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Effect of acute working memory stimulation on motor learning

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HIGHLIGHTS
- Acute working memory stimulation did not enhance complex motor skill learning.
- Working memory stimulation caused an initial performance impairment in the experimental group.
- Both groups learned the task, but WM stimulation briefly hindered early performance.

ABBREVIATIONS

d	Cohen's d
DLPFC	Dorsolateral prefrontal cortex
ICF	Informed Consent Form
η^2	Partial eta squared
PI	Proactive interference
SPSS	Statistical Package for the Social Sciences
tDCS	Transcranial direct current stimulation
WM	Working memory

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BACKGROUND: Working memory (WM) plays an important role in motor learning, particularly at the beginning of the process.
AIM: The present study aimed to investigate the effect of acute working memory stimulation on the learning of a complex motor skill.
METHODS: Twenty-four college students (12 males, 12 females), aged 18 to 40 years, practiced the golf putting motor task. Twelve participants in the experimental group performed the N-back cognitive task (level two-back) for five minutes as acute WM stimulation before the golf putting motor task, while the control group remained seated looking at a blank screen for the same duration.
RESULTS: The results found that learning occurred in both groups; however, acute WM stimulation did not enhance this learning process in the stimulated group. Unexpectedly, WM stimulation caused an initial impairment in performance for the stimulated group during the first acquisition block.
INTERPRETATION: This suggests that acute WM stimulation, as applied in this study, did not facilitate learning and may have temporarily hindered initial performance in a complex motor skill.

KEYWORDS: N-back task | Skill acquisiton | Radom practice | Golf putting task | Complex motor skill

INTRODUCTION

Motor learning is defined by the processes of progressive changes that occur through practice [1]. These changes transition from an initial phase, characterized as cognitively demanding, to a later phase described as more automatic [2,3]. These behavioral modifications are determined by alterations in the functioning and communication of neurophysiological substrates that affect the acquisition, consolidation, and retention of procedural memories [4].

It has been observed that cognitive processes play a significant role in motor learning, particularly at the beginning of the learning process [5]. Among these cognitive processes, working memory (WM), which allows individuals to actively and temporarily maintain and manipulate information related to the task at hand [6], plays an essential role. WM is fundamental to the human capacity for problem-solving [5]. The problem-solving in the initial stages of motor learning is to maintain the task's goals on WM, engage in more controlled planning, and activate error correction mechanisms required in cognitive processes [7].

Individual differences in WM capacity can influence the execution and learning of different skills [7]. The quality of WM function can be enhanced through training [8,5] and via transcranial direct current stimulation (tDCS) [9]. These improvements in WM function can be explained by alterations in cortical excitability in the left dorsolateral prefrontal cortex (DLPFC). Thus, neuromodulation has emerged as an effective factor in optimizing motor learning. It is possible that acute stimulation of WM function before motor practice may act as a factor that optimizes motor learning. To the authors' knowledge, only two studies have investigated the effect of WM stimulation on motor learning [10,11]. Kimura and Nakano [10] observed that WM stimulation using the N-back cognitive task immediately before practice led to better performance on a motor sequence task in the early phase of practice. This task involved a cursor-tracking movement with a 165° visuomotor rotation, requiring adaptation to an altered mapping between hand movement and visual feedback. Importantly, this task can be considered relatively simple, as it involves few degrees of freedom and low variability of movement.

Subsequently, Kimura and Nakano [11] confirmed the positive effect of WM stimulation on motor performance and investigated prefrontal cortex excitability, but no alterations in DLPFC excitability were observed. These two studies indicate that the type of cognitive and motor task can differentially affect motor performance and learning. Another question that can be raised from the analysis of these two studies [10,11] is that the motor tasks used had low complexity.

Generally, tasks used to investigate the effects of motor learning have been relatively simple, including only one degree of freedom, which requires a small amount of practice to reach performance asymptotes, thus placing a relatively moderate demand on cognitive processes such as attention, memory, or processing capacity [12]. Complex motor skills impose a greater demand on the central nervous system [13]. One way to classify task complexity may be based on degrees of freedom. Degrees of freedom refer to the number of variables that need to be controlled during movement execution [14,15], where a complex system needs to organize itself to produce a specific outcome [16].

In the present study, task complexity will be defined by an increase in the number of degrees of freedom. The golf-putting task used here requires the control of multiple joints and muscle groups for precise execution, coordination of posture, trunk, arm, and wrist movements, and continuous adjustment to the target distance and environment. This contrasts with the simpler discrete motor tasks used in studies Kimura and Nakano [10,11], which required fewer degrees of freedom and less multisegmental coordination. Therefore, golf putting can be considered a complex motor skill. This way, a complex motor skill will be considered one that necessarily involves the control of multiple joints and muscle groups for its execution [4]. More complex movements involve control of a greater number of degrees of freedom and require more practice to achieve the goal [17]. Bernstein [16] considers motor coordination as the control of the degrees of freedom of the system and that modifications made in one joint during the movement reflect and provoke changes in the action of the others.

Understanding the importance of WM for motor learning, it is necessary to comprehend the role of acute WM stimulation in the motor learning of a complex skill, such as golf putting. Based on previous findings in the literature, it is possible to expect that at least in the initial phase of practice, WM stimulation will positively impact motor performance. From the logic that there is an increased demand for cognitive processes such as attention, memory, or processing capacity in more complex tasks [12], it is possible to hypothesize that acute WM stimulation may affect not only performance but also the consolidation of the complex motor skill, thus characterizing better motor learning.

It is important to distinguish between performance and learning: while initial improvements may reflect short-term effects of practice or working memory stimulation, motor learning is inferred from retention and transfer of skill performance. Therefore, the inclusion of retention and transfer tests in the experimental design allows us to assess whether improvements are maintained and generalized beyond the immediate practice context.

MATERIAL AND METHODS

Twenty-four college students of both sexes (12 males and 12 females, counterbalanced by group), aged 18 to 40 years (mean 26.58 ± 5.99), were recruited through advertisements within the university campus, constituting a convenience sample. Inclusion criteria were right-handed participants with a minimum laterality quotient of 80 points on the Edinburgh Handedness Inventory (Oldfield, 1971), normal or corrected-to-normal vision, no previous experience with the motor task, no self-reported neurological impairments, not taking controlled medications, and no injuries that would prevent proper performance of the golf-putting task. All volunteers signed an Informed Consent Form (ICF), and the study was approved by the local research ethics committee. Participants were randomly assigned to one of two groups: experimental (n = 12) and control (n = 12).

Regarding sample size, an a priori power analysis (with a desired power of .8 and an alpha level of .05) initially suggested a target of 19 participants per group. However, due to unforeseen logistical and operational constraints encountered during the data collection period within the university environment, it was only feasible to recruit and test 12 participants per group. For this sample size (n=12 per group), the achieved statistical power was approximately .6. This sample size, while not fully meeting the initial power analysis recommendation, represents the maximum achievable under the prevailing practical conditions. The potential implications of this reduced statistical power are further discussed in the Limitations section.

Cognitive Task

The cognitive task applied was the N-back task, level two-back, using the Brain Workshop software (Dual N-Back, version 4.8.4), an open-source program widely employed in research on working memory training. In this task, the same stimulus is consecutively presented in random positions across nine possible locations. The participant needs to keep these positions active in their working memory (WM) and respond by pressing a key when the stimulus occupies the same position as the last stimulus, the second-to-last stimulus, or the third-to-last stimulus, depending on the N-back level chosen by the researcher. In the present study, the N-back task, level two-back, version 4.8.4, was used. Thus, the participant was required to press the "A" key on the keyboard whenever they identified that the present stimulus was in the same position as the second-to-last stimulus. The program identifies the level of correctness percentage-wise, considering 100% as all the times the participant should have correctly pressed the A key and correctly not pressed the key during the established task time. Failure to press the key when it should be pressed and pressing the key when it should not be pressed were considered errors, reducing the participant's correctness percentage in that N-back session. The execution time of the N-back task was five minutes.

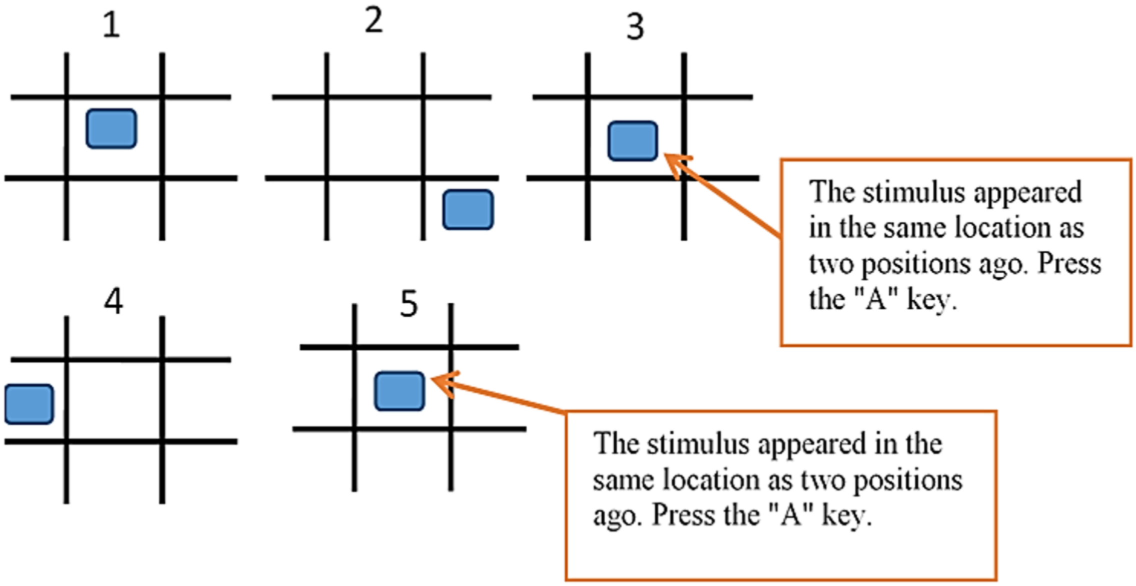

Figure 1. Simulation of the N-Back Task - Level 2 Back.

Motor Task

Motor learning was investigated using a golf-putting task performed on a 4.00 m × 1.50 m felt track, with a 14 cm diameter circle serving as the target. Putting was performed using a standard putter and a golf ball. The objective was to place the ball inside the target circle.

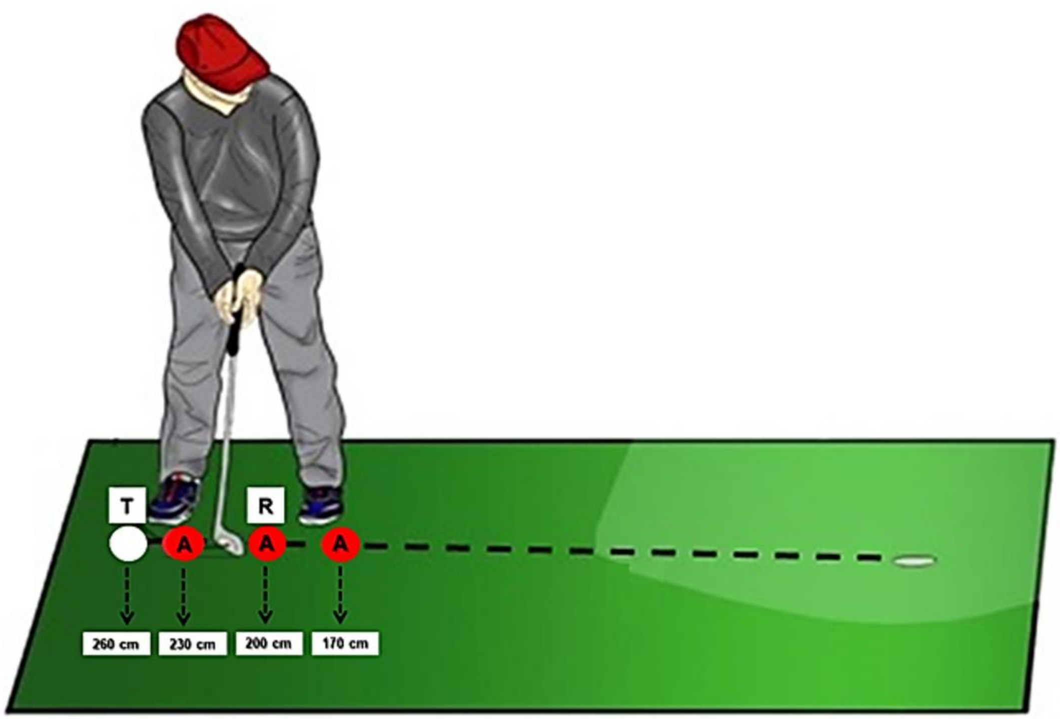

Figure 2. Simulations of the Motor Task - Source: Parma, 2020 (adapted figure).

Experimental Environment

All experiments were conducted in a quiet room at the Federal University of Minas Gerais, Brazil. Initially, the participants were instructed to sit in a comfortable chair in front of a desk with a microcomputer (Lenovo, model 80YF, 14 inches). The control group participants remained seated in the chair looking at a blank screen on the computer for five minutes before the motor task. The experimental group participants, instead of looking at a blank screen, performed the N-back cognitive task, level 2-back, for five minutes.

Experimental Design and Procedures

The experiment was divided into the following phases: pre-test, acquisition, post-test, and transfer test. On the first day, volunteers performed a pre-test consisting of 12 trials of the motor task. The acquisition phase was conducted on the first and second data collection days, with 48 trials each day. The centers of the targets varied at three distances (1.7 m, 2.00 m, and 2.3 m). All participants performed the same pseudo-random sequence, in which no distance was presented twice in a row, with 16 trials at each distance. The post-test and transfer test were conducted approximately 24 hours after the acquisition phase, each consisting of 12 trials, with the transfer test performed immediately after the post-test. For the transfer test, the target center was placed at a distance of 2.6 m. To infer overall performance, the radial error was considered, calculated as the distance from the center of the ball to the center of the target at the end of each trial, with the value subtracted from 7 cm (radius of the target). This indicated that a hit (0 cm error) was considered whenever at least half of the ball was within the boundaries of the target.

Camera

A video camera (JVC model GZ-HM30BUB) with a capture frequency of 60 Hz was used to obtain data regarding the final distance of the ball to the target after the completion of each trial. The camera was positioned above the mat, perpendicular to the ground, pointing directly at the target. The captured image covered 120 cm before and after the target, and the entire width within these marks. The data were subsequently analyzed using the Kinovea video analysis software, which is widely used by sports scientists in motion analysis studies [18,19,20]. Two lines, one meter apart from each other, were marked on the side of the mat, and this distance was used as a reference for video analysis. After the ball stopped after each stroke, we paused the video and marked the distance from the center of the ball to the center of the target, which was measured by the software. The data were then transposed to a separate spreadsheet.

Statistical Analysis

Descriptive analysis was performed using the mean radial error. The data were organized into blocks of twelve trials for the pre-test, post-test, and transfer test; eight blocks of twelve trials in the acquisition phase; the delta between the first block of the acquisition phase and the pre-test; and the change in performance from the final block of the first session (4th block) to the initial block of the second session (5th block) of the acquisition phase, reflecting retention across the no-practice interval. Data normality was assessed using the Shapiro–Wilk test. The assumptions of homoscedasticity and sphericity were assumed. For inferential analysis in the pre-test, transfer test, post-test, and deltas, Student's t-test for independent samples was used. For the analysis of the acquisition phase and the difference between pre-test and post-test, two-way ANOVA (2 groups x 2 time points) with repeated measures on the second factor was conducted. Post-hoc analysis was performed using Duncan's test. Effect size was calculated using partial eta squared (η^2) for ANOVAs and Cohen's d (d) for t-tests. The significance level adopted was 0.05. Data organization and analysis were performed using the Statistical Package for the Social Sciences (SPSS) version 20.0.

RESULTS

Accuracy

The pre-test analysis showed that both groups had the same performance $t_{(22)}=-.01$, $p=.99$, $d=.01$. The analysis of the acquisition phase showed that both groups improved their performance from the beginning to the end of the phase $F_{(1,7)}=5.11$, $p=.01$, $\eta2=.19$. Duncan's post-hoc test indicated that the 1st block had a higher number of errors compared to the 2nd, 3rd, 7th, and 8th blocks ($p< .05$). However, there was no difference between the groups $F_{(1,22)}=.45$, $p=.51$, $\eta2=.02$, and there was no interaction effect $F_{(1,7)}=1.32$, $p=.25$, $\eta2=.06$. In the post-test analysis, no significant difference was found between the groups $t_{(22)}=-.92$, $p=.37$, $d=.38$, nor in the transfer test $t_{(22)}=.23$, $p=.82$, $d=.09$ (Figure 3).

In the analysis of the delta between the pre-test and the first block of the acquisition phase, the control group (M = 28.96±13.61) showed a greater variation from pre-test to the first block of the acquisition phase than the stimulated group (M = 21.070±10.92). In the analysis of the delta from the fourth to the fifth block of the acquisition phase, there was no significant difference $t_{(22)}=-.17$, $p=.87$, $d=.07$ (Figure 4).

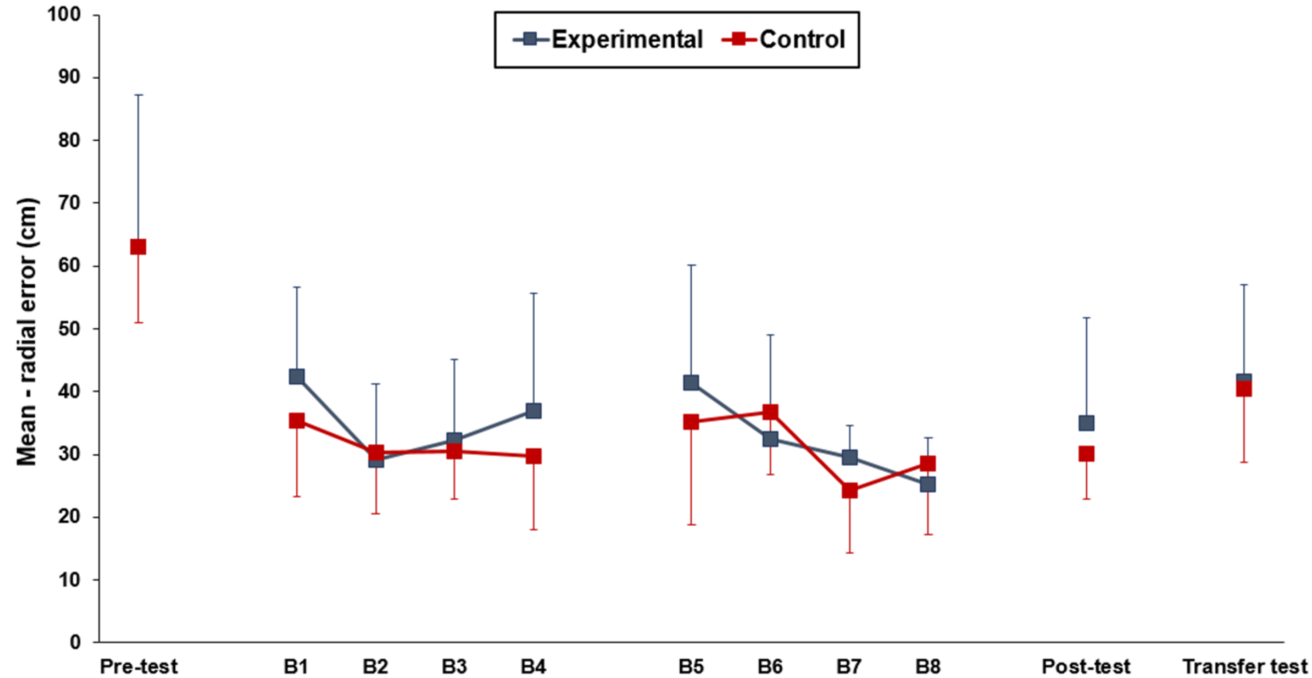

Figure 3. Mean radial error in the pre-test, acquisition phase, post-test, and transfer test in blocks of twelve trials.

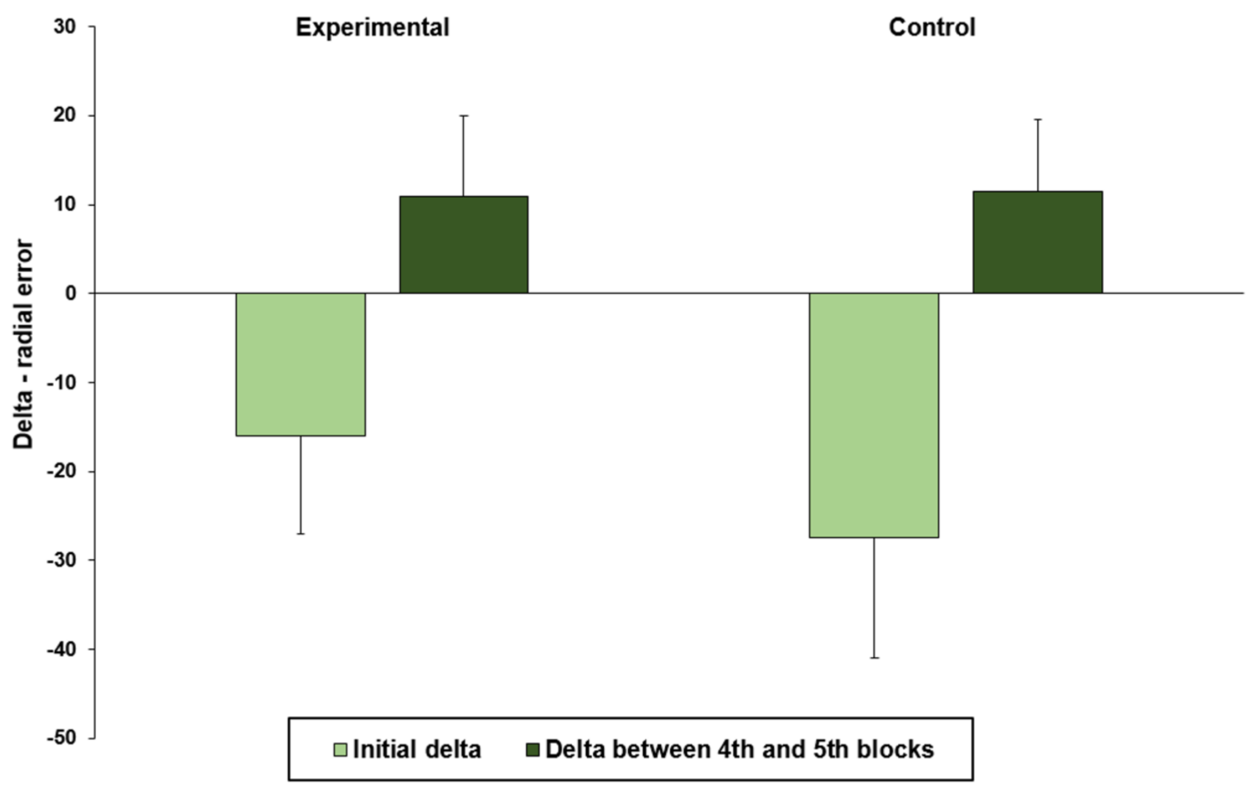

Figure 4. Mean delta in initial learning and blocks 4 and 5 of the experimental and control groups.

Variability

Regarding variability, the groups did not differ in the pre-test $t_{(22)}$=.01, p=.99, d=.01. In the comparison between groups, no significant difference was found $F_{(1,22)}$=.86, p=.36, $\eta2$=.04. However, a significant difference was found in the comparison between Blocks

$F_{(1,7)}$=3.49, p=.01, η2=.14, and Duncan's post-hoc test indicated that the 1st block showed greater variability than blocks 3 and 7 (p < .05). There was an interaction between blocks and groups $F_{(1,7)}$=3.33, p=.01, η2=.13. The Duncan post-hoc test shows that the first block of acquisition was more variable in the experimental group. In the post-test and transfer test, no significant differences were found. In the post-test, the comparison between groups did not find significant difference $t_{(22)}$=1.12, p=.28, d=.46, as well as in the transfer test $t_{(22)}$=−.22, p=.83, d=.09 (Figure 5).

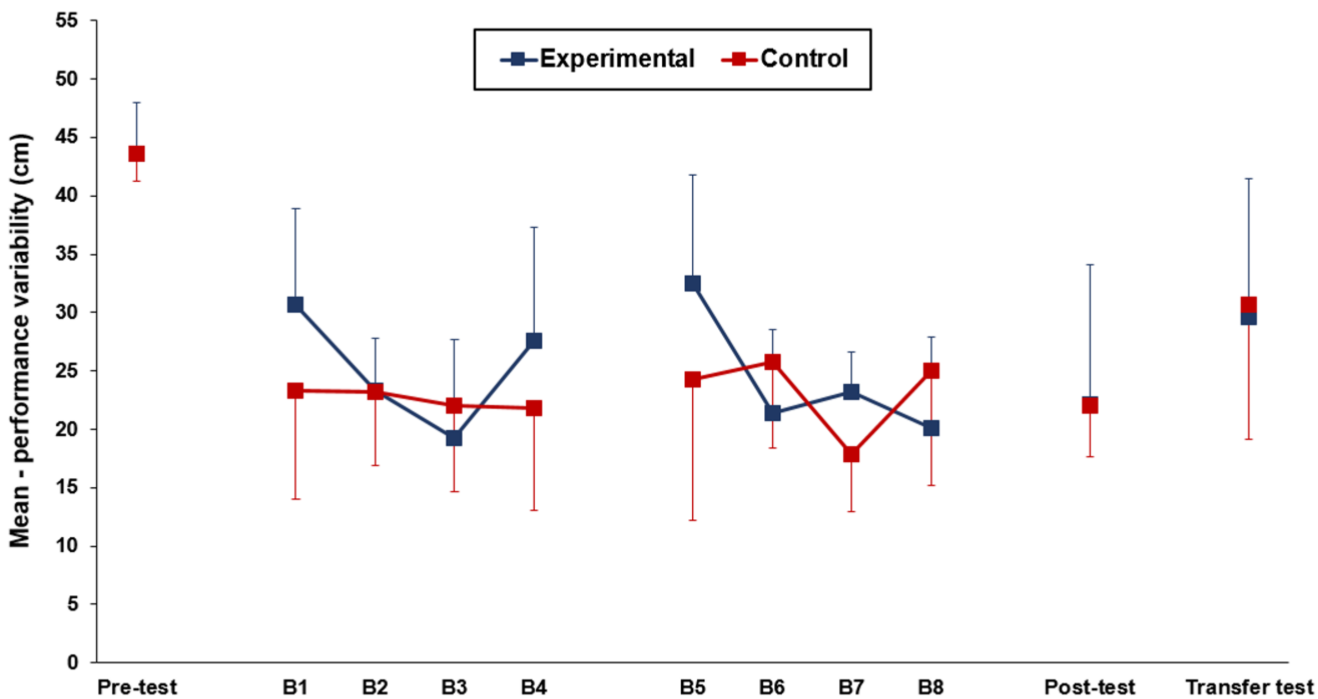

Figure 5. Mean performance variability in the pre-test, acquisition phase, post-test, and transfer test in blocks of twelve trials.

DISCUSSION

In the present study, our objective was to investigate the role of acute working memory (WM) stimulation in the motor learning of a complex motor skill. The proposed hypotheses assumed that acute WM stimulation would have positive impacts on the initial performance and learning of a complex motor skill. Contrary to expectations, the results found in this study did not confirm the hypotheses, as the analyses did not identify better performance of the stimulated group participants in any of the study phases. Learning was observed in both groups through the performance assessed from pre- to post-test. This result was expected, considering that practice is the main factor for motor learning [4]. However, acute WM stimulation did not differentially improve the performance of the stimulated group.

Unexpectedly, WM stimulation caused impairments to the participants in the initial stage of learning. This finding was verified through the analysis of the delta between the pre-test and the first acquisition block. In the pre-test, both groups showed similar performance. However, between the pre-test and the beginning of the acquisition phase, the group that underwent WM stimulation showed an immediate decline in performance, making more errors in the first acquisition block. Two hypotheses can be proposed to explain this finding: (1) mental fatigue and (2) proactive interference (PI).

The first hypothesis is the less likely one. Mental fatigue can cause various adverse events, including a decline and reduction in endurance and performance [21]. Penna et al., [22] demonstrated that cognitive activity prior to physical exercise is detrimental to performance as it impairs information processing and decision-making. Fatigue was induced in the athletes' inhibitory control capacity through the application of the Stroop test for thirty minutes [23,24]. showed that subjects fatigued by two hours of a cognitive task had difficulties focusing their attention, planning, and adaptively adjusting their strategies based on the errors generated. Boksem et al., [25] indicated that subjects fatigued by three continuous hours of a visual attention task had difficulties adequately preparing their responses and maintaining attention while ignoring irrelevant information. Additionally, fatigued subjects corrected their errors less frequently, and their error performance adjustment was impaired [26].

Therefore, the involvement of cognitive control is essential, especially in novel and complex tasks, but it is affected under conditions where subjects are fatigued [26]. The analysis of results from studies on prolonged cognitive stimulation shows that extensive protocols, involving more than thirty minutes of cognitive stimulation [23,24,25], induce fatigue leading to impairments in cognitive performance. In the present study, however, the exposure to the cognitive task was limited to only five minutes. This duration is considerably shorter than the cognitive protocols typically used to induce mental fatigue (≥ 30 minutes), thus making it unlikely that fatigue was the main factor explaining the initial performance impairment in the experimental group. Nevertheless, we acknowledge that even brief cognitive demands cannot completely rule out the possibility of short-term fatigue-like effects. For this reason, the role of mental fatigue is considered improbable, although a minor contribution cannot be entirely excluded.

Furthermore, to better relate our results to the question of learning, we analyzed differences between early and late acquisition blocks. Both groups improved over time, indicating learning progression. The initial decline in the experimental group likely reflects the immediate effect of acute WM stimulation rather than a failure of learning.

Given that participants were university students, prior activities such as classes or other cognitive tasks could potentially influence pre-test performance. Although these activities were not formally controlled, the random assignment of participants to groups and comparable pre-test performance suggest no systematic baseline differences.

Finally, the absence of group differences in the retention test may involve mechanisms beyond task complexity. Possible factors include: short-term fatigue-like effects induced by acute WM stimulation, attentional switching costs from transitioning between cognitive and motor tasks, and task novelty, particularly in the transfer test. These considerations provide a more complete understanding of the observed learning outcomes.

Jost et al., [27] observed that performing cognitive tasks in sequence can create a conflict of information, leading to inhibition in the response to the current task. Gade and Koch [28] reported that this inhibition passively decays over time. Such task-switching costs are complex and appear to require cognitive control to enable flexibility. This inhibitory effect can be explained by interference theory, which posits that different pieces of information compete within memory systems [29,30]. In particular, previously learned items can generate proactive interference (PI) [31]. reducing the ability to recall a current item due to similarity with items stored earlier. PI may occur because of an inability to suppress a response, either due to persistent inhibition of the currently relevant task set or continued activation of a previously relevant task set [32,33].

According to Pashler [34], when different tasks are performed in close succession, response selection can be impaired due to interference between current and previous task sets. Thus, it is understood that proactive interference (PI) exerts significant control over the amount of information that can be retrieved from working memory (WM) [35]. May et al., [36] showed that part of the variation in performance can be attributed to PI. Redick, Heitz, and Engle [37] report that WM is a system that evolves to deal with proactive interference. This hypothesis is aligned with the result of the present study, as the effect of impairment in learning related to PI was only observed in the first acquisition block. Shortly after, the groups equalized in performance, and the experimental group managed to catch up with the control group in reducing radial error. Regarding the unconfirmed hypothesis of a better learning rate attributed to the experimental group, a possible explanation is that WM training often does not transfer to another task [38]. Despite tasks requiring similar cognitive processes such as WM, there may be a difference in how these processes are recruited, diminishing the effectiveness of acute WM training in learning a complex motor skill.

Therefore, understanding the underlying mechanisms of WM stimulation is necessary to comprehend how stimulation in a given WM task can truly influence mechanisms that enhance performance and learning in other tasks that also rely on working memory. Li et al., [39] mention that the effects of cognitive intervention should be studied to discern whether the effects of the intervention are restricted to a small set of skills, with little effect on other behaviors, or if cognitive mechanisms and generalizable capacities have been improved. In the domain of WM, interventions may influence a specific type of WM task without improving overall WM function capacity.

Limitations of the studies

The current study has following limitations: A primary limitation is that the study's sample size was determined by practical considerations. While an a priori power analysis (with a desired power of .8 and an alpha level of .05) initially suggested 19 participants per group, unforeseen logistical and operational constraints encountered during the data collection period within the university environment limited recruitment to 12 participants per group. For this actual sample size, the achieved statistical power was approximately .6, which may have reduced the ability to detect subtle effects and thus impacts the generalizability of certain null findings. Additionally, the study did not assess possible neural or cortical excitability induced by the N-back cognitive task, preventing a full understanding of the underlying mechanisms by which working memory stimulation might influence performance and learning in other tasks. Finally, the intervention group was not stratified by levels of working memory capacity, which could have provided insight into how individuals with different baseline capacities respond to acute working memory stimulation.

CONCLUSION

In conclusion, the present findings suggest that acute stimulation of working memory (WM) via the N-back task did not facilitate motor learning and, in fact, appeared to impair performance during the initial phase. These results partially contradict previous studies on WM training and stimulation, which may be explained not only by the complexity of the motor task employed here, but also by design constraints, participant characteristics, and the sensitivity of the measures used. Given the central role of WM in problem-solving and learning, further research is needed to explore how WM stimulation can enhance cognitive functioning and contribute to the acquisition of complex motor skills, taking into account these multifactorial influences.

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