Effects of Resistance Training Volume on Consolidation of Motor Learning

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STUDENTERRAPPORT

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Effects of Resistance Training Volume on Consolidation of Motor Learning

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ABSTRACT

OBJECTIVE: The aim of this study was to investigate the effects of resistance training (RT) volume on consolidation of motor learning.

METHODS: Thirty-one participants (25 ± 2.21 years) were randomly assigned to an RT-group that performed one set (1-SET; $n = 10$) or three sets (3-SET; $n = 11$) in all exercises or control (CON; $n = 10$) that rested during RT-session. All groups performed a visuomotor accuracy tracking task (VAT), which consisted of a baseline test and acquisition phase composed of three blocks: $Block_1$ (B_1), $Block_2$ (B_2) and $Block_3$ (B_3). 1-SET and 3-SET performed RT after B_3 while CON rested for 25 minutes. Two retention tests were conducted. 1-SET and 3-SET performed first retention (R_0) after RT. CON performed R_0 after 25 minutes of rest. Second retention (R_7) was completed seven days after R_0. Furthermore, a plateau test was executed after R_7.

RESULTS: All groups improved from baseline to B_3 ($p < 0.01$). Furthermore, there was no significant GROUPxTIME interaction from B_3 to R_0 and R_7 ($p = 0.90$). Additionally, no differences were found in VAT-scores between groups from baseline to B_3 ($p = 0.34$) and B_3 to R_0 and R_7 ($p = 0.86$). No significant changes in VAT-scores were found from B_3 to R_0 and R_7 ($p = 0.48$).

CONCLUSION: VAT increased motor skill performance throughout the online acquisition phase while RT, regardless of volume, did not lead to additional offline improvements, indicating no beneficial effects on consolidation of motor skill at R_0 and R_7.

KEYWORDS:
strength training; motor memory; consolidation; neuroplasticity; BDNF; lactate

1 | INTRODUCTION

Motor learning is defined as a dual-component process: I. skill acquisition and II. skill maintenance[1]. Skill acquisition refers to the process in which an individual acquires the ability to identify an appropriate movement goal given a particular task context, select the correct action given a sensory stimulus, and execute that action with accuracy and precision[1]. In contrast, skill maintenance refers to the ability to maintain performance levels of existing skills under changing conditions[1] . An example of motor learning could be the acquisition of a new motor skill such as walking during infancy[2]. Motor skills play a fundamental role in numerous daily activities[3], which highlights the importance of understanding the mechanisms behind motor learning in order to improve them effectively. The mechanism that facilitates motor learning is neuroplasticity, which refers to the nervous system's ability to reorganize and change its structure and function[4,5]. The structural reorganization occurs for example when a new motor skill is being learned (online learning) and can also happen between sessions (offline learning)[5]. The latter describes the consolidation process, wherein improvements in skill occur after the end of practice and the fragile memory turns into a stable and robust memory[5]. The process of consolidation may be subject to various influences, including practice and sleep, consequently exerting an effect on the acquisition of motor skills[5,6]. These processes can therefore be seen as necessary since they play an important role with regards to acquiring a new motor skill.

Studies have shown that it is possible to further improve motor skill learning with the addition of exercise. A review investigated the effects of aerobic exercise on motor skill learning, and results suggest that it can improve motor learning[7]. However, the timing of the aerobic exercise matters, since aerobic exercise prior to skill practice reinforces short-term, non-sleep consolidation processes, while exercise after skill practice can improve long term sleep-dependent consolidation[7]. A potential explanation for increased motor memory consolidation could be the increased brain derived neurotrophic factor (BDNF) expression following the physical activity session[8]. BDNF is essential for neuronal survival and growth, and it also participates in neuronal plasticity, which is essential for learning and memory[8].

The evidence is not clear for why BDNF is increased following exercise, and the mechanisms are not fully understood[9]. It has been proposed that a key mechanism that might trigger the production of BDNF is lactate, since higher lactate concentrations following high intensity interval training led to greater BDNF expression compared to moderate intensity training[10]. The reason why lactate could be a subject to explaining increased BDNF expression is due to the fact that it can pass the blood-brain barrier[9]. Hereby lactate will exert its neurotrophic and metabolic effects on neurons such as entering the neuron cell body and increase intracellular nicotinamide adenine dinucleotide (NADH), resulting in increased calcium levels and BDNF gene expression[9]. The released BDNF can thereby enhance neuroplasticity through different mechanisms such as neurogenesis and synaptogenesis[9].

It is therefore evident that physical exercise can improve motor skill learning, but few studies have investigated if exercise type plays a role. One study investigated this topic with hockey, circuit training, and resistance training (RT)[11]. In the study, the exercise was scheduled to be performed immediately following motor skill training, which theoretically primes the phase of memory consolidation[7]. The study found that hockey, circuit training, and RT improved the participants' one-day retention test score in a visuomotor accuracy tracking task (VAT) after physical exercise[11], supporting the notion that different exercise modalities can enhance motor skill learning. This might be due to the elevated blood lactate (BLAC) levels post exercise, which leads to increased BDNF production[11]. Since multiple sets of RT leads to higher BLAC levels[12], and thereby increased BDNF, it could potentially lead to increased motor skill performance. The study, which examined different exercise modalities' effects on motor skill learning and BLAC levels, did not examine the relationship between volume in each exercise modality and its effect on motor skill performance[11,12]. Therefore, the aim of the present study was to further analyze the effects of RT on motor learning in terms of how RT volume affects consolidation of motor learning. We hypothesized that: **I.** performance in the motor skill VAT would improve throughout the motor acquisition phase, and **II.** it was hypothesized that the one set (1-SET) group and three sets (3-SET) group would retain motor performance more effectively compared to control group (CON) in a dose-response relationship.

2 | MATERIALS AND METHODS

2.1 | Participants

In the present study, 33 individuals were recruited, of whom 31 completed the intervention (23 men and 8 women). Two participants missed a session and were therefore excluded from the study. All participants signed a written consent form prior to the intervention. Descriptive data of the participants, sorted in groups, are presented in (Table 1).

Individuals had to be ≥18 years to participate in the study. Furthermore, individuals were not allowed to participate, if they: had injuries and/or pain preventing them from performing the RT exercises, were either current or past users of substances listed by Anti-Doping Denmark, had a chronic illness/psychiatric disorder or were professional musicians.

TABLE 1 Descriptive data of the male and female participants in each group.

Group	**CON (n = 10)**	**1-SET (n = 10)**	**3-SET (n = 11)**
Age (years)	25 ± 2.21	26 ± 1.90	26 ± 2.32
Height (centimeter)	181.0 ± 8.36	178.5 ± 11.74	178.5 ± 8.05
Body weight (kilograms)	81.48 ± 12.10	91.43 ± 22.35	78.99 ± 11.26
RT experience (1-4)	3 ± 0.80	3 ± 0.50	3 ± 0.64
Sex (male; female)	8; 2	8; 2	7; 4

2.2 | Experimental procedure

The intervention consisting of three sessions (session 1, session 2 and session 3) lasted four weeks, as depicted in (Figure 1). The experimental procedure was inspired by a pilot study that was conducted prior to the main experiment. During session 1, the participants had to fill out two questionnaires: one regarding RT experience and one regarding anthropometric data. This data was used for the stratification process later. The participants 12RM were thereafter tested in the following RT exercises: leg press, seated cable flyes and machine-assisted pull-ups.

Session 2 was extended to two weeks since its duration couldn't be accommodated within one week's time. In session 2, the participants first completed a questionnaire regarding sleep quality for the previous night, followed by a BLAC measurement from a fingertip of their non-dominant hand. They were then introduced to the motor skill: VAT. In the VAT, a baseline test was first performed, followed by three acquisition blocks: $Block_1$ (B_1), $Block_2$ (B_2) and $Block_3$ (B_3). After completion of B_3, the participants were then subjected to one of the following procedures: **I.** one set or **II.** three sets to failure with a load corresponding to 12RM in the aforementioned exercises or **III.** control (25 minutes rest). In this regard the participants were stratified and randomized into one of the three interventions prior to session 2, based on the stratification parameters: Sex and RT experience. A BLAC measurement was carried out two minutes after completing the RT intervention[12]. Session 2 ended with participants performing their first retention test (R_0), which was identical to the baseline test.

The participants were then instructed to attend session 3 seven days post their individual session 2. Three participants were unable to complete session 3 seven days post session 2, resulting in six or eight days of retention. Session 3 began with participants filling out the questionnaire regarding sleep quality for the previous night. They performed thereafter a second retention test (R_7), which was identical with the two tests in session 2. Lastly, the session ended with the participants performing a plateau test.

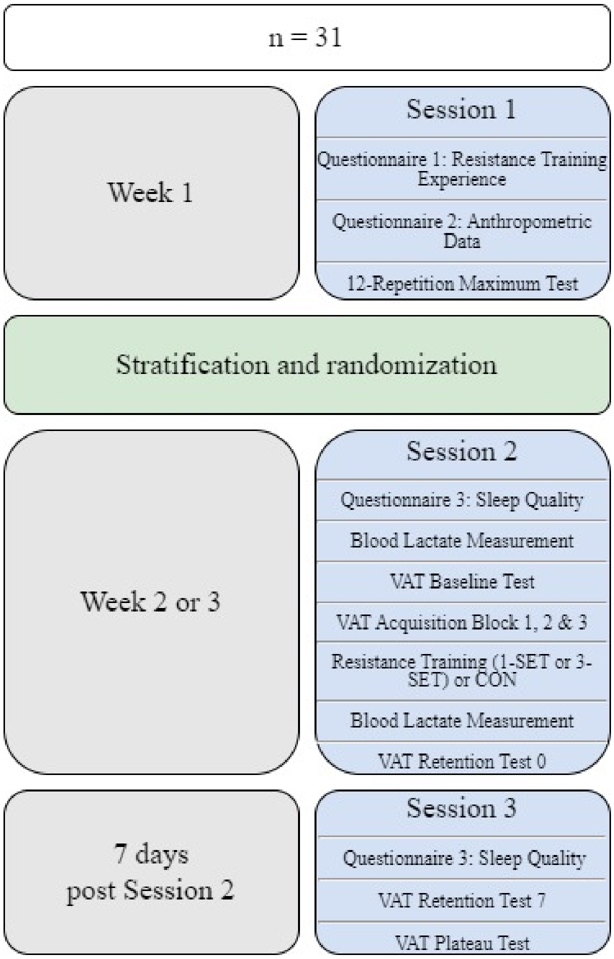

Fig. 1 Study design. In this study, a total of 31 participants engaged in and completed the experimental protocol. In the first week, the participants had their first session (session 1), wherein they filled out two questionnaires: One regarding resistance training experience and one regarding anthropometric data. Additionally, a 12-repetition maximum test was conducted. Participants were then stratified and randomized, based on these data, into one of the following groups: 1-SET, 3-SET or CON. The second session (session 2) began in the second or third week. Two weeks were allocated for session 2, since difficulties among participants arose during planning their arrival, which would lead to overlapping visits among them if only one week was allocated. The reason for this was session 2 was time consuming. Third session (session 3) began seven days post their individual session 2.

2.2.1 | Visuomotor accuracy tracking task

This study tested fine motor skill acquisition and retention by a VAT (FollowMe 1.12, Knud Larsen, Aalborg University, Denmark). A handheld dynamometer was used to run the VAT (The Ultium Hand Grip Dynamometer SmartLead, NORAXON, Scottsdale, Arizona, USA). Before performing the VAT, the participants were seated on a chair while holding the dynamometer in their dominant hand. Their dominant forearm was positioned on the table. A maximal voluntary contraction (MVC) test of the finger flexors was then performed prior to session 2 and session 3. The participants were given three trials in the MVC-test to reach their peak force. A force equal to 10% of their peak force was used as summit point in each of the six different patterns. The MVC-trials lasted for three seconds with one minute rest in between trials. Afterwards, the participants were instructed to follow a pattern on a computer screen using the handheld dynamometer. There were six different patterns to follow, each lasting five seconds. An example of a pattern participants had to follow is depicted in (Figure 2). To follow the patterns participants had to either squeeze or release the handle representing a rise or fall of the slope, respectively. Prior to baseline test and R_7, participants were instructed to squeeze and release the handle to familiarize them with the task.

The patterns were performed in blocks of either 10 or 20 trials and emerged in randomized sequences. The baseline and retention tests encompassed 10 trials, whereas the acquisition blocks and the plateau test encompassed 20 trials. At the beginning of each pattern, the participants were presented with a countdown on the computer screen displaying: 3, 2, 1, GO! Each pattern had a preparation phase, consisting of a one second horizontal line (0-1 second), followed by the actual performance phase of four seconds (1-5 seconds). Only data from the performance phase was extracted and used in the statistical analysis. Participants were given one minute rest between blocks. To measure motor performance, the Root Mean Square Error (RMSE) was used. RMSE was calculated in MATLAB (Version: 23.2.0.2515942 (R2023b) Update 7). A low score indicated high skill level and vice versa.

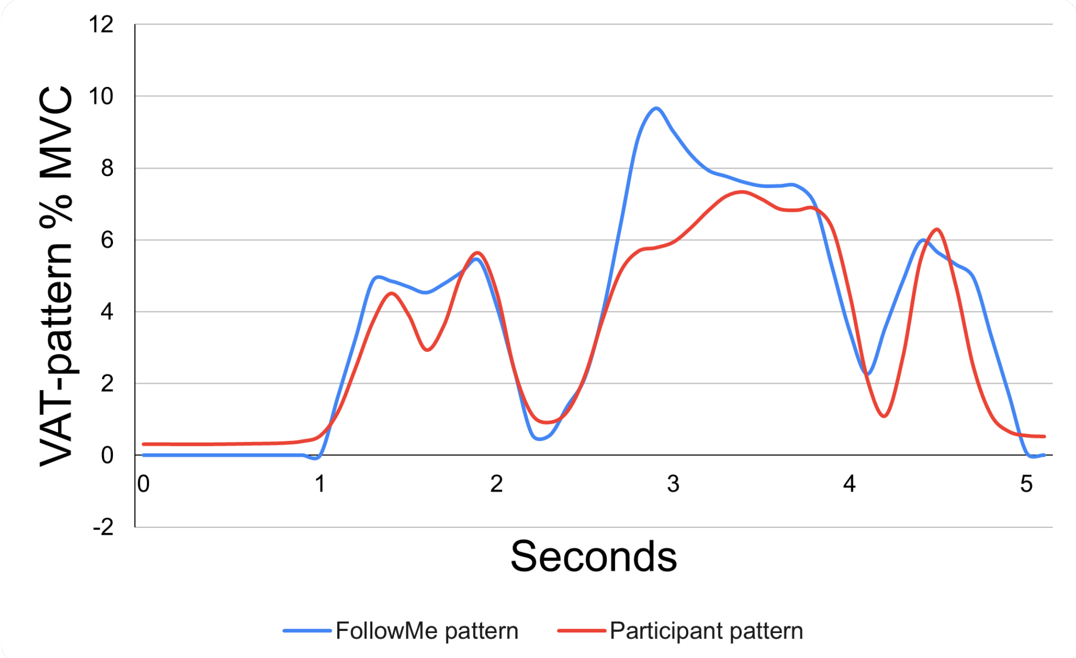

Fig. 2 Visuomotor accuracy tracking task. The blue graph represents an example of the pattern participants had to follow during the visuomotor accuracy tracking task (VAT). Squeezing the handle led to an increase in slope while a release led to a decrease. The red graph illustrates a sample participant's performance in replicating the computer-generated pattern.

2.2.2 | 12 Repetition Maximum Test

During session 1, the participants completed a 12RM-test. The purpose of the 12RM-test was to determine their individual load, which they would use during the RT in session 2. Before performing the exercises, the participants were informed to complete every repetition with a full range of motion (ROM) and were given technical instructions for each exercise in order to standardize the difficulty of exercises for the participants.

Prior to the 12RM-test, the participants warmed up to maximize performance [13] and reduce the risk of injury [14]. The warm-up consisted of a minimum of three sets of 12 repetitions in each of the three exercises, in which the load was progressively added until they reached an appropriate weight for a 12RM-attempt. Adjustments of the load were specific to each participant and was based on their repetitions in reserve (RIR). An agreement from both parties had to be reached, with regards to how much load should be added, before continuing onto the next warm-up set. Participants were asked how many RIR they had left upon completing a warm-up set, and based on the RIR, a specific rest interval was given to the participant. The RIR number dictated the duration of the pause as following: RIR 7 or higher = one minute of rest, RIR 4-6 = two minutes of rest and RIR 3 or less = three minutes of rest. If a participant reached RIR 0 at 10-11 repetitions or reported 1 or 2 RIR after a set of 12 repetitions, an estimated 12RM was calculated. The following equation $y = 102.54e^{-0.019x}$, developed on data from [15], was used for the calculation of estimated 12RM. In this equation, x represents the number of repetitions and y represents percentage of 1RM.

2.2.3 | Resistance training intervention

Participants in the CON were instructed to rest for 25 minutes outside the experiment zone after completing the VAT. CON's rest time was based on 1-SET's RT workout duration, which lasted 25 minutes. The duration of the RT session in 3-SET was 50 minutes.

The RT-groups, 1-SET and 3-SET, first performed a warm-up previous to the RT exercises, following the same protocol as previously mentioned in 2.2.2. After completing the warm-up, the RT-groups performed one set and three sets to failure with a load equal to their 12RM in the exercises, respectively. 3-SET had three minutes of rest between their working sets. Same criteria for valid repetitions were set as mentioned in 2.2.2, to standardize the repetitions in the exercises.

2.2.4 | Blood lactate measurements

BLAC measurements were collected with the finger prick method (Accutrend® Plus System, Roche Diagnostics, Switzerland). BLAC was measured since it could be used as an indirect biomarker for BDNF production, since the correlation between them are high, especially in this type of RT program [16]. 1-SET and 3-SET received a BLAC measurement in session 2 pre and post RT, while CON received their pre and post 25 minutes of rest.

All participants had their non-dominant hand heated for two minutes before their first BLAC measurement. CON received additional heating after 25 minutes of rest. A sample was taken immediately after the heating. The heating increased the arterial blood flow to the fingers, which ensured ample blood supply when extracting it from the fingertip. These considerations were based on a study and experience gained from the pilot study [17]. BLAC measurements were performed two minutes after RT, since an RT study found BLAC concentrations were at its peak at this point [12].

2.2.5 | Questionnaires

Four questionnaires were used in this study. The first questionnaire collected data on participants RT experience. This was achieved through a scoring system, that was inspired by a study [18]. The parameters this study used from the original study were: current continuous training period, period without training and previous training experience. Participants were given a score for each parameter and the mean (rounded to nearest integer) of the three parameters was calculated. The mean value ranged from 1 to 4 points represented by the classifications: **1.** Beginner **2.** Intermediate **3.** Advanced or **4.** Highly advanced. The second questionnaire was dedicated to gather information on anthropometric data (sex, age, height, and body weight). Moreover, a question regarding consent to BLAC measurement (Yes/No) was added. Furthermore, a third questionnaire was utilized to investigate if sleep duration differed between groups. Finally, participants were asked to answer a fourth questionnaire after the main experiment, which gathered information on video gaming hours per week.

2.3 | Stratification and randomization

Descriptive data of the participants was used to characterize the sample and to stratify on behalf of sex and RT experience, which has previously shown to impact visuomotor skills. [19,20]. In this study, the stratification process was inspired by a review [21]. The stratification parameters, sex, and RT experience were used to create a matrix, in which sex (male or female) covered the horizontal sequences, while RT experience **1.** Beginner **2.** Intermediate **3.** Advanced or **4.** Highly advanced covered the vertical sequences. The participants were then assigned to the blocks.

Randomization was utilized in this study to randomly assign participants the number 1, 2 or 3, which represented: **1.** 1-SET, **2.** 3-SET or **3.** CON. This was performed for every block horizontally. GraphPad QuickCalcs Web site: https://www.graphpad.com/quickcalcs/randomize1/ (accessed Marts 2024) was used to execute this. This made it possible to extract the given outcomes equally within a block, if the block's number of subjects exceeded the number of outcomes.

2.4 | Statistical analysis

Shapiro-Wilk tests were employed to assess the normal distribution of measured parameters, including $Baseline_{\text{VAT-score}}$, $B_{1\ \text{VAT-score}}$, $B_{2\ \text{VAT-score}}$, $B_{3\ \text{VAT-score}}$, $R_{0\ \text{VAT-score}}$, $R_{7\ \text{VAT-score}}$, $Plateau_{\text{VAT-score}}$, number of hours slept and BLAC concentrations, to determine if a parametric test, or a nonparametric test should be applied. A significance level of $\alpha = 0.05$ was applied. Normal distribution was assumed when $p > 0.05$.

Due to most of the data being normally distributed and the robustness of the test against deviations from normal distribution, multiple two-way mixed model ANOVAs were therefore applied. Three separate two-way mixed model ANOVA tests were conducted on the VAT-score with the same between-subject group factor (1-SET, 3-SET and CON) but different within-subject factors. The first test included the time points $Baseline$, B_1, B_2 and B_3 to assess online acquisition. The second test encompassed $Block_3$, R_0 and R_7 to assess retention and consolidation, and the third focused on R_7 and $Plateau$ to assess whether participants had reached a performance plateau. To correctly execute a two-way mixed model ANOVA, seven assumptions must be met[22]. One of these was violated in 1-SET under the within-subject factor R_7, where an outlier with a studentized residual value of 3.68 was identified. As this participant was not an outlier in other tests, it was therefore decided to include this participant. In instances where the assumption of sphericity was violated, the Greenhouse-Geisser correction was employed. This adjustment was necessary for the within-subject factors: ($Baseline$-B_1-B_2-B_3) and (B_3-R_0-R_7). Apart from this, the VAT-score met all seven assumptions. Additionally, a post hoc test with Bonferroni correction was employed to identify the location of potential interactions or main effects.

Furthermore, the analysis was also extended to include the number of hours slept and BLAC concentration, with the variables time pre and post RT for BLAC concentration, and day session 2 and 3 for the number of hours slept. 'Number of hours slept' displayed heterogeneous variance as assessed by Levene's test ($p < 0.05$). The BLAC concentration did not meet the requirements for homogeneity of variances and covariances according to Box's test ($p < 0.001$). Despite these limitations, two-way mixed model ANOVAs were still applied to these tests.

Finally, a one-way ANOVA was conducted to examine potential differences between groups in the mean video gaming hours per week. In cases where the assumption of homogeneity of variances was violated, a Welch ANOVA was applied. If significant differences between groups were identified, a two-way mixed model ANOVA was subsequently performed. The between-subjects factor was defined by average video gaming hours per week (0 hours, > 0 and ≤ 10 hours, and > 10 hours per week), while the within-subjects factor was defined by time points ($Baseline$, B_1, B_2 and B_3). The Greenhouse-Geisser was employed since the assumption of sphericity was violated.

A significance level of 0.05 was applied for the ANOVA tests. Data were reported as mean ± SD unless otherwise stated. All statistical analyses were conducted in SPSS (IBM SPSS Statistics 29.0.0.0).

3 | RESULTS

Shapiro-Wilk tests were carried out, and the results indicated that the majority of the data were normally distributed. VAT-scores were normally distributed ($p > 0.05$), except for 1-SETxR_7 and 1-SETx$Plateau$ ($p < 0.05$). A total of 12 GROUPxTIME combinations (GTC) emerged. When calculating the total possible combinations in BLAC, which was three groups on two separate time points, it led to six GTC. The same applied for the number of hours slept, which led to another six GTC, thereby totaling 12 GTC. The factor BLAC was normally distributed for four out of six GTC ($p > 0.05$), whereas 1-SETxBLAC pre-RT and CONxBLAC post-RT were not normally distributed ($p < 0.05$). Additionally, the factor: Numbers of hours slept, was normally distributed for five out of six GTC ($p > 0.05$), whereas number of hours slept for 3-SETxSession2 was not normally distributed ($p < 0.05$). The factor: average video gaming hours per week was normally distributed for 1-SET ($p > 0.05$) but not for CON and 3-SET ($p < 0.05$). Lastly, all groups (0 hours, > 0 and ≤ 10 hours, and > 10 hours per week) in VAT-scores were normally distributed ($p > 0.05$)

3.1 | Acquisition

All groups improved mean VAT-scores significantly at all time points from $Baseline$ to B_3 in acquisition, as confirmed by a main effect of time ($F_{(1.97, 55.14)} = 154.68$; $p < 0.01$; $\eta_p^2 = 0.85$; $\epsilon = 0.66$). Absolute change (AC) and relative change (RC) scores in mean total from baseline to B_3 across all groups were 0.71%MVC and 33.39%, respectively. No significant GROUPxTIME interaction was found on VAT-score ($F_{(3.94, 55.14)} = 0.36$; $p = 0.83$; $\eta_p^2 = 0.03$; $\epsilon = 0.66$). Furthermore, there was no significant main effect of group ($F_{(2, 28)} = 1.12$; $p = 0.34$; $\eta_p^2 = 0.07$), which demonstrates that there were no differences in skill level among groups throughout the acquisition phase ($Baseline$, B_1, B_2 and B_3). Mean scores and ± SD are presented in Figure 3.

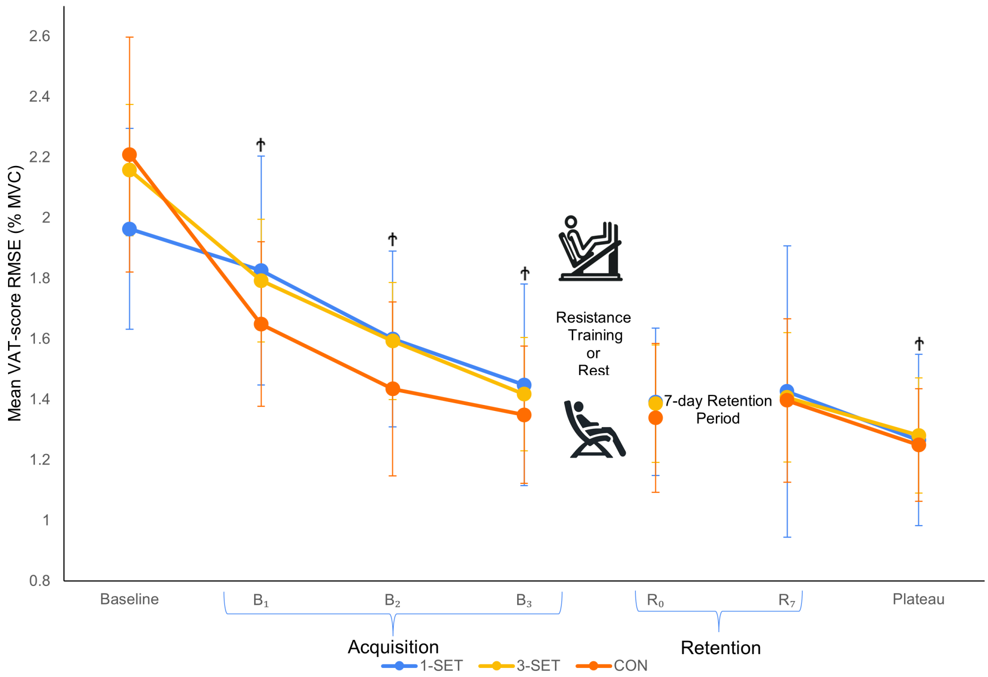

Fig. 3 VAT-scores across time points. Mean visuomotor accuracy tracking task scores (VAT-scores) ± SD across different timepoints during the acquisition phase (baseline to $Block_3$ (B_3)), the retention tests (R_0 to R_7) and the plateau test. A decrease in the mean VAT-score signifies an improvement in skill level. ‡ indicates a significant improvement relative to the previous time point in the VAT-score.

3.2 | Retention and plateau tests

There was no significant interaction between GROUPxTIME on VAT-score ($F_{(2.97, 41.59)} = 0.20$; $p = 0.90$; $\eta_p^2 = 0.01$; $\epsilon = 0.74$). All groups showcased no significant improvement in VAT-score at all time points from B_3 to R_7 in the skill retention tests ($F_{(1.49, 41.59)} = 0.67$; $p = 0.48$; $\eta_p^2 = 0.02$; $\epsilon = 0.74$). AC and RC-scores in mean total from B_3 to R_0 across all groups were 0.03%MVC and 2.33%, and from B_3 to R_7 it was < 0.01%MVC and 0.31%, respectively. Additionally, there was no significant main effect of group ($F_{(2, 28)} = 0.15$; $p = 0.86$; $\eta_p^2 = 0.01$), which demonstrates no differences in skill level among groups across timepoints in retention (B_3, R_0 and R_7). ΔMean scores and ± SD are presented in Figure 4.

All groups improved VAT-scores from R_7 to plateau test in skill level, indicated by a main effect of time, ($F_{(1, 28)} = 23.57$; $p < 0.01$; $\eta_p^2 = 0.46$). For all groups, AC and RC-scores in mean total from R_7 to $Plateau$ across all groups were 0.14%MVC and 10.01%, respectively. No significant interaction GROUPxTIME was found on VAT-score ($F_{(2, 28)} = 0.12$; $p = 0.90$; $\eta_p^2 < 0.01$). Moreover, there was no significant main effect of group ($F_{(2, 28)} = 0.12$; $p = 0.89$; $\eta_p^2 = 0.85$), which demonstrates that there were no differences between groups in skill level and all groups did not reach a plateau in skill level.

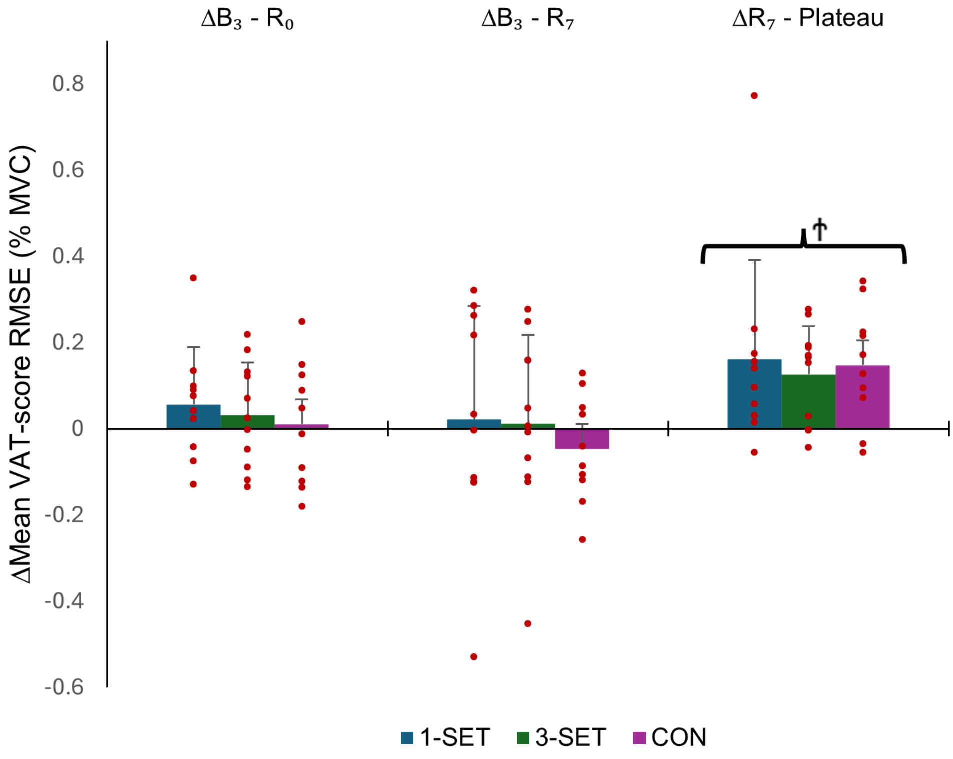

Fig. 4 ΔMean VAT-scores. Changes in mean visuomotor accuracy tracking task scores (VAT-scores) ± SD from *Block 3* (B_3) to first retention (R_0) and second retention (R_7) for all groups (1-SET, 3-SET and CON). A positive ΔMean VAT-score indicates an improvement in skill level. ‡ indicates a significant improvement in VAT-scores within groups.

3.3 | Blood lactate

A GROUPxTIME interaction was found between BLAC pre and post RT ($F_{(2, 28)} = 21.99$; $p < 0.01$; $\eta_p^2 = 0.61$). A simple main effects analysis showed a significant increase in BLAC from pre to post RT for 1-SET (7.23 [95% CI: 4.54, 9.92] mmol/L; $p < 0.01$), which corresponded to a RC of 386.63%. Furthermore, a significant increase was also observed in 3-SET (7.27 [95% CI: 5.24, 9.31] mmol/L; $p < 0.01$), which corresponded to a RC of 320.35%. There was no significant change in CON (2.40 [95% CI: -1.40, 0.92] mmol/L; $p = 0.65$), corresponding to a slight decreased RC of 11.76%. Additionally, there were no differences between all groups in BLAC at pre RT ($F_{(2, 28)} = 0.67$; $p = 0.53$; $\eta_p^2 = 0.05$). This indicates that all groups had the same preconditions for BLAC. Furthermore, 1-SET (7.30 [95% CI: 4.42, 10.18] mmol/L; $p < 0.01$), who experienced an increase in RC corresponding to 405.56%, and 3-SET (7.84 [95% CI: 5.02, 10.65] mmol/L; $p < 0.01$), who experienced an increase in RC corresponding to 435.36% compared to CON, had significantly greater BLAC concentrations compared to CON at post RT. No significant differences in BLAC (-0.54 [95% CI: -2.79, 3.35] mmol/L; $p = 0.89$) were found between 1-SET and 3-SET at post RT. Mean BLAC measurements are illustrated in Figure 5.

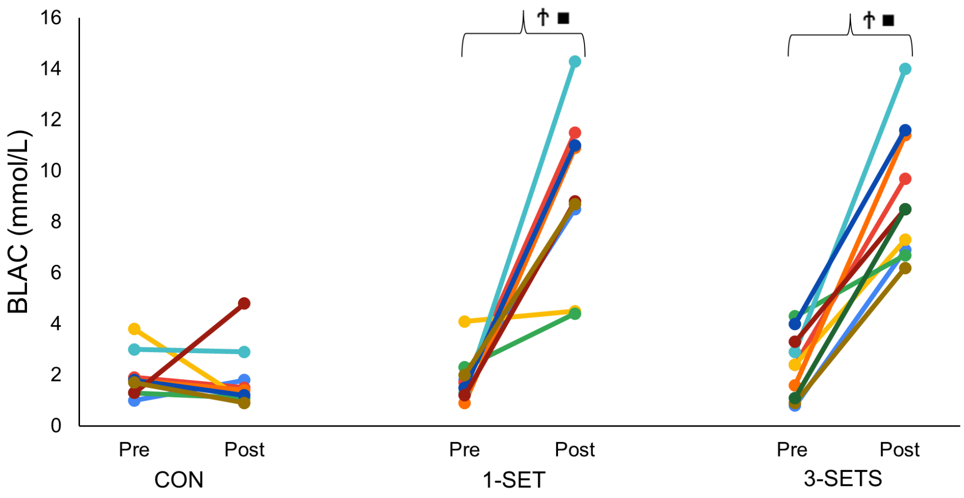

Fig. 5 Blood lactate measurements. Blood lactate (BLAC) levels (mmol/L) measured pre and post resistance training for all groups (CON, 1-SET and 3-SET). Individual participant data are displayed, with each line representing changes in BLAC levels for a single participant. ‡ indicates significant changes from pre to post within groups. ■ denotes significant differences in post RT BLAC levels between groups.

3.4 | Number of hours slept

There were no significant differences in the number of hours slept between session 2 and session 3 across groups ($F_{(2, 28)} = 0.074$; $p = 0.79$; $\eta_p^2 < 0.01$). AC and RC-scores in mean total from session 2 to session 3 were 0.03 and 1.06%. No significant GROUPxTIME interaction was found ($F_{(2, 28)} = 0.20$; $p = 0.82$; $\eta_p^2 = 0.01$). Furthermore, no differences between the number of hours slept was found between groups across sessions ($F_{(2, 28)} = 2.7$; $p = 0.08$; $\eta_p^2 = 0.16$). This indicates that all groups had the same preconditions for sleep before the acquisition and retention tests.

3.5 | Mean video gaming hours per week

Homogeneity of variances was violated, as assessed by Levene's test of homogeneity of variance ($p = 0.02$). The mean gaming hours per week was significantly different between groups (Welch's $F_{(2, 16)} = 4.02$; $p = 0.04$). Mean video gaming hours per week for 3-SET, CON and 1-SET were as following (3.14 ± 4.60 hours), (8.35 ± 9.61 hours) and (10.90 ± 7.96 hours), respectively. Games-Howell post hoc analysis revealed that the increase from 3-SET to 1-SET in average video gaming hours per week, (7.76 [95% CI: 0.24, 15.28] hours) was significant ($p = 0.04$). Furthermore, no significant differences were found between CON and 3-SET (5.21 [95% CI: -3.64, 14.07] hours; $p = 0.30$) and between 1-SET and CON (2.55 [95% CI: -5.85, 10.95] hours; $p = 0.736$) All groups (0 hours, > 0 and ≤ 10 hours, and > 10 hours per week) showcased significant increasing in VAT-scores in all time points, as confirmed by the main effect of time ($F_{(1.99, 55.60)} = 154.88$; $p < 0.01$; $\eta_p^2 = 0.85$, $\epsilon = 0.66$). No significant GROUPxTIME interaction was found on VAT-score ($F_{(3.97, 55.60)} = 0.70$; $p = 0.60$; $\eta_p^2 = 0.03$; $\epsilon = 0.66$). Furthermore, there was no significant main effect of group ($F_{(2, 28)} = 3.06$; $p = 0.06$; $\eta_p^2 = 0.18$), which indicates that there were no differences in skill level between groups.

4 | DISCUSSION

The aim of this study was to investigate the effects of RT volume on consolidation of motor learning. Our first hypothesis was: Performance in the motor skill VAT would improve throughout the motor acquisition phase. The findings in this study did support this hypothesis, since VAT-scores improved significantly from baseline to B_3 for all groups, which aligns with numerous other studies[23–25].

There are multiple mechanisms that could explain this observation. First, participants gained experience by performing multiple trials, leading to motor acquisition. This aligns with the fact that use-dependent motor learning has proven to be effective at promoting changes in motor behavior[26]. The orienting network could thereby filter visual information more effectively and transmit it to the executive control network, which could then accomplish better decision-making events that would affect the VAT-score positively[27]. Another factor could be the reorganization in the participant's brain. Participants performed the VAT, hence online learning occurred, which could explain their VAT-score improvement from baseline to B_3[28]. Another important contributing factor could be the establishment of retrograde flow, which ensures cell survival and axon growth by transporting the neurotrophins from axon to cell body[29]. Additionally, this observation could also be explained by neuroplastic events, such as increases in the central nervous system's gray matter[30]. If the increases in gray matter occurred in areas that are important for visual information processing, such as the intraparietal sulcus and midtemporal area of the visual cortex, it could then have a positive effect on the VAT-score[31].

Furthermore, we hypothesized that the 1-SET and 3-SET groups would retain motor performance more effectively compared to CON in a dose-response relationship. The outcome in this study did not support this hypothesis, since no significant differences were found between groups during the retention tests.

However, the participants VAT-score did not worsen to baseline levels, which means the consolidation process, wherein the fragile memory turns more robust, has occurred, and the participants were able to maintain the skill level at R_0 and R_7[5]. This would indicate that long term potentiation, which is modulated by neurotrophic factors, occurred, leading to increase of strength in link between active neurons[32]. This could explain why the performance was sustained after seven days of retention. Though, it is noteworthy why they did not improve at R_0. A reasonable explanation could be that they did not further practice VAT in this interval, or the effects of fast learning were coming to an end[28]. It can therefore be suggested that the participants were coming closer to the end of their performance curve, and further gains would require, most likely, additional time and practice, which the plateau test accounted for. All groups improved their VAT-score at plateau test, indicating further improvements due to motor training were still possible.

Although the participants' score did not return to baseline levels at retention tests, it did not improve either. Therefore, the outcome opens the discussion of why RT did not improve motor performance further than no RT, even though the literature supports the notion that RT can lead to increased BDNF production, which is essential for motor learning, and better retention compared to a control group[8,11]. It is possible that the RT session led to undesired outcomes, such as lactate binding to HCAR1, rather than entering the neuron cells and exerts its effect to produce BDNF[9]. However, this would be an unexpected scenario, since RT has been documented to be the most efficient at producing BDNF[33]. Though it is documented that higher lactate concentration may favor binding to HCAR1, leading to various downstream effects, such as modulation of neuronal excitability and metabolic responses, while lower lactate concentrations may favor uptake into neurons through monocarboxylate transporters[34]. Evidence suggests that neurons allow a maximal lactate influx of 1 mmol/L into the cell but blocks lactate entry at 3 and 10 mmol/L due to protection of lactate-induced acidosis[35]. Additionally, when neurons are in a high energy state with ample of ATP and glucose available, the propensity for lactate to be used in energy metabolism decreases, favoring its binding to HCAR1 instead[36,37]. This is relevant, since participants were given three minutes of rest in between working sets, which is an adequate amount of rest period to reestablish high energy state[38]. This could potentially lead to decrease in neuronal calcium spiking frequency, and thereby inhibit neuronal activity[34]. This is important to understand because the release of BDNF, triggered by activities such as repetitive action potentials, from Golgi-derived vesicles in the regulated secretion pathway, depends on sustained increases in intracellular calcium levels[8,9]. With regards to high energy states, the presence of astrocytes, which transfers lactate to neurons, could also play a role[39]. In essence, astrocytes functions as energy reservoirs for neurons, and they are mobilized when required[36]. This process is critical to mediate synaptic plasticity and memory consolidation[39].

Therefore, it is possible that this observation is caused by the study design. As previously mentioned, the long rest intervals might have led to neurons in high energy state, wherein affinity for lactate binding to HCAR1 rose[36,37]. Lactate would therefore not enter the neuron and aid in BDNF production, which is essential for neuroplasticity[9].

4.1 | Study limitations

A few limitations were detected throughout the present study. First, it is worth noting that some of the participants had previous experience of using the VAT. This could potentially have influenced their VAT-score, thereby increasing the variability in the outcomes, and led to these participants reaching plateau even though no between groups differences for VAT-score were observed throughout the study. However, since the extent of their experience and the number of participants involved were unknown, the influence of this factor remains unclear.

This study also included participants with prior gaming experience. The inclusion of experienced gamers (individuals playing video games regularly) was necessary to ensure a sufficient sample size for this research because the majority in our social network had experience with gaming. Research has shown that gamers possess greater fine motor skills[40], and faster and more accurate visuomotor control than non-gamers[41]. Since we did not stratify for this when randomizing the groups and we found that 1-SET had significantly higher mean gaming hours per week compared to 3-SET, this could possibly have affected the outcomes. However, despite the initial differences observed between the groups, subsequent analyses indicated that when participants were re-categorized based on the number of hours played (0 hours, > 0 and ≤ 10 hours, and > 10 hours per week) there were no significant differences in VAT acquisition between the groups. Furthermore, no significant GROUPxTIME interaction was observed. Therefore, when participants were stratified based on the mean gaming hours per week parameter, and the results still indicated no GROUPxTIME differences, it indicates that gaming experience did not influence the results.

Furthermore, it is up to discussion whether the RT protocol used in this study was designed optimally to induce improvements in motor performance. We observed a BLAC post RT similar to other studies[11]. We used three minutes of rest between sets to let participants recover and thereby increasing RT-volume[42]. However, since other studies showed an effect of a protocol using 1 minute of rest, where metabolic stress is maximized, it can be suggested, that shorter rest intervals may be superior to induce motor performance enhancing effects.

To our knowledge, the literature on RT and motor memory consolidation is scarce, which led to constraint in the study design. Therefore, the variables in this study were designed primarily on literature with regards to RT, lactate response of RT and BDNF response of RT. Theoretically, this should have improved the motor performance, and since it did not, it raises the question whether the variables were optimized efficiently in this study. The present study used a rest interval of three minutes between sets to sustain a high RT volume, which is compromised when rest periods are 1 minute between sets to failure[42]. However, another study, which examined this topic, used rest intervals of 1.5-2.5 minutes, and found a motor performance enhancing effect of the RT-intervention compared to the control group[11]. Longer rest intervals may therefore interfere with the benefits of RT with regards to motor learning compared to shorter rest intervals.

Finally, another possible limitation was the number of exercises in the RT protocol. The present study utilized three exercises of one or three sets to mechanical failure at 12RM in the RT protocol compared to the aforementioned study, which implemented five exercises with four sets of eight repetitions[11]. Whether additional exercises could have had an increase in the overall lactate and BDNF production, consequently leading to different outcomes in the three groups for VAT-score, remains to be investigated.

4.2 | Perspectives

The practical implications of this study's results can be considered valuable, since they shed light on a topic that can, potentially, gain more relevance in future. The reason for that is the world's current elderly population (60+ years) is 11% and is, based on estimations, expected to reach 22% by 2050[43]. Aging is associated with increased risk of stroke, wherein 70% of all strokes occur above the age of 65[44]. Stroke leads to neurological deficits, which makes exercise therapy such as RT important since it can improve cognitive functions, physical health, and mental health[45]. Therefore, if future studies discover the optimal RT variables for improving motor learning, such as RT volume, the knowledge can thereby be implemented in clinical practice. This could be beneficial for stroke patients under rehabilitation programs.

5 | CONCLUSION

This study confirms that motor performance of the VAT improved when individuals perform the motor skill, during motor acquisition, since all groups improved from baseline to B_3, indicating that online motor learning occurred. Furthermore, the main findings showcased that RT had no effects on retention of the motor skill, since no GROUPxTIME interaction was found from B_3 to R_7, which contradicts existing literature. This observation indicated no differences between groups in offline learning. Further research is required to examine whether RT can induce enhanced motor learning effects and what the optimal RT parameters may be.

References

1. Krakauer J, Hadjiosif A, Xu J, Wong A, Haith A. Motor Learning. *Comprehensive Physiology* 2019; 9: 613-63.
2. Newell KM. What are Fundamental Motor Skills and What is Fundamental About Them?. *Journal of Motor Learning and Development* 2020; 8(2): 280-314.
3. Gaul D, Issartel J. Fine motor skill proficiency in typically developing children: On or off the maturation track?. *Human Movement Science* 2016; 46: 78-85.
4. Chang Y. Reorganization and plastic changes of the human brain associated with skill learning and expertise. *Frontiers in Human Neuroscience* 2014; 8.
5. Dayan E, Cohen LG. Neuroplasticity subserving motor skill learning. *Neuron* 2011; 72(3): 443-54.
6. Diekelmann S, Born J. The memory function of sleep. *Nature reviews neuroscience* 2010; 11(2): 114-26.
7. Wanner P, Cheng FH, Steib S. Effects of acute cardiovascular exercise on motor memory encoding and consolidation: A systematic review with meta-analysis. *Neuroscience & Biobehavioral Reviews* 2020; 116: 365-81.
8. Bathina S, Das UN. Brain-derived neurotrophic factor and its clinical implications. *Archives of medical science* 2015; 11(6): 1164-78.
9. Müller P, Duderstadt Y, Lessmann V, Müller NG. Lactate and BDNF: key mediators of exercise induced neuroplasticity?. *Journal of Clinical Medicine* 2020; 9(4): 1136.
10. Saucedo Marquez CM, Vanaudenaerde B, Troosters T, Wenderoth N. High-intensity interval training evokes larger serum BDNF levels compared with intense continuous exercise. *Journal of applied physiology* 2015; 119(12): 1363-73.
11. Thomas R, Flindtgaard M, Skriver K, et al. Acute exercise and motor memory consolidation: Does exercise type play a role?. *Scandinavian journal of medicine & science in sports* 2017; 27(11): 1523-32.
12. Wirtz N, Wahl P, Kleinöder H, Mester J. Lactate kinetics during multiple set resistance exercise. *Journal of sports science & medicine* 2014; 13(1): 73-7.
13. Fradkin AJ, Zazryn TR, Smoliga JM. Effects of warming-up on physical performance: a systematic review with meta-analysis. *The Journal of Strength & Conditioning Research* 2010; 24(1): 140-8.
14. Woods K, Bishop P, Jones E. Warm-up and stretching in the prevention of muscular injury. *Sports medicine* 2007; 37: 1089-99.
15. Nuzzo JL, Pinto MD, Nosaka K, Steele J. Maximal number of repetitions at percentages of the one repetition maximum: A meta-regression and moderator analysis of sex, age, training status, and exercise. *Sports Medicine* 2023; 54: 1-19.
16. Marston KJ, Newton MJ, Brown BM, et al. Intense resistance exercise increases peripheral brain-derived neurotrophic factor. *Journal of science and medicine in sport* 2017; 20(10): 899-903.
17. Zavorsky GS, Lands LC, Schneider W, Carli F. Comparison of fingertip to arterial blood samples at rest and during exercise. *Clinical Journal of Sport Medicine* 2005; 15(4): 263-70.
18. Junior ERTS, Salles dBF, Dias I, Ribeiro AS, Simão R, Willardson JM. Classification and determination model of resistance training status. *Strength & conditioning journal* 2021; 43(5): 77-86.
19. Mathew J, Masson GS, Danion FR. Sex differences in visuomotor tracking. *Scientific reports* 2020; 10(1): 11863.
20. Kraemer WJ, Fleck SJ, Maresh CM, et al. Acute hormonal responses to a single bout of heavy resistance exercise in trained power lifters and untrained men. *Canadian journal of applied physiology* 1999; 24(6): 524-37.
21. Kang M, Ragan BG, Park JH. Issues in outcomes research: an overview of randomization techniques for clinical trials. *Journal of athletic training* 2008; 43(2): 215-21.

22. Murrar S, Brauer M. Mixed model analysis of variance. *The SAGE encyclopedia of educational research, measurement, and evaluation* 2018; 1: 1075-8.

23. Roig M, Skriver K, Lundbye-Jensen J, Kiens B, Nielsen JB. A Single Bout of Exercise Improves Motor Memory. *PLOS ONE* 2012; 7: 1-8.

24. Lutz K, Martin M, Jäncke L. Transfer of Motor Learning in a Visuomotor Tracking Task for Healthy Old and Young Adults. *Zeitschrift für Neuropsychologie* 2010; 21: 247-58.

25. Thomas R, Beck MM, Lind RR, et al. Acute exercise and motor memory consolidation: the role of exercise timing. *Neural plasticity* 2016; 2016.

26. Leech KA, Roemmich RT, Gordon J, Reisman DS, Cherry-Allen KM. Updates in motor learning: implications for physical therapist practice and education. *Physical therapy* 2022; 102(1): pzab250.

27. Wang H, Fan J. Human Attentional Networks: A Connectionist Model. *Journal of cognitive neuroscience* 2007; 19: 1678-89.

28. Wessel MJ, Zimerman M, Hummel FC. Non-invasive brain stimulation: an interventional tool for enhancing behavioral training after stroke. *Frontiers in human neuroscience* 2015; 9: 265.

29. Ginty DD, Segal RA. Retrograde neurotrophin signaling: Trk-ing along the axon. *Current opinion in neurobiology* 2002; 12(3): 268-274.

30. Kodama M, Ono T, Yamashita F, et al. Structural gray matter changes in the hippocampus and the primary motor cortex on an-hour-to-one-day scale can predict arm-reaching performance improvement. *Frontiers in human neuroscience* 2018; 12: 209.

31. Draganski B, Gaser C, Busch V, Schuierer G, Bogdahn U, May A. Changes in grey matter induced by training. *Nature* 2004; 427(6972): 311-312.

32. Lynch MA. Long-term potentiation and memory. *Physiological reviews* 2004; 84(1): 87-136.

33. Zhou B, Wang Z, Zhu L, et al. Effects of different physical activities on brain-derived neurotrophic factor: A systematic review and bayesian network meta-analysis. *Frontiers in Aging Neuroscience* 2022; 14: 981002.

34. Castro Abrantes dH, Briquet M, Schmuziger C, et al. The lactate receptor HCAR1 modulates neuronal network activity through the activation of Gα and G$\beta\gamma$ subunits. *Journal of neuroscience* 2019; 39(23): 4422-33.

35. Hertz L, Dienel GA. Lactate transport and transporters: general principles and functional roles in brain cells. *Journal of neuroscience research* 2005; 79(1-2): 11-8.

36. Wu A, Lee D, Xiong WC. Lactate metabolism, signaling, and function in brain development, synaptic plasticity, angiogenesis, and neurodegenerative diseases. *International Journal of Molecular Sciences* 2023; 24(17): 13398.

37. Briquet M, Rocher AB, Alessandri M, et al. Activation of lactate receptor HCAR1 down-modulates neuronal activity in rodent and human brain tissue. *Journal of Cerebral Blood Flow & Metabolism* 2022; 42(9): 1650-65.

38. Rahimi R. Effect of different rest intervals on the exercise volume completed during squat bouts. *Journal of sports science & medicine* 2005; 4(4): 361-6.

39. Beard E, Lengacher S, Dias S, Magistretti PJ, Finsterwald C. Astrocytes as key regulators of brain energy metabolism: new therapeutic perspectives. *Frontiers in physiology* 2022; 12: 825816.

40. Borecki L, Tolstych K, Pokorski M. Computer Games and Fine Motor Skills. In: Pokorski M., ed. *Respiratory Regulation - Clinical Advances*Springer Netherlands; 2013; Dordrecht: 343-8.

41. Bediou B, Adams DM, Mayer RE, Tipton E, Green CS, Bavelier D. Meta-analysis of action video game impact on perceptual, attentional, and cognitive skills.. *Psychological bulletin* 2018; 144(1): 77-110.

42. Miranda H, Fleck SJ, Simao R, Barreto AC, Dantas EH, Novaes J. Effect of two different rest period lengths on the number of repetitions performed during resistance training. *The Journal of Strength & Conditioning Research* 2007; 21(4): 1032-6.

43. Kanasi E, Ayilavarapu S, Jones J. The aging population: demographics and the biology of aging. *Periodontology 2000* 2016; 72(1): 13-8.

44. Kelly-Hayes M. Influence of age and health behaviors on stroke risk: lessons from longitudinal studies. *Journal of the American Geriatrics Society* 2010; 58: 325-8.

45. Westcott WL. Resistance training is medicine: effects of strength training on health. *Current sports medicine reports* 2012; 11(4): 209-16.