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Practice organization and the level of mental effort via pupil dilation: a study with a complex task

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HIGHLIGHTS

- Random practice improved transfer test performance compared to constant practice.
- Pupil dilation was only greater in the post-test for the random practice group.
- An interaction between pupil dilation and performance in learning tests was found.
- Only random practice reduced offline changes in motor errors during the transfer test.

ABBREVIATIONS

CP	Constant practice group
RP	Random practice group

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BACKGROUND: This study explores the impact of practice organization on motor skill acquisition, focusing on random versus constant practice. Random practice involves executing tasks in a non-sequential order, while constant practice consists of repetitive execution of the same task. Previous research indicates that random practice typically yields worse initial performance and then better learning outcomes due to greater demands on memory processes.
AIM: This study aimed to assess motor performance via a complex task and pupil dilation in both practice conditions, hypothesizing that random practice would initially hinder performance but enhance outcomes in post- and transfer tests, as well as elicit higher pupil dilation.
METHODS: Twenty right-handed adults with no prior golf experience were randomly assigned to constant or random practice groups and performed a golf putting task over two consecutive days. Motor performance (radial error) and perceptual effort (pupil dilation) were recorded using video analysis and eye-tracking technology.
RESULTS: The results showed that the random practice group did not demonstrate higher error rates or greater pupil dilation than the constant practice group during practice. While the random group performed better in the transfer test, pupil dilation levels remained consistent across both groups.
INTERPRETATION: The findings indicate that the random group performed significantly better than the constant practice group in the transfer test, suggesting enhanced motor learning. Despite the lack of expected differences in pupil dilation, this study highlights the need for further research on mental effort in practice organization, particularly with more complex motor tasks that require significant cognitive engagement.

KEYWORDS: Motor learning | Practice schedule | Mental effort | Pupil dilation | Complex task

INTRODUCTION

The study of practice organization is a key area in Motor Behavior, as it is one of the primary factors that professionals manipulate to facilitate motor skill acquisition. One of the most researched practice schedules is random practice [1], which involves the execution of tasks, or variation of a task, in a non-sequential, unpredictable order for the learner (e.g., tasks: BCACABCBAABC). Another approach to structuring motor skill practice is constant practice, where participants repeatedly perform the same skill (e.g., task: AAAAAAAAAA) [1,2]. Research indicates that variable practice, such as random practice, results in poorer performance during practice (acquisition phase) compared to more repetitive practices like constant practice. This occurs due to the greater demand on planning and execution processes required at each new attempt. Random practice involves increased perceptual and memory processing compared to constant practice, which does not require entirely new action planning, but rather minor adjustments based on the previous attempt with the same action goal [2].

However, a result opposite to that observed during practice is expected in learning tests. Due to the more demanding perceptual and memory processes experienced during random practice, the formation of a motor memory that is more resistant to time and interference is expected [2]. This would reflect in improved performance on retention and transfer tests. A consistent finding across studies is that variable practices place greater demands on perceptual [3] and memory processes [4], which is believed to be responsible for the superior learning outcomes observed in random practice compared to constant practice.

The "practice variability hypothesis" suggests that variable practice leads to the development of stronger memory schemas for the learning process compared to constant practice [4,5]. This hypothesis has guided research on practice organization for over four decades, shaping new studies from a neuroscience perspective [1]. This body of work has greatly enhanced our understanding of the role of working memory and long-term memory in motor learning, as well as the neurobiological mechanisms underlying different practice structures [3]. More recently, studies have presented findings that highlight the effects of random practice beyond memory functions. Random practice seems to place higher mental effort demands on the learner's perceptual processes compared to constant practice [1,2]. The frequent changes introduced in random practice from one trial to the next require learners to engage in visual scanning to gather information about the upcoming goal [6]. In contrast, the importance of visual scanning during constant practice is likely reduced, as the repetitive nature of the task allows the learner to keep the goal active in working memory. With the goal remaining the same across consecutive trials, the need for ongoing visual search diminishes.

Bicalho et al. [6] explored mental effort in practice organization through oculomotor behavior, using pupil dilation as an indicator. Their findings revealed that random practice led to greater pupil dilation, signaling increased mental effort compared to constant practice. This trend persisted in the retention and transfer learning tests, suggesting that the heightened mental effort observed during random practice was sustained even after a break from practice. Although random practice resulted in better performance during the learning tests, the relationship between mental effort and performance was not directly examined in study Bicalho et al. [6]. Moreover, the motor task used in their research was a relatively simple sequential typing task. In contrast, more complex tasks like golf putting, which involve greater degrees of freedom [7] and require more intensive visual scanning in the environment, are likely to demand higher mental effort, particularly during random practice.

To deepen our understanding of mental effort across different practice schedules, this study investigated motor performance and pupil dilation in both random and constant practice using a golf putting task. In this specific case, conducting an initial study is justified by the need to previously evaluate the methodological and operational feasibility of using pupil dilation measures in a complex task such as putting [7]. We hypothesized that random practice would result in lower performance during the acquisition phase, but lead to higher performance during the learning tests [2]. The random practice will present a higher level of pupil dilation in the post-test and transfer test. Additionally, we expected that the results from the learning tests would correlate with the levels of pupil dilation [6].

METHODS

Subjects

Twenty healthy volunteers (10 women and 10 men) aged 18 to 40 years (mean age 23.6 ± 4.9), self-identified as right-handed, and scored at least 80 points (mean of 94.17 ± 6.63) on the Edinburgh Handedness Inventory [8], took part in this study. The sample size was based on the range of 8 to 10 subjects per group, as used in Porter et al. [9] and Mousavi et al. [10]. We calculated the sample size based on the means and standard deviations reported by Porter et al. (2007) in the post-test that alternated between blocked and random trials. The minimum sample size required was nine participants per group. No volunteers had prior experience with golf, mini-golf, or putting, and all were unfamiliar with the motor task. Participants reported no injuries that could hinder golf putting performance.

The study was approved by the local ethics committee (Universidade Federal de Minas Gerais) and adhered to the ethical standards set by the Declaration of Helsinki (2014 version) for research involving human subjects. All participants provided written informed consent after receiving a detailed explanation of the study prior to participation.

Instruments and Task

Eye-tracker system

The eye-tracking system was used to evaluate the level of pupil dilation. It consisted of a mobile eye tracker, model World Camera 200 Hz binocular (Pupil Labs, Berlin, Germany), a mobile data collection system, model Pupil Mobile Bundle (Pupil Labs, Berlin, Germany), and a desktop computer, model Inspiron Small with an Intel i7-7700 processor for processing the eye tracker signals (Dell, Eldorado do Sul, Brazil).

Motor tasks

The participants practiced the motor task called golf putting on a green felt track measuring 3.5 meters in length and 1.45 meters in width, with a target diameter of 11.5 centimeters, located 1.20 meters from the end of the track. The task was similar to those used in previous studies [7] (cf. Figure 1). The putting was performed using a standard putter and a regular golf ball. To assess the accuracy of the shots, a camera (USB Camera Module Board – Model OV2710, 2MP, 16Hz) was installed and positioned above the track to enable the calculation of the performance variable. The analysis of the distance between the ball and the target in each attempt was performed using the video analysis software Kinovea.

Experimental Procedures

The study was conducted over two consecutive days. On the first day, participants signed the informed consent form and completed the Edinburgh Handedness Inventory [8]. Volunteers were randomly assigned and counterbalanced by gender into two experimental groups: a random practice group (RP), characterized by greater motor variability, consisting of 10 volunteers, and a constant practice group (CP), characterized by less motor variability, also consisting of 10 volunteers.

After reviewing the collection procedure with the volunteer, the eye-tracking glasses were fitted and calibrated. Then, the volunteers began the motor task. On the first day, all participants performed 10 trials during the pre-test at a distance of 2.2 meters from the target, followed by 90 trials in the acquisition phase. The random practice group (RP) had three different ball-to-target distances: target 1 (2.10m), target 2 (2.20m), and target 3 (2.30m) (Figure 1). Participants in this group completed 30 putts from each of the three distances, with the trials distributed randomly so that the order was unpredictable for the learner. The sequence of putts was generated using Python programming language. The constant practice group (CP) performed all putts from the same distance (target 2 at 2.20m). The tests took place approximately 24 hours after the acquisition phase, with the retention test for both groups conducted at a distance of 2.20m, and the transfer test at 2.50m (target 4), with each consisting of 10 trials (Figure 1).

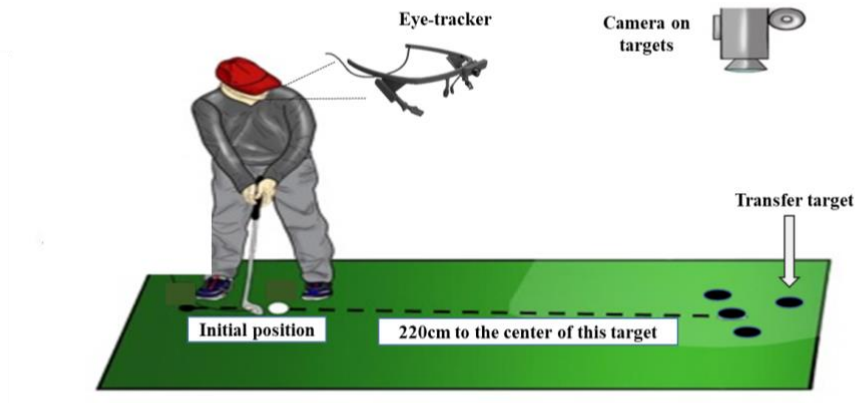

Figure 1. Participants were asked to stand laterally to the putter and to hold it with the right-hand bellow the left-hand.

Before each trial, an audio recording was played for the participants, indicating the correct positioning for the putt. Additionally, the audio played for the random practice group (RP) specified the target for each trial, which could be target 1, 2, or 3, as verbally announced by the researcher. The target sequence was identical for all participants in the RP group. The audio presented to the CP group was the same as that given to all participants during the pre-test, practice, and learning tests. Both audio recordings lasted 15 seconds. The interval between the commands "focus on the ball" and "start when you're ready" was kept consistent.

Dependent variables

The variables were: (a) radial error (characterized by the distance between the ball after the attempt and the center of the circular target), and (b) the level of pupil dilation. To assess motor performance, radial error was considered, defined as the distance from the center of the ball to the center of the target at the end of each attempt. This value was then subtracted by 7 cm (the radius of the target), meaning a successful shot (0 cm error) was recorded whenever at least half of the ball was within the target's limits.

Pupil dilation was processed using the Pupil Labs rendering software. By rendering the videos of each participant, it was possible to access the raw data on pupil dilation. Initially, participants underwent a recording session where they were asked to focus on areas of interest. This recording generated baseline information on maximum pupil dilation before the start of practice. Only data with reliability above 60% were used, in accordance with the protocol provided by the Eye Tracking manufacturer. However, the condition of pupil dilation when the eyes fixated on areas of interest contributed to an increase in the reliability of this information, reaching an average confidence level of 91%. Maximum pupil dilation was inferred as the gain in peak pupil diameter in each trial. The average pupil dilation was defined as the gain in the mean signal courses within each trial. The peak dilation value was subtracted from the baseline to obtain the change in pupil dilation diameter for each trial, and this was used to calculate the average for each block. Finally, the average for each block (pre-test, and retention and transfer tests) was used for each. The online change was characterized by the difference between the last block and the first block of acquisition. The change Offline 1 was characterized by the difference between the retention test block and the last block of acquisition, already the change offline 2 was characterized by the difference between the transfer test block and last block of the acquisition phase.

Statistical analysis

Descriptive statistical analysis was conducted using the mean and intra-subject standard deviation of the dependent variables, organized into blocks of 10 practice trials. Prior to the main analyses, data were tested for normality using the Shapiro-Wilk test. All variables met the assumptions for parametric testing; therefore, parametric tests were used throughout the analyses. A two-way ANOVA with repeated measures on the second factor (2 groups x 9 trial blocks) was used for the acquisition phase. When statistical differences were detected, post-hoc analyses were performed using Tukey's HSD test. An ANOVA with repeated measures on the second factor (2 groups x 2 trial blocks) was used to compare the groups between the pre- and post-test. Fisher's Least Significant Difference test was used as post-hoc test due to the small number of comparisons [11]. Student's t-tests for independent measures were used to compare the groups in the transfer test, and the deltas for online and offline changes. These analyses were applied to motor performance and oculomotor measures. If the data did not meet the normality assumptions, similar non-parametric analyses were adopted. To analyze the relationship between pupil dilation and motor performance, a factorial regression analysis was conducted using pupil dilation levels in the post-test and transfer test as regressors, and the performance measures from the tests as independent variables. A significance level of $p<0.05$ was considered. The data were analyzed using Statistica (Statsoft) version 12.

RESULTS

Pre- and post-test

The inferential analysis of radial error revealed a significant effect for Group [$F(1,18) = 4.55$; $p = 0.04$; $\eta^2p = 0.20$], a significant effect for Blocks [$F(1,18) = 58.44$; $p < 0.01$; $\eta^2p = 0.76$], and a significant Group x Block interaction [$F(6,128) = 10.87$; $p < 0.01$; $\eta^2p = 0.37$]. The random practice group showed a significantly lower level of radial errors compared to the constant practice group ($p < 0.05$), and the post-test block showed a significantly lower radial error level than the pre-test block ($p < 0.05$). Post-hoc analyses of the Group x Block interaction revealed the following key findings: (1) the random practice group had significantly fewer radial errors than the constant practice group in the pre-test ($p = 0.03$), with no significant difference between groups in the post-test ($p = 0.70$) (cf. Figure 2).

Practice phase

The inferential analysis of radial error did not reveal a significant effect for Group [$F(1,18) = 0.60$; $p = 0.44$] or for the Group x Block interaction [$F(8,144) = 1.37$; $p = 0.21$]. However, a significant effect was found for Block [$F(8,144) = 2.45$; $p = 0.01$; $\eta^2p = 0.12$]. The post-hoc analyses indicate that block 1 was different from blocks 6, 7, and 9, as well as block 2 was different from blocks 3, 5, 6, 7, 8, and 9 ($p < 0.05$) (cf. Figure 2).

Transfer test

The inferential analysis of radial error revealed a significant difference between groups [$t(18) = -3.59$; $p < 0.01$; $d = 0.57$]. The random group presented a significantly lower level of radial error than the constant group (cf. Figure 2).

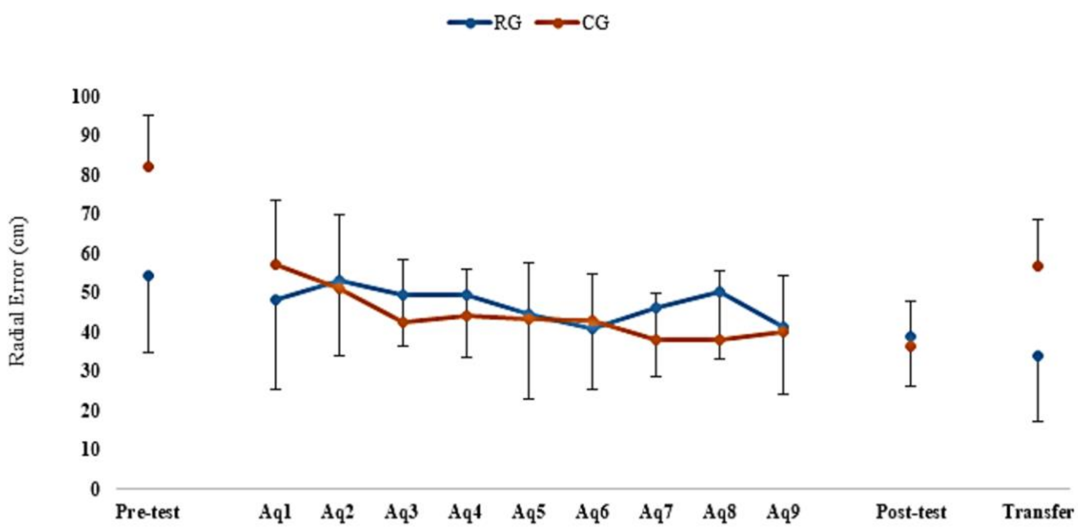

Figure 2. Results of pupil dilation (mm) in pre-test, acquisition phase, post-test and transfer test. RG = random practice group. CG = constant practice group.

Online changes

The inferential analysis of radial error did not reveal a significant difference between groups [$t(18) = 1{,}01$; $p < 0.32$; $d = 0.45$] (cf. Figure 3).

Offline changes 1

The inferential analysis of radial error did not reveal a significant difference between groups [t(18) = 0.10; p = 0.92; d = 0.04] (cf. Figure 3).

Offline changes 2

The inferential analysis of radial error revealed a significant difference between the groups [t(18) = -2.37; p = 0.02; d = -1.06]. While the constant practice group exhibited an increase in error from the last block of the practice phase to the transfer test block, the random group showed a decrease in error (cf. Figure 3).

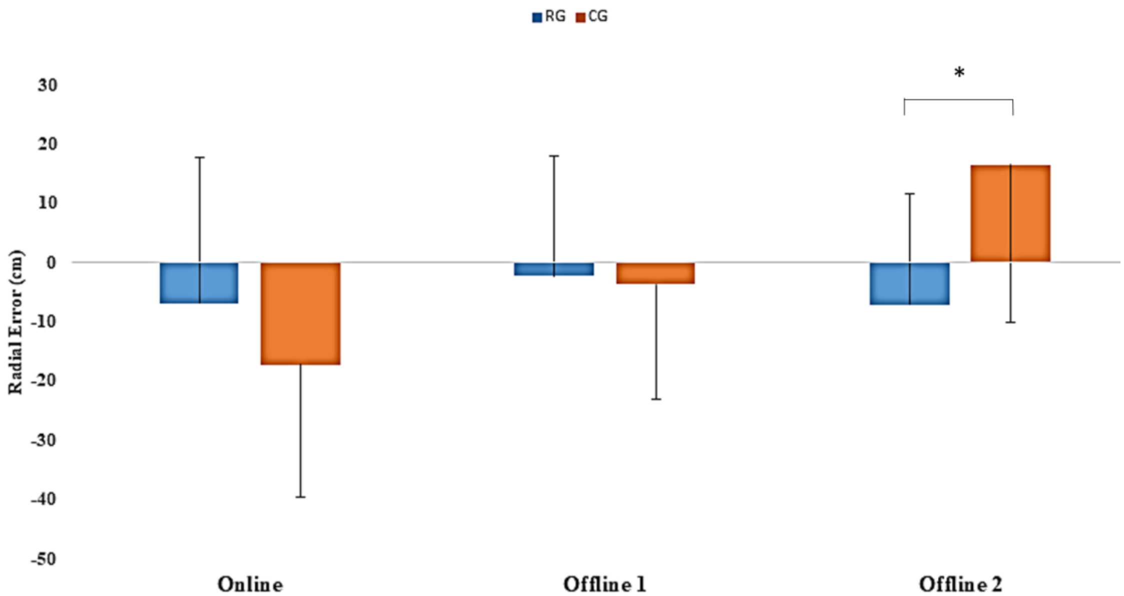

Figure 3. Results of radial error (cm) in online and offline changes. RG = random practice group. CG = constant practice group.

Pupil dilation

Pre- and post-test

The inferential analysis of pupil dilation did not reveal a significant effect for Group [F(1,18) = 0.03; p = 0.85; η^2p = 0.00] and Block [F(1,18) = 0.79; p = 0.38; η^2p = 0.04]. A significant Group x Block interaction was found [F(1,18) = 4,76; p = 0.04; η^2p = 0.20]. The post-hoc analyses indicate that the post-test of the random group presented higher pupil dilation than the pre-test of the same group ($p < 0.05$) (cf. Figure 4).

Transfer test

The inferential analysis of pupil dilation did not reveal a significant difference between the groups [t(18) = 0.80; p = 0.43; d = 0.36] (cf. Figure 4).

Association between pupil dilation and motor performance

The factorial regression analysis indicated that the level of pupil dilation, considered in isolation for both the post-test [F(2,15) = 0.41; p = 0.67; η^2p = 0.05] and the transfer test [F(2,15) = 0.33; p = 0.72; η^2p = 0.04], was not associated with motor performance. However, the interaction between pupil dilation levels in the post-test and transfer test was significantly associated with motor performance in both tests [F(2,15) = 4.25; p = 0.03; η^2p = 0.36]. The variance in the dependent variables was explained by an R^2 of 0.04 for pupil dilation in the post-test and by an R^2 of 0.11 in the transfer test.

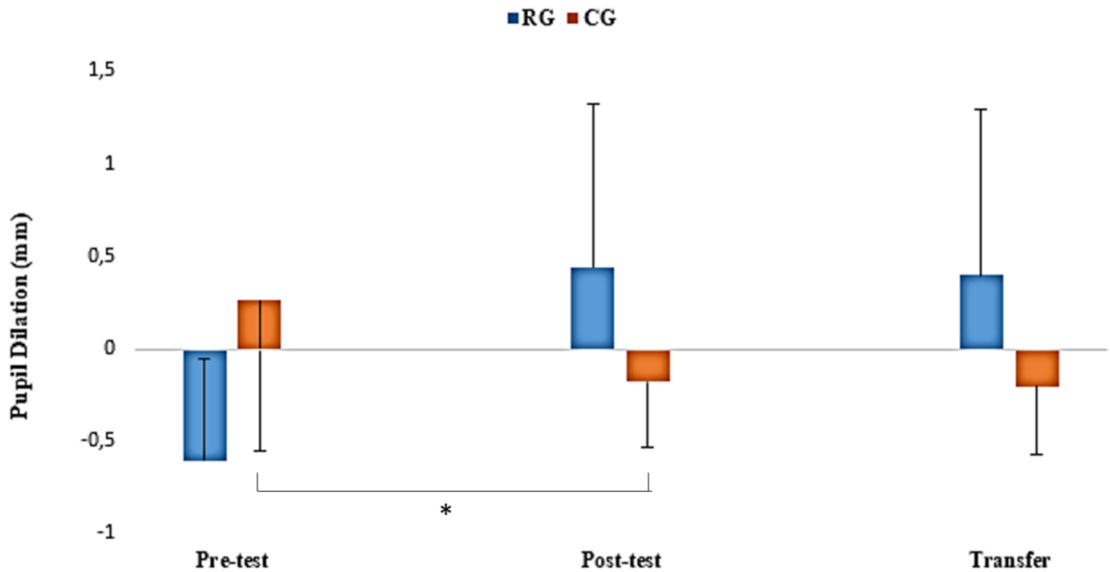

Figure 4. Results of pupil dilation (mm) in pre-test, acquisition phase, post-test and transfer test. RG = random practice group. CG = constant practice group.

DISCUSSION

The present study aimed to investigate the mental effort involved in practice organization. We hypothesized that random practice would result in lower performance during practice but lead to higher performance during the post-test and transfer test. We also expected that random practice, compared to constant practice, would show a higher level of pupil dilation in both the post-test and transfer test. Additionally, we anticipated that the results from the learning tests would correlate with levels of pupil dilation. Only one of these hypotheses was supported. In the pre- and post-test analysis, the random group showed a lower level of errors than the constant group. This result did not support the hypothesis that random practice would result in better skill retention, that is, in the post-test. However, analysis of the transfer test indicated that the random group performed better only in the transfer test, suggesting superior motor learning. Pupil dilation levels were identical between groups across all analyses.

The motor performance hypothesis in the acquisition phase

Our motor performance analysis did not show, as expected, that random practice led to worse performance during the acquisition phase compared to constant practice. Previous studies investigating practice organization using the golf-putting task have yielded mixed results. Most studies explore practice organization through the contextual interference paradigm, comparing more repetitive (blocked) practice with random practice. More studies have shown advantages for blocked practice over random practice during the acquisition phase [12,13] than those that did not [14]. A possible explanation for our findings during the practice phase is the initial advantage exhibited by the random group in the pre-test. Despite counterbalancing for sex and randomizing group assignments, a significant initial advantage for the random group was still observed.

This initial advantage appears to have facilitated the random group's performance during practice. As a result, despite following a less demanding practice schedule, the constant practice group did not surpass the performance of the random practice group. However, the initial advantage observed in the random group during the pre-test diminished throughout the acquisition phase, suggesting that constant practice supports performance improvement by offering trial-to-trial repetition. Individual differences can emerge even in randomized studies. The repetition during the practice phase created an optimal type of stimulus that favored the performance of the constant group. Consequently, the initial difference in proficiency dissipated throughout practice.

The motor performance hypotheses: (1) across the pre-test and post-test, and (2) in the transfer test

The hypothesis that random practice would result in lower performance during practice, but lead to higher performance in the post-test and transfer test, was partially supported. The optimal type of stimulus during constant practice allowed the group to develop a memory strong enough to be retrieved 24 hours later. The initial advantage observed in the random group during the pre-test disappeared in the post-test. It is not uncommon to find similar levels of learning in retention tests (post-test) when comparing variable practice to constant practice [15,16,17]. Considering that during the acquisition phase, the constant practice group completed 60 more trials of the distance and direction required in the retention test compared to the random group, this type of practice context facilitates a good level of skill retention, despite the initial proficiency disadvantage of the constant group.

The superiority of random practice has been well-documented in the literature, particularly in studies involving golf putting [12,14,16]. In our study, this superiority was observed in the transfer test. Two movement parameters were varied trial-to-trial during random practice: the level of absolute force, due to different target distances, and movement direction, due to different target angles. Our results can be explained by Schmidt's [3] propositions that varying movement parameters lead to greater abstraction of movement rules. Variations in force and direction make trial-to-trial corrections more difficult, leading to more demanding internal processes involving mnemonic functions. This fosters stronger motor schemas that support better performance during the transfer test. The constant group, on the other hand, practiced with only one target, meaning they focused on just one parameter: force and distance. This group experienced fewer parameter adjustments during practice, which negatively influenced their transfer performance [21].

The pupil dilation hypothesis and its correlation with motor performance

Despite the better transfer performance observed in the random group, the pupil dilation analysis did not reveal any differences between the groups at any point in the study. Research specifically examining the mental effort involved in practice organization is limited. Lelis-Torres et al. [5] and Bicalho et al. [6] explored this topic using electroencephalographic and oculomotor measures, respectively. Both studies found differences favoring a higher level of mental effort in random practice. Lelis et al. [5] reported that throughout practice, sensorimotor and working memory measures decreased more in the constant practice condition than in the random practice condition. Later, Bicalho et al. [6] observed greater pupil dilation during random practice.

So, what are the possible explanations for the different results observed among these studies? Lelis-Torres et al. [5] and Bicalho et al. [6] investigated the mental effort in practice organization, applying sequential typing motor tasks requiring mainly the learning of timing. In the present study, it was applied a discrete task with a higher level of elements involving a higher level of complexity. In this context, task complexity refers to the number of degrees of freedom or variables involved in controlling a motor skill [20]. Lelis-Torres et al. [5] and Bicalho et al. [6] employed a task with a single degree of freedom, where participants sequentially pressed four keys using their index finger. Such tasks typically require minimal practice to reach performance plateaus [23] and place relatively low demands on programming both relative and absolute dimensions. Increased task complexity affects various factors, including the control of variable aspects of movement. For example, force production relies on coordinated neuromuscular patterns, which are themselves dependent on the number of motoneurons involved [24].

It is possible that the sensorimotor control required by golf putting is sufficiently high that a ceiling effect was observed in pupil dilation when comparing random and constant practice. That is, even the simplest practice demands enough mental effort to control execution on a trial-to-trial basis. Additionally, considering the constant group's initial disadvantage, participants in this group may have exerted extra effort to meet the task's goals, resulting in a similar level of performance to that of the random group. If this is the case, the similar levels of pupil dilation observed during practice, as well as the post- and transfer tests, may have been significantly influenced by individual differences rather than the practice organization itself. The analysis of the relationship between pupil dilation and motor performance in the post- and transfer tests suggests that the combined pupil dilation levels from both tests partially explain motor performance. This result leaves open the possibility of further investigating the relationship between mental effort and practice organization using more complex motor tasks.

Despite the limitations of this study, the results suggest several avenues for further investigation. First, our findings indicate that our methods are adequate, but we need to increase the sample size to better observe the relationship between mental effort and practice organization. An ad hoc sample size calculation indicates that we need to add 13 participants to each practice group. Another avenue for exploration is whether less proficient learners are affected differently by practice organization, potentially influencing their levels of pupil dilation due to the higher demands of mental effort in this group.

CONCLUSION

In this study, we investigated the influence of random and constant practice on motor performance and mental effort, as measured by pupil dilation, during a golf-putting task. While the random practice group demonstrated superior motor learning, particularly in the transfer test, no significant differences in pupil dilation were observed between the groups throughout the study. Our findings are consistent with the idea that the random practice group's advantage in motor learning may be related to greater cognitive demands involved in processing movement parameters, as widely supported in the existing literature. However, the absence of significant differences in pupil dilation, a physiological indicator of mental effort, may reflect limitations in the sensitivity of this measure, potentially influenced by individual variability and the cognitive complexity of the task.

These results open avenues for further exploration into the relationship between practice organization, task complexity, and mental effort. Future studies with larger sample sizes and consideration of individual learner proficiency may provide more insight into how practice conditions affect both motor performance and mental effort.

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