WANT TO FOSTER NEW MOTOR LEARNING FOLLOWING HIGH CONTEXTUAL INTERFERENCE PRACTICE: BETTER CONSOLIDATE PREVIOUS LEARNING FIRST

A Thesis

by

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ABSTRACT

High contextual interference (CI) practice regimes aid in the retention and transfer of skilled actions. The elaboration perspective, still considered a viable explanation for the benefit of high CI training, proposes that a richer network of task specific knowledge is developed from random practice thus, affording the learner a variety of ways to retrieve task relevant information during delayed tests. One would expect that new tasks, similar to previously trained exemplars, will be acquired faster and retained with greater success following random as opposed to blocked practice. That is, the presence of a rich memory network should provide a suitable foundation from which to incorporate new related task knowledge. To examine this prediction subjects practiced three unique motor tasks in either a blocked or random format. Original practice consisted of nine trials for each seven-element motor sequence in a blocked or random schedule. An additional nine trials of practice with the novel motor sequence was experienced by all participants shortly after original training in the Experiment 1. While the typical retention benefit emerged for random practice for the original motor tasks, no practice schedule effect was revealed for new learning. Experiment 2 examined the possibility that increasing the interval between original training and supplemental practice with the novel motor task might benefit from a greater time interval. By increasing this interval from 2–min to 24-hr afforded individuals an opportunity to consolidate the memory network developed following random or blocked practice. Congruent with Experiment 1 the CI effect emerged in the form of superior retention of the motor tasks acquired via random practice. Moreover, following the

longer temporal interval, random practice facilitated the rate at which new task information was used to execute a new skill which was also reflected in superior retention than observed following blocked practice. Interestingly, following consolidation, both practice schedules exhibited a task-independent benefit when first required to perform the novel task, and offline improvement in performance across a 24-hr interval. These data will be discussed with respect to broader learning benefits from inducing greater CI and the importance of memory consolidation for motor learning.

DEDICATION

This work is dedicated to the love of my family.

ACKNOWLEDGEMENTS

I would like to sincerely thank my advisor, Professor David Wright, for the unstinting support, guidance, encouragement and advice he has provided throughout my time as his student. I would also like to thank Dr. Charles Shea and Dr. Lisa Geraci. Their mentoring, encouragement, and advice led this research to be better quality of work.

A special feeling of gratitude is given to my loving parents and sister; and I would have never accomplished my master's thesis without their endless love, encouragement and support. Thank you Dad, Mom, and Sister for always being there for me with unwavering support and love.

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

Being able to effectively execute motor skills is central to our everyday lives illustrated by the range of skills that we perform on a regular basis such as driving a vehicle, typing on a computer keyboard, or playing a musical instrument. For this reason researchers have spent considerable time trying to identify practice procedures that support or expedite the acquisition of motor skills. While the importance of extensive practice has been highlighted in recent years (Karni et al., 1995; Steele & Penhune, 2010), it has also been revealed that the manner in which practice is organized influences motor skill learning. This is exemplified in work addressing a practice phenomenon, referred to as the contextual interference (CI) effect, which focuses on best practice for improving the acquisition of multiple, related skills (Brady, 1998, 2004; Magill & Hall, 1990; J. B. Shea & Morgan, 1979).

Shea and Morgan (1979) were the first to examine the influence of varying levels of CI for motor skill learning. In their original experiment, and many that followed, CI was manipulated by arranging training such that the learner practices multiple motor tasks in either a random or blocked order. *Random* practice (RP), as it is called, is assumed to create relatively high interference throughout training because of the changes in task demands that occur from trial to trial. Alternatively, relatively less CI is created when using *blocked* practice (BP) which involves the repeated performance of the same motor task prior to the introduction of practice with another task. Shea and

Morgan (1979) revealed the counterintuitive finding that experiencing RP rather than BP, that is, experiencing greater rather than less interference, disrupts initial performance but supports superior delayed retention efforts. This finding is quite robust having been demonstrated in the laboratory (Immink & Wright, 2001; Li & Wright, 2000) and in more applied contexts (Goode & Magill, 1986; Ollis, Button, & Fairweather, 2005; Schneider, Healy, & Bourne, 1998; Smith & Davies, 1995). The effectiveness of greater CI during practice for enhancing learning has been reported for a variety of subject populations (Porretta & Obrien, 1991), and has been shown to be useful in the clinical setting (Adams & Page, 2000; Knock, Ballard, Robin, & Schmidt, 2000).

THEORETICAL ACCOUNTS FOR THE CONTEXTUAL INFERFERENCE EFFECT

Two theoretical accounts have been offered as explanations of the efficacy of increasing CI in practice. Lee and Magill (1985), proposed the forgetting-reconstruction position that focuses on the extensiveness of trial-to-trial preparatory processing during RP and BP. In RP, information about practiced motor tasks is frequently exchanged in working memory throughout practice such that knowledge specific to any one particular task is likely forgotten between repetitions. As a result, on any individual trial, the learner is forced to complete more extensive preparation to execute the next motor task. In other words, forgetting of task-specific knowledge occurs between trials and obligates the learner to frequently construct an action plan on each trial in RP (Lee & Magill, 1983, 1985). On the other hand, BP involves repeatedly performing the same motor task which removes the need to consider the specific requirements of different motor tasks. In this case the learner is only required to maintain knowledge of the current motor task in working memory to prepare the any one motor task across trials in BP. Lee and Magill suggest that the lack of exchange of information in working memory reduces the need and/or opportunities to modify "the process of developing and implementing an action plan" (p.19, Lee & Magill, 1985). Being able to effectively manufacture the appropriate plan for executing the motor task is assumed to be central to successful test performance in the context of the forgetting-reconstruction account.

An alternative explanation for the CI effect, called the elaboration perspective, was proposed by Shea and colleagues (J. B. Shea & Zimny, 1983; J. B. Shea & Zimny, 1988; Wright, 1991). This account also focuses on the preparation for the execution of a set of motor tasks by highlighting the use of two qualitatively unique categories of information processing during BP and RP (Wright, 1991). Intra-task processing consists of motor task analysis that excludes reference to information directly related to other motor skills concurrently being acquired and/or other extant related knowledge. Intra-task processing is assumed to be the primary mode of operation during BP. On the other hand, inter-task processing, serves to highlight the similarities and differences between the motor tasks that are being acquired. This latter form of processing mode is thought to be especially important because it encourages the extraction of relationships between each of the practiced tasks as well as other available, but related, knowledge and is assumed to occur more frequently during RP. According to Shea and Zimny (1988) an understanding of relationships between motor tasks, as a consequence of using inter-task processing, forms the basis for the development of a more intricate memory network that offers more robust access to task-specific knowledge at a later time. Thus, for the purpose of accomplishing superior delayed test performance, the elaboration hypothesis places significant emphasis on the developing memory network and the resultant access to the knowledge contained in the network.

DEVELOPING A FUNCTIONAL MEMORY NETWORK USING RANDOM PRACTICE

It is becoming increasing apparent that the development of functional and structural neural networks that exhibit temporary coupling is associated with improved memory retrieval and is a hallmark of skilled sequential behavior. Recently the first efforts to examine the contribution of different levels of CI during practice to the establishment of inter-regional functional connectivity have emerged. Lin et al. (2013) examined fMRI data collected in conjunction with RP and BP of motor tasks to evaluate the development of connectivity with two particular neural regions that are frequently considered central to motor task acquisition, contralateral dorsolateral prefrontal cortex (DLPFC) and premotor (PM) regions (Lin et al., 2013). Importantly for the present purposes, relatively greater CI during practice, induced through RP, enhanced inter-regional coupling between DLPFC and PM areas with key sensorimotor sites. Specifically, a couple of days of RP led to functional connectivity between DLPFC and superior medial frontal regions, the SMA, caudate nucleus, and the inferior and superior parietal areas. This was also true for the PM area which again showed practice-dependent neural networks emerging with M1, the cerebellum, and parietal areas following some initial exposure to RP but not BP. As this connectivity developed there was a concomitant reduction in blood oxygenated level dependent (BOLD) signal at the neural sites that exhibited increased connectivity. The increased functional connectivity in conjunction with the decreased BOLD signal was interpreted as greater efficiency and/or economy for planning a motor task during RP. Following RP, DLPFC connectivity with regions central to strategic control (i.e., superior medial frontal area) and using motor chunks (i.e., SMA and caudate nucleus) survived across a 72-hr test period. Temporary connectivity developed during RP did not occur for individuals in BP. Lin et al.'s (2013) interpretation of these data was that practice involving greater CI results in a resilient adaptation in the connectivity between the strategic network and the sensorimotor network to facilitate successful retrieval of the well-practiced motor tasks (also see, Yang, Lin, & Chiang, 2014).

An alternative technology, diffusion-weighted magnetic resonance imaging (DWI), affords the opportunity to go beyond a description of transitory functional connectivity and explore structural connectivity. DWI is a non-invasive brain imaging technique that takes advantage of the fact that tissue (e.g., brain white matter) with directional structure, will reveal water diffusion that is directionally dependent which in turn can be quantified using fractional anisotropy (FA). FA has been associated with white matter integrity and structural connectivity strength of specific white matter tracts (Johansen-Berg, 2010; Johansen-Berg & Rushworth, 2009). This technique was recently adopted to examine the influence of practice with varying levels of CI on indices of structural connectivity within tracts previously described as critical for skilled performance (Song, Sharma, Buch, & Cohen, 2012). Motor tasks were practiced in either RP or BP and were tested immediately after training, 12-hr, 24-hr, and 1-week later. As expected individuals exposed to RP demonstrated reliably better performance immediately after training was completed which was further sustained across a one week period. FA data were separately correlated with skilled performance at 1-week for BP and RP participants to assess the relationship between key white matter micro structural connectivity and performance. FA in white matter connecting the contralateral sensorimotor cortex and the posterior putamen, part of the sensorimotor striatum, was associated with performance observed after RP. This pathway has been identified as crucial to long-term performance improvements from neuroimaging studies. Moreover, it has been suggested that this pathway is central to long-term storage of motor memory (Penhune & Steele, 2012). In contrast, the performance for BP participants was correlated with FA in a section of a cortico-striatal tract that links lateral prefrontal cortex with anterior putamen. The anterior putamen is part of the associative striatum which previous neuroimaging studies have revealed to be important during the early learning of motor tasks during which retrieval is poor (Dayan & Cohen, 2011; Wymbs, Bassett, Mucha, Porter, & Grafton, 2012).

CHAPTER II

EXPERIMENT 1

INTRODUCTION

While not extensive, the aforementioned functional and structural connectivity data are consistent with the general claim of the elaboration account that RP contributes to the use of a more intricate memory network that is conducive to accessing motor memories across a broader timeframe. In essence, these recent neurophysiological data describe the neural implementation of a memory network linked with RP described in more general terms in the elaboration account (Lin et al., 2013; Yang et al., 2014). Indeed, adaptations in the neural architecture resulting from RP, as well as others such as increase cortical excitability, have been explicitly interpreted as key reasons for more effective retrieval following RP but not BP (Lin et al., 2013; Lin et al., 2012). The present work considers the possibility that these changes in neural connectivity associated with RP may provide an additional behavioral advantage that, to date, has not been considered. Specifically, access to a more expansive memory architecture, following RP, may provide the foundation to more effectively encode and retrieve novel motor tasks practiced in the future. The primary focus of the present experiments is to determine if prior exposure to a high CI practice environment provides performance and learning benefits during subsequent bouts of skill acquisition.

To date, we know of only one study that examined future learning benefits from prior experience with RP or BP (Hodges, Lohse, Wilson, Lim, & Mulligan, 2014). In this work individuals initially trained and were tested following RP or BP and were then required to practice an additional set of motor skills again in either a random or blocked format. Thus the study involved four permutations of RP and BP namely: RP-BP, RP-RP, BP-RP, and BP-BP. In a second experiment, participants that completed a stint of RP or BP were encouraged to self-select a practice schedule when learning the second sets of skills, The general hypothesis forwarded by Hodges et al. was that being privy to RP during initial training would encourage strategies that are successful for learning. This would be particularly advantageous for those individuals administered BP for the second set of motor skills as they would be expected to conduct planning operations demanded by RP that would overcome the anticipated shortcomings of BP. Alternatively, if previous training exerts a strong influence on subsequent learning prior administration of BP would undermine the expected advantage of RP for the later practice bout (Hodges et al., 2014).

While evidence emerged that initial practice does play a part in the general strategy implemented by the learner in future periods of practice, for example individuals with RP experience tended to exhibit more frequent task switching when given the choice of task to practice (see Experiment 2), the most striking finding from Hodges et al. (2014) was that the most recent practice format was the critical determinant of the delayed test outcome. That is, if the learner was privy to RP rather than BP, their test performance benefitted. It should be noted that previous experience with RP did improve later acquisition in BP (but not retention) suggesting enhanced capacity to encode information about the new motor tasks. These data then do not provide overwhelming support for the notion that the processing strategies encouraged, and rendered beneficial for learning, as a result of experiencing relatively greater CI in practice, influence behaviors beyond those encountered during a specific bout of training. This claim is supported further by the equivocal findings regarding successful transfer following RP and BP (Lin et al., 2012; Lin et al., 2011; J. B. Shea & Morgan, 1979). Unfortunately Hodges et al. (2014) focused on the extended influence of RP or BP on the performance of a new set of motor skills.

A more parsimonious approach to evaluating the influence of the practice schedule of previous learning for new learning would be to consider this issue when acquiring a single rather than multiple novel tasks after RP and BP. This approach removes potential interactions between the processing strategies that might be adopted during the separate acquisition phases involving different sets of motor tasks.

To address this issue participants in Experiment 1 practiced three unique motor tasks in either BP or RP after which they were immediately administered an additional block of training with a novel motor task. Twenty-four hrs later, performance for all the previously experienced motor tasks, three from the original bout of RP or BP as well as the novel motor task, was assessed. It was expected that for the motor tasks originally practiced in either BP or RP, the typical CI effect would emerge. That is, individuals exposed to BP would exhibit superior performance during acquisition but those experiencing RP would reveal better retention for these tasks. With respect to performance of the novel task, if exposure to RP is beneficial, it was anticipated that this practice should lead to (a) greater savings as evidenced by superior performance on the initial trial for the novel task, (b) faster rate of acquisition of the novel task, and/or (c) greater delayed retention of the novel task. In the case of (c) it is possible that the delayed benefit might be manifest as offline gain for the new task knowledge as a result of RP whereas BP would reveal evidence of forgetting.

METHODS

Participants

All right-handed undergraduate students (N=45)[1] participated in the experiment for course credit. The participants had no prior experience with the experimental tasks and were not aware of the specific purpose of the study. All subjects completed an informed consent, approved by Texas A&M University's Institutional Review Board, before participation in the experiment.

Apparatus and Task

The motor tasks used in the proposed work are modeled after those used by Walker and colleagues (Walker, Brakefield, Hobson, & Stickgold, 2003). This type of motor skill has been characterized as a serial reaction time task (Rhodes, Bullock, Verwey, Averbeck, & Page, 2004) and has been used extensively to examine motor sequence learning but its use in the present study is novel with respect to examination of the CI effect. This task was performed on a standard PC keyboard and involved typing a predetermined set of seven key presses repeatedly as quickly and accurately as possible for 30 sec using different orders of the "V", "B", "N", and "M" keys. The order in which

[1] Fifteen participants were included in a control condition referred to as the NP (no practice) condition. The data from these individuals was used as a control condition for both Experiment 1 and 2. These individuals only practiced the novel motor sequence on Day 1 and returned twenty-four later to complete test trials for all motor tasks.

these keys were depressed for each separate motor task was determined by the sequential illumination of four boxes, displayed on a computer screen in a spatially compatible manner with the fingers. For example, participants were instructed to associate the leftmost box with the “V” and depress this key when this box was illuminated. Alternatively, if the rightmost box was illuminated the participant was instructed to press the rightmost key which was the “M” key. The target tasks were executed with the participant’s non-dominant hand throughout training and retention test.

Four distinct 7-key motor tasks were used, three of which were trained using random (RP) or blocked (BP) practice with the fourth novel task being encountered by all participants after training with the other three tasks was completed. The target motor tasks each consisting of seven-keys, were 4-1-3-2-4-2-3, 3-2-4-1-2-4-3, and 1-4-2-3-1-3-2 where “1” represented the leftmost key (i.e., “V”) and “4” was associated with the rightmost key (i.e., “M”). The novel task also consisted of seven-keys, namely, 1-4-2-3-1-3-2. All features of this experiment was programmed using E-Prime® 1.1 (Psychology Software Tools, Inc., Sharpsburg, PA).

Procedure

Prior to any participation all participants read and signed an informed consent. Individuals were then randomly assigned to one of two different practice schedule conditions, BP or RP. RP involved random presentation of the three 7-key motor tasks during the initial acquisition phase on Day 1 (See Figure 1). Individuals assigned to BP completed practice with one motor task before experiencing any practice with another task. Approximately 2-min after the completion of BP or RP, all participants received training with the novel motor task. In addition to the RP and BP conditions, one additional experimental condition, referred to as NO practice (NP), was included as a control condition to provide a baseline for acquisition and retention performance of the novel motor task in the absence of previous RP or BP (see Figure 1). All participants returned to the laboratory approximately 24-hr after the completion of practice with the novel motor task to complete test trials for all the motor tasks practiced the previous day.

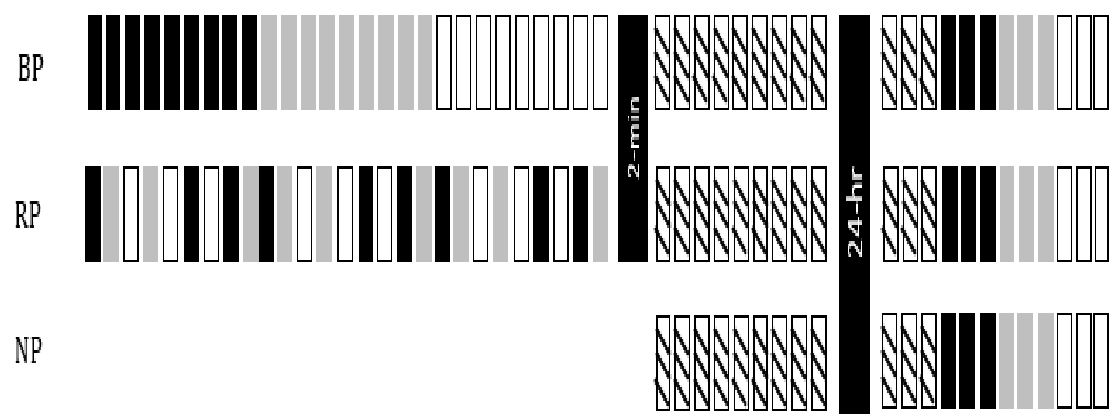

Figure 1. Timeline for participants in random (RP), blocked (BP), and no (NP) practice conditions in Experiment 1. Each trial (represented by a single rectangle) involved repeated execution of a unique motor task (represented by black, gray, white, hatched rectangles) for 30-s. Acquisition involved 9 trials of the three motor tasks (black, gray, white) in BP or RP resulting in 32 total trials of practice. This was followed 2-min later by nine additional 30-s trials with a new motor task (hatched). 24-hr after practice with the novel task three 30-s trials for each task were presented in blocked format.

Each trial with a motor task was 30-s in duration during which the participant was expected to repeatedly execute the required sequence of seven key presses as fast and accurately as possible for the duration of the trial. Each trial of practice was followed by 30-s of rest. All RP and BP participants were administered three blocks of practice during the initial phase of acquisition with each block consisting of nine 30-s trials each separated by 30-s of rest. Thus, the initial acquisition phase consisted of 27 30-s trials that included 9 trials for three separate motor tasks. Importantly, during BP, all trials of practice during any block of nine trials involved practice with only one motor task. For RP, each block of nine trials included three 30-s trials for each of the three separate motor tasks experienced during the initial bout of practice. Two min after completing RP or BP these participants performed an additional block of nine 30-s trials with the novel motor task. Participants assigned to the NP condition also completed nine trials with the novel task. Again, each trial with the novel task was separated by 30-s of rest.

Twenty-four hours after completion of acquisition, all participants in the BP, RP, and the NP conditions completed a test block that involved 12 30-s trials. The first three trials involved the novel motor task experienced the previous day. The remaining nine 30-s trials included three for each of the original motor tasks presented in a blocked format. For all trials *speed*, the number of correctly executed sequences of 7-key strokes for a 30-s trial, and *error*, the percentage of erroneous key presses/ 30-s trial, were recorded for each individual. Krakauer and Shadmehr (2006) proposed that *sequence learning*, the acquisition of sequence order per se is indexed by error rate and is distinct from *skill learning* which is reflected in speed.

RESULTS

Acquisition of Motor Tasks Practiced in Random and Blocked Practice

Figure 2A and B displays mean speed and error respectively for each practice trial for individuals trained with RP and BP. Mean speed and error for each trial during acquisition was calculated for each individual and submitted to separate 2 (Practice Schedule: Random, Block) x 9 (Trial: 1-9) Analysis of Variance (ANOVA) with repeated measures on the last factor.

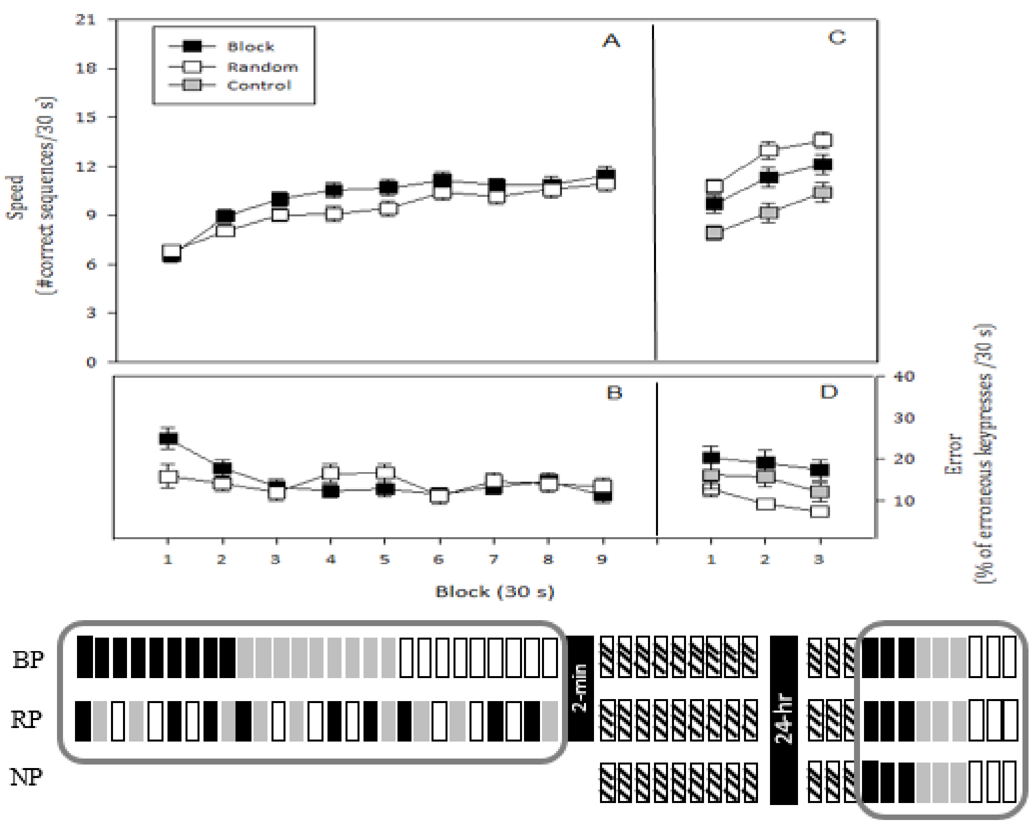

Figure 2.A and B displays mean speed and error respectively for each practice trial during acquisition for individuals trained with random (white symbol) or blocked (black symbol) practice in Experiment 1. C and D displays mean speed and error for each trial during the test block for individuals that experienced random, blocked, or no (gray symbols) practice in Experiment 1. Highlighted box indicated data included in this figure.

This analysis revealed a significant main effect of Trial, for both speed, $F(8,224) = 49.70$, $p<.01$, and error, $F(8,224) = 4.03$, $p<.01$. These main effects are consistent with the expectation that an individual's motor performance should improve with practice. Specifically, there was a 68% increase in speed while also reducing error by approximately 40% across training. There was also a significant Practice Schedule x Trial interaction for error, $F(8,224) = 2.52$, $p<.01$. Simple main effect analyses indicated that error was significantly greater for individuals in BP (M = 25.1%, SEM = 2.6)[2] than RP (M = 15.9%, SEM = 2.8) for Trial 1 [$F(1,232) = 3.87$, $p<.01$. Error did not differ reliably for the remaining eight trials during practice as a function of an individual's practice schedule. There was also a marginally significant Practice Schedule x Trial interaction for speed, $F(8,224) = 1.86$, $p=.07$. Speed for the individuals in BP was greater than that reported for RP participants for Trials 2-5 with no reliable differences as a function of practice schedule for all other trials.

Retention of Motor Tasks Practiced during Random and Blocked Practice

Figure 2C and D displays mean speed and error respectively for each trial during the test block for the original motor tasks for individuals that experienced RP, BP, and NP. Mean speed and error for each trial during the test block was calculated for each individual and submitted to separate 3 (Practice Schedule: RP, BP, NP) x 3 (Trial: 1-3) ANOVA with repeated measures on the last factor. This analysis revealed a significant main effect of Practice Schedule for speed, $F(2,42) = 4.94$, $p<.01$. Post-hoc analysis indicated that RP led to significantly greater speed during the test (M = 12.4

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[2] M = Mean, SEM = Standard Error

sequences/30 sec, SEM = 0.5) than observed for BP participants (M = 11 sequences/30 sec, SEM = 0.6). Speed for BP participants was in turn greater than for individuals in the NP condition that had no prior experience with these motor tasks (M = 9.2 sequences/30 sec, SEM = 0.5) suggesting that prior BP provided some retention benefit. This analysis also revealed significant main effects of Trial for both speed, $F(2, 84) = 44.54$, $p<.01$, and error, $F(2,84) = 3.39$, $p<.05$. Post-hoc assessment indicated that performance continued to improve across test trials [Trial 1 (speed = 10.2 sequences/30 sec, error = 16.6%), Trial 2 (speed = 12.2 sequences/30 sec, error = 14.2%), and Trial 3 (speed = 12.8 sequences/30 sec, error = 12.5%).

Enhancement, Stabilization, and/or Forgetting of Motor Memories Developed via Random or Blocked Practice

In order to assess if performance of the original motor tasks for the individuals that experienced either RP or BP exhibited enhancement, stabilization, or forgetting across the 24-hr retention interval, mean speed and error for the last trial of acquisition and the first test trial for each individual was submitted to separate 2 (Practice Schedule: Random, Block) x 2 (Trial: acquisition, retention) ANOVAs with repeated measures on the last factor. This analysis revealed a significant main effect of Trial for speed, $F(1,28) = 5.14$, $p<.05$. Post-hoc analysis indicated that speed at the end of acquisition was greater (M = 11.2 sequences/30 sec, SEM = 0.5) than observed for the first test trial (M = 10.2 sequences/30 sec, SEM = 0.5). For error only, there was a significant Practice Schedule x Trial interaction, $F(1,28) = 4.08$, $p=.05$. Simple main effect analysis indicated that for individuals in RP error did not differ from the end of acquisition (M =

13.5%, SEM = 1.9) to the initial trial of retention (M = 12.9%, SEM = 1.9). In contrast, BP participants displayed a significant increase in error from acquisition (M = 11.3%, SEM = 1.7) to test (M = 20.3%, SEM = 2.8), [$F(1,28) = 7.1$, $p<.01$]. Moreover, error at the end of acquisition did not differ as a function of practice schedule but RP led to reliably lower error during the initial test trial compared to BP.

In summary, with respect to performance of the motor skills originally experienced by random and blocked practice participants, the present data are in concert with the extensive literature documenting the efficacy of RP for motor skill acquisition. While there was a tendency for BP to perform a little better during acquisition, delayed test performance was superior following RP (Magill & Hall, 1990). In Experiment 1, the test benefit afforded by RP resulted from mitigating the large forgetting rate displayed by BP participants especially for error.

Savings for Novel Motor Task Acquisition Following Random and Blocked Practice

Figure 3 depicts the change in both mean speed and error between Trial 1 during original BP or RP and for Trial 1 of practice with the novel motor task for the individuals that were exposed to random or blocked practice prior to performance of the novel task. In order to examine if there was some immediate transfer of motor task knowledge to the novel motor task following BP and RP, mean speed and error from the first trial during the original BP or RP and Trial 1 from practice with the novel motor task was calculated for each individual and subjected to separate 2 (Practice Schedule: Random, Blocked) x 2 (Task: Original, Novel) ANOVA with repeated measures on the last factor.

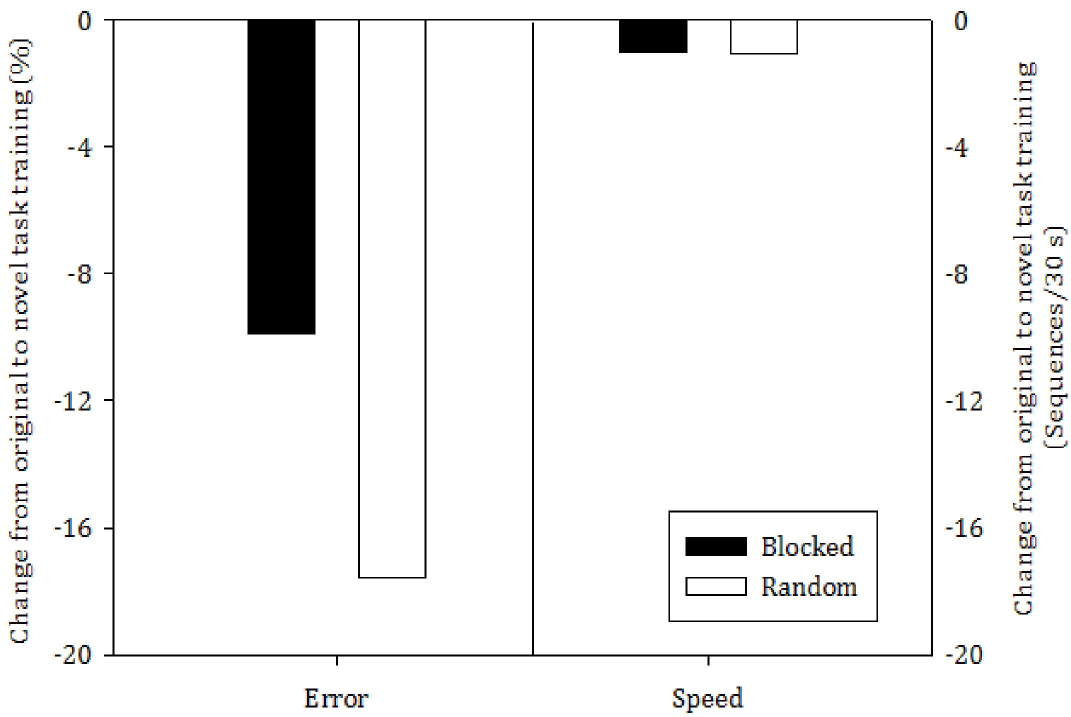

Figure 3. Depicts the change in both mean error (left panel) and speed (right panel) between Trial 1 during original BP or RP and for Trial 1 of practice with the novel motor task for the individuals that were exposed to random (white bar) or blocked (black bar) practice prior to performance of the novel task for Experiment 1.

These analyses revealed significant main effects of Trial for both speed, $F(1,28) = 5.12$, $p<.05$, and error, $F(1,27) = 9.48$, $p<.01$. Post-hoc analyses revealed that both speed and error for Trial 1 of the novel motor task deteriorated from that observed when first performing motor tasks during blocked or random practice (see Figure 3). The lack of significant Practice Schedule main effect and Practice Schedule x Task interaction suggests prior BP and RP resulted in a similar performance decrement when first encountering the novel motor task. Thus, neither practice schedule afforded any immediate performance benefit for novel motor task acquisition.

Acquisition of a Novel Motor Tasks Following Random and Blocked Practice

Figure 4 A and B displays mean speed and error respectively for each trial of acquisition of a novel motor task following prior RP, BP, or NP. Mean speed and error for each trial during practice of the novel motor task was calculated for each individual and submitted to separate 3 (Practice Schedule: RP, BP, NP) x 9 (Trial: 1-9) ANOVAs with repeated measures on the last factor. These analyses revealed significant main effects of Trial, for speed, $F(8,336) = 34.21$, $p<.01$, and error, $F(8,334) = 9.62$, $p<.01$. These main effects verify the expectation that practice with a single novel motor task should improve with practice (Karni et al., 1998). Specifically, there was a 112% increase in speed with a 61% reduction in error. The lack of main effect of Practice Schedule and/or Practice Schedule x Trial interaction suggests that prior experience practicing motor tasks in either RP or BP provided no advantage to the rate at which the novel motor sequence improved across acquisition.

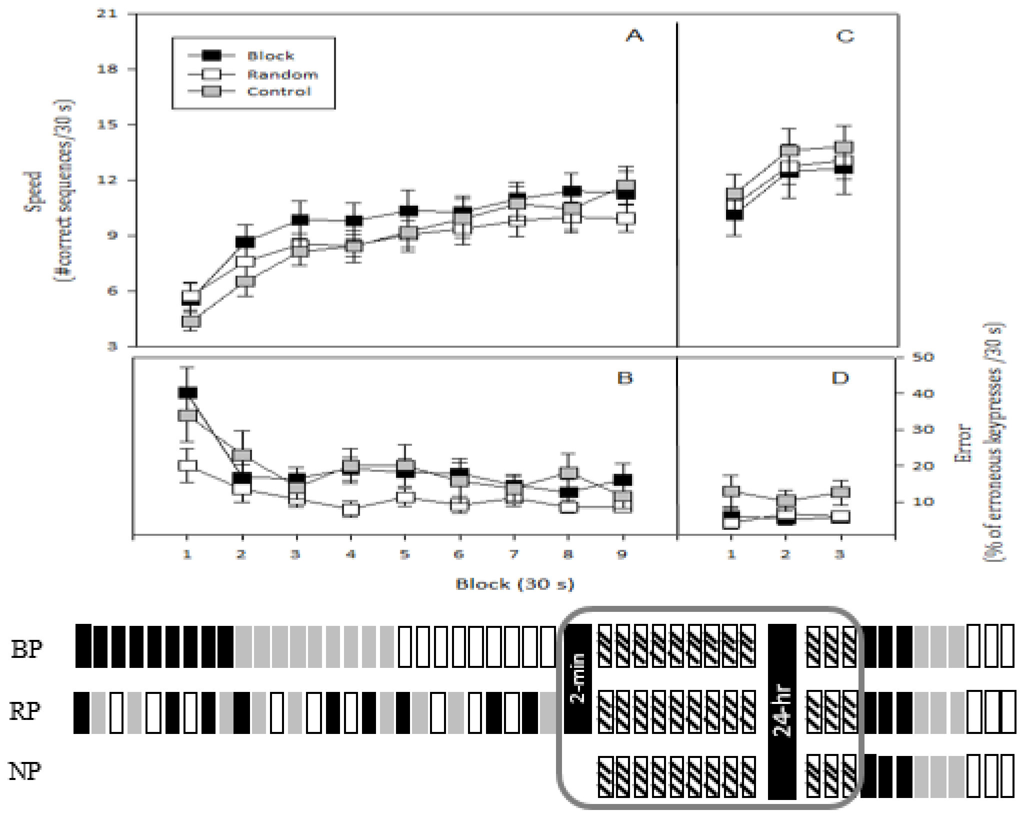

Figure 4.A and B displays mean speed and error respectively for each practice trial with the novel motor task for individuals that previously experienced random (white symbol), blocked (black symbol) or no (gray symbol) practice in Experiment 1. C and D displays mean speed and error for each trial during the test block with the novel motor tasks for individuals that had previously experienced random, blocked, or no practice in Experiment 1. Highlighted box indicated data included in this figure.

Retention of a Novel Motor Task Following Random and Blocked Practice

Figure 4 C and D displays mean speed and error respectively for each trial block during the delayed retention test for the novel motor task for individuals that experienced RP, BP, or NP. Mean speed and error during the delayed test was calculated for each individual and submitted to separate 3 (Practice Schedule: Random, Block, Control) x 3 (Trial: 1-3) ANOVAs with repeated measures on the last factor. These analyses revealed a significant main effect of Trial for speed, $F(2,84) = 36.12$, $p<.01$. Post-hoc assessment indicated that speed increased from Trial 1 (M = 10.7 sequences/30 sec) to Trial 2 (M = 12.9 sequences/30 sec) but showed no additional improvement at Trial 3 (M = 13.2 sequences/30 sec). As was the case during acquisition of the novel motor task, no test benefit was garnered from prior RP or BP beyond that provided by practice of the task per se (i.e., NP condition).

Enhancement, Stabilization, and/or Forgetting of the Novel Motor Task

In order to assess if performance of the novel motor task during the delayed retention test for individuals in the RP, BP, and NP conditions exhibited consolidation, stabilization or forgetting across the 24-hr retention interval, mean speed and error for the last trial of acquisition and the first trial at retention of the novel task for each individual was submitted to separate 3 (Practice Schedule: RP, BP, NP) x 2 (Trial: acquisition, retention) ANOVAs with repeated measures on the last factor. These analyses revealed no reliable effects indicating that performance of the novel motor task was maintained across the 24-hr retention interval. This was the case not only for those individuals that merely practiced the new task (i.e., the NP condition) but also for the participants experience acquiring similar motor tasks in RP or BP.

In summary, access to prior practice of motor tasks, irrespective of the practice schedule, exerted no influence of the subsequent performance of a novel motor skill. This was manifest as an absence of any savings in performance during the first trial of the new motor task (see Figure 3), no impact on the rate at which performance of the novel motor task improved across training (see Figure 4A and B), and no influence on retention performance 24-hr after training (see Figure 4C and D).

DISCUSSION

The goal of the Experiment 1 was to evaluate the efficacy of prior RP and BP for subsequent acquisition and delayed retention of a novel motor task. It was assumed, on the basis of recent empirical evidence, that RP rather than BP is more effective for developing a memory network that facilitates effective retrieval of acquired motor task knowledge (Lin et al., 2013; Lin et al., 2012; Lin et al., 2011). This being the case, the present work entertained the idea that an existing memory network, containing similar task-specific knowledge, would be beneficial for facilitating the storage and/or eventual retrieval of novel motor memories. To test this proposal, training of three unique motor tasks that occurred in either RP or BP formats was immediately followed by practice with a unique motor task.

As expected, acquisition of the original three motor tasks in BP was generally more successful than observed during RP as revealed by greater speed during some trials during acquisition whilst exhibiting a similar level of error. Nonetheless, by the conclusion of practice, individuals exposed to RP and BP performed similarly (see Figure 2A and B). In contrast, performance of the motor tasks during the 24-hr delayed test phase was superior for the individuals exposed to RP (see Figure 2C and D). This was manifest as greater speed, or skill learning, for the test trials while also exhibiting less labile sequence knowledge. It's noteworthy that despite exhibiting greater speed, the performance for BP participants was as error-prone as that of the individuals that had no previous practice suggesting very limited learning benefit from this practice schedule. These data then are in general agreement with an extensive literature addressing the CI effect (Brady, 1998, 2004; Magill & Hall, 1990; J. B. Shea & Morgan, 1979; J. B. Shea & Zimny, 1983; J. B. Shea & Zimny, 1988).

Practice of the novel motor task showed the expected improvement in both speed and error with training (Karni et al., 1998). Indeed, the improvement for the novel task was considerably greater than observed for the original training in blocked and random formats. This is likely a result of three motor tasks being acquired in the initial acquisition phase as opposed to just one task in the latter phase. It is important to note however that recent experience with RP or BP afforded no benefit for either acquisition or delayed test efforts with the new motor task beyond merely being afforded equivalent practice with the target motor task only.

These data are counter to recent evidence indicating that prior RP provides an advantage for the encoding (i.e., acquisition) of a novel motor task (Hodges et al., 2014). It is important to note however that Hodges et al. required participants to learn a new "set" of motor tasks following an initial episode of RP or BP rather than just a single task as was the case in Experiment 1. The lack of benefit for encoding new task knowledge in the present work may be a function of the more "sparse" processing environment offered by the context of learning only one additional skill following BP and/or RP. Alternatively, the lack of effectiveness of prior RP or BP might be a function of the limited time window from the end of training to introduction of the novel motor task training. This interval may not impact knowledge of the trained motor task exemplars experienced during that episode per se but does not afford sufficient time to integrate and extract relationships between information that would be especially critical for new learning. Thus, memory networks developed with a brief time delay between training blocks are adequate for supporting retention, at least when presented in a random format, but offer little functionality for generalization or transfer (Lin et al., 2012; Lin et al., 2011).

CHAPTER III

EXPERIMENT 2

INTRODUCTION

As noted the lack of integration of knowledge in the memory network that developed as a result of RP or BP prior to new learning may have been a direct result of insufficient time occurring between the two bouts of practice encountered by participants in Experiment 1. Recall that practice of the novel motor task occurred approximately 2-min after RP or BP. It is possible that the memory network that emerges from the original bout of practice is more functional (i.e., supports both skill retention and generalization), if given sufficient time to consolidate. *Consolidation* is the process by which novel and usually labile memories, declarative or procedural, encoded during a period of training are transformed into more stable representations and, more importantly, become integrated into a network of existing knowledge (Diekelmann & Born, 2010; McGaugh, 2000; Wright, Rhee, & Vaculin, 2010). It has been proposed that the consequence of consolidation is elaboration of (a) the new memory itself (e.g., more distinct), and (b) the network within which task knowledge is incorporated (e.g., increased associations). Such enrichment can then be used to promote generalization to other memories through the extraction of common rules or schema and has been reported to elicit novel inferences or insights (Diekelmann & Born, 2010; Stickgold & Walker, 2013). The impact of consolidation is manifest behaviorally as (a) increased resistance to interference from another similar task, referred to as "stabilization" and/or (b) an improvement of performance that occurs at test despite the absence of any extra practice called "offline enhancement." Stabilization, via consolidation, is assumed to be a time-dependent process requiring approximately 4-6 h between the initial bout of practice and the presentation of interfering activity. Clearly, the opportunity for the stabilization of knowledge about the three original motor tasks practiced in Experiment 1, and potentially the resultant memory network of which this information was a part, was undermined by the 2-min interval used in Experiment 1. Offline enhancement, resulting from further consolidation after a memory is stabilized, is reported to be greater if the learner sleeps between training and test especially for motor tasks that are learned explicitly (Press, Casement, Pascual-Leone, & Robertson, 2005). Again, participants in Experiment 1 were not privy to sleep between practice of the original three motor tasks and the novel task. As a result, the participants in Experiment 1 would not have had the opportunity to benefit from consolidation that has been reported to occur offline possibly allowing further updating in the quality of the knowledge garnered during the original practice phase that may have contributed to greater retention and transfer capability (Walker et al., 2003).[3]

The goal in Experiment 2 was to try to maximize the opportunity for consolidation between RP or BP and the subsequent practice with the novel motor task. To accomplish this the temporal interval between the completion of practice with the initial three motor

[3] The present experiment does not attempt to distinguish between the unique benefit from consolidation leading to stabilization and/or enhancement. The goal in Experiment 2 was merely to maximize the possibility that participants would benefit from consolidation. Based on the extant literature it was assumed that by using a 24-hr interval between acquisition bouts, stabilization and enhancement were both feasible, and potentially beneficial, due to adequate temporal spacing and exposure to sleep.

tasks and the novel task was increased from 2-min (Experiment 1) to 24-hr in Experiment 2. It was assumed that consolidation responsible for both stabilization and any offline improvement could be entertained by RP and BP participants thereby facilitating the quality of the developed memory network such that it might support the acquisition of a novel motor skill. Experiment 2 again involved participants practicing three 7-element motor tasks in either a blocked or random format. Rather than experiencing practice of the novel motor task immediately after acquisition of the aforementioned motor tasks, this practice occurred 24-hr after RP or BP. Subsequent retention of the novel motor task as well as the original three motor tasks was again assessed 24 hours later. Thus, the retention interval for the motor tasks acquired in RP and BP was 48-hr. Since test performance for the novel motor task was assessed 24-hr after training, the control NP condition from Experiment 1 was again used as a baseline from which to evaluate the effectiveness of RP and BP for learning the novel motor task.

Consistent with the findings from Experiment 1 and a great deal of the extant literature, the CI effect was expected to emerge (Brady, 2004; Lee & Magill, 1983; Magill & Hall, 1990; J. B. Shea & Morgan, 1979). That is, individuals exposed to BP would exhibit superior performance during acquisition but those experiencing RP would reveal better retention. This is despite Experiment 2 incorporating a longer retention interval (i.e., 48-hr) than in Experiment 1 (Lin et al., 2012; Lin et al., 2011). With respect to performance of the novel task, the predictions from Experiment 1 were again pertinent. Specifically, it was predicted that prior exposure to RP but not BP would be beneficial for (a) increased savings indicated by superior performance on the initial trial for the novel task compared to that during the initial trial during RP or BP, (b) faster rate of acquisition of the novel task, and/or (c) greater delayed retention of the novel task. In the case of (c) it is possible that the delayed benefit might be manifest as offline gain for the new task knowledge as a result of RP whereas BP would reveal evidence of forgetting (Lin et al., 2011).

METHODS

Participants

Right-handed undergraduate students (N=34) participated in the experiment for course credit. The participants had no prior experience with the experimental task and were not aware of the specific purpose of the study. No individual that participated in Experiment 1 was included in Experiment 2. All subjects completed an informed consent, approved by Texas A&M University's Institutional Review Board, before participation in the experiment.

Apparatus and Task

The apparatus and task method was identical to that used in Experiment 1.

Procedure

Participants were randomly assigned to one of two different practice schedule conditions, BP and RP. The protocol for BP and RP in Experiment 2 was identical to that used in Experiment 1. In contrast to Experiment 1, a 24-hr interval was incorporated between the completion of RP or BP and the additional set of 9 trials with a novel task that were experienced by all participants. Retention of the novel motor task as well as the original motor tasks encountered during RP and BP was assessed 24-hr later (See Figure 5).

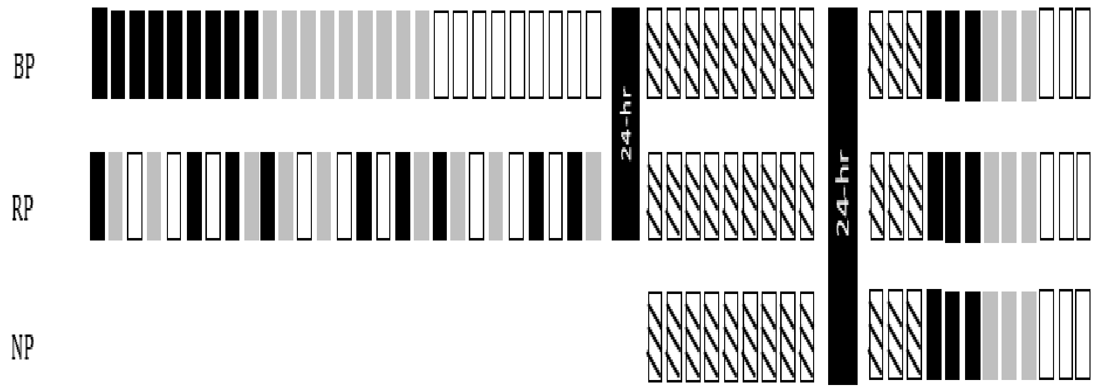

Figure 5. Timeline for participants in random (RP), block (BP), and no (NP) practice conditions in Experiment 2. Each trial (represented by a single rectangle) involved repeated execution of a unique motor task (represented by black, gray, white, hatched rectangles) for 30-s. Acquisition involved 9 trials of the three motor tasks (black, gray, white) in BP or RP resulting in 32 total trials of practice. The important deviation from Experiment 1 was that the nine additional 30-s trials with a new motor task (hatched) were administered 24-hr later. 24-hr after practice with the novel task three 30-s trials for each task were presented in blocked format.

RESULTS

Acquisition of Motor Tasks Practiced in Random and Blocked Practice.

Figure 6A and B displays mean speed and error respectively for each practice trial block for individuals trained via RP and BP. Mean speed and error during acquisition was calculated for each individual and submitted to separate 2 (Practice Schedule: Random, Block) x 9 (Trial: 1-9) ANOVAs with repeated measures on the last factor. This analysis revealed a significant main effect of Trial, for both speed, $F(8, 256) = 75.87$, $p<.01$, and error, $F(8, 256) = 7.04$, $p<.01$. These main effects are consistent with the expectation that individuals benefit from practice.

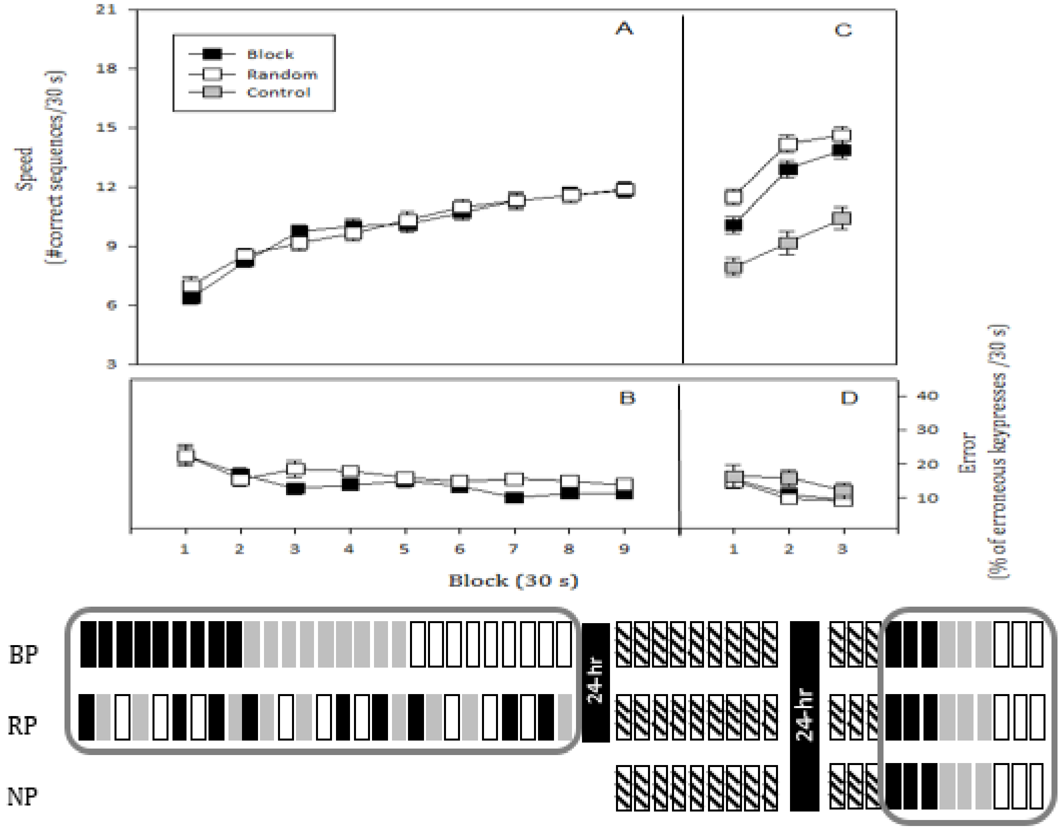

Figure 6.A and B displays mean speed and error respectively for each practice trial during acquisition for individuals trained with random (white symbol) or blocked (black symbol) practice in Experiment 2. C and D displays mean speed and error for each trial during the test block for individuals that experienced random, blocked, or no (gray symbols) practice in Experiment 2. Highlighted box indicated data included in this figure.

Specifically, individuals displayed approximately 78% increase in speed and reduced error by 44% across trials in acquisition. The lack of a significant Practice Schedule main effect and Practice Schedule x Trial interaction suggests that individuals assigned to RP and BP showed similar improvements across trials in the initial phase of acquisition.

*Retention of Motor Tasks Practiced in Random and Blocked Practice***.**

Figure 6 C and D displays mean speed and error respectively for each trial during the delayed retention test for individuals that experienced RP, BP, or NP. Mean speed and error were calculated for each individual and submitted to separate 3 (Practice Schedule: RP, BP, NP) x 3 (Trial: 1-3) ANOVAs with repeated measures on the last factor. These analyses revealed a significant main effect of Practice Schedule for speed, $F(2,46) = 13.90$, $p<.01$. Post-hoc analysis indicated that individuals exposed to RP (M = 13.5 sequences/30 sec, SEM = 0.4) exhibited significantly greater speed than their BP counterparts (M = 12.3 sequences/30 sec, SEM = 0.4) who in turn displayed greater speed than the individuals in the NP condition (9.2 sequences/30 sec, SEM = 0.5). There was also a significant main effect for Trial, for both speed, $F(2, 92) = 72.72$, $p<.01$, and error, $F(2.92) = 9.30$, $p<.01$. Post-hoc analyses indicated a reliable improvement from Trial 1 (speed = 10.79 sequences/30 sec, error = 15.3%) to Trial 2 (speed = 13.54 sequences/30 sec, error = 10.4%) and again at Trial 3 (speed = 14.25 sequences/30 sec, error = 9.2 %).

Enhancement, Stabilization, and/or Forgetting of Motor Memories Developed via Random and Blocked Practice

In order to assess whether performance during the delayed retention test for the individuals exposed to RP and BP exhibited enhancement, stabilization, or forgetting across the 48-hr retention interval, mean speed and error for the last trial of acquisition and the first trial at retention for each individual was submitted to separate 2 (Practice Schedule: RP, BP) x 2 (Trial: acquisition, retention) ANOVAs with repeated measures on the last factor. This analysis revealed a significant main effect of Trial for speed, $F(1,32) = 11.69$, $p<.01$. Post-hoc analysis indicated that mean speed at the end of acquisition was greater (M = 11.9 sequences/30 sec, SEM = 0.4) than that observed for the first trial at retention (M = 10.8 sequences/30 sec, SEM = 0.4). There were no reliable effects observed for error.

Despite the retention interval being extended to 48-hr between the completion of acquisition and the test trials, RP continued to be associated with superior learning of the trained motor tasks. The present data, unlike some other studies addressing the influence of CI during skill acquisition, did not reveal performance differences as a result of practice schedule during practice. As was the case in Experiment 1, the test advantage following RP was a result of minimizing the extent of forgetting that occurred across the 48-hr interval.

Savings for Novel Motor Task Acquisition Following Random and Blocked Practice

Figure 7 depicts the change in both mean speed and error between Trial 1 during original blocked or random practice and for the same trial when practicing the novel motor task for the individuals that were exposed to random or blocked practice prior to performance of the novel task. In order to examine if there was some immediate transfer of motor task knowledge to the novel motor task as a result of BP or RP, mean speed and error from the first trial during the original practice and with the novel motor task was calculated for each individual and subjected to separate 2 (Practice Schedule: Random, Blocked) x 2 (Task: Original, Novel) ANOVA with repeated measures on the last factor.

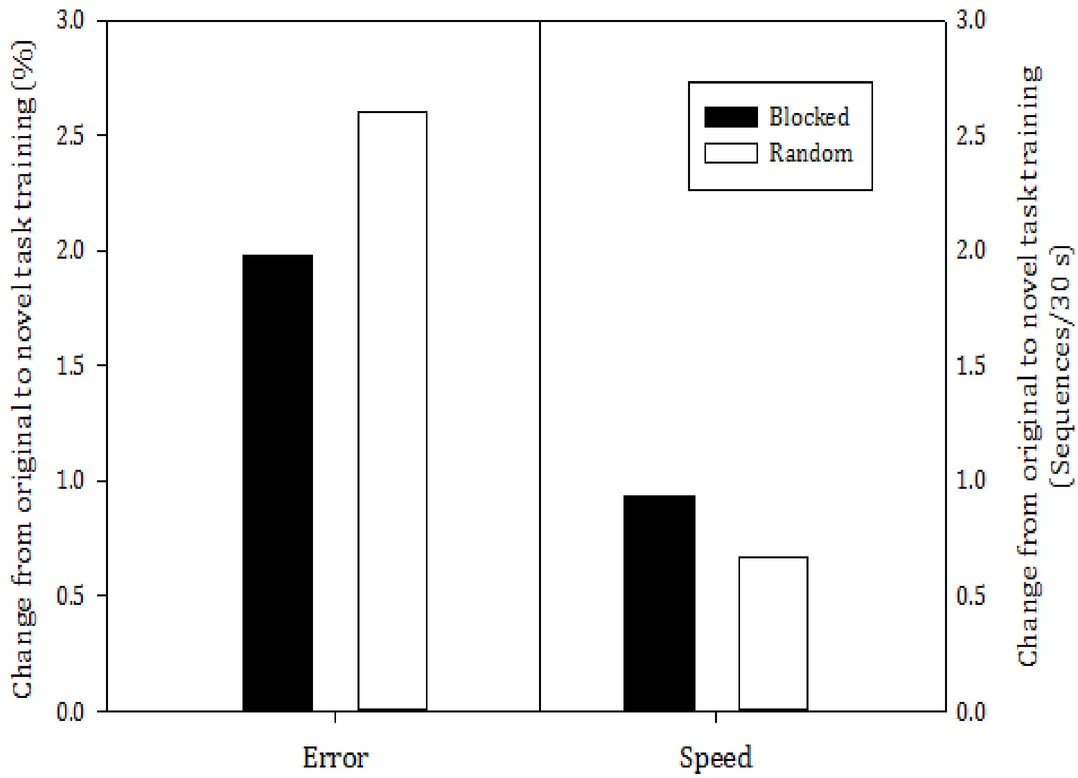

Figure 7.Depicts the change in both mean error (left panel) and speed (right panel) between Trial 1 during original BP or RP and for Trial 1 of practice with the novel motor task for the individuals that were exposed to random (white bar) or blocked (black bar) practice prior to performance of the novel task for Experiment 2.

These analyses only revealed a marginally significant main effect of Trial for speed, $F(1,29) = 3.68$, $p=.06$. Post-hoc analyses revealed that speed for the novel motor task displayed some savings (i.e., improvement) from that observed when first performing motor tasks during BP and RP. The lack of significant Practice Schedule main effect and Practice Schedule x Task interaction suggests that exposure to either BP or RP conveys this savings in speed when first encountering the novel motor task.

Acquisition of a Novel Motor Tasks Following Random and Blocked Practice

Figure 8A and B displays mean speed and error respectively for each trial block during acquisition and delayed retention for the novel motor task as a function of previous exposure to RP and BP and for individuals that only practiced the novel task. Mean speed and error for each trial during acquisition of the novel motor task was calculated for each individual and submitted to separate 3 (Practice Schedule: RP, BP, NP) x 9 (Trial: 1-9) ANOVAS with repeated measures on the last factor. These analyses revealed significant main effects of Practice Schedule [speed, $F(2,46) = 10.27$, $p<.01$; error, $F(2,46) = 3.28$, $p<.05$] and Trial [speed, $F(8,357) = 46.98$, $p<.01$; error, $F(8,357) = 6.72$, $p<.01$]. For error, individuals experiencing RP (M = 11.3%, SEM = 2.5) and BP (M= 13.8%, SEM = 2.4) exhibited similar error which was significantly lower than that observed for the participants in the NP condition (M = 19%, SEM = 5.1). Moreover, participants reduced error across practice by approximately 59%. For all participants, error on Trial 1 (M = 24.7%, SEM = 4.8) was significantly greater then observed for the remaining trials during which error was gradually reduced. Interpretation of the aforementioned main effects of Practice Schedule and Trial for speed was superseded by a significant Practice Schedule x Trial interaction, $F(16,357) = 1.71$, $p<.05$. Simple main effect analyses indicated that, for Trial 1, speed did not differ for participants previously exposed to RP (7.8 sequences/30 sec, SEM = 0.5) and BP (7.3 sequences/30 sec, SEM = 0.4). However, both RP and BP participants exhibited greater speed than individuals in the NP condition (M = 4.4 sequences/30 sec, SEM = 0.5).

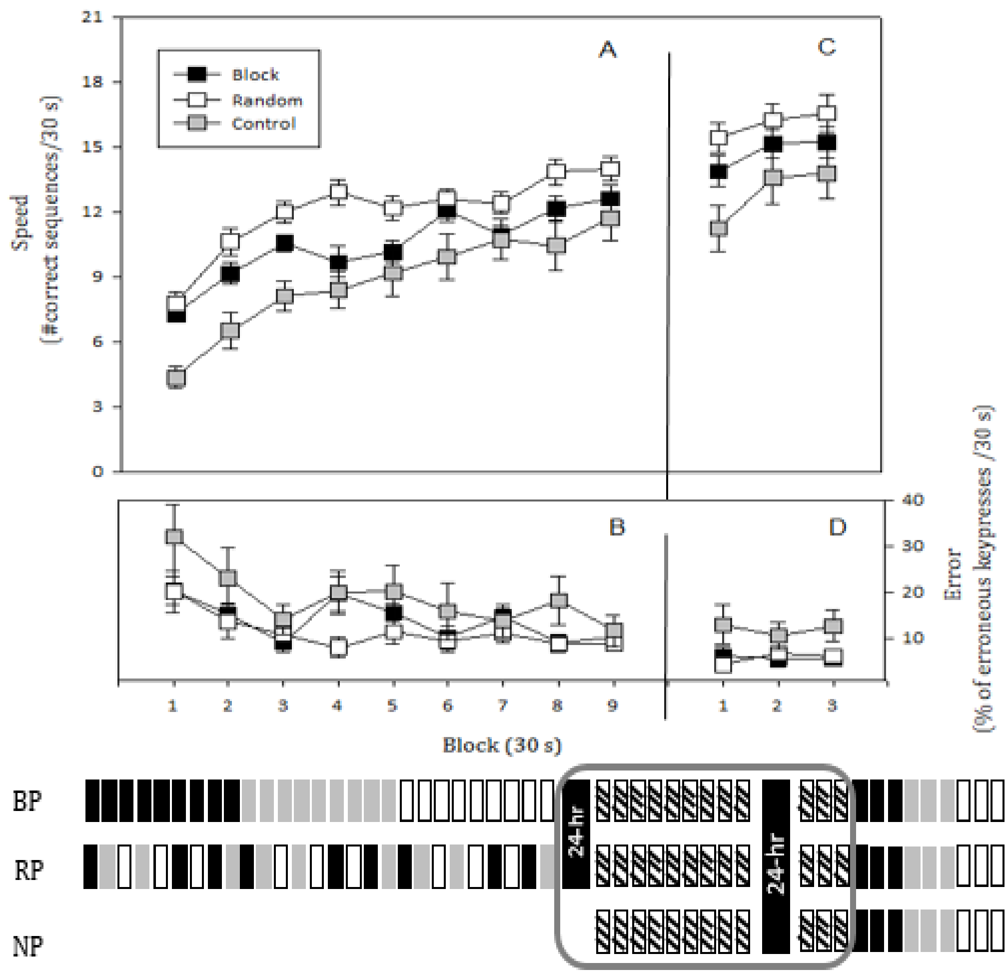

Figure 8.A and B displays mean speed and error respectively for each practice trial with the novel motor task for individuals that previously experienced random (white symbol), blocked (black symbol) or no (gray symbol) practice in Experiment 2. C and D displays mean speed and error for each trial during the test block with the novel motor tasks for individuals that had previously experienced random, blocked, or no practice in Experiment 2. Highlighted box indicated data included in this figure.

For all subsequent trials, except Trial 6, RP participants displayed greater speed than both the BP and NP participants. Beyond Trial 1, individuals that had experienced BP exhibited greater speed than their NP counterparts during only three trials during acquisition (i.e., Trials 2. 3, and 6).

Retention of a Novel Motor Tasks Following Random and Blocked Practice

Figure 8 C and D displays mean speed and error respectively for each trial block during the delayed retention test for the novel motor task for individuals that experienced RP, BP, or NP. Mean speed and error during the delayed test was calculated for each individual and submitted to separate 3 (Practice Schedule: RP, BP, NP) x 3 (Trial: 1-3) ANOVAs with repeated measures on the last factor. These analyses revealed a significant main effects of Practice Schedule [speed, $F(2,46) = 3.50$, $p<.05$; error, $F(2,46) = 3.40$, $p<.05$] and Trial [speed, $F(2,86) = 14.57$, $p<.01$]. Post-hoc analysis revealed that despite a similar level of error for RP (M = 5.8%, SEM =1.4) and BP (M = 5.8%, SEM = 1.7) participants during retention, being exposed to RP resulted in significantly greater speed for the novel motor task (M = 16.1 sequences/30 s, SEM = 0.8) during the test trials compared to BP (M = 14.8 sequences/30 s, SEM = 0.7). Importantly, access to either RP and BP provided a benefit for both speed and error for the test trials when compared to performance of the individuals that only practiced the novel motor task (speed: M =12.9 sequences/30 s, SEM =1.1; error, M =12%, SEM =3.6). Finally, during the test trials, speed for the novel motor task improved from Trial 1 (M = 13.6 sequences/30 sec, SEM = 0.8) to Trial 2 (M = 15.02 sequences/30 sec, SEM = 0.9) but revealed no reliable improvement at Trial 3 (M= 15.17 sequences/30 sec, SEM = 0.9).

Enhancement, Stabilization, and/or Forgetting of the Novel Motor Task

To assess if the benefits of RP revealed in the previous section are a result of enhancement, stabilization, or forgetting across the 24-hr retention interval, mean speed and error for the last trial of acquisition and the first trial at retention of the novel task for each individual was submitted to separate 3 (Practice Schedule: RP, BP, NP) x 2 (Trial: acquisition, retention) ANOVAs with repeated measures on the last factor. For speed, this analysis revealed a significant main effect of Practice Schedule, $F(2,46) = 4.64$, $p<.01$, and Trial, $F(1,43) = 5.53$, $p<.05$. Interpretation of these main effects is superseded by a significant Practice Schedule x Trial interaction, $F(2,43) = 3.44$, $p<.05$. Simple main effect analyses indicated that speed did not differ reliably for individuals previously exposed to RP (M = 14.0 sequences/30 sec, SEM = 0.57), BP (M = 12.65, SEM = 0.63) and NP (M =11.73, SEM = 1.02) at the completion of acquisition [$F(2,89) = 1.97$, p>05]. In contrast, speed for Trial 1 during the test phase differed as a function of practice schedule [$F(2,89) = 6.92$, $p<.01$]. Post-hoc analysis indicated that speed for individuals that experienced RP (M = 15.4 Sequences/30 s, SEM = 0.7) was greater that observed for the individuals exposed to BP (M = 13.9 sequences/30 s, SEM = 0.7) which was in turn greater than speed reported for the NP condition (M = 11.3 Sequences/30 s. SEM = 1.0). Both RP [$F(1,43) = 5.67$, $p<.01$] and BP [$F(1,43) = 4.54$, $p<.05$] participants exhibit a reliable increase in speed from the end of acquisition to the first test trial suggesting that performance was enhanced across the 24-hr interval between training and test. In contrast, the individuals that only practice the novel task revealed no change in speed from the end of training to the beginning of the test phase [$F(1,43) = 0.59$, $p>.05$] revealing stabilization across the retention interval as a consequence of merely practicing the novel motor task. No reliable effects were reported for error (all p's $\geq .19$).

DISCUSSION

The primary purpose of Experiment 2 was to afford participants that practiced three motor tasks, in either blocked or random practice formats, sufficient time to consolidate acquired knowledge of these tasks prior to the introduction of supplemental practice with a new motor. In Experiment 1, during which the temporal interval between two periods of acquisition was much shorter, no benefit, either for acquisition or delayed retention, was reported from prior experience with RP or BP when it came to learning the new skill. This is despite the fact that evidence exists that claims that RP facilitates the establishment of an elaborate set of connections between neural regions critical for displayed more skilled behaviors (Penhune & Steele, 2012) which has been argued to be the neural basis for an effective retrieval structure supporting, at a minimum, access to previously practice task knowledge (Lin et al., 2013; Lin et al., 2012; Lin et al., 2011). The proposal assessed in Experiment 2 was that this network becomes more effective at supporting additional learning, beyond just the practice task exemplars, if given adequate time for consolidation of the memory network to occur. Separating the two phases of acquisition by 24-hr was assumed to be sufficient to allow this to occur for consolidation associated with stabilization and offline enhancement (Diekelmann, Wilhelm, & Born, 2009; Robertson, 2012; Robertson & Cohen, 2006)

The data from Experiment 2 revealed an immediate advantage for the individuals that received prior RP or BP, in the form of savings for the first trial with the novel motor task that was not present for the first trial with each task during BP and RP (see Figure 7) or for the individuals in the NP condition (see Figure 8A). These data suggest some non-specific task knowledge was obtained from prior practice that facilitates how the learner approaches a new learning episode that is not schedule dependent (Verwey & Wright, 2004). It is not surprising that this particular benefit was for localized to speed, or skill learning, as knowledge of the new sequential order is by definition task-specific.

Early during training, by Trial 2, an advantage emerges for the RP participants in the form of greater speed suggesting quick generalization of skill learning that is schedule-dependent (Figure 6a, Trial 2-9). Thus, there was a distinct benefit of prior RP for transferring coordinated skilled behavior when new learning occurs at least 24-hr after previous skill acquisition in a random format. It's worth noting that there is some benefit to just having some prior practice experience as revealed by BP individuals exhibiting overall a lower error rate in conjunction with greater speed for a some trials during acquisition of the novel motor task when compared to the NP condition. The finding that prior exposure to either RP or BP provide an advantage beyond merely practicing the to-be-learned motor task may speak to the utility of practice variability for transfer (C. H. Shea & Wulf, 2005).

Despite acquisition of the novel motor task being poorer following BP compared to RP, this did not eliminate the effectiveness of consolidation occurring during the retention interval following both RP and BP. While the relative performance at the conclusion of acquisition was maintained at test for individuals in RP and BP (i.e., similar error rate but greater speed for RP participants), individuals from both practice schedule conditions exhibited a reliable improvement in speed which was greater than that observed at the conclusion of practice the previous day. Such enhancement has been ascribed to consolidation that occurs during periods of sleep (Walker et al., 2003). This benefit however is unlikely a result of the provision of sleep because the individuals in the NP condition did not show this improvement despite access to a full night's sleep. This latter finding is inconsistent with an extensive literature addressing sleep-dependent enhancement during sequence learning (Diekelmann et al., 2009; Rasch & Born, 2013; Walker, 2005; Walker et al., 2003) This discrepancy may have occurred as a result of how performance enhancement was assessed in the present work (Rickard, Cai, Rieth, Jones, & Ard, 2008). We will return to this issue in the general discussion.

In summary, a couple of novel and important observations surfaced in Experiment 2. First, prior exposure to BP facilitates the initial execution of new motor sequence knowledge as a result of non-sequence specific transfer. In addition, this practice format supported the engagement of offline consolidation resulting in delayed performance enhancements for new sequence knowledge. Second, the benefits just ascribed to BP were also evident for individuals with RP experience, thus, may have occurred merely as a result of exposure to prior physical practice with related motor tasks per se and/or a consequence of experience with some practice variability. Third, a unique advantage was demonstrated for RP with respect to the rate of improvement for the novel task across training. Prior RP appears then to offer some unique capability to extract and/or encode key task information necessary for skill learning beyond that offered from BP.

While the focus of Experiment 2 was on the influence of the practice schedule from recent learning on the acquisition of new skilled behavior it should not be overlooked that Experiment 2 provided more evidence of superior test performance of motor tasks learned during the original bout of random or blocked training (Brady, 2004; Magill & Hall, 1990). In Experiment 2 we replicated the test benefit observed following RP in Experiment 1 but extended the retention interval from 24-hr to 48-hr. These data provide further evidence of the robustness of this training phenomenon for motor learning (Lin et al., 2013; Lin et al., 2012).

CHAPTER IV

GENERAL DISCUSSION AND CONCLUSIONS

INCREASING CONTEXTUAL INTERFERENCE DURING ACQUISITION OF A SERIAL REACTION TIME TASK IMPACTS SEQUENCE AND SEQUENCE AND SKILL LEARNING

Greater CI during training has been described as a best practice for improving the acquisition of multiple, related skills (Brady, 1998, 2004; Magill & Hall, 1990; J. B. Shea & Morgan, 1979). Inducing more CI in training enhances learning for a variety of subject populations (Porretta & Obrien, 1991), has been used successfully in the clinical setting (Adams & Page, 2000; Knock et al., 2000), and can facilitate learning for a variety of skill domains (Brady, 2004; Carlson, Khoo, Yaure, & Schneider, 1990; Carlson & Yaure, 1990; Magill & Hall, 1990; Schneider, Healy, & Bourne, 2002). The present work examined the use of more CI to learn relatively short motor sequences such as those encountered during speech, playing musical instruments, or manipulating mobile devices. This type of motor skill has been characterized as a serial reaction time task (Rhodes et al., 2004) and has been used extensively to examine motor sequence learning but its use in the present study is novel with respect to examination of the CI effect. It has been argued that improvement in performance of this type of motor task involves sequence and skill learning (Krakauer & Shadmehr, 2006). According to Krakauer and Shadmehr *sequence learning*, involves the acquisition of sequence order per se (*error rate* in the present study) and is distinct from *skill learning* which is associated with speeded execution of a known sequence (*speed* in the present work).

Findings from both Experiment 1 and 2 were in general agreement with the extent literature (Brady, 2004). This was especially true with respect to the benefit of RP for retention. While exposure to equivalent amounts of RP or BP supported maintenance of sequence order this was not the case for skill learning, indexed by speed. In this case, RP was more effective in maintaining the knowledge required to execute the sequence of key presses quickly. Skill learning appeared more vulnerable to the passage of time for the individuals trained in BP as evidence by the greater loss in speed in Experiment 2 with the longer retention interval. These data intimate that practice in a random format, while useful for establish detailed knowledge of sequence order, is especially useful for facilitating processes instrumental in using sequence knowledge to exhibit improvement in skill learning (i.e., implementing the motor skill). The present data does not speak directly to specific motor planning process(es) that determine this outcome although there are data implicating response programming as a viable candidate (Immink & Wright, 2001; Wright, Brueckner, Black, Magnuson, & Immink, 2004).

Varying levels of contextual interference during practice influence a learner's capability for new motor learning

Most studies that are designed to examine the influence of CI during learning focus on the issue of retention which was discussed in the previous section. A unique contribution of the work presented herein is the focus on the effectiveness of practice schedules for assisting new learning. In essence these experiments examined if exposure to a practice environment that incorporates greater CI exerts broader learning benefits beyond just the motor skills encountered during training. There is some reason to believe this is the case. Specifically, an ever growing body of literature is emerging demonstrating that temporary connectivity between key neural regions identified as crucial for long-term retention develops during RP but not BP. Lin et al.'s (2013) proposed that temporary connectivity between components of strategic and sensorimotor networks, advanced through RP, are central to exhibiting successful retrieval of the well-practiced motor tasks (also see, Yang et al., 2014). At the core of the present work is the claim that having access to a more robust memory network should be useful in promoting subsequent learning of related skills. Indeed, there are data, albeit limited, indicating that prior RP aids later acquisition even if conducted in a blocked format (Hodges et al., 2014).

The present findings revealed a number of interesting features of practice that suggest prior training has a number of explicit and positive influences on subsequent learning. With respect to the advantages that can be garnered from maximizing CI (i.e., using RP) per se, this appears to be restricted to encoding and ongoing use of new knowledge during acquisition. Individuals that were privy to RP showed a rapid propensity to limit errors during acquisition, as did BP participants, indicating that identifying the sequence of key presses was accomplished quickly. However, it was only individuals trained in a random format that were able to demonstrate a concomitant capacity to quickly execute this newly acquired sequence knowledge, that is, exhibit skill improvement (Krakauer & Shadmehr, 2006). These data are in agreement with those recently reported by Hodges, et al. (2014).

Previous RP also led to a task-independent benefit during new learning episodes revealed as a "savings" when first encountering the novel sequence. This was restricted to speed suggesting effective transfer of a general capability in coordinating the fingers in rapid fashion. This benefit was not restricted to RP participants however as a similar enhancement were revealed for BP participants. Thus, the task-independent skill learning observed is apparently a result of (a) prior motor task practice per se, or (b) previous exposure to practice variability. Both (a) and (b) are present in BP and RP but not for the NP condition. At this point it is not clear if (a) or (b) best accommodates this feature of new learning. However, this issue is easily resolved by comparing the efficacy of practice specificity and variability conditions for improving subsequent novel motor task acquisition and retention (C. H. Shea & Kohl, 1990).

Having the opportunity to consolidate motor memories has a variety of influences on motor learning

CONSOLIDATION OF MOTOR MEMORIES FOLLOWING BOTH RANDOM AND BLOCKED CAN FACILITATE LATER MOTOR LEARNING

What was not noted in the previous section when detailing the positive impact both RP and BP has on future learning endeavors, is that these gains only occurred when sufficient time elapsed between the original bout of RP/BP and training with the new motor skill. That is, only after the learner was afforded a chance to consolidate motor memories following RP and BP, is additional training impacted. Recall that in Experiment 1, despite the fact the typical CI effect was demonstrated, there is no evidence that familiarity with either practice format provides any advantage for subsequent sequence or skill learning of the novel motor task. In Experiment 1 the participants were given only a brief time (i.e., 2 min) between each practice phase. The basic premise of Experiment 2 was that by increasing the temporal interval to 24-hr between RP or BP and acquisition of the novel motor task, consolidation critical for memory stabilization and/or enhancement might occur (Rasch & Born, 2013; Walker, 2005).

The specific performance benefits for the learner's future attempts at motor learning garnered through post-BP and/or RP consolidation processes are detailed in the previous section. It is worth reiterating however that the impact of consolidation for future motor skill acquisition was not all schedule dependent as evidence by BP individuals also gaining from the additional time in Experiment 2. Thus, motor memory constructed from either just experiencing some prior practice and/or practice variability appears susceptible to post-practice consolidation. We will return to the issue of variability shortly. At this point what is not known is if consolidation engaged (a) because of the mere passage of sufficient time allowing stabilization, or (b) from access to a night of sleep instigating enhancement was most important for the reported gains following RP and BP. Going forward, this issue needs experimental attention.

CONSOLIDATION FOLLOWING BLOCKED BUT NOT RANDOM PRACTICE IS REQUIRED TO STABILIZE SEQUENCE KNOWLEDGE ACQUIRED DURING PRACTICE

There has been speculation as to the possibility that the learner's practice schedule may be important for establishing stable memory traces as a result of differential reliance on post-practice consolidation processes (Robertson, Pascual-Leone, & Miall, 2004). Specifically, Robertson et al. speculated that interleaved practice sessions (i.e., RP) might produce motor memories that are not susceptible to interference, that is, they are rapidly stabilized online as a result of ongoing demands associated with RP. By contrast, prolonged practice with any one task when learning multiple tasks (i.e., BP) was proposed to result in more labile knowledge that requires consolidation. If Robertson et al. are correct, individuals exposed to BP would need extra time prior to experiencing any new learning to ensure adequate recall of previously acquired motor memories. Indeed, there are data congruent with this notion (Osu, Hirai, Yoshioka, & Kawato, 2004).

Robertson et al.'s claim speaks to the impact of consolidation, not for future learning, but its direct impact on recall of the specific motor exemplars experienced during BP and RP. As predicted by this position, when additional time between practice with the tasks presented in blocked or random format and "interfering" practice was provided (i.e., Experiment 2), little change in the performance of the motor tasks acquired via RP was evident. Both speed and error rate, indicators of the extent of skill and sequence learning respectively, were remarkably alike with respect to both absolute performance level during the test as well as relative loss from the completion of acquisition (see Figures 2A-D, 6A-D).

In the case of BP however, the opportunity to consolidate the original motor memories had a positive impact on sequence but not skill learning, that is, memory for the sequence order. This is based on the observation that error rate for the original motor tasks was substantially reduced during the retention trials during Experiment 2 compared to Experiment 1 despite similar performance at the conclusion of practice in both Experiments.[4] According to Robertson et al., in Experiment 1 the BP condition engaged in supplemental practice during a time window during which critical consolidation processes are undertaken to stabilize motor memories. Expanding the time window enabled these individuals to perform these processes and as a result retention benefits were observed. These data imply that a shortcoming of BP is that it impedes the learner's ability to complete consolidation pertinent to initially "stabilizing" new acquired knowledge. This finding needs to be verified directly but could be accomplished by examining the impact of locating the acquisition phase for the novel motor task approximately 6-hr after BP. This time interval has been shown to be sufficient to afford stabilization while also removing the contribution of consolidation associated with sleep (Walker et al., 2003). Finally, it is worth noting that a selective impact of consolidation on different dimensions of behavior during procedural learning reported following BP, specifically sequence learning (i.e., error rate) and skill learning (i.e., speed), has been reported previously during the learning of a single motor task (Walker et al., 2003; Wright et al., 2010).

CONSOLIDATION MAY BE LESS RELIABLE FOR EMBELLISHING THE INDIVIDUAL MOTOR TASKS PRACTICED BUT IS CRITICAL FOR EXIBITING GENERALIZED PERFORMANCE CAPACITY CENTRAL TO NEW MOTOR LEARNING

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[4] It should be noted that superior sequence learning, less error, on the part of BP in Experiment 2 occurred following a 48-hr rather than the 24-hr interval used in Experiment 1.

In the present work it is difficult to overlook the more general finding that the addition of a longer time window between bouts of acquisition in Experiment 2 had a broader, positive impact than observed in Experiment 1. Moreover, the majority of these benefits revolved around the usefulness of previously acquired motor memories for facilitation of new motor learning. That is, affording the learner's the opportunity to consolidate motor memories developed as a result of BP or RP, exerted a greater influence on an individual's subsequent capacity to generalize their acquired knowledge as opposed to contributing in any significant way to making existing memories more distinct or elaborate thus facilitating their recall.

As already noted, a great deal of effort has been expended to understand the importance of consolidation for procedural learning. Initial efforts focused exclusively on how consolidation stabilizes and further enhances declarative or procedural skills following practice. In the present work the control group, the NP condition, practiced a single motor task and returned 24-hr later to be tested. Individuals in this condition showed no evidence of offline enhancement despite having the identical training and test protocol used in most early studies documenting enhancement when being privy to a night of sleep (Walker et al., 2003). This is counter to data reported by Walker et al. that revealed a non-trivial improvement in both sequence and skill learning, in the order of 20%, as a result of consolidation. It should be noted however that in the present study, we assessed the impact of consolidation on the basis of the change in performance from the last trial of acquisition and the initial trial at test. In all of the work referenced earlier, conducted by Walker and others (Kuriyama, Stickgold, & Walker, 2004; Walker et al., 2003), performance as a result of consolidation was determined using a comparison the last three trials of training to all three test trials. If we were to adopt the same approach for the NP condition used in the present work the improvement in speed from training to test would have been 17% with little change in error rate.[5] Indeed, using this method would have also led to the conclusion that both RP and BP benefitted significantly from consolidation in a much more widespread fashion in both Experiment 1 and 2. However, to adopt this method, would have ignored the observation that this was just not the case for the initial trial at test. Concerns as to how to assess the influence of post-practice consolidation processes has not gone unnoticed (Rickard et al., 2008).

One possibility is that the impact of post-practice consolidation is not an active process, independent of practice[6], engaged to embellish motor memories during the latent periods between bouts of practice. This "active processing" claim is central to current theorizing addressing offline enhancement (Rasch & Born, 2013; Walker, 2005). Rather, a more consistent with the present findings, is that the influence of consolidation on a motor memory remains dormant until brief exposure to physical practice is provided which acts as a trigger to instigate a rapid updating of a motor memory when it is recalled for execution. As such, the benefit of conducting post-practice consolidation does not emerge during the first but later trials in the form of a more rapid acquisition rate for subsequent blocks of practice. This accounts proposes that there is an important interaction between post-practice consolidation process (es) and physical practice in

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[5] Recall that the same NP control condition was used for both Experiment 1 and 2.

[6] Although some might argue the claim that neuronal replay during sleep is a form of practice (Rasch & Born, 2013)

determining the ongoing state of motor memory. A more sinister account of these findings is that the role of consolidation and/or the existence of offline enhancement during procedural learning is not as robust as currently claimed in the literature. Indeed there has been speculation as to both the reliability of this effect (Brawn, Fenn, Nusbaum, & Margoliash, 2010) and or the appropriateness of the acquisition-test protocol for determining enhancement (Rickard et al., 2008).

Returning for a moment to a key finding in the present work regarding the influence of consolidation during skilled learning. More specifically, that allowing this process to be completed has a positive impact on realizing generalized motor behavior. This finding is not entirely new.

A recent claim suggest that sleep plays an especially critical role in more general memory processing and this role is not bound to consolidation of trained exemplars. Instead, it is argued that consolidation during sleep involves an active integration of newly acquired knowledge that goes on offline. For example, Ellenbogen, Hu, Payne, Titone, and Walker (2007) had participants learn five individual premises (A>B, B>C, C>D, D>E, E>F) without being informed that these pairs contained an embedded hierarchy. It was only after an interval that contained sleep, not wake, that the participants displayed a reliable advantage in relational memory even for distantly connected inferential judgment (B>F). It appears then, consolidation, especially that occurring during sleep, contributes to the construction of informational schemas that might be especially useful for new learning, demonstrating unique insight, and or creativity (Ellenbogen, Hu, Payne, Titone, & Walker, 2007; Walker, 2009a, 2009b).

Obviously, the role of sleep per se for the generalized learning associated with RP and BP needs to be examined independent of consolidation associated with stabilizing motor memories shortly after practice is completed.

CREATING SUFFICIENT CONTEXTUAL INTERFERENCE TO MAXIMIZE THE ADVANTAGE OF CONSOLIDATION TO MOTOR LEARNING

One final novel feature of the present study was the manner in which RP was created in Experiment 1 and 2. By using a variation of the serial reaction time task in conjunction with adopting the protocol used by Walker and colleagues, RP used here, in effect, entailed a modified form of BP. Recall that a trial in both experiments involved 30-sec of repeating a to-be-learned sequence of seven key-presses that are executed anywhere from ~5-15 times in this interval. While the RP format used did involve the alternation of three unique motor task during practice (see Figure 1 and 2), as is traditionally the case, this format deviated from the most common organization of this practice format designed to induce the largest amount of interference (J. B. Shea & Morgan, 1979).

This raises two important points. First, it is quite remarkable, that despite not maximizing the extent of CI in the RP condition, the commonly reported learning advantage of RP was clearly evident suggesting that this practice effect is very robust. Second, had the traditional organization of RP been used, one is left to wonder if broader learning differences as a function of practice schedule would have surfaced. Recall that following consolidation, the only practice schedule-dependent benefit pertained to the rate at which a novel task could be executed. Given the importance of consolidation for information integration, and RP supposed affinity for encouraging the learner to extract task relationships, it was initially anticipated that RP would be more fruitful in its support of future learning endeavors (J. B. Shea & Zimny, 1983; J. B. Shea & Zimny, 1988). Maybe, the extent of CI created in these experiments had a part to play in the boundaries of the benefits observed.

CHAPTER V

FUTURE STUDIES

A number of issues were raised in discussing the outcomes that emerged in the present set of experiments that are needed to clarify aspects of the findings detailed. These are delineated below:

a) Replicating the present study while using a discrete sequence production task offers the opportunity to examine if the lack of a “true” RP format in the present study influenced the extensiveness of the benefits observed from this practice format. If this were indeed the case this would suggest that maximizing the extent of interference during practice is central to optimizing the effectiveness of post-practice consolidation for motor learning (Abrahamse, Ruitenberg, de Kleine, & Verwey, 2013).

b) If (a) fails to change the outcomes reported in these experiments, it would be prudent to delineate the contribution of practice variability to new learning. There is a long-history suggesting that broadening the range of training exemplars during practice aids transfer. For example, both practice schedules provided a task-independent benefit during the initial phase of new learning as well as retention benefits in Experiment 2. These common benefits, occurring across practice schedule, are conceivably a result of practice variability. Novel training proceeded by physical practice of a single task compared to multiple tasks (RP and BP in present work) would allow assessment of this issue.

c) Specific roles of consolidation related to stabilization and enhancement were purposefully avoided in the present work. Rather, the design of the Experiment 2 assumed both might be important and as such used a time interval during Experiment 2 in order that each might operate. It is of course possible that consolidation related to one of these activities might be more critical than the other to the findings reported in the present work. Future efforts should consider attempting to dissect the unique contributions of consolidation and enhancement. There are numerous variations of the designs previously used to address sequence learning and sleep-dependent consolidation that could be adopted to address this issue (Korman, Flash, & Karni, 2005; Walker et al., 2003).

d) Finally, a small part of the premise for the present work was predicated on recent findings that detail unique uses of the neural systems, important for sensorimotor learning, following RP and BP. Much of this work however has relied on neural imaging extracted during acquisition when individuals are practice quite distinct tasks, and presumably different neural processing, at specific time points during training. The present design, in which individuals exposed to prior RP and BP eventually perform the same task in the same time frame, offers a novel but effective approach to querying how various neural regions are coordinated to achieve successful motor behavior as a result of alternative practice formats. This work is currently underway in our laboratory using functional near infrared spectroscopy (fNIRS) as a means of implementing neural imaging.

REFERENCES

Abrahamse, E. L., Ruitenberg, M. F. L., de Kleine, E., & Verwey, W. B. (2013). Control of automated behavior: insights from the discrete sequence production task. *Frontiers in Human Neuroscience, 7*. doi: Artn 82 Doi 10.3389/Fnhum.2013.00082

Adams, S. G., & Page, A. D. (2000). Effects of selected practice and feedback variables on speech motor learning. *Journal of Medical Speech-Language Pathology, 8*(4), 215-220.

Brady, F. (1998). A theoretical and empirical review of the contextual interference effect and the learning of motor skills. *Quest, 50*(3), 266-293.

Brady, F. (2004). Contextual interference: A meta-analytic study. *Perceptual and Motor Skills, 99*(1), 116-126. doi: DOI 10.2466/pms.99.1.116-126

Brawn, T. P., Fenn, K. M., Nusbaum, H. C., & Margoliash, D. (2010). Consolidating the Effects of Waking and Sleep on Motor-Sequence Learning. *Journal of Neuroscience, 30*(42), 13977-13982.

Carlson, R. A., Khoo, B. H., Yaure, R. G., & Schneider, W. (1990). Acquisition of a Problem-Solving Skill - Levels of Organization and Use of Working Memory. *Journal of Experimental Psychology-General, 119*(2), 193-214. doi: Doi 10.1037/0096-3445.119.2.193

Carlson, R. A., & Yaure, R. G. (1990). Practice Schedules and the Use of Component Skills in Problem-Solving. *Journal of Experimental Psychology-Learning Memory and Cognition, 16*(3), 484-496. doi: Doi 10.1037/0278-7393.16.3.484

Dayan, E., & Cohen, L. G. (2011). Neuroplasticity Subserving Motor Skill Learning. *Neuron, 72*(3), 443-454. doi: DOI 10.1016/j.neuron.2011.10.008

Diekelmann, S., & Born, J. (2010). SLEEP The memory function of sleep. *Nature Reviews Neuroscience, 11*(2), 114-126. doi: Doi 10.1038/Nrn2762

Diekelmann, S., Wilhelm, I., & Born, J. (2009). The whats and whens of sleep-dependent memory consolidation. *Sleep Medicine Reviews, 13*(5), 309-321. doi: DOI 10.1016/j.smrv.2008.08.002

Ellenbogen, J. M., Hu, P. T., Payne, J. D., Titone, D., & Walker, M. P. (2007). Human relational memory requires time and sleep. *Proceedings of the National Academy of Sciences of the United States of America, 104*(18), 7723-7728.

Goode, S., & Magill, R. A. (1986). Contextual Interference Effects in Learning 3 Badminton Serves. *Research Quarterly for Exercise and Sport, 57*(4), 308-314.

Hodges, N. J., Lohse, K. R., Wilson, A., Lim, S. B., & Mulligan, D. (2014). Exploring the Dynamic Nature of Contextual Interference: Previous Experience Affects Current Practice But Not Learning. *Journal of Motor Behavior, 46*(6), 455-467.

Immink, M. A., & Wright, D. L. (2001). Motor programming during practice conditions high and low in contextual interference. *Journal of Experimental Psychology-Human Perception and Performance, 27*(2), 423-437. doi: Doi 10.1037//0096-1523.27.2.423

Johansen-Berg, H. (2010). Behavioural relevance of variation in white matter microstructure. *Current Opinion in Neurology, 23*(4), 351-358. doi: Doi 10.1097/Wco.0b013e32833b7631

Johansen-Berg, H., & Rushworth, M. F. S. (2009). Using Diffusion Imaging to Study Human Connectional Anatomy. *Annual Review of Neuroscience, 32*, 75-94. doi: DOI 10.1146/annurev.neuro.051508.135735

Karni, A., Meyer, G., Jezzard, P., Adams, M. M., Turner, R., & Ungerleider, L. G. (1995). Functional Mri Evidence for Adult Motor Cortex Plasticity during Motor Skill Learning. *Nature, 377*(6545), 155-158.

Karni, A., Meyer, G., Rey-Hipolito, C., Jezzard, P., Adams, M. M., Turner, R., & Ungerleider, L. G. (1998). The acquisition of skilled motor performance: Fast and slow experience-driven changes in primary motor cortex. *Proceedings of the National Academy of Sciences of the United States of America, 95*(3), 861-868.

Knock, T. R., Ballard, K. J., Robin, D. A., & Schmidt, R. A. (2000). Influence of order of stimulus presentation on speech motor learning: A principled approach to treatment for apraxia of speech. *Aphasiology, 14*(5-6), 653-668.

Korman, M., Flash, T., & Karni, A. (2005). Resistance to interference and the emergence of delayed gains in newly acquired procedural memories: Synaptic and system consolidation? *Behavioral and Brain Sciences, 28*(1), 74-+.

Krakauer, J. W., & Shadmehr, R. (2006). Consolidation of motor memory. *Trends in Neurosciences, 29*(1), 58-64.

Kuriyama, K., Stickgold, R., & Walker, M. P. (2004). Sleep-dependent learning and motor-skill complexity. *Learning & Memory, 11*(6), 705-713.

Lee, T. D., & Magill, R. A. (1983). The Locus of Contextual Interference in Motor-Skill Acquisition. *Journal of Experimental Psychology-Learning Memory and Cognition, 9*(4), 730-746. doi: Doi 10.1037//0278-7393.9.4.730

Lee, T. D., & Magill, R. A. (1985). Can forgetting facilitate skill acquisition? In D. Goodman, R. B. Wilberg & I. M. Franks (Eds.), *Differing perspectives on memory, learning and control* (pp. 3-22). Amsterdam: North Holland.

Li, Y. H., & Wright, D. L. (2000). An assessment of the attention demands during random- and blocked-practice schedules. *Quarterly Journal of Experimental Psychology Section a-Human Experimental Psychology, 53*(2), 591-606. doi: Doi 10.1080/027249800390628

Lin, C. H., Chiang, M. C., Knowlton, B. J., Iacoboni, M., Udompholkul, P., & Wu, A. D. (2013). Interleaved practice enhances skill learning and the functional connectivity of fronto-parietal networks. *Human Brain Mapping, 34*(7), 1542-1558. doi: Doi 10.1002/Hbm.22009

Lin, C. H., Chiang, M. C., Wu, A. D., Iacoboni, M., Udompholkul, P., Yazdanshenas, O., & Knowlton, B. J. (2012). Age related differences in the neural substrates of motor sequence learning after interleaved and repetitive practice. *Neuroimage, 62*(3), 2007-2020. doi: DOI 10.1016/j.neuroimage.2012.05.015

Lin, C. H., Knowlton, B. J., Chiang, M. C., Iacoboni, M., Udompholkul, P., & Wu, A. D. (2011). Brain-behavior correlates of optimizing learning through interleaved practice. *Neuroimage, 56*(3), 1758-1772. doi: DOI 10.1016/j.neuroimage.2011.02.066

Magill, R. A., & Hall, K. G. (1990). A Review of the Contextual Interference Effect in Motor Skill Acquisition. *Human Movement Science, 9*(3-5), 241-289. doi: Doi 10.1016/0167-9457(90)90005-X

McGaugh, J. L. (2000). Neuroscience - Memory - a century of consolidation. *Science, 287*(5451), 248-251.

Ollis, S., Button, C., & Fairweather, M. (2005). The influence of professional expertise and task complexity upon the potency of the contextual interference effect. *Acta Psychologica, 118*(3), 229-244. doi: DOI 10.1016/j.actpsy.2004.08.003

Osu, R., Hirai, S., Yoshioka, T., & Kawato, M. (2004). Random presentation enables subjects to adapt to two opposing forces on the hand. *Nature Neuroscience, 7*(2), 111-112.

Penhune, V. B., & Steele, C. J. (2012). Parallel contributions of cerebellar, striatal and M1 mechanisms to motor sequence learning. *Behavioural Brain Research, 226*(2), 579-591. doi: DOI 10.1016/j.bbr.2011.09.044

Porretta, D. L., & Obrien, K. (1991). The Use of Contextual Interference Trials by Mildly Mentally-Handicapped Children. *Research Quarterly for Exercise and Sport, 62*(2), 244-248.

Rasch, B., & Born, J. (2013). About Sleep's Role in Memory. *Physiological Reviews, 93*(2), 681-766.

Rhodes, B. J., Bullock, D., Verwey, W. B., Averbeck, B. B., & Page, M. (2004). Learning and production of movement sequences: Behavioral, neurophysiological, and modeling perspectives. *Human Movement Science, 23*(5), 699-746.

Rickard, T. C., Cai, D. J., Rieth, C. A., Jones, J., & Ard, M. C. (2008). Sleep does not enhance motor sequence learning. *Journal of Experimental Psychology-Learning Memory and Cognition, 34*(4), 834-842. doi: Doi 10.1037/0278-7393.34.4.834

Robertson, E. M. (2012). New Insights in Human Memory Interference and Consolidation. *Current Biology, 22*(2), R66-R71.

Robertson, E. M., & Cohen, D. A. (2006). Understanding consolidation through the architecture of memories. *Neuroscientist, 12*(3), 261-271.

Robertson, E. M., Pascual-Leone, A., & Miall, R. C. (2004). Current concepts in procedural consolidation. *Nature Reviews Neuroscience, 5*(7), 576-582.

Schneider, V. I., Healy, A. F., & Bourne, L. E. (1998). Contexual interference effects in foreign language vocabulary acquisition and retention. In A. F. Healy & L. E. Bourne, , Jr. (Eds.), *Foreign language learning: Psycholinguistic studies on training and retention.* (pp. 77-90). Mahwah, NJ, USA: Lawrence Erlbaum Associates, Inc., Publishers.

Schneider, V. I., Healy, A. F., & Bourne, L. E. (2002). What is learned under difficult conditions is hard to forget: Contextual interference effects in foreign vocabulary acquisition, retention, and transfer. *Journal of Memory and Language, 46*(2), 419-440. doi: DOI 10.1006/jmla.2001.2813

Shea, C. H., & Kohl, R. M. (1990). Specificity and Variability of Practice. *Research Quarterly for Exercise and Sport, 61*(2), 169-177.

Shea, C. H., & Wulf, G. (2005). Schema theory: A critical appraisal and reevaluation. *Journal of Motor Behavior, 37*(2), 85-101.

Shea, J. B., & Morgan, R. L. (1979). Contextual Interference Effects on the Acquisition, Retention, and Transfer of a Motor Skill. *Journal of Experimental Psychology-Human Learning and Memory, 5*(2), 179-187. doi: Doi 10.1037/0278-7393.5.2.179

Shea, J. B., & Zimny, S. T. (1983). Context effects in memory and learning. In R. A. Magill (Ed.), *Memory and Control of Action* (pp. 145-166). Amsterdam: North Holland.

Shea, J. B., & Zimny, S. T. (1988). Knowledge incorporation in motor representation. In O. J. Meijer & J. Roth (Eds.), *Complex Movement Behaviour* (pp. 345-366). Amsterdam: North Holland.

Smith, P. J. K., & Davies, M. (1995). Applying contextual interference to the Pawlata roll. *Journal of Sports Sciences, 13*(6), 455-462. doi: Doi 10.1080/02640419508732262

Song, S. B., Sharma, N., Buch, E. R., & Cohen, L. G. (2012). White Matter Microstructural Correlates of Superior Long-term Skill Gained Implicitly under Randomized Practice. *Cerebral Cortex, 22*(7), 1671-1677. doi: DOI 10.1093/cercor/bhr247

Steele, C. J., & Penhune, V. B. (2010). Specific Increases within Global Decreases: A Functional Magnetic Resonance Imaging Investigation of Five Days of Motor Sequence Learning. *Journal of Neuroscience, 30*(24), 8332-8341.

Stickgold, R., & Walker, M. P. (2013). Sleep-dependent memory triage: evolving generalization through selective processing. *Nature Neuroscience, 16*(2), 139-145.

Verwey, W. B., & Wright, D. L. (2004). Effector-independent and effector-dependent learning in the discrete sequence production task. *Psychological Research-Psychologische Forschung, 68*(1), 64-70. doi: DOI 10.1007/s00426-003-0144-7

Walker, M. P. (2005). A refined model of sleep and the time course of memory formation. *Behavioral and Brain Sciences, 28*(1), 51-+.

Walker, M. P. (2009a). The Role of Sleep in Cognition and Emotion. *Year in Cognitive Neuroscience 2009, 1156*, 168-197.

Walker, M. P. (2009b). Sleep-dependent memory integration. *Frontiers in Neuroscience, 3*(3), 418-419.

Walker, M. P., Brakefield, T., Hobson, J. A., & Stickgold, R. (2003). Dissociable stages of human memory consolidation and reconsolidation. *Nature, 425*(6958), 616-620.

Wright, D. L. (1991). The Role of Intertask and Intratask Processing in Acquisition and Retention of Motor-Skills. *Journal of Motor Behavior, 23*(2), 139-145.

Wright, D. L., Brueckner, S., Black, C. B., Magnuson, C., & Immink, M. A. (2004). Long-term motor programming improvements occur via concatenation of movement sequences during random but not during blocked practice. *Journal of Motor Behavior, 36*(1), 39-50. doi: Doi 10.3200/Jmbr.36.1.39-50

Wright, D. L., Rhee, J. H., & Vaculin, A. (2010). Offline Improvement during Motor Sequence Learning Is Not Restricted to Developing Motor Chunks. *Journal of Motor Behavior, 42*(5), 317-324.

Wymbs, N. F., Bassett, D. S., Mucha, P. J., Porter, M. A., & Grafton, S. T. (2012). Differential Recruitment of the Sensorimotor Putamen and Frontoparietal Cortex during Motor Chunking in Humans. *Neuron, 74*(5), 936-946.

Yang, H. O., Lin, C. H. J., & Chiang, M. C. (2014). Using Group Independent Component Analysis to Investigate Resting-State Functional Networks Underlying Motor Sequence Learning. In F. C. Su, S. H. Wang & M. L. Yeh (Eds.), *1st Global Conference on Biomedical Engineering & 9th Asian-Pacific Conference on Medical and Biological Engineering* (pp. 120-123). Switzerland: Springer International Publishing.