CORTICAL EXCITABILITY CHANGES EMERGE IN M1 FOLLOWING

TRAINING WITH A NOVEL BIMANUAL COORDINATION PATTERN

A Dissertation

by

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ABSTRACT

Conceptually, motor skill memory has been divided into two distinct forms, which are explicit and implicit memory representations. These two memory components have distinct neural processing pathways. Extensive studies focusing on discrete and serial reaction time tasks (SRTT) have been done to explore these processing pathways to establish a link between memory consolidation processes and cortical excitability changes in motor cortex (M1) after training. Research has revealed distinct cortical excitability changes in M1 that differentiate a SRTT as either implicit or explicit. In the area of motor skill/learning, rhythmic bimanual coordination tasks are often treated as different from SRTT for a variety of reasons. The primary goal of this study was to determine if cortical excitability changes in M1 following training with a 90° bimanual coordination pattern would be more like changes observed after training with an SRTT in an implicit or explicit context. To accomplish the goal, transcranial magnetic stimulation (TMS) was used to probe M1 excitability before and after training. A secondary goal of this study was to examine whether or not training altered participants' ability to perceptually discriminate aspects of the trained coordination pattern. A feature of explicit representation is the ability to recall the sequence after training, a feature not characteristic of an implicit representation. A recognition test introduced after a delayed-retention test of the trained 90° pattern was used to determine if training and delay interval interacted to establish changes in perceptual discrimination ability. The bimanual task required participants to produce the 90° relative phase pattern with finger abduction/adduction motions. Training

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was facilitated by using a Lissajous plot to provide concurrent feedback. Before training and at 6 and 21 minutes after training motor evoked potentials (MEPs) were measured from the first dorsal interosseous (FDI) muscle. Participants had either a 30 minute or 6-hour delay after training before performing a set of retention test trials of the 90° bimanual pattern and then performing a recognition test of the finger motions used to produce the 90° pattern. At the end of training participants produced the 90° phase pattern with smaller error and variability compared to the beginning of training, and maintained the skill level gained at the end of practice until the delayed retention test. Cortical excitability increased above baseline at the 6 min and 21 min TMS probes after training, consistent with the pattern observed following training with an implicit SRTT. Participants were able to perceptually discriminate finger motions of the trained 90° pattern during the recognition test. The results suggest that participants' developed an explicit representation of the bimanual 90° pattern. However, the ability to both produce and perceptually discriminate coordination patterns based on relative phase also suggest that relative phase as an order parameter links perception to action and thereby constrains and facilitates both action and perception processes in a similar manner.

DEDICATION

This dissertation is dedicated to my beloved parents,

for their unconditional love and encouragement.

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Contributors

Part 1, faculty committee recognition

This work was supervised by a dissertation committee consisting of Professors John J. Buchanan, Charles Shea, and David L. Wright of the Department of Health and Kinesiology and Assistant Professor Jessica A. Bernard of the Department of Psychological and Brain Science.

Part 2, student/collaborator contributions

All work for the dissertation was completed by the student, under the advisement of John J. Buchanan of the Department of Health and Kinesiology and in collaboration with Austin Mcculloch and Chen Jing of the Department of Health and Kinesiology.

Funding Sources

NOMENCLATURE

BW45   Bandwidth 45

BW22   Bandwidth 22

DLFPC   Dorsal Lateral Prefrontal Cortex

EMG   Electromyography

FDI   Flexor Dorsal Interosseous

MEP   Motor Evoked Potential

M1   Primary Motor Cortex

RT   Reaction Times

rMT   Resting Motor Threshold

rTMS   Repetitive transcranial magnetic stimulation

SRTT   Serial Reaction Time Tasks

TMS   Transcranial Magnetic Stimulation

TtPR   Time to perceptual response

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1. INTRODUCTION

Memories, which represent knowledge gained through experience and practice, are thought to be encoded into declarative or procedural representations. Declarative memory is defined as encoded knowledge that represents a known factor or known event. Procedural memories are defined as encoded knowledge that represents the ability to perform a specific motor skill. For instance, a typist or pianist produces a series of finger movements to fulfill the goal of making a document or playing a piece of music. Declarative knowledge is the ability to identify the letters on the keys and the notes of the music, whereas procedural knowledge is the ability to accurately move the fingers to hit the keys in either task. Procedural memories can be formed without conscious awareness of the rules being learned and can be considered to reflect learning by doing whereby neural pathways used to perform the perceptual-motor task are modified with practice (Willingham, 1998). In contrast, the forming of a declarative memory is characterized by the conscious awareness of the task, events, and goals being learned. Reading text and reading music are declarative in that encoding the goal requires conscious awareness of the rules of spelling and reading of musical scores. Neuropsychologists have provided empirical evidence that both procedural and declarative memory encoding systems have independent neural pathways (Cohen & Squire, 1980). Research has revealed that patients with amnesia that have severely impaired declarative memory processes show intact procedural memory processes at a comparable skill level to healthy controls (Cavaco, Anderson, Allen, Castro-Caldas, & Damasio, 2004; Cohen & Squire, 1980). Alternatively, patients with a lesion in the motor system pathways that play a significant role in

performance exhibit impaired procedural skill learning but not impaired declarative skill learning (Willingham, 1998). The study presented here examined the development of a procedural memory associated with a bimanual motor skill task.

1.1 Sequence learning

In the motor learning literature, the use of tasks defined as either explicit or implicit have provided a means to study the formation of declarative and procedural memories underlying the execution of learned motor skills. When a motor skill is encoded with extensive knowledge about execution processes and goals, then the task is often labeled as having an explicit representation. When a motor skill is encoded without the extensive descriptive knowledge regarding execution processes and goals, then the task is often labeled as an implicit task. Implicit motor tasks are designed to invoke procedural memory formation, and explicit motor tasks are designed to invoke a declarative memory component for a task. Many motor skills can be encoded as both implicit and/or explicit representations. Motor sequencing tasks are an often used task in the motor learning literature to study implicit and explicit representation. These tasks often take the form of pressing a series of keys or hitting a series of targets in a predefined order (Cohen, Pascual-Leone, Press, & Robertson, 2005; Panzer, Krueger, Muehlbauer, Kovacs, & Shea, 2009; Park & Shea, 2003, 2005; Verwey & Wright, 2004). Improvement in skill is measured through shorter reaction times (RT) to the target, a decrease in response time to the entire sequence, and a reduction in errors – missed targets. Motor sequencing tasks often use visual cues to guide the sequential movement of the limb(s). A consequence of prolonged training with the same visual cue to signal the start of the sequence is that it allows

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participants to develop an awareness of the trained sequence. This approach promotes explicit learning by increasing awareness of the beginning of the sequence. When the start of the sequence is not coded to a very specific visual cue, e.g., different colors, then there is a greater chance of inducing implicit sequence learning (Robertson, Pascual-Leone, & Press, 2004b).

Motor skill memories are thought to be encoded in both a spatial representation of the task goal and a motor representation of the task goal (Brooks, 1986; Kovacs, Mühlbauer, & Shea, 2009c; Panzer et al., 2009; Verwey & Wright, 2004). For example, the motor memory of a melody played by a pianist might consist of a spatial goal represented as the written score and a motor goal represented as the sequence of finger movements that press the piano keys. Research suggests that the goal-based representation is encoded through a circuit that includes the dorsolateral prefrontal cortex (DLPFC) and inferior parietal lobule (IPL), while the movement-based representation is encoded within a circuit that includes the primary motor cortex and subcortical areas (Grafton, Hazeltine, & Ivry, 1998; Hikosaka, Nakamura, Sakai, & Nakahara, 2002). A finding that further supports the idea of a separate spatial and motor encodings is that the spatial goal of a motor skill is processed over sleep but not over wakefulness, whereas the motor goal (or movements) is processed over wakefulness but not over sleep (Cohen et al., 2005). Participants in the study by Cohen et al. (2005) trained with an SRTT using the right-hand. After training, participants performed the SRTT with the untrained left-hand in order to probe for differences in the spatial and movement-based representations. A transfer test with the left-hand was setup to preserve either the spatial goal of training, same order of

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visual stimuli, or preserve the motor goal, same order of finger movements. The transfer test was administered after a 12 hr wake period or a 12 hr period with an interval of sleep. The results revealed a consolidation of the spatial goal over a night of sleep, while the motor goal was consolidated over the wakefulness interval (Cohen et al., 2005).

Consolidation is an off-line process whereby skill improvements occur between practice sessions. These off-line improvements take place without physical practice and are either sleep-dependent or sleep-independent. Numerous studies regarding SRTT have provided evidence that participant awareness of learning a new skill is an important factor to predict the type of consolidation (Cohen et al., 2005; Fischer, Hallschmid, Elsner, & Born, 2002; Robertson et al., 2004b). Improvements are sleep-dependent when participants are instructed to learn the sequence of finger movements (Fischer et al., 2002). Participants intentionally acquire the skills and develop an explicit representation of the sequence. Skills can also be acquired unconsciously, in this case, participants develop an implicit representation, and off-line improvement is not sleep-dependent (Cohen et al., 2015; Robertson et al., 2004). Also, off-line consolidation can be time-dependent when participants learn a skill implicitly (Press, Casement, Pascual-Leone, & Robertson, 2005; Robertson, Press, & Pascual-Leone, 2005).

The serial reaction time task (SRTT) has been used quite often to explore memory consolidation as a function of the wake/sleep cycle. When the SRTT is learned as an implicit task, significant improvements occur during wakefulness (Press et al., 2005; Tunovic, Press, & Robertson, 2014). By contrast, when participants acquire a movement sequence explicitly, the performance improvement over wakefulness does not occur

(Brown & Robertson, 2007; Cohen et al., 2005). Both of the above findings have been linked to activation of the primary motor cortex (Aizenstein et al., 2004; Tunovic et al., 2014; Ungerleider, Doyon, & Karni, 2002). The study presented will try to determine if rhtyhmic bimanual skill learning is more similar to implict or explicit learning observed in SRTT over an interval of wakefulness.

1.2 Motor skill learning and cortical excitability

Transcranial Magnetic Stimulation (TMS) is a technique that passes an electrical current through a coil (figure of eight, circle) to generate a magnetic field that is perpendicular to the axis of the coil. The generated magnetic field can pass through skin, muscle, and bone and thereby alter the cortical excitability of the brain if it is a large enough pulse. The TMS pulse, if large enough, can produce a measurable motor evoked potential (MEP) which is a small muscle contraction in a targeted muscle in the M1 strip. The TMS technique allows the researcher to measure cortical excitability following cognitive or motor skill learning. The MEP provides a quantification of the state of postsynaptic cortical excitability and intracortical processes at the time of stimulation (Bestmann & Krakauer, 2015). Several studies have been conducted to explore the relationship between MEPs and motor output changes following learning (Bagce, Saleh, Adamovich, Krakauer, & Tunik, 2013; Muellbacher, Ziemann, Boroojerdi, Cohen, & Hallett, 2001). Muelbacher et al. (2001) suggested that there is not an identical representation of the MEP amplitude change in motor output that occurs during training that remains for a prolonged period of time. Specifically, Muellbacher et al. showed that during the acquisition phase of a pinch force task that MEP amplitude linearly increased

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as the required target force increased. However, in a retention test, given on average 30 days after practice stopped, participants maintained the acquired motor skill while MEPs were decreased to baseline levels. In other words, there is a disparity in the MEP changes and motor output throughout the different stages of motor learning (Muellbacher et al., 2001).

Furthermore, a study conducted by Bagce et al. (2013) revealed changes in cortical excitability following learning, independent of performance and error, by using a gain adaptation of finger movement in a virtual reality setting. Bagce et al. (2013) used a gain adaptation task with different amplitudes of finger movements required for low and high gains during adaptation, with opposite motor outputs required following adaptation. Excitability was tracked through changes in MEP amplitude in first dorsal interosseus (FDI) muscle elicited with single pulse TMS. Excitability increased when the performance reached the asymptotic level in both cases, regardless of the different change in finger movement amplitude (Bagce et al., 2013). More recently, Tunovic et al. (2014) reported distinct changes in cortical excitability of M1 following different types of training with the SRTT. In experiment 1 of Tunovic et al. (2014), cortical excitabilty associated with the FDI muscle increased slightly above baseline after traning with an implicit SRTT, and decreased significantly below baseline following training with an explicit SRTT. This initial probe was at 6 minutes post-training. At a 21 minute post-training time point, cortical excitabilty was above baseline after implicit and explicit task training. The decrease in cortical excitability changes after explicit skill learning in experiment 1 was interpreted as a physiological marker that blocks consolidation over wakefulness with

experiments 2 and 3 in Tunovic et al. (2014). These results show that the nature of the encoding process, implicit vs explicit, can lead to the emergence of different cortical excitability patterns following training. Overall, the findings from the several studies just reviewed imply that MEPs act as a physiological marker of motor cortex excitability associated with motor skill learning, but the relationship between MEPs and behavioral outputs is still questionable (Bestmann & Krakauer, 2015). The TMS technique has been used extensively to study motor skill learning in discrete and serial motion tasks. As a technique, TMS has not been used extensively to explore cortical excitability changes associated with the learning of rhythmic bimanual tasks (Nomura, Jono, Tani, Chujo, & Hiraoka, 2016; Vancleef, Meesen, Swinnen, & Fujiyama, 2016). The current experiment was designed to examine if cortical excitability changes in M1 emerge at delayed time points following training with a novel rhythmic bimanual coordination pattern that are consistent or inconsistent with the findings from SRTTs.

1.3 Coordination dynamics and bimanual skill learning

Theories of inter-limb coordination have been developed with respect to 1:1 bimanual coordination patterns of the fingers, arms, and wrists (Haken, Kelso, & Bunz, 1985; Schoner & Kelso, 1988). In-phase (0°) and anti-phase (180°) bimanual coordination patterns are inherently stable patterns, and the in-phase pattern is more stable than the anti-phase pattern (Kelso, 1984). However, another relative phase pattern, such as a 90° relative pattern, is an inherently unstable pattern and either extensive practice is needed to produce it (Zanone & Kelso, 1992; Zanone & Kelso, 1997) or very specifics type of concurrent augmented visual feedback (Kovacs, Buchanan, & Shea, 2009b; Park &

Buchanan, 2018; Wilson, Snapp-Childs, Coats, & Bingham, 2010). The inability to produce the 90° pattern stems from the influence of the system's intrinsic dynamics, such that coordination patterns between limbs other than 0° or 180°, are drawn to these two attractors, for example, 35° or 50° patterns are drawn to 0°, and 135° or 150° patterns are drawn to 180° (Schoner & Kelso, 1988). This initial instability of 90° without practice or visual aid may be associated with neural crosstalk between the crossed and uncrossed corticospinal pathway activating non-homologous muscles (Cattaert, Semjen, & Summers, 1999; Kennerley, Diedrichsen, Hazeltine, Semjen, & Ivry, 2002). Furthermore, Kelso and colleagues (Kelso, 1984; Kelso, Scholz, & Schöner, 1986) have demonstrated transitions during rhythmic bimanual coordination as a function of movement frequency. Both the in-phase and anti-phase patterns are stable and accurate at low movement frequencies (1 to 2 Hz). When movement frequency is gradually increased, anti-phase undergoes a loss of stability and an abrupt phase transition to the more stable in-phase coordination pattern occurs at a critical movement frequency. Central to this theoretical approach to motor control are the concepts of stability, loss of stability, and pattern change, all of which may be key aspects when learning a new motor skill.

As reviewed, the motor sequence literature has focused on defining actions as implicit or explicit and sought to identify how different possible representations of an action, spatial versus motor, consolidate over intervals of wakefulness and sleep. Within the coordination dynamics framework, the issues of spatial and motor representations are addressed and connected through the concept of shared information found in the order

parameters, e.g., the relative phase, for perception-action processes (Buchanan, 2015; Kelso, 1994; Park & Buchanan, 2018; Wilson & Bingham, 2008; Wilson et al., 2010).

Studies examining bimanual skill learning have used a variety of visual and auditory metronome setups to pace bimanual coordination at a particular frequency and to provide a way of directing the participants to the goal coordination pattern. An experiment by Zanone and Kelso (1992) had individuals flex and extend their index fingers (inserted into metal shafts that oscillated about the knuckle) on the horizontal plane and used a visual metronome to specify the required relative phase pattern. Participants were instructed to synchronize a reversal of index finger motion to the onset of the corresponding flashing LED. On the first day, participants performed scanning trials consisting of 13 different relative phase patterns between 0˚ and 180˚ in 15˚ increments. On the second day, participants performed four consecutive blocks of training trials at a 90° relative phase pattern between the hands. After the practice trials, the learned pattern becomes a novel attractive state of the underlying coordination dynamics. For example, in-phase and anti-phase are an initially stable pattern (attractors) before practice, but the to-be-learned pattern stabilizes after practice, and in some instances, the anti-phase pattern can become temporally destabilized (Zanone & Kelso, 1992). In the retention test, the 90° pattern was performed without the visual metronome after 4 days of practice. Conceptually, the phase represented by the flashing LEDs (spatial goal) was internalized as a basic motor representation that could be produced without the visual aid. Does this mean that a spatial representation was not developed? Research has shown that learning relative phase patterns such as 90°, 60°, and 120° can lead to changes in perceptual discrimination

processes when the visual information is displayed in perceptual identification tasks (Buchanan, 2015; Haken, 1990; Maslovat, Hodges, Krigolson, & Handy, 2010; Park & Buchanan, 2018). The ability to discriminate the newly trained pattern from other patterns is taken to represent that the encoding during training was in the form of the information contained in the dynamics of the practiced relative phase pattern, thereby linking action production to action perception.

An experiment by Kovacs et al. (2009a), had participants receive concurrent Lissajous feedback either with or without an auditory metronome during task training with a 90° pattern. The Lissajous display consists of a cursor that participants move around a template in a visual display. Participants flexed and extended their forearms about the elbow on the horizontal plane (forearms were supported) with the vision of the limbs not allowed. The flexion-extension motion of the arms is mapped to the x and y motion along the template in the Lissajous display. After only 5 min of practice, participants in the no-metronome condition showed remarkable stability and accuracy compared to the metronome condition. Zanone and Kelso (1992) required four days of training to achieve accuracy and stability of the 90° pattern. However, removal of the Lissajous plot resulted in a performance breakdown, indicating a dependence on the feedback.

Several experiments were designed in order to manipulate the demand of perceptual information associated with bimanual coordination and the Lissajous training context (Kovacs, Buchanan, & Shea, 2009a; Kovacs et al., 2009b). Kovacs et al. (2009b) conducted an experiment to examine whether the participants can produce a wide range of relative phase patterns with low error and variability under the condition that Lissajous

feedback is provided, the vision of limbs occluded, and when metronomes are not used. The task was to move the cursor in the pattern depicted by a template in the display with flexion and extension motion of forearms. One group received concurrent Lissajous feedback while another group was instructed to match the left- and right-limbs movement frequency to visual metronomes that defined the pattern in a manner consistent with Zanone and Kelso (1992). All participants performed three blocks of practice and one block of test trials. Each block consisted of 14 trials (the pattern of individual trials changed 0° to 180° in 30° increments). The Lissajous group performed with higher accuracy and lower variability than the metronome group after just 5 minutes of practice (Kovacs et al., 2009b). However, when Lissajous feedback was removed error and variability in performance, measured with relative phase, increased significantly. This detriment revealed that the participants had not developed a procedural memory representation of the practiced pattern but were able to use the salient information provided to detect their coordination error and perform the necessary corrections. Zanone and Kelso (1992) demonstrated that prolonged practice without the Lissajous results in stable memory representation of the 90° pattern that does not need visual information to support its production. The current experiment will use the Lissajous plot to promote rapid improvement in performance and then test performance at different delay intervals to see if consolidation occurs over a period of wakefulness, something not examined in the work by Kovacs and colleagues. As reviewed, wakefulness intervals reveal difference between SRTT tasks considered implicit or explicit.

1.4 Bimanual skills and cortical excitability

In the bimanual coordination literature, TMS has been used in combination with rhythmic in-phase and anti-phase tasks as a means to examine EMG activity and H-reflex modulation (Carson, Riek, & Bawa, 1999) and to probe inhibitory and excitatory connections between hemispheres (Carson et al., 2004; Chen et al., 2005). TMS has been used in combination with discrete bimanual tasks to examine the connection from dorsal pre-motor cortex to M1 (Neva, Singh, Vesia, & Staines, 2014; Neva, Vesia, Singh, & Staines, 2015). Cortical excitability changes in M1 after bimanual training have also been reported for rhythmic in-phase movements of the wrists (Byblow et al., 2012) and discrete in-phase movements of the wrists (Byblow et al., 2012; Neva, Legon, & Staines, 2012). Anti-phase movements have not been associated with increased cortical excitability after training; however, in the Byblow et al. study both in-phase and anti-phase were produced by having participants actively move one wrist as the other wrist was passively moved (Byblow et al., 2012). A consistent conclusion across the above studies is that interhemispheric connections are important for the production of intrinsically stable bimanual patterns. Consistent changes in M1 cortical excitability following the production of intrinsically stable patterns, however, has not been demonstrated.

A recent study has examined cortical excitability levels between the intrinsically stable in-phase (0°) and anti-phase (180°) bimanual patterns and the unstable 90° relative phase pattern (Nomura et al., 2016). In the Nomura et al. (2016) study, cortical excitability using TMS was probed during the actual production of the patterns and the possibility of prolonged enhanced excitability was not examined. Participants were asked to produce the

three different rhythmic bimanual coordination patterns, 0˚, 90˚, and 180˚, with abduction/adduction motions of both index fingers on the horizontal plane. MEPs of the right FDI muscle elicited by TMS were measured during task performance. During the task, participants were instructed to trace a target presented on a monitor in the form of a Lissajous figure. An auditory metronome was provided to pace movement frequency. Before the TMS session, participants practiced each pattern for 100 cycles before being exposed to the TMS procedure. The lengthy 'practice' was due to the difficulty of producing the 90˚ pattern. The Lissajous figure allowed for rapid tuning consisted with the work of Kovacs and Colleagues (Kovacs et al., 2009a, b). The TMS procedure was used to probe MEP amplitude during different phases (flexion-extension) of the rhythmic motion of the right finger in a manner similar to the work by Carson and colleagues (Carson et al., 1999; Carson et al., 2004). Overall, the MEP amplitude of the FDI muscle during the performance of the 90˚ pattern was bigger than for the 0˚ and 180˚ patterns. The authors interpreted the increased cortical excitability when producing 90˚ to most probably be the result of the difficulty of the task thereby requiring greater effort to execute or acquire the skill (Nomura et al., 2016). The Nomura study could not determine if the large MEP in 90° was linked to execution or acquisition (100 practice cycles). They also did not examine post-training cortical excitability in any of the patterns as did Byblow et al. (2012) for the in-phase and anti-phase patterns. Another recent study by Vancleef and colleagues was designed to look for cortical excitability changes in M1 after learning a set of complex rhythmic bimanual patterns (Vancleef et al., 2016). In the study, participants trained on a bimanual tracking task for four days and had a retention test seven

days later. The task required the production of multi-frequency bimanual patterns, such as 1:2 and 3:2 using wrist and finger motions. TMS invoked MEPs in the right flexor carpi radialis were recorded to investigate the effect of tDCS on cortical excitability. Although performance improved across the training days, no change in MEP amplitude was found before and after the training. Vancleef et al. (2016) concluded that the muscle measured for MEP changes might not have been the best for the task performed. These results show that a clear understanding of M1 excitability changes after bimanual training with an initially unstable pattern, such as 90°, is not present in the literature.

A study needs to be done that better isolates a specific muscle linked to the specific bimanual task, such as in the Nomura et al. (2016) study. The primary goal of this study was to investigate changes in cortical excitability of M1 following the learning of a novel bimanual coordination pattern, the 90° relative phase pattern. TMS was used to probe M1 cortical excitability before and after training. The study also examined perceptual awareness of the coordination pattern that was practiced. In the SRTT literature, sequence learning is often discussed with regard to implicit and explicit knowledge representation. Implicit implies no expressive or declarative knowledge of the sequence after a practice session, whereas explicit knowledge implies a declarative representation of the knowledge of the sequence following training (Robertson, Pascual-Leone, & Miall, 2004a; Tunovic et al., 2014). Perceptual links to coordination have also been examined with rhythmic motor tasks (Buchanan, 2015, 2016). In several bimanual studies, training with the relative phase pattern of 90° enhanced the ability to perceptually discriminate the trained pattern and identify relevant features of the coordination pattern such as arm lead-lag (limb

position) (Maslovat et al., 2010; Park & Buchanan, 2018). Training with single limb multi-joint tasks on relative phase patterns of +60° and +120° have produced increased perceptual awareness of the patterns and their symmetry partners -60° and -120 (Buchanan, 2016; Buchanan, Ramos, & Robson, 2015). A secondary goal of this study was to examine whether or not motor skill training altered participants' ability to identify aspects of the trained coordination pattern perceptually. An interesting feature of the Tunovic et al. (2014) study was that post-training MEPs were below baseline for those trained explicitly on atask, while those trained implicitly had post-training MEPs above baseline. The link between baseline and post-training MEPs in bimanual coordination tasks hasnot been examined with regard to changes in perceptual awareness. A perceptual recognition test was given after a delayed retention test to examine the implicit/explicit nature of the motor task representation with regard to informational constraints associated with action-perception processes from a dynamical systems perspective.

2. METHOD

2.1 Participants

College students (N= 32, 12 Male, 20 Female) received class credit for participation in the experiment. The participants had no prior experience with the experimental task. A short form of the Edinburgh handedness inventory (4 categories) was administered and handedness was quantified as follows: 1) right-handed score 61 to 100, 2) mixed hand score, 60 to -60, and 3) left-handed score, -61 to -100. Thirty participants were classified as strong right-handed (Mn = 97.5, Std. Dev. = 7.6), one was classified as mixed hand (score of 25), and the data for one participant was lost. The Texas A&M University IRB approved the experimental protocol and consent form in accordance with the Helsinki Declaration. Prior to undergoing TMS stimulation, all participants filled out a contraindication form regarding TMS. None of the participants had any contraindications to TMS. Each participant signed a written consent form after volunteering to participate. All participants received TMS stimulation prior to and after training with a bimanual coordination task.

2.2 EMG, MEPs, and TMS stimulation protocol

Muscle activity and Motor Evoked Potentials (MEPs) were measured via EMG surface electrodes (Ag/AgCl) that were placed over the belly-tendon montage of the right FDI muscle (Figure.2C). The EMG signal was amplified with a gain of 1000 and band-pass filtered (10-500Hz) and sampled at 2000 Hz using a 16-bit analog to a digital system. Prior to the initiation of the TMS session, the experimenter made sure that the EMG signal was properly detected from the participant's right-hand first dorsal interosseous (FDI)

muscle when active and at rest before beginning the TMS session. Single-pulse TMS was delivered with a standard figure of eight coil (70mm loop diameter) connected to a Magstim Rapid2 stimulator (Magstim Company, Dyfed, UK). The TMS device combined with the MEP measure were used to determine the hotspot of the FDI muscle and provide a measure of cortical excitability (Figure 1).
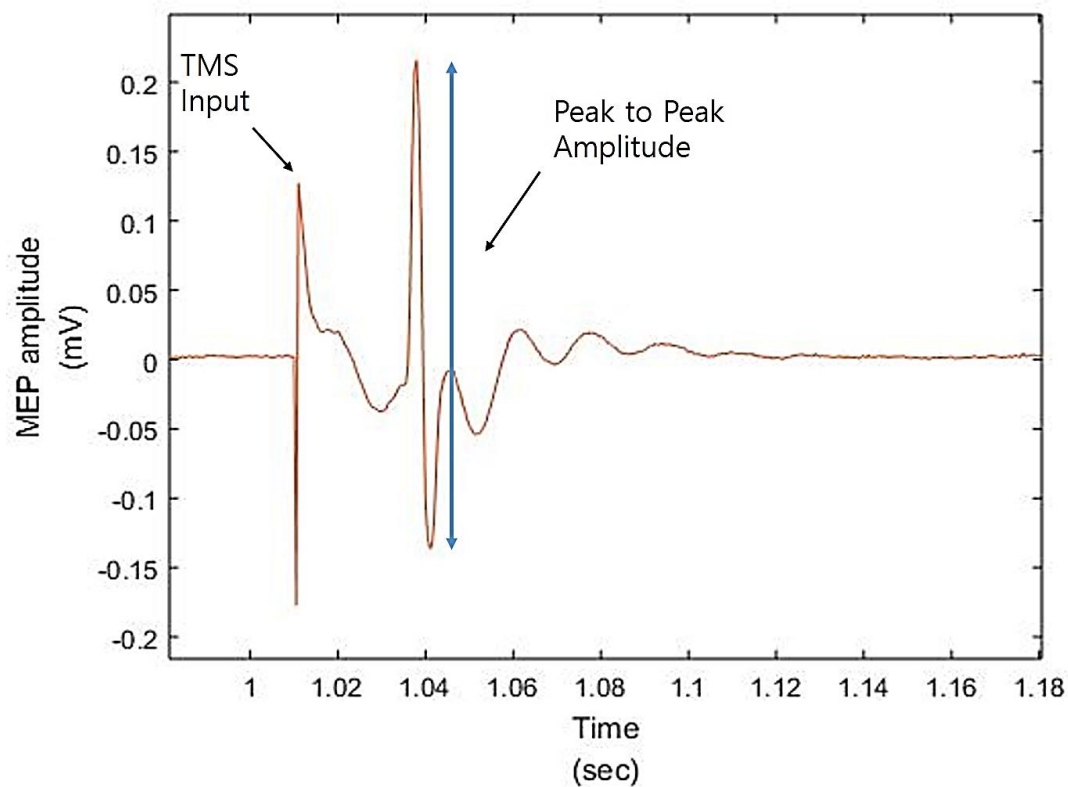
Figure 1. MEP amplitude was determined by identifying the peak to peak amplitude of the FDI EMG trace (blue double head arrow) following each TMS stimulation.

The localization of the hotspot of the right-hand FDI within left-hemisphere M1 was a five step process. Step 1: a stretchable cap (swim cap) was placed on each participant's head and two points were marked in line with the nasion and inion to ensure the cap was aligned throughout the entire TMS session. Step 2: the points corresponding

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to Cz, C3 and Fz based on the international 10-20 system were located. To determine the location of Cz, a measure over the center line of the scalp from the Nasion to the Inion was taken and the midway point (50 % of the total length) was marked. Next, a measure from preauricular point to preauricular point was taken, and the midway point (50 % of the total length) was marked. The intersection of these two points was labeled Cz. The point C3 was marked as 20% lateral from Cz and the point Fz was marked as 20% anterior from Cz (Figure 2A,B). Step 3: lines were drawn on the cap to link Cz, Fz, and C3 to form a right triangle. Step 4: the center hole of an array of five holes (plastic template) was placed at the midpoint of the hypotenuse of the right triangle and this center point was labeled 'a' and was marked on the cap. The other four holes were equidistance from the center hole and labeled b-e. These five points were used to search for the M1 hotspot of the right-hand FDI muscle. Step 5: a straight line linking the point 'a' to the point Fz (Figure.2A, dotted red line) and this line was used to orient the direction of the figure of eight coil during the stimulation.

Figure 2. Schematic representation of template used for localizing hotspot of M1 (A), a-e denote the candidate sites for FDI within M1. The site that obtains an optimal MEP amplitude and visible twitch is the M1 hotspot. The location and orientation of the figure of eight coil on the scalp during the TMS session (B). The location of EMG surface electrodes on the right first dorsal interosseous (FDI) muscle (C).

The five candidate sites labeled a-e (Figure 2A) were used to find the hotspot of the FDI muscle along M1. The search for the hotspot started with the center point 'a'. The initial single pulse stimulation intensity of the figure of eight coil was set to 40% and was increased in intensity in steps of 5% until an MEP $\geq 50\mu V$ peak-to-peak amplitude and a visible twitch in the finger was observed (Figure 1). If the just set intensity produced MEPs $\geq 50\mu V$ combined with fingers twitches in 5 of 10 pulses, then the intensity was lowered in steps of 3% until reaching a minimum intensity that elicited MEPS in five out of ten pulses with $\geq 50\mu V$ peak-to-peak amplitude and a visible finger twitch. The TMS intensity derived for point 'a' was labeled the minimum output intensity associated with the resting motor threshold (rMT). The rMT was tested at the other four points in the order b, c, d, and e. At each point ten TMS pulses were delivered. The hotspot of the right-hand FDI

muscle was determined by the point where the maximum average MEP amplitude had been obtained when 5 of 10 pulses produced a visible finger twitch. Whichever point was labeled the hotspot was used to determine baseline cortical excitability and cortical excitability in two post-training TMS sessions. The TMS intensity for recording cortical excitability was 20% above the intensity of TMS at the rMT and was used to determine baseline excitability and post-training excitability.

The location of the hotspot and recording of the baseline TMS excitability level lasted 15-25 minutes. The two post-training TMS sessions spanned an interval of approximately 24 minutes (Figure 3). After the initial TMS baseline session participants were trained to produce a 90° relative phase pattern using their index fingers. The bimanual training session lasted 30 minutes. After the completion of the training session, participants had their cortical excitability measured at two post-training intervals of 6 and 21 minutes.
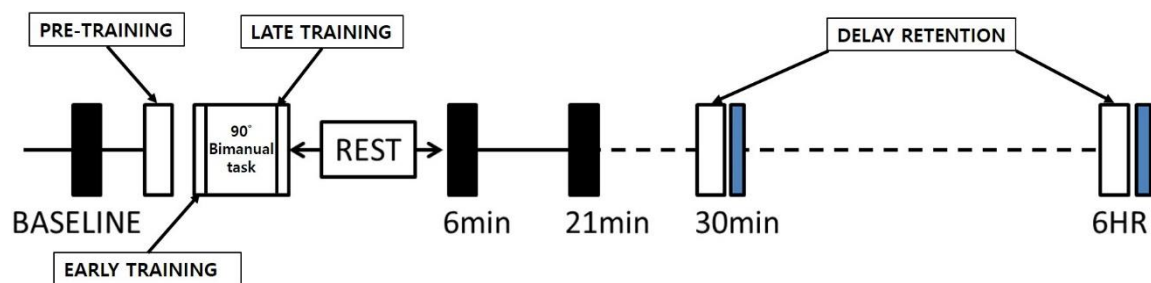
Figure 3. Schematic representation of the experimental timeline. Participant's *baseline* cortical excitability as the magnitude of MEPs in the right FDI muscle elicited by single-pulse TMS is measured (black bar). Participants then perform a pre-training bimanual coordination test with Lissajous feedback (the first-white bar), and they then train with the 90° pattern (white box). Post-training MEPs are measured at 6 min and 21 min intervals (black bar). Participants perform the bimanual task after either a 30-min delay or a 6-hr delay from the completion of training, and then are given a perceptual discrimination test immediately after the retest (blue bar).

During each TMS session, participants experienced 20 pulses of TMS at 120% of their rMT. The averaged MEP peak-to-peak amplitude across the 20 pulses was taken as the measure of cortical excitability. The experimenter monitored the MEPs recordings, and when motion artifacts were observed before the stimulation, the trial was discarded, and the participants had additional stimulation. The raw MEP amplitude was used for statistical analysis.

2.3 Bimanual coordination task and performance measures

The task required rhythmic abduction-adduction movements of the index fingers on the horizontal plane (Figure. 4). Participants sat at a table with their hands pronated and forearms supported by wooden blocks to reduce fatigue. Participants grabbed a horizontal bar attached to a desk and extended both index fingers horizontally. Each index finger was also supported by a block to constrain motion to the horizontal plane. A pilot study revealed a strong tendency for individuals to move the index fingers in both the horizontal and vertical plane, thus the use of blocks to constrain motion to the horizontal plane and abduction-adduction only. Small infra-red LED markers were placed on each index finger (tip) to record the abduction-adduction motion of the fingers (Figure 4). The motion of the markers was captured with the Optotrak Certus camera system (Northern Digital, Inc.). The coordination task consisted of a set of pre-training, training, and post-training trials. The vision of the limbs was blocked with a wooden box to maintain the participant's attention focused on the visual training display.
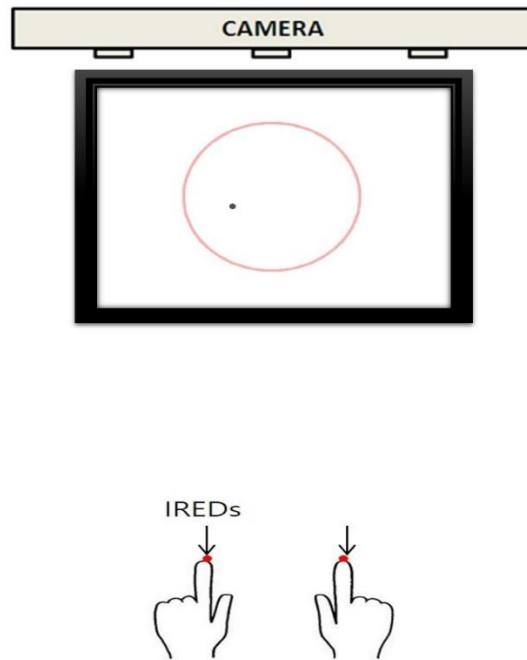
Figure 4. Illustration showing an overhead view of the experimental setup and infra-red markers (identified by arrows). The figure and a black dot on the screen representing the template in the Lissajous. The visual stimulus was displayed on a projector screen 2 meters from the model, and the screen size of the projected display was 1 meter on diagonal.

The visual training display consisted of a template displayed in a *Lissajous* plot and online displacement feedback (moving cursor) that represented the abduction-adduction motion of the two index fingers in real time. The visual training display was displayed on a projector screen positioned in front of the participants (Figure. 4). The task required a participant to move the cursor along the template in the Lissajous plot. Right finger abduction-adduction motion moved the cursor horizontally and left finger abduction-adduction motion moved the cursor vertically with respect to a template. Participants were instructed to trace the templates in the Lissajous plot as accurately as possible at a comfortable pace by continuously abducting/adducting their fingers. Movement amplitude was fixed throughout the experiment and was specified by the length

or diameter of the Lissajous figure. The relative phasing (ϕ) between the two fingers was manipulated across the three sets of training trials. The primary muscle used in producing the adduction motion of the index finger is the FDI. The TMS coil was used to produce MEPs in this muscle.

Table 1. Summary of testing conditions including a number of trials, display shown, feedback, and pattern performed.

Condition	Trials (length)	Pattern
Pre-training test	7 (20 sec)	0˚ × 3 trials, 180˚ × 3 trials, 90˚× 1 trials
Training	20 (30 sec)	90˚
Post-training test	3 (30 sec)	90˚

The bimanual coordination task started within 10 minutes of completing the TMS baseline measure of cortical excitability. Participants first performed a set of seven pre-training trials (0°, 180°, and 90°, Table 1) to orient them to the task and the movement of the cursor along the template in the Lissajous plot. Each pre-training trial lasted for 20 secs. The 0° pattern required participants to abduct and adduct the fingers simultaneously. The 180° pattern required the participants to abduct one finger while adducting the other finger. The 90°pattern required one finger to lead the other finger by a ¼ of a cycle so that when one finger was at peak abduction or adduction, the other finger was half-way between its points of peak abduction and adduction. The experimenter did not provide any explicit verbal instruction or demonstration for the pre-training trials. The 0° pattern was represented by a positive sloped line template (+1), the 180° pattern was represented by a negative sloped line template (-1), and the 90° pattern was represented by a circle template in the Lissajous plot (Figure 4). After the pre-training trials, participants were asked if they

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understood the task, and if they responded yes the training session began. In the training session, each training test trial lasted 30 seconds and a 30 second break followed every training trial. In the training session, participants performed 20 trials of the 90° relative phase pattern by attempting to trace the circle template with the cursor in the Lissajous plot. At the end of the training session, MEPs of the right FDI muscle were again determined at 6 min and 21 min. After the 6 and 21 min MEP sessions participants were assigned to a 30 min or 6 hr delay interval before performing three post-training test trials. Participants in the 30 min Delay-test went directly from the 21 min TMS session to the post-training test session. The condition of the post-training test was the same as the training session. After completing the post-training trials, a perceptual recognition test of finger motion patterns was performed.

The IREDs on the fingertips were sampled at 100 Hz and dual pass filtered (Butterworth, 10Hz) before computing all behavioral measures with software routines developed with MATLAB R2014a (The Mathworks, Inc.). A continuous relative phase (ϕ_c) was computed to examine the spatiotemporal coordination of the fingers during the task. The main motion direction was along the *x*-axis (horizontal motion plane). The *x*-axis displacement data (dx_i) for each finger was differentiated (dx_i/dt_i) with a three-point algorithm. The *x*-axis displacement and velocity signals for each finger were then normalized to the range -1, 1, and the normalized signals were used to an compute individual phase angle (θ_i) for the left (θ_l) and right (θ_r) index fingers, $\theta_i = tan^{-1}[dx_i/(dx_i/dt_i)]$. The continuous relative phase was derived by subtracting the phase angle of the left finger from the phase angle of the right finger, $\phi_c = \theta_r - \theta_l$. Circular

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statistics were applied to ϕ_c before computing a mean (ϕ_{Mn}) and standard deviation (ϕ_{SD}).

An absolute error value associated with the computed ϕ_{Mn} ($\phi_{AE} = ABS$ (*required* - | ϕ_{Mn} |)

was used to assess goal attainment. A decrease in ϕ_{AE} from early to late practice indicates

an improvement in performance. The standard deviation of relative phase (ϕ_{SD}) provided

an assessment of performance variability, with a decrease from early to late practice

indicating an increase in stability

Assessment of performance was also examined using two time on task measures

(computed as percentages) that provide an estimate of how many of the total individual

relative phase points from the ϕ_c time series fell within a given range of the target relative

phase of 90˚. Two bandwidth intervals were defined: a bandwidth of ±45˚ BW45) and a

bandwidth of ±22.5˚(BW22) (Figure 5). Performance improvements based on these

measures are be indicated by an increase in the amount of time spent within a given

bandwidth interval from early to late in practice.
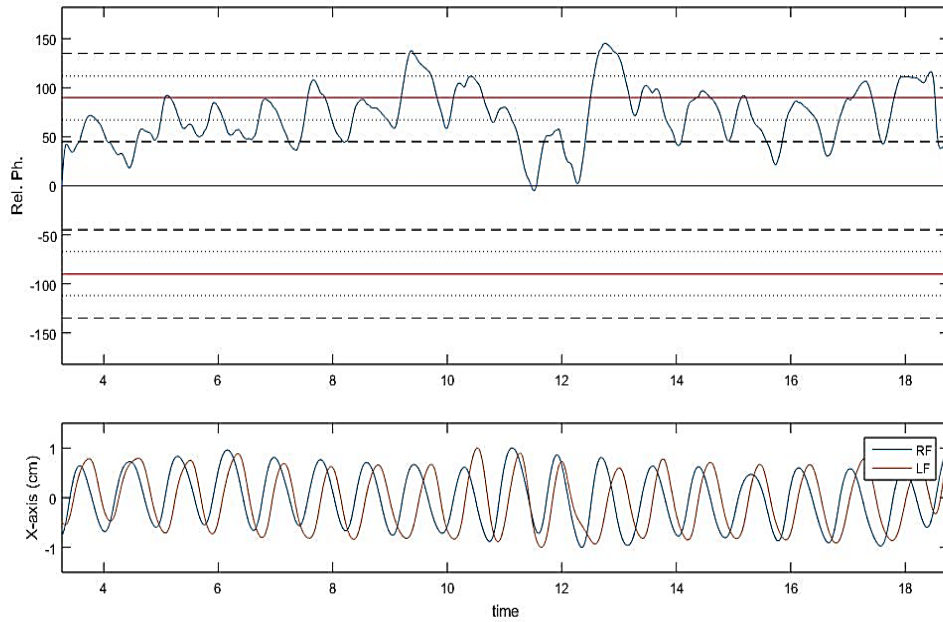
Figure 5. Example of one participant's continuous relative phase (upper plane) and finger movement data (lower plane) from 90˚ pattern training trial. Target relative phase (red solid line), bandwidth ±45° (dashed line) and ±22.5° (dotted line).

A peak picking routine was used to define the extreme points of the finger movement from the x-axis time series (bottom of Figure 5). The time of the abduction reversals were determined and used to compute an average movement frequency for the left and right finger motions. Movement frequency was self-paced and after each trial participants were encouraged to move faster. The distance from the full abduction to full adduction of finger motion was used to compute an average movement amplitude for the left and right finger. The circle template had a diameter of 4 cm and this is the required amplitude for the task.

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2.4 Recognition task

A perceptual discrimination test was given when participants completed the 90°
post-training trials. For the perceptual test, participants viewed static images of 12
different index finger positions (see Figure 6A). The complete set of images consisted of
three different finger positions associated with coordination patterns of 0˚, 45˚, 90˚
(trained pattern), and 180˚. The participants were familiar with three patterns represented
by the static images: pre-training (0 ˚, 90 ˚, 180 ˚), training (90 ˚), and post-training (90 ˚).
Each image was viewed three times for a total of 36 trials. Participants were asked to
determine ('yes' or 'no') if a static image represented a position of the index fingers used
to produce the trained 90° pattern. For the three 90° images, a 'yes' represents a correct
response, for the other nine images a 'no' represents a correct response. Each picture was
randomly presented. Participants sat with their right-hand on a keyboard (keypad 1 and 3
keys) and their left-hand on a desk. Participants were not allowed to try and produce the
trained pattern during the perceptual test. The images were presented as follows: 1) a
screen with a blue cross appeared and participants were told to focus on the cross (see
Figure 6B); 2) this focus screen disappeared after 2 secs and a finger image appeared for
3 secs then disappeared; 3) a screen prompting the participant to answer yes (press 1 key)
or no (press 3 key) appeared. After the participant responded, the focus screen appeared
again. Participants were given written instructions on the recognition task and were
provided with example trials to clarify how the test works. A time to perceptual response
(TtPR) measure was calculated from the time the finger image disappeared to the time that
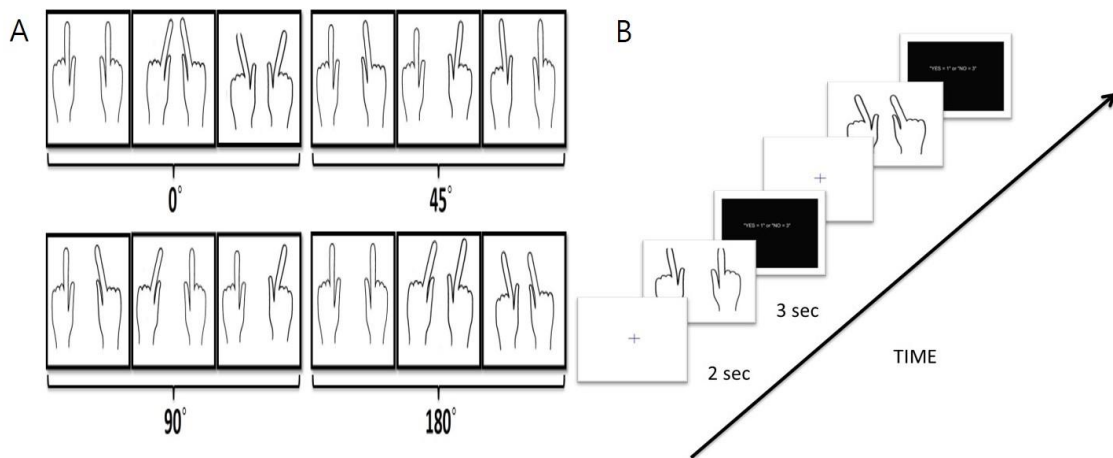a response key was pressed by a participant.

Figure 6. The 12 static images for the recognition test are shown (A). For each relative phase pattern there were three different images. The images were randomly presented three times for a total of 36 perceptual discrimination trials. A schematic representation of the recognition test is shown (B). The figure is not drawn to scale.

2.5 Statistics

The MEP amplitude data were analyzed with an independent sample t-test to check for differences between the 30 min. and 6 hr. delay groups in baseline cortical excitability. Even though the delay manipulation occurred after the three TMS sessions, delay interval was a factor in a mixed–repeated measures 2×3 ANOVA with Delay-retention test (30 min., 6 hr.) a between factor and TMS session (base, 6 min., 21 min.) a repeated factor. The raw MEP values from the 6 minute and 21 minute TMS sessions for each participant were normalized to the baseline mean. One-sample t-tests were used to determine if the percentage change in MEP value at 6 and 21 minutes was significantly greater than zero.

The behavioral training data measures, performance accuracy (ϕ_{AE}), performance stability (ϕ_{SD}), time on task measures (BW45 and BW22), movement frequency, and

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movement amplitude from the training and post-training trials were partitioned into three Blocks. Block 1 consisted of early training (trials 1-3), Block 2 consisted of late training (trials 18-20), and Block 3 consisted of the three post-training trials. All the behavioral measures, except the movement frequency and movement amplitude, were analyzed with mixed repeated-measure ANOVAs with Delay-retention (30 min., 6 hr.) a between-group factor and Block (1, 2, and 3) a within factor. The movement amplitude and movement frequency data were analyzed with mixed repeated measure ANOVAs with Delay-retention (30min, 6hr) and finger (right, left) a between group factor and Block(1,2 and 3) a within facotr. Post-hoc comparisons were done with Tukey's HSD test (α= .05).

The response data from the perceptual recognition test were analyzed using chi-square to test the independence of the variables correct response and Delay-retention, and correct response and relative phase pattern. The percentage of correct responses was computed and the data was subject to an arcsine transformation to avoid the violation of normality assumption. The percentage of correct responses and TtPR values were analyzed with seperate 2 Delay-retention (30 min, 6 hr) $\times$ 4 (Pattern: 0°, 45°, 90°, 180°) ANOVAs.

3. RESULTS

3.1 MEPs amplitude

Example time series of TMS induced MEPs from the FDI muscle are shown in Figure 7A. An increase in amplitude is seen in the post-training 6 min and 21 minute intervals compared to the baseline signal before training. The idependent sample t-test of the raw MEP data, t (30) = .86, p = .39, revealed that there was no significant difference between the 30 min. and 6 hr. groups in baseline cortical excitability. The ANOVA of the raw MEP data revealed a main effect of session indicating that cortical excitability significantly changed across the three TMS sessions ($F_{(2,60)} = 5.87$, $p < .005$, $\eta_p^2 = .17$) (Figure 7B). Post-hoc tests revealed that cortical excitability was significantly increased at the 6 min (+.11±.03 mV; paired t test, $t_{(31)} = 3.18$, $p = .003$) and 21 min (+.07±.03 mV; paired t test, $t_{(31)} = 2.15$, $p = .03$) TMS sessions compared to the baseline session. There was no significant difference between the 6 min and 21 min TMS sessions ($p = .19$). The main effect of Delay-retention ($p > .20$) and Delay-retention × Block interaction (p > .41) were not significant. The normalized MEP amplitudes at the 6 min. (28% ±8.7%; $t_{(31)} = 3.19$, $p = .002$) and 21 min. (21% ±8.3%; $t_{(31)} = 2.53$, $p = .009$) TMS sessions were significantly different from zero based on one sample t-tests.
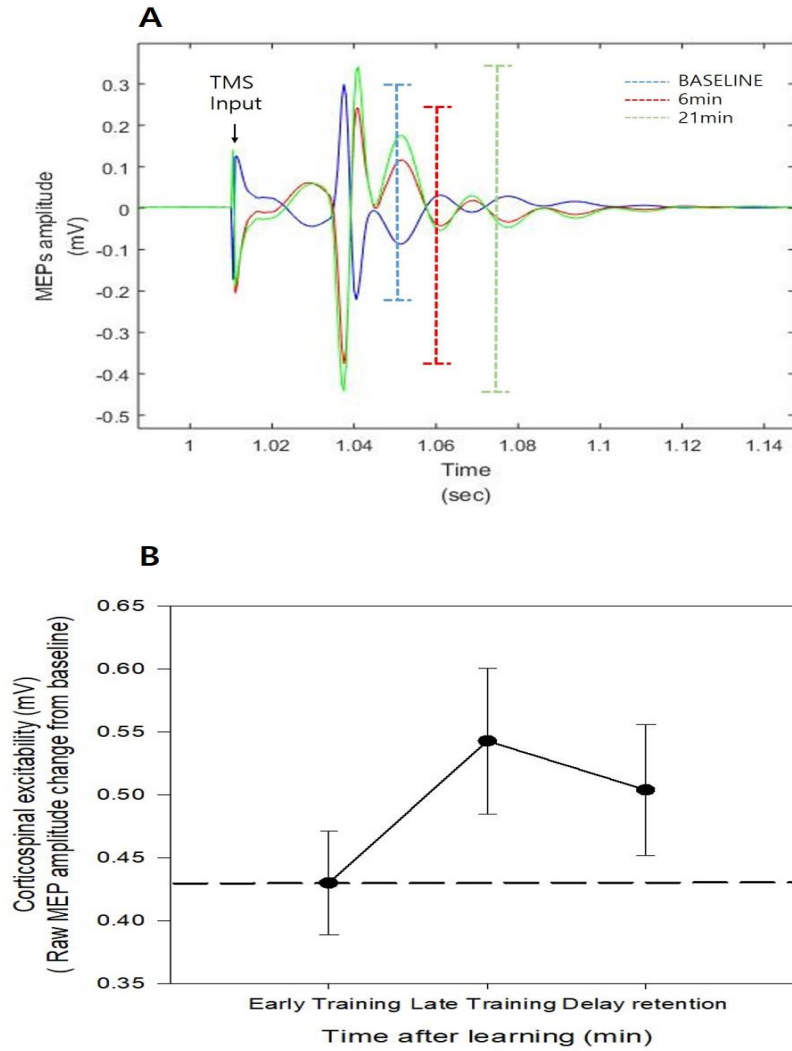
Figure 7. An example of an averaged MEP signal at each time point (A). Raw MEP mean amplitudes from the baseline, 6min, and 21 min time point are plotted. The dotted line denotes the baseline and error bars represent SEM.

3.2 Task performance

3.2.1 Bimanual accuracy

The analysis of the ϕ_{AE} data revealed a significant change in task performance across the training Blocks ($F_{(2,60)} = 37.37$, $p < .001$, $\eta_p^2 = .55$) (Figure 8A). Post hoc (p

< .05) comparisons of the Block effect found the ϕ_{AE} value to be significantly larger for the early training Block 1 trials compared to the late training Block 2 and delay-retention Block 3 trials. There was no difference between Blocks 2 and 3. The main effect of Delay-retention ($F_{(1,30)} = .42$, $p = .51$) and the Delay-retention × Block interaction effect ($F_{(2,60)} = .49$, $p = .61$) were not significant.

Figure 8. Absolute error (ϕ_{AE}) of relative phase and (A) and relative phase variability (ϕ_{SD}) (B) for early learning (Block 1), late learning (Block 2), and post-training trials (Block 3) are plotted. The asterisk represents a significant difference between the early learning trial block and the late-learning and post-training blocks. Error bars represent SEM.

3.2.2 Bimanual stability

The analysis of ϕ_{SD} revealed a significant change in relative phase variability across Blocks ($F_{(2,60)} = 18.98$, $p < .001$, $\eta_p^2 = .38$) (Figure 8B). Post hoc (p < .05) omparisons of the Block effect found coordination variability to be significantly larger in the early training Block 1 trials compared the late training Block 2 trials and the Delay-retention Block 3 trials. There was no difference between the Block 2 and Block 3 trials

(Figure. 8B). The Delay-retention effect ($F_{(1,30)} = 1.39$, $p =.24$) and Delay-retention $\times$ Block interaction effect ($F_{(2,60)} = .23$, $p =.79$) were not significant.

3.2.3 Time on task

The analysis of the BW45 data revealed a significant difference across Blocks ($F_{(2,60)} = 37.02$, $p < .001$, $\eta_p^2 = .55$) (Figure 9A). Post-hoc tests ($p < .05$) of the Block effect found that the time spent on task in Block 1 was significantly shorter than the late training Block 2 trials and the Delay-retention Block 3 trials. There was no difference between the Block 2 and Block 3 trials (Figure. 9A). The Delay-retention ($F_{(1,30)} = 0.37$, $p =.54$), and Delay-retention $\times$ Block interaction ($F_{(2,60)} = 0.57$, $p = .56$) were not significant.
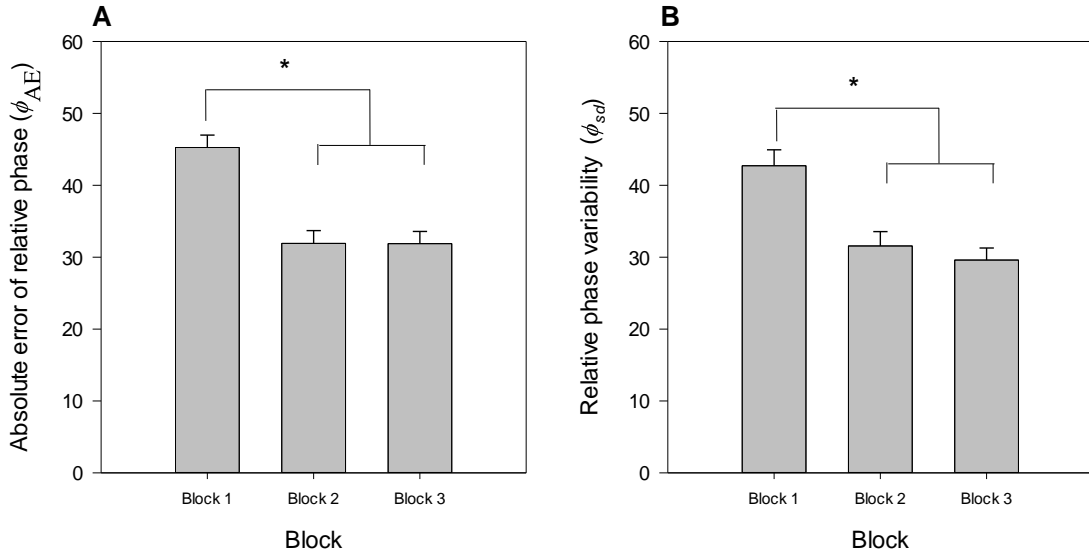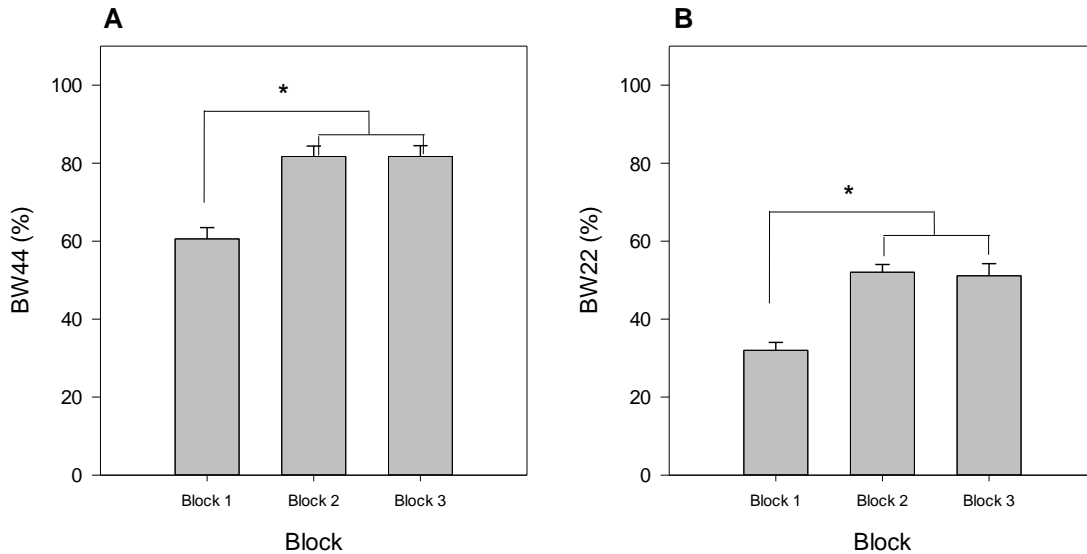

Figure 9. The time on task means (A: BW45, B: BW22) from the early-learning (Block 1), late-learning (Block 2), and post-training trials (Block 3) at the target relative phase of 90˚ are plotted. The asterisk represents a significant difference between the early learning trials and the other blocks. Error bars represent SEM.

The analysis of the BW22 data found a main effect of Block ($F_{(2,60)} = 34.92$, $p < .001$, $\eta_p^2 = .53$) (Figure 9B), while the Delay-retention effect ($F_{(1,30)} = .43$, $p = .51$) and the Delay-retention $\times$ Block interaction effect ($F_{(2,60)} = .55$, $p = .57$) were not significant. Post-hoc tests ($p < .05$) of the Block effect found that the time spent on task in Block 1 was less compared to the time spent on task in the late training Block 2 trials and the Delay-retention Block 3 trials. There was no difference between the Block 2 and Block 3 trials (Figure. 9B).

3.2.4 Movement frequency

The analysis of the movement frequency data revealed a significant change in movement frequency across Blocks ($F_{(2,120)} = 45.00$, $p < .001$, $\eta_p^2 = .42$) and Delay-condition and Finger interaction ($F_{(1,60)} = 4.88$, $p = .032$, $\eta_p^2 = .07$) was a significant (Figure 10A). Post hoc comparisons of the Block effect found movement frequency to increase significantly from the early training Block 1 trials compared the late training Block 2 trials ($p < .05$), with frequency remaining fixed from Block 2 to Block 3 (Figure. 10A). Post hoc comparisons of the Delay-retention and Finger interaction effect found left finger movement frequency (.79 Hz. ±.09) was faster than the right finger (.57 Hz. ±.14) for the 30 min Delay group. Whereas, the right finger movement frequency (.74 Hz. ±.13) was faster than the left hand (.50 Hz. ±.07). Movement frequency of The Delay-retention effect ($F_{(1,30)} = .34$, $p = .55$), Delay-retention $\times$ Block interaction effect ($F_{(2,120)} = .36$, $p = .69$), Finger $\times$ Block interaction ($F_{(2,120)} = 2.68$, $p = .07$), and Delay-retention $\times$ Finger $\times$ Block interaction ($F_{(2,120)} = .15$, $p = .85$) were not significant.

3.2.5 Movement amplitude

The analysis of the movement amplitude data found a main effect of Block ($F_{(2,120)} = 29.74$, $p < .001$, $\eta_p^2 = .33$) and Finger ($F_{(1,60)} = 32.94$, $p < .001$, $\eta_p^2 = .35$) (Figure 10B), while the Delay-retention effect ($F_{(1,60)} = .19$, $p = .66$), Delay-retention × Finger ($F_{(1,60)} = .08$, $p = .76$), Finger × Block ($F_{(1,60)} = .61$, $p = 54$), Delay-retention × Finger × Block ($F_{(2,120)} = .02$, $p = .98$) and the Delay-retention × Block interaction effect ($F_{(2,120)} = .29$, $p =.74$) were not significant. The amplitude of left hand (3.53±.55) was significantly larger than the right hand (2.76±.42). Post-hoc tests revealed that movement amplitude increased significantly from Block 1 to Block 2 (p< .05), while remaining constant from Block 2 to Block 3 (Figure. 10B).
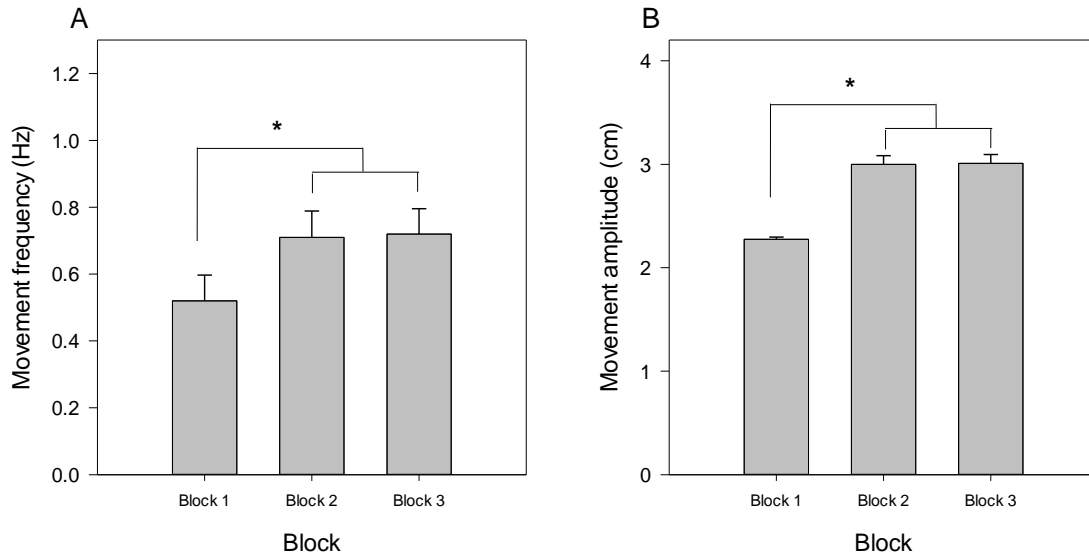

Figure 10. The movement frequency (A) and amplitude (B) from the early-learning (Block 1), late-learning (Block 2), and post-training trials (Block 3) at the target relative phase of 90° are plotted. The asterisk represents a significant difference between the early learning trials and the other blocks. Error bars represent SEM.

3.3 Recognition test

3.3.1 Percentage of correct response

A chi-square test was performed to test the null hypothesis that the variables correct response and Delay-retention group (30 min. and 6 h.) are independent. The chi-square test was not significant, $X^2(1, N = 1152) = 3.12, p = .07$, indicating that the variables correct response and Delay-retention group are independent. The percentage of correct response for the 30 min Delay-retention group was 45.8% and the 6hr Delay-retention group was 51%. A chi-square test was performed to test the null hypothesis that the variables correct response and relative phase pattern (0°, 45°, 90°, 180°) are independent. The chi-square test was significant, $X^2(3, N = 1152) = 117.07, p < .00$. The null hypothesis can be rejected, indicating that the variables correct response and relative phase pattern are not independent (Figure 11A). The percentage of correct responses for the four relative phase patterns was as follows: 90°: 74.3%, 0°: 48.6%, 180°: 43.1%, and 45°: 30.6%). (Figure. 11A). The analysis of the percentage of correct responses (after arcsin transform) found a main effect of Pattern ($F_{(3,120)} = 15.06, p < .001, \eta_p^2 = .27$), while the Delay-retention effect ($F_{(1,120)} = .76, p = .38$) and the Delay-retention × Pattern interaction effect ($F_{(3,120)} = .49, p = .68$) were not significant. Post-hoc tests of the Pattern effect found that the percentage of correct responses for the 90° pattern was higher compared to other three patterns' percentage of correct responses (Figure 11A). There were no differences between the remaining three patterns.
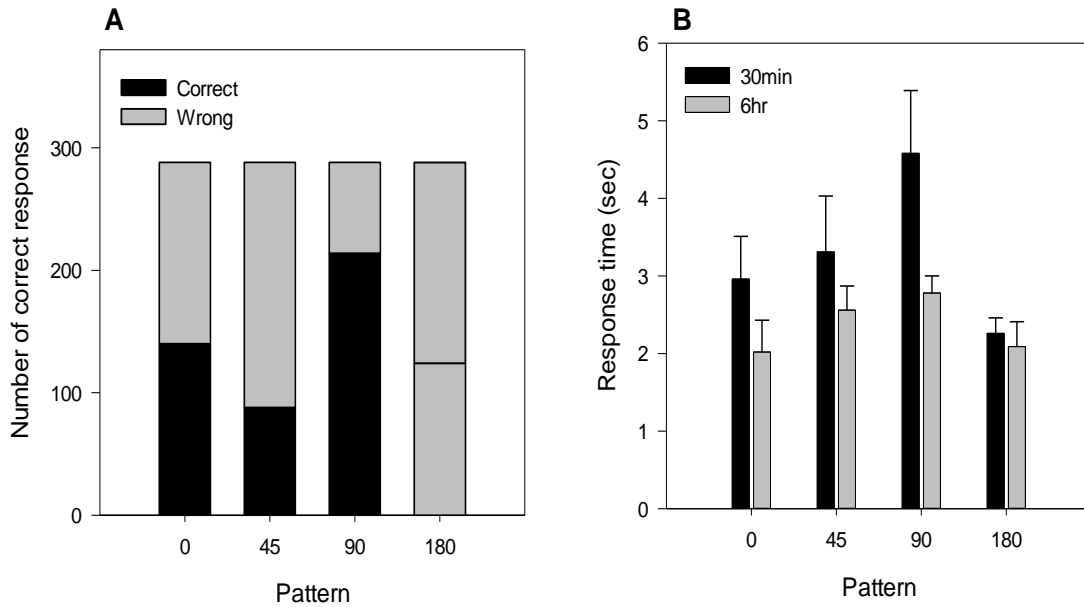
Figure 11. Total number of correct perceptual responses are represented by the black shading while the gray shading represents the number of wrong responses (A). Mean response time (B) in the recognition test is plotted as a function of the four relative phase patterns. Error bars represent SEM (B).

3.3.2 Time to perceptual responses (TtPR)

The analysis of the TtPR data revealed significant main effects of Delay-retention ($F_{(1,120)} = 7.09$, $p < .009$, $\eta_p^2 = .05$) and Relative phase pattern ($F_{(1,120)} = 3.59$, $p < .017$, $\eta_p^2 = .08$). The Delay-retention × relative phase pattern interaction ($F_{(3,120)} = 0.96$, $p = .41$) was not significant. Overall, the 6 hr. Delay-retention group (Mn = 2.36, Std. Dev. = 1.22) had a shorter TtPR than the 30 min group (Mn = 3.28, Std. Dev. = 2.55). Post-hoc tests of the Pattern effect found that the longest TtPR was associated with the 90˚ pattern images compared to the other three patterns. There was no difference between the 0˚, 45˚, and 180˚ pattern images. The largest difference between groups was associated with images for the 90° relative phase pattern. An a-posterior independent t-test, *t* (30) = *2.13, p < .05,*

revealed that the 6 hr. delay group had a shorter TtPR for the 90° relative phase pattern compared to the 30 min delay group (Figure. 11B).

4. DISCUSSION

The primary goal of the present experiment was to extend the findings of recent experiments demonstrating the link between cortical excitability change and motor skill performance in bimanual tasks and serial reaction time tasks (Nomura et al., 2016; Tunovic et al., 2014). Recent sequential learning research has suggested that cortical excitability changes associated with implicit or explicit SRTT motor tasks are tightly linked to differences in cortical excitability changes that occur after practice and are responsible for controlling off-line improvements (Tunovic et al., 2014). A recent bimanual experiment found increased cortical excitability during the performance of the less stable 90˚ pattern compared to the intrinsically stable in-phase and anti-phase pattern bimanual patterns (Nomura et al., 2016). Whether cortical excitability is enhanced for an extended period of time post-training with an unlearned bimanual task has not been documented. The present experiment sought to determine if cortical excitability changes would emerge after training with the less stable 90° bimanual pattern, and whether or not the excitability pattern if it did emerge would be more consistent with activity changes following training with an implicit or explicit SRTT.

Participants trained with the 90˚pattern over a 20 minute interval with concurrent feedback provided with a Lissajous plot/template. Overall, post-training MEPs increased compared to baseline MEPs after training with the 90° bimanual coordination task. The current results expend the Nomura et al. (2016) findings that cortical excitability increases while performing the 90˚ pattern and demonstrate an increase in cortical excitability that is maintained for 21 min. post-training. Tunovic et al. (2014) reported that post-training

MEPs after the implicit and explicit task were larger at a 21 min delay from the completion of the training and maintained until 2 hr later. A 6 minute delay after training with the implicit task in the Tunovic et al. study was characterized by a non-significant increase in MEP amplitude above baseline, with a significant decrease in MEP amplitude below baseline after tranining with an explicitt task. In the current task, a significant increase in MEP amplitude was found at 6 minutes compared to baseline. Overall, the pattern of M1 excitabilty change in the current task was more like that found after tranining with the implicit SRTT in the Tunovic et al. (2014) study. Some studies have shown that disruption of post-training M1 activity with rTMS immediately (Muellbacher, Ziemann, Wissel, Dang, & Kofler, 2002; Robertson et al., 2005) blocks off-line consolidation. The finding of the current study coincides with the idea that increased M1 activity may play a crucial role in the early consolidation phase of motor skill learning that is implicit in nature.

One plausible explanation for the increase in cortical excitability is that the activity of M1 increased due to the cost of effort in producing the 90˚ pattern (Nomura et al., 2016). A brain imaging study conducted by Debaere et al. (2003) found that movement externally guided by integrated visual feedback was associated with increased activity in the superior parietal cortex, premotor cortex, thalamus, and cerebellar lobule VI. Without integrated visual feedback, activity was increased in the basal ganglia, supplementary motor area, cingulate motor cortex, and cerebellar lobule IV-V/dentate nucleus (Debaere, Wenderoth, Sunaert, Van Hecke, & Swinnen, 2003). A subsequence experiment by Debaere et al. (2004) observed that highly involved brain areas during early learning of a novel coordination pattern were the same areas activated when the movement was

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externally guided with visual feedback, whereas, the highly involved areas when the participant's coordination pattern reached a performance plateau by the end of practice were different areas, such as primary motor, cingulate motor, premotor and basal ganglia, together with cerebellar dentate nuclei. These areas are consistent with the highly activated areas when the movements were internally generated (Debaere, Wenderoth, Sunaert, Van Hecke, & Swinnen, 2004; Rémy, Wenderoth, Lipkens, & Swinnen, 2008). More importantly, with repect to M1, learning related activations have been observed following the intensive practice with sequential finger movement tasks (Kami et al., 1995) and bimanual coordination tasks (Debaere et al., 2004; Nomura et al., 2016). A prominent increase in M1 activation was obvious following intensive practice, but no such increase was observed after the practice of in- or anti-phase patterns or untrained sequence (Kami et al., 1995; Nomura et al., 2016). In the present study, participants were trained with integrated Lissajous feedback throughout the entire experiment and quickly tuned in the desired coordination pattern and maintained their skill level to the retention test. This result indicates that increased post-training MEPs of M1 were elicited by the acquisition of the novel coordination pattern.

The use of the Lissajous plot allowed participants to rapidly improve in the performance of the 90° relative phase pattern across a 20 minute training interval. Relative phase error decreased, coordination stability increased, and the BW measures revealed a change in the strength of the attraction of the 90° from the early training block to late training block. All of the results are consistent with previous results that have used the Lissajous plot to rapidly train individuals on less stable and more difficult bimanual

patterns in comparison to in-phase and anti-phase (Buchanan & Wang, 2012; Kovacs et al., 2009a, b; Kovacs, Buchanan, & Shea, 2010). Participants performed the retention test at either a 30 min. and 6 hr. delay after completing the initial training bout. The Lissajous plot was present during the delay-retention test, similar to sequencing tasks that use the visual stimulus to drive the sequence of key presses. Performance did not improve over either delay interval, performance also did not decrease. This lack of off-line improvement is inconsistent with previous studies that demonstrated off-line enhancment following training with an implicit motor sequence task (Press et al., 2005; Robertson et al., 2004b; Tunovic et al., 2014). SRTT studies suggest that off-line enhancement can start to emerge after at least a 6 hr delay between practice and retesting (Wilson & McNaughton, 1994). However, Robertson et al. (2004a) asserted that off-line skill enhancment is not a general motif of all procedural learning. Specifically, kinematic adaptation and dynamic adaptation experiments have not convincingly shown off-line improvement (Brashers-Krug, Shadmehr, & Bizzi, 1996; Krakauer, Ghilardi, & Ghez, 1999). Participants in force adaptation studies modify their movement corresponding to the applied force in order to produce accurate reaching movements. Participants quickly adapt and produce a desirable reaching trajectory. However, small skill increases in the re-test trials compared to the beginning of the training do not necessarily represent off-line improvements (Robertson et al., 2004a), and may represent more of an off-line stabilization process. Stabilization is the idea that performance from the end of practice to the retest remains constant, i.e., a loss in the performance gain does not emerge. The current findings are consistent with the idea of off-line stabilization occurring after 30 min. and 6 hr. Performing a bimanual

coordination task with the cursor on the Lissajous template would be considered a short-term adaptation with online feedback control (Shea, Buchanan, & Kennedy, 2016). Participants can show remarkably low relative phase error and variability after only 5 min of practice with Lissajous feedback, but when the feedback is withdrawn error and variability increase significantly (Kovacs et al., 2009a). Shea et al. (2016) asserted that the participant's movement is externally defined and driven when the integrated Lissajous feedback is available, and performance degradation indicates that participants have not developed an internal representation in the form of developing an attractor within the landscape of relative phase. The Lissajous was not removed in the current retest context. Future work needs to explore whether or not increased time delays may remove any dependence of the Lissjaous plot for performance. Although the performance data did not reveal off-line enhancment, the perceptual discrimination test suggests that a difference was emerging between the 30 min and 6 hr group.

To examine the implicit/explicit nature of the bimanual coordination task, participants performed a perceptual discrimination test immediately after the delayed retention test. Both groups of participants were able to discriminate the static finger motions representative of the trained 90° (74.3%) pattern more consistently than the static images associated with the other three patterns (0˚: 48.61%, 45˚: 30.55%, 180˚: 43.05%). The motor skill training process selectively influenced the perceptual discrimination of the action without the direct vision of the movements. Experimental evidences suggests a link between the perception and production of actions such that an increased production capability emerging through motor training/learning should improve the visual

recognition of action (Buchanan, 2016; Calvo-Merino, Glaser, Grèzes, Passingham, & Haggard, 2005; Calvo-Merino, Grèzes, Glaser, Passingham, & Haggard, 2006; Casile & Giese, 2006; Maslovat et al., 2010; Park & Buchanan, 2018). Physical practice with dancing routines has been shown to improve competency ratings, a form of internal perceptual evaluation, to perform the rehearsed sequences compared to unpracticed routines (Cross, Hamilton, & Grafton, 2006). Similar changes in competency after training have also been observed in single-limb tasks following training with novel relative phase patterns (Buchanan, 2015; Buchanan et al., 2015). A study investigating the visual recognition of gait patterns from point-light stimuli that desociated visual and motor learning have revealed that subjects learn novel upper-body movements without visual stimulation showing selective improvement in the visual recognition of the learned motor pattern (Casile & Giese, 2006). This is consistent with the previous bimanual studies that have shown that training with the relative phase pattern of 90˚ improved the perceptual discrimination ability regarding the trained pattern (Maslovat et al., 2010; Park & Buchanan, 2018). In terms of the relative phase pattern of 90˚, Park & Buchanan (2018) revealed that physical training and observational training can enhance the ability to discriminate the trained pattern perceptually (see also, Buchanan et al., 2015).

Overall, the 6 hr. delay-retention group evaluated the static images more quickly than the 30 min. delay-retention group. This suggests that 6 hr group may have an advantage as a result of the longer time between training and retraining. Although a Delay-retention × pattern interaction was not found in the ANOVA of the TtPR data, the means suggest the 6 hr. delay-retention group responded faster than the 30 min delay group for

the 90˚ pattern. This was tested with an independent sample t-test, The t-test indicated that the TtPR mean for the 6 hr group was significnalty shorter than the 30 min group when evaluating the 90° pattern. The faster TtPR after the 6 hr. delay- may be an indicator of consolidation in the form of off-line enhancement with regard to perceptual discrimination processes that should depend on the ability to more accuractly produce the pattern based on a number of studies (Buchanan et al., 2015; Maslovat et al., 2010; Park & Buchanan, 2018). Even though the participants were able to perceptually discriminate the trained pattern, a concept more consistent with learning a task explicitly, the changes in the post-training MEPs were more consistent with participants that learned an implicit version of the SRTT (Tunovic et al., 2014). This result indicates that the memory processing pathway associated with the bimanual coordination pattern is different from that of an implicit or explicit version of SRTT.

5. CONCLUSIONS

Both delayed retention groups showed improvement in performance over training and maintained their acquired skill level in the delayed retention trials. In the current task, participants' M1 cortical excitability increased after training. Off-line differences in motor skill consolidation were not found as a function of delay-interval. The use of the Lissajous plot most probably nullified any possible consolidation differences in the form of off-line enhancement with regard to motor skill performance. However, the TtPD findings are suggestive of possible consolidation changes emerging in the 6 hr delay compared to the 30 min delay group with regard to perceptual discrimination processes linked to action production. The changes in post-training MEPs associated with the memory representation regarding bimanual coordination task is distinct from that of SRTT. Future research needs to further clarify post-training changes in MEP following bimanual coordination training.

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