




High Mental Fatigue Magnitude Generates Greater Impaired Resistance Exercise Performance Than Moderate Mental Fatigue Magnitude in Trained Adults

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ABSTRACT

Mental fatigue (MF) has been widely investigated in resistance exercise (RE). However, the results remain inconsistent, likely due to variability in the cognitive load across studies and, most importantly, the lack of individualized assessments of self-reported MF levels among participants before initiating the RE session. Therefore, the present study aimed to analyze the acute effect of different levels of MF induced by prior cognitive effort on the subsequent number of repetitions performed during an RE session. In a crossover trial, 20 participants were randomly assigned to three experimental conditions: a control and two mentally fatiguing conditions. In the MF conditions, the participants performed a computerized Stroop word-color (ST) task until reaching 40 mm (moderate MF) and 80 mm (high MF) on the visual analog scale for MF. Following all three conditions, participants completed an RE session consisting of six sets of half back-squat performed to muscle failure with a fixed load of ~45% 1RM (1.0 m.s⁻¹). Physical and perceptual parameters—including total repetitions, repetitions per set, repetitions per velocity loss, and rating of perceived exertion (RPE)—were measured during the RE session. Participants exhibited a lower number of repetitions and a higher RPE during RE in the high MF condition compared to the moderate MF and control conditions, with a significant difference also observed between the moderate MF and control conditions ($p < 0.05$). In summary, these findings suggest that a high level of subjective MF results in a greater magnitude of impairment in physical performance during an RE session.

1 | Introduction

Resistance exercise (RE) refers to a form of physical exercise that causes muscles to contract against an external resistance, whereas resistance training (RT) is commonly used to indicate the effects of multiple RE sessions (Schoenfeld et al. 2016).

Previous studies have shown that RT is widely employed to enhance muscle strength hypertrophy (Grgic et al. 2022; Lopez et al. 2020; Schoenfeld et al. 2016; Schoenfeld et al. 2017). However, various loading parameters must be acutely manipulated to optimize these adaptations, such as intensity-load zone, rest intervals, exercise order, velocity, time under tension,

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Highlights

- High levels of mental fatigue significantly reduce resistance exercise performance compared to moderate and control conditions.
- A dose–response relationship was observed, with greater subjective mental fatigue leading to higher perceived exertion and fewer repetitions performed.
- Individualized assessment of mental fatigue before training may help optimize resistance exercise outcomes in trained adults.

training frequency, and the number of sets and repetitions (Grgic et al. 2022; Lopez et al. 2020; Schoenfeld et al. 2016; Schoenfeld et al. 2017). Previous meta-analyses have demonstrated that volume is one of the primary variables for gains in muscle strength and hypertrophy (Krieger 2010; Lopez et al. 2020; Schoenfeld et al. 2017; Schoenfeld, Ogborn, et al. 2017). From this perspective, velocity-based training (VBT) has emerged as a precise approach for quantifying and prescribing intensity and volume in resistance exercise (González-Badillo and Sánchez-Medina 2010). Within this framework, velocity loss (VL) (e.g., 10%, 20%, 30%) serves as an objective marker of neuromuscular fatigue accumulation and is used to regulate training volume and intensity (Pareja-Blanco et al. 2017). Thus, factors that may influence RE volume, such as mental fatigue (MF) (Alix-Fages et al. 2023), should be considered by coaches and practitioners.

Mental fatigue (MF), resulting from cognitive tasks with low or high mental demand, induces symptoms such as tiredness, lack of energy, increased perception of effort, task disengagement, and reduced motivation (Brown et al. 2020; Pageaux et al. 2015; Schiphof-Godart et al. 2018; Smith et al. 2018). Consequently, this psychobiological state is associated with alterations in cortical brain activity (Bafna and Hansen 2021), which may bidirectionally interact with physiological and psychological changes and negatively impact various outcomes in subsequent tasks requiring executive functions (e.g., sustained attention, working memory, and inhibitory control) (Van Cutsem et al. 2017). For example, an RE session, which depends on physical performance (e.g., repeated muscular contractions), may be affected. Regarding physical performance, a previous meta-analysis demonstrated a small to moderate yet significant negative effect of prior cognitive effort on physical performance ($g = -0.38$ [95% CI $-0.46, -0.31$]), with subgroup analyses indicating effects on isometric resistance ($g = -0.57$), motor ($g = -0.57$), dynamic resistance ($g = -0.51$), and endurance performance ($g = -0.26$) (Brown et al. 2020). More recently, other meta-analyses have confirmed these findings in endurance performance (Giboin and Wolff 2019; Habay et al. 2023). Regarding volume in RE sessions, the detrimental effects of MF appear to be similar, as evidenced by a reduction in the number of repetitions for both upper- (standardized mean difference: -0.41) and lower-limb (standardized mean difference: -0.39) exercises (Alix-Fages et al. 2023).

It is important to note that studies investigating the effects of prior cognitive effort on RE session volume have varied considerably in cognitive load used for inducing MF, such as

cognitive task duration and task type (e.g., challenging arithmetic/balance tasks, vigilance tests, social media use on smartphones, and congruent and incongruent Stroop tests) (Alix-Fages et al. 2023). For instance, (De Lima-Junior et al. 2024) demonstrated that 30 min of prior cognitive effort using the Stroop task impaired total volume (i.e., the number of repetitions to muscular failure in the half-squat exercise) in a RE session (standardized mean difference: -0.84). (Gantois et al. 2021) induced MF through 30 min of social media app use on smartphones and found similar results, with detrimental effects on volume during an RE session (standardized mean difference: -0.33). The scientific literature suggests no relationship between the duration of cognitive effort, considered a component of cognitive load, and the effect magnitude of MF on physical performance (Giboin and Wolff 2019; Habay et al. 2023). Thus, it is reasonable to assume that different cognitive loads result in varying subjective perceptions of MF, which could explain the inconsistent findings regarding the effects of MF on RE volume.

Another limitation in investigating the effect of prior cognitive effort on RE volume is the lack of individualization of self-perceived MF levels among participants before initiating the session. For example, previous studies that standardized cognitive load to 30 min found variability in self-induced MF levels [measured using a Visual Analog Scale (VAS) ranging from 0 to 100 mm], as reported by participants, with dispersion variability values of approximately 20 arbitrary units (a.u.) (De Lima-Junior et al. 2024; Gantois et al. 2021; Queiros et al. 2021). Therefore, it is likely that different magnitudes of self-perceived MF result in varying degrees of impairment in RE volume. In this sense, understanding how different levels of MF can impair performance in an RE session may help practitioners monitor the magnitude of MF immediately before RE sessions and/or avoid previous cognitive effort before RE sessions. Additionally, insight into the effects of different levels of MF on RE performance may help professionals predict whether a given training session will be more or less impaired by a specific prior level of MF. Also, understanding how MF affects performance across different VL thresholds provides valuable insights into the neuromuscular and perceptual mechanisms underlying fatigue-related performance decrements.

Thus, the objective of this study was to analyze the acute effect of different levels of MF from prior cognitive effort on the subsequent number of repetitions during an RE session. We hypothesized that a high level of MF would result in a greater reduction in the number of repetitions during RE sessions compared to a moderate level of MF and control conditions.

2 | Methods

2.1 | Participants

We estimated the sample size for an analysis of variance (ANOVA) with repeated measures and within-subjects interactions. The sample size was estimated using G*Power software version 3.1.9.2 (Universität Kiel, Kiel, Germany) with power = 0.95, effect size (Effect size $f = 0.29$) for the number of repetitions at resistance exercise in mentally fatigued adults

(Gantois et al. 2021), $\alpha = 0.05$, number of experimental conditions = 3, number of measurements = 6, correlation among repeated measures = 0.5, and nonsphericity correction = 1. Results indicated that 15 participants would be necessary for the study. Twenty resistance-trained young men aged between 18 and 30 years old were recruited for the study.

As inclusion criteria, participants had to be free from neuromuscular and skeletal muscle injuries or disorders in the lower limbs, not using drugs or medications that could affect physical performance, and trained in RT [for example, at least 1.25 times their body mass in half-back squat for one-repetition maximum (1-RM)]. They were excluded from the study if they did not attend all experimental sessions. The study was conducted according to the Declaration of Helsinki, and ethical approval was granted by the ethics committee of the local university. The subjects received written instructions describing all the procedures, risks, and benefits related to participation in the study and signed an informed consent form. Subjects were informed that this study aimed to investigate the effects of different cognitive tasks on the neuromuscular performance of half-back squat exercises.

2.2 | Experimental Design

This study employed a within-participant experimental design (i.e., experimental condition and time factors). Each subject performed three trials (i.e., Control, Moderate MF, and High MF), separated by at least 72 h and distributed in a random and balanced order established using a website (randomizer.org). The participants were unaware of the order of the conditions. The physiological (pupil diameter), behavioral (response time), and perceptual (subjective MF, mental demand, and effort) measures were taken before, during, and/or immediately after the initial manipulation [i.e., Stroop Color task or control (seated for 20-min)], as illustrated in Figure 1. Subsequently, a half back-squat exercise session measured the number of repetitions to failure for different velocity loss (VL) thresholds (i.e., 10%, 20%, 30%, 40%, and 50%). The number of repetitions per VL was recorded to analyze from which point in the set mental fatigue could impair performance.

The rating of perceived exertion (RPE) was measured at every five repetitions. The resistance exercise experimental sessions were always performed between 4:00 and 7:00 p.m. to avoid any circadian rhythm influence. To minimize the potential effects of food intake on the outcomes, standardized procedures previously suggested were adopted (Pageaux et al. 2015; Solon-Júnior et al. 2025). Also, before each session, participants completed a self-report questionnaire about what they had done in the previous 6 hours. Sessions were rescheduled if the participant reported mental fatigue greater than 25 mm on the visual analog scale, according to previously established criteria (Kamali et al. 2019).

The participants were asked to avoid any physical exercise, vigorous activity, and alcohol ingestion 24 h before experimental visits and refrain from consuming caffeine at least 6 h before each training session. In addition, instructions were given to the participants to maintain at least 7 h of daily sleep. Neuromuscular measures (e.g., countermovement jump) and perceptual measures (e.g., subjective recovery) were used as a checklist immediately before experimental sessions. It was considered acceptable to proceed with the experimental sessions if the CMJ performance was within $\pm 5\%$ of the average of the previously conducted familiarization tests and the perceived recovery level, assessed by the total recovery scale, was greater than 16.

2.3 | Resistance Exercise Session

The resistance exercise session was conducted in the afternoon (4:00–7:00 p.m.). It included only the half-back squat exercise. The range of motion allowed was 90° and was limited by the Smith machine (Righetto, São Paulo, Brazil) used in the training and tests. A velocity-based training protocol was performed (González-Badillo and Sánchez-Medina 2010) instead of a traditional loading-based resistance training session. The subjects performed six sets with an intensity load for $1 \pm 0.05 \text{ m}\cdot\text{s}^{-1}$ ($\sim 45\%$ 1-RM) until they reached momentary concentric muscle failure (inability to perform the exercise correctly), with a rest interval of 150 s between sets. The choice of the target velocity ($\sim 1.0 \text{ m}\cdot\text{s}^{-1}$), which corresponds to approximately 45% of the 1RM for the half back-squat exercise, was based on previous

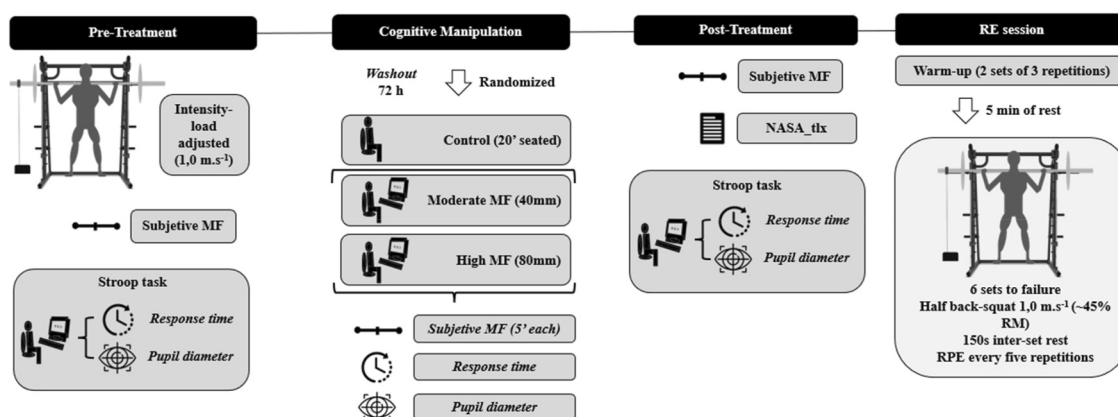


FIGURE 1 | Experimental design of the study. NASA_tx = national aeronautics and space administration task load index; RE = resistance exercise; RPE = rate of perceived exertion; Subjective MF = subjective mental fatigue.

studies of mental fatigue and resistance exercise (Alix-Fages et al. 2023). On the other hand, the reason for using the target velocity approach of $\sim 1.0 \text{ m}\cdot\text{s}^{-1}$, linked to $\sim 45\%$ of the 1RM estimated by velocity, allowed precise and safe control of intensity during the sessions. Furthermore, direct measurement of the 1RM in all participants could increase the risk of prior fatigue (González-Badillo and Sánchez-Medina 2010).

A target mean propulsive velocity to be attained in the first (usually the fastest) repetition of the 1st set in each session was used as an estimation of % 1RM. Following the standardized warm-up [2 sets of 3 repetitions with intensity-load adjusted to match the velocity that was intended for that session ($1.00 \pm 0.05 \text{ m}\cdot\text{s}^{-1}$), adopting an interval rest of 2 min] and before the first half-back squat exercise set, the intensity load (kg) was individually adjusted to match the velocity associated ($\pm 0.05 \text{ m}\cdot\text{s}^{-1}$) with the $\sim 45\%$ 1-RM that was intended for that session. The participants started the resistance exercise session after 5 min of rest and a standardized warm-up. During the resistance exercise session, subjects received immediate velocity feedback while being encouraged to perform each repetition in maximal intentional velocity in the muscle concentric contraction and self-selected velocity in the muscle eccentric contraction.

Barbell velocity for each repetition of the half-back squat exercise was measured using a linear encoder unit (Vitruve, Madrid, Spain), a device that has been considered reliable for monitoring bar velocity (Ruiz-Alias et al. 2024). This equipment is a linear position transducer attached to the barbell using a string, which measures each repetition's linear displacement and duration at a resolution of 100 Hz to estimate the kinematic and kinetic parameters for every repetition. The volume was calculated as the total number of repetitions performed in all sets throughout the entire experiment.

2.4 | Cognitive Manipulation

2.4.1 | Control

The control group remained seated for 20 min before a resistance exercise session to ensure temporal equivalence with the moderate and high mental fatigue experimental conditions. A researcher remained in the experimental room next to the participant. The use of electronic devices (e.g., smartphones, tablets, and computers) was prohibited during those 20 min. The researcher only called the participant's attention in case they fell asleep.

2.4.2 | Moderate MF

The Stroop task was used as an experimental manipulation to impose cognitive effort (PsychoPy v1.85.6, University of Nottingham, United Kingdom). Previous studies have shown that execution of the Stroop task for 30–45 min induces MF in physically active subjects (Lopes et al. 2020; Penna et al. 2021). Thus, herein, we individualize the cognitive load to produce similar mental fatigue levels in all participants (Habay

et al. 2021). Therefore, we employed incongruent trials (one trial every 2500 milliseconds) of the Stroop task until the participant presented a 40 mm value on the VAS of MF immediately before starting the resistance exercise session. The VAS of MF was measured every 5 min during the Stroop task. In this sense, the Stroop task duration differed between participants. The task was performed in a silent and illuminated room, with the participants seated comfortably on a chair in front of a 21-inch monitor wearing noise-dampening earphones to avoid noise distractions. In this task, four words (blue, yellow, red, and green) were presented in Arial font size 60, one at a time, in a randomized order, at the center of a computer screen. The words were inked with the colors blue, yellow, red, or green in an incongruent manner (e.g., the word blue painted with red ink). Subjects were instructed to press as quickly and accurately as possible a colored button on the computer keyboard corresponding to the correct response. The word's ink determined the correct response. If the ink was blue, green, or yellow, subjects should press the button corresponding to the ink color (e.g., if the word “green” appeared inked in yellow, the yellow button should be pressed). If, however, the ink color was red, the button that should be pressed was the button corresponding to the word's meaning, not the ink color (e.g., if the word “blue” appeared inked in red, the blue button should be pressed). Each word remained on the screen for 2500 ms or until subjects pressed a response button. The test was paced with an interval of 1000 ms between the response and the next stimulus. Behavioral performance was measured as response time (ms) for correct answers. The impaired response time throughout the Stroop task has been suggested as a behavioral indicator of MF (L. D. S. Fortes et al. 2022; Martin et al. 2016). For statistical analysis the Stroop task was divided into four blocks, considering the time (percentage) necessary for the 40 mm value on the VAS of MF (i.e., 25%, 50%, 75%, and 100%).

2.4.3 | High MF

It followed the same procedures for the Moderate MF condition but employed incongruent trials (one trial every 2500 ms) of the Stroop task until the participant reached an 80 mm value on the VAS of MF immediately prior starting the RE session. For statistical analysis, the Stroop task was divided into four blocks, considering the time (percentage) necessary to reach 80 mm value on the VAS of MF (i.e., 25%, 50%, 75%, and 100%).

2.5 | Manipulation Checks

2.5.1 | Subjective Mental Fatigue

The subjective rating of MF was assessed using the 100-mm VAS. This scale has two anchors, from 0 (none at all) to 100 (maximal). The participants were required to answer, “How mentally fatigued do you feel now?”. The definition of “mental fatigue” was provided to participants, and examples of “none at all” (no feelings of tiredness and lack of energy) and “maximal” (maximum feelings of tiredness and lack of energy) were given based on tasks of prolonged periods of demanding cognitive activity. Participants were instructed to draw a single vertical

line to reflect MF throughout the 100 mm scale to reflect their perceived level of MF. To quantify values, we measured distance in millimeters from 0 to 100.

2.5.2 | Stroop Task Pre- and Post-Cognitive Manipulation

The incongruent Stroop task was used to evaluate inhibitory control (PsychoPy v1.85.6, University of Nottingham, United Kingdom). The modified incongruent Stroop task employed in this study was based on the paradigm introduced by Wallace and Baumeister (2002). We employed the Stroop task with 100 incongruent trials (one trial every 2500 ms). The task was performed in a silent, well-lit room, with participants seated comfortably in a chair in front of a 21-inch monitor and wearing earphones to reduce noise distractions. In this task, four words (blue, yellow, red, and green) were presented in Arial font size 60, one at a time, in a randomized order, at the center of a computer screen. The words were inked incongruently in blue, yellow, red, or green. Subjects were instructed to press a colored button on the computer keyboard corresponding to the correct response as quickly and accurately as possible. Each word remained on the screen for 2500 ms or until subjects pressed a response button. The test was paced with an interval of 1000 ms between the response and the next stimulus. Behavioral performance was measured as response time (ms) for correct answers. Two sessions with at least 72-h intervals were required to identify all participants' Stroop task reliability values. We evaluated the response time using intraclass coefficient correlation (ICC) = 0.96 (CI_{95%} = 0.93–0.99).

2.5.3 | Pupil Diameter

Pupil diameter was recorded continuously throughout the incongruent Stroop color test (100 trials) using portable Eye Tracking-XG equipment (Applied Science Laboratories, USA) with a sampling frequency of 60 Hz. Gaze position was calibrated before the initial task using three-point calibration. Using the SMI BeGaze 3.2 software system (SMI, Berlin, Germany), the raw data from each participant were extracted for further processing in RStudio software. A low-pass Butterworth filter (4 Hz) was applied to produce a reliable signal profile. The eye-tracker then detected blinks, saccades events, artifacts, and outliers' values (mean \pm 2*SD) and removed them using a linear interpolation algorithm. Pupil diameter was used to assess cognitive effort (Bafna and Hansen 2021). The pupil diameter was averaged over the 500 ms prior to stimulus onset to determine resting pupil diameter. During this period, the participants viewed a fixation cross with the same luminosity as the letters, preventing interference from environmental lighting. Stimulus-evoked pupil data were analyzed in RStudio software in the same manner as the baseline pupil diameter. Both pupil diameter during the Stroop task pre-and post-cognitive manipulation, and the mean pupil diameter during cognitive manipulation, were exported for further analysis. Note that pupil diameter data during the cognitive manipulation were not collected for the Control condition, as participants in this condition remained seated only. Resting pupil diameter was measured during the 500 ms preceding each stimulus presentation (fixation cross

period) to establish baseline values unaffected by stimulus-evoked responses.

2.5.4 | Mental Demand and Effort

The mental demand and effort subscales from NASA Task Load (NASA-TLX) (Ciofi-Silva et al. 2023; Hart and Staveland 1988) were used to assess the participants' subjective mental load after the Stroop word-color task. To facilitate the participants' understanding, they provided their responses for each domain in a 100 mm horizontal line, similar to a VAS.

2.6 | Measures

2.6.1 | Number of Repetitions per Set and VL

The participants were asked to perform the half back-squat exercise with the maximum intended velocity during the concentric phase and self-selected velocity during the eccentric phase. Two work metrics were calculated: the total number of repetitions per set and the total volume for the resistance exercise session (i.e., the sum of repetitions across the six sets). Total repetitions refers to the number of repetitions performed until muscular failure.

The number of repetitions per velocity loss (VL) during sets and sessions was quantified. The VL percentages of 10%, 20%, 30%, 40%, and 50% were used throughout the sets. The barbell velocity (Vitruve, Madrid, Spain) for each repetition of the half back-squat exercise was used to quantify the number of repetitions for the different VL percentages. VL was calculated as the percentage decrease in mean propulsive velocity from the fastest repetition (i.e., first) to each subsequent repetition within a set: $VL (\%) = [(V_{fastest} - V_{current})/V_{fastest}] \times 100$. This metric provides an objective, real-time assessment of neuromuscular fatigue development during resistance exercise.

2.6.2 | Rating of Perceived Exertion (RPE)

RPE was monitored using a CR-10 scale (Borg 1982) during the half back-squat exercise. The participants were instructed to provide their RPE for every five repetitions. Once differences in the number of repetitions were found (e.g., control, moderate, and High MF experimental conditions), the mean RPE was compared in an iso-work (i.e., the percentage for the number of repetitions). Thus, we calculated the RPE mean for the 25, 50 (26–50), 75 (51–75), and 100% (76–100) of the number of repetitions for each experimental condition. This approach allows for valid comparisons of perceived exertion across conditions despite differences in absolute performance volume.

2.7 | Statistical Analysis

The Shapiro-Wilk test was used to evaluate data distribution. Central tendency (mean) and dispersion (standard deviation) measures described the research variables. Generalized Estimated Equation (GEE) was used to analyze an experimental

condition (High MF vs. Moderate MF vs. Control) \times time (pre- vs post-cognitive effort) interaction for subjective MF, response time, and pupil diameter, adopting experimental condition and time as within-factor. This same statistical test also was used to analyzing an experimental condition (High MF vs. Moderate MF) \times time (25% vs. 50% vs. 75% vs. 100% of total time) interaction for subjective MF, response time, and pupil diameter, utilizing experimental condition, and time as within-factors. It was used by the GEE to analyze an experimental condition (High MF vs. Moderate MF vs. Control) \times time (1st vs. 2nd vs. 3rd vs. 4th vs. 5th vs. 6th set or VL10% vs. VL20% vs. VL30% vs. VL40% vs. VL50%) interaction for number of repetitions, adopting experimental condition and time as within-factor. The GEE was used to analyze an experimental condition (High MF vs. Moderate MF vs. Control) \times time (5th vs. 10th vs. 15th vs. 20th repetition) interaction for RPE, utilizing experimental condition and time as within-factor. We used generalized models because they have been considered advantageous compared to traditional models (i.e., ANOVA or MANOVA) in neuroscience research with repeated measures data (Melo et al. 2021). The sphericity assumption was assessed using the Mauchly test, and Greenhouse-Geiser correction was applied when needed. A one-way ANOVA with repeated measures was utilized to compare subjective mental demand and effort according to experimental condition (High MF versus Moderate MF versus Control). The post-hoc Bonferroni test was utilized to identify the localization of statistical differences. The η^2 was used to determine the ES and was interpreted using the following cutoffs (Cohen 1992): small effect, $\eta^2 < 0.03$; moderate effect, $0.03 \leq \eta^2 < 0.10$; large effect, $0.10 \leq \eta^2 < 0.20$; very large effect, $\eta^2 \geq 0.20$. Data were processed in the Statistical Package for Social Sciences Version 25.0 (IBM Corp., Armonk, NY, USA) and GraphPad Prism 9.0 (San Diego, CA, USA). A significance level of 5% was adopted.

3 | Results

3.1 | Manipulation Checks

3.1.1 | Subjective Mental Fatigue

A significant condition \times time interaction effect was found for the subjective MF [see Figure 2a; $F_{(2,36)} = 1544.0$, $p = 0.001$, $\eta^2 = 0.28$, ES = very large]. Post-hoc Bonferroni tests indicated significant increases in subjective MF from pre- to post-cognitive manipulation in both the High MF (mean change: +79.1 mm, $p < 0.001$) and Moderate MF (mean change: +38.2 mm, $p < 0.001$) experimental conditions, whereas no significant change was observed in the Control condition (mean change: -0.3 mm). Furthermore, post-manipulation MF levels were significantly higher in the High MF condition when compared to both the Moderate MF and Control conditions [see Figure 3a; $F_{(3,57)} = 81.80$, $p = 0.01$, $\eta^2 = 0.11$, ES = large].

3.1.2 | Mental Demand and Effort

A significant statistical difference was found between experimental conditions for the mental demand subscale [see Figure 2b; $F_{(2,36)} = 323.0$, $p = 0.001$, $\eta^2 = 0.88$, ES = very large].

The Bonferroni post-hoc analysis revealed greater mental demand for the High MF compared to the Moderate MF and Control condition ($p < 0.05$). In addition, the Bonferroni post-hoc analysis revealed a higher mental demand for Moderate MF compared to the Control condition ($p < 0.05$).

A significant statistical difference was found between experimental conditions for the effort subscale [see Figure 2b; $F_{(2,36)} = 459.0$, $p = 0.001$, $\eta^2 = 0.89$, ES = very large]. The Bonferroni post-hoc analysis indicated greater effort for High MF condition than Moderate MF and Control condition ($p < 0.05$). Subsequently, the Bonferroni post-hoc analysis indicated higher effort for Moderate MF than the Control condition ($p < 0.05$).

3.1.3 | Stroop Task Response Time Pre and Post-Cognitive Manipulation

A significant group \times time interaction effect was found for the response time [see Figure 4a; $F_{(2,36)} = 102.0$, $p = 0.001$, $\eta^2 = 0.36$, ES = very large]. The Bonferroni post-hoc test indicated a decreased response time for High MF compared to Moderate MF and Control conditions ($p < 0.05$). In addition, the Bonferroni post-hoc analysis also revealed a decreased response time for Moderate MF than Control conditions ($p < 0.05$).

3.1.4 | Response Time During the Cognitive Manipulation

A significant group \times time interaction effect was found for the isotime response time [see Figure 3b; $F_{(3,57)} = 102.0$, $p = 0.001$, $\eta^2 = 0.36$, ES = very large]. The Bonferroni post-hoc test indicated decreased response time for High MF than Moderate MF experimental conditions (75% and 100%) ($p < 0.05$). Note that response time data were not collected for the control condition, as participants in this condition did not perform the cognitive manipulation.

3.1.5 | Pupil Diameter Pre- and Post-Cognitive Manipulation

A significant group \times time interaction effect was found for the pupil diameter [see Figure 4b; $F_{(2,36)} = 16.90$, $p = 0.01$, $\eta^2 = 0.08$, ES = moderate]. The Bonferroni post-hoc test suggested a decreased pupil diameter for High MF when compared to Moderate MF and Control conditions ($p < 0.05$). Then, the Bonferroni post-hoc analysis also indicated increased pupil diameter for Moderate MF than control conditions ($p < 0.05$).

3.1.6 | Pupil Diameter During the Cognitive Manipulation

A significant group \times time interaction effect was found for isotime pupil diameter [see Figure 3c; $F_{(3,57)} = 15.0$, $p = 0.001$, $\eta^2 = 0.08$, ES = moderate]. The Bonferroni post-hoc test indicated decreased pupil diameter for High MF when compared to Moderate MF condition (75% and 100%) ($p < 0.05$).

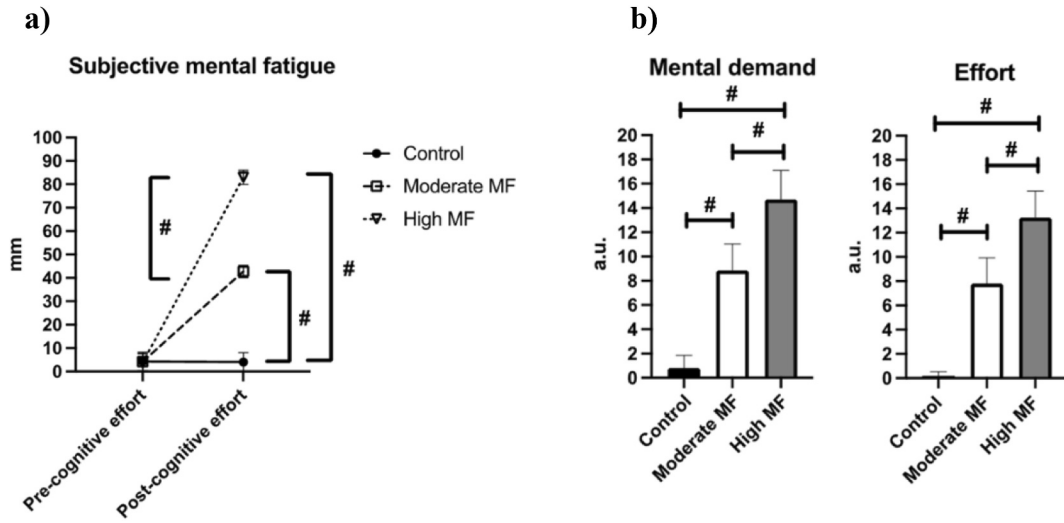


FIGURE 2 | Manipulation checks (subjective mental fatigue, mental demand, and effort) according to experimental condition (high MF, moderate MF, and control) and time (pre-and post-cognitive effort). # $p < 0.05$ statistical difference between experimental conditions.

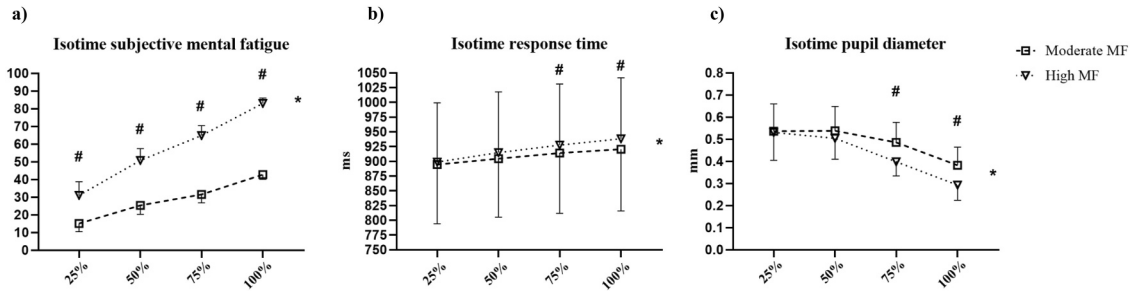


FIGURE 3 | Analysis isotime for the manipulation checks (subjective mental fatigue, response time, and pupil diameter) according to experimental condition (high MF, moderate MF, and control) and time (25%, 50%, 75%, and 100%). * $p < 0.05$ a significant main time effect; # $p < 0.05$ statistical difference between experimental conditions.

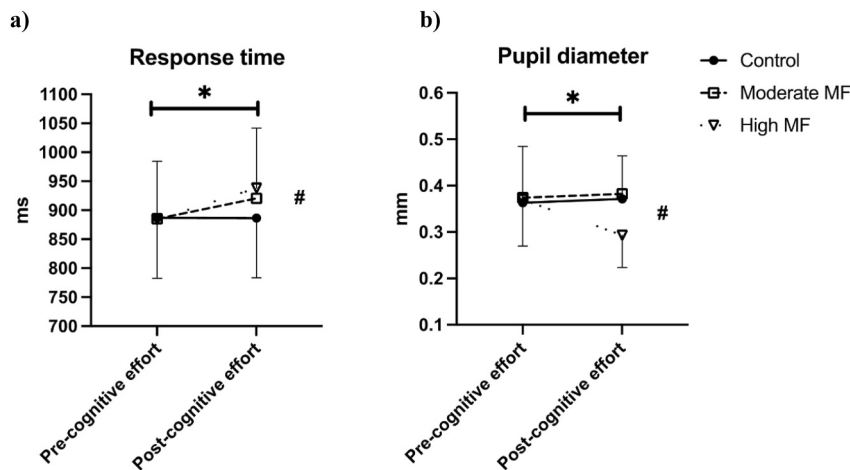


FIGURE 4 | Response time and pupil diameter during the Stroop task according to experimental condition (high MF, moderate MF, and control) and time (pre-and post-cognitive effort). * $p < 0.05$ a significant difference from “pre-cognitive effort” to “post-cognitive effort”; # $p < 0.05$ statistical difference between experimental conditions.

3.2 | Number of Repetitions

3.2.1 | Set and Total

There was a significant difference between the experimental conditions for the total number of repetitions [see Figure 5a; Control: 174.75 ± 25.06 repetitions; Moderate MF: 158.00 ± 16.73 repetitions; High MF: 143.55 ± 16.72 repetitions] ($F_{(2,38)} = 16.64$, $p = 0.001$, $\eta p^2 = 0.46$, ES very large). The total number of repetitions was lower for the High MF condition than the Moderate MF ($p = 0.003$, $d = 0.86$, ES large effect) and control ($p = 0.001$, $d = 1.46$, ES very large effect) conditions. Also, the total number of repetitions was higher for the Control condition than Moderate MF ($p = 0.004$, $d = 0.78$, ES moderate effect).

A significant condition \times time interaction was found for the number of repetitions at muscle failure [see Figure 5b; $F_{(4,92)} = 3.81$, $p = 0.01$, $\eta p^2 = 0.08$, ES = moderate]. The Bonferroni post-hoc test indicated a decrease in the number of repetitions from “1st” for “6th” set ($p < 0.05$), with a lower number of repetitions for High MF when compared to Moderate MF and Control conditions ($p > 0.05$). The Bonferroni post hoc also revealed greater attenuation in the number of repetitions for Moderate MF than the Control condition ($p > 0.05$).

3.2.2 | Velocity Loss Threshold

A significant condition \times time interaction was found for the number of repetitions [see Figure 5c; $F_{(4,92)} = 33.0$, $p = 0.001$, $\eta p^2 = 0.17$, ES = large]. The Bonferroni post-hoc test indicated an increase in the number of repetitions from “VL10” until “VL50” ($p < 0.05$), with a greater increase for Control when compared to High MF and Moderate MF conditions ($p < 0.05$). The Bonferroni post-hoc also revealed a greater increase in the number of repetitions for Moderate MF than High MF condition (VL30, VL40, and VL50) ($p < 0.05$).

3.3 | Rating of Perceived Exertion (RPE)

A significant condition \times time interaction was found for the RPE [see Figure 5d; $F_{(4,92)} = 29.80$, $p = 0.001$, $\eta p^2 = 0.06$, ES = moderate]. Post-hoc Bonferroni tests indicated progressive increases in RPE across the four iso-work intervals (25%, 50%, 75%, and 100% of total repetitions; $p < 0.05$). RPE was

significantly higher in the High MF condition when compared to both Moderate MF and Control experimental conditions at all time points ($p < 0.05$). Additionally, RPE was higher in the Moderate MF condition when compared to the Control condition across all intervals ($p < 0.05$), demonstrating a dose-response relationship between MF magnitude and RPE during the resistance exercise session.

4 | Discussion

This study aimed to analyze the acute effect of MF level from previous cognitive effort on a subsequent number of repetitions (volume) during an RE session. The main findings showed fewer repetitions for the High MF than Moderate MF and control experimental conditions. These findings corroborate the initial hypothesis.

The results of the present study regarding subjective, behavioral, and physiological manipulation checks are consistent with some previous findings that induced MF using the Stroop task (De Lima-Junior et al. 2024; Ferreira et al. 2023). For example, for effort and mental demand (Figure 2b), subjective MF (Figure 2a), and response time in the computerized Stroop word-color task (Figure 4a), our findings showed a detrimental effect of high and moderate MF compared to the control condition. Notably, a greater magnitude of deleterious effect was found for all the aforementioned manipulation checks in the high MF condition for the post-cognitive manipulation comparisons and the comparisons made during the cognitive effort (Figure 4a and 4b). In this context, it is reasonable to suggest that participants with greater subjective MF experienced an overload of the brain's sensory and attentional systems (Bigliassi 2021), as they had to exert more effort and mental demand for the Stroop task and, consequently, required more time to process the information and provide the correct response. This suggests greater impairment in inhibitory control, as observed in Figure 4a in the present study. Thus, it is evident that a higher level of MF leads to greater subjective and behavioral alterations.

Interestingly, regarding pupil diameter, our results revealed a significant reduction in mean pupil diameter after the cognitive manipulation, particularly in the High MF experimental condition (see Figure 4b). Furthermore, during the cognitive manipulation, it was found that the mean pupil diameter

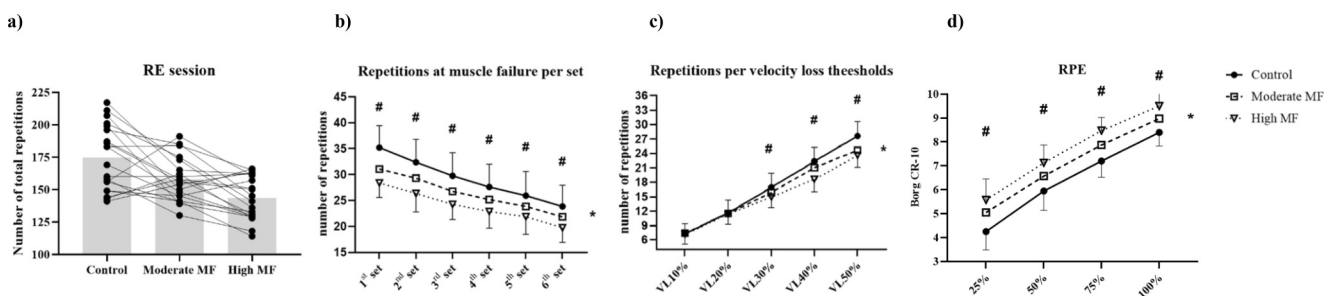


FIGURE 5 | Number of repetitions in half-back squat exercise and rating of perceived exertion according to experimental condition (high MF, moderate MF, and control) and sets (1st, 2nd, 3rd, 4th, 5th, and 6th) or velocity loss threshold (VL10, VL20, VL30, VL40, and VL50) or iso-work (25%, 50%, 75%, and 100%). * $p < 0.05$ a significant main time effect; # $p < 0.05$ statistical difference between experimental conditions.

decreased to a greater extent in the High MF condition when compared to the Moderate MF experimental condition (see Figure 3c). Indeed, these results corroborate previous scientific research that found a reduction in pupil diameter after the cognitive task (De Lima-Junior et al. 2024). Although stimulus-evoked pupil dilation during task execution reflects momentary increases in mental effort and cognitive processing demands, the sustained reduction in baseline (resting) pupil diameter observed post-task is consistent with previous research indicating that MF is associated with decreased tonic arousal, reduced task engagement, and diminished motivation (Bafna and Hansen 2021; Hopstaken et al. 2015). This pattern aligns with the psychobiological model of MF, which posits that prolonged cognitive demands deplete regulatory resources, leading to reduced motivational drive and increased perception of effort during subsequent tasks (Marcora et al. 2009).

Specifically regarding the findings related to velocity loss, no negative effect of MF was found for VL 20%. This result corroborates previous studies that monitored resistance training using the velocity-based approach (L. S. Fortes, Lima Júnior, et al. 2022). The authors indicated that mentally fatigued subjects did not experience performance impairment during RE when repetitions were stopped upon reaching a 20% velocity loss. This suggests that coaches and practitioners can train even under MF as long as repetitions are performed until a 20% velocity loss. On the other hand, regarding the results related to the total number of repetitions, repetitions to failure per set, and repetitions by velocity loss (i.e., VL30, VL40, and VL50%), a greater detrimental effect was observed in the high MF condition compared to the control and moderate MF conditions. Indeed, the negative effect of MF on RE is well-documented (Alix-Fages et al. 2023), particularly those performed to concentric failure, such as the protocol employed in this study. However, the magnitude of this effect may vary depending on the level of MF following cognitive effort. For example, although (De Lima-Junior et al. 2024) found a detrimental effect size (i.e., SMD) of MF on RE volume of -0.84 , (Queiros et al. 2021) and (Gantois et al. 2021) reported a negative effect of -0.77 and -0.33 , respectively. Interestingly, the mean difference between the experimental condition and the control condition for self-reported subjective MF after cognitive effort in the studies by (De Lima-Junior et al. 2024), (Queiros et al. 2021), and (Gantois et al. 2021) was -49 a.u., -23.3 a.u., and -12.9 a.u., respectively. Therefore, based on these previous studies, a possible relationship between subjective MF level and impaired RE volume is suggested, which could corroborate our findings.

To date, this is the first study to demonstrate that higher subjective MF levels result in greater impairment of physical performance, specifically during an RE session. These findings may be explained by an increase in RPE in the high MF condition compared to the control and moderate MF conditions during the RE session (Figure 5c), which may have led to earlier disengagement from the exercise (Giboin and Wolff 2019; Marcora et al. 2009; Martin et al. 2018). In this context, it is likely that the higher the subjective level of MF, the greater the impairment in executive functions, which could early increase the RPE during the RE session, considered a crucial factor in regulating task intensity and maintaining engagement (Bigliassi 2021; Hutchinson and Tenenbaum 2007).

The present study has strengths that may contribute to advancing the understanding of MF and RE performance. First, although recent scientific literature has individualized the level of MF immediately before physical exercise (L. d. S. Fortes et al. 2024), this study provides better insights. It is the first study to compare the effects of different levels of subjective MF on human performance. Additionally, subjective, behavioral, and physiological measures as manipulation checks before, during, and after cognitive manipulation are highlighted as important factors to be considered in MF studies (Proost et al. 2022). Therefore, measuring subjective MF immediately before a RE session can be a quick and valuable solution. By assessing the prior level of MF, coaches can monitor training based on velocity loss thresholds (20%). This approach allows for the controlled accumulation of residual fatigue while maintaining the necessary number of repetitions to promote optimal adaptations without interference from MF (L. D. S. Fortes et al. 2022).

On the other hand, despite its strengths, some limitations of this study should be considered. The first limitation concerns the participants and the exercise used. Although young, resistance-trained males were recruited, the exercise type was commonly used in previous studies. The findings cannot be generalized to females, untrained individuals, or other exercises. Another factor to consider is that subjective MF and/or pupil diameter, although collected immediately before the RE session, were not assessed during the RE session, which could explain a likely greater reduction in attentional focus and motivation in the High MF condition. Also, although our results have relevant implications for coaches and practitioners, the findings are based on acute interventions and outcomes. Therefore, their repeated long-term effects remain unknown. Future studies should investigate repeated RE sessions under MF in chronic outcomes such as muscle hypertrophy. Finally, and perhaps most importantly, an important limitation of the present study concerns the control condition design. Although participants in the High MF and Moderate MF experimental conditions reached standardized, individualized levels of subjective MF (80 and 40 mm on the VAS, respectively), the control condition did not impose a specific MF threshold. Consequently, baseline MF levels in the control condition were not standardized across participants, which may have introduced variability in the interpretation of results for this condition. Previous research has demonstrated considerable inter-individual variability in baseline MF levels, even in resting or “control” states (Schampheleer et al. 2025). Future studies should consider establishing a standardized baseline MF criterion (e.g., ≤ 10 mm on the VAS) for control conditions to minimize this source of variance and enhance the precision of between-condition comparisons.

5 | Conclusion

The results of the present study suggest that the higher the level of subjective mental fatigue after cognitive effort, the greater the effect size on resistance exercise performance. From a practical standpoint, considering that resistance training practitioners engage daily in cognitive tasks, subjectively monitoring levels of mental fatigue becomes essential to enable better training adaptations. Furthermore, considering that no detrimental effect

of mental fatigue was found for a 20% velocity loss in resistance exercise, coaches may adopt approaches such as VBT to train mentally fatigued individuals.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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