previous exercise-cognition studies have claimed an improvement in executive function based on shortened reaction times in either congruent or incongruent trials, it remains debatable whether the improvements in a choice reaction task, such as the congruent trial, truly reflect executive functions, which are believed to be reliant on the prefrontal cortex.

Conclusion

The findings of this study highlight the beneficial impact of a single session of barbell resistance exercise on cognitive performance. Notably, the research underscores the temporal dimension of this effect, revealing that the enhancement is most pronounced approximately 10 minutes after the exercise session and lasts for about 1 to 1.5 hours post-exercise. These insights suggest that by designing training programs targeting muscular strength improvement with free-weight, multiple-joint, structural exercises, and concurrently scheduling cognitive challenging tasks within about an hour post-training session, one may potentially maximize the benefits from the exercise both athletically and cognitively.

Trial Registration and Protocol

This protocol has been registered on ClinicalTrials.gov under the identifier NCT05407259. Additionally, a segment of this trial is a registered report and is available on the Open Science Framework at the following link: https://osf.io/ehvyf. The trial period commenced on June 1, 2022, and concluded on May 31, 2023. The trial status is closed.

Data Sharing Statement

All raw data is available on the Open Science Framework (https://osf.io/4fkpc), in a folder with the same name as this article's title. All personal information was stored securely at the laboratory. No digital information was obtained. Other information that could expose a participant's identity will not be released without the permission of the participant.

Research Ethics and Consent Statements

The protocol was approved by the institutional review board at National Taiwan Normal University (202205HM003). We confirm that this study complies with the Declaration of Helsinki. The first author described the main aspects of this study to potential participants before they decide whether to provide informed consent. The informed consent form was written in traditional Chinese and was reviewed by the Center of Research Ethics, National Taiwan Normal University. It was not available in English.

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Disclosure

The authors report no conflicts of interest in this work.

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