PRIMING ERROR DETECTION TO AUGMENT LEARNING OF AN UPPER EXTREMITY MOTOR TASK: A PROOF-OF-PRINCIPLE STUDY

by

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A dissertation submitted to the faculty of
The University of Utah
in partial fulfillment of the requirements for the degree of

Doctor in Philosophy

in

Rehabilitation Science

Department of Physical Therapy and Athletic Training

The University of Utah

August 2017

The University of Utah Graduate School

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ABSTRACT

Preparing the nervous system prior to practicing a new task may be a viable way to augment motor learning. This approach, known as priming, attempts to make the nervous system more effective *during* practice by preparing it *prior* to practice. The development and adaptation of motor behavior occurs through a process of error-based learning. An error response in a cognitive task elicits an amplified neurophysiological response within the prefrontal cortex that is thought to indicate activation of the error monitoring system. This amplified neurophysiological response is indicative of an increase in error detection as a means to improve performance. Priming the error detection system might make error detection in a subsequent motor task easier and faster than if the system were not primed. This ultimately might result in improved learning. If successful, priming error detection may prove to effectively improve learning of new skills (or relearning of previously-learned motor skills) in rehabilitation.

We evaluated the effect of priming error detection on learning a motor task. We hypothesized that priming error detection would result in improved motor performance throughout the learning process (up to one week) on the trained task and untrained tasks when compared to a group who was not primed for error detection.

Thirty healthy young adults were randomized into two groups. Each group trained on a functional reaching task following completion of their respective priming task. Motor performance on the trained task and two other untrained tasks were assessed one day after training and one week after training. Another group was recruited as a no-training group to determine if improvements on the untrained tasks were due to motor skill transfer.

Results of this study demonstrated that priming error detection just prior to training may increase the rate, but not the amount, of motor task learning. Further, the groups improvement on the untrained tasks (i.e., transfer tasks) was not due to motor skill transfer as the no-training group improved a similar amount.

Collectively, priming error detection prior to motor training may be a viable method for augmenting learning of a motor task. Further, the results suggesting that transfer did not occur should be interpreted cautiously as our testing conditions may have caused sufficient repetitions of the transfer tasks throughout the protocol that a learning effect occurred.

TABLE OF CONTENTS

Chapters

LIST OF FIGURES

Figures

ACKNOWLEDGEMENTS

I would like to thank my committee, Lorie Richards, Lee Dibble, Sydney Schaefer, Heather Hays, and Jason Watson, for their mentorship, patience, and support. I am especially grateful to Dr. Lorie Richards for her diligence in transforming me from a clinician to a clinician scientist and to Dr. Sydney Schaefer for her consistent support and high expectations. I would additionally like to thank Genevieve Olivier for her assistance and, above all, her friendship throughout this process. I would not have been able to complete this effort without the support of my family and friends near and far. Most importantly, I would like to thank my wife, Shawna, and my daughter, Emmalyn, for their patience, understanding, and unwavering support.

CHAPTER 1

INTRODUCTION

Motor skill learning is ubiquitous across the life span as humans frequently encounter new tasks that require different movement patterns than those already in their repertoire. Whether the skill is altogether new or whether the skill is reintroduced following a neurological injury, finding ways to augment the ability to learn that motor skill is a priority in the neuroscience community. One viable option to augment learning of a motor skill is to prepare the nervous system prior to practicing the new skill. This phenomenon, known as *priming*, attempts to make the nervous system more effective *during* practice by preparing it *prior to* practice, with the ultimate goal of maximizing learning[1]. Numerous studies have demonstrated that the ability to acquire and learn a motor skill improves when certain interventions are administered prior to practicing a motor task. Examples of these priming interventions include non-invasive brain stimulation[2,3], aerobic exercise[4-6], and active passive bilateral therapy[7]. Although the mechanisms of these priming interventions are proposed to differ, their goals are the same. For example, non-invasive brain stimulation is said to increase the excitability of the neural circuits involved in learning a motor task[3,8]. Aerobic exercise is thought to up-regulate neurotrophic factors that are critical for learning, making them more available during motor practice[9]. Furthermore, active-passive bilateral therapy is proposed to rebalance the primary motor cortex's excitability following neurological injury[7,10]. While each priming intervention relies on a unique neural mechanism, they all alter the state of the brain, making it more conducive to learning[11,12].

Motor behavior is developed and adapted through the process of error-based learning[13,14]. When a novel motor task is introduced, the neural connections underlying performance are unrefined, so motor commands are typically not sufficient to produce accurate or smooth task-related movements. At initial performance, the motor system makes a prediction about the movement[15]. Following the movement, the sensory system relays the consequences of that movement back to the motor system. The difference between the predicted movement and the actual movement is the error[16]. The next movement, therefore, takes into account the error that occurred during the previous movement. As exposure to the task increases, the neural connections are honed due to the learner's error adjustments, resulting in a more effective task performance[17,18]. Therefore, error detection and correction are thought to be critical for motor learning[14,19,20].

The anterior cingulate cortex (ACC) is one area of the brain thought to play a role in error detection and correction[21-23]. It serves cognitive control functions that allow the adaptation of behavior due to changing task demands and altered environmental conditions[24,25]. This prefrontal error monitoring system has been heavily studied by recording the error-related negativity (ERN), an event-related potential that is time locked to an error response[21,23,26]. The error detection and correction processes of this brain region have predominately been studied using cognitive tasks that require response inhibition[27]. These tasks (e.g., Simon task[28], Erikson Flanker task[29]) assess one's ability to suppress responses that are inappropriate in a particular context. The ERN occurs after commission of an error and is indicative of an increase in error detection as a means to improve performance[26]. This signal represents an error between the actual output and the best estimate of the correct response[21,23]. This error is then used for future motor commands as part of the feedback process[26]. The implications of this response are seen behaviorally as well. Performance on a trial following a trial in which an error is made and detected is slower and more accurate, indicating that individuals are paying more attention to their performance by slowing down to ensure that they do not make another error[21,23]. There is also support that the size of the ERN is directly related to the size of the error[30]. Thus, if an error is more costly or if performance of the cognitive task emphasizes accuracy, the amplitude of the ERN is larger than if an error has little meaning or performance on the cognitive task emphasizes speed[26].

As error detection and correction is critical for motor learning, learning might be improved if the error detection and correction system could be heightened (i.e., primed) just prior to practice of the task to be learned. Priming the system first might make it easier and faster to detect errors that occur in the subsequently practiced task than if the system is not primed. As a result, this priming may lead to better or faster learning of the practiced task.

Despite the abundance of literature concerning the ERN and error-based motor learning, no studies have attempted to prime error detection in order to augment learning of a subsequent motor task. If such priming is beneficial, it may ultimately be an efficient method for enhancing learning of new, or recovery of previously-learned, motor skills in rehabilitation. Therefore, the objective of this study is to determine if priming error detection augments one's acquisition and learning of a subsequent motor task in a population of healthy young adults.

The process of motor learning can be observed through performance improvements by measuring accuracy, speed, or movement strategies of the practiced motor task. In this study, the motor tasks require participants to maximize movement speed while minimizing errors in order to complete each trial as fast as possible. To investigate the process of learning, motor performance will be measured during the practice phase (acquisition), one day following completion of training (early retention), and one week following completion of training (delayed retention). To test whether training results in improvement on other untrained motor tasks (i.e., *transfer*), performance on two untrained tasks will be measured prior to training on the trained task (pretest), immediately following training on the trained task (posttest), and one week following completion of training (delayed retention). Assessing learning at multiple time periods should maximize our chances of identifying a priming effect, if one in fact exists. To meet this end, the following specific aims were addressed:

Aim 1: To test whether priming error detection prior to training a previously untrained motor task improves the amount of acquisition and retention of the motor task.

Aim 2: To test whether priming error detection prior to training a previously untrained motor task improves the rate of acquisition of the motor task.

Aim 3: To test whether priming error detection prior to training a previously untrained motor task improves the amount of transfer to different motor tasks.

For the purposes of this study, motor skill acquisition was defined as a practice-induced change in motor performance during practice. Motor learning was defined as a practice-induced change in motor performance when assessed following a period of rest that occurs after practice has ended. Our overall hypothesis was that priming error detection would augment the ability to learn a motor task as measured via acquisition, retention, and motor skill transfer when compared to that which occurs without such priming. In order to accomplish our overall purpose and test our general hypotheses, we conducted a series of experiments evaluating the effect of priming error detection on learning a motor task in a population of healthy young adults. These chapters and their rationales are briefly described below with extensive details provided in the chapters that follow.

Priming error detection to augment learning of a motor task

Several studies suggest that learning can be enhanced when certain interventions are administered prior to practice of a motor task[1]. This effect is termed priming and is evident with interventions that include non-invasive brain stimulation[2,3] and aerobic exercise[4-6]. To date, literature focusing on priming as a means of improving motor learning has not considered the error detection and correction processes that are necessary for learning[13,14] and whether error detection during motor learning can be primed has not been studied. Our first experiment, therefore, aimed to evaluate the effect of priming error detection on the acquisition, learning, and transfer of a motor task. We compared motor performance on an upper extremity motor task for individuals whose error detection was primed prior to motor training to individuals whose error detection was not primed prior to motor training. Specifically, we sought to answer this question by assessing motor performance on three motor tasks: A trained task and two transfer (i.e., untrained) tasks. In addition, we assessed motor performance over a range of time: 1) during the acquisition phase, 2) one day following training (early retention), and 3) one week following training (delayed retention). We hypothesized that priming error detection would result in an improvement in 1) amount and rate of acquisition, 2) improved performance on the trained task at early retention relative to pretest performance, and 3) improved performance on all three tasks at delayed retention relative to pretest, when compared to the group who was not primed for error detection.

Exploring the limits of transfer

Motor skill transfer occurs whenever the skills learned in one task are applied successfully to the performance of another task[31]. Being able to transfer specific learning to new tasks is important because it is impossible to practice for each and every motor task that one may encounter[32].

A second way to measure motor learning is to test whether training on one motor task results in an improvement on another untrained task[31,33]. As a follow-up to experiment I (Chapter 2), our second experiment aimed to determine if the improvement on the transfer tasks in experiment I was actually due to a transfer effect (from the trained task), or if improvement was due to exposure to the transfer task that occurred during test-retest of that task. The experimental protocol was also designed to determine whether task similarity (e.g., spatiotemporal characteristics) between the trained task and the transfer tasks affects the amount of transfer. One transfer task had many similarities to the trained task while the other had few similarities to the trained task.

To test experiment II, we combined the performance data on the two transfer tasks from the two groups who had performed the motor training in experiment I. We then recruited a separate group who participated in the same study protocol, except instead of training on the trained task, they rested for 70 minutes between the pretest and the posttest. We hypothesized that the motor improvements demonstrated on the transfer tasks during experiment I were in fact due to training on the trained task (i.e., a transfer effect) instead of a rapid learning effect. We further hypothesized that the transfer task that had many similarities to the trained task would exhibit more motor skill transfer than the transfer task that had few similarities to the trained task.

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CHAPTER 2

PRIMING ERROR DETECTION TO AUGMENT LEARNING OF A MOTOR TASK

Abstract

Learning of a motor task may be augmented when the neural system is primed, or prepared, prior to training on a task of interest. Currently, interventions to prime the system have been limited. Due to the importance of error in motor learning, this study attempted to amplify the error detection system within the anterior cingulate cortex using a priming intervention with a goal of improving the ability to detect errors during training of a subsequent motor task.

The purpose of this study was to determine if priming error detection results in improved acquisition and learning of a subsequent motor task, when measured up to one-week. In addition, we sought to determine if priming error detection results in improved ability to transfer the training of the trained task to other untrained tasks.

Prior to motor training, the experimental group performed a prime to heighten error detection, whereas the control group performed a task that did not heighten error detection. The process of motor learning for each group was assessed during the acquisition phase, one day, and one week after the completion of training on the trained task and the untrained tasks.

Both groups learned the trained task with no differences in the rate or amount of learning between groups. Both groups also demonstrated a similar ability to improve performance on the untrained tasks despite not training on them. Secondary analyses revealed that when the groups were restructured based on their performance of the prime (as opposed to the group they were randomized to), the group primed for error detection learned the trained task at a faster rate than the group not primed for error detection.

These results suggest that priming error detection prior to motor training may be a way to augment learning of a motor task. Further investigation into the validity of this priming technique is warranted.

Introduction

Identifying ways to augment learning of a motor task is a priority in the neurorehabilitation research domain. Decades of motor learning research have given us a reasonable understanding of ways in which to maximize learning *during* motor practice. A newer approach attempts to make a neural system more effective during practice by preparing it *prior to* practice. This approach, known as *priming*, involves administering an intervention prior to practicing the motor task of interest[1]. The mechanism of action is dependent on the nature of the priming activity; however, the goal is to maximize learning by making the nervous system more responsive during subsequent task practice[1]. For example, priming with aerobic exercise is said to up-regulate growth factors, including brain-derived neurotrophic factor, which is critical for learning[2,3]. Priming in the form of non-invasive brain stimulation is said to increase the activation or excitability in cortical areas involved in learning a target task[4-6]. Priming using active-passive bilateral therapy is proposed to re-balance the primary motor cortex's excitability following a stroke[7,8]. Each of these methods results in a temporary change in the state of the brain, making it more responsive to learning mechanisms such as long-term potentiation and synaptic strengthening or sprouting[9,10].

Error-based learning is a basic principle of motor adaptation and learning based on the forward model of control theories[11-15]. Task-related movements are produced using a feed forward approach, in which the nervous system creates internal (and subconscious) movement simulations during motor planning, control, and learning. This theory states that the nervous system uses the motor system's current state to predict the movements needed to successfully complete a task (the goal), while it also predicts the sensory consequences of the motor commands required to produce the intended movements[16]. When the task is new, or under-practiced, the neural connections underlying performance are unrefined, so motor commands are typically not sufficient to produce accurate or smooth task-related movements. Thus, errors in task performance will occur and when such errors occur, the learner's sensory system detects the differences between the predicted and the actual sensory outcome and then uses that error signal to update the motor commands for the subsequent action. As exposure to the task increases, the neural connections are honed due to the learner's error adjustments resulting in more effective task performance. Therefore, error detection and correction are thought to be critical for motor learning[11,17-19].

One area of the brain thought to play a role in error detection is the anterior cingulate cortex (ACC). This prefrontal performance monitoring system has been studied by recording the error-related negativity (ERN), an event-related potential, following the commission of an error[20-22]. This time locked response is thought to indicate an interaction between the ACC and the prefrontal cortex as the dual mechanisms of goal maintenance and conflict monitoring are coordinated[23-25]. This error monitoring system has traditionally been thought to contribute to the feedback processing of errors, as the ERN becomes evident after an error is made, particularly under conditions that emphasize accuracy[20,22,26]. The role of the error detection and correction process following an error is evident by the performance observed on subsequent trials of the cognitive task[22,26]. Performance is slower and more accurate on the trial following a trial in which an error is made and detected, indicating that individuals are paying more attention to their performance by slowing down to ensure that they do not make another error.

As error detection and correction is critical to motor learning, it might be beneficial to learning if the activity in that system could be amplified, or primed, just prior to engaging in the learning task. Detecting errors might be easier and faster if the error detection system is primed, than if that system is not primed. Thus, priming may cause learning to occur at a greater rate or to a greater extent.

Despite the large base of literature surrounding the ERN and error-based motor learning, no studies have attempted to augment learning by priming error detection prior to motor practice. If such priming enhances motor learning, it may ultimately be an efficient method for increasing learning of new or recovery of previously-learned motor skills in rehabilitation.

This research is the first step in determining the effectiveness of augmenting a cognitive error detection signal for the benefit of motor learning. Therefore, the objective of this proof-of-principle study is to determine if priming error detection results in improved acquisition and learning of a subsequent motor task in a population of healthy young adults. The authors hypothesized that the group receiving the error detection prime would be better able to detect their errors in a subsequent task, resulting in more learning when compared to a group who did not receive such prime.

Methods

Participants

Due to the novel nature of this paradigm, an a priori power analysis was conducted on learning this trained task over time. The analysis determined that a total of 20 participants were needed given an effect size of 1.33 (Cohen's D), a power set at .80, and alpha level set at .05. To be conservative, we chose to include 15 participants in each group.

Thirty adults participated in this study. Exclusion criteria were (1) outside the ages of 18-35, (2) had one or more reported neurological conditions, (3) acute or chronic musculoskeletal condition that would affect upper extremity motor function, (4) uncorrected vision loss, and (5) mixed handedness. Hand dominance was based on self-report. Of the 30 participants, 29 of them were right-handed. Participants also reported their level of arousal prior to initiating baseline motor measures, immediately following completion of the cognitive task and again at the beginning of day 2 and day 8 sessions using the Stanford Sleepiness Scale[27]. This study was approved by a university Institutional Review Board and informed consent was obtained prior to enrollment.

Experimental protocol

All participants were first tested on two trials of three motor tasks to establish baseline performance: the trained task and two untrained (transfer) tasks. Prior to initiating the cognitive task, participants were randomly assigned to one of two groups using a blocked randomization technique. Those randomized to the accuracy group (experimental; n=15) completed 400 trials of a computer-based cognitive task with instructions emphasizing accuracy over speed. Those randomized to the speed group (control; n=15) completed the same number of trials on a cognitive task although their instructions were to emphasis speed over accuracy. Immediately following completion of the cognitive task, all participants completed 50 trials of the trained motor task (acquisition) followed by two additional trials of each transfer task (posttest). Participants returned on day 2 (early retention) for two additional trials of the trained task and again on day 8 (delayed retention) for two further trials of all three motor tasks (see Figure 2.1). All trials for each of the tasks were performed with the participant's non-dominant hand to ensure each task was under-practiced and not over-learned.

Priming error-detection using a cognitive task

The cognitive task we chose to use was a variant of the Simon task[28]. The Simon task is a choice reaction time task that requires distinct responses for each possible class of stimulus. Elicitation of the ERN has proven to be robust when using a task of this nature,[26] demonstrating that error detection processes are activated during this task. Two variants of the Simon task were used: one for the accuracy group and another for the speed group.

For both variants of the task, each trial began with a presentation of a fixation cross in the center of the screen for 250 milliseconds followed by a blank screen for 100 milliseconds. A stimulus (arrow) was then presented for 100 milliseconds in either the right or the left side of the computer screen and pointing to the right or the left. Participants were instructed to respond as quickly (speed group) or as accurately (accuracy group) as possible, pushing one of two buttons corresponding to the direction of the arrow while ignoring the spatial location on the screen. For each cognitive task, arrows were presented in one of two conditions: congruent (e.g., arrow pointing right and on the right side of screen) and incongruent (e.g., arrow pointing right but on the left side of screen). For each group, there was a high proportion of congruent trials (75%, 325 trials) to incongruent trials (25%, 75 trials). Each cognitive task consisted of 5 blocks of 80 trials, each separated by a 30-second rest break. The first block was preceded by 20 practice trials.

In order to ensure that the speed group had little regard for error, a 250-millisecond response deadline was imposed to create speed pressure[29]. The cognitive task for the accuracy group on the other hand had a 750-millisecond response deadline that provided less emphasis on speed[29]. Task instructions also differed for each group. The instruction to the speed group participants emphasized responding to the stimuli as quickly as possible. The instructions to the accuracy group participants emphasized responding to the stimuli as accurately as possible. The combination of accuracy instructions and a long response period has been shown to increase the neurophysiological response of the error detection system when an error occurs[29]. In contrast, the short response deadline in the speed group's cognitive task, along with instructions to emphasize speed, provides little to no increase in the neurophysiological response within the error detection system following an error[26].

For each cognitive task, if a response deadline was not met on a given trial, a message appeared to the participant as "Deadline Missed. Faster!" If more than 33% of deadlines were missed within a 15-trial span, a message appeared indicating that the participant was missing too many deadlines and that it was imperative that the deadlines be met, even if it resulted in errors. Response collection began with the onset of the stimulus and continued for 1,100 milliseconds. Reaction time (RT) and accuracy (% correct) were collected from each cognitive task.

Trained task-Functional reaching task (Figure 2.2)

This task required multi-joint reaching and tool use, and was adapted from the simulated feeding subset of the Jebsen Hand Function Test[30], which is often used clinically to measure hand function in activities of daily living. We have previously developed and used this task with healthy young adults[31], adults with chronic post-stroke hemiparesis[32], and non-demented older adults[33] and have validated this task against the 'gold standard' of point-to-point reaching[34].

This task required participants to spoon beans (kidney, raw) with their non-dominant hand from a central, proximal "start" cup to 3 distal "target" cups as fast as possible. The start cup was secured at the middle of one end of the test board. The 3 target cups (9.5 centimeters in diameter) were secured to the board 16 centimeters from the start cup at 45 degrees, 90 degrees, and 135 degrees. The test board was placed such that the start cup was oriented along the participant's midline and 15 cm in front of the seated participant. A plastic spoon was placed on the board 5 centimeters lateral to the start cup. One repetition of the motor task consisted of spooning 2 beans at a time from the start cup to a target cup with the non-dominant hand. Participants completed a repetition first to the target cup ipsilateral to the hand used, next to the center target cup, and finally to the cup contralateral to the hand used. This sequence was repeated five times to complete each trial. Thus, one trial consisted of 15 repetitions. The starting position was with the non-dominant hand to the side of the spoon. Each trial began as the administrator gave a verbal cue "go" and ended when the spoon was returned to the starting position after the final repetition. The time it took to complete the 15 repetitions ("trial time") to the nearest millisecond was the measure of performance, with faster times indicating better performance. All trials were timed via stopwatch. Number of errors during training were tabulated. We defined an error as (1) spooning the wrong number of beans into a cup, (2) dropping beans on the table, or (3) placement of beans in an incorrect cup. All errors had to be corrected before moving on. Participants were given no explicit feedback about their performance throughout the training.

Transfer task #1- Object placement task (Figure 2.3)

This task required multi-joint reaching and fine motor skill and has been adapted from the flip cards subsection of the Wolf Motor Function Test[35]. This task required participants to move a standard playing card (9 cm x 6.5 cm) with their non-dominant hand from a central, proximal "start" box to three distal target boxes as fast as possible. The boxes (9 cm X 9 cm X 2.5 cm) were secured to a board with 3 boxes secured radially at 45 degrees, 90 degrees, and 135 degrees, respectively, all 16 centimeters from the start box. The start box was 15 cm in front of the seated participant at midline with the cards face down. One repetition of the task consisted of placing one card at a time, face up, from the start box to a target box with the non-dominant hand. During each trial, participants first moved to the ipsilateral target box, next to the center target box, and then to the contralateral box, relative to the hand used. This sequence was repeated ten times to complete each trial. The participant started with their non-dominant hand to the side of the start box. Each trial began on the administrator's verbal "go" and ended when the last card came to rest in the target box. The time it took to complete the 30 repetitions ("trial time") was the measure of performance, with faster times indicating better performance. All trials were timed via stopwatch to the nearest millisecond. Participants were given no explicit feedback about their performance. This task was selected because it shares similar spatiotemporal characteristics (reaching trajectories) to the functional reaching task that was trained.

Transfer task #2- Dexterity task (Figure 2.4)

This task required fine motor skill and has been adapted from the applied dexterity subset of the Arthritis Hand Function Test, a clinical measure of hand function with real-world objects[36]. The adapted item involves fastening buttons with one hand. Like the functional reaching task, we have previously tested this motor task in healthy young adults[31] and adults with chronic post-stroke hemiparesis[32].

The task consisted of a board with 10 buttons (2.5 cm diameter) that were sewn 5.3 cm apart vertically to a piece of heavyweight linen fabric, 3.0 cm from the edge. The buttonholes were 3.7 cm in length. Both pieces of fabric were double-layered (2-ply) and were secured to a wooden board (61 cm x 34 cm), with the placket centered in line with the participant's non-dominant shoulder, 15 cm in front of them. The button-side of the fabric was folded onto the board, while the button-side of the fabric was unfolded on the non-dominant to midline onto the table prior to each trial. Fabric weight (65.6 g/m2) and thread count (15 per cm) were measured according to ASTM Test Methods D3776-96 and D3775-98, respectively (ASTM, 2001 a, b).

Participants were instructed to fasten each button sequentially, using their non-dominant hand starting at the button furthest from them. Upon successful fastening of the last button, participants were then instructed to unfasten each button in reverse order. Prior to each trial, participants sat with their non-dominant hand in their lap. Each trial began as the administrator gave a verbal “go” and ended when the last button was unfastened. The time it took to complete the task (“trial time”) was the measure of performance, with faster times indicating better performance. All trials were timed via stopwatch to the nearest millisecond. Participants were given no explicit feedback about their performance. This task was selected because of its dissimilar spatiotemporal characteristics compared to that of the functional reaching task.

Quantifying motor learning

We measured the acquisition and learning of the trained task by measuring performance at three different time points relative to pretest: 1) at the end of training (end of acquisition), 2) one day following the completion of training (early retention), and 3) one week following the completion of training (delayed retention).

We also measured the rate of improvement in response to training during the acquisition phase. To do this, we generated performance curves by plotting trial time (measured in seconds) as a function of trial number (trial 1-50), and modeled the data using an exponential decay function:

$$y= a+be^{-x/c},$$

where a is the final trial time value that the exponential decay function approaches (i.e., asymptote), b is the scale of the learning from the first trial time to the value a, x is the trial number, and c is the rate at which learning occurs (i.e., the decay constant). In this model, the exponential decay constant, 1/c, is the number of trials needed to obtain $(1-e^{-1})$ or 63.2% of the final learned amount (or asymptote, a). This approach has been used previously to quantify upper extremity motor adaptation and learning in healthy and clinical populations[33,37-40]. We used the value c as the rate of improvement in this study.

In addition, we measured the ability to transfer training from the trained task to other tasks that were not trained by measuring performance at two time points relative to pretest: 1) immediately following training (posttest) and 2) one week following training (delayed retention).

Data analyses

JMP 13.0 was used for all statistical analyses. Despite the data not being normally distributed ($W=.96$, $p<.001$), parametric tests were used as mixed model analysis of variance (ANOVA) models have a robustness to some non-normality[41].

To examine performance on the cognitive tasks, individual mean RT and accuracy were calculated for each group. Reaction time (RT) and accuracy data were analyzed with a 2 (group: speed vs. accuracy) X 2 (condition: congruent vs. incongruent) ANOVA. Trials in which there was no response given, or ignored, were excluded from all analyses, removing 2% of data.

To examine the amount of improvement in motor performance on the trained task between the two groups, we performed a 4 (testing time: pretest, end of acquisition, early retention, delayed retention) x 2 (group: accuracy vs. speed) mixed ANOVA. Testing time was a within-subjects factor while group was a between-subjects factor. Simple main effects were explored using Post hoc Tukey-Kramer Honestly Significant Difference (HSD) tests.

To examined the influence of priming on the rate of improvement in motor learning, we first calculating the rate of improvement for each participant in both groups and used a 95% confidence interval to test whether the average group rate was significantly different from zero. An independent t-test was then performed to determine if the rate was different between the groups.

To examine the amount of improvement in motor performance on the transfer tasks between the two groups, we performed a 3 (testing time: pretest, posttest, delayed retention) x 2 (group: accuracy vs. speed) mixed ANOVA. Testing time was a within-subjects factor while group was a between-subjects factor. Simple main effects were explored using Post hoc Tukey-Kramer HSD tests. Separate ANOVAs were performed for each transfer task.

Results

Participant characteristics

Fifteen subjects in each group completed the priming protocol prior to motor training. Mean +/- SD age was 25.6 +/- 3.5 years. The groups were not significantly different in sex (p=.245, FET), age $t_{(28)} = -.89$, p=.379, or level of arousal at any time point

$F_{(3, 109.9)} = .376$, p= .77. The groups were not significantly different in the number of errors committed during training of the functional reaching task $t_{(19.02)} = -1.61$, p= .124.

Cognitive task performance

Mean RT and accuracy are presented in Tables 2.1 and 2.2, respectively, as a function of group and stimulus condition. The RT analysis on correct trials revealed a main effect of stimulus condition, $F_{(1, 25.16)} = 105.53$, p<.0001 with the congruent trials (M = 302.13, SD = 78.40) responded to faster than the incongruent trials (M= 418.55, SD=110.52). There was a main effect of group, $F_{(1, 27.54)} = 37.40$, p<.0001 with the speed group responding faster (M= 269.68, SD= 69.88) than the accuracy group (M= 361.99, SD= 91.67), indicating that our experimental manipulation resulted in different behaviors between the two groups. There was also an interaction between group and stimulus condition $F_{(1, 25.16)} = 6.91$, p= .0144, indicating the difference between congruent RT and incongruent RT was greater in the accuracy group.

Turning to the analysis of accuracy, once again there was a main effect of stimulus condition, $F_{(1, 28)} = 97.03$, p<.0001 with the congruent stimuli responded to more accurately (M= 97.0%, SD = 5.1%) than the incongruent stimuli (M= 55.3%, SD= 33.1%). There was a main effect of group $F_{(1, 28)} = 33.34$, p<.0001), with the accuracy group (mean=89.0% SD=20.7%) responding more accurately than the speed group (M=63.2% SD=35.3%). There was also an interaction between group and stimulus $F_{(1, 28)} = 23.47$, p<.0001, indicating that the difference between congruent accuracy and incongruent accuracy was greater in the speed group.

The effect of priming error detection of motor learning

Figure 2.5 shows performance on the functional reaching task for both groups at pretest, end of acquisition, early retention, and delayed retention. There was a main effect of time $F_{(3, 230)} = 40.323$, $p<.0001$, however no main effect of group $F_{(1, 230.9)} = .184$ $p=.67$ nor an interaction of time and group $F_{(3, 230)} = .791$ $p=.50$ were noted. Post-hoc analyses revealed that mean trial time was significantly lower (faster) at each testing time compared to pretest; end of acquisition vs. pretest: ($p<.001$); early retention vs. pretest: ($p<.001$); delayed retention vs. pretest: ($p<.001$), indicating that performance improvements due to training were retained for up to one week post training.

The rate of improvement due to training can be seen in the mean performance curve for each group (Figure 2.6). The rate of the accuracy group was significantly different from 0 (95% CI -.05--.37) while the rate of the speed group was not (95% CI .02--.26). However, this difference was not statistically significant, $t_{(28)} = -.878$, $p=.194$.

Figure 2.7 shows performance on the object placement task for both groups at pretest, posttest, and delayed retention. There was a main effect of time $F_{(2, 172)} = 16.682$, $p<.0001$, however no main effect of group $F_{(2, 172.5)} = .302$ $p=.58$ nor an interaction of time and group $F_{(2, 172)} = .258$ $p=.77$ were noted. Post-hoc analyses revealed that mean trial time was significantly lower (faster) at each testing time compared to pretest: posttest vs. pretest ($p=.0004$) and delayed retention vs. pretest ($p<.0001$). Performance at posttest was also statistically different than performance at delayed retention ($p=.032$), indicating that performance improved on the task throughout the protocol despite not training on the task.

Figure 2.8 shows performance on the dexterity task for both groups at pretest, posttest, and delayed retention. There was a main effect of time $F_{(2, 172.5)} = 29.43$, $p<.0001$, however no main effect of group $F_{(1, 161.8)} = .094$ p=.76 nor an interaction of time and group $F_{(2, 172.5)} = .404$ p=.67 were noted. Post-hoc analyses revealed that mean trial time was significantly lower (faster) at each testing time compared to pretest: posttest vs pretest ($p<.0001$) and delayed retention vs. pretest ($p<.0001$), indicating that performance improved from pretest to posttest and those improvements were maintained for up to one week.

Reclassifying participants based on cognitive task performance

In order to get a true representation of the effect of priming error detection for the augmentation of motor learning, we wanted to ensure that each participant followed the instructions of their respective cognitive task. Upon inspection (Figure 2.9), we noted that performance of three participants in the accuracy group implied that they did not prioritize accuracy over speed, suggesting that error detection was not primed in these individuals. On the other hand, there was one participant in the speed group whose cognitive performance mirrored those in the accuracy group, leading us to believe that individual may have benefitted from the prime.

After reclassifying those individuals based on their cognitive performance (see Table 2.3), motor performance analyses were re-run (Speed n= 17, Accuracy n= 13). The shifting of these participants revealed similar results in the amount of improvement on the functional reaching task (Figure 2.10). There was a main effect of time $F_{(3, 229.9)} = 42.28$, $p<.0001$, however no main effect of group $F_{(1, 230.2)} = 2.64$, p= .105 nor an interaction of time and group $F_{(3, 229.9)} = 1.84$, p=.141 were noted. Post-hoc analyses revealed that mean trial time was significantly lower (faster) at each testing time compared to pretest; end of acquisition vs. pretest: ($p<.001$); early retention vs. pretest: ($p<.001$); delayed retention vs. pretest: ($p<.001$) indicating that performance improvements due to training were retained for up to one week post training.

The revised group's rate of improvement due to training can be seen in the mean performance curve for each revised group (Figure 2.11). The rate of the revised accuracy group was significantly different from 0 (95% CI -.11--.48) while the rate of the revised speed group was not (95% CI .04--.15). The rate of improvement in the revised accuracy group was statistically faster than the rate of improvement in the revised speed group $t_{(18.59)} = 2.50$, $p=.011$, indicating that the revised accuracy group acquired the motor task faster than the revised speed group.

Figure 2.12 shows the revised group's performance on the object placement task at pretest, posttest, and delayed retention. There was a main effect of time $F_{(2,\ 172)} = 14.94$, $p<.0001$, however no main effect of group $F_{(2,\ 172.5)} = 3.38$ $p=.07$ nor an interaction of time and group $F_{(2,\ 172)} = .271$ $p=.76$ were noted. Post-hoc analyses revealed that mean trial time was significantly lower (faster) at each testing time compared to pretest; posttest vs. pretest: ($p=.008$); and delayed retention vs. pretest: ($p<.0001$). Performance at posttest was also statistically different than performance at delayed retention ($p=.045$), indicating that performance improved on the task throughout the protocol despite not training on the task.

Figure 2.13 shows the revised group's performance on the dexterity task at pretest, posttest, and delayed retention. There was a main effect of time $F_{(2,\ 171.7)} = 29.799$, $p<.0001$, however no main effect of group $F_{(1,\ 172.5)} = .006$ $p=.94$ nor an interaction of time and group $F_{(2,\ 171.7)} = .398$ $p=.67$ were noted. Post-hoc analyses revealed that mean trial time was significantly lower (faster) at each testing time compared to pretest: posttest vs.

pretest (p<.0001) and delayed retention vs. pretest (p<.0001), indicating that performance improved from pretest to posttest and those improvements were maintained for up to one-week.

Discussion

The purpose of this experiment was to test if priming for error detection prior to motor skill training improves the ability to learn a motor task in a neurologically intact population. Results showed that both groups learned the trained task as measured at one week post training. Both groups also demonstrated improved motor performance on each transfer task at delayed retention relative to pretest despite not training on them. Our primary analyses found that the group primed for error detection (accuracy group) prior to motor training did not exhibit faster or greater learning compared to the group that was not primed (speed group). However, a secondary analysis suggested that the rate of acquisition on the functional reaching task may have been effected by the error detection prime. This analysis was performed after reclassifying participants according to their cognitive task performance (Table 2.3). Based on cognitive task performance, participants who performed their cognitive task with an emphasis on accuracy acquired the trained task at a significantly faster *rate* than the participants who performed their cognitive task with an emphasis on speed. Similar to the initial analysis, however, there was no difference in the *amount* of learning at any time point on any task. Collectively, the results of this study suggest that priming error detection may augment learning of a motor task.

Our experimental approach and hypothesis were driven by two factors: error detection and error-driven learning. When performing a cognitive task in which the cost of errors is high (emphasis on performing the task accurately) and an error is made, a neurophysiological response signals action of the performance monitoring system[26]. This response is believed to occur in the medial prefrontal/ACC region of the brain[42-44]. This system is thought to serve cognitive control functions that enable the brain to adapt behavior to changing task demands and environmental circumstances[24,45,46]. The amplitude of the error signal (ERN) provides insight into the cost of the error, suggesting that the larger the amplitude, the more costly the error[26,47,48]. When an error is costly, there is more attention directed to the error, as evident by an enlarged ERN, in an effort to ensure that the error is corrected or that it does not occur again. With this in mind, our goal was to create an intervention to amplify error detection. Performance of a cognitive task with an emphasis on accuracy triggers costly errors[26]. As a result, we proposed that the amplified error detection would then promote error detection in a subsequent motor task, leading to better learning.

One might question whether the cognitive task actually amplified error detection processes for the accuracy group compared to the speed group. While we did not measure brain activity during our priming task, the cognitive tasks used in this study were developed based on previous studies that measured ERN activity. In those studies, the ERN, indicative of heightened error detection, was found elevated only under instructions that emphasized accuracy[20,22]. Our behavioral results in the cognitive tasks were similar to the studies that did measure ERN[26]. For example, our speed group responded much faster to the incongruent trials than did the accuracy group (Table 2.1). Our accuracy group was much more accurate on the incongruent trials than the speed group (Table 2.2). This behavior, collectively, suggests that the accuracy group emphasized accuracy at the cost of speed whereas the speed group emphasized speed at the cost of accuracy. Therefore, we believe that it is likely that the accuracy group experienced amplified error detection while the speed group did not.

As discussed earlier, research shows that an error on a cognitive task has implications on the subsequent trial within that task[20,22]. However, the persistence of error detection beyond the subsequent trial has not been tested. Therefore, we cannot be sure if the amplified error detection carried forward to the subsequent motor task in this study. It is clear that the effects of such processes can last long periods of time during situations in which there are extreme consequences of error– soldiers monitoring activity in war zones[49], or professionals involved in a medical error[50], for example – but perhaps this does not occur, or occurs to a lesser extent, in relatively safe situations of experimental laboratory tasks.

Task dissimilarity might be another potential reason why the effect of priming was limited. The fact that our priming intervention and target tasks were in different domains (cognitive versus motor, respectively) may have diminished the priming effect. Our study's overall focus on augmenting motor learning prompted us to select tasks in the motor domain as our target tasks. Our priming intervention was based on a cognitive task because of the abundance of literature supporting a measurable response to error in that task[20,22,26]. However, the task domain in which the errors occur may change the effectiveness of the priming. After all, errors may be different across different domains. If an error occurs while driving (i.e., speeding ticket or traffic accident), the error is likely to facilitate the driver to drive slower and safer. It is not, however, necessarily reasonable to suggest that the driving error would benefit behavior in a task unrelated to driving. Had there been a stronger connection between the errors in the cognitive task and the errors in the motor task, the priming effect may have been larger (more extensive)[15].

Lastly, the nature of our trained motor learning task, itself, may not have been ideal to determine the effect of priming error detection. The trained motor learning task was generally novel. It is unlikely that participants previously performed an identical real-life task. However, it was not completely novel in the sense that participants were familiar with the concept of the task and had previous experience moving objects with a spoon with their dominant hands. Thus, participants had the basic coordinated movement in their repertoire to complete this task, despite demonstrating that refinement was possible through practice. Yet error-based learning primarily occurs in the early phases of learning when the learner is developing the neural connections underlying performance for the particular task[51]. As the learner's performance begins to stabilize or plateau, they move into a more refined phase of learning in which their performance is more consistent[51], thereby relying on error to a lesser extent. Likely because this task was not completely novel[52-54], and because the study included healthy young learners with intact neuromuscular systems[55-57], average motor performance for each group plateaued during acquisition rather quickly (trial 3.8 for accuracy group and 3.9 for the speed group; trial 3.4 for the revised accuracy group and 5.9 for the revised speed group), thereby allowing error-driven learning to play a role in only a small number of trials. Testing for the priming effect under conditions of truly novel learning may be a better test of this hypothesis.

Limited statistical power because of the modest sample size (N=30) may have played a role in limiting the significance of some of the statistical comparisons that were conducted. A between-group and an interaction at delayed retention post-hoc analysis revealed effect sizes of d=.06 and d=.15, respectively.

Conclusion and future research

Our results suggest learning of a motor task following an error detection prime may be augmented in a population of healthy young adults. These results, however, should be interpreted cautiously. While the rate of acquisition was statistically different when the groups were reorganized based on their cognitive performance (as opposed to their randomized group), the analysis was performed post-hoc. It does, however, warrant further investigation to determine the validity of using a cognitive task to prime error detection to augment learning of a subsequent motor task. In addition, future research should continue to explore the mechanism of error detection in the ACC and its relationship to the motor system by determining the persistence of the response and if that response has implications for tasks in different domains.

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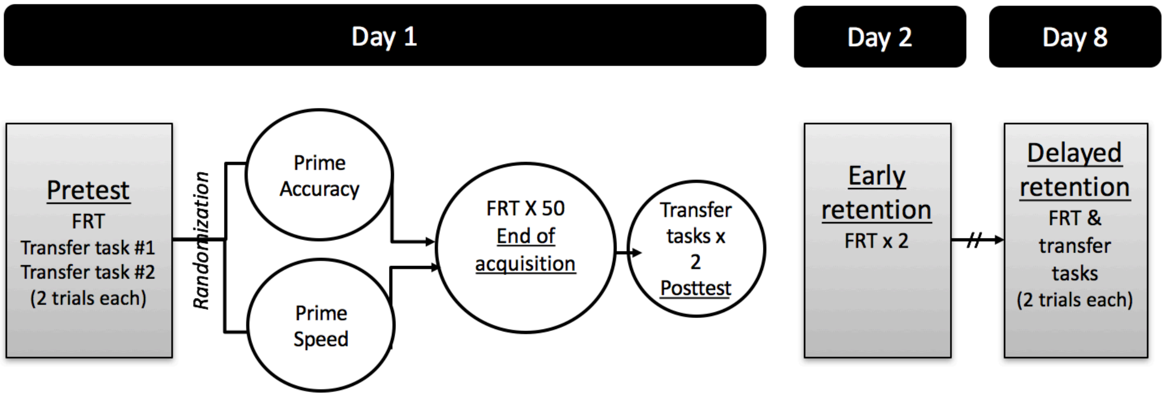

FRT: Functional reaching task
Transfer task #1: Object placement task
Transfer task #2: Dexterity task

Figure 2.1: Study activity diagram

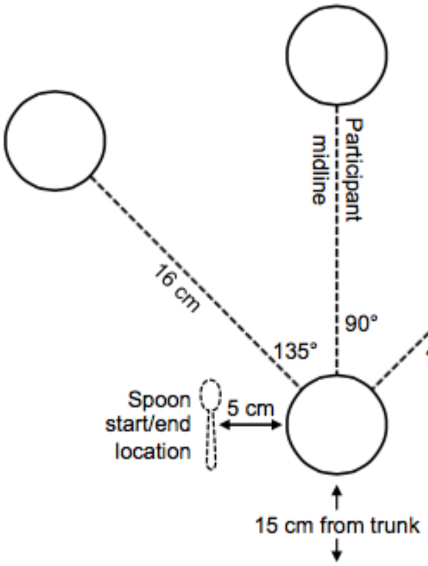

Figure 2.2: Functional reaching task

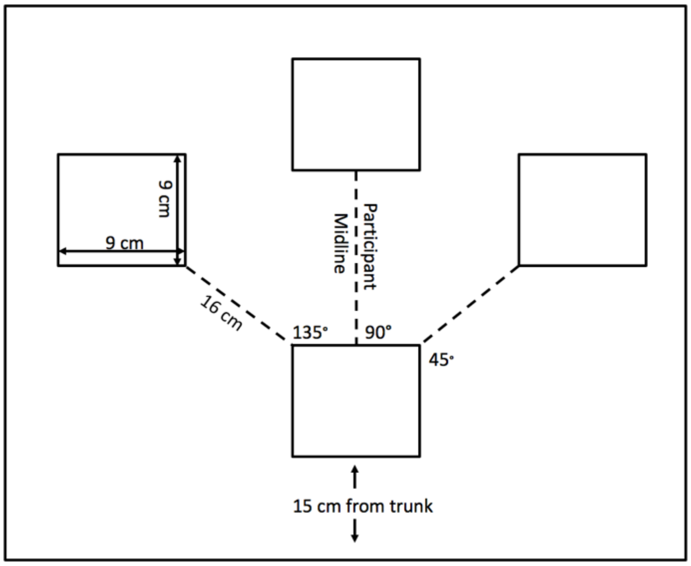

Figure 2.3: Object placement task

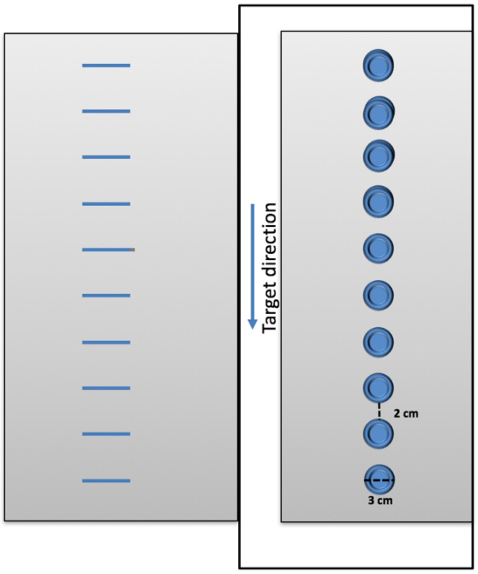

Figure 2.4: Dexterity task

Table 2.1: Average reaction time (in milliseconds) as a function of group and stimulus condition

SIMON TASK CONDITION

GROUP	Congruent Mean (SD)	Incongruent Mean (SD)
SPEED	257.70 (29.24)	279.06 (46.95)
ACCURACY	338.86 (35.19)	419.98 (72.54)

Table 2.2: Average accuracy (in percentages) as a function of group and stimulus condition

SIMON TASK CONDITION

GROUP	Congruent Mean (SD)	Incongruent Mean (SD)
SPEED	94.3 (6.2)	32.1 (21.7)
ACCURACY	99.6 (0.7)	78.4 (25.4)

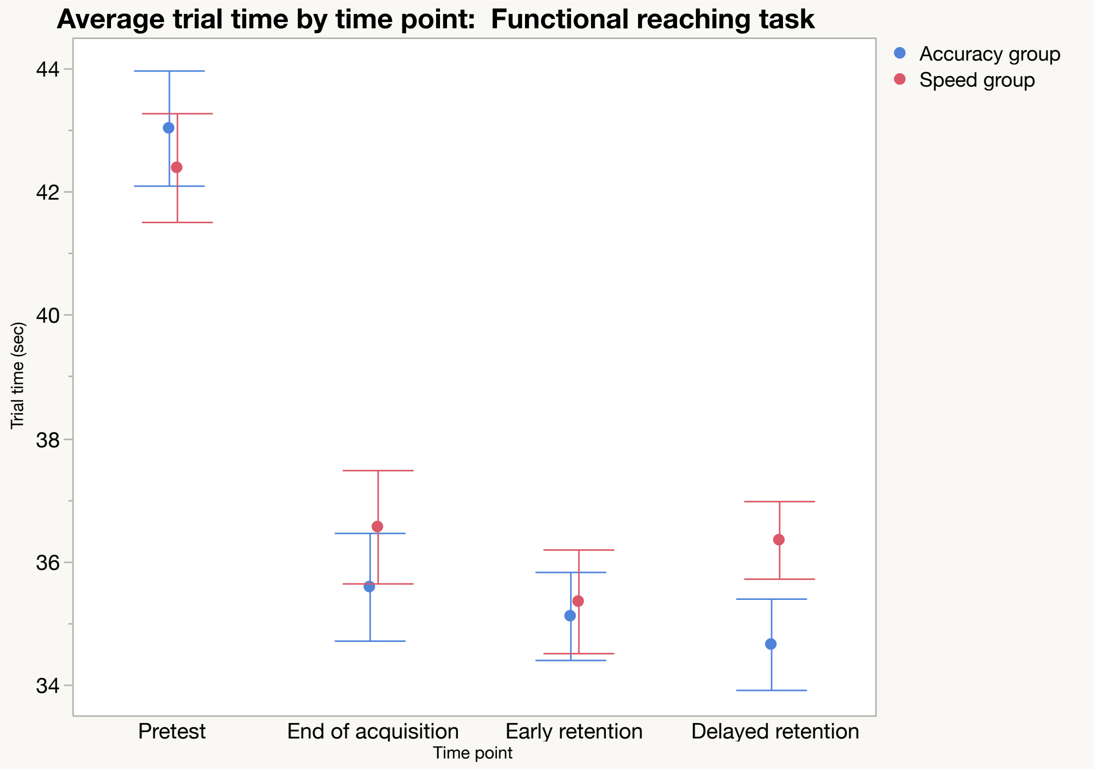

Figure 2.5: Average trial time by time point: Functional reaching task

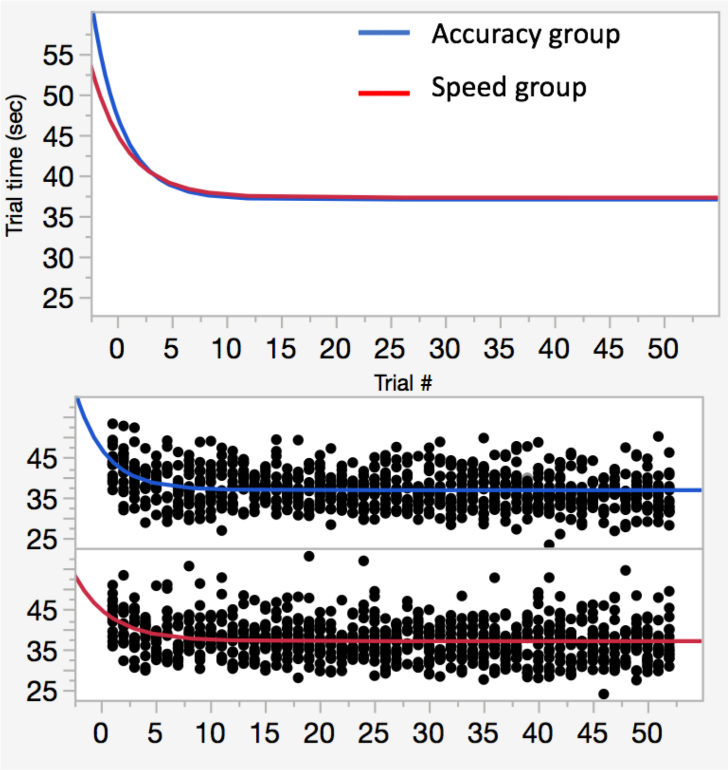

Figure 2.6: Rate of acquisition by group as determined by the exponential decay function

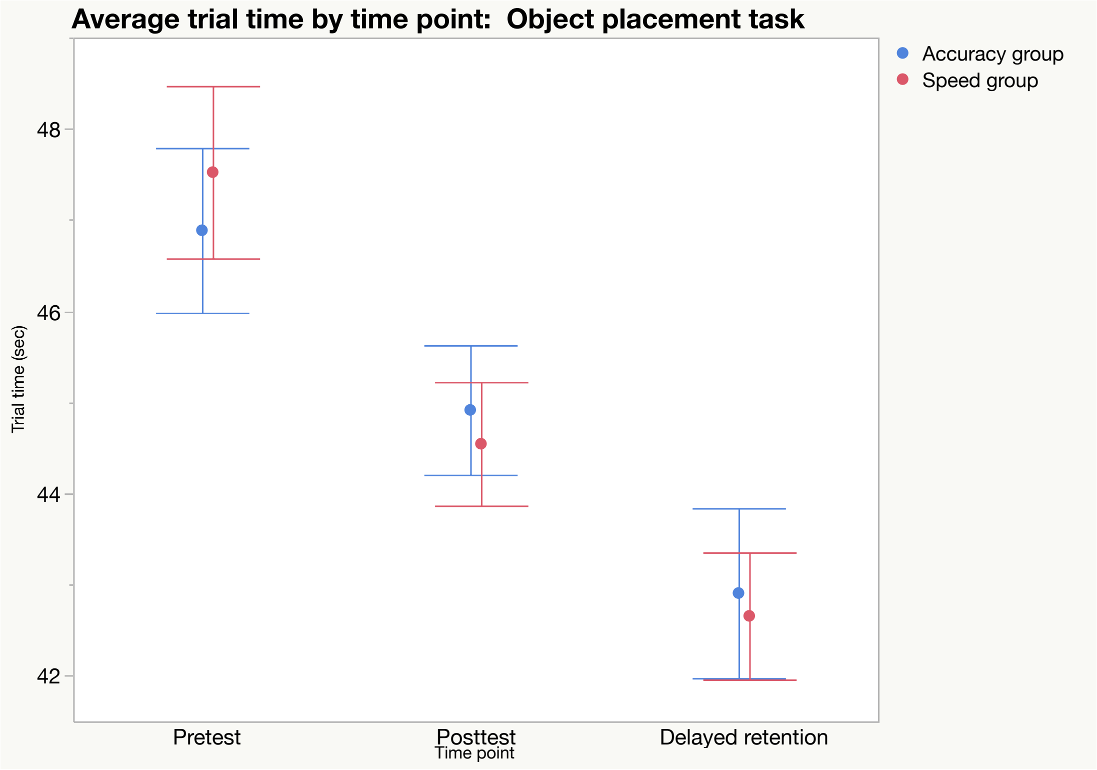

Figure 2.7: Average trial time by time point: Object placement task

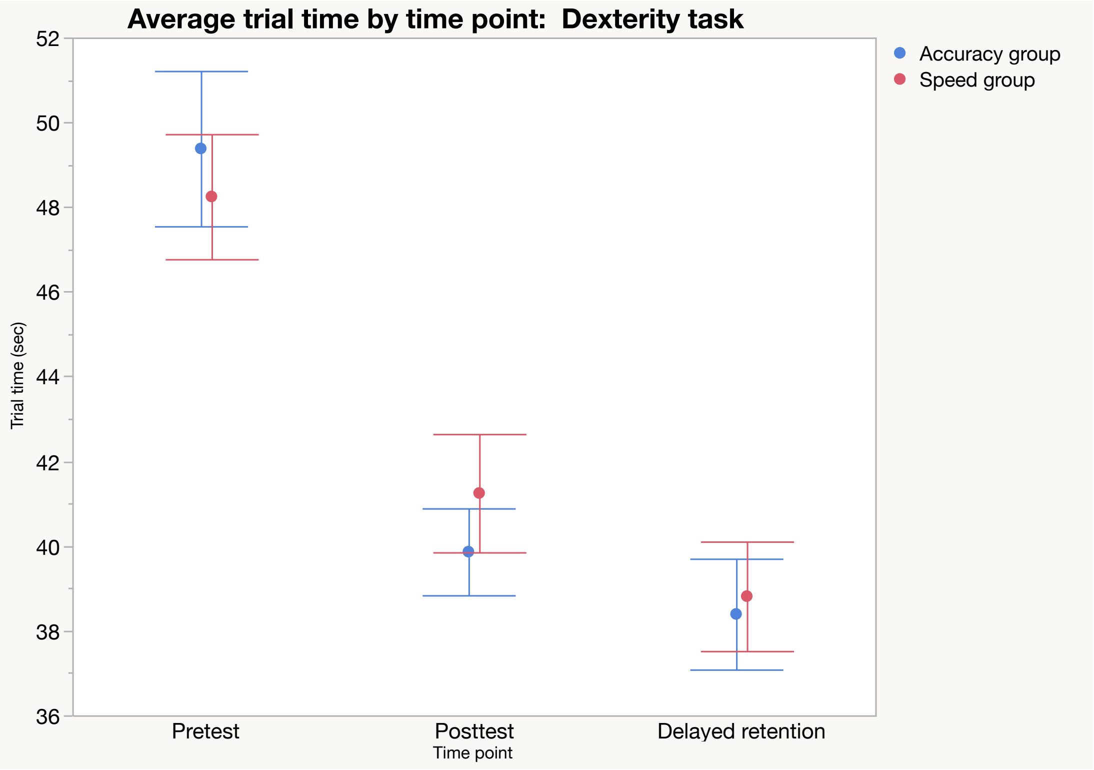

Figure 2.8: Average trial time by time point: Dexterity task

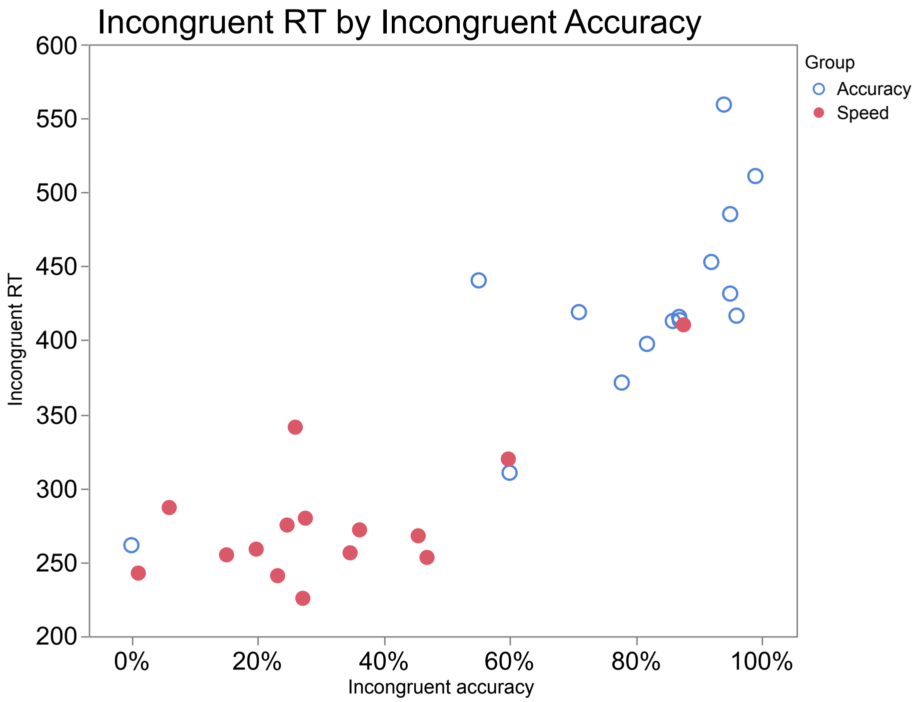

Figure 2.9: Individual cognitive task performance: Incongruent reaction time by incongruent accuracy

Table 2.3: Reclassified participants according to cognitive task performance

Participant #	Original Group	% correct (incongruent)	Av. RT (incongruent)	Outcome
2	Accuracy	0	261.54	Switched to speed group
23	Accuracy	60	310.50	Switched to speed group
26	Accuracy	55.1	440.49	Switched to speed group
29	Speed	87.6	410.47	Switched to Accuracy group

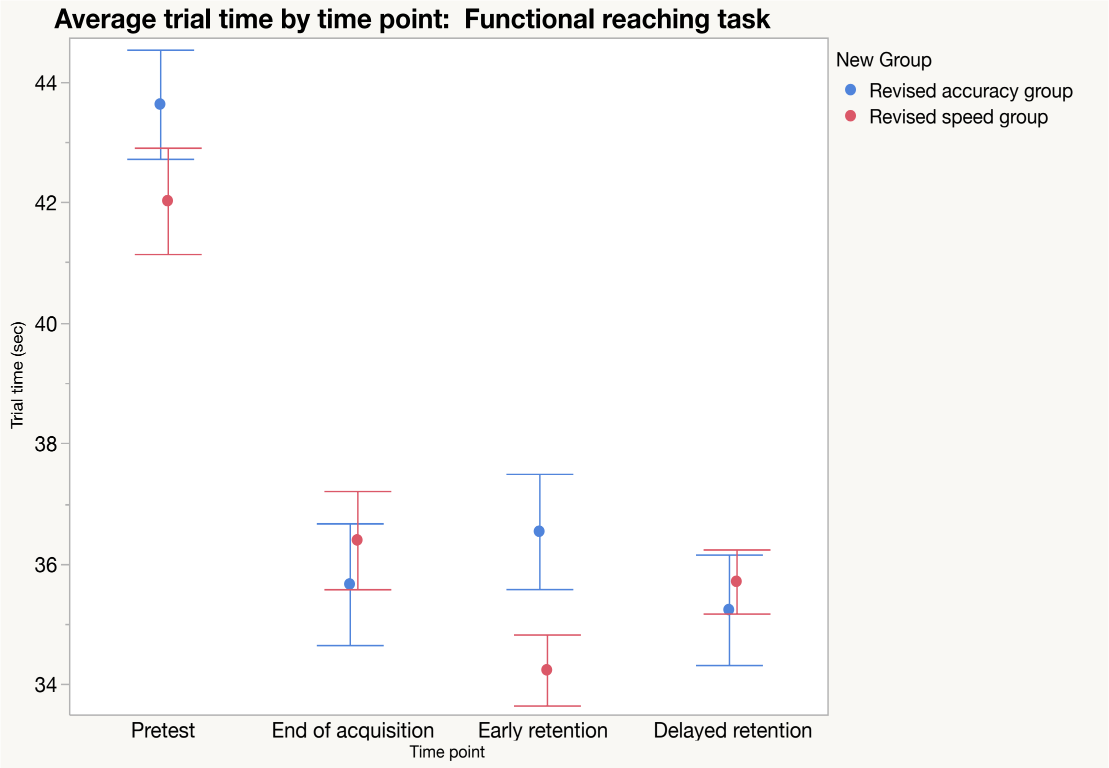

Figure 2.10: Average trial time by time point: Functional reaching task (revised groups)

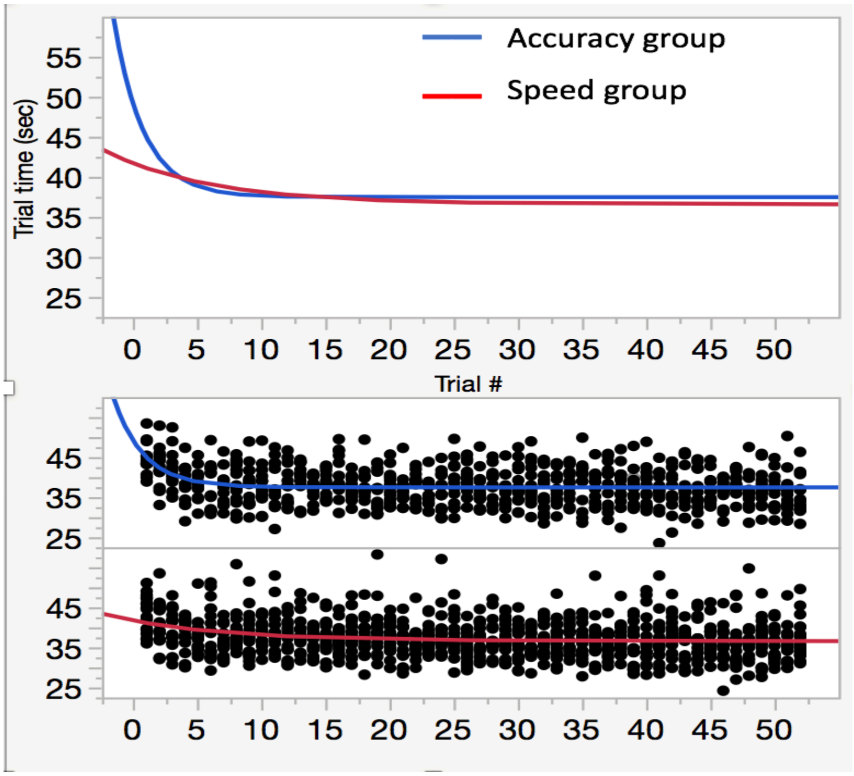

Figure 2.11: Rate of acquisition by group (revised) as determined by the exponential decay function

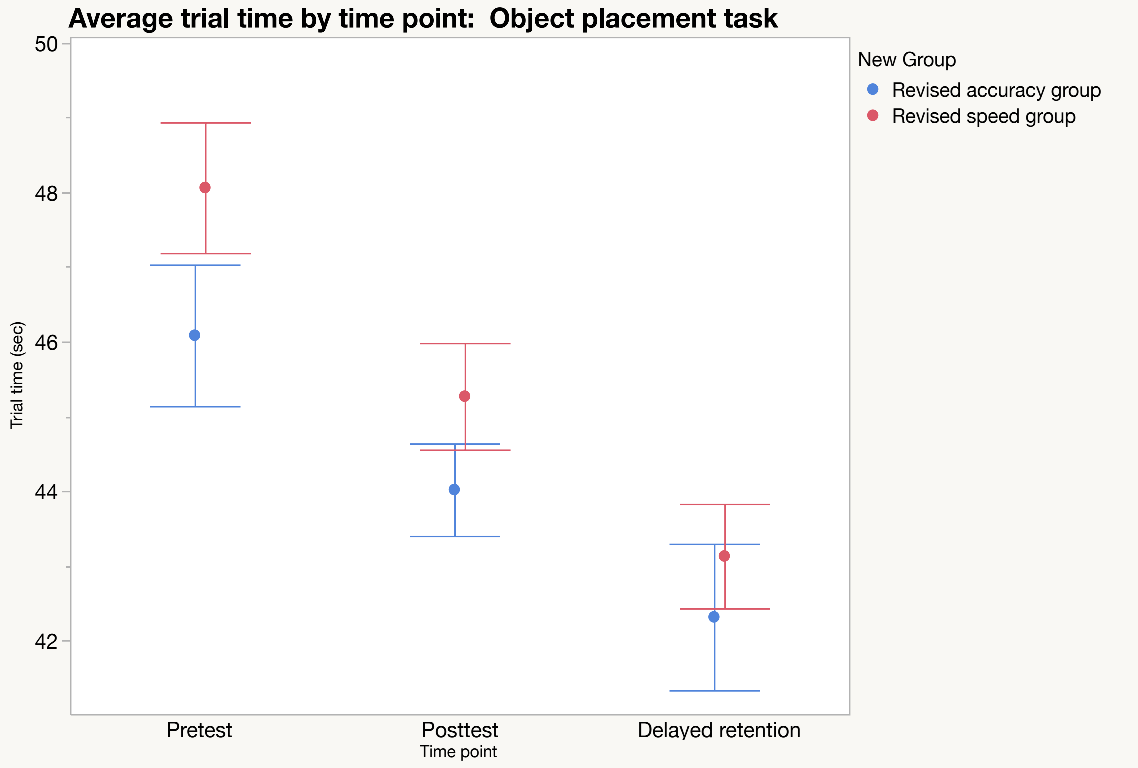

Figure 2.12: Average trial time by time point: Object placement task (revised group)

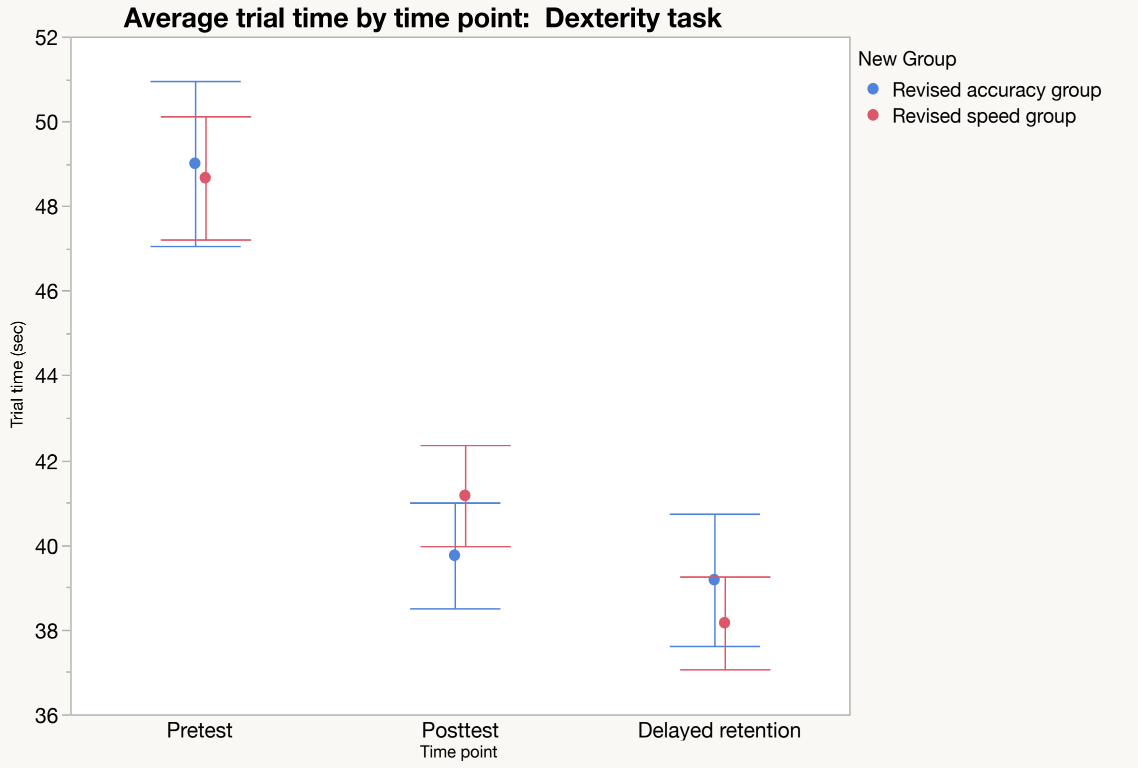

Figure 2.13: Average trial time by time point: Dexterity task (revised group)

CHAPTER 3

EXPLORING THE LIMITS OF TRANSFER

Abstract

Training on one task resulting in an improvement on another is known as motor skill transfer. Using functional tasks to assess motor skill transfer is important because the tasks are relevant and depict tasks that are performed on a daily basis. However, the prevalence and extent of transfer from one functional task to another functional task is not clear.

The purposes of the current study were to test if training on an established functional reaching task transfers to two functional tasks that were not trained (one with many similarities to the trained task and one with few similarities to the trained task) and to test the persistence of the transfer effect.

Two groups of healthy young adults participated in the study protocol. The training group trained on the functional reaching task while the no-training group rested. Performance on two other untrained functional upper extremity motor tasks were assessed before, immediately after training/rest, and one week after training/rest.

Only the training group improved on the functional reaching task suggesting an effect of training. There was no between group difference in amount of improvement for both of the transfer tasks, suggesting that training on the functional reaching task does not

transfer to the other functional upper extremity tasks.

These results should be interpreted cautiously, as participants performed so many repetitions of the transfer tasks throughout the study protocol that they experienced a learning effect merely by performing the transfer tasks during test trials. Furthermore, participants had normal neuromuscular systems and the transfer tasks were not completely novel; therefore, improvement on each task was small. Ultimately, the learning that was fostered by the testing conditions may have eliminated our ability to adequately detect a transfer effect.

Introduction

Motor skill learning occurs throughout the lifespan as humans encounter new tasks that require new movement patterns. It is important to be able to transfer previously learned skills to new tasks because it is impossible to practice for each and every motor task that one may encounter. Generally speaking, this process, termed *motor skill transfer*, occurs whenever training on one motor task results in an improvement on an untrained task[1].

Literature suggests that motor skill transfer may occur in a neurologically intact population. However, the task characteristics or the conditions of practice have been difficult to define and observe; therefore, the limitations and possibilities of motor skill transfer are unclear. There has been a long-standing perception that the amount of transfer is dependent on the degree of similarity between the trained task and the transfer task[1-7]. However, literature appears to suggest equivocal findings. The trained task and the transfer task in visuomotor adaptation studies often share very similar characteristics. They are generally performed in similar workspaces[8,9], with similar sets of muscles and joint movements[10-12], and are measured in the same units[13,14]. Despite these highly-controlled conditions, transfer of training is only partial, at best[15-17]. On the other hand, results from clinical observations show robust improvements on tests that systematically measure the ability to move the arm and hand following training on tasks that differed substantially from the items included in the test[18-23]. While training variability may be a driving factor in this transfer[24-26], these results provide contradictory evidence to support the importance of task similarity in transfer.

Further, the uncertainty and ambiguous results of motor skill transfer might be due to the fact that motor skill transfer is defined in numerous ways. Some studies define motor skill transfer as improvement on some variation of the trained task. One example of this is a study in which participants who trained on a point-to-point reaching task with a 30-degree angular force were able to transfer that learning to reaching to other degrees of rotation[27]. A second way to define motor skill transfer is the ability to transfer learning from a trained effector to an untrained effector. Examples of this include studies in which the transfer task is essentially the same as the trained task, but is tested on an untrained limb, providing evidence that transfer can occur from hand-to-hand[28-31], foot-to-foot[32-34], or from hand-to-foot[35]. Lastly, and discussed above, a third way to define motor skill transfer is as improvement on an untrained task following training on several different therapist-selected tasks. In this example, the "untrained tasks" are often items on an impairment-based outcome measure (e.g., Fugl Meyer).

Despite the different paradigms used to investigate transfer, collectively, results have provided little insight into a definitive direction of study. Therefore, research should focus on assessing transfer to tasks that are relevant, salient, and serve a practical function in daily life. Such *functional tasks* are composed of naturalistic movements in which the movements are purposeful and made up of several sub-movements, not unlike tasks that are performed during one's daily routine[36-38]. This idea of using functional tasks to assess transfer is compelling because it connects experimental research to more relevant real-world conditions, and the tasks are more meaningful (and less contrived) to participants than many lab-based experimental motor tasks used in research. Although there is no literature to suggest that the neural mechanisms of transfer are any different when using functional tasks, their relevancy provides a reason to delve deeper into understanding the transfer that occurs in those tasks.

It is less common to find studies that define transfer as improvement on an untrained functional task following training on a different functional task that uses the same effector. Cherry et al.[39] found that training on a stability platform balance task did not transfer to an untrained single leg stance task. Contrastingly though, Schaefer and Lang[38] (2012) showed that inter-functional task transfer did occur between a functional reaching task and a dexterity task. There is no clear indication why the two studies found conflicting results. While both studies incorporated functional tasks, the differences between the tasks used in the two studies were vast. In Cherry's study[39], both the trained and untrained tasks were functional lower extremity gross motor tasks. There were clear differences between the trained and untrained task, but the two tasks shared a similar goal (i.e., maintaining balance). In Schaefer and Lang's study[38], the trained and untrained tasks were both functional upper extremity fine motor tasks, but they incorporated very different spatiotemporal characteristics from one another, while also having different task goals.

These contradictions leave us wondering whether the amount of transfer that occurs depends on the effector used and on whether we test fine or gross motor tasks. The results of these studies raise the question: Is the similarity of the tasks' goals and the similarity of the spatiotemporal characteristics of the tasks variably important, depending on the effector tested and/or whether fine versus gross motor tasks are tested?

While Schaefer and Lang's results suggest that transfer can occur from one functional task to another, further investigation is warranted. Their study utilized a single-session design and measured transfer to a task with very few similarities between the trained task and the transfer task. While their results should not be considered definitive, their study has provided a foundation to further explore transfer between functional tasks. Using this foundation, the current study provides a platform to investigate whether, within upper extremity fine motor tasks, transfer can also occur between two functional tasks with similar characteristics.

Therefore, in an effort to expand on Schaefer and Lang's (2012) study, the purposes of this study were threefold. 1) to determine if Schaefer and Lang's results of transfer of training from a functional reaching task to a dexterity task (with few similarities to the trained task) can be replicated, 2) to determine if training on the functional reaching task transfers to another functional task (with many similarities to the trained task), and 3) to determine if the effect of transfer persists up to one week following training.

If Schaefer and Lang's results of transfer from the functional reaching task to the dexterity task can be replicated, it will provide further evidence that transfer between functional tasks does occur. Assessing transfer from the established functional reaching task to another functional task (with many similarities to the trained task) will allow further investigation into the effects of task similarity. And finally, assessment of motor skill transfer one week post training will provide insight into the persistence of the transfer effect, if in fact an effect is present.

Methods

Participants

Thirty-nine adults (mean+/- SD age: 25.8 +/- 3.5 years, 27 males and 12 females) participated in this study. All participants reported no neurological or musculoskeletal conditions and hand dominance was determined based on self-report. Informed consent was obtained prior to participation. This study was approved by a university Institutional Review Board prior to enrollment.

Figure 3.1 illustrates the study design. Two groups of participants were recruited separately: a training group and a no-training group. Baseline performance was assessed by having all participants perform two trials of all three motor tasks. The trained motor task was a functional reaching task. The first of two transfer tasks was an object placement task that simulated sorting. This task shared many similarities to the trained task. The second transfer task was a dexterity task that simulated dressing. This task shared few similarities to the trained task. The training group then completed 50 trials of the functional reaching task. In the no-training group, instead of training, participants rested for 70 minutes (the average time it took the training group to train on the task). After completion of the last trial or the end of the rest period, all participants then completed 2 additional trials of each transfer task (posttest). All participants returned on day 2 to complete two trials of the functional reaching task (early retention) and again on day 8 to complete 2 trials of all three tasks (delayed retention). The order of the motor tasks during testing sessions was randomized using a counterbalance technique for each group.

The trained task

Functional reaching task. This task required multi-joint reaching and tool use, and has been adapted from the simulated feeding subset of the Jebsen Hand Function Test, used clinically to measure hand function in activities of daily living[40]. We have previously developed and used this task (see Figure 3.2) in healthy young adults[38], adults with chronic post-stroke hemiparesis[41], and non-demented older adults[42,43] and have validated this task against the 'gold standard' of point-to-point reaching[44].

On the administrator's verbal cue "go", participants were required to spoon raw kidney beans from a central, proximal "start" cup to 3 distal "target" cups with their non-dominant hand as fast as possible. The 3 target cups (9.5 centimeters in diameter) were secured to a board radially at 45 degrees, 90 degrees, and 135 degrees at a distance of 16 centimeters from the "start" cup, which was placed along the participant's midline. During each trial, participants first picked up the spoon and then proceeded to place beans from the start cup to the ipsilateral cup (in relation to the non-dominant hand), then to the center cup, and finally to the contralateral cup. This sequence was repeated five times to complete the trial, therefore each trial consisted of 15 repetitions. Trial time was stopped as the spoon was replaced at its starting position (5 centimeters lateral to the start cup). The time it took to complete 15 repetitions ("trial time") was the measure of performance with faster times indicating better performance. All trials were timed via stopwatch to the nearest millisecond. Participants were given no explicit feedback about their performance.

Transfer tasks

Object placement task (with many similarities to the trained task). This task required multi-joint reaching and fine motor skill and has been adapted from the flip cards subsection of the Wolf Motor Function Test[45]. This task required participants to move a standard playing card (9 cm x 9 cm) with their non-dominant hand from a central, proximal "start" box to three distal target boxes as fast as possible (see Figure 3.3). The boxes (9 cm X 9 cm X 2.5 cm) were secured to a board with 3 boxes secured radially at 45 degrees, 90 degrees, and 135 degrees, respectively, all 16 centimeters from the start box. The start box was 15 cm in front of the seated participant at midline with the cards face down. One repetition of the task consisted of placing one card at a time, face up, from the start box to a target box with the non-dominant hand. During each trial, participants first moved to the ipsilateral target box, next to the center target box, and then to the contralateral box, relative to the hand used. This sequence was repeated ten times to complete each trial. The participant started with their non-dominant hand to the side of the start box. Each trial began on the administrator's verbal "go" and ended when the last card came to rest in the target box. The time it took to complete the 30 repetitions ("trial time") was the measure of performance, with faster times indicating better performance. All trials were timed via stopwatch to the nearest millisecond. Participants were given no explicit feedback about their performance.

Dexterity task (with few similarities to the trained task). This task required fine motor skill and has been adapted from the applied dexterity subset of the Arthritis Hand Function Test, a clinical measure of hand function with real-world objects[46]. The particular item adapted involves fastening buttons with one hand. Like the functional reaching task, we have previously tested this motor task (see Figure 3.4) in healthy young adults[38], and adults with chronic post-stroke hemiparesis[41].

The task consisted of a board with 10 buttons (2.5 cm diameter) that were sewn 5.3 cm apart vertically to a piece of heavyweight linen fabric, 3.0 cm from the edge. The buttonholes were 3.7 cm in length. Both pieces of fabric were double-layered (2-ply) and were secured to a wooden board (61 cm x 34 cm), with the placket centered in line with the participant's non-dominant shoulder, 15 cm in front of them. The button-side of the fabric was folded onto the board, while the button-side of the fabric was unfolded on the non-dominant to midline onto the table prior to each trial. Fabric weight (65.6 g/m2) and thread count (15 per cm) were measured according to ASTM Test Methods D3776-96 and D3775-98, respectively (ASTM, 2001 a, b).

Participants were instructed to fasten each button sequentially, using their non-dominant hand starting at the button furthest from them. Upon successful fastening of the last button, participants were then instructed to unfasten each button in reverse order. Prior to each trial, participants sat with their non-dominant hand in their lap. Each trial began as the administrator gave a verbal "go" and ended when the last button was unfastened. The time it took to complete the task ("trial time") was the measure of performance, with faster times indicating better performance. All trials were timed via stopwatch to the nearest millisecond. Participants were given no explicit feedback about their performance. This task was selected because of its dissimilar spatiotemporal characteristics compared to that of the functional reaching task.

Data analyses

JMP 13.0 was used for all statistical analyses and our criterion for statistical significance was set at alpha= .05. The Shapiro-Wilk test was used to verify normal distribution for each variable.

Though data were not normally distributed (W=.969; p<.0001), parametric tests were used due to a mixed model's robust nature[47]. To test the effect of training on transfer of motor performance where "trial time" was the dependent variable, we used a 3 X 2 mixed model ANOVA with time point (pretest vs. posttest vs. delayed retention) as the within-subjects factor and group (training vs. no-training) was the between-subjects factor. Separate ANOVAs were performed for each motor task. Simple main effects were explored using Post hoc Tukey-Kramer Honestly Significant Difference (HSD) tests.

Results

Participant characteristics

A total of 39 subjects completed the priming protocol prior to the motor training/no training period (training group=30, no-training group=9). The groups were not significantly different in age $t_{(12.8)} = -.68$, p=.506 or sex (p=.693).

Functional reaching task (trained task)

Figure 3.5 shows average group performance on the functional reaching task. There was not a main effect of group $F_{(1, 2.86)} =.329$, p= .608. There was a main effect of time $F_{(2, 230.8)} =25.81$, p<.0001 as well as an interaction between time and group $F_{(2, 230.8)} =6.18$, p= .002. Post-hoc analyses reveal that performance of the no-training group was no different at early retention compared to pretest (p=.381) nor was it different at delayed retention from pretest (p=.539). Performance, however, was faster for the training group at early retention compared to pretest (p<.0001) as well as at delayed retention compared to pretest (p<.0001). As expected, these results indicate that performance improvement on the functional reaching task was dependent on practice.

Object placement task (with many similarities to the trained task)

Figure 3.6 shows group performance on the object placement task. Again, there was a main effect of time $F_{(2, 229.2)}$ =18.73, p<.0001, but no main effect of group $F_{(1, 2.265)}$ =2.409, p=.169. Unlike the trained task, there was no time by group interaction $F_{(2, 229.20)}$ =2.050, p=.131. Post-hoc analyses revealed that across groups, participants were faster at posttest compared to pretest (p<.0001) and at delayed retention compared to pretest (p<.0001). These results suggest that training on the functional reaching task did not benefit performance of the object placement task beyond exposure to the task at pretest.

Dexterity task (with few similarities to the trained task)

Figure 3.7 shows group performance on the dexterity task. There was a main effect of time $F_{(2, 229)}$ =32.23, p<.0001. However, there was not a main effect of group $F_{(1, 1.412)}$ =6.90, p=.169 or an interaction between time and group $F_{(2, 229)}$ =.118, p=.888. Post-hoc analyses revealed that participants were faster at posttest compared to pretest (p<.0001) and at delayed retention compared to pretest (p<.0001). No differences in group or an interaction effect suggest that training on the functional reaching task did not benefit performance of the buttoning task beyond exposure to the task at pretest.

Trial by trial transfer?

The above analyses suggest that the improvement on the object placement task and the dexterity task from pretest to delayed retention in the training group was not due to transfer of training as the no training group demonstrated a similar amount of improvement in both tasks. However, motor performance at each time point consisted of two trials. Perhaps, transfer occurred early in the performance of these tasks, but the culmination of exposure throughout the protocol resulted in learning the tasks due to practice. In order to determine if transfer of skill to each transfer task occurred early in task performance, we plotted average group performance on each trial throughout the protocol (trials 1-6). Due to insufficient power, we chose to only consider descriptive statistics.

For both the object placement task (Figure 3.8) and the dexterity task (Figure 3.9), there appears to be improvement from trial one to trial two in both groups. However, performance does not appear to improve after trial two in either group. Had transfer occurred, we would expect the training group's trial 3, which occurred immediately following the completion of training, to be different than trial 3 of the no-training group. This analysis provides further evidence that transfer did not occur in this study.

Discussion

The purposes of this study were to 1) attempt to replicate Schaefer and Lang's[38] results of transfer between the functional reaching task to the dexterity task (a task with few similarities to the trained task), 2) determine if training on the functional reaching task transfers to another functional task (a task with many similarities to the trained task), and 3) determine if the effect of transfer persists up to one week following training. Results show that the training group improved on the functional reaching task as measured at delayed retention relative to pretest. The no-training group did not improve on the functional reaching task, suggesting that the training group improved on this task due to training. Performance on both transfer tasks yielded no between-group differences, with both groups improving on both transfer tasks at subsequent testing. This indicates that the training group's improvement on each transfer task was not due to motor training transfer, and is contrary to the transfer of training found in Schaefer and Lang's study[38].

Although inconsistent with Schaefer and Lang's results[38], our findings suggest that transfer from one functional task to another does not occur, which is comparable to previous findings from other studies. Winstein et al. (1989)[48] studied the effects of balance retraining on standing balance and locomotor performance. While both were gross motor lower extremity tasks, they differed considerably in task characteristics. Similar to our findings of no effect of transfer from the functional reaching task to dexterity task (task with few similarities to the trained task) in this study, Winstein found that a reduction in standing balance asymmetry (trained task) did not lead to a reduction in limb asymmetry during gait (transfer task). What is somewhat surprising, however, is that we found no transfer from the functional reaching task to the object placement task (a task with many similarities to the trained task). This is contradictory to studies that show transfer occurs, albeit only partially, between variations of an upper extremity task that involve subcomponents of a functional movement (i.e., point-to-point reaching)[15-17].

Because motor skill transfer did not occur in our study, we are unable to make inferences about the effect of task similarity between the trained task and the transfer task. We are also unable to determine the persistence of the transfer effect.

In planning this study, we made several protocol changes that might explain the contradictory results between our study as compared to Schaefer and Lang's[38]. Those changes included lengthening the duration of the study, increasing the number of trials at each testing time, and altering the measurement of performance. We made these changes in an attempt to improve our ability to detect a transfer effect if an effect was in fact present. However, our methodological alterations may have inadvertently caused our participants to perform so many repetitions of the transfer tasks throughout the study protocol that they experienced a learning effect merely by performing the transfer tasks during test trials. Additionally, because participants were healthy young subjects with normal neuromuscular systems, and the transfer tasks were not completely novel, the room for improvement on each task was small[49-51]. Therefore, the learning promoted by the testing conditions may have eliminated our ability to adequately detect a transfer effect. When measuring transfer of training, there may be a fine line between providing enough exposure to assess performance and providing too much exposure that results in learning.

Beyond replicating the results of skill transfer as presented in the Schaefer and Lang study[38], one purpose of this study was to assess the persistence of the transfer effect. To do this, the protocol was extended to one week after training ended. If an effect of transfer was present at posttest, this delayed retention test would have detected whether the effect was resistant to time (one week). Also, it is not uncommon for a training effect that is not evident immediately after training to emerge following a period of rest[52-54]. Therefore, this extended protocol would have allowed us to determine if the transfer effect requires a consolidation period. Due to the extension of the protocol, participants were assessed on each transfer task at pretest, posttest, and delayed retention. As Schaefer and Lang's study[38] was a single-session study design, their participants were only assessed at pretest and posttest. Had this study replicated Schaefer and Lang's results, a transfer effect would have existed at posttest (as it did in their study). Because of our lack of transfer at posttest in the present study, it is clear that the extension of the protocol did not cause the present results to differ from Schaefer and Lang's[38].

There were several methodological changes that resulted in more task exposure for participants in the current study. Schaefer and Lang's study measured performance using one trial of each task at each testing time point. In contrast, the current study measured performance by calculating the average of two trials for each task at each testing time point. This change was intended to improve performance stability, thereby avoiding a warm-up decrement[55-57]. While this goal may have been achieved, the change also resulted in doubling participant exposure to each of the tasks. There was also a difference in how motor performance was measured. Schaefer and Lang held trial time constant throughout their protocol. The dependent variable for both tasks (trained and untrained) was the number of successful repetitions performed in 20 seconds. On average, participants performed 4 repetitions for each task at pretest. The current study, on the other hand, held number of repetitions constant, dependent on task, with trial time as the dependent variable. The rationale for this change was to ensure that each group performed the same number of repetitions of the transfer tasks. This would have allowed us to attribute change over time to *transfer* instead of change being confounded by differences in practice dose between participants and/or groups[58-61]. This discrepancy, and the averaging of two trials at each time point to measure performance, resulted in participants in the current study performing 30, 60, and 40 repetitions of the functional reaching task, the object placement task, and the dexterity task, respectively, at *each* testing time point. These numbers of repetitions stand in sharp contrast to the average of 4 repetitions of each task that were performed at pretest in the Schaefer and Lang study.

Collectively, these differences likely resulted in the participants experiencing a learning effect in this current study, as a result of performing so many repetitions at pretest. Therefore, our ability to determine if training on the functional reaching task transfers to other untrained functional tasks was minimized. One way to combat this problem in the future is to use kinematic data as a means of measuring performance changes that occur *within* a trial[62,63]. This technique would have allowed us to assess change in performance across repetitions, which might have helped determine the dose that results in performance assessment versus learning as a result of practice. Beyond time-based measurements, kinematic data could provide insight into other changes (dependent variables) that may occur as a result of practice (e.g., total movement distance, peak velocities, angular upper extremity displacement, etc.). The change in these variables over time can provide insight into the central factors of sensorimotor control and learning such as spatio-temporal coordination and may provide evidence of learning earlier than a time variable.

This problem of overexposure to tasks may have been compounded by the tasks themselves. Motor learning research over the years has used a number of different motor tasks in order to better understand the motor learning process. These tasks have ranged from a simple, non-skilled isolated thumb activity[64] to tasks incorporating multiple joints and multiple degrees of freedom[65-67]. Using functional motor tasks to probe motor skill transfer, as we have done in this study, has advantages and disadvantages. Functional motor tasks simulate activities that one may encounter each and every day[36-38]. This familiarity may add relevance to the task and therefore promote learning[68]. These tasks can also often be created quickly using items that are acquired inexpensively. Another advantage of using functional tasks is that they are applicable to any population. Often, the ease with which these tasks can be transported from one location to another allows for assessment or training in a clinical or community setting.

Despite the benefits of using tasks that simulate functional activities, there are disadvantages as well. In order to measure learning, or the relatively permanent change in performance due to practice[1], a motor task must be under-learned at onset of the study[38]. It is difficult to find a functional task that is relevant to participants' daily lives, yet is under-learned. In an attempt to solve this problem, the current study required that the participant's use their non-dominant upper extremity to perform all trials of all tasks. The fact that the participants' performance did improve with practice confirms that performance improvement was still possible on these tasks. However, these tasks were familiar to the participants. While this familiarity keeps the participants interested, it is detrimental to assessing change in performance due to practice[49-51]. To illustrate this point, consider the learning process as a whole. When a task is completely novel, the rules and the goals of the task are not fully understood. Thus, early exposure requires a considerable amount of cognitive resources as the learner attends to the step-by-step execution of the task as a means of matching the motor outcome to the task goal. As familiarity improves, cognitive resources can be delegated outside the task[69]. The time it takes to progress through this process is dependent on the familiarity of the motor task and the learner. If those are held constant, however, a task that is familiar to the learner can often be learned faster (i.e., with less exposure) than a task that is unfamiliar, thereby resulting in an unwanted ceiling effect.

This response may make it difficult to assess transfer because exposure at pretest may result in task learning even if the task is under-learned to begin with (as was the case in this study).

Due to the participant's intact neuromuscular system, in combination with task familiarity, learning of all the tasks occurred very rapidly (even before the intervention portion of the protocol began), making inferences about motor skill transfer impossible in this study. Had individuals with motor impairment been included[70-72], this study protocol may have allowed testing of our motor skill transfer hypotheses. Although the tasks would still be familiar to an impaired individual, compromised motor abilities would result in a sense of novelty as the participant attempted to relearn the coordinated movement patterns required to successfully perform the tasks with their changed neural networks. This process would likely occur at a much slower rate than the learning that occurs in people with healthy neuromuscular systems[70-76].

Limited statistical power because of the modest sample size (N=39) may have played a role in limiting the significance of some of the statistical comparisons that were conducted. A post-hoc analysis looking at the interaction at delayed retention revealed effect sizes for the object placement task and the dexterity task as .51 and .22, respectively. Despite the low power (β=.26 and .09, object placement task and dexterity task, respectively), these modest effect sizes indicate that our null effect may have been a product of our small sample size.

Conclusions and future research

The overall goal of this study was to provide further understanding of motor skill transfer between distinct functional tasks. The results of this study showed that training on the functional reaching task did not transfer to the object placement or the dexterity task, suggesting that inter-task transfer of motor skill training does not occur. However, jumping to such a conclusion may be premature as there were a number of factors within our study that may have distorted our results.

Understanding motor skill transfer and identifying ways to maximize it is critical. Assessing transfer in a variety of ways, including with the use of functional tasks, will allow for a better understanding of *what* is transferring and to what extent. No matter the paradigm used, careful consideration must be placed in designing these studies in order to see an effect if such an effect exists, instead of measuring learning that may occur due to overexposure.

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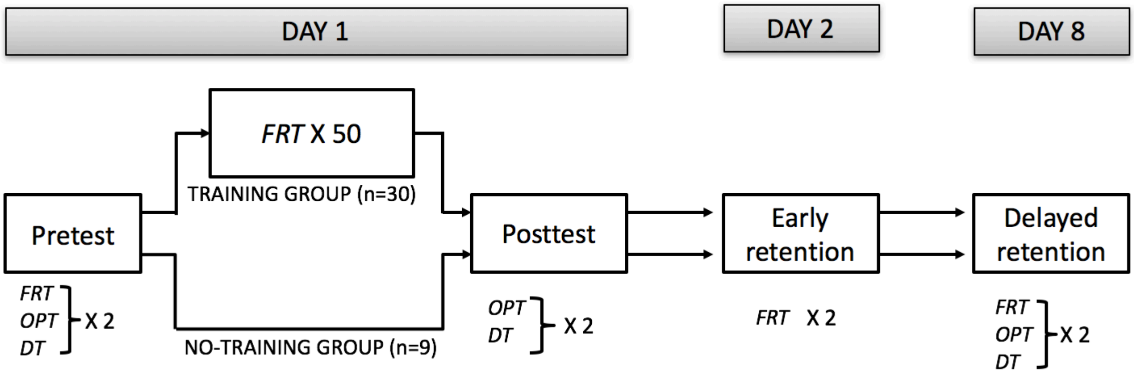

FRT: Functional reaching task (trained task)
OPT: Object placement task (transfer task)
DT: Dexterity task (transfer task)

Figure 3.1: Study activity diagram

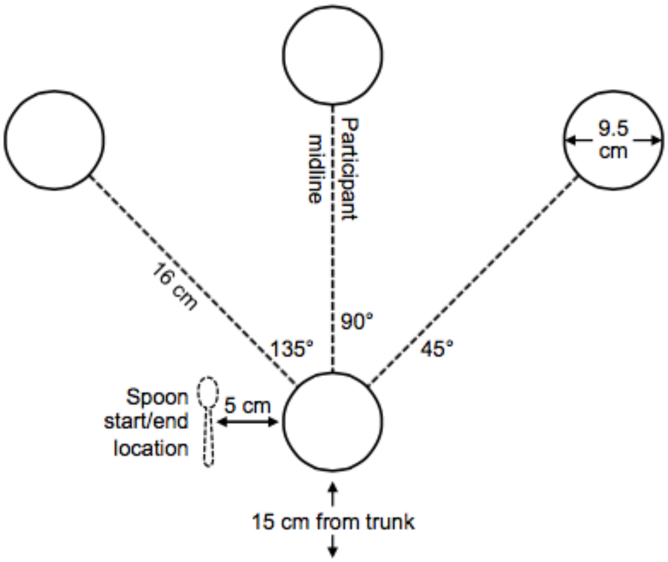

Figure 3.2: Functional reaching task

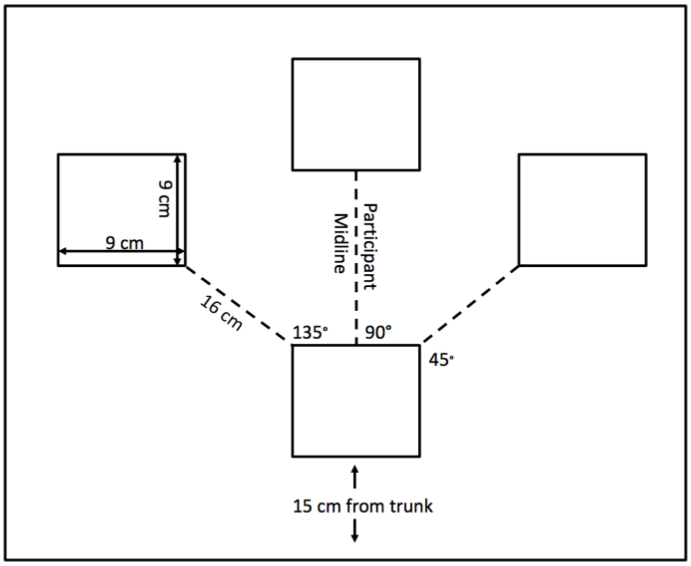

Figure 3.3: Object placement task

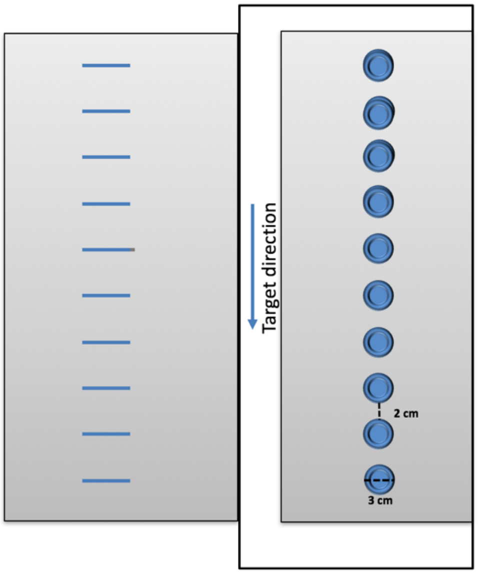

Figure 3.4: Dexterity task

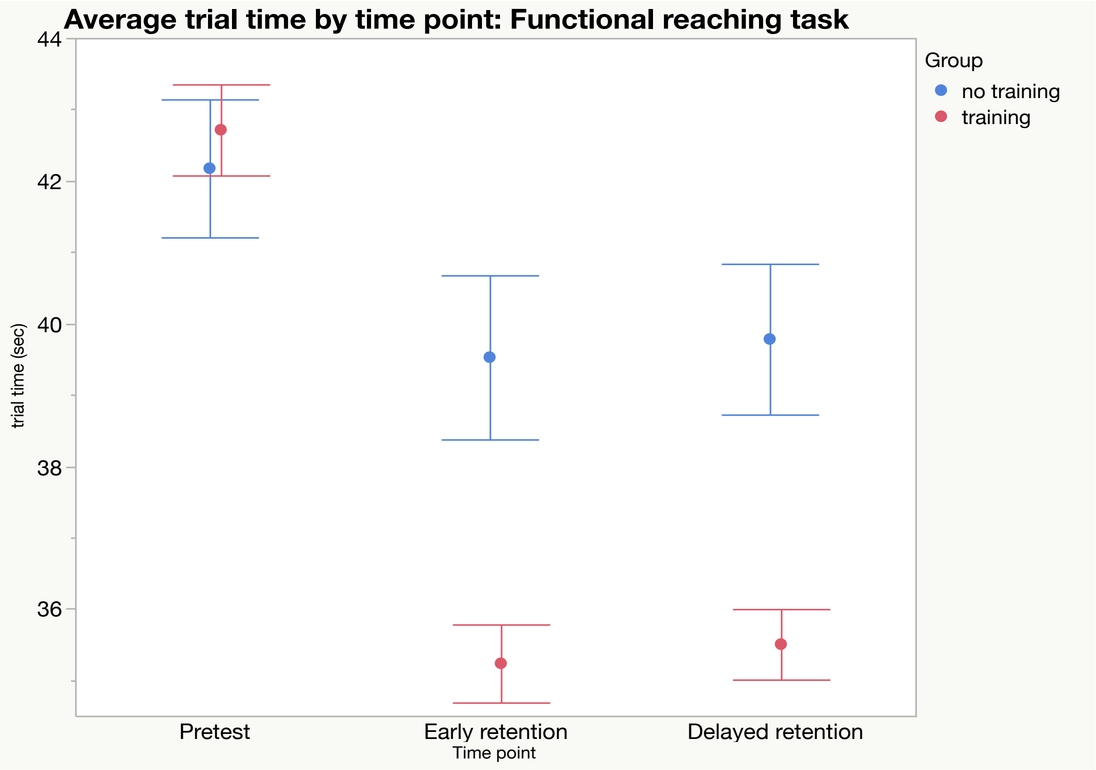

Figure 3.5: Average trial time by time point: Functional reaching task

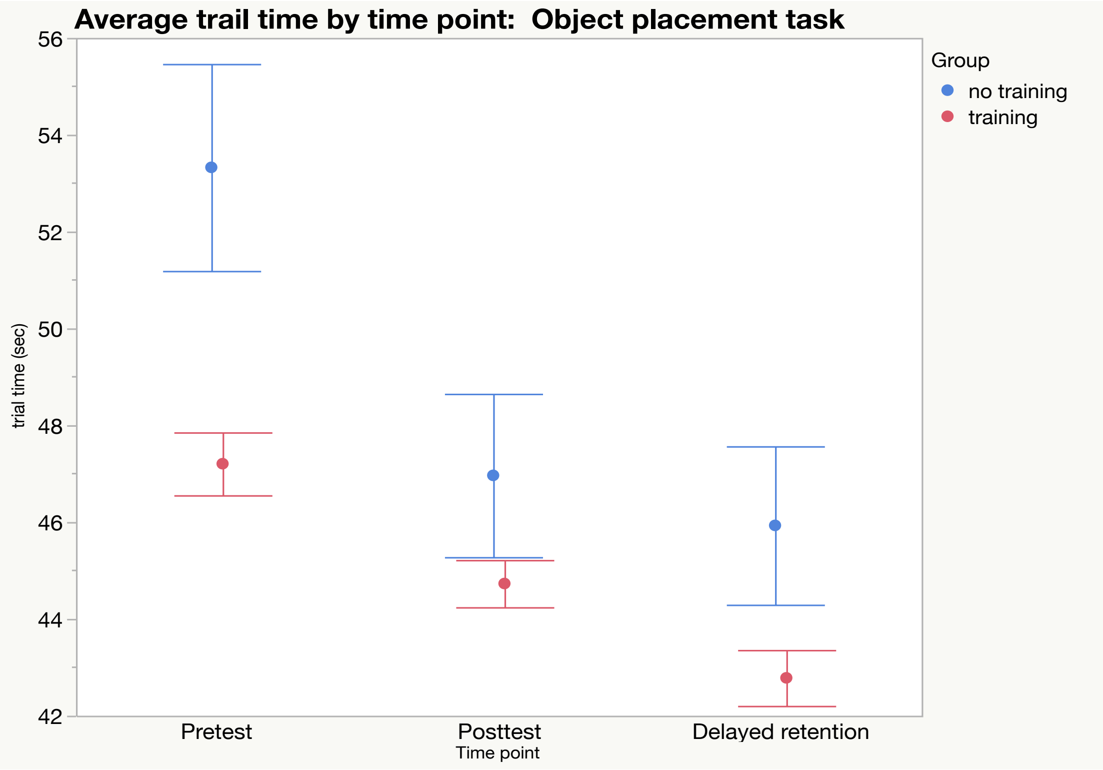

Figure 3.6: Average trial time by time point: Object placement task

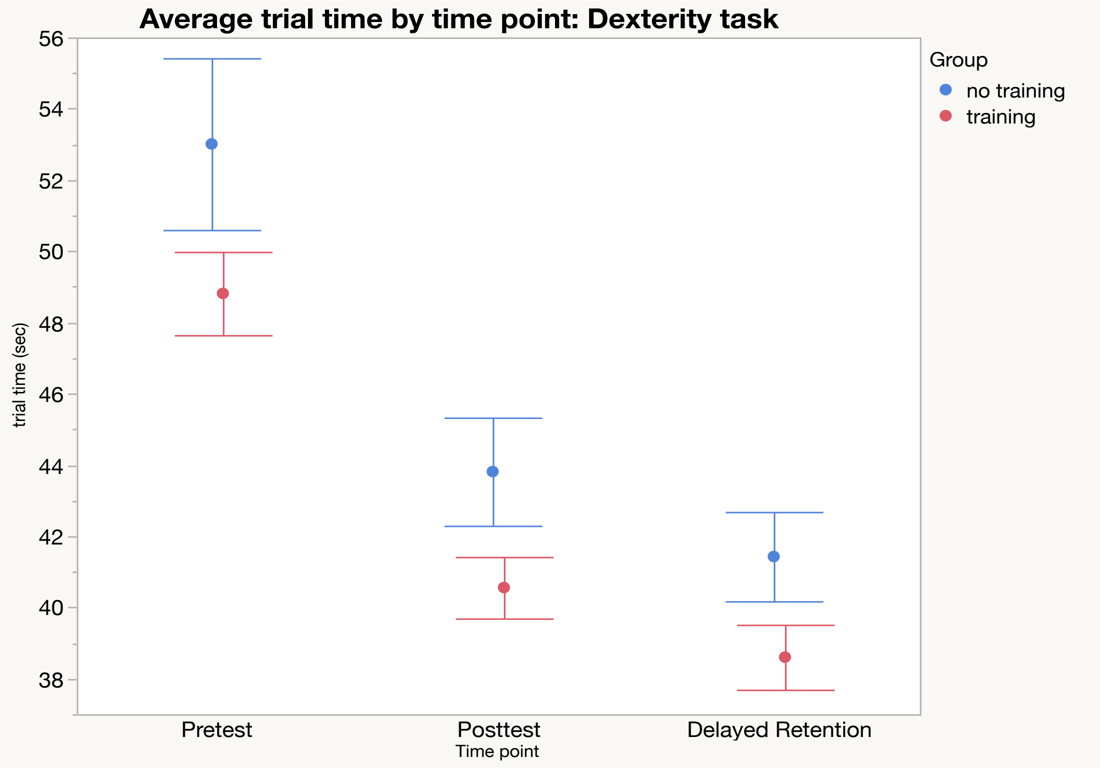

Figure 3.7: Average trial time by time point: Dexterity task

Figure 3.8: Average trial time by trial number: Object placement task

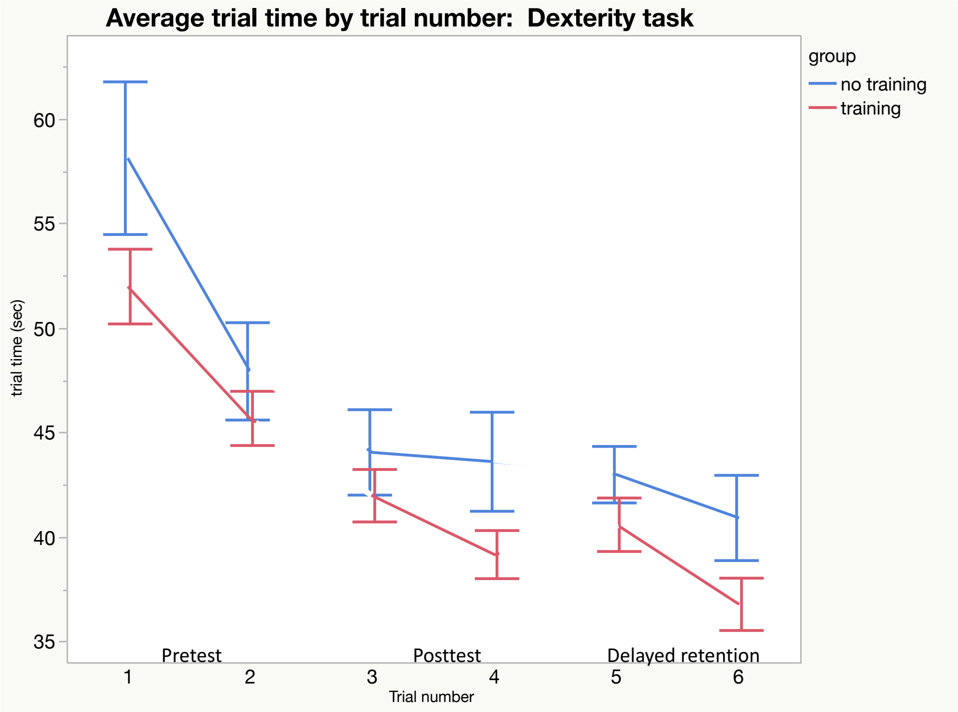

Figure 3.9: Average trial time by trial number: Dexterity task

CHAPTER 4

GENERAL DISCUSSION

Learning and relearning of motor skills is critical across the lifespan, whether an individual is learning a work-related task in order to provide for his/her family or relearning the basic self-care skills needed for independent living following a stroke. Until recently, research has focused on identifying practice variants that optimize learning of a motor skill when applied *during* the practice phase[1-5]. A newer approach attempts to make a neural system more effective *during* practice by preparing it *prior to* practice[6]. This approach, known as priming, involves administering an intervention prior to practicing the motor task of interest[6]. While this research is still in its infancy, literature suggests that this approach may be a viable option for augmenting learning of a motor task[7-11]. The mechanism by which priming occurs depends on the intervention used. Fundamentally, each priming mechanism creates a temporary change in the state of the brain, making it more conducive to learning[6]. While the majority of priming interventions thus far have targeted the motor system, we chose to target a different mechanism essential motor learning: error detection and correction.

Learning from errors is one of the most basic principles of motor learning[12-15]. The process of learning involves updating motor commands through repetitive exposure to motor errors, and gradually reducing the errors as the movement becomes refined[16,17].

When an error occurs during task execution, the error detection system identifies a mismatch between the intended action and the executed action. This error detection process can be measured via EEG, specifically through the ERN component[18,19]. Error detection processing is more pronounced under conditions that emphasize accuracy. This activation of the error detection system within the ACC is not only evident on EEG, but is also seen behaviorally[18-20]. Performance is slower and more accurate on the trial following a trial in which an error is made and detected, indicating that individuals are paying more attention to their performance by slowing down to ensure that they do not make another error.

Due to the importance of error detection and correction in motor learning, the authors hypothesized that priming the error detection system immediately prior to task training might improve learning of that task. Priming the error detection system might make error detection easier and faster than if the system were not primed. This ultimately might result in learning at a greater rate or to a greater extent. If successful, priming error detection may prove to effectively improve learning of new skills (or relearning of previously-learned motor skills) in rehabilitation. Therefore, the purpose of the preceding studies was to determine, in healthy young adults, if performing a task that amplified error detection immediately prior to motor training would augment learning of the trained motor task.

We began by performing a study to determine whether priming error detection would augment learning of a functional reaching task[21-23] when measured during the acquisition phase, one day after training, and one week after training. We also sought to determine if priming error detection would improve motor skill transfer from the trained task to other untrained tasks. We hypothesized that the rate of acquisition and the amount learned for both the trained task and the transfer tasks would be better in the group that performed the error detection prime prior to motor training. Results of this study demonstrated that perhaps amplifying error detection just prior to training does increase the rate, but not the amount, of motor task learning. Both groups (accuracy and speed) learned the functional reaching task to a similar degree and at a similar rate in our initial analyses. However, in a subsequent analysis in which we reclassified participants by their adherence to the speed or accuracy instructions, our data showed that the reclassified accuracy group learned the task at a faster rate than did those in the reclassified speed group. Additionally, both groups improved on the transfer (i.e., untrained) tasks, however, there were no differences between groups. Future research should test whether the behavioral consequences of error can be elicited in tasks other than the cognitive task used in this study and the extent to which behavioral consequences of error can carry over into other domains.

As there were no priming effects, but an improvement in performance on both the transfer (i.e., untrained) tasks in the first experiment, the second experiment sought to determine if the improvements observed in the transfer tasks during experiment I were due to transfer of training from the functional reaching task, or if improvements were instead due to a test-retest learning effect resulting from the testing protocol. Because there were no differences in transfer task performance between the priming groups (accuracy and speed) during experiment I, we combined the groups to form a “training” group for experiment II. We then recruited another group as the “no-training” group. This latter group performed the experiment I testing protocol except they did not train on the functional reaching task. The authors hypothesized that the no training group would not improve on the transfer tasks as much as the training group. If transfer tasks improvements were only observed in the trained group, it could be concluded that the trained group's improvement was due to an effect of motor skill transfer from the trained task. However, results indicated that the no training group improved on both transfer tasks, and that the improvement was similar to that achieved by the training group. Taken together, these results suggest that the training group improved on the transfer tasks because they were exposed to the transfer tasks multiple times as part of the testing protocol, not because of motor skill transfer. Therefore, these results suggest that inter-task transfer of motor skill does not occur in these tasks. Future research should determine the dose at which exposure results in learning of the motor tasks used in these experiments.

Although error-based learning and error detection are rooted in research, the joint application of using error detection to prime a subsequent motor task is a novel undertaking. Therefore, the authors created a series of experiments intended to allow the hypotheses to be optimally tested. However, in retrospect, the combination of many factors including *study design*, *motor tasks*, and the *sampled population* might not have provided a platform to best test the hypotheses, after all.

Study design

The chosen study design was selected to test the effects of priming error detection on motor learning of the trained task and the transfer (untrained) tasks, over the period of one week (delayed retention). While performance at delayed retention was our primary outcome of interest, we also assessed motor performance at other time points throughout the protocol. This was done by taking the average of two trials at each time point. While this reoccurring exposure likely did not compromise our testing of the trained task (experiment I), it most likely created a problem assessing transfer of training to the transfer tasks (experiment II).

A goal of experiment II was to expand on a previous study[21] in which training on the functional reaching task transferred to improved performance on the dexterity task in a single-session design. Our study protocol for experiment II differed in order to assess the effects of transfer up to one week post-training, and also to maximize the transfer effect if, in fact, an effect was present. These differences in study protocol between our current experiment and the original study[21] unintentionally resulted in a large discrepancy in the amount of transfer task practice performed during the testing sessions in our experiment, compared to the original study. Therefore, our results, which suggest that transfer of training does not occur between distinct functional tasks, should be interpreted cautiously. Our protocol may have contributed to providing participants with sufficient repetitions of each transfer task throughout the study protocol to create a learning effect just from repeated exposure to the transfer tasks at each testing time point.

Motor tasks

The motor tasks used in these studies were selected because of their relationship to subsets of clinical assessments used to objectively assess hand and arm function for activities of daily living[24-26]. These tasks simulate activities that one may encounter each and every day[21,27,28]. This familiarity can have benefits, however, it appeared to be problematic in our studies.

In experiment I, the participant’s familiarity with the functional reaching task may have limited our ability to detect any benefit of priming error detection. The premise of the prime was to amplify error detection for the benefit of the subsequent motor task. However, error-based learning primarily occurs in the early phases of learning when the neural connections underlying performance are being developed. It is likely that task familiarity allowed participants to move through the learning process very rapidly[29-31], and resulted in stable performance around trial 5 during the acquisition phase. While improvements continued to occur, the refined performance is thought to be driven by errors to a lesser extent[32]. Therefore, the minimal benefits of the error detection prime noted in experiment I may have been attributed to the minimal trials in which error driven learning played a significant role.

It is also likely that task familiarity played a role in the null effects seen in experiment II. While each task was novel in the sense that the participants were unlikely to have ever performed an identical task, the tasks simulated activities that are performed during one's daily routine. Despite performing the tasks with their non-dominant upper extremity and showing that improvement was possible through practice, participants likely started with the basic coordinated movement in their repertoire. Participants' familiarity with the concepts and goals of each task may have caused a rapid learning effect that occurred during the pretest[29-31]. Given this, future studies should consider the implications of task familiarity a priority. When tasks are less familiar, there is more room for learning, thereby increasing the likelihood of identifying any effects of learning augmenters.

Sampled population

While our ultimate goal is to maximize motor skill relearning for individuals following neurological damage, the authors chose to test this paradigm in a neurologically intact sample. Testing a homogenous sample eliminated the difficulty of finding a neurologically impaired sample who could perform our motor tasks given the large heterogeneity of post-stroke hemiparesis. While the neurologically intact sample was relatively easy to collect, their intact motor capabilities presented problems in measuring change in motor performance over time. The problems were multi-focal (as discussed above), however, ultimately our sample learned the motor tasks at a rapid rate, making inferences on the benefit of an error detection prime and the transfer of motor skills difficult. Consequently, assessing the benefit of an error detection prime on learning a motor task in a neurologically impaired population may have been a better test of our hypotheses, after all. Although the tasks would be familiar to this population, their impaired motor abilities would provide a sense of novelty as the participants attempted to relearn the coordinated movement patterns or develop new movement patterns necessary for successful task performance. This process, likely to occur at a much slower rate in those without motor impairments[33-39], may have yielded an altogether different effect from the error detection prime.

Priming the nervous system prior to task practice appears to be a valid method for augmenting motor skill learning. While the results of our study are inconclusive, they provide support that utilizing a naturally occurring error-related response in the ACC may be beneficial for detecting errors and thus augmenting learning of the subsequent task.

In order for an intervention to be a learning augmenter, the mechanisms of the intervention must link closely with the mechanisms of motor learning. Other interventions suggested to augment learning have harnessed neurotrophic factors thought to be responsible for learning or have increased cortical excitation in cortical areas important for learning. Our results suggest that priming interventions may be able to utilize the cognitive aspects of learning as opposed to targeting only the motor components. Despite the differences between these mechanisms and those proposed to occur in our study, a priming intervention is only successful if there is a temporary change in the state of the brain that makes it more conducive to learning[40,41].

Beyond the effect of priming error detection on the trained task, we were also interested in the effect of priming error detection on the untrained tasks. The importance of transfer of training from one functional task to another using the same effector cannot be understated. Often times, individuals following neurological damage rely on this concept as a means of returning to independent living. Despite its importance, there are few studies that consider inter-functional task transfer. While Schaefer and Lang[21] found transfer from one functional task to another functional task, our results provide evidence to the contrary. However, our results should be considered with caution, because it is likely that our study was confounded by providing too much transfer task practice during test trials, resulting in a learning effect. Whether a properly designed study would support the occurrence of transfer from one functional task to another remains unknown.

Limitations

The experimental findings reported in this dissertation contribute to understanding the effects of an error detection prime on motor learning and motor skill transfer in a population of healthy young adults. However, this work was limited by a number of factors. One limitation we encountered was ensuring that participants performed their assigned cognitive task according to the task directions. We proactively implemented response deadlines for each cognitive task to manage this expected problem, however, there was still variability in individual performance. Because performance on the assigned cognitive tasks can alter the experimental manipulation, future studies should have participants prioritize accuracy/speed to a greater extent (e.g., provide reward for performance) or dismiss those participants who do not perform the cognitive task based on a criterion value.

An additional limitation of this dissertation was the way in which the "no-training" group was incorporated in experiment II. Our original experimental design only consisted of the Accuracy group and the Speed group. However, in order to determine if improvement on the transfer (untrained) tasks was a result of motor skill transfer versus an effect of learning due to task exposure, a control group had to be recruited. This recruitment was a sample of convenience and was not randomized. Further, because this group was recruited late, it was difficult to enroll an equal number of subjects. Future studies measuring motor skill transfer should recruit a control group (i.e., "no training" group) simultaneously with the "training" group to ensure that proper randomization occurs.

Future research

Our study results suggest that priming error detection prior to training a subsequent motor task may augment the learning of that task in a population of healthy young adults.

However, while the results were far from definitive, they do warrant further investigation of the validity of using a cognitive task to prime error detection as a means of augmenting learning of a subsequent motor task. Further, research should continue to use functional motor tasks to test the amount of transfer that occurs between trained and untrained tasks.

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