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Research Article

Keywords:

Posted Date: November 17th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11594118/v1

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Additional Declarations: No competing interests reported.

Variability and not predictability of target location influences search behaviour in de-novo skill learning

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Submission Date: November 02, 2026

Abstract

Complex de-novo learning requires search for new movement coordination patterns. Search is defined as the systematic change over trials in the amount and structure of variability within the involved degrees of freedom to perform the task. Varying the presentation of target locations during practice of a virtual lateral interception task increases search behaviour, compared to presenting targets in blocked fashion. However, it remains unclear whether the variability in target locations during random practice or predictability of target locations in blocked practice influences search behaviour. In this study, a serial practice condition is introduced with a predictable sequence of target locations to delineate the contribution of variability and predictability. It is hypothesized that if variability influences search behaviour, serial and random practice would yield comparable performance; alternatively, comparable performance between serial and blocked practice would suggest that predictability influences search behaviour. Different types of search behaviour are assessed to determine whether practice conditions differentially influence them. No significant differences in task performance between practice-groups were found in post-test and transfer-test. Amount of search was similar across practice-groups in the search for new movement coordination patterns. However, search in Random and Serial practice groups was significantly higher than in Blocked practice when stabilizing the coordination pattern. While the amount of search varied based on the type of search, the structure of search was similar across practice-groups. It is concluded that changes in target locations induced movement variability that contributed to the search behaviour rather than the predictability of the target locations.

Introduction

When acquiring a new motor skill such as learning to play tennis or skating on ice, individuals demonstrate variations during their practice. This variability is considered to be helpful in discovering movement patterns to successfully perform the task[1–6]. Variability in movements can also be introduced through practice schemes by altering the presentation schedules of different task conditions. A learning phenomenon that is often found in this approach is the contextual interference effect[7,8]. The contextual interference effect suggests that Blocked practice yields faster acquisition while training with Random practice showed more flexible task performance measured through better results in retention and transfer tests[9–11]. Mehta et al.[1,9] demonstrated that introduction of variability with Random practice in de-novo motor learning increases search behaviour and results in more flexible movement coordination patterns as compared to Blocked practice. However, these effects on search behaviour, due to practice schedules, could originate from introducing variability through random ordering of task conditions or due to the predictability of repeating the same task conditions. For example, in Blocked practice of reaching and interception tasks, the interception locations are consistently the same, making target location predictable across trials. While in Random practice the target locations are randomized making the task not only variable but also unpredictable. In this study, we try to delineate whether the effects of contextual interference and search behaviour in

de-novo learning were a result of variability in task performance or the (un)predictability of target location.

Lee and Magill[12] introduced the Serial practice condition to address the issue of whether variability or unpredictability due to non-consecutive repetition of task conditions led to better retention and transfer performance. In Serial practice, a sequence of different task conditions is repeated at a fixed interval. Serial practice is variable and more predictable, as compared to Random practice (different conditions presented in a random order). Whereas Blocked practice (same conditions are presented in a series) is not variable and highly predictable. Several studies have reported incongruent results in task performance due to different presentation order of the practice conditions[13]. Some studies have found similar task performance between Serial and Blocked practice in learning golf strokes and underhand volleyball serves by novices[14,15]. While others found Serial and Random practice to be similar in the context of learning a variety of volleyball skills[13,16]. Furthermore, researchers have found better retention with Blocked and Serial practice in tennis serve performance of skilled athletes[17] or no differences at all in learning a variety of other simple motor and sports skills[7,18]. Most of these studies included children or novices with limited to no prior experience in motor skills being acquired. It is not yet clear whether performance after training with Serial practice is similar to Blocked or Random practice and under which task conditions is this effect a function of variability and/or predictability.

In short, the contextual interference effect has not been unambiguously established in the literature. Characteristic of previous studies is that the effectiveness of practice schedules on various tasks has been primarily evaluated on pre- and post-performance measures. Limited focus has been given to the processes at work *during* practice to reveal the underlying mechanisms of the training effects due to varying practice schedules[18–21]. Hence, to gain a better fundamental understanding of how different practice schedules influence the process of learning, there is a need to look at the changes in performance during practice. To this end the current paper examines how introducing variability in practice schedules impacts the search processes at work during practice to find new coordination patterns in the degrees of freedom (DoF) during de-novo learning.

Search for a novel coordination pattern requires individuals to vary their movements to narrow in on the collection of movement solutions suitable for a given task. To understand this process, consider a state space spanned by all the involved DoF[2,22–24]. Since the focus of this work is at the level of joint angles, the relevant state space is the joint space spanned by all the involved joint angles. Within this joint space, there is a subspace of all the possible combinations of joint angles for successful task performance, which we term the solution space. To learn a novel task, the joint space needs to be searched in order to arrive at the solution space. This implies that, during search, variability in movement is necessary and, most likely, structured [5,25,26]. Earlier studies established that as a result of these search processes, variability along the manifold of the solution space is retained and variability influencing task performance is reduced over practice [1,4,9,27,28]. The question addressed in this article is how could different practice schedules influence this search behaviour?

The premise of this study is that Random practice pushes the movement system in each trial into different regions of the joint space in subsequent trials, providing more opportunities for its exploration, but, potentially, also preventing a fast convergence to the solution. Meanwhile, in Random practice there is no information about subsequent trials, thus predictability is low, which also might affect the search behaviour. Whereas, with Blocked practice there is low variability and high predictability, most likely resulting in limited exploration of the joint space and occupying a very local region within the solution space. Serial practice provides the condition where the subsequent trial is different and at the same time predictable. Therefore, if the search behaviour in Serial practice has comparable characteristics as Random practice, then the increased search behaviour stems from the fact that there is variability in target positions between two consecutive trials. On the contrary, if the search behaviour in Serial practice has characteristics comparable to Blocked practice, predictability affects the search behaviour. Hence, introducing Serial practice is an effective manipulation to identify if the differences in search behaviour emerge due to the varied presentation of task conditions or due to predictability of the next trial.

Literature suggests that de-novo motor learning proceeds in stages and the contribution of motor variability differs between these stages [5,29]. The initial stage involves learning to perform the task i.e. finding the solution space resulting in the appropriate movement coordination patterns. Success is limited and is accompanied by large movement variability to facilitate search for appropriate novel movement coordination patterns in the task during this stage. It is hypothesized that the search behaviour would mostly be driven by non-local changes within the joint space [30]. Following this, the later stage of learning is characterized by further refining task execution and finding the location on the solution space which is more tolerant to perturbations or disturbances[27,31]. The learner consistently performs the task successfully, which is accompanied by relatively local changes along the solution space that requires only low degrees of variability in task execution. This suggests that the role of variability and in turn the search behaviour differs corresponding to these learning stages. Would the different practice schedules then influence search behaviour differently in the initial and later stages of learning?

As follows from the above, the different stages of learning can be captured based on the learner's performance on consecutive trials. The initial stage of learning can be operationalized if the current and the preceding trials were unsuccessful (Repeat-Miss) while the later stage of learning would constitute successful trials which were also preceded by successful trials (Repeat-Hit). The rationale for this classification of trials stems from the fact that if one is unsuccessful in performing the task, one would continue to search for the solution space, which has a higher chance of unsuccessful task performance because the solution space is only a small part of the joint space. Once the solution space is found on a successful trial, search takes place along or close to the solution space to find more tolerant regions in the subsequent trials. The number of successful hits and misses is considered as a measure to quantify the stages of learning since motor learning exhibits substantial inter-individual variability and progress at different temporal rates across individuals[32]. The authors previous work characterized aspects of search but no distinction between the different types of

search processes was made[1,33]. In this study we are interested in examining whether introducing variability through practice schedule influences the structure of search in different types of search behaviour. Structure of search refers to whether the search takes place along the solution space or in the rest of the joint space. With Blocked practice we expect acquisition to be faster, therefore the search for the solution space takes less practice phases, implying overall higher number of Repeat-Hit trials than in Random and Serial practice. Furthermore, we expect search behaviour to be higher with Random practice than Blocked practice within both the types of search; when searching the joint space to find the solution space as well as when searching along the solution space to stabilize the coordination pattern. If indeed variability of target locations influences search then the search behaviour in Serial practice should be comparable to the Random practice.

Since variability is integral to search, this study investigates how practice scheduling variability versus practice predictability impacts search behaviour. We employed a virtual lateral interception task wherein the virtual paddle was controlled based on an abstract mapping among the upper limb joint angles. This task necessitated the learning of a new movement coordination pattern. Different groups were assigned to different practice schedules viz. Blocked, Serial, and Random. The authors previous work [1,9] has already established the formation of new stable coordination patterns in this task; therefore, the present study focuses on search behaviour. The structure of search behaviour at the level of the joint angles is determined using the Joint Deviation Vector analysis by computing projection vectors along the solution space (JDVUCM) and orthogonal to it within the joint space (JDVORT) with respect to a reference joint configuration[34,35]. The changes in these joint deviation vectors provide insights on how search is structured in different parts of the joint space in de-novo learning. Key distinctions of this study were the inclusion of a Serial practice group and an increased number of practice trials to ensure enhanced learning. We hypothesized that search within the joint space (JDVORT) and along the solution space (JDVUCM) would not be different for Random practice and Serial practice but differ with Blocked practice if variability is expected to influence search. Alternatively, if the structure in search behaviour was not different between Blocked and Serial practice, then predictability influences search behaviour. Furthermore, the second key research question addressed in this study is - Does variability in practice scheduling have differing influence on the structure of search in different types of search behaviour? We hypothesize that JDVORT will reduce faster with blocked practice than Random and Serial practice in Repeat-Miss trials, reflecting the search for the solution space, and we expect JDVUCM to be higher in Random and Serial practice than blocked practice in Repeat-Hit trials, reflecting search along the solution space.

Methods

Participants

Right-handed participants with normal or corrected to normal vision and no neurological disorder or impairment to their non-dominant hand were recruited from the student population of University of Groningen. The study was approved by the

Central Ethics Review Board (CTc) of the University Medical Center Groningen (R17753). Participants provided written informed consent prior to the start of the experiment. A nominal monetary reward was provided for participation.

Task

The task is similar to the earlier studies of the authors[1,9] (these papers contain detailed information of the experimental setup, measurements and parts of the analyses) wherein participants intercept a downward moving ball presented on a vertical screen, with a paddle controlled by the movements of their non-dominant upper limb. A non-intuitive abundant mapping (Eq.1) is introduced in the task between the upper limb joint angles (SAA: shoulder abduction-adduction, EPS: elbow pronation-supination, EFE: elbow flexion-extension and WUR: wrist ulnar-radial deviation) and the lateral movement of the virtual paddle. The upper limb joint movements were captured using inertial measurement units (MTw Awinda, Movella Technologies, The Netherlands) placed on the left arm and the chest (Figure 1). The joint angles were computed using a customized script within the Unity Engine (ver. 2021, Unity Technologies) software which was used to present the virtual task. The data was sampled at 50 Hz. Calibrations for the IMU placement and range of motion of the participants were performed prior to the start of the task[36,37].

$$P = \begin{bmatrix} 8 & 8 & 8 & 8 & -16 \end{bmatrix} \begin{bmatrix} SAA \\ EPS \\ EFE \\ WUR \\ 1 \end{bmatrix} \quad \text{Eq.1}$$

The participants were provided instructions about the task and the objective which was to intercept the moving ball with the paddle. A trial commenced (i.e. the ball appeared after a Random delay of 700 ms to 1200 ms and began its descent) only once the paddle was brought to the centre of the screen on the interception axis. The ball could start from 4 - ball departure positions (BDP) at the top of the screen and leave the screen at 4 - ball arrival positions (BAP) at the bottom of the screen resulting in 16 different ball trajectories (Fig. 1). Participants performed 712 trials within a duration of 2 hours which were divided into 4 successive sessions of pre-test (24 trials), practice (640 trials), post-test (24 trials) and transfer-test (24 trials). Four new BAP were introduced in the transfer-test session (see Fig. 1). For the purposes of the analysis, the practice session was divided into 5 phases of 128 trials each based on the BAP.

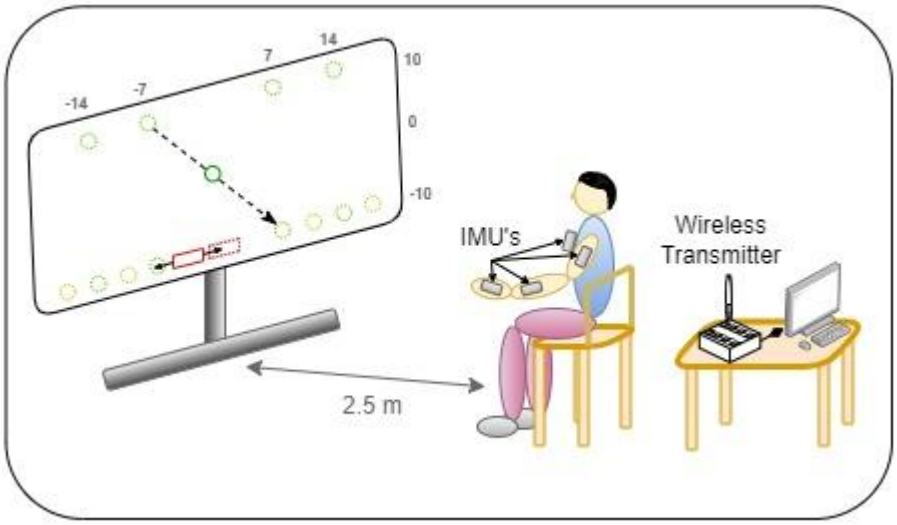


Fig.1 Illustration of the experimental task. Participant with 4 Inertial Measuring Units is seated in front of a large screen. The virtual lateral interception task has 4 different BDPs (circles on top of the screen) and 4 BAPs for the training and test sessions in green and 4 BAPs for the transfer test in yellow. The paddle (solid rectangle) and the ball (solid circle) with a representative ball trajectory (dashed arrow) are shown. The dashed rectangle represents the starting position of the paddle on each trial

The participants were Randomly allotted into one of the three practice groups – Blocked, Serial and Random. In Blocked practice all trials to a particular BAP are presented consecutively while in Random practice the BAP are block Randomized and in Serial practice a fixed sequence of BAPs is repeated throughout the practice session. The sequence of trials in serial practice is randomized across participants but each BAP is presented once before repeating the same BAP again. In the test sessions, 8 trials of each practice schedule are presented.

Data Analysis

The data analyses were performed using customized scripts in Matlab (Mathworks Inc. R2025a). A trial was defined as the time the ball moved from a BDP to a BAP. The joint angles in this time period were filtered using a second order recursive Butterworth filter with a cutoff frequency of 2.5Hz. Each trial was time normalized to 100 timestamps and trials with higher than +/- 2 units deviation of paddle position from the centre at the start of the trial were removed as outliers. All dependent variables are computed at the end of the trial. The practice phase is designated based on each BAP separately i.e. for each BAP the first 32 trials constitute phase 1, and so on, until phase 5.

Task performance was estimated based on the absolute error. To categorise trials into 4 types, a hit was established when the error was smaller than 1.25 units. The trials were then categorized based on the task outcome (hit vs miss) of the current trial with respect to the preceding trial to the same BAP (Table 1). Note that due to the random presentation of BAPs, a variable number of trials to other BAPs could be in-between subsequent trials to the same BAP that were used in this analysis. The analysis on different trial types was performed based on the sum of trials of each trial type in each

phase. The change in number of trials of each type would provide insights on different stages of learning.

Table 1: Categorization of trials in practice phase. Four types of trials identified based on performance: Repeat-Miss, Miss-Hit, Hit-Miss and Repeat-Hit.

Task Performance (Trial)	Miss (Current Trial)	Hit (Current Trial)
Miss (Previous Trial)	Repeat-Miss	Miss-Hit
Hit (Previous Trial)	Hit-Miss	Repeat-Hit

The amount of search was calculated as the Euclidean distance between the end joint configurations of two successive trials to the same ball arrival position. The joint deviation vector (JDV) analysis was used to evaluate the structure of search behaviour wherein projected distances along the dimension of the solution space (Uncontrolled Manifold; UCM) and orthogonal to it were computed for each trial with respect to a reference configuration [34,35,38]. The reference configuration was computed as the mean joint configuration (at the end of the trial) in the last phase of practice for each participant ($\overline{\Theta}$) and their joint deviation ($\Delta\Theta_r$) for each trial (r: trial number) from the practice phases (Eq.2). The deviations were projected along the UCM ($\Delta\Theta_r^{UCM}$) and orthogonal ($\Delta\Theta_r^{\perp}$) to it (Eq. 3 & 4). The magnitudes of the joint deviation vectors for each trial were then calculated based on the projections (Eq. 5 and 6). The 4 contributing upper limb joint angles were considered as the elemental variables (EV) and the paddle position as the performance variable (PV). The mapping (Eq.1) was used as the Jacobian (J) to partition the variability. The analysis was performed for every participant on each BAP and phase separately. To study the different types of search, only Repeat-Miss and Repeat-Hit trials were considered in the JDV analysis.

$$\Delta\Theta_r = \overline{\Theta} - \Theta_r \quad \text{Eq.2}$$

$$\Delta\Theta_r^{UCM} = \sum_{i=1}^{EV-PV}\left(\Delta\Theta_r \cdot null(J)\right) \times null(J) \quad \text{Eq.3}$$

$$\Delta\Theta_r^{\perp} = \Delta\Theta_r - \Delta\Theta_r^{UCM} \quad \text{Eq.4}$$

$$JDV_{UCM}(r) = \frac{\left|\left|\Delta\Theta_r^{UCM}\right|\right|}{\sqrt{EV-PV}} \quad \text{Eq.5}$$

$$JDV_{\perp}(r) = \frac{\left|\left|\Delta\Theta_r^{\perp}\right|\right|}{\sqrt{PV}} \quad \text{Eq.6}$$

Statistical Analysis

All statistical analyses were performed using JAMOVI (Version 2.6.26). Linear Mixed Effects (LME) analyses were performed for all the dependent variables pertaining to task performance and search behaviour with intercept of participants as a Random

effect. All dependent variables were log transformed to ensure normal distribution of the data. Results with $p<0.05$ were considered significant. For significant effects, all pair-wise post hoc comparisons were performed using estimated marginal means and Bonferroni corrections were applied. Note that the statistical effects are based on the estimated marginal means of the linear mixed model and differ from the trends of the actual means (presented in appendix; Fig. 7 to 11).

To evaluate task performance, two separate linear mixed effects analysis were performed on absolute error for test sessions and practice sessions. For the test sessions, a linear mixed model was fit with Practice Group (Blocked, Serial and Random), Test Condition (Blocked, Serial and Random) and Test Session (Pre, Post and Transfer) as fixed effects. For the practice sessions, a linear mixed model was fitted with Practice Group (Blocked, Serial and Random) and Practice Phase (1 to 5) as fixed effects.

The amount of search was statistically evaluated using linear mixed effects model with Practice Group (Blocked, Serial and Random), Practice Phase (1 to 5) and Trial Type (Repeat-Miss and Repeat-Hit) as fixed effects.

JDV variables were analysed using linear mixed effects model with Practice Group (Blocked, Serial and Random), Practice Phase (1 to 5), Variance Type (JDVUCM and JDVORT) and Trial Type (Repeat-Miss and Repeat-Hit) as fixed effects.

For the analysis of the trial types, trial data were aggregated into phase-level counts and the number of observations per participant (10; 2 trial types in 5 practice phases) was insufficient to estimate the intended random-effects structure. Therefore, the analysis was simplified to a repeated-measures ANOVA on the aggregated number of trials within each phase. A Mixed ANOVA with Greenhouse Geisser correction was performed and posthoc analysis was done using Bonferroni correction and Generalized eta squared are reported for effect size. Practice Group (Blocked, Serial and Random), Practice Phase (1 to 5) were within subject measures and Trial Type (Repeat-Miss and Repeat-Hit) was the between-group measure.

Results

60 right-handed participants (21.63 +/- 3 yrs, 18 Male and 42 Female) performed the task.

Task Performance

The Linear Mixed Effects (LME) model on absolute error in test sessions revealed a significant main effect of Test Session ($F(2,4120.30) = 1052.49$, $p<0.001$) and interaction effect of Practice Group x Test Session ($F(4,4120.3) = 7.414$, $p<0.001$). Pairwise comparisons were performed on each individual level of the interaction effect of Practice Group x Test Session. They show that performance significantly improved from pre-test to post-test and transfer-test for all the groups and was statistically similar within each test session across groups (Fig. 2). However, performance deteriorates from post-test to transfer-test for Random and Serial practice groups but not for

Blocked practice. Additionally, no group differences were observed in the pre-test (p=1 for all pairwise comparisons within pre-test).

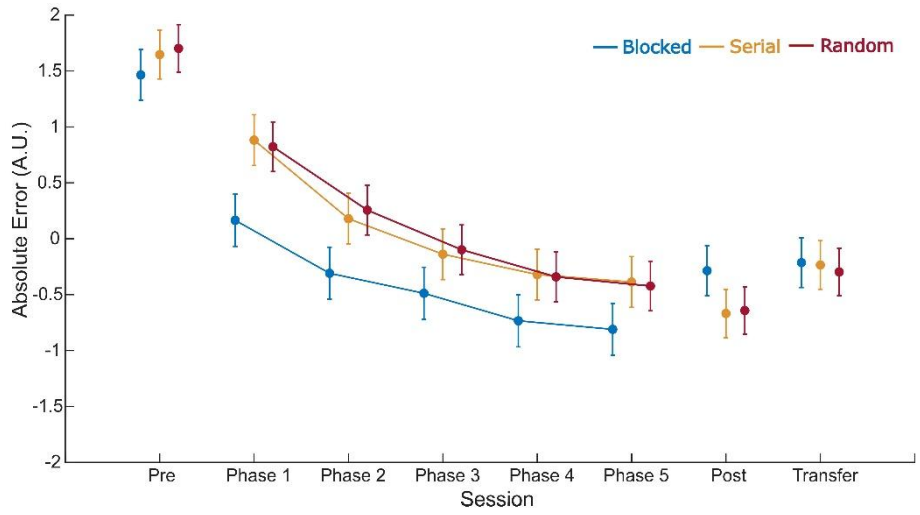


Fig.2 Estimated Marginal Means of task performance across sessions (Test and Practice) for the practice groups

The LME model on absolute error in practice session revealed significant effects of Practice Group ($F(2,57) = 5.81$, $p=0.005$), Practice Phase ($F(4,37475.20) = 831.11$, $p<0.001$) and Practice Group x Practice Phase ($F(8,37475.2) = 7.97$, $p<0.001$). Pairwise comparisons revealed that performance during practice is better in Blocked group as compared to Random and Serial groups only in the first phase and performance improved until phase 4 of practice for all the groups (Fig. 2). These results suggest that participants learn to perform the task and the acquisition is faster with Blocked practice.

Trial Types

The Mixed ANOVA on number of trials revealed significant main effects of Trial Type ($F(1.11,63.42) = 156.66$, $p<0.001$, $\eta_G^2 = 0.67$) and Phase ($F(2.08,118.35) = 52.79$, $p<0.001$, $\eta_G^2 = 0.002$). Interaction effects of Trial Type x Practice Phase ($F(3.15,179.58) = 110.95$, $p<0.001$, $\eta_G^2 = 0.33$) and Trial Type x Practice Group ($F(2.23,63.42) = 7.04$, $p=0.001$, $\eta_G^2 = 0.15$) were also significant. Posthoc analysis on Trial Type x Practice Phase revealed only Repeat-Hit and Repeat-Miss trials significantly differed between consecutive practice phases (Fig. 3a). Repeat-Hit trials increased across all phases and Repeat-Miss trials significantly decreased until phase 4. Interestingly, number of Repeat-Hit and Repeat-Miss trials were not significantly different in the first phase of practice, but from there on the number of Repeat-Hit trials was significantly higher than the other trial types. Additionally, posthoc analysis on Trial Type x Practice Group revealed group differences in different trial types (Fig. 3b). The number of Repeat-Miss trials were similar across all groups while number of Repeat-Hit trials were significantly higher in Blocked practice than Random and Serial practice. On the contrary Miss-Hit and Hit-Miss trials were significantly lower in Blocked than Serial and Random practice groups. No group differences were observed in Repeat-Miss trials. Since significant change in number of trials across practice phases was

observed in Repeat-Hit and Repeat-Miss categories, these were the only trial types considered for further analysis.

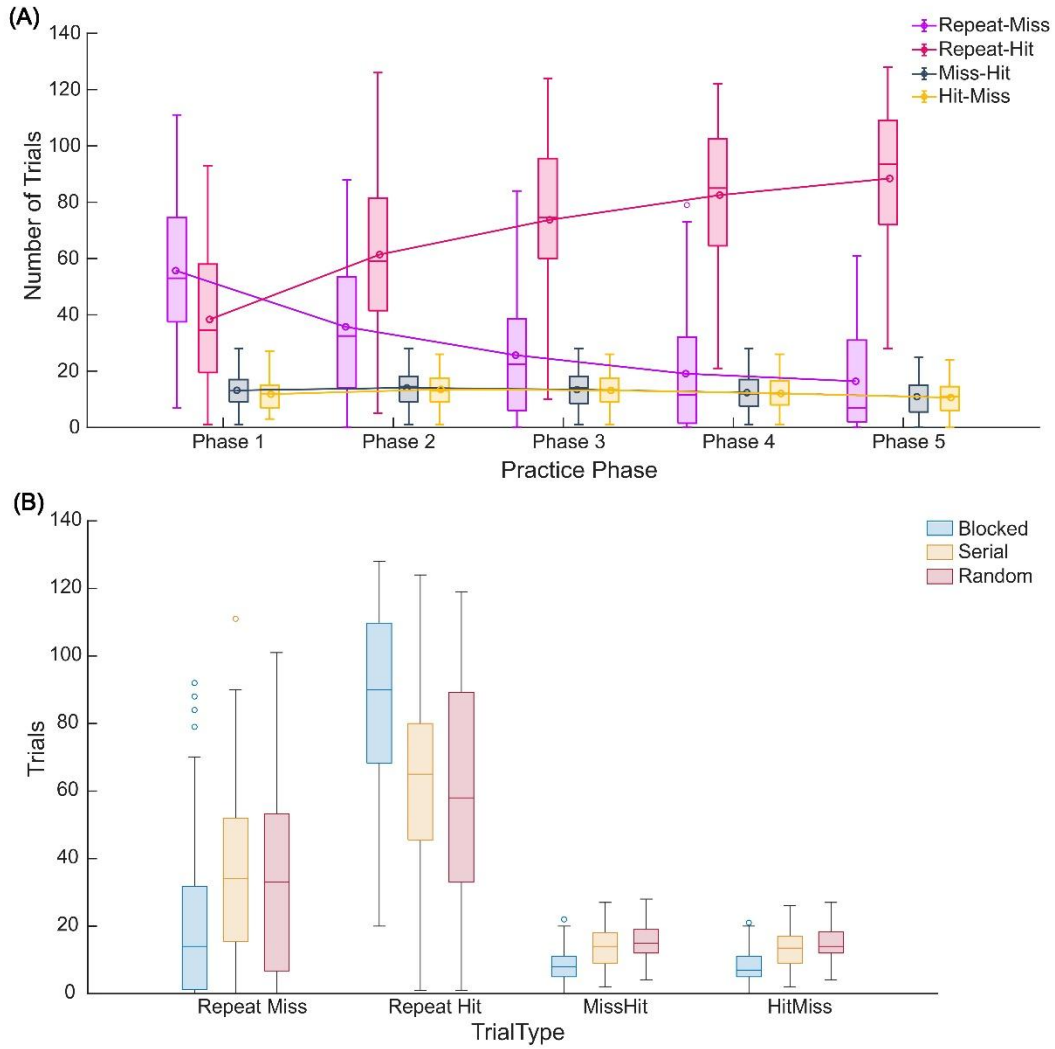


Fig. 3 (A) Mean number of trials for each trial type across practice phases. Circles represent the mean and the error bars correspond to 95% confidence interval. (B) Median number of trials for each trial type in different practice groups. The error bars represent data within 1.5 times the interquartile range

Amount of Search in Joint Space

The LME model on trial-to-trial difference in joint configurations during practice session revealed significant main effect of Practice Group ($F(2,58.6) = 10.52$, $p<0.001$), Trial Type ($F(1,29047.2) = 2285.42$, $p<0.001$) and Practice Phase ($F(4,29552.4) = 218.40$, $p<0.001$). All interaction effects were significant including the 3-way interaction of Practice Group x Trial Type x Practice Phase ($F(8,29564) = 5.37$, $p<0.001$). Posthoc pairwise comparison for Practice Group x Trial Type x Practice Phase revealed that amount of search reduces with practice for all the practice groups and for both trial types (Fig. 4). The reduction in amount of search between the initial two practice phases was significant for Random and Serial practice but not for Blocked practice in

both trial types. Amount of search is higher in Repeat-Miss than Repeat-Hit across all phases for all practice groups. There were no significant differences between the groups in Repeat-Miss trials. Search is higher in Random and Serial groups compared to Blocked in Repeat-Hit trials across all practice phases. In summary, search is higher in Repeat-Miss than in Repeat-Hit trials. Variability in both trial types decreases across the phases, but for Repeat-Miss the reduction is equal over groups and for Repeat-Hit the search is higher and decreases more for Serial and Random practice groups than for Blocked group (Fig. 4).

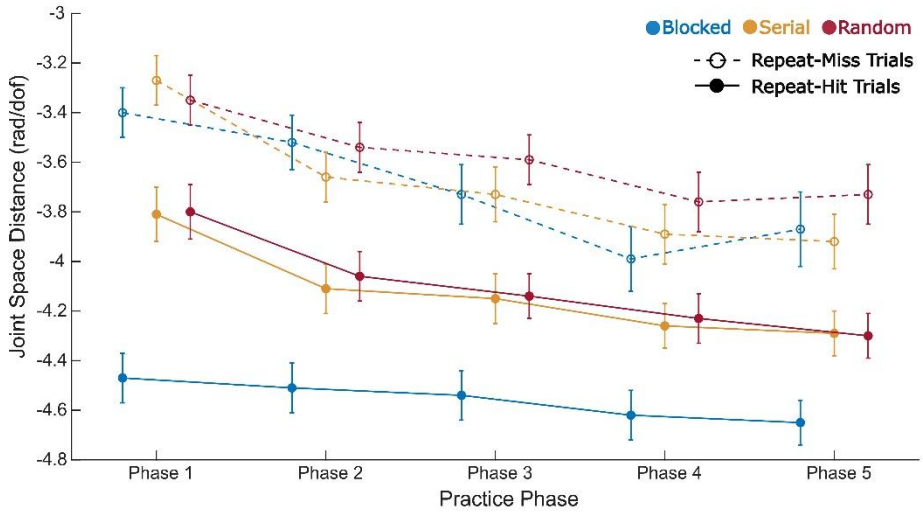


Fig. 4 Estimated Marginal Means of joint space distance across practice phases on Repeat-Miss trials (Dashed lines with unfilled circles) and Repeat-Hit trials (Solid lines with filled circles). Circles represent the mean and the error bars correspond to 95% confidence interval

Structure of Search

The LME model on joint deviation vectors for different trial types revealed all main effects and interaction effects of fixed parameters to be significant except the main effect of Practice Group and the interaction effect of Practice Group x Variance Type (significances of all effects can be found on the open access database). Noteworthy are the interaction effect of Practice Group x Practice Phase x Variance Type ($F(8,59524.80) = 3.15$, $p = 0.001$), Trial Type x Practice Phase x Variance Type ($F(4,59524.80) = 119$, $p<0.001$) and Trial Type x Practice Group x Variance Type ($F(2,59524.8) = 8.89$, $p<0.001$).

The posthoc results for Practice Group x Practice Phase x Variance Type reveal no practice group differences between JDVUCM and JDVORT across practice phases. The results however reveal structured change in variability such that JDVUCM is significantly greater than JDVORT across all phases. Both JDVUCM and JDVORT reduce with practice until practice phase 4 and only JDVUCM continues to reduce until phase 5 for Random and Serial practice groups (Fig. 5a). As an exception to this effect, the Blocked practice group exhibited no reduction in either JDVUCM or JDVORT between practice phases 2 and 3. Additionally, JDVUCM in Serial group was

significantly higher than in Blocked group during the first practice phase (difference = -0.31, p = 0.044) but no differences were observed with the Random practice group.

In the pairwise comparisons for Trial Type x Practice Phase x Variance Type, we found both JDVORT and JDVUCM reduce across practice phases (until practice phase 4) in Repeat-Miss trials, in the first practice phase JDVORT is larger than JDVUCM and JDVORT reduces much faster than JDVUCM over practice phases such that JDVUCM is larger than JDVORT in the last 2 practice phases (JDVUCM is not significantly different to JDVORT in practice phases 2 and 3). In Repeat-Hit trials, JDVUCM was significantly greater than JDVORT across all practice phases. JDVUCM reduces significantly across all practice phases and JDVORT reduces only between the first two and the last 2 practice phases (Fig. 5b).

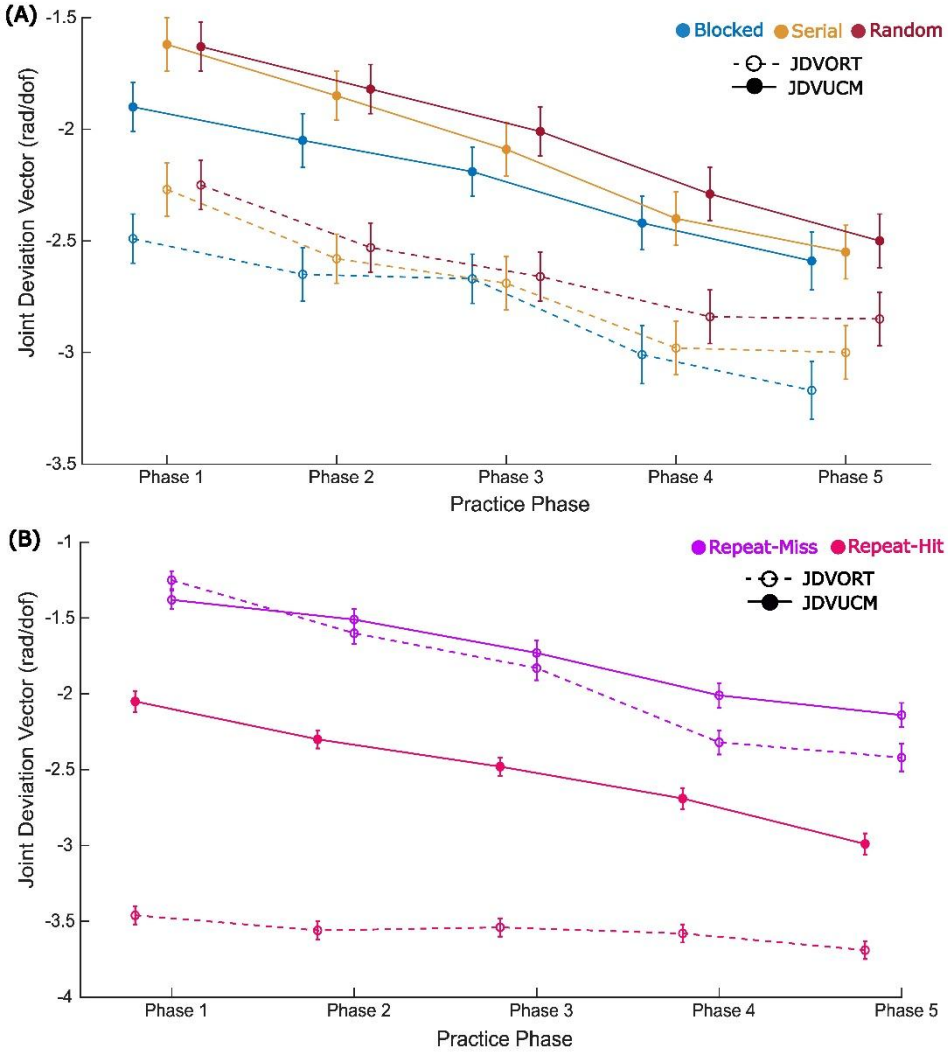


Fig. 5 (A) Estimated Marginal Means of JDVORT (Dashed lines with unfilled circles) and JDVUCM (Solid lines with filled circles) across practice phases for Blocked, Serial and Random practice groups. Circles represent the mean and the error bars correspond to 95% confidence interval. (B) Estimated Marginal Means of JDORT (Dashed lines with unfilled circles) and JDVUCM (Solid lines with filled circles) across phases for the two trial types (Repeat-Miss and Repeat-Hit). Circles represent the mean and the error bars correspond to 95% confidence interval

The posthoc comparisons for Trial Type x Practice Group x Variance Type show that for Repeat-Miss and Repeat-Hit trials, JDVUCM is higher than JDVORT. The difference between JDVUCM and JDVORT across all groups for Repeat-Hit is much larger than Repeat-Miss trials (Table 2, Appendix). No group differences were found in Repeat-Miss trials while both JDVUCM and JDVORT are higher for Serial and Random practice compared to Blocked practice in Repeat-Hit trials (Fig. 6).

In summary, both JDVUCM and JDVORT reduce faster in Random and Serial practice in comparison to Blocked practice. There are distinct differences in the structure of search between the two trial types. While in Repeat-Miss trials both JDVUCM and JDVORT reduce across practice phases, in Repeat-Hit trials only JDVUCM significantly reduces (note that JDVORT was minimal in these trials). Furthermore, no group differences were observed for Repeat-Miss trials whereas in Repeat-Hit trials, higher variability was found in Serial and Random practice than Blocked practice.

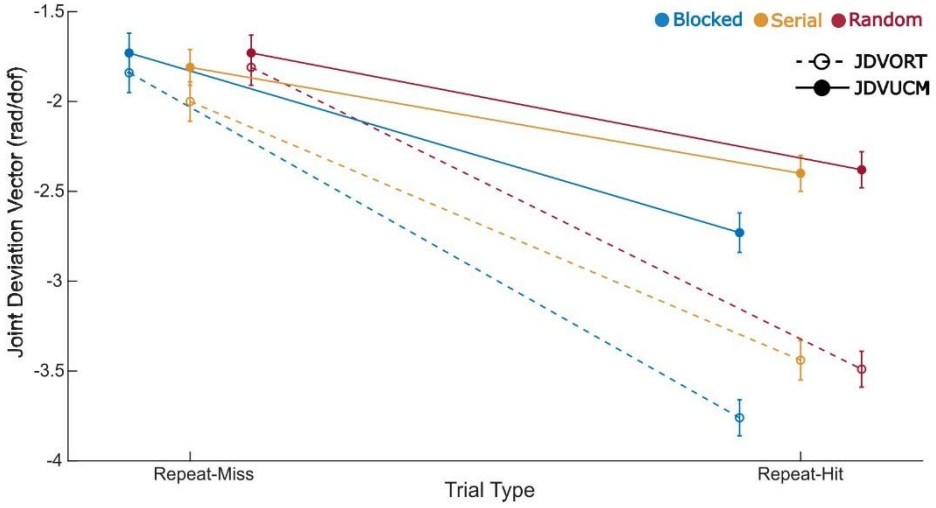


Fig. 6 Estimated Marginal Means of JDVORT (Dashed lines with unfilled circles) and JDVUCM (Solid lines with filled circles) across practice groups for Repeat-Miss and Repeat-Hit trials. Circles represent the mean and the error bars correspond to 95% confidence interval

Discussion

This study identified variability rather than predictability in practice scheduling as the key factor contributing to increased search behaviour during de-novo skill learning, as performance and search behaviour in the Serial practice condition were comparable to those in the Random practice condition and differed significantly from the Blocked practice condition. Furthermore, the amount and structure of joint variability during search varied depending on the type of search behaviour. Notably, variations in practice schedule influenced the amount of search in Repeat-Hit trials, but not in Repeat-Miss trials. Repeat-Hit trials, reflecting search for other coordination patterns meeting task goals, showed more search in Random and Serial Practice compared to Block Practice. With respect to the structure of search, Repeat Miss trials showed reduction in both search along the solution space (JDVUCM) and search orthogonal

(JDVORT) whereas Repeat Hit trials only showed reduction in JDVUCM and JDVORT was constant throughout. These results demonstrate how introducing variability during practice affects search behaviour and changes in the structure of search behaviour depending on the type of search.

The results from task performance reveal lack of evidence for the contextual interference effect as no group differences were observed within post-test and transfer-test. However, asymptotic reduction in error during practice and improved performance in post-test as well as transfer-test provide evidence for learning of the de-novo virtual lateral interception task. Overall task performance during practice and in test sessions were comparable for Serial and Random practice groups and differences were only observed with Blocked practice. Only in the initial phase of practice did Blocked group perform better than Serial and Random group. A surprising finding was that both the Serial and Random practice groups performed better in the post-test than in the transfer test, whereas no difference in performance between the two test sessions was observed for the Blocked practice group. In short, we found evidence of faster motor skill acquisition with Blocked practice and we found poorer transfer with Random and Serial practice. To an extent, these results corroborate with our previous studies utilizing the same setup[1,9] and provide increasing evidence for the lack of contextual interference effect in redundant de-novo skill learning tasks[15,18]. In a football shooting study, Vilela et al.[39] demonstrated a lack of learning differences between Blocked and Random groups during practice and tests (pre, post and transfer). However, in our study a notable finding was the similar task performance in Serial and Random groups as compared to Blocked group during practice.

The trial type analysis was performed to segregate the different types of search behaviour. The trials were classified based on the task success on the current trial and the preceding trial to the same BAP, resulting in 4 types: Repeat-Miss, Miss-Hit, Hit-Miss and Repeat-Hit trials. Repeat-Miss and Repeat-Hit trials exhibited significant changes across practice phases, with the frequency of Repeat-Miss trials decreasing and that of Repeat-Hit trials increasing. Whereas Miss-Hit and Hit-Miss remained low in number across practice suggesting that these trials were probably due to incidental one-off success or failure. While there is potential to study these latter trials for better understanding the transitions in learning behaviour, for the purposes of the current study we only focused on Repeat-Miss and Repeat-Hit trials. Group differences were also observed in Repeat-Hit trials with significantly greater number of trials in Blocked practice than in Serial and Random practice groups. This result validates the task performance analysis wherein Serial and Random practice groups show significant differences with respect to Blocked practice group during practice.

Although task performance did not differ between the groups as expected, analyses of search behaviour did reveal group differences. The amount of search reduced with practice and increased search behaviour was observed in the Serial and Random groups as compared to the Blocked group only when stabilizing the movement coordination pattern. Comparison of the two trial types revealed differences between the types of search behaviour. As expected, individuals displayed higher amounts of variability in Repeat-Miss trials than in Repeat-Hit. Moreover, the amount of variability in Repeat-Hit trials decreased faster for Serial and Random practice groups than

Blocked practice, but Blocked practice started at a lower level of variability. The commensurate behaviour observed across the Serial and Random groups indicates that the search process is governed by variability instead of predictability.

With regards to structure of search, search orthogonal to the solution space reduced faster than the search along the solution space for all practice groups (see fig 5A). The results confirm the findings of Mehta et al. 2025b on differential reduction and structured change in variability during search for novel coordination patterns. In Mehta et al. 2025b Random practice groups showed higher JDVUCM and JDVORT than Blocked practice in the initial phase of practice but similar results were not observed in this study. However, Serial practice group had significantly higher JDVUCM than Blocked practice in the first practice phase. Participants search more along the solution space with Serial practice than Blocked practice in the initial practice phases.

The structure of search also differed according to the trial type. In Repeat-Miss trials both JDVUCM and JDVORT reduced with practice while in Repeat-Hit trials JDVUCM reduced but not JDVORT (see Figure 5B). However, note that JDVORT was already quite low from the start. The result of Repeat-Hit trials is interesting because this reveals that individuals continue to search within the solution space even though they successfully perform the task. Furthermore, differences due to different practice groups were more prominent when evaluating the trial types (see Figure 6). The search behaviour was similar across groups in Repeat-Miss trials, however, in Repeat-Hit trials both JDVUCM and JDVORT were higher in Serial and Random practice as compared to Blocked practice. This suggested that different practice schedules did not influence the search for the solution space, but once the solution space was found, Blocked practice group zoned in on a more localized area while Random and Serial practice groups continued to search along the solution space scanning a larger region of it.

Traditionally, contextual interference effects have been evaluated only based on the performance in retention and transfer tests[40,41]. In our studies the effects of varying practice schedules were found only in practice phase and not on the performance in test sessions (post-test and transfer-test). Differences in search behaviour during practice may improve our understanding of the mechanisms governing the contextual interference effect, which has received scant attention. Our presupposition was that possibly an increased exploration of the DoF space and occupying a larger region within the solution subspace would allow for better transfer. We observed that the introduction of variability through Random and Serial practice scheduling increased exploration along the solution space compared to Blocked practice. But this increased exploration with random and serial practice did not translate into better performance in transfer tasks. This suggests that the effects of different practice schedules vary across different types of search behaviour. In skill acquisition of golf putting and basketball free throws[42], favourable results were found for starting with Blocked practice and transitioning to Serial practice followed by Random practice during training for better retention and transfer. However, such findings in contextual interference literature are not consistent[18,20]. Future research should focus on investigating the search behaviour during the practice phase across different tasks to

understand the mechanism of why the contextual interference effect is evident in certain tasks and specific training schedules but not in others.

A limitation of the present study is that trial type was classified solely based on the outcomes of two successive trials. While it can be interpreted from the increase in Repeat-Hit trials during later stages of practice that participants are consistently successful in performing the task. A more accurate identification of these search processes can be obtained by explicitly identifying the changes in the length of trial sequences with either repeated misses or repeated hits. Initially in practice, one would expect longer sequences of successive misses, as learners explore the solution space. As practice progresses, sequences of successive hits would grow longer.

There is a growing trend of using body machine interfaces in tandem with virtual reality for motor rehabilitation. Development of such rehabilitation technologies should embed motor learning principles to improve recovery[43,44]. This study lays the groundwork towards identifying practice conditions and movement outcome measures to enhance motor rehabilitation. One factor to consider is the degree of variability introduced during training, as greater variability increases task difficulty[45]. Our study suggests that in the initial stages of training there is no effect of practice variability, therefore patients could be trained with blocked practice and in the later stages of learning, variability can be introduced. Another factor to account for is motor abundancy in the movement system. Several studies have used the uncontrolled manifold hypothesis to study changes in motor coordination due to motor disorders[46]. However, motor abundance can also be used to improve task performance during re-learning. Using UCM measures during learning, shift the focus from individual joints to providing insights on how combinations of joint angles compensate for each other to stabilize task performance. Andrade et al.[47] show correlation between greater use of motor abundance and better performance by the paretic upper limb in stroke patients when performing a virtual transportation task. Motor abundance allows for flexibility in movements and formation of coordination patterns unique to each patient accounting for their disability. Effective practice design and relevant outcome measures that cater to individual differences in patients is key to motor rehabilitation[44].

In conclusion, the contextual interference effect in post-test and transfer-test was not observed even with increased number of practice trials to induce thorough learning. While limited evidence for the contextual interference effect was found in task performance, we observed similar search behaviour patterns between Random and Serial practice groups suggesting that changes in target locations induced movement variability that contributed to the search behaviour and not the predictability of the target locations. Initially, when searching for a new movement coordination pattern the amount and structure of variability was similar across different practice groups and differences were observed only when stabilizing the coordination pattern.

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Acknowledgements

The authors would like to acknowledge the contributions of Mart Bekker for assistance in data acquisition.

Funding

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 956003.

Author contributions

A.M., J.S., D.T. and R.B. conceived the work. A.M. carried out the experiments and performed the data analyses. A.M., J.S., D.T. and R.B. contributed to writing the manuscript. All authors have reviewed the manuscript.

Ethics approval and consent to participate

The study was approved by the Central Ethics Review Board (CTc) of the University Medical Center Groningen (R17753). The study was conducted in accordance to the Helsinki Declaration. All participants provided written informed consent prior to the start of the experiment.

Data and code availability statement

All the data and relevant codes used for analysis during the study will be made available at 10.5281/zenodo.15488730 on publication.

Competing interests statement

The authors declare no conflict of interest.

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