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RESEARCH ARTICLE

The effect of practice pattern on the acquisition, consolidation, and transfer of visual-motor sequences

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Abstract The contextual interference hypothesis proposes that when learning multiple skills, massing practice leads to better within-day acquisition, whereas random practice leads to better retention and transfer. In this experiment, we examined the effect of practice pattern on the learning, consolidation (retention), and transfer of visual-motor sequences. On Day 1, participants were randomly assigned to the Massed, Alternating, or Random condition. On Day 2, all participants were tested for consolidation and transfer. Learning was assessed through changes in accuracy and response synchronization. We found that massed practice led to enhanced sensorimotor integration and timing (as measured by response synchronization), whereas random practice led to better stimulus–response association (as measured by accuracy). On day 2, all groups showed consolidation for both measures, as well as transfer for accuracy but not response synchronization. Overall, this pattern of results provides limited support for the contextual interference hypothesis. Our findings are consistent with differential encoding of specific domains of motor performance. We propose that learning of the more explicit stimulus–response association is a fast process that benefits from random practice because it requires the acquisition of this association in multiple contexts. Once the association is learned, it seems resistant to interference and transferrable to a novel sequence. In contrast, learning of the sensorimotor integration and timing is a slower process that benefits from blocked training because practice in a single context allows fine-tuning of the response. Given that all groups showed consolidation, we postulate that learning that occurs in the context of interference can show consolidation.

Keywords Practice pattern · Contextual interference · Consolidation · Transfer · Motor sequence learning · Adults

Introduction

In everyday life, a vast array of motor skills can be learned simultaneously. A central question in the study of motor learning is how to structure practice of multiple skills in order to facilitate learning and retention. For instance, when a pianist is faced with learning Rachmaninoff's four piano concertos, what is the optimal way to organize their practice sessions? Should she learn one concerto before proceeding to the next one, or alternatively, should she learn all four concertos concurrently? Previous work has shown that when more than one motor skill is learned in a single session, massed patterns of practice lead to better within-day acquisition, but random patterns of practice lead to better retention and transfer. This effect was first termed "contextual interference" by Battig (1972) in describing the results of verbal memory experiments and was then applied to the domain of motor learning by Shea and Morgan (1979) (see Magill and Hall 1990; Schmidt and Bjork 1992; Brady 2008 for reviews). The current study examined the effect of three different practice patterns on visual-motor sequence learning over two consecutive days. The three practice patterns were tested: Massed, Random, and an intermediate Alternating condition in which blocks of the same sequence were alternated during practice.

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Many studies of motor sequence learning have looked at how a single novel sequence is acquired and retained over several training sessions (Nissen and Bullemer 1987; Karni et al. 1998; Willingham 1998; Doyon et al. 2002; Savion-Lemieux and Penhune 2005; Seidler et al. 2005). Commonly, learning has been characterized by three stages that correspond to specific points in the pattern of incremental changes that occur while practicing a new sequence (Karni 1996; Willingham 1998; Hikosaka et al. 1999; Doyon et al. 2003; Korman et al. 2003). Within the first training session, fast and significant improvements in performance are observed, typically over a relatively small number of practice trials. This stage is followed by slower and more gradual gains that take place over a number of days or weeks, leading to an eventual plateau in performance (Karni et al. 1998; Hikosaka et al. 2002; Korman et al. 2003; Savion-Lemieux and Penhune 2005). A third, intermediate stage, referred to as consolidation, has been the focus of much recent interest. This stage occurs between the first and second training sessions and is thought to be sleep-dependent (Brashers Krug et al. 1996; Walker et al. 2003; Fischer et al. 2005; Criscimangna-Hemminger and Shadmehr 2008). Consolidation has been measured in a number of different ways (see Robertson et al. 2004; Krakauer and Shadmehr 2006 for review). One is improvement in performance after a period of rest or a night of sleep, with no additional practice. Another is resistance to interference by learning of a second sequence or task. The last is the ability to transfer learning to another sequence or task.

Support for the presence of separable stages of motor learning comes from functional imaging studies showing that different cortical and subcortical regions are preferentially activated at different stages of learning (Penhune and Doyon 2002; Doyon and Benali 2005; Floyer-Lea and Matthews 2005; Penhune and Doyon 2005). For instance, it has been postulated that while the cerebellum, rostral striatum, as well as motor, prefrontal, and parietal cortical regions are mainly active during early learning, the caudal striatum, as well as motor and parietal cortical areas are involved in consolidation and the later stage of learning (Doyon and Benali 2005). It has been suggested that distribution of practice over time is important for a maximum benefit of practice to be gained, as the time delay allows for these neural changes to occur (Korman et al. 2003; Savion-Lemieux and Penhune 2005; Criscimangna-Hemminger and Shadmehr 2008). This stage has been argued to be sleep-dependent, with a number of studies showing consolidation effects after a night of sleep compared with simple passage of time (Fischer et al. 2002; Walker et al. 2003; Robertson et al. 2004; Krakauer and Shadmehr 2006).

Another important factor influencing how well a motor sequence is acquired and consolidated is the pattern of practice. This factor may be particularly relevant when learning more than one sequence, as is commonly the case in real-life situations. Early studies of verbal memory in the 1960s revealed that practice in which learning trials were presented in a blocked order, where all trials of one task are learned together before those of a second one are introduced, resulted in better within-day acquisition but poorer retention and transfer to a novel task, compared to practice in which learning trials were presented in a random order (Battig 1966; Battig 1972). This effect has been termed “contextual interference,” as it was postulated that high degrees of interference during initial learning enhance across-day retention and transfer of learned skills to a novel task (Battig 1972; Magill and Hall 1990). Potential factors contributing to the contextual interference effect include, but are not limited to, the task and the practice schedule (Magill and Hall 1990; Schmidt and Bjork 1992).

Two principal theories have been put forward to explain the contextual interference effect: the elaboration hypothesis (Shea and Zimny 1983, 1988) and the action plan reconstruction hypothesis (Lee and Magill 1985). The elaboration hypothesis suggests that learning skills in a random fashion leads to more elaborative processing and therefore, more comprehensive and retrievable memories in the long term. The reconstruction hypothesis postulates that learning skills in a random manner requires the learner to actively reconstruct many action plans, which in turn leads to more effortful processing and a more permanent memory (for a more detailed review of the two hypotheses see, Brady 2008). Support for this theory comes from an fMRI study of contextual interference on motor sequence learning (Cross et al. 2007). Their results showed that random practice slowed initial performance, but improved retention. Consistent with the proposed mechanisms underlying contextual interference, they showed that during acquisition, the random practice group took more time to plan their movements and showed greater activity in motor regions associated with movement planning and response selection.

Since Shea and Morgan’s (1979) original experiment, numerous studies in the motor skill domain have investigated the contextual interference effect (see Magill and Hall 1990; Brady 2008 for reviews). However, results have been somewhat inconclusive. As Brady (2004) noted in his meta-analytic study “the literature on contextual interference contains many studies performed with different groups, different tasks, small sample sizes, and low power, thus rendering generalizations based solely on probability misleading” (p. 117). In fact, many recent studies conducted in both laboratory (e.g., bimanual coordination, sequential aiming, pursuit-tracking) and applied settings (e.g., pistol-shooting, endoscopic surgery, volleyball; Maslovat et al. 2004; Keller et al. 2006; Sekiya 2006; Russell and

Newell 2007; Zetou et al. 2007; Kurahashi et al. 2008) have yielded inconsistent evidence. For example, Maslovat et al. (2004) found that the random group outperformed the blocked group on the learning and retention of bimanual coordination patterns, and no group effects were found during the transfer test.

The majority of studies looking at contextual interference have focused on the learning of gross motor skills, whereas very few studies have looked at fine motor skill learning. Studying contextual interference may be especially relevant in settings in which optimal performance of fine motor movement is required, such as playing a musical instrument. In addition, studies investigating the influence of contextual interference on motor learning have typically used an interference condition involving a high degree of contextual interference, in which three or more tasks are presented in an unsystematic or random order. However, many day-to-day fine motor tasks are not acquired in an unsystematic or random order but rather are learned in a controlled and predictable manner (e.g., practicing the piano, learning to type). Therefore, in the present experiment, we used the multi-finger sequencing task (MFST), a variant of the classical serial reaction time task (SRT; Nissen and Bullemer 1987), to study the effect of the pattern of practice on fine motor sequence learning, across two consecutive days. In the MFST, participants had to reproduce sequences of key presses on an electronic keyboard, using four fingers of their right hand. The MFST is thought to be more naturalistic and similar to learning a tune on the piano. Two sequences were presented in a blocked, alternating, or random fashion on the first day of testing. On the second day, participants were either presented with the last block they practiced on Day 1 (to test for consolidation) or a novel transfer sequence. Given that recent research in both animals and humans has suggested that specific aspects of motor skill are learned and retained differently, and that learning of these parameters may be subserved by different brain networks (Hikosaka et al. 2002; Savion-Lemieux and Penhune 2005; Ghilardi et al. 2009), we examined the effect of patterns of practice on two different aspects of performance. The first aspect is sequence accuracy, a component of the task that requires the association of the visual stimulus with the motor response. The second aspect is response synchronization, a more procedural component that requires fine-grained sensorimotor integration and timing. Overall, we hypothesized that if the contextual interference effect was operative, participants in the Massed condition would perform better than those in the two other conditions on the first day of learning, whereas participants in the Alternating and Random conditions would perform better at consolidation and transfer to Day 2.

Method

Participants

The total sample was comprised of 81 healthy undergraduates (27 men and 54 women). All participants were between the ages of 18 and 35 years. All participants were neurologically healthy and right-handed, as assessed using an adapted version of Crovitz and Zener's (1962) handedness questionnaire. Given that a previous study in our laboratory found behavioral differences in motor skill performance between adult musicians and non-musicians, participants in the present study were selected to have less than 3 years of musical training and experience, as measured using a modified version of the Global Index of Musical Training and Experience questionnaire (Watanabe et al. 2007). Participants were requested to refrain from drinking alcohol prior to each testing session. Three additional participants were tested but were excluded from the final sample due to experimental error. The experimental protocol was approved by the Concordia University Human Research Ethics Committee, Montreal, Quebec. Participants provided written informed consent and were compensated for their time.

Multi-finger sequence task and stimuli

The Multi-finger sequence task (MFST) is a variant of the classical Serial Reaction Time (SRT) task originally designed by Nissen and Bullemer (1987). In the MFST, participants reproduced 13-element sequences of key presses on a MIDI-compatible electronic keyboard (Yamaha P-90), using four fingers of their right hand (i.e., index, middle, ring, and pinkie). Participants were cued to press one of the four marked keys by visual stimuli presented on the computer monitor (21-in. Sony Trinitron Multiscan G520 computer monitor, running at 100 Hz). The visual display consisted of four rectangular gray bars (11.5 cm × 3 cm) which remained on the screen for the entire duration of each trial. During a trial, the gray bars each turned red in a given order. The red illumination of a gray bar indicated that the corresponding key was to be pressed. The total inter-tap interval was 750 ms, during which the red bar was lit for 500 ms and the interval between the end of one stimulus and the beginning of the next was 250 ms. Additionally, there was a 2,000 ms delay between trials.

Each trial of the MFST consisted of a 13-element sequence and each block of practice included 12 trials. Three sequences were employed which were all designed to be of equal difficulty (sequence A: 1, 2, 4, 3, 1, 4, 2, 3, 2, 1, 3, 4, 1; sequence B: 2, 4, 1, 3, 2, 1, 4, 3, 1, 2, 3, 4, 2; and sequence C; 3, 1, 4, 2, 1, 3, 4, 1, 2, 4, 3, 2, 3). In addition, the same key was never pressed twice in succession and the same transition between two fingers never occurred twice consecutively. Breaks were provided between blocks to prevent fatigue and optimize performance.

A computer (Windows 2000) recorded all generated responses from the midi-compatible electronic keyboard. In-house custom software written in C++ was used to create and control the presentation of the visual stimuli and automatically recorded the onset and offset of participants' key presses, which were subsequently used to calculate the indices of learning.

Procedure

Testing included two learning sessions on two consecutive days, approximately 24 h apart. On Day 1, participants were randomly assigned to one of three conditions (Fig. 1): a massed condition (*n* = 23), an alternating condition (*n* = 24), or a random condition (*n* = 23). In the massed condition, participants received four blocks of sequence A followed by four blocks of sequence B. In the alternating condition, participants received eight alternating blocks of sequences A and B. In the random condition, participants received eight blocks in which both sequences A and B were quasi-randomly presented within each block. On Day 2, within each condition, participants were divided into two groups (with 11–12 participants per group). The groups received either: one block of sequence B followed by one block of sequence A (i.e., consolidation group); or one block of a novel sequence C (i.e., transfer group; Fig. 1). Of note, participants in the random condition received two blocks in which both sequences A and B were quasi-randomly presented within each block. An additional control group was tested, in which 11 participants received four blocks of only one sequence on Day 1, followed by one block of that same sequence on Day 2. This additional group was included to test for consolidation of one sequence without any interference. The order of sequence presentation was counterbalanced, and on each testing day, participants were first familiarized with the electronic keyboard and the computer-generated stimuli.

Participants were told that they would be learning different motor sequences, but they were not explicitly taught the sequences. They were asked to follow along with the stimuli as accurately as possible, by pressing the key that corresponded to the location of the red illuminated rectangular bar. In order to minimize anticipatory responses and maximize response synchronization, participants were also instructed to synchronize their response with the visual stimulus by waiting until the red bar illuminated. As such, participants were not instructed to respond "as fast as possible" as is typically the case in classical SRT studies (Nissen and Bullemer 1987).

Behavioral measures

Learning was assessed by measuring changes in accuracy and response synchronization. Accuracy was scored individually, by calculating the percentage of correct key presses made for each sequence type (i.e., A, B, or C) within each trial and block. Response synchronization was calculated for correct key presses only; it characterized each participant's response time (ms) relative to the stimulus onset, averaged across trials and blocks of practice, for each sequence type. Anticipatory responses were included in the measure because previous studies have shown that anticipation increases with learning (Penhune and Doyon 2002; Savion-Lemieux and Penhune 2005). If response synchronization was a classic reaction time (RT) measure, anticipatory responses would be excluded as RT measures the time it takes the participant to make a response after the onset of the stimulus.

As in previous experiments in our laboratory, accuracy represented a component of the task which requires the association of the visual stimulus with the motor response; whereas, response synchronization represented a more

Fig. 1 Experimental design: A, B, and C represent three different thirteen key-press sequences. A and B were used during training and C only at transfer. A represents the first sequence learned and B the second sequence learned; the actual sequences were counter-balanced across subjects

	Day 1	**Day 2**	
Massed condition	A A A A B B B B	B A	(***consolidation group***; n = 12)
	A A A A B B B B	C	(***transfer group;*** n = 11)
Alternating condition	A B A B A B A B	B A	(***consolidation group***; n = 12)
	A B A B A B A B	C	(***transfer group***; n = 12)
Random condition	$\boxed{AB}$ x 8 blocks	$\boxed{AB}$ $\boxed{AB}$	(***consolidation group***; n = 12)
	$\boxed{AB}$ x 8 blocks	C	(***transfer group***; n = 11)
Control group	A (or B) x 4	A (or B)	(n = 11)

procedural component that requires fine-grained sensorimotor integration and timing. Dependent measures were individually averaged across trials for each sequence type within each block of practice on the MFST.

Of note, participants in the random condition completed six trials of A and six trials of B within each block of practice. In order to analyze an equivalent number of A and B trials within each block (i.e., 12 trials) across all groups, the six trials of one sequence from one block were averaged with the six trials of the same sequence from the following block (e.g., six trials of A, Block 1 + 6 trials of A, block 2/12).

Results

Independent samples *t* tests indicated no significant differences for average performance for sequences A and B collapsed across blocks on Day 1 ($P > 0.211$) for either behavioral measure, indicating that the sequences were of equal difficulty. Moreover, there were no significant differences between the sexes for average performance for sequences A and B on Day 1, for either behavioral measure ($P > 0.113$), when randomly selecting an equal number of men and women; therefore, behavioral data were collapsed across this dimension.

Analyses were conducted by day. For Day 1, the data were analyzed with repeated measures analyses of variance (ANOVAs; Greenhouse-Geiser correction), with Group as the between-subject factor and Block as the within-subject factor. Differences across the four blocks of A and across the four blocks of B were evaluated separately. Using repeated measures ANOVAs (Greenhouse-Geiser correction), with Group as the between-subject factor and Block as the within-subject factor, we also assessed for consolidation of sequences B and A. For sequence B, we compared performance on the last block of B on Day 1 to the first block of B on Day 2 (free of across-day interference). For sequence A, we compared performance on the last block of A on Day 1 to the first block of A on Day 2 (in the context of within- and across-day interference). Using the same type of analyses for transfer, we compared performance on the last block of B on Day 1 to the first block of C on Day 2, when the sequence was novel and free of across-day interference. Additionally, a one-way ANOVA was used to compare the percent change for each measure for both consolidation and transfer. This score was calculated by subtracting performance on Day 1 from performance on Day 2, and dividing the total by performance on Day 1 (i.e., for consolidation of B: first block of B on Day 2—last block of B on Day 1/last block of B on Day 1; for consolidation of A: first block of A on Day 2—last block of A on Day 1/last block of A on Day 1; for transfer: first block of C on Day 2—last block of B on Day 1/last block of B on Day 1). Significant main effects and interactions were analyzed using pairwise comparisons, with Bonferroni adjustment for multiple comparisons. The α level was set at 0.05 for all statistical tests. Effect sizes were reported for all significant main effects and interactions, using partial eta square (η^2).

Day 1

When comparing sequence A between the Massed, Alternating, and Random groups across the four blocks of practice on Day 1, for percent correct (Fig. 2a), there was a significant main effect of Block $F\ (2, 4) = 5.03$, $P = 0.008$ ($\eta^2 = 0.070$), such that block 1 was significantly less accurate than block 2, $p = 0.006$. There was also a significant main effect of Group $F\ (2, 67) = 3.78$, $P = 0.028$ ($\eta^2 = 0.101$), such that the Random group was significantly more accurate than the Alternating group $P = 0.034$; the Alternating and Massed groups did not differ. There was no significant Block X Group interaction $P = 0.471$. For response synchronization (Fig. 2b), there was a significant Block X Group interaction $F\ (3.8, 126.99) = 4.34$, $P = 0.003$ ($\eta^2 = 0.116$). In line with our hypothesis, the Massed group showed significant improvements across all blocks of practice ($P < 0.005$), the Alternating group showed some significant improvements (specifically when comparing block 1 to blocks 2, 3, and 4; $P < 0.058$), but the Random group showed no significant improvements.

When comparing sequence B between the Massed, Alternating, and Random groups across the four blocks of practice on Day 1, a similar pattern of results emerged. For percent correct (Fig. 3a), there was a significant main effect of Group $F\ (2, 67) = 4.52$, $P = 0.014$ ($\eta^2 = 0.018$), such that the Random group was significantly more accurate than the Alternating group $P = 0.013$, and the Alternating group and the Massed group did not differ. No significant main effect of Block or Block X Group interaction was found ($P > 0.137$). For response synchronization (Fig. 3b), there was a significant Block X Group interaction $F\ (4.89, 163.67) = 3.06$, $P = 0.012$ ($\eta^2 = 0.084$). Post hoc analyses revealed that the Massed and Alternating groups showed significant improvements when comparing block 1 to all other blocks ($P < 0.031$) and when comparing block 2 to block 4 ($P = 0.001$); whereas the Random group showed no significant improvements across blocks on this measure.

Rate of change (Day 1)

An additional set of analyses was performed to quantify and compare the absolute rate of change between the first and last blocks of practice on Day 1, relative to the first block of practice on Day 1, for each sequence type and for each behavioral measure. To do this, the slope for each

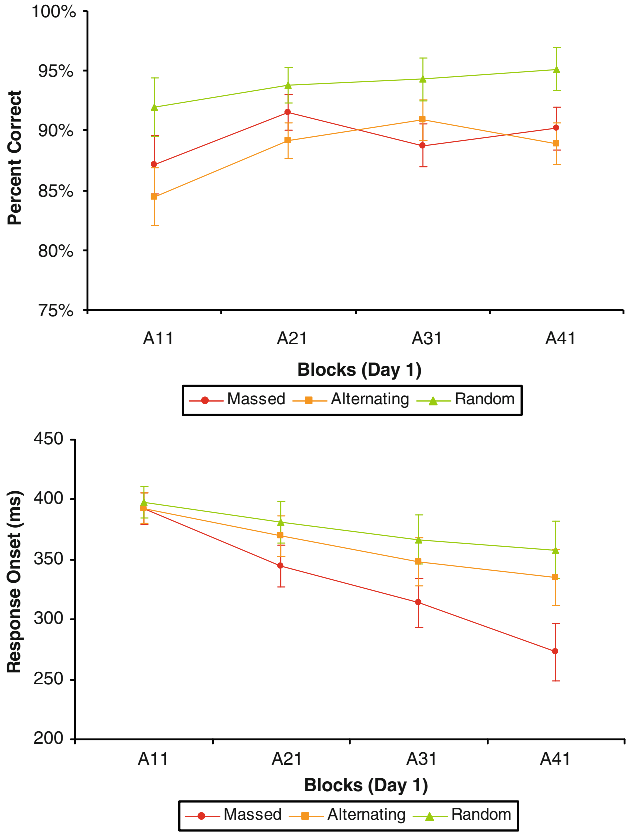

Fig. 2 Acquisition of sequence A: Average accuracy (**a**) and response synchronization (**b**) data for the Massed, Alternating, and Random conditions across four blocks of acquisition on Day 1

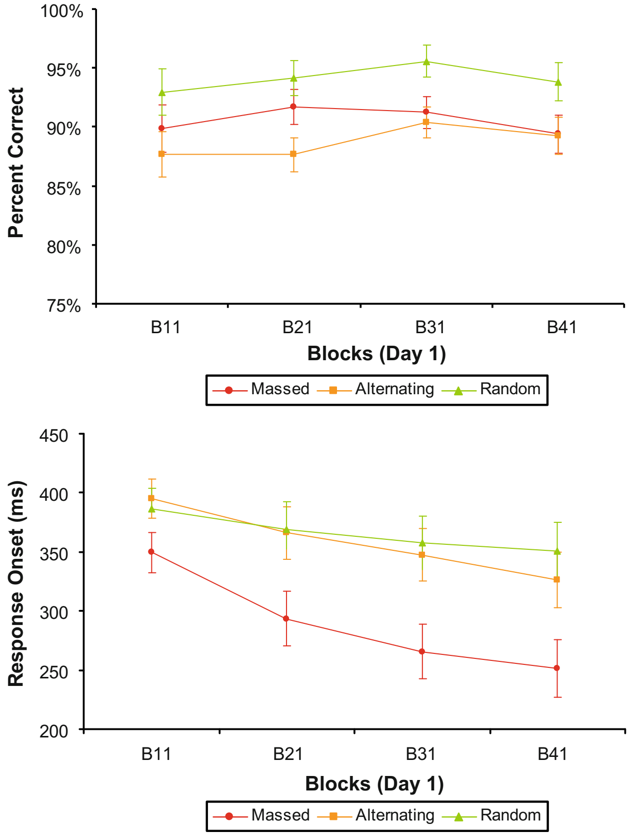

Fig. 3 Acquisition of sequence B: Average accuracy (**a**) and response synchronization (**b**) data for the Massed, Alternating, and Random conditions across four blocks of acquisition on Day 1

measure and sequence type was calculated and normalized to the first block of practice of the same sequence type. We used a one-way ANOVA, with Group (Massed, alternating, Random) as the between-subject factor and Bonferroni adjustment for multiple comparisons.

When comparing rate of change for sequence A, for percent correct, there was no significant difference in rate of change between the Massed, Alternating, and Random groups $P = 0.781$. For response synchronization, there was a significant main effect of Group $F\ (2,\ 69) = 5.318$, $P = 0.007$, such that the Massed group showed the greatest rate of change compared to the other two groups ($P < 0.078$); the Alternating and Random groups did not differ from each other in their rate of change.

When comparing rate of change for sequence B, for percent correct, there was no significant difference in rate of change between the Massed, Alternating, and Random groups $P = 0.672$. For response synchronization, there was a significant main effect of Group $F\ (2,\ 69) = 5.231$, $P = 0.008$, such that the Massed group showed a greater rate of change compared to the Random group $P = 0.006$; the other groups did not significantly differ from each other.

We also compared the rate of change between sequences A and B, for each behavioral measure, using a 3 (Group) × 2 (Sequence Type) repeated measures ANOVA. Results indicated that for percent correct, there was a marginally significant main effect of Sequence Type $F\ (1, 67) = 2.885$, $P = 0.094$ ($\eta^2 = 0.041$), such that there was a greater rate of change for sequence A compared to sequence B. No other significant results were noted. For response synchronization, there were no significant main effects and no interaction.

Finally, given the differential pattern of results found for accuracy and response synchronization on Day 1, we also compared the two measures to each other using a 3 (Group) × 2 (Measure) repeated measures ANOVA (Greenhouse-Geiser correction) for each sequence type. Findings showed that for sequence A, there was a significant Group X Measure interaction $F\ (2,\ 67) = 5.091$, $P = 0.009$ ($\eta^2 = 0.132$). Post hoc comparisons showed that all groups demonstrated significant differences in the rate of change between the two behavioral measures $P < 0.001$ (with greater changes on the response synchronization measure). For sequence B, the same pattern of results emerged such that there was a significant Group X Measure interaction $F\ (2, 67) = 5.144$, $P = 0.008$ ($\eta^2 = 0.133$), with all groups showing significant differences in the rate of change between the two behavioral measures $P < 0.02$

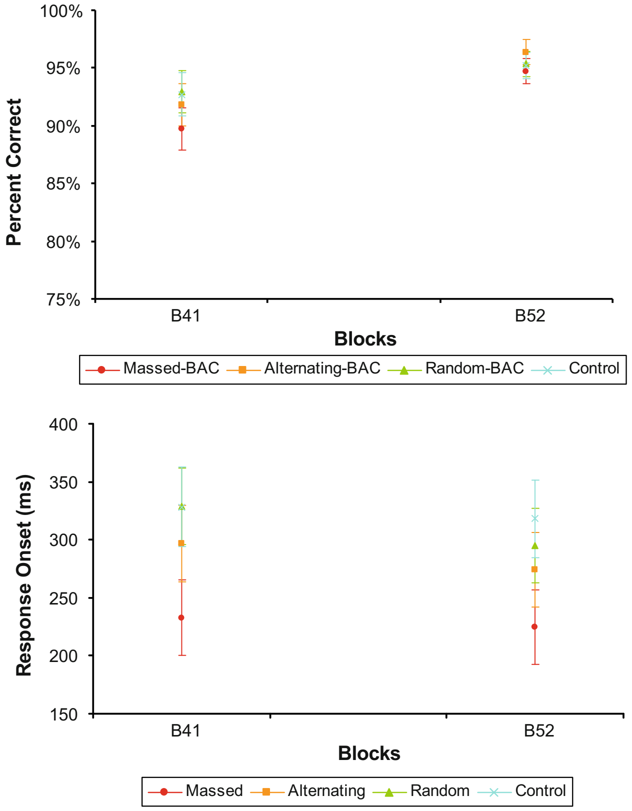

Fig. 4 Consolidation without Day 2 interference: Average accuracy (**a**) and response synchronization (**b**) data for the Massed, Alternating, and Random conditions across the last block of B on Day 1 and the first block of B on Day 2

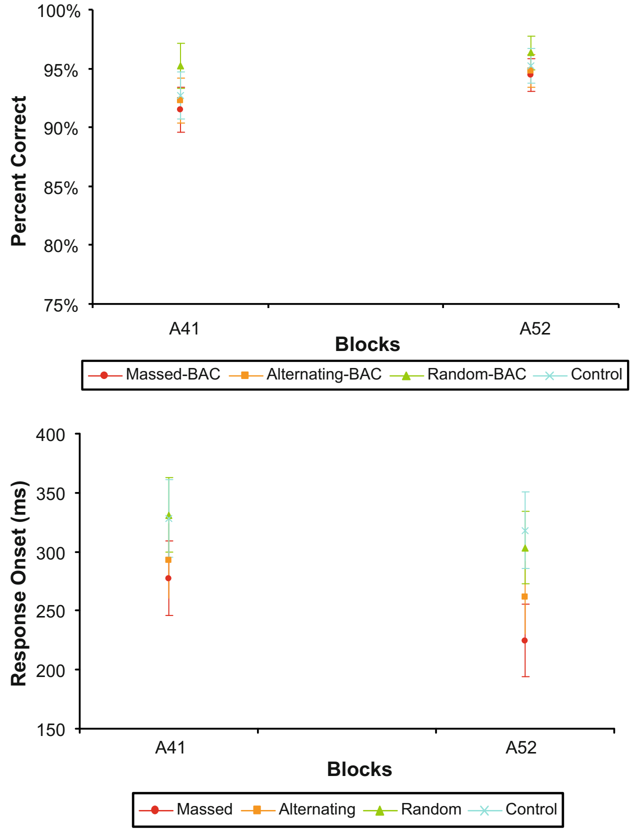

Fig. 5 Consolidation with interference: Average accuracy (**a**) and response synchronization (**b**) data for the Massed, Alternating, and Random conditions across the last block of A on Day 1 and the first block of A on Day 2

(with greater changes on the response synchronization measure).

Consolidation

When comparing performance on the last block of B on Day 1 to performance on the first block of B on Day 2, between the Massed, Alternating, Random, and Control groups, we found a similar pattern of results for both measures. For percent correct (Fig. 4a), there was a significant main effect of Block F (1, 43) = 15.9, $P < 0.001$ ($\eta^2 = 0.270$), indicating overall significant improvements across days regardless of group. A significant main effect of Block F (1, 43) = 7.66, $P = 0.008$ ($\eta^2 = 0.151$) was also found for response synchronization (Fig. 4b), with overall significant improvements across days. No other significant main effect of Group or interactions were found for either measure ($P > 0.175$), suggesting overall consolidation of sequence B, free of between-day interference, regardless of practice pattern.

We also contrasted performance on sequence A on Day 2 to performance on the last block of practice on sequence A on Day 1, in order to look at consolidation of A in the context of interference from practice on sequence B, both within and across days. Overall, there was a significant main effect of Block for both percent correct (Fig. 5a) F (1, 43) = 8.24, $P = 0.006$ ($\eta^2 = 0.161$) and response synchronization (Fig. 5b) F (1, 43) = 10.56, $P = 0.002$ ($\eta^2 = 0.197$), with post hoc analyses indicating general improvements on Day 2. No other significant main effects or interactions were found for both measures ($P > 0.29$), suggesting overall consolidation of sequence A, in the context of within- and between-day interference, regardless of practice pattern.

An additional set of analyses was performed to evaluate the percent change for each measure on consolidation of sequences B and A on Day 2. No significant results were found between sequence types for either behavioral measure.

Transfer

We compared performance on the last block of B on Day 1 to the first block of C on Day 2, free of across-day interference,

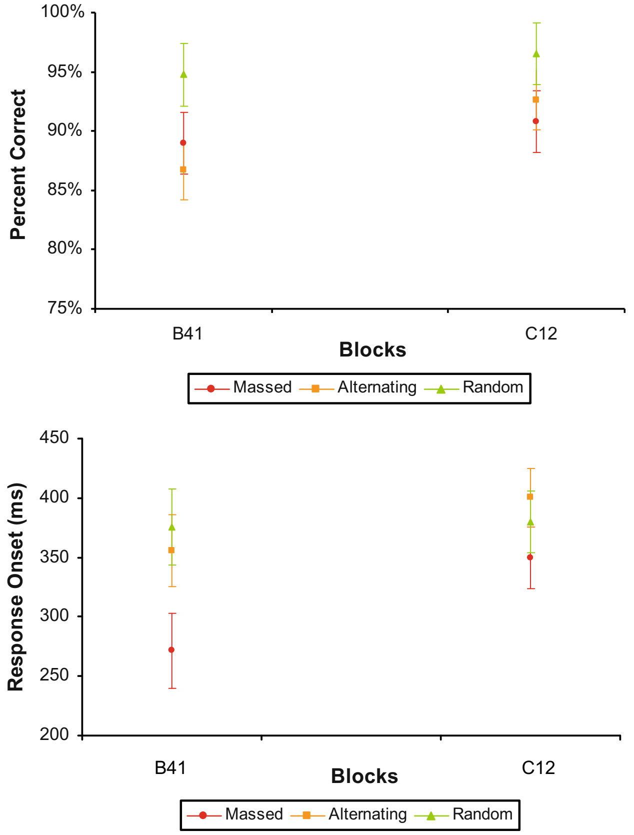

Fig. 6 Transfer: Average accuracy (**a**) and response synchronization (**b**) data for the Massed, Alternating, and Random conditions between the last block of B on Day 1 to the first block of C on Day 2

for the Massed, Alternating, and Random groups. For percent correct (Fig. 6a), there was a marginally significant main effect of Block *F* $(1, 31) = 3.12$, $P = 0.087$ ($\eta^2 = 0.091$), such that C was more accurate than B, indicating a certain degree of transfer. For response synchronization (Fig. 6b), there was a significant main effect of Block *F* $(1, 31) = 8.13$, $P = 0.008$ ($\eta^2 = 0.208$), this time showing better performance for B compared to C indicating a loss in performance and/or interference likely leading to negative transfer. No other significant main effects or interactions were found ($P > 0.084$; Fig. 6b).

An additional set of analyses was performed to evaluate the percent change of transfer from sequence B to sequence C for each measure. No significant differences were found between groups for either behavioral measure ($P > 0.297$).

Discussion

The current study was motivated by early research findings from the contextual interference literature, which demonstrated that high levels of contextual interference typically lead to poor within-day learning, but better across-day retention and transfer. Thus, in this experiment, we looked at the effect of three practice patterns (Massed, Alternating, and Random) on the learning (within-day), consolidation (across days), and transfer of visual-motor sequences. Overall, we found that on Day 1, for response synchronization, the Massed group showed the greatest improvements in performance across the blocks of practice whereas the Random group showed the least improvements. For response accuracy, surprisingly, the Random group performed better than the Massed and Alternating groups. In other words, massed practice led to enhanced sensorimotor integration and timing (as measured by response synchronization), whereas random practice led to better stimulus–response association (as measured by response accuracy). On Day 2, all groups showed consolidation of the sequences as evidenced by significant improvements in both accuracy and response synchronization between the last block of practice on Day 1 and the first block of practice on Day 2. Further, all groups showed transfer of learning to a novel sequence for response accuracy, but not response synchronization. Taken together, the overall pattern of results provides only partial support for the contextual interference hypothesis, with enhanced performance for the Massed group on Day 1 for response synchronization, but not accuracy. Further, the Random group did not show better performance at consolidation or transfer. Our findings are consistent with differential encoding of specific domains of motor performance and we therefore suggest rethinking the contextual interference hypothesis to take into account different measures of learning. Moreover, given that all groups showed consolidation, we postulate that the learning that occurs in the context of interference can show consolidation, which is not entirely consistent with previous studies showing interference when a second sequence is learned immediately following the first (Brashers Krug et al. 1996; Walker et al. 2003).

An interesting and novel finding that has not been previously reported in the contextual interference literature is the dissociation we found between the behavioral measures used to assess learning and transfer. In many laboratory studies looking at contextual interference from a motor skill perspective, participants are required to move/respond as rapidly as possible (e.g., Shea and Morgan 1979; Seidler 2004; Garcia et al. 2008). Thus, the dependent measure is often "response time". In the present study, we broke down fine motor learning into two different components: accuracy, a component of the task that requires the association of the visual stimulus with the motor response, and response synchronization, a component that requires fine-grained sensorimotor integration and timing. Interestingly, we showed that practice pattern had a differential effect on the learning of these two measures, as we found that massed practice led to enhanced sensorimotor integration and timing, whereas random practice led to better stimulus–response association. We also showed transfer of learning to a novel sequence for response accuracy but not response synchronization, regardless of practice pattern. Taken together, these results support the idea that different components of a motor skill are learned and transferred in different ways (Hikosaka et al. 1999; Savion-Lemieux and Penhune 2005; Ghilardi et al. 2009).

Based on our findings, we propose that learning the stimulus–response association, or explicit ordering of the task, is a fast process that benefits from structuring initial practice in a random fashion, because it requires the participant to acquire the stimulus–response association in multiple contexts by flexibly switching between the two sequences. This process likely requires greater generalization of the stimulus–response association, as well as more effortful processing and attention. Moreover, once the association has been learned, it seems to be resistant to interference and transferrable to a novel sequence. This is consistent with the elaboration or reconstruction hypotheses of contextual interference, but also applies to acquisition. On the other hand, learning of the sensorimotor integration and timing, or dynamic elements of the task, is a slower process that benefits from structuring initial practice in a blocked fashion, possibly because practice in a single context allows for error-correction and fine-tuning of the response. Interestingly, this component of the task seems to be more resistant to transfer, because without a constant context, the fine timing of the response is difficult to acquire. One model that provides support for this dissociation is that of Hikosaka et al. (1999, 2002). The authors propose that motor sequence skills are handled as two types of sequences when represented within the brain: one spatial and one motor. The spatial sequence, or explicit ordering of the task, requires a high level of attention, is learned quickly, can be identified by rapid improvements in accuracy, and is encoded in the loops between the rostral basal ganglia (BG), prefrontal and parietal cortices, and the lateral cerebellum (CB). The motor sequence, or dynamic elements of the task, requires little attention, is learned more slowly, can be identified through improvements in synchronization, and is encoded between the loops in the caudal BG, motor cortex, and medial CB. Hikosaka's model can further be interpreted in light of the "elaboration" and "action plan reconstruction" hypotheses (Shea and Zimny 1983; Lee and Magill 1985, respectively), from the contextual interference literature. As Brady (2008) writes in his review, both hypotheses share a common characteristic, as they suggest that scheduling practice in a random fashion fosters cognitive processing that enhances encoding and thus transfer of the effects. Combining these views with Hikosaka et al.'s model (1999, 2002), we would predict that a random practice pattern is advantageous when initially learning the stimulus–response component of the MFST because it is the one that requires greater cognitive control and attention. Moreover, when this component is learned in the context of multiple sequences, it is more readily transferrable to a novel sequence. In contrast, massed practice benefits learning of the sensorimotor integration and timing components of the MFST because these are the aspects that are under less cognitive control. These components appear to be slower to learn, and more difficult to maintain and transfer, requiring ongoing practice and limited interference. For example, both a novice and skilled pianist may be able to play the correct notes of one of Bach's preludes, but in order to be synchronous and in time, the skilled pianist may have benefitted from more ongoing practice.

The classic design for testing the contextual interference effect focuses on the effects of practice pattern on tests of retention and transfer on the second day, as these phases best reflect the "permanence and adaptability" of sequence learning (Ste-Marie et al. 2004). Because of this, many experiments only compare retention and transfer across training condition but do not compare them to final performance at acquisition. Thus, while studies often claim that random practice results in better Day 2 performance, this performance is not usually compared to performance at the end of acquisition. Therefore, in the present experiment, we were interested in comparing retention and transfer to the acquisition phase. This is also advantageous, because we can compare and discuss our retention results in the context of the motor consolidation literature. Consolidation has been defined and measured in several ways (Robertson et al. 2004; Krakauer and Shadmehr 2006): improvements in performance after a period of rest or a night of sleep, with no additional practice; resistance from interference by learning of a second sequence or task; the ability to transfer learning to another sequence or task. Interestingly, we found no group differences for consolidation of either sequence B (free of across-day interference from practice on any sequence) or sequence A (in the context of within- and across-day interference from practice on sequence B). Thus, practice pattern did not have any effect on consolidation. This demonstrates that learning that occurs in the context of interference can show consolidation, which is not entirely consistent with previous studies showing a graded interference effect for consolidation (Brashers Krug et al. 1996; Walker et al. 2003). Similar findings have been reported by Criscimangna-Hemminger and Shadmehr (2008), who proposed that with either enough practice or passage of time, motor memory becomes stable and less resistant to interference. Similarly, it has been shown that even in the early learning phase, if practice is adequate, long-lasting functional and neural changes occur that result in a stable, long-term memory of the motor skill (Baddeley and Longman 1978; Shea et al. 2000; Hauptmann and

Karni 2002; Ofen-Noy et al. 2003; Savion-Lemieux and Penhune 2005). Thus, it appears that in the present experiment the amount (48 trials of each sequence) and the distribution of practice over 2 days, regardless of the practice pattern, was sufficient to lead to general within-day and across-day improvements.

In summary, the results of the present experiment present a new way of understanding the effect of practice pattern on the acquisition, consolidation, and transfer of visual-motor sequences. Overall, our results challenge the contextual interference hypothesis. We therefore suggest that the contextual interference effect be reconsidered at the behavioral measures level, such that each measure represents a component of sequence learning that can be differentially influenced by practice pattern. Based on the dissociation of our results for accuracy and response synchronization, we postulate that learning the stimulus–response association is a fast and transferrable process that benefits from learning in multiple contexts. On the other hand, learning of the sensorimotor integration and timing aspects of the task is a slow process that is more resistant to transfer and that is promoted by learning in a single context that allows fine-tuning of the response. Thus, when a pianist is faced with learning Rachmaninoff's four piano concertos, learning the association between the musical notes and which keys to hit could be accomplished while learning all four concertos simultaneously (given that the stimulus–response association is a fast and transferrable process); however, learning the sensorimotor integration and timing aspects of the concertos may require practicing one concerto at a time to allow fine-tuning of each piece. Finally, given that all groups showed consolidation, we postulate that learning that occurs in the context of interference can show consolidation.

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