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An Examination of the Contextual Interference Effect and the Errorless Learning Model during motor learning

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Abstract

The purpose of this study was to investigate the combined effects of random and block practice, with errorless and errorful conditions, on motor learning. One hundred-twenty participants (all male, Mage=21.19±1.4 years) were randomly assigned to one of eight groups. Participants completed a dart throwing task across a pre-test, acquisition phase, retention test (48 hours later) and two secondary-task transfer tests (Tr 1 after acquisition; Tr 2 after retention). The structure of practice in the acquisition sessions was different depending on the assigned group. In the retention test, evidence supporting the CI effect was found in the 'errorless' conditions, but not in the 'errorful' conditions. In the transfer tests, the findings indicated that the impact of errorless and errorful conditions on participants' automation levels depends on the structure of practice. Participants in the Random-Errorless group performed better in the transfer tests than those in the Random group and the Random-Errorful group, suggesting greater automation levels following errorless practice. However, no differences were found between the Block-Errorless group and the Block-Errorful group on the transfer test, and under a serial structure of practice greater performance was found on the transfer tests for the errorful group compared to the errorless group.

Keywords: Skill acquisition, implicit learning, cognitive effort, error processing, challenge point framework

Introduction

First introduced by Battig (1979), and later integrated into motor learning by Shea and Morgan (1979), the contextual interference (CI) effect postulates that the structure of practice impacts the acquisition of motor skills (Brady, 2008; Magill & Hall, 1990; Wright et al., 2016). It is now well-established that for sequential and fine motor movements in adults, learning a set of diverse tasks is better accomplished when it takes place under random conditions (performing tasks in an interleaving unpredictable order) than when the practice program is blocked (completing tasks in the same skill sets before moving to a new task) (Brady, 2004; Barreiros, Figueiredo, & Godinho, 2007). The typical research finding is that a blocked structure of practice results in superior motor performance during practice relative to a random trial arrangement. However, a random practice structure results in superior learning (e.g., retention and transfer test performance), relative to a blocked arrangement of trials during practice. This paradoxical finding, commonly referred to as the CI effect (Magill & Hall, 1990), is discussed in the Challenge Point framework by Guadagnoli & Lee (2004). This framework contends that learning is related to the information available for processing during practice, which should be altered depending on the difficulty of the task and the skill level of the performer. In the context of the CI effect, the challenge point framework builds on the body of research in the motor learning literature to predict that the advantage of random practice will be greatest for tasks with low nominal difficulty and smallest for tasks of high nominal difficulty (see also Bjork, 1998). This is based on the theoretical explanations for the CI effect and the increased cognitive demand (potential available information) that underpins the benefits of a random structure of practice (see also Marteniuk, 1976).

Although the CI effect is a relatively robust finding in the literature, there is still debate about the underlying mechanisms of this phenomenon. The *elaboration hypothesis* suggests that random practice is more effective because it allows learners to make more elaborative contrasts and comparisons between the practiced tasks because the skills differ from trial to trial (Shea & Zimny, 1983). In contrast, the *reconstruction hypothesis* posits that random practice yields superior outcomes because learners experience partial forgetting of one skill as they are practicing other skills, which promotes learning as the motor program must be continually reconstructed (Lee & Magill, 1985). Both hypotheses indicate how random practice promotes more information processing (i.e. cognitive effort) compared to block practice (Lee, 2012), which optimizes learning within the practice environment (Guadagnoli & Lee, 2004).

One of the drawbacks of the current research on the CI effect is that the continuum for the practice structure from low to high interference is scalarized in a qualitative form based on phenomenological similarities (Schöllhorn, 2016). In other words, there is no guideline to quantify block and random practice schedules against levels of interference, and no distinction is made between different random practice schedules. An attempt to study contextual interference schedules in a quantitative manner was a study carried out by Buszard et al. (2017). The purpose of their study was to develop a standard for estimating the levels of contextual interference during practice. To serve this purpose, the researchers used a coordinate plane consisting of four quarters. The first quarter targeted high levels of between-skill (e.g., executing tennis services randomly among other tennis skills) and within-skill (e.g., executing different types of tennis services randomly) interference. The second quarter targeted interactions between high between-skill and low within-skill (e.g., executing only one type of tennis service) interference. The third quarter targeted low levels of between-skill (e.g., executing tennis services independent of other tennis skills) and high levels of within-skill interference. Finally, the fourth quarter targeted low levels of between-skill and within-skill interference. Although this quantitative method is unique, it has two major weaknesses. First, it does not consider the variations in the parameters as an important source of change. A number of studies have shown that changing the parameters of a generalized motor program, especially in applied research, leads to stronger contextual interference effects (Wrisberg & Lui, 1991; Hall, Domingues, & Cavazos, 1994; Sekiya, Magill, & Anderson, 1996). Second, sports which utilize a single motor pattern (e.g., dart throwing, shooting, bowling) can hardly be accounted for by Buszard et al.'s (2017) coordinate plane because between-skill interference is not applicable for such sports. If parameter change is to be used as a source of interference, a question that requires more research is how parameter changes that make the task easier or harder should be structured and whether, for example, starting practice with an easier task parameter is more beneficial for learning compared to starting with a more difficult task parameter.

In a tangential line of investigation, motor learning researchers have proposed the important role of error processing on motor skill acquisition (Holroyd, Yeung, Coles, &

Gohen, 2005; Koehn, Dickinson, & Goodman, 2008). In the errorless learning literature, it is proposed that when a binary error occurs, the performer attempts to identify why they did not achieve the desired outcome, and generate explicit hypotheses about how to improve performance in the future (Maxwell, Masters, Kerr, & Weedon, 2001). Therefore, an errorful trial probably leads to greater cognitive effort due to the additional processing that takes place when compared with an errorless trial (Lam et al., 2010). It has been shown that, compared to errorful learning, errorless learning improves performance on retention tests, and alleviates a drop-in performance when executing synchronous cognitive tasks in a transfer test (e.g., Capio, Poolton, Sit, Holmstrom, & Masters, 2013; Maxwell et al., 2001; Poolton, Masters, & Maxwell, 2005), although this is suggested to be more efficient on simple learning tasks (Prather, 1971). It is suggested that errorless learning promotes more implicit learning as it reduces the amount of explicit hypothesis-testing and conscious awareness of the rules early in practice (Masters and Maxwell, 2004).

A related concept to ‘errors’ in the motor learning literature is that of ‘noise’, which traditionally referred to variability of movement and deviations in performance and was avoided during practice (Fitts, 1954). However, recent research has shown that higher levels of task-related variability predicted faster learning (Wu et al., 2014) and that motor noise is a central component of motor learning (Herzfeld & Shadmehr, 2014). In this approach, noise is on a continuous scale and is a descriptor of the structure or dynamics system output, which is considered distinct from variability (standard deviation of errors) (Slifkin & Newell, 1998). While the concepts of binary errors and continuous noise are related, there are different ways of examining these and the current paper focuses on the errorless learning approach. In the errorless learning literature, the amount of noise and movement variability between each trial is not specifically manipulated, but instead the environment is manipulated in order to minimize the number of binary errors the learner produces early in practice (e.g., starting from a closer distance to the target, starting with smaller targets, etc.). For example, Maxwell et al. (2001) asked participants to complete 400 trials of a golf-putting task at different distance intervals from a specified target. For the errorless group, the researchers first set the hole at a short distance, and then after every 50 trials, they increased the distance by 25 cm. The errorful learning group performed the task along the same distance intervals, but in an opposite direction (i.e., from long to short distance). Finally, a third group performed the task randomly. The results showed that participants in the random and errorful groups had poorer subsequent performance on the task than those in the errorless group. Specifically, the findings indicate that reducing errors during the beginning of practice reduced the involvement of explicit hypothesis testing resulting in more implicit learning, as demonstrated by more robust performance under secondary task load for errorless learners compared to errorful learners.

The inclusion of transfer tests with a secondary task is common in the motor learning literature, especially when examining implicit learning, as it allows for the participants' automation level to be gauged (Chauvel et al. 2012; Kal, Van Der Kamp, Houdijk, 2013; Maxwell, Masters, Eves, 2000). The automation level is of high significance in learning motor skills as automated motor skills should not be affected by factors that drain the cognitive resources, such as fatigue, psychological pressure, and multi-task performance. The implicit learning theory suggests that implicit learning would lead to more automation and less conscious control compared to explicit learning, resulting in superior performance in a secondary-task transfer test (Masters, Poolton, Maxwell, Raab, 2008; Maxwell et al., 2001; Poolton, Maxwell, Masters, Raab, 2006).

A review of the evidence on the effects of block and random practices suggest that cognitive effort is a byproduct of functional learning (Magill & Hall, 1990). However, the evidence coming from the studies on implicit (i.e., errorless) and explicit (i.e., errorful) motor learning suggests that minimizing overt cognitive effort during the learning process is recommended (Maxwell, Masters, & Eves, 2003; Maxwell et al., 2001). Rendell, Masters, Farrow, and Morris (2011) investigated the contradiction between these two bodies of literature by examining the CI effect in a kicking and handball task using a number of measures that have typically been applied in the implicit motor learning literature (e.g., performance during a secondary task transfer). Interestingly, the findings indicated that random practice may share characteristics of implicit learning. Random practice resulted in greater cognitive load across practice, compared to block practice, as predicted by the CI literature. Performance in the transfer test with a secondary task showed no difference between the groups on the simple handball task, but for the more complex kicking task, the random group showed significantly better performance compared to the block group. The authors contended that high levels of cognitive effort emerging from changing tasks during random practice of a complex skill, may prevent the learner's conscious focus on the practiced movement, leading to a more implicit learning style (see also, Rendell et al., 2009). The study by Rendell et al. (2011) demonstrated the superiority of random practice over block practice for simultaneous performance of the primary and secondary tasks, however, they did not examine the role of error processing in CI effect.

Broadbent, Causer, Williams, and Ford (2017) used a perceptual-cognitive task in tennis to examine the role of error processing in the CI effect. Using a probe reaction time task in Experiment 1, it was shown that random practice elicits greater cognitive demand compared to blocked practice. In Experiment 2, the authors inserted a cognitively demanding secondary task into the intertrial interval of blocked and random practice, and investigated the effects of errors on performance of the primary and secondary task. Decision time on the primary task was slower following an error compared to an errorless trial, but only for the random group and not the blocked group. Moreover, for the random group performance on the secondary task was negatively affected following an error compared to an errorless trial. Based on these findings, the authors proposed an alternative hypothesis for the CI effect termed the *error-processing hypothesis.* This alternative theory, incorporates the elaboration hypothesis and reconstruction hypothesis, but also proposes that it may not only be the frequent randomized switching of tasks that leads to increased cognitive effort, but the combination of task switching with error processing. This additional cognitive demand during practice reduces performance in acquisition but results in enhanced learning as shown through performance in retention and transfer tests.

Broadbent et al.'s (2017) error processing hypothesis provides a plausible explanation for the contradiction between implicit learning and contextual interference (Rendell et al., 2011; 2009). According to the hypothesis, processing more errors during random practice increases cognitive effort, which in return, increases the load exerted on the working memory system. By increasing the cognitive load placed on the working memory system, the error processing and increased cognitive effort experienced in random practice would reduce the explicit processing related to the underlying hypotheses of task performance, and ultimately learning occurs in an implicit fashion (Broadbent et al., 2017). However, this hypothesis does contradict the errorless learning literature which suggests that simplifying the task and reducing the learner's errors will result in less hypothesis testing and greater performance. Therefore, both the error processing hypothesis for the CI effect, and the errorless learning hypotheses from the implicit learning theory, make similar predictions about the underlying learning mechanisms, but appear to achieve optimal learning by different practice conditions. It is possible that the varying levels of interaction between task switching and error processing could lead to different levels of learning. This notion is supported by Bootsma, Hortobagyi, Rothwell & Caljouw (2018), who suggests that the challenge point framework is only applicable when a certain amount of errors is present. Furthermore, a recent paper that provides an extension to the challenge point framework, highlights that while increased challenge in practice can be beneficial for learning, the increase in errors that accompanies this challenge can have motivational costs that can negatively impact learning (Hodges & Lohse, 2022). Research to date has yet to examine the impact of errorless and errorful practice conditions on the CI effect in a systematic manner, to investigate the optimal practice condition for motor performance and learning (Guadagnoli & Lee, 2004).

The present study sought to investigate the combined effects of random and block practice, with errorless and errorful practice conditions, on motor learning and automation. In doing this, we have attempted to introduce a method for quantifying contextual interference with an emphasis on (a) changing the parameters of the same motor learning program and (b) changing the functional task difficulty. On this basis, the various practice groups in this study occupy different points in the challenge point framework (Guadagnoli & Lee, 2004), and the inclusion of a retention test and transfer test with a secondary task, allow for a sophisticated investigation in to the interaction between practice structure (random, blocked, serial), task difficulty, error processing (errorless, errorful) and implicit learning, on motor skill acquisition.

Therefore, in this study, the main purpose was to investigate the CI effect and the errorless learning model on learning dart throwing skills and importantly examine the combination of these practice conditions to potentially develop an interference-error model. We predict that random practice will promote greater learning compared to block practice due to increased processing requirements (Broadbent et al., 2017). We also predict that errorless practice conditions will promote greater levels of automation, and therefore greater performance under secondary task demands in the transfer test, due to reduced error processing requirements (Masters et al., 2008). The combination of random practice with errorless conditions is therefore predicted to facilitate the greatest learning compared to other combinations of conditions although this study is exploratory in nature.

Methods

Research Design

In this study, a quantitative method is proposed for scheduling contextual interference. The proposed method includes a combination of block, serial and random schedules (contextual interference) with errorless motor learning (implicit and explicit motor learning). The method is schematically presented in Figure 1. As shown in the figure, combinations of block, serial, and random practice schedules with errorless and errorful schedules results in eight different practice types as the following;

(1) Random practice (i.e., random execution from different distances from the target),
(2) Random-Errorless practice (i.e., first, random execution from distances close to the target and then, from distances far from the target),
(3) Random-Errorful practice (first, random execution from distances far from the target and then, from distances close to the target),
(4) Serial-Errorless practice (executing a trial across from the closest to the farthest distance from the target and then, repeating the trial),
(5) Serial-Errorful practice (executing a trial across from the farthest to the closest distance from the target and then, repeating the trial),
(6) Block-Errorless practice (Full execution of the closer distance and then, full executions of the farther distances),
(7) Block-Errorful practice (Full execution of the farther distance and then, full executions of the closer distances), and finally,
(8) Constant practice (execution at one distance throughout practice)

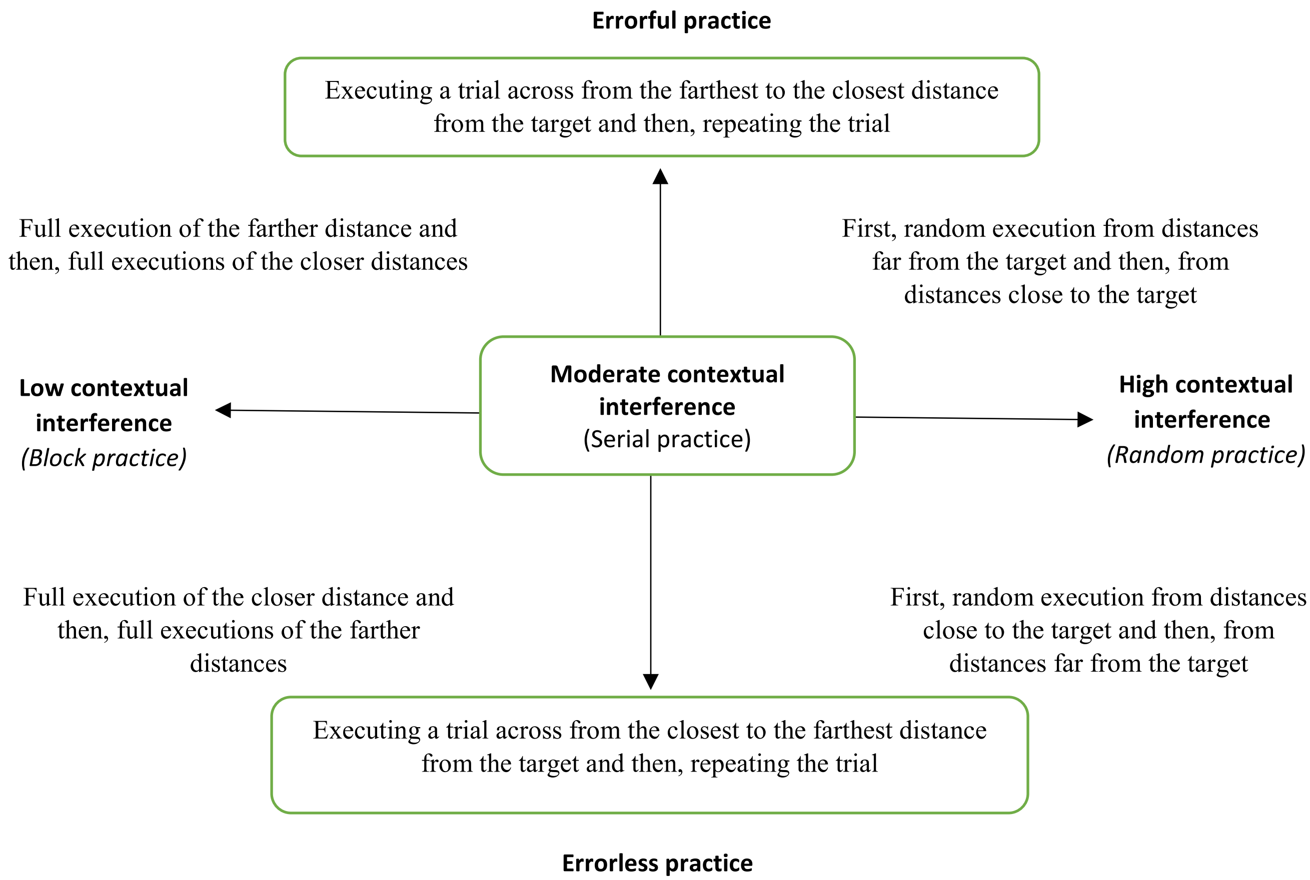

Figure 1. The method for quantification of contextual interference

Participants

A cohort of 120 male students with a mean age of 21.19 years old (SD= 1.4), a mean mass of 73.64 kg (SD= 11.53), and a mean height of 1.76 cm (SD= 0.076) were sampled and randomly assigned to one of eight groups each consisting of 15 participants. All the participants were right-handed (assessed through Edinburgh's (1971) handicap questionnaire), healthy (assessed through Goldberg and Hillier's (1979) general health questionnaire), had either normal eyesight or wore modified glasses (assessed through the Snellen chart), and had no dart throwing experience. All subjects participated in the study voluntarily and signed the informed consent form. All experimental methods were approved by a university ethics committee.

Research methodology

Figure 2 shows the various distances from which the darts were thrown to the target by the participants. As illustrated in the figure, there were seven different throwing distance. The closest distance, 137 cm from the target (from the front foot), was set as the minimum distance for throwing the dart. Each sequential distance was determined by adding 33.33 cm to the preceding distance. This method resulted in the farthest distance to the target being 337 cm. The height of the score board from the ground was 173 cm. Participants were instructed to throw the dart striking the center of the target during each trial.

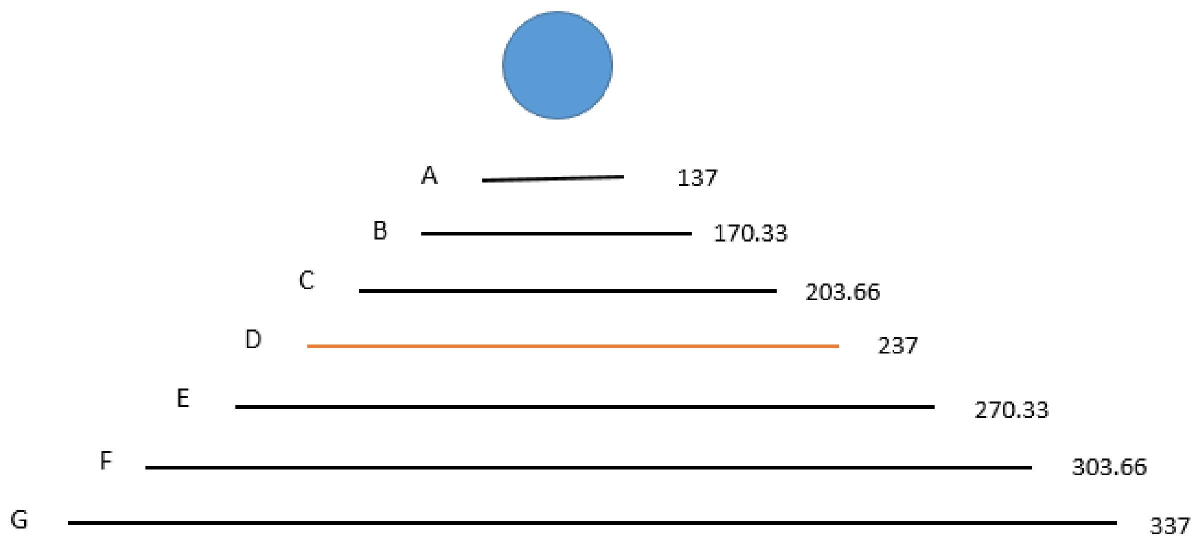

Figure 2. Different distances from the target for throwing the dart

After modeling the throwing pattern and presenting the required information, each participant took a short pre-test (i.e., 10 throws from distance D). Subjects participated in the pre-test without any instructions. Before each acquisition session, the throwing pattern was displayed three times. In the first acquisition session, during the display of the pattern, the position of the legs, bending the body forward and throwing the dart through the elbow and wrist joint were emphasized. The instructions regarding the execution of the pattern were provided only once at the beginning of the first session and was the same for all participants. The pretest was followed by three acquisition sessions of 70 trials (210 trials in total) across three consecutive days. After every 10 trials, the participant was allowed to take a two-minute rest. At the end of each day of practice, an immediate acquisition test (i.e., 10 throws from distance D) was taken by the participant. On the final practice day, after the final acquisition session, a transfer test (Transfer test 1) was included (i.e., 10 throws from distance D with a secondary task). Participants returned 48 hours following the third day of practice and completed a retention test (i.e., 10 throws from distance D) and another transfer test (i.e., Transfer test 2; 10 throws from distance D with a secondary task). Table 1 shows the practice and testing schedule for each of the experimental conditions.

Table 1. Practice and testing program of groups

Experimental Groups	Pre-test	Acquisition Sessions (three sessions in consecutive days)*	Acquisition Test (after each acquisition session)	Secondary-Task Transfer Test 1 (after Acquisition)	Retention Test (48 hours later)	Secondary-Task Transfer Test 2 (after Retention)
Block-Errorless	10 throws in distance D	A:10 throws, B:10 throws, C:10 throws, D:10 throws, E:10 throws, F:10 throws, G:10 throws	10 throws in distance D	10 throws in distance D	10 throws in distance D	10 throws in distance D
Block-Errorful	10 throws in distance D	G:10 throws, F:10 throws, E:10 throws, D:10 throws, C:10 throws, B:10 throws, A:10 throws	10 throws in distance D	10 throws in distance D	10 throws in distance D	10 throws in distance D
Serial-Errorless	10 throws in distance D	A, B, C, D, E, F, G: one throw from each distance – repeat ten times	10 throws in distance D	10 throws in distance D	10 throws in distance D	10 throws in distance D
Serial-Errorful	10 throws in distance D	G, F, E, D, C, B, A: one throw from each distance – repeat ten times	10 throws in distance D	10 throws in distance D	10 throws in distance D	10 throws in distance D
Random	10 throws in distance D	A, C, B, E, D, F, G, B, D, F, E, B, a, G, C, D, E, F, A, G, D, E, D, B, G, B, A, G, F, G, F, D, B, C, G, D, A, E, A, G, F, B, C, D, C, G, E, D, B, F, C, A, D, C, A, C, F, G, E, A, C, B, E, C, A, F, E, F, E, B	10 throws in distance D	10 throws in distance D	10 throws in distance D	10 throws in distance D
Random-Errorless	10 throws in distance D	A, B, C, A, C, B, B, A, C, B, C, A, C, A, B, C, B, A, A, C, B, B, C, A C, D, E, C, E, D, E, C, D, E, D, C D, C, E, D, E, C, C, D, E, E, D E, F, G, E, G, F, F, E, G, F, G, E G, E, F, G, F, E, E, F, G, F	10 throws in distance D	10 throws in distance D	10 throws in distance D	10 throws in distance D
Random-Errorful	10 throws in distance D	E, F, G, E, G, F, F, E, G, F, G, E G, E, F, G, F, E, E, F, G, F, G, E C, D, E, C, E, D, E, C, D, E, D, C D, C, E, D, E, C, C, D, E, E, D A, B, C, A, C, B, B, A, C, B, C, A, C, A, B, C, B, A, A, C, B, B	10 throws in distance D	10 throws in distance D	10 throws in distance D	10 throws in distance D

Constant	10 throws in distance D	70 Throws from distance D	10 throws in distance D	10 throws in distance D	10 throws in distance D	10 throws in distance D

*According to figure 2, the letters A to G indicate the closest distance to the target (i.e., A), to the farthest distance to the target (i.e., G)

Test of automation level (Transfer tests)

A secondary task was employed during the transfer tests in order to assess the participants' automation levels. Automation test was performed in both acquisition stage (immediately after the third day acquisition test [transfer 1]) and retention (immediately after the retention test [transfer 2]). In these tests, each participant was asked to perform a secondary cognitive task at the same time as performing the primary task (i.e., throwing the dart). For the secondary task, each participant was required to count the number of specific horn sounds played in the gym via a speaker and report the number to the researcher at the end of the test. Three different horn sounds were played, but the participant only had to pay attention to one of them and report how many times it was heard. Participants were encouraged to focus on both tasks and try to perform as well as possible on both.

Evaluation method

Participants threw darts to a target, which was a 45-cm-diameter board and was placed 173 cm above the ground. Two-dimensional error was used in order to calculate performance errors whereby a point was set up on the board with the dimension's x and y for each throw. Then, the root mean square error (RMSE) was used in order to calculate the performance errors:

$$\text{RMSE}=\sqrt{(\sum \mathcal{X}^2+\sum \mathcal{Y}^2)}$$

For this purpose, the coordinate axis was drawn on the dart screen. According to the coordinate, for each throw, two scores of X and Y (ordered pair) were recorded. A continuous interval scale for error was used to (i.e., distance from the target) rather than a binary scale (i.e., hit target or did not hit target) to provide more insight in to the movement variability and deviation in performance. The greater the distance from the target the greater the degrees of error. There was a 10-second interval between each trial and during this period, the participants score on that trial was measured and recorded by the lead researcher. The use of any video recording during the performance could have led to increased anxiety for the participant and possibly impacted performance, and therefore the measurement was completed manually after each trial by the lead researcher.

Data analysis

Before analyzing the performance of the groups across the test phases, group absolute errors in the pre-test were compared via a one-way ANOVA. The results of the comparison showed that the groups had no significant difference in the dependent variable before the initiation of practice ($F_{7, 119} = .615$, $p = 0.742$).

Factorial analysis of variance (ANOVA) with mixed design was employed in order to compare the groups' performance on the pre-test, three phases of acquisition and retention test (8 Group x 5 Test). If significant differences were observed, follow-up tests were used to determine where differences resided. Separate repeated measures ANOVAs (to compare the results of the tests for each group) and Separate one-way ANOVAs (to compare the groups in each test) were completed, with follow-up Bonferroni Pairwise comparisons. To examine differences between the groups on the two transfer tests (i.e., Transfer test 1 after the acquisition phase and Transfer test 2 after the retention test), one-way ANOVAs were conducted, with follow-up Bonferroni Pairwise comparisons to infer the specific differences between the groups. In order to describe the data, the indices of mean and standard deviation were used. The Shapiro-Wilk test was used to test normal distribution assumption. Also, the variance-covariance homogeneity assumption was tested with Mauchly's sphericity test before the repeated measures ANOVAs. A significance level is set at 0.05 and d Cohen is between 0 and 1.

A priori power analysis was adopted for estimating the power statistics of the obtained results. For this purpose, G Power software was used wherein the *p* value was set at .05. Given the mean effect sizes of the previous studies on contextual interference (Brady 2004; r = .38) and errorless learning (Hardwick, Rottschy, Miall, Eickhoff, 2013; r = .56), the power of the within-between factorial ANOVA with repeated measures and one-way ANOVA was respectively found to be .99 and .97. These results seemed very insightful regarding the sample size (N=120), number of the groups (N=8) and tests (N=5), and mean correlation between the test results (r=.04) in the present study.

Results

Prior to running the mixed design ANOVA (8 Group x 5 Test), the assumption of the normality of distribution (i.e., the Shapiro-Wilk test), variance consistency between the groups (i.e., the Levine test) and consistency of the variance-covariance matrix (Mauchly's W= 0.867, p= 0.072) were checked.

Table 2 shows the results of the factorial ANOVA conducted in the present study. As shown in this table, the test main effect, the group main effect and the interactive effect were all statistically significant. Due to the statistical significance of the interactive effect, follow-up repeated measures ANOVAs (to compare the results of the tests for each group) and one-way ANOVAs (to compare the groups in each test) were completed. The results of the repeated measures ANOVAs for the different groups are shown in Table 3. As observed from the table, there was a significant main effect for all groups. The results of the follow up paired comparisons between the tests showed that there was a significant difference between the pre-test and the retention test for all the groups; Block-Errorless (MD=1.043, Cohen's *d*=0.72, p=0.001), Block-Errorful (MD=2.042, Cohen's *d* =0.87, p= 0.001), Serial-Errorless (MD= 1.22, Cohen's *d*= 0.76, p= 0.001), Serial-Errorful (MD= 2.031, Cohen's *d* = 0.72, p= 0.001), Random (MD= 2.36, Cohen's *d* = 0.88, p= 0.001), Random-Errorless (MD= 3.2, Cohen's *d* = 0.92, p= 0.001), Random-Errorful (MD= 0.965, Cohen's *d* = 0.48, p= 0.04) and Constant (MD= 0.821, Cohen's *d* = 0.53, p= 0.003). In contrast, the majority of groups did not show significant changes across acquisition with only the Serial-Errorless group showing a significant improvement from acquisition 1 to acquisition 2 (MD= 0.383, p= 0.014) and the Random-Errorful group showing a significant decrement in performance from acquisition 1 to acquisition 2 (MD= -1.001, p= 0.015). However, between-group differences were found across the acquisition phases, which we have reported below.

Table 2. The results of the Factorial ANOVA

Source	Sum of Squares	df	Mean Square	F	Sig	Partial Eta Square
Test	222.063	4	55.516	117.195	0.001	0.511
Group × Test	120.529	28	4.305	9.087	0.001	0.362
Error (Test)	212.219	448	0.474			
Group	66.606	7	9.515	8.446	0.001	0.345

Table 3. The results of the follow-up repeated measure ANOVAs to compare the sessions in each group

Source	Sum of Squares	df	Mean Square	F	Sig	Partial Eta Square
Block-Errorless	39.764	2.368	16.795	25.169	0.001	0.643
Block-Errorful	31.565	4	7.891	15.003	0.001	0.517
Serial-Errorless	46.847	2.299	20.373	48.369	0.001	0.776
Serial-Errorful	34.413	2.369	14.527	11.835	0.001	0.458
Random	50.172	1.971	25.457	20.362	0.001	0.593
Random-Errorless	77.098	2.471	31.201	39.673	0.001	0.739
Random-Errorful	23.437	1.793	13.074	12.248	0.001	0.467
Constant	39.296	2.445	16.070	30.759	0.001	0.687

In order to compare the groups in the acquisition and retention tests, one-way ANOVAs were used. As shown in Table 4, except for the acquisition test on the first session, there was a significant difference between the groups in all tests. The Bonferroni post hoc test of multiple comparisons was used to examine the location of the significant difference in each phase. The full table of these results can be found in the supplementary materials. In acquisition 2, the Random group and the Random-Errorful group performed significantly worse than the Block-Errorless, Serial-Errorless, Random-Errorless, and Constant group, *p's* > .05. In acquisition 3, the random, Random-Errorful and Block-Errorful groups performed significantly worse than the Block-Errorless, Serial-Errorless and Constant group, *p's* > .05. Furthermore, the Random-Errorful group performed significantly worse than the Random-Errorless and Serial-Errorful group, *p's* > .05. With regards to the retention test performance,

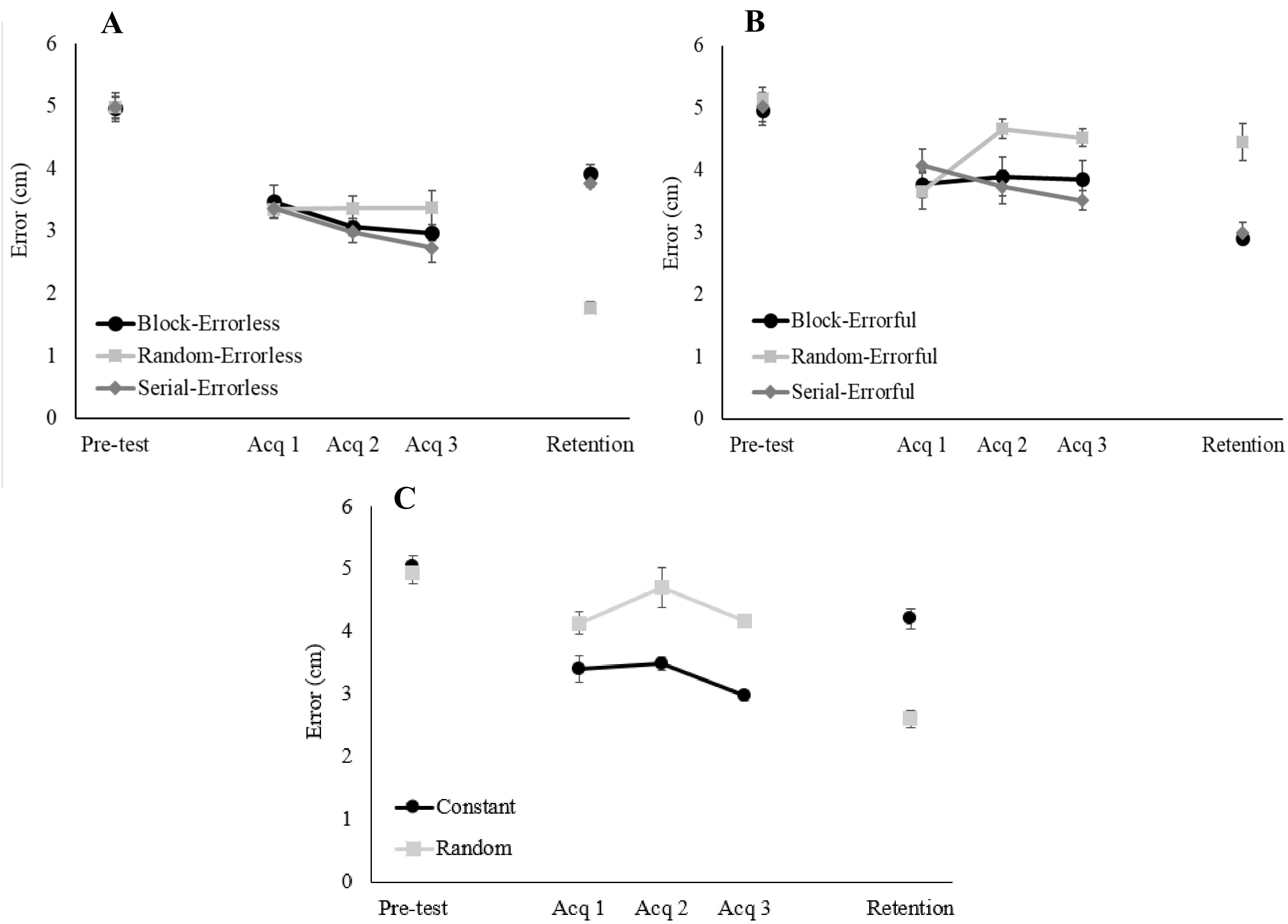

Figure 3. (A) The performance of the Block-Errorless, Serial-Errorless and Random-Errorless groups in the Pre-test, Acquisition tests, and in the Retention test. (B) The performance of the Block-Errorful, Serial-Errorful and Random-Errorful groups in the Pre-test, Acquisition tests, and in the Retention test. (C) The performance of the Constant and Random groups in the Pre-test, Acquisition tests, and in the Retention test.

the specific interest in this study was the impact of errorless and errorful conditions on the classic CI effect (e.g., the difference between the block, serial and random structure of practice). As shown in Figure 3a, the Random-Errorless group performed significantly better in the retention test compared to the Block-Errorless group (p = .001) and the Serial-Errorless group (p = .001). No significant difference was found between the Block-Errorless and Serial-Errorless groups (p = 1.00). In contrast, when examining the errorful conditions, as shown in Figure 3b, the Random-Errorful group had significantly worse performance compared to the Serial-Errorful group (p = .001) and the Block-Errorful group (p = .001). No significant difference was found between the Serial-Errorful group and the Block-Errorful group (p = 1.00). Furthermore, the Random group performed significantly better in the retention test compared to the Random-Errorful group (p = .001), but significantly worse than the Random-Errorless group p = .001). Finally, the Constant group performed similarly to the three errorless groups across the acquisition phases, but in the retention test performed similar to the Random-Errorful group with worse performance compared to the majority of the other groups. As shown in Figure 3c, the Constant group performed better than the random group in acquisition, but in the retention test the random group performed better.

Table 4. One-way ANOVAs to compare the groups at each session

Source	Sum of Squares	df	Mean Square	F	Sig	Partial Eta Square	95% Confidence Interval
Acquisition 1	10.484	7	1.498	2.022	0.058	0.12	3.498 - 3.817
Acquisition 2	45.704	7	6.529	8.784	0.001	0.354	3.556 – 3.929
Acquisition 3	41.444	7	5.921	10.591	0.001	0.398	3.336 – 3.681
Retention	87.032	7	12.433	31.397	0.001	0.662	3.133 – 3.523

One-way ANOVAs and the Bonferroni post hoc test were conducted in order to compare the groups' performance on the two secondary-task transfer tests (i.e., Transfer test 1 after the acquisition phase and Transfer test 2 after the retention test). In order to ensure that all groups paid attention to the secondary task, the group's performance in the secondary task (absolute error of reported horns) was compared. The result of the one-way ANOVA showed that there was no significant difference between the groups on either of the transfer tests (p's > .05). As shown in Table 5, the differences between the groups for primary task performance in both the transfer tests were statistically significant. The Bonferroni post hoc test of multiple comparisons was used to examine the location of the significant group differences in each transfer test. The full table of these results can be found in the supplementary materials.

Table 5. One-way ANOVAs to compare the groups at the transfer tests

Source	Sum of Squares	df	Mean Square	F	Sig	Partial Eta Square	95% Confidence Interval

Transfer Test 1 (Acquisition Phase)	14.943	7	2.135	8.002	0.001	0.333	4.675 - 4.905
Transfer test 2 (Retention Phase)	31.566	7	4.509	26.965	0.001	0.628	4.426 – 4.661

The specific interest with the secondary-task transfer tests in this study was to examine the automation levels of the different structures of practice when combined with errorless and errorful conditions. For a random structure of practice, the manipulation of errors during practice significantly altered the participants' automation levels. As shown in Figure 4a, the Random-Errorless group performed significantly better in both the secondary-task transfer tests compared to the Random group (Tr 1, $p = .043$; Tr 2, $p = .018$) and the Random-Errorful group (Tr 1, $p = .001$; Tr 2, $p = .001$). Moreover, the Random-Errorful group performed significantly worse compared to the Random group on Transfer test 2 ($p = .001$), but not in Transfer test 1 ($p = 1.00$). In contrast, as shown in Figure 4b the Serial-Errorless group performed significantly worse on Transfer test 2 compared to the Serial-Errorful group ($p = .002$), but not in Transfer test 1 ($p = .102$). Finally, as shown in Figure 4c, there was no significant difference found between the Block-Errorless and Block-Errorful groups in either transfer test (Tr 1, $p = 1.00$; Tr 2, $p = 1.00$). The Constant group performed significantly worse than the Blocked-Errorful group in Transfer test 1 ($p = .037$), but not in Transfer test 2 ($p = .121$), and showed no difference compared to the Block-Errorless group (p's > .05). It appears that the impact of errorless and errorful conditions on participants' automation levels depends on the structure of practice, with errorless conditions promoting greater automation under random practice, errorful conditions promoting greater automation under serial practice, and no difference in automation levels being found between errorless and errorful conditions when under a blocked structure of practice.

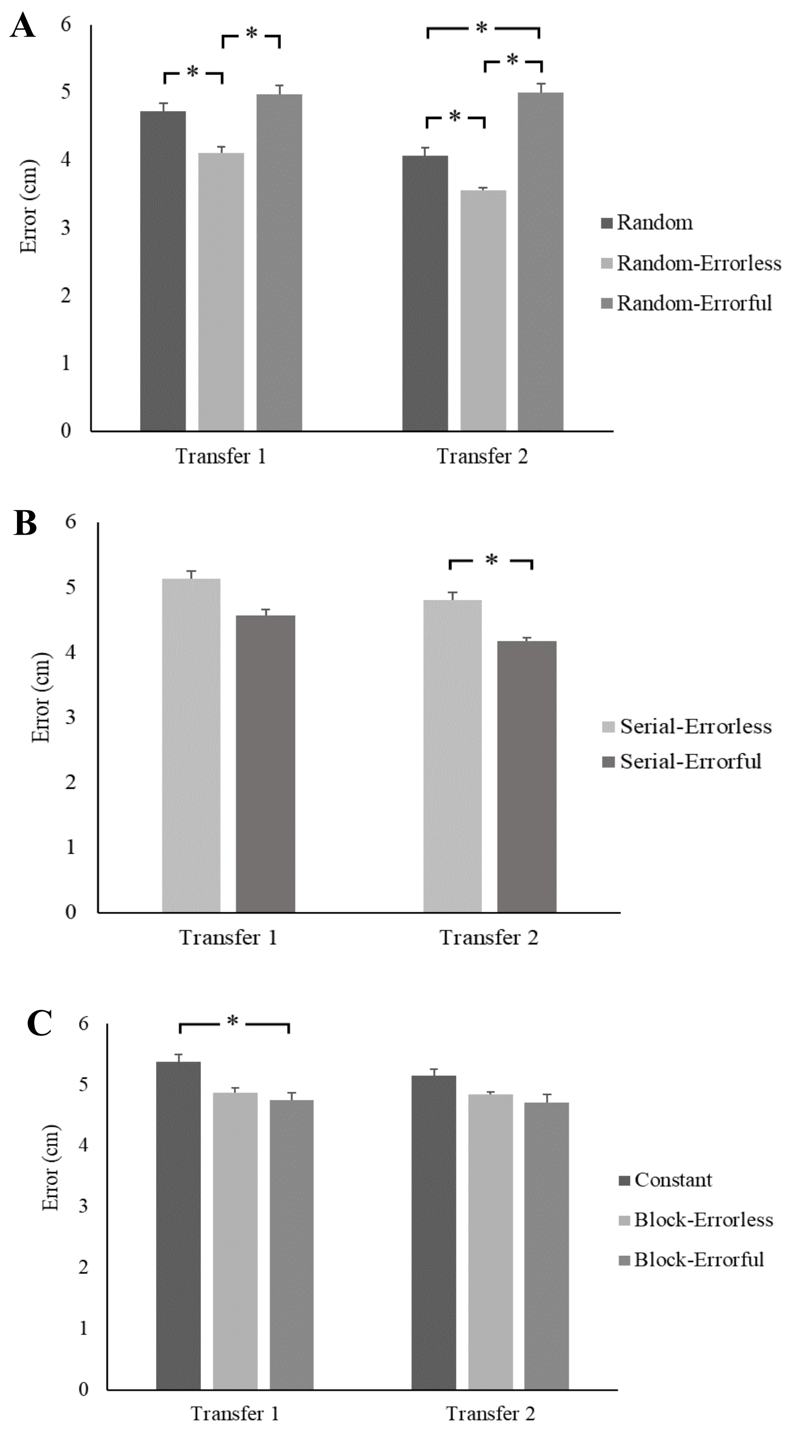

Figure 4. (A) The primary task performance of the Random, Random-Errorless, and Random-Errorful groups in the two secondary-task transfer tests. (B) The primary task performance of the Serial-Errorless, and Serial-Errorful groups in the two secondary-task transfer tests. (C) The primary task performance of the Constant, Block-Errorless, and Block-Errorful groups in the two secondary-task transfer tests. **p* < .05

Discussion

The aim of the present study was to investigate the effect of a combination interference-error model during practice (combining block, serial and random schedules with errorless and errorful structure) on learning and automation of a dart throwing task. The findings will be discussed in line with theories from the CI literature (e.g., *elaboration hypothesis* [Battig, 1979; Shea & Zimny, 1983]; *reconstruction hypothesis* [Lee & Magill, 1985]; *error-processing hypothesis* [Broadbent, et al., 2017]) and the theories of implicit motor learning (Maxwell et al., 2001; Maxwell et al., 2003; Rendell et al., 2011), as well as the challenge point framework by Guadagnoli & Lee (2004).

The classic CI effect predicts that performance during acquisition is greater for blocked practice and that learning, as shown through performance in the retention and transfer test, is greater for random practice (Shea & Morgan, 1979; Brady, 1998; Magill, & Hall, 1990; Lee & Simon, 2004; Farrow & Buszard, 2017). In the present study, while greater performance of the block-errorless group in the acquisition phase was not observed, support for the CI effect was found in the errorless groups as the Random-Errorless group performed more accurately in the retention test compared to the Block-Errorless and Serial-Errorless groups. However, in the errorful groups we found the opposite of the CI effect as the Block-Errorful group outperformed the Random-Errorful in the retention test. This supports the notion that the predictions of the challenge point framework may only applicable when a certain amount of errors is present (Bootsma et al., 2018). It appears that for this dart-throwing task with novice participants, the combination of random practice and errorful practice was not optimal and increased the functional task difficulty too much for learning to take place. According to the challenge point framework, for learners who are beginners/novices such as in the current study, when too much information becomes available and requires processing, motor learning will decline due to the increased functional difficulty (Guadagnoli & Lee, 2004). Moreover, the increase in errors can have psychological costs and alter motivations levels which can negatively impact learning (Hodges & Lohse, 2022). In the Random-Errorful group it appears that the increased processing requirements due to the random structure and increased error processing due to the errorful condition, resulted in a learning decline as the cognitive load exceeded an optimal level (Guadagnoli & Lee, 2004). In contrast, the combination of random practice and errorless practice appeared optimum for the participants in this task, demonstrating the greatest learning compared to all other groups, including the Random group. Even though the challenge point framework considers the importance of the functional difficulty of the task for maximizing learning, it does not specify the mechanisms underpinning this. The challenge point framework argues that random practice is more beneficial compared to block practice for skills with low nominal difficulty as the former results in a more demanding practice condition. However, the framework does not provide detail in to the antecedents of the cognitive demand (i.e., either task switching or error processing).

The Random-Errorless group performed the task from distances closest to the target in a random order during practice. This type of practice has several important features that may benefit learning. First, participants in this group benefited from randomly changing the practiced tasks according to the elaboration hypothesis (Shea & Zimny, 1983) and reconstruction hypothesis (Lee & Magill, 1985). This feature addresses why this group perhaps performed better than the constant, block and serial groups. Second, the similarity between the tasks was high, especially compared to traditional random practice. Since the three distances closest to the target (i.e., 137 cm, 170.33 cm and 203.66 cm) were similar in the parameters required to perform the tasks (particularly the parameter of force), noticing the differences between the tasks would be difficult. Battig (1979) suggests that the similarity between learning tasks is a potential source of interference. According to Battig (1979), the coding of similar tasks creates more interference during practice, which in return, results in better retention. The idea is that engaging in extra elaborative process, in an attempt to understand differences and between-skill details, requires additional cognitive effort, which can be beneficial to learning. This feature perhaps explains why the Random-Errorless group showed greater learning compared to the Random group who would not have had this additional process due to task similarity. However, both the Random-Errorless and Random-Errorful groups could have seemingly benefited from the increased processing due to switching between different tasks with high levels of similarity, but these two groups had contrasting levels of learning.

The important difference between the Random-Errorless and Random-Errorful groups appears to be the demands on working memory during acquisition, which we argue to be due to the amount of error processing taking place. In the errorful conditions, the individuals’ performance was further from the target across the acquisition sessions suggesting greater movement variability and deviation in performance (i.e., greater “noise), which has been suggested to indicate a greater exploratory process (Slifkin & Newell, 1999). When an error occurs, or performance is far from the target, the performer engages in additional processes to identify why they did not achieve the expected outcome, and hypothesize about how to improve performance in the future resulting in greater cognitive demands compared to an errorless trial (Maxwell et al. 2001; Lam et al., 2010). The error-processing hypothesis by Broadbent et al. (2017), suggests the combination of task switching with error processing increases the cognitive demand during practice and results in decreased acquisition performance and also enhanced learning for a random structure of practice. The current study builds on from this by suggesting that it is a delicate balance between these two factors. The results showed that for the current dart-throwing task with novice participants, that a combination of random practice with high similarity and reduced error processing had benefits to the participants’ learning. In contrast, combining random practice with high similarity and increased levels of error processing was detrimental to learning. Interestingly, blocked practice and increased levels of error processing (i.e. Block-Errorful group) was somewhat beneficial to learning compared to other groups such as the Random-Errorful group. This finding suggests that task switching through random practice is only one of the sources causing cognitive effort; another important source is error processing, which is directly related to the difficulty of the task (Lam et al., 2010). As predicted by the challenge point framework (Guadagnoli & Lee, 2004), there is an optimum challenge point during practice which will facilitate the greatest learning (see also, Christina & Bjork, 1991). The present study demonstrated that both between-task changes and error processing are responsible for generating an appropriate level of practice challenge. In simple tasks (i.e., low nominal difficulty), less processing is required due to fewer errors happening, and therefore, there are the resources available to benefit from the additional processes associated with random practice with high task similarity. In contrast, for more difficult tasks (i.e., high nominal difficulty) with increased error processing, there are not the resources available to engage with the elaborative and reconstructive processes and therefore working memory becomes overwhelmed which is detrimental to learning. It would be interesting for future research to examine the same groups in the current study, but with a task of differing nominal difficulty, and with participants of different skill level, to see any changes in the optimal structure of practice for learning.

While the current findings are in line with the challenge point framework (Guadagnoli & Lee, 2004), and somewhat in line with the error-processing hypothesis for the CI effect (Broadbent, et al., 2017), the findings do contradict the implicit learning hypothesis for the CI effect proposed by Rendell et al. (2011). This study proposed that high levels of cognitive effort emerging from task switching during random practice, may promote an implicit style of learning as the individuals working memory is overwhelmed and they cannot consciously focus on the task being practiced (see also, Rendell et al., 2009). With this in mind, in the current study, it would have been predicted that the condition with the highest demand on working memory, the Random-Errorful group, would promote the most implicit learning condition and therefore the greatest performance in the retention and transfer tests, but this was not the case. As discussed in the previous paragraphs, the Random-Errorful group performed the worst in the retention test out of all the groups. Similarly, in the transfer test, in which a secondary task was used to examine the level of automation (as a consequence of implicit learning), the Random-Errorful group was again one of the worst performing groups on the primary task, with only the Constant group performing worse. This suggests that high levels of cognitive effort during practice due to task switching and error process will overwhelm working memory, but will not result in learning the skill implicitly.

With regards to the transfer test findings, many studies have shown that, compared to explicit learning, implicit learning would lead to higher automation levels as shown through greater performance with a secondary task (Lam, Maxwell & Masters, 2009; Poolton et al. 2006; Tse, Wong & Masters, 2017). Based on the findings by Maxwell et al. (2001), we predicted that the errorless groups would promote more implicit learning compared to errorful conditions. This prediction was supported in the random groups, with the Random-Errorless group outperforming the Random-Errorful group in both transfer tests suggesting greater levels of automation and implicit learning following errorless practice. However, with a blocked structure of practice there was no significant difference between the errorless and errorful conditions in either transfer test, and with a serial structure of practice the Serial-Errorful group actually performed significantly better compared to the Serial-Errorless group in the second transfer test, suggesting a greater level of automation following errorful conditions. This latter finding contradicts those obtained by Maxwell et al. (2001) and Capio et al. (2011). In these studies, it was suggested that more error processing promotes greater levels of hypothesis testing and the formation of explicit rules resulting in reduced levels of automation. Abdoli, Farsi, and Ramezanzade (2011) indicated that an optimal level of working memory demand is needed for implicit learning. In their research, three secondary tasks with different levels of difficulty (i.e., easy, moderate, and difficult) were used to examine the impact on implicit learning. Their results showed that a difficult secondary task actually reduced the level of implicit learning. Therefore, they concluded that, for implicit learning to happen, there is an optimal level of demand that should be placed on working memory. The current findings somewhat support this, by suggesting that it is not just the manipulation of error processing that can impact the levels of implicit learning achieved, but rather the interaction between error processing and structure of practice such that optimal levels of working memory resources are utilized.

Interestingly, the Random group performed significantly better than the Constant group in the retention and transfer tests. This finding contradicts the especial effect in motor learning, which suggests that practicing a single action from within a class of actions produces an advantage in performance (Breslin et al., 2012). It is possible that the number of practice trials in the current study was not enough to create the especial effect for the Constant group (Keetch et al., 2005), but based on the superior learning shown by the Random group, the current findings show more support for the CI effect, and the important elaborative and reconstructive processes that are encouraged through task switching (Capio et al., 2012). Moreover, based on the Random groups' enhanced performance on the transfer tests, compared to the Constant group, the current study shows some support for the paper by Rendell et al.'s (2011), which suggests that random practice may be more underpinned by implicit learning and leads to higher levels of automation, compared to blocked or constant practice. If only errorless practice is responsible for creating implicit learning conditions and more automation, then the level of automation of block-errorless and random-errorless groups should be similar. However, this is not the case in the current study as the random-errorless group shows greater levels of automation (Rendell, 2011; 2009).

While this study provided a systematic examination of the CI effect combined with the Errorless Learning model to explore optimal learning conditions, there were limitations that need to be acknowledged. In this study, participant's errors were analysed using a continuous scale (i.e., distance from the target) rather than in a binary manner (i.e., centre target hit or not), which is less common in the errorless learning literature and is more common in research examining variability of movement (e.g., Wu et al., 2014). The analysis of distance from the target provided insight in to the continuous deviations in performance from trial to trial, but the design of the study was based on the errorless learning literature (e.g., Maxwell et al., 2001). Participants threw at a target with a specific center point visible and so participants saw the binary result of their performance (i.e., whether it hit the center or not). Participants were not given any extrinsic feedback on the specific amount of movement variability on each trial (i.e., the distance from the target). This is the same procedure as studies in the errorless learning literature (e.g., Maxwell et al., 2001). So, while we analysed performance using a continuous scale (i.e., distance from the target), we presume the error processing of the participants is similar to that of previous studies using the errorless learning approach, although we cannot be sure of this. Future research should look to provide more quantifiable insight in to processing of movement variability and 'noise' during an errorless learning approach. Herzfeld & Shadmehr (2014) suggest that individuals begin with large amounts of motor variability as they explore the possible motor outcomes based on the task and environment; in the case of the current study the throw action to hit the target at the different distances. Once the task is achieved, such as hitting the center target in the current study, the individual attempts to repeat the same movement and processes whether they achieve the task or not. To provide more insight in to binary error processing and continuous processing of noise and movement variability in motor learning, the differential learning (DL) approach could be a fruitful one for future research. DL is based on promoting large inter-trial fluctuations and links to the concept of stochastic-resonance (Schollhorn et al., 2006). Stochastic-resonance is a phenomenon where the presence of noise in a nonlinear system is essential for the optimal performance of the system (McDonell, Stocks, Pearce & Abbott, 2006). Accordingly, it is suggested that in future research, the potential of both errorless learning model and DL approach be considered.

Another limitation is the lack of evaluation of participants' cognitive effort during practice is a notable limitation of this study. Insight in to the changes in cognitive effort during practice and its effect on performance will allow for a greater understanding of the interaction between the CI effect and the errorless learning model. With advances in technology, it is suggested that in future research, cognitive effort be examined using neurological measures such as TMS, EEG or fMRI, which have been used to examine the CI effect (e.g., Cross et al., 2007; Lin et al., 2008; Lin et al., 2010) and error processing (e.g., Holroyd et al., 2002; Rodriguez-Fornells et al., 2002; Yeung et al., 2004), to see differences across the combined practice conditions. Furthermore, the task in this study was a skill with a low level of difficulty and with young healthy novice participants. Future research should look to test the findings from this study when learning more complex motor tasks and with more skilled participants, as well other populations such as the elderly (see Bootsma et al., 2021), to allow for a full understanding of these practice conditions in line with the Challenge Point Framework (Guadagnoli & Lee, 2004).

Conclusions

Overall, the current study provided unique insight in to skill acquisition by providing an in-depth examination of the interaction between contextual interference, error processing, and implicit learning. The findings showed some support for tenets of all the various theories and hypotheses from the different bodies of literature. Support was shown for the CI effect but only under the errorless practice condition and not when combined with errorful practice conditions. The study also showed some support for the error-processing hypothesis by Broadbent et al. (2017), as increasing the error processing enhanced performance in a blocked structure of practice. Furthermore, the benefits of errorless practice were observed (Maxwell et al., 2001), but only in the random practice condition. This result suggests that errorless practice should be combined with conditions that create more variability (random practice) for greater effectiveness. This variability leads to instability during action organization and can be used to enhance motor learning (Herzfeld & Shadmehr, 2014; Newell & Corcos 1993). There was also some support for the implicit learning theory (Rendell et al., 2011) as random practice promoted greater performance under secondary task conditions compared to constant practice. Overall, the random-errorless group showed the best performance in retention and transfer tests and the random-errorful group performed the worst. Interestingly, none of the theories were completely supported and actually the main finding from this study is that the optimal learning condition requires a complex balance between task difficulty, individual skill level, contextual interference and error processing. This supports the

Challenge Point Framework by Guadagnoli & Lee (2004). Future research is required to explore the interaction between these factors to fully understand how to enhance skill acquisition. The model presented in this study for the quantitative analysis of contextual interference and error processing can be a criterion for researchers and practitioners in the future (see Figure 1). It is suggested that the quantitative model proposed in this study be re-examined for tasks of varying complexities and with individuals of different skill levels.

Declaration of Conflicting Interests

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