INTERMANUAL TRANSFER OF RETRIEVAL-INDUCED FORGETTING IN MOTOR SEQUENCE LEARNING

Yingtong Peng

Hamilton College, USA

Abstract. Previous studies have found that Retrieval-Induced Forgetting (RIF) affects motor-sequence learning on the keyboard, but no studies have examined whether practicing with a different effector induces forgetting. This experiment examined whether left-hand practice causes competition and induces forgetting of other right-hand learned, but unpracticed keyboard sequences using mouse sequences as memory baseline. This experiment used two primary ways through which right hand movements can be translated onto left hands, transpositional translation (same visual representations but different fingers) and mirrored translation (same fingers but reversed visual representations) of right-hand sequences on left hand to examine whether they induced forgetting differently. RIF appeared in all three between-subject groups such that the overall recall accuracy for practiced keyboard sequences (Rp+) was higher than that of the unpracticed sequences, and the recall accuracy for unpracticed keyboard sequences (Rp-) was lower than that of the unpracticed mouse sequences (Nrp). However, RIF did not vary across groups: right hand, left-hand transposition, and left-hand mirror practice all induced forgetting with no interaction with sequence types. The present findings are consistent with an abstract representation of sequential finger movements that can be translated across hands such that retrieval-practice on a different hand could induce forgetting of motor sequences originally learned on the other.

Keywords: Retrieval-induced forgetting, motor learning, bimanual crosstalk.

1. Introduction

Retrieving motor memory, just like retrieving other types of memory, by recalling through practicing certain actions can activate many other related but different motor memories. For example, the movements involved with sweeping floor might elicit one's memory of playing golf because of the similarities in action, power, and muscles involved. The activation of related memory, however, must be inhibited during the movement to eliminate interference and prioritize the execution of the currently retrieved memory due to the limited capacity of working (Anderson, 2003). Retrieval-induced forgetting (RIF), a phenomenon originally discovered in semantic memory, shows that recalling memories can cause forgetting of other related but unrecalled memories with such inhibitory mechanisms to avoid interference (e.g., Anderson, Bjork, & Bjork, 1994).

In general, studies on RIF usually consist of three sequential phases: learning phase, retrieval-practice phase, and testing phase. In the first learning phase, participants study multiple sets of related items that for example, require similar movements (motor learning) or belong to similar semantic categories (semantic learning), such that retrieving memory for items only causes forgetting of other items in the same set, but not in other sets. Different sets of items are manipulated through experiment design so that items from the same set are more likely to elicit interference through activation of related memory during retrieval than items from a different set. In the second retrieval-practice phase, participants are cued to randomly retrieve some (normally half) of the studied items from each set. In the third testing phase, following a distraction task, participants are tested for all items learned in the first learning phase, whether practiced or not in the second phase. According to the presence or absence during the retrieval-practice phase, items are categorized into retrieval-practiced (Rp+) items, non-retrieval-practiced (Rp-) items from practiced sets, and non-practiced (Nrp) items from unrelated sets. Recall accuracy for the three item types is then compared. As one might predict, Rp+ items benefit from both retrieval-practice, and are thus better recalled than Rp- and Nrp items. However, RIF further demonstrates that recall accuracy for Rp- items is significantly lower than that of Nrp items, contrary to the benefit one might expect from having retrieved the set of Rp items.

The earliest finding of RIF was discovered in a study that asked participants to study 8 six-item categories, consisting of four "strong exemplar" categories like "Fruit Orange" and four "weak exemplar" categories like "Tree Hickory" (Anderson et al., 1994). Half of the items from half of the categories were practiced three times during retrieval practice by giving participants cues (e.g., Fruit Or__). Participants then received a test in which they were cued with each category name and asked to freely recall any items from that category for recall accuracy. Researchers found impaired recall for the unpracticed items compared to the unrelated (baseline) recall accuracy. Furthermore, the recall for unpracticed strong items exhibited more absolute and proportional impairment than the recall for unpracticed weak items, showing that retrieval practicing of some items in a category after studying can impair the memory for other items within the same category due to their semantic similarities, but not for items in other categories. Later studies then found that episodic associations and semantic integration between practiced and unpracticed items protect memories from RIF (Anderson & McCulloch, 1999; Goodmon & Anderson, 2011), showing that competition between memories is necessary for RIF.

Since the early studies, many researchers have expanded findings of RIF from only semantic items into other domains of memory to show the prevalence of this phenomenon. Studies have found that participants do not have to know the meaning of the items, but simply grouping items together into categories could elicit RIF (Tempel & Frings, 2015). Also, studying color stimuli that are categorized into different shapes could elicit RIF (Ciranni & Shimamura, 1999). Those studies suggest that RIF does exist in other realms of memory beyond semantic memory, such as episodic memory, visuospatial memory, or even impressions on personality traits (MacLeod & Macrae, 2001).

Different mechanisms have been proposed to account for RIF. The interference hypothesis proposes that the memory for Rp+ items is strengthened and made easier to remember, thereby occupying a "response channel" during the testing phase, which blocks the memory of Rp- items. Such a blocking effect is stronger on Rp- items compared to Nrp items because of their closer relatedness to Rp+ items (Raaijmakers & Jakab, 2013). In contrast, the inhibition hypothesis argues that the retrieval of one item interferes with other items in the same set for conscious recollection, and that Rp- items are inhibited for better performance on Rp+ items during the retrieval-practice phase (Anderson, 2003). Lastly, the mental context hypothesis suggests that Rp+ items are associated with both the encoding context and the retrieval-practice context, Rp+ and Rp- items are both activated for retrieval-practice context during the testing phase, but for Nrp items, encoding context is activated during the testing phase. The recall for Rp- items is thus hindered because Rp- items had not been associated with the encoding context after its coactivation with Rp+ items as compared to Nrp items (Jonker, Seli, & Macleod, 2013).

When it comes to motor learning, different motor tasks have been used to assess RIF. A study found that just mental rehearsal, instead of executing the motion was enough to temporarily disrupt the recall for motor memory in a hand-reaching task that involved visuomotor rotation (Yin & Wei, 2014). Other research has shown that RIF affects motor actions by asking participants to learn motor sequences by pressing keys on the keyboard to execute sequential finger movement (SFM) (e.g., Tempel, Aslan, & Frings, 2015; Tempel & Frings, 2016; Tempel, Aslan, & Frings, 2017). Tempel and Frings (2016) instructed participants to consecutively press three keys on a keyboard in response to a letter cue and an animation on screen, showing which digits should be moved to learn each item during the learning phase. Items were put into different categories as sequences were either performed on the left or right side of the keyboard, all using right hands. Each item was presented ten times. During the retrieval-practice phase, participants attempted to recall sequences they learned in response to their letter stimuli by executing them using the same keys as in the learning phase. The participants received no feedback about their accuracy during the retrieval-practice and were then tested for recalling all items according to the letter cues after a distraction task.

To elicit RIF, there must be competition during retrieval practice between Rp+ and Rp- items. Rp- items are only inhibited if such inhibition is necessary to avoid interference for Rp+ items. (Murayama et al., 2014). In previous studies on RIF in motor learning, sequences executed using

different hands, motor sequences recalled by clicking on blocks on the screen instead of pressing keys, and sequences executed using different keys on the keyboard have been used to establish items of different sets (unrelated items) for participants to be learned. However, the question of whether the items that are categorized as "unrelated" by the researchers are truly unrelated to the participants remains debatable and requires further studying. It remains relatively unknown if retrieval-practice of items using different effectors (left or right hand), body parts (fingers or hand), or even different keys on the same keyboard would also induce RIF as the recall might still interfere with or inhibit the originally studied items despite the existing differences that separate them into different categories. In one experiment (Tempel & Frings, 2017), the experimental group was asked to use the opposite index fingers to indicate a sequence by pressing on response keys. No RIF appeared for participants who used the opposite index finger for retrieval practice, as compared to a standard condition, in which RIF did occur when participants used right index fingers in both retrieval-practice and testing phase. The results seem to suggest a lack of translation between two effectors. But the situations may become different when multiple fingers (from first to pinkie) are involved on both hands to elicit stronger activation of a series of sequential motion represented by motor memory. Few studies have examined if the retrieval of Rp+ items using a different effector during the retrieval-practice phase, while returning to the same effector as in the learning phase during the testing phase would also elicit RIF. In other words, it is not clear whether or to what extent the competition between Rp+ and Rp- items can be transferred bimanually. Furthermore, when more than one digit is involved, it is unknown whether it is the recall of the previously learned spatial sequence or the effector movement that triggers the competition between Rp+ and Rp- items.

Using a between-subject design, I asked all participants to learn sequences with their right hands in the learning phase but to use either their right hand (R) or left hand to recall either the same sequence [left-hand transposition (LT)] or the same motor representation using different keys [Left-hand mirror (LM)] during the retrieval-practice phase by assigning them into different between-subject groups. (Figure 1)

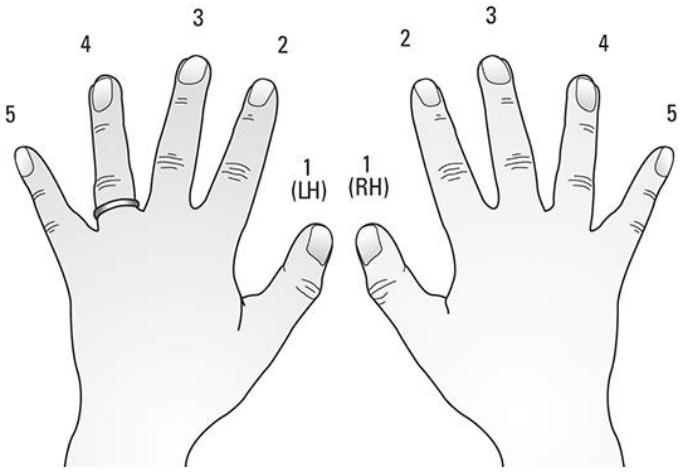


Figure 1 Illustration of finger mapping patterns for left and right hand.

Note. If all participants learned the sequence "254" using their right hand during the learning phase, the control group would still use their right hand for the same sequence during the retrieval-practice phase. In the practice phase, the two experimental groups would practice with their left hands. The LT group would practice the "same" "523" sequence that is spatially identical but executed by different fingers, and the LM group would practice the "same" "254" sequence for a symmetrical but different spatial sequence (excluding the thumb).

The purpose of the current study is to address the question of whether RIF remains present when retrieval of Rp+ items are executed using a different effector. Previous studies have shown that bimanual pointing and drawing tasks are both subject to intermanual interference over an extensive training period, suggesting that spatial interference between two hands is not eliminated through practice (e.g., Albert & Ivry, 2009; Stanciu, Biehl, & Hesse, 2017). Results from previous studies

may imply that for a SFM task, bimanual translation for the same sequential movement may also be difficult because of the limitation in translating an abstract sequence into actions. In this case, because the majority of the cognitive function is invested in translation, more learning instead of retrieval-practicing may take place while participants are recalling Rp+ items. As a result, with bimanual alternation for encode-practice-testing phases, RIF may diminish because of the weak connection between practiced and learned sequences for their different motor representation, despite being the exact same spatial sequence. However, the translation of symmetrical motor movements (same fingers, but spatially mirrored sequences), instead of abstract sequences, during the retrieval-practice phase may still be similar enough for the reinforcement of motor memory for Rp+ items to be translated across hands during the retrieval-practice phase, and to elicit competition between Rp+ and Rp- items.

I hypothesized that retrieval practice would produce interference between motor programs only for the LM group, but not the LT group, when motor programs learned with the right hand successfully translate to the left hand to reinforce the motor memory of Rp+ items through execution of sequences that represent the symmetrical motion, but not the identical sequence on the left hand.

I also hypothesized that RIF, (i.e., a significantly higher recall accuracy for the Nrp items than Rp- items), would occur only in the control and LM groups, but not in the LT group, because executing the same sequence using an opposite hand involves actions from different fingers, which requires cognitive load to translate abstract sequences into motion. In other words, such hand translation involves new learning instead of retrieval practicing, which would diminish the competition between Rp+ and Rp- items during retrieval, and free motor memory for Rp- from Rp+ inhibition, which would then boost Rp- recall accuracy during the testing phase. Furthermore, I expected that RIF would still occur in the LM group because although sequences are recalled by the LM group as the same actions on the same fingers on different hands, the translation process in this case would carry less cognitive load, and therefore the competition between Rp+ and Rp- items would persist.

Hypothetically, being affirmed that RIF was only present for the R group and the LM group but not in the LT group, I further hypothesized that participants in the LT group did not experience RIF because practicing the same sequence using different fingers on left hand require much translation in finger movements such that much of the participants' cognitive function was invested in the translation process instead of the recall of the original sequences themselves. If new learning, instead of retrieval practicing, was indeed involved only for the LT group during the retrieval-practice phase, a longer time would be needed for the LT group to finish responding to each letter cue during practice. Participants in the LT group would first need to recall the sequence related to the letter cue, then translate the sequence into actions of different fingers on the other hand. If this were indeed the process required for the LT group during retrieval practice, it would lead to a longer time on average for participants to finish recalling each sequence after they are presented with a letter visual cue.

I also hypothesized that because participants with expertise in keyboard instruments (having learned at least one keyboard instrument for more than 2 years in their lifespan) could translate the sequences between their right hand and left hand better, a similar retrieval-practice process would still play a significant role for the LT group even though translation was required, RIF would be found present in all three groups for participants with expertise in musical instruments.

2. Method

2.1 Participants

A total of 40 undergraduate students at Hamilton College (27 women and 12 men, one preferred not to answer; age M = 19.43 years, SD = 1.11 years; 34 were strongly or moderately right-handed) who reported normal or corrected to normal vision and normal finger mobility participated in the study. Participants received either course extra credit or $10 monetary compensation for participation.

All experimental procedures were approved by the Institutional Review Board of Hamilton College (315-859-4181) and written informed consent to participate in the study was obtained from all participants.

2.2 Stimuli

The experiment was conducted using iMac® 21.5-inch Retina personal computers, Apple® Mighty Mouse MA086LL/A and Apple® Aluminum Keyboard with Numeric Keypad MB110LL/B. The software Inquisit® 6 served for running the experiment. The items consisted of twelve three-key sequential finger movements (SFMs) performed with four fingers (Table 1), first learned in the learning phase by either pressing keys on right hand or clicking on the corresponding boxes using a mouse. Six items (a to f) were performed by pressing keys on the keyboard, and six (items u to z) by clicking on the corresponding boxes on the screen with a mouse.

During the learning phase, a letter appeared on the screen, together with four boxes representing the four keys on the keyboard that participants used to learn the sequences, with the next corresponding key press or mouse-click of the sequence highlighted. The highlighted boxes changed as soon as they pressed the correct key or clicked on the boxes as indicated on the screen (Figure 2). Participants were instructed to try their best to remember all sequences as they performed them. An "incorrect" caption appeared on the screen for one second if a wrong key was pressed, then the next key in the sequence was highlighted. A warning sign appeared on the screen if no action was taken after the next box was highlighted on the screen for 15 seconds, reminding the participants that they were too slow. The learning for the next key then continued.

During the practice and testing phase, only a letter and four boxes (used for showing the participants' own responses) appeared on the screen. The boxes were highlighted only when participants click on them for mouse sequences, or when the corresponding keys were pressed for keyboard sequences. The participants were instructed to recall the sequence related to the letter stimuli without feedback on their performance (Figure 3).

Table 1 Sequences learned.

Category	Sequence	Sequence Name
Right hand	J K K	a
Right hand	K ; J	b
Right hand	J ; J	c
Right hand	L L ;	d
Right hand	; ; ;	e
Right hand	L J ;	f
Mouse	J K J	u
Mouse	; L K	v
Mouse	K J K	w
Mouse	; ; J	x
Mouse	K K ;	y
Mouse	J ; L	z

Note. "J", "K", "L", ";" represent keys on the keyboard and four boxes on the screen from left to right learned with the right hand for all groups during the learning phase. The sequences were translated into "A", "S", "D", "F", during retrieval practice phase for the experimental groups.

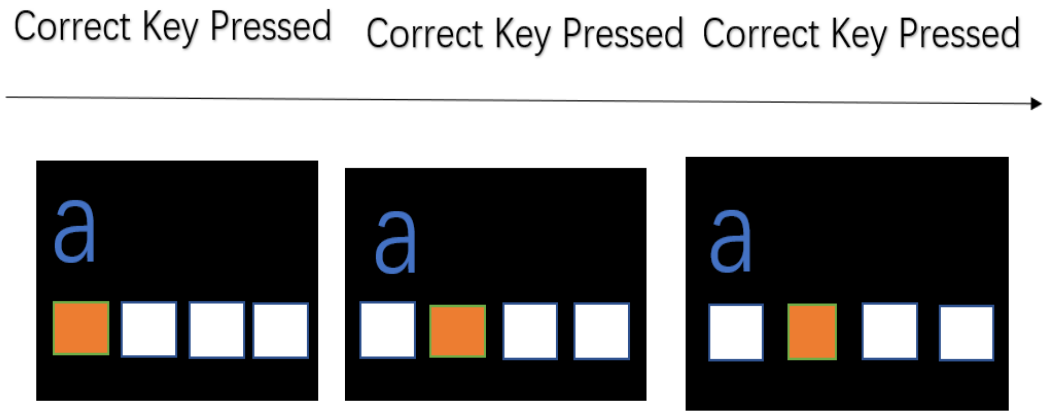


Figure 2 Presentation of stimuli on screen during the learning phase.

Note. All 12 sequences appeared in random order for 10 times during the learning phase.

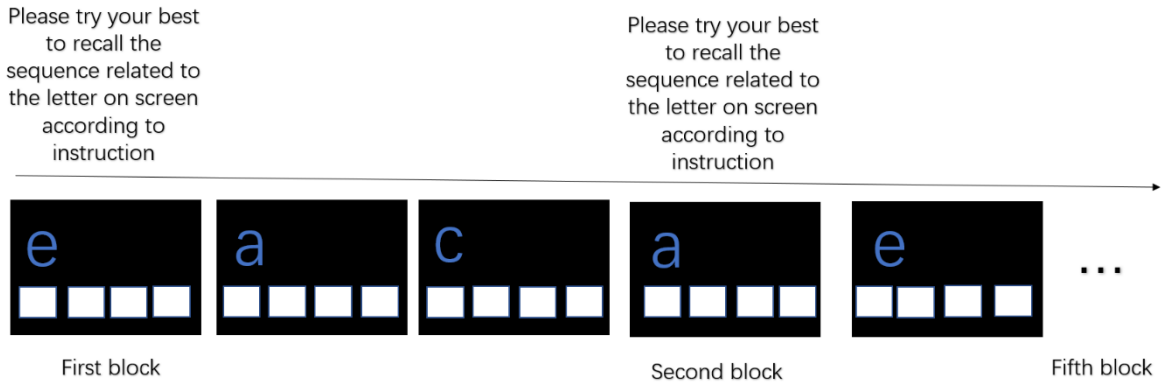


Figure 3 .Presentation of stimuli on screen during the retrieval-practice phase.

Note. The box will be highlighted when participants press its corresponding key or click on the box (for different sequence types), without feedback on their performance.

3. Procedure

Before the experiment started, participants were asked about their demographic information, including their gender, age, handedness, vision, and finger mobility. Each participant was then randomly assigned to one of 3 groups: left-hand transposition (LT), left-hand mirror (LM), or right hand (R).

The experiment consisted of four phases (learning, retrieval-practice, distraction, and testing). In the learning phase, participants were instructed to consecutively either press three keys with their right-hand fingers or click their mouse on three boxes on the screen in response to the displayed letter and its corresponding key sequence as indicated on the screen, while trying to remember all the sequences (Figure 2). In each block, all 12 sequences (including keyboard and mouse sequences) were learned once in random order. This process was repeated for 10 blocks in the learning phase.

In the retrieval-practice phase, participants were asked to retrieve selected finger sequences in response to their letter stimuli; half of the finger sequences from a to f (a, c, and e) (Rp+ items) were practiced in random order (Figure 3). The process was repeated 5 times. Depending on their assigned group, participants were asked either to practice the sequences with their right hand as they first learned it (R), with their left hand to generate the same box positions on screen but with different

fingers (LT), or with their left hand to generate symmetrical finger movements (LM) but reversed box positions on screen using left-sided keys on the keyboard (A, S, D, F) (Figure 4). Sequences were cued by the letter appearing on the screen. Corresponding boxes on the screen were highlighted when keys were pressed, but no feedback about the accuracy of their recall was given. Accuracy and response time used to complete each trial were recorded.

After a 3-min distractor task (music break), in the testing phase, participants were then presented with 12 letter stimuli in alphabetical order within each category (keyboard and mouse) with the two categories in counterbalanced order. Participants were instructed to respond by performing the keyboard or mouse sequences as they first learned them using either their right-hand fingers (items a to f) or their mouse (items u to z) (Figure 5). Like the retrieval-practice phase, letter cues and boxes were presented on the screen, and corresponding boxes were highlighted when keys were pressed or when boxes were clicked. Recall for all sequences are recorded as either "correct" or "incorrect" for recall accuracy analysis and will not be shown to participants. All sequences were tested once. Upon tested for all sequences learned, participants were asked about their experiences with musical instruments, the types of instruments they learned, and their training time in years. Participants were then thanked and dismissed.

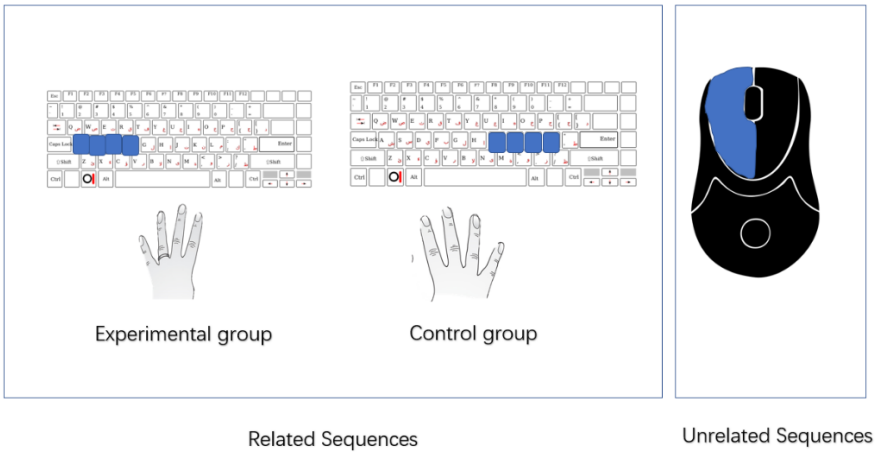


Figure 4 Equipment and hands used for different sequences and groups during the practice phase (indicated by blue region).

Note. For the LT group, sequence "b" will be practiced as "S", "F", "A". For the LM group, sequence "a" will be practiced as "D", "A", "F".

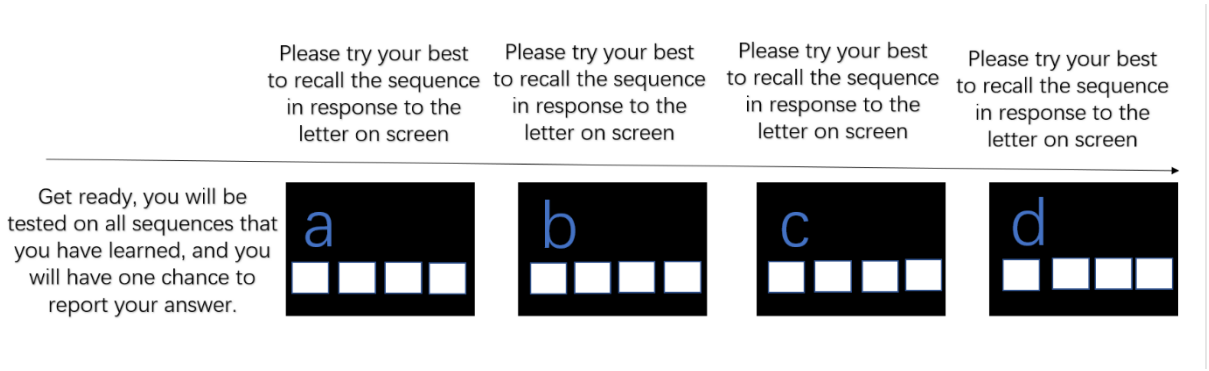


Figure 5 Presentation of stimuli on screen during the testing phase

Note. The box will be highlighted when participants press its corresponding key or click on it (for different sequence types), without feedback on their performance.

3.1 Design

The mixed design study had 3 between-subjects groups [left-hand transposition (LT), left-hand mirror (LM), right hand (R)] by 3 within-subject sequence types [Related practiced items (Rp+), related unpracticed items (Rp-), unrelated unpracticed items (Nrp)]. The within-subject dependent variable was sequence recall accuracy of different item types.

The between-subject dependent variable measures the presence or absence of RIF. The presence of RIF requires two results in the testing phase. First, the items that were practiced in the practiced set (Rp+) should produce better accuracy than the items that were never practiced (Rp- and Nrp), demonstrating an enhanced memory from retrieval-practice. Second, the items that were never practiced nor part of a practiced set (Nrp) should produce better accuracy than those that were never practiced but were part of a practiced set (Rp-).

3.2 Response Time Analysis

In order to verify the hypothesis that more new learning than retrieval practices actually took place for participants in the LT group during the retrieval-practice phase, which led to high cognitive load during retrieval practice for the LT group, the average response time for each key press or mouse click during the retrieval-practice phase was compared across three groups (LT, LM, and R), based on the hypothesis that extra time was needed for the translation process. A significantly longer time needed between each key press or mouse click would suggest that more cognitive processing and potentially learning a new set of asymmetrical finger movements took place.

3.3 The Effects of Keyboard Instrument Experiences

Participants' expertise in keyboard instruments (having learned at least one keyboard instrument for more than 2 years in their lifespan) was investigated through survey questions at the end of the experiment for further data analysis to verify the hypothesis that RIF would be found in all three groups for participants with expertise in keyboard instruments due to their possibly exceptional efficiency in transferring the memory of sequential finger movements (SFM) across hands.

4. Results

Forty participants successfully completed the experiment. Nine participants who showed no improvement in recall accuracy (equal to or below chance) in the testing phase were excluded from data analysis. The data from two participants who were originally assigned to the left mirror group (LM) were included instead in the left transposition group (LT) because they exhibited left transposition sequence patterns during the retrieval-practice phase, yet still showed learning in both practice and testing phases, suggesting that they had misunderstood the instructions at the beginning of the retrieval-practice phase.

4.1 Retrieval-Induced Forgetting

A 3 between-subjects retrieval-practice methods (Right hand [R], Left-hand Transposition [LT], Left-hand Mirror [LM]) x 3 within-subjects sequence types (Rp+, Rp-, Nrp) mixed-measures ANOVA was conducted on key recall accuracy in sequences (Figure 6). There was a significant main effect of sequence types, $F(2,28) = 28.94$, $p < .001$, $\eta_p^2 = .508$. However, neither main effect of retrieval-practice method, $F(2,28) = 0.264$, $p = .77$, nor an interaction, $F(2,27) = 0.48$, $p = .75$, was found.

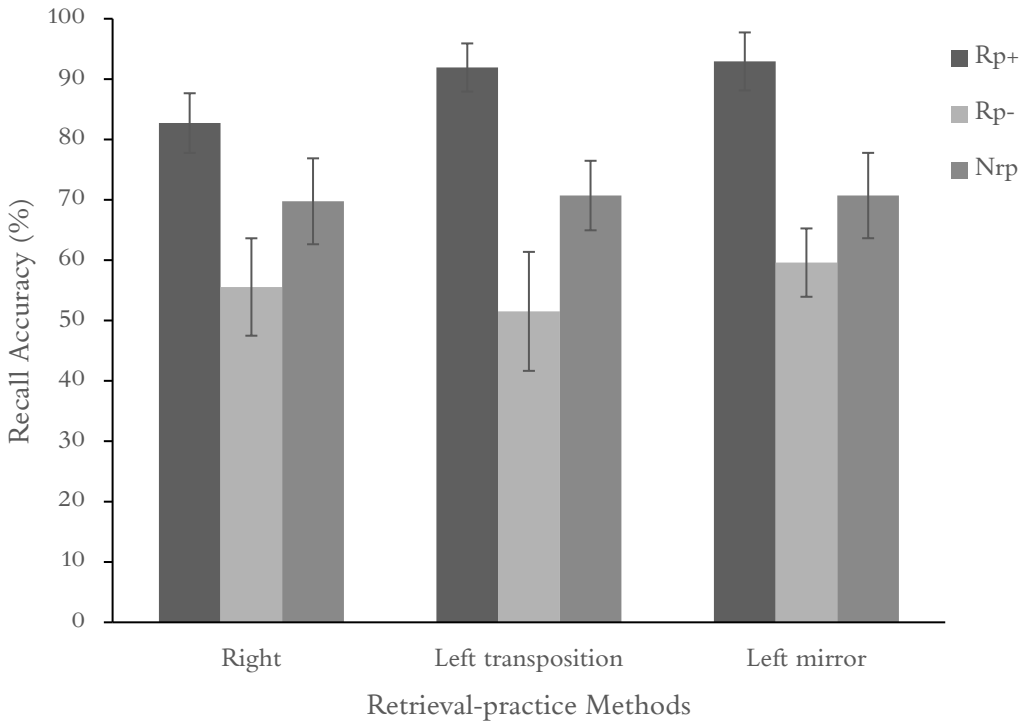


Figure 6. Mixed-measures ANOVA showed main effect of sequence types but no mean effect of retrieval-practice methods or interaction.

Note. Rp+ = retrieval-practiced keyboard sequences (related practiced category); Rp- = unpracticed keyboard sequences (related unpracticed category); Nrp = non-practiced mouse sequences (unrelated unpracticed category). Standard errors are shown by error bars.

Paired-samples *t* tests were then conducted between the sequence types (Rp+ vs. Rp- vs. Nrp) to determine whether Retrieval-Induced Forgetting (RIF) was present. A paired-samples *t* test between Rp+ (M = 89.61, SD =14.89) and Rp- (M = 55.56, SD = 25.34) sequences was statistically significant, $t(30) = 7.74$, $p < .001$, estimated Cohen's d = 1.39; 95% CI [25.06, 43.04], such that the participants successfully recalled higher percentage of key presses from practiced keyboard (Rp+) sequences than from unpracticed keyboard (Rp-) sequences. Likewise, Rp+ sequences were different from Nrp (M = 70.43, SD = 20.66) sequences, $t(30) = 5.37$, $p < .001$, estimated Cohen's d = 0.965; 95% CI [11.89, 26.46], such that participants successfully recalled a higher percentage from practiced keyboard (Rp+) than from unpracticed mouse (Nrp) sequences. The significantly higher recall accuracy in Rp+ sequences compared to the other two sequence types showed an effect of practice on performance in the testing phase. Most importantly, Rp- sequences differed from Nrp sequences, $t(29) = 3.02$, $p = .005$, estimated Cohen's d = 0.542; 95% CI [4.82, 24.93], such that participants recalled fewer sequences accurately from unpracticed keyboard (Rp-) than from unpracticed mouse (Nrp) sequences. This difference indicates that RIF was present, when collapsed over the retrieval-practice methods (Figure 7). That is, the ability to recall unpracticed sequences was hindered by practicing related sequences compared to the unpracticed and unrelated recall accuracy baseline.

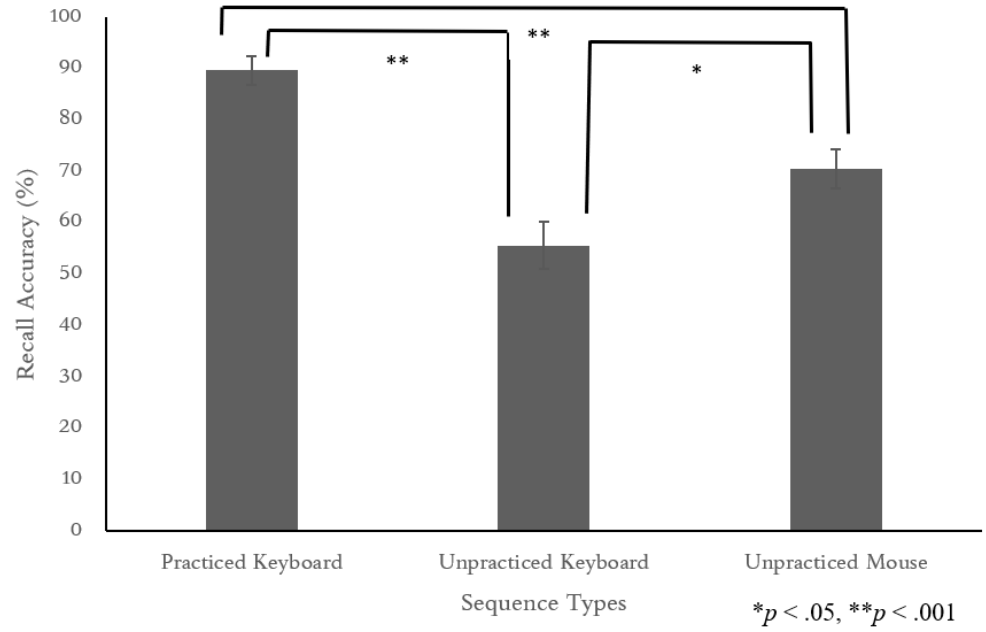


Figure 7.Paired-samples t tests between sequence types showed RIF collapsed over the retrieval-practice methods.

Note. Error bars indicate standard errors.

4.2 Response Time

The mean key press response time (RT) during the retrieval-practice phase was recorded (Figure 8). A One-way between-subjects ANOVA was conducted on RT for retrieval practice method, where a longer response time is interpreted as higher cognitive load. There were no significant differences in mean response times between groups, $F(2, 28) = 2.56$, $p = .095$.

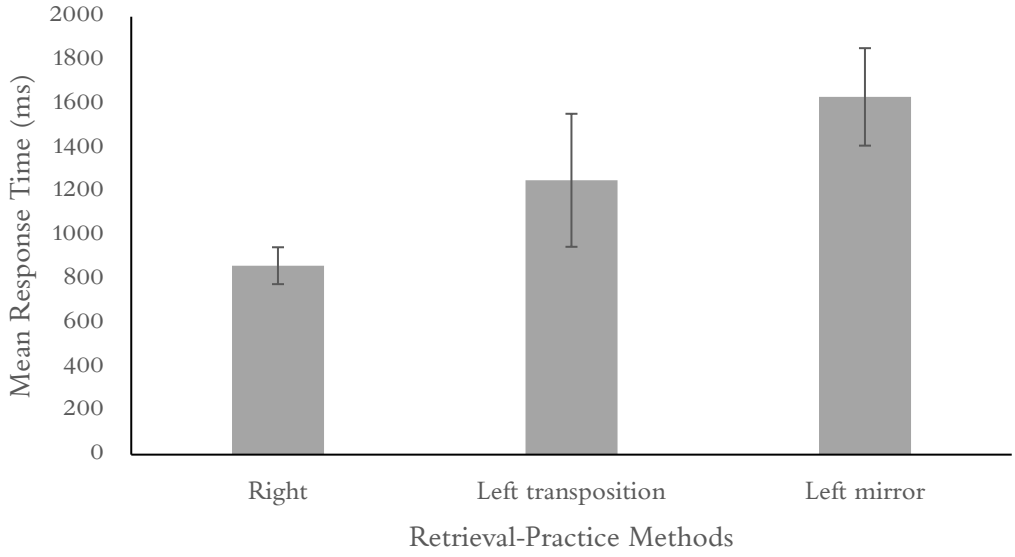


Figure 8 .One-way between-subjects ANOVA showed no significant difference in mean response time between retrieval-practice methods during retrieval-practice phase.

Note. Error bars indicate standard errors.

4.3 The Effects of Keyboard Instrument Experience

Out of the 31 participants who completed the experiment and showed significant learning during the testing phase, 15 participants self-reported that they had received keyboard or piano training for more than 2 years in their lifespan.

To further investigate the effect of keyboard instruments' experience on RIF for sequences learned and practiced on keyboard, a 2 (pianist vs. non-pianists) x 3 (retrieval-practice method) x 3 (sequence types) mixed-measures ANOVA was conducted on percent recall accuracy for sequence key presses. Neither main effect of keyboard instrument experience, $F(1, 29) = 0.057$, $p = .81$, nor interaction between keyboard instrument experience and retrieval-practice method, $F(2, 28) = 0.79$, $p = .47$, nor interaction between keyboard instrument experience and sequence types, $F(1, 29) = 0.177$, $p = .68$, was found to be statistically significant, suggesting that there was no evidence that keyboard instrument training had a significant impact on RIF in sequence learning.

5. Discussion

The recall accuracy for practiced keyboard sequences (Rp+) was higher than that of unpracticed keyboard (Rp-) and unpracticed mouse (Nrp) sequences when collapsed across all groups, indicating that participants showed enhancement in memory for sequences that were practiced during the retrieval-practice phase. Furthermore, as hypothesized, the recall accuracy for unpracticed mouse sequences (Nrp) was higher than that of the unpracticed keyboard sequences (Rp-), suggesting that the retrieval practice of keyboard sequences (Rp+) elicited robust forgetting of unpracticed keyboard sequences (Rp-), relative to the unrelated mouse-clicking sequences (Nrp). In sum, the hypothesized indicative pattern of Retrieval-Induced Forgetting (RIF) was present collapsed across all groups. However, neither a main effect of retrieval-practice method nor an interaction between sequence type and retrieval-practice method was found, suggesting that different retrieval-practice methods (i.e., using a right-hand, left-hand transposition, or left-hand mirror practice) did not affect the overall recall accuracy or RIF during the testing phase.

To assess whether left-hand practice introduced a higher cognitive load compared to right-hand practice, mean response time for each key during retrieval-practice phase was compared across retrieval-practice methods. Unlike what I hypothesized, no difference in response times was found between different retrieval-practice methods, suggesting that there may not be a large increase in cognitive load that facilitated RIF when participants translated their right-hand learned sequences to their left hand. I further explored whether keyboard instrument experience (having practiced for 2 years or more in lifespan) facilitates RIF of keyboard sequences translated across hands differently and found no difference in overall recall accuracy or RIF (within-group or between-group) between keyboard instrument players and non-keyboard instrument players, suggesting that keyboard instrument experience may not affect RIF of motor sequences learned on keyboard.

Previous studies have investigated the effects of different retrieval-practice strategies on RIF. For example, Storm et al. (2011) found that generating a creative novel with common associates to cue words caused the forgetting of other associates in semantic memory. Yin and Wei (2014) found that the mere mental rehearsal of learned movements induced forgetting in motor memory. However, no previous study has determined whether practicing with a different hand from the original learning hand would induce RIF. The current study explored the translation of RIF across hands in motor learning and found that practicing right-hand learned keyboard sequences with the left hand also induced forgetting, regardless of whether the practiced pattern was mirrored or translated compared to the original sequences.

Furthermore, the current study proposes new potential neural pathways through which RIF plays its role in strengthening and weakening motor memories. Previous neuroimaging studies have associated many brain regions with RIF in semantic memory. For example, a functional Magnetic Resonance Imaging (fMRI) study found significant differences in the metabolic activity of left ventrolateral prefrontal cortex (VLPFC), precuneus, and right inferior parietal lobe (IPL) between

recall of impaired and facilitated information, and found that the activation of left anterior VLPFC and left posterior temporal cortex predicted RIF; whereas the activation of precuneus and right IPL predicted retrieval-induced facilitation (Wimber et al., 2008). Another fMRI study found an association between selective retrieval and increased BOLD responses in the posterior temporal and parietal cortices, bilateral hippocampi, and in the dorsal lateral prefrontal cortex (DLPFC), as well as a strong negative correlation between neural activity of medial and lateral prefrontal areas and subsequent forgetting (Wimber et al., 2009). Other studies have also confirmed the same brain regions involved in RIF, including event-related potential (ERP) recordings at prefrontal sites during retrieval-practice that predicted RIF (Johansson et al., 2007), a transcranial Direct Current Stimulation (tDCS) study that successfully abolished RIF by stimulating the right Inferior Frontal Gyrus (rIFG) (Stramaccia et al., 2017), and a controlled lesion study conducted on rats with temporary inactivation of the hippocampus or mPFC that successfully blocked the RIF effect (Wu et al., 2014). It has been theorized that although the hippocampus and the temporal cortex are involved with retrieval of memory after learning, the PFC plays an important role in mediating competition between related memories by providing extra activation to the practiced items and make sure that they outcompete the related unpracticed items during practice (Norman et al., 2007).

Few neuroimaging studies have been conducted on RIF in motor learning. However, bimanual coordination and interference have been major topics in studies of motor learning. Studies have shown that when two hands attempt to concurrently execute incongruent movements guided by symbolic cues, the reaction time dramatically increases compared to the ones guided by spatial cues, suggesting that the cost was primarily associated with the selection and assignment of movement goals (Diedrichsen et al., 2006; Oliveira & Ivry, 2008). It has also been found that spatially guided movements increased activation in premotor and superior parietal areas, whereas symbolically guided movements increased activations in the basal ganglia, anterior cingulate, and inferior frontal and parietal cortices (Oliveira & Ivry, 2008). More specifically, Diedrichsen et al. (2006) identified the role of left-lateralized network in translating symbolic cues to actions, including left IPS/SPL, left ventral premotor cortex, and left inferior frontal cortex. Likewise, Ossmy and Mukamel (2016) found increased activity in both left and right SPL when unimanual training enhanced performance of the same task in the untrained hand. These brain regions involved with translation of actions may still play particularly important roles in the current study when participants attempt to translate right-hand learned sequences to their left hand.

Based on previous neuroimaging studies, it is very likely that in the current study RIF during retrieval-practice phase involves complicated communication across multiple brain regions, including the translation of sequences by the left-lateralized network, the internal generation of movements by the basal ganglia, anterior cingulate, inferior frontal and parietal cortices, as well as the facilitation and competition between memories by the prefrontal cortex. Future neuroimaging studies should further investigate whether these neuropathways involved in different functions are coactivated during RIF in motor learning when forgetting is induced by different practicing methods.

Besides the possible neural mechanisms, the current results question the definition of "related" or "unrelated" items established by previous RIF studies, especially in the realm of motor memory. For RIF in semantic memory, previous studies have commonly used words that are in the same semantic category as related items (e.g., "apple", "orange" and "banana" are all fruits; Anderson et al., 1994). For motor memory, however, related items are often defined differently across studies. Studies have used movement directions (Tempel & Frings, 2015), larger-scale body movements (Tempel & Frings, 2015), as well as left hand and right hand (Tempel & Frings, 2013) to establish different categories of motor memory. However, the current study shows that left-hand practice can induce RIF in right-hand learned sequences, suggesting that left-hand and right-hand sequences may actually have similar representations in motor memory, despite previous reports of RIF when left- and right-hand sequences were categorized as "unrelated" from each other. The current results provide an important direction for future research to investigate how closely finger movements are related between left and

right hand in terms of neural representations, and what extent of "unrelatedness" in movements would be enough to elicit RIF in motor learning.

Although no difference was found on average response time between groups in retrieval-practice phase, there was a trend that the mean response time for the right-hand (R) group was lower than that of the left transposition (LT) group, than that of the left mirror (LM) group. Previous studies have successfully associated longer response times with higher cognitive loads (Palada et al., 2019; Hunter, 2021), and found that bimanual pointing movements with different amplitudes (in which bimanual interference and coordination occurs) increased reaction time compared to equal amplitude movements (Stanciu et al., 2017). The current findings in response time suggest that left-hand practice of right-hand learned sequences may elicit higher cognitive investment in movement translation and initiation compared to right-hand practice. However, since no difference in RIF was found between retrieval-practice methods, the additional cognitive load that possibly deals with extra movement processing and translation may not have any substantial influence on RIF. Future studies should further investigate how cognitive load on the practiced items during retrieval-practice phase affects RIF.

The current study also found no differences between keyboard instrument players and other participants in overall recall accuracy or RIF. There were several factors that could potentially contribute to finding. First, the sample size of the current study was relatively small such that a 3 (retrieval-practice method) *2 (keyboard instrument experience) between-group design greatly reduces the power of differences. Secondly, other studies have shown that piano training is a form of long-term motor memory that benefits from sleeping during consolidation (Song, 2009). Retrieval-induced forgetting is more involved with short-term motor memory that may adopt very different brain mechanisms from long-term keyboard instrument training (Kang & Choi, 2015). Previous study has also found that the transfer from a unimanual sequence production task to a bimanual version was very limited, suggesting that unimanual and bimanual sequences are learned in separate representations (Yokoi et al., 2017). As a result, the current study may not be a good representation of keyboard instrument training, also because music training also involves auditory memory and coordination of both hands (Weiss et al., 2015), whereas the current study focuses on translation of movement from one hand to the other. Lastly, keyboard typing is becoming a basic skill in daily life, especially for college students; participants who are not keyboard instrument players may also have similar sequence translation ability from right hand to left hand since most people type with both hands.

Unlike previous RIF studies on motor learning that showed participants animations of finger movements and then asked the participants to reproduce the sequence immediately after each animation during the learning phase (Tempel & Frings, 2015; Tempel & Frings, 2015), the current study adopts a slightly different learning method by showing the participants one key at a time to guide them through the sequences. This learning method might better mimic a real-life situation in which the learning of a certain movement in dance or sports is broken down into a combination of many smaller movements (e.g., shooting in basketball, pitching in baseball, serving in tennis), which increases the external validity of the study. However, one limitation of this learning method is that due to differences in memory abilities and focus level of participants, some participants may spend much shorter time in the learning phase by going through the sequences too fast. There were also participants who reported that some sequences were harder to remember than others, and they would have taken the chance to practice the harder sequences more in a real-life situation. These limitations in learning methods may harm the learning efficiency and the external validity in a RIF study. One way to potentially optimize the learning experience in future research would be to make all 12 sequences available at the same time during the learning phase but set a time limit of 20 minutes for learning. This method would ensure that all participants spend the same time in learning and practice the harder sequences more if they want. An optimized learning phase in RIF studies would increase the external validity of the study and make the practice effect more robust while preventing

circumstances in which participants fail to remember the practiced sequences before the retrieval-practice phase.

Another direction for future research is to explore the effect of stress and time pressure on RIF in motor learning. Many studies have found that stress during the testing phase, induced either physiologically or mentally, eliminated RIF in semantic memory (Koessler et al., 2009; Koessler et al., 2013; Verde & Perfect, 2011). These findings are particularly important for studying RIF in motor learning, because in real-life situations, people often encounter time restrictions for recalling after motor learning, especially in sports. Athletes are often required to react quickly to their opponents by performing a movement they just learned. However, many studies have also found that stress and time pressure can result in compromised performance and in motor learning (Manley et al., 2018; Furuya et al., 2021; Lam et al., 2009), But under these conflicting effects of stress and time pressure on RIF and on motor learning, no studies have investigated how stress and time pressure affect RIF in a motor learning context. Future studies should replicate the current study with a between-group comparison of stressed vs. unstressed group to show if stress or time pressure can still eliminate RIF in the testing phase for motor learning, even when different practice methods are adopted.

Despite a few limitations, the current study still provides important insights to the understanding of RIF in motor learning by showing that left-hand retrieval could induce forgetting of right-hand learned sequential finger movements. The study not only further expands previous findings on RIF in motor learning, but also provides possible directions for future research, including behavioral and neurological measurements. Most importantly, it offers practical implications and suggestions for motor learning, especially in sports or music exercises. For example, baseball pitching and tennis serving involve very similar elbow motion yet different upper body mechanics, which could induce interference and forgetting in motor memories when the two motor sequences are learned in a short time span. The current study suggests that this unwanted side effect of practice can transfer across hands during practice, which may provide insights for sports coaches and music teachers to avoid RIF by adjusting their schedules to separate the learning and practicing of similar but different motor movements on both hands.

References

[1] Albert, N. B., & Ivry, R. B. (2009). The persistence of spatial interference after extended training in a bimanual drawing task. Cortex, 45(3), 377-385. doi:10.1016/j.cortex.2007.11.012

[2] Anderson, M. C. (2003). Rethinking interference theory: Executive control and the mechanisms of forgetting. Journal of Memory and Language, 49(4), 415–445. doi:10.1016/j.jml.2003.08.006

[3] Anderson, M. C., Bjork, R. A., & Bjork, E. L. (1994). Remembering can cause forgetting: Retrieval dynamics in long-term memory. Journal of Experimental Psychology: Learning, Memory, and Cognition, 20(5), 1063–1087. doi:10.1037/0278-7393.20.5.1063

[4] Anderson, M. C., Bjork, R. A., & Bjork, E. L. (1994). Retrieval-induced forgetting paradigm American Psychological Association (APA). doi:10.1037/t31768-000

[5] Ciranni, M. A., & Shimamura, A. P. (1999). Retrieval-induced forgetting in episodic memory. Journal of Experimental Psychology. Learning, Memory, and Cognition, 25(6), 1403-1414. doi:10.1037/0278-7393.25.6.1403

[6] Diedrichsen, J., Grafton, S., Albert, N., Hazeltine, E., & Ivry, R. B. (2006). Goal-selection and movement-related conflict during bimanual reaching movements. Cerebral cortex, 16(12), 1729–1738. doi:10.1093/cercor/bhj108

[7] Escamilla, R. F., & Andrews, J. R. (2009). Shoulder muscle recruitment patterns and related biomechanics during upper extremity sports. Sports medicine, 39(7), 569–590. doi:10.2165/00007256-200939070-00004

[8] Furuya, S., Ishimaru, R., & Nagata, N. (2021). Factors of choking under pressure in musicians. PloS one, 16(1), e0244082. doi:10.1371/journal.pone.0244082

[9] Goodman, L. B., & Anderson, M. C. (2011). Semantic integration as a boundary condition on inhibitory processes in episodic retrieval. Journal of Experimental Psychology. Learning, Memory, and Cognition, 37(2), 416-436. doi:10.1037/a0021963

[10] Hunter, C. R. (2021). Dual-Task Accuracy and Response Time Index Effects of Spoken Sentence Predictability and Cognitive Load on Listening Effort. Trends in Hearing, 25. doi:10.1177/23312165211018092

[11] Johansson, M., Aslan, A., Bäuml, K. H., Gäbel, A., & Mecklinger, A. (2007). When remembering causes forgetting: Electrophysiological correlates of retrieval-induced forgetting. Cerebral cortex, 17(6), 1335–1341. doi:10.1093/cercor/bhl044

[12] Jonker, T. R., Seli, P., & MacLeod, C. M. (2013). Putting retrieval-induced forgetting in context: An inhibition-free, context-based account. Psychological Review, 120(4), 852–872. doi:10.1037/a0034246

[13] Kang, M. S., & Choi, J. (2015). Retrieval-Induced Inhibition in Short-Term Memory. Psychological science, 26(7), 1014–1025. doi:10.1177/0956797615577358

[14] Koessler, S., Engler, H., Riether, C., & Kissler, J. (2009). No retrieval-induced forgetting under stress. Psychological science, 20(11), 1356–1363. doi:10.1111/j.1467-9280.2009.02450.x

[15] Koessler, S., Steidle, L., Engler, H., & Kissler, J. (2013). Stress eliminates retrieval-induced forgetting--does the oral application of cortisol?. Psychoneuroendocrinology, 38(1), 94–106. doi:10.1016/j.psyneuen.2012.05.004

[16] Lam, W. K., Maxwell, J. P., & Masters, R. (2009). Analogy learning and the performance of motor skills under pressure. Journal of sport & exercise psychology, 31(3), 337–357. doi:10.1123/jsep.31.3.337

[17] Loftice, J., Fleisig, G. S., Zheng, N., & Andrews, J. R. (2004). Biomechanics of the elbow in sports. Clinics in sports medicine, 23(4), 519–viii. doi:10.1016/j.csm.2004.06.003

[18] Manley, H., Beattie, S., Roberts, R., Lawrence, G. P., & Hardy, L. (2018). The benefit of punishment sensitivity on motor performance under pressure. Journal of personality, 86(3), 339–352. doi:10.1111/jopy.12318

[19] Murayama, K., Miyatsu, T., Buchli, D., & Storm, B. C. (2014). Forgetting as a consequence of retrieval: A meta-analytic review of retrieval-induced forgetting. Psychological Bulletin, 140(5), 1383-1409. doi:10.1037/a0037505

[20] Norman, K. A., Newman, E. L., & Detre, G. (2007). A neural network model of retrieval-induced forgetting. Psychological review, 114(4), 887–953. doi:10.1037/0033-295X.114.4.887

[21] Oliveira, F. T., & Ivry, R. B. (2008). The Representation of Action: Insights From Bimanual Coordination. Current directions in psychological science, 17(2), 130–135. doi:10.1111/j.1467-8721.2008.00562.x

[22] Ossmy, O., & Mukamel, R. (2016). Neural Network Underlying Intermanual Skill Transfer in Humans. Cell Reports, 17(11), 2891–2900. doi:10.1016/j.celrep.2016.11.009

[23] Palada, H., Neal, A., Strayer, D., Ballard, T., & Heathcote, A. (2019). Using response time modeling to understand the sources of dual-task interference in a dynamic environment. Journal of experimental psychology. Human perception and performance, 45(10), 1331–1345. doi:10.1037/xhp0000672

[24] Raaijmakers, J. G. W., & Jakab, E. (2013). Rethinking inhibition theory: On the problematic status of the inhibition theory for forgetting. Journal of Memory and Language, 68(2), 98–122. doi:10.1016/j.jml.2012.10.002

[25] Song S. (2009). Consciousness and the consolidation of motor learning. Behavioural brain research, 196(2), 180–186. doi:10.1016/j.bbr.2008.09.034

[26] Stanciu, I., Biehl, S. C., & Hesse, C. (2016). Increased cognitive demands boost the spatial interference effect in bimanual pointing. Psychological Research, 81(3), 582-595. doi:10.1007/s00426-016-0762-5

[27] Stanciu, I., Biehl, S. C., & Hesse, C. (2017). Increased cognitive demands boost the spatial interference effect in bimanual pointing. Psychological research, 81(3), 582–595. doi: 10.1007/s00426-016-0762-5

[28] Storm, B. C., Angello, G., & Bjork, E. L. (2011). Thinking can cause forgetting: Memory dynamics in creative problem solving. Journal of Experimental Psychology: Learning, Memory, and Cognition, 37(5), 1287–1293. doi:10.1037/a0023921

[29] Stramaccia, D. F., Penolazzi, B., Altoè, G., & Galfano, G. (2017). TDCS over the right inferior frontal gyrus disrupts control of interference in memory: A retrieval-induced forgetting study. Neurobiology of learning and memory, 144, 114–130. doi:10.1016/j.nlm.2017.07.005

[30] Tempel, T., Aslan, A., & Frings, C. (2015). Competition dependence of retrieval-induced forgetting in motor memory. Memory; Cognition, 44(4), 671-680. doi:10.3758/s13421-015-0578-3

[31] Tempel, T., & Frings, C. (2014). Interference in episodic memory: Retrieval-induced forgetting of unknown words. Psychological Research, 79(5), 795-800. doi:10.1007/s00426-014-0604-2

[32] Tempel, T., & Frings, C. (2014). Interference within hands: retrieval-induced forgetting of left and right hand movements. Acta Psychologica, 148, 1–5. doi:10.1016/j.actpsy.2014.01.003

[33] Tempel, T., & Frings, C. (2015). Directed forgetting benefits motor sequence encoding. Memory; Cognition, 44(3), 413-419. doi:10.3758/s13421-015-0565-8

[34] Tempel, T., & Frings, C. (2015). Categorization by movement direction: retrieval-induced forgetting of motor sequences grouped by motion features. Quarterly Journal of Experimental Psychology, 68(3), 473–486. doi:10.1080/17470218.2014.945098

[35] Tempel, T., Loran, I., & Frings, C. (2015). Dancing your moves away: How memory retrieval shapes complex motor action. Journal of Experimental Psychology. Applied, 21(3), 300–312. doi:10.1037/xap0000052

[36] Tempel, T., & Frings, C. (2016). How motor practice shapes memory: Retrieval but not extra study can cause forgetting. Memory, 24(7), 903-915. doi:10.1080/09658211.2015.1059858

[37] Tempel, T., Aslan, A., & Frings, C. (2016). Competition dependence of retrieval-induced forgetting in motor memory. Memory; Cognition, 44(4), 671-680. doi:10.3758/s13421-015-0578-3

[38] Tempel, T., & Frings, C. (2017). Retrieval-induced forgetting is retrieval-modality specific: Evidence from motor memory. Cognition, 162, 143-152. doi:10.1016/j.cognition.2017.02.005

[39] Verde, M. F., & Perfect, T. J. (2011). Retrieval-induced forgetting in recognition is absent under time pressure. Psychonomic Bulletin & Review, 18(6), 1166–1171. doi:10.3758/s13423-011-0143-4

[40] Weiss, M. W., Vanzella, P., Schellenberg, E. G., & Trehub, S. E. (2015). Pianists exhibit enhanced memory for vocal melodies but not piano melodies. Quarterly Journal of Experimental Psychology (2006), 68(5), 866–877. doi:10.1080/17470218.2015.1020818

[41] Wimber, M., Bäuml, K. H., Bergström, Z., Markopoulos, G., Heinze, H. J., & Richardson-Klavehn, A. (2008). Neural markers of inhibition in human memory retrieval. The Journal of Neuroscience : the Official Journal of the Society for Neuroscience, 28(50), 13419–13427. doi:10.1523/JNEUROSCI.1916-08.2008

[42] Wimber, M., Rutschmann, R. M., Greenlee, M. W., & Bäuml, K. H. (2009). Retrieval from episodic memory: neural mechanisms of interference resolution. Journal of Cognitive Neuroscience, 21(3), 538–549. doi:10.1162/jocn.2009.21043

[43] Wu, J. Q., Peters, G. J., Rittner, P., Cleland, T. A., & Smith, D. M. (2014). The hippocampus, medial prefrontal cortex, and selective memory retrieval: Evidence from a rodent model of the retrieval-induced forgetting effect. Hippocampus, 24(9), 1070-1080. doi:10.1002/hipo.22291

[44] Yin, C., & Wei, K. (2014). Interference from mere thinking: Mental rehearsal temporarily disrupts recall of motor memory. Journal of Neurophysiology, 112(3), 594-602. doi:10.1152/jn.00070.2014

[45] Yokoi, A., Bai, W., & Diedrichsen, J. (2017). Restricted transfer of learning between unimanual and bimanual finger sequences. Journal of neurophysiology, 117(3), 1043–1051. doi:10.1152/jn.00387.2016