MEMORY CONSOLIDATION IN LEARNING A BIMANUAL

COORDINATION SKILL

A Thesis

by

CHAOYI WANG

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2012

Major Subject: Kinesiology

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Committee Members,   David L. Wright
    Steven M. Smith
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ABSTRACT

Memory Consolidation in Learning a Bimanual Coordination Skill. (May 2012)

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Chair of Advisory Committee: Dr. John J. Buchanan

The present study was conducted to examine the process of consolidation when learning a difficult bimanual coordination pattern. There are two phenomena associated with the process of consolidation, an enhancement in performance without additional practice and the stabilization following an interference task. Both phenomena have been widely examined in sequence skill learning studies. However, few studies have examined the consolidation effect after training with a continuous and rhythmic bimanual coordination pattern. The first goal of this study was to determine if sleep enhances the performance of a minimally trained 1:2 pattern of bimanual coordination in a manner that has been observed with sequencing skills: that is, will performance significantly improve after an overnight sleep? A recent study by Buchanan & Wang (in-press) showed that by manipulating the position of a visual-augmented-feedback cursor, either behind or to-the-side of a 1:2 bimanual coordination template, an advantage of the side cursor position was found in the no-feedback retention test after a fifteen-minute break. The second goal of this study was to determine whether an overnight sleep interacts with the position of visual feedback during training and thus overrides the

difficulty in performing a continuous bimanual coordination task during a no-feedback retention test.

In the present experiment, the effect of an overnight sleep on learning a 1:2 pattern of bimanual coordination was accessed with six test trials presented immediately (IMM group) or 24 hours (SLEEP group) after 5 minutes of practice. The test trials included three trials with feedback and three trials with feedback removed. For either the IMM or SLEEP group, half of the participants practiced with the behind cursor position and the other half practiced with the side cursor position.

The results indicated that the SLEEP group showed an improvement in performance from the acquisition trials to the feedback test trials whereas the IMM group did not. The advantage of the side cursor position at the no-feedback retention test was not evident in the current study. These results are consistent with our two predictions and provide some evidence of sleep associated enhancement in learning a 1:2 pattern bimanual coordination skill.

DEDICATION

This thesis is dedicated to my beloved parents, for their endless love and encouragement.

ACKNOWLEDGMENTS

I would like to express my deep gratitude to the members of my committee. I want to especially thank the chair of my committee, Dr. John Buchanan. I really appreciate your guidance and each of your insightful feedbacks on my writings and presentations over the past three years of my graduate study. I would also sincerely thank Dr. David Wright and Dr. Steven Smith. Thank you so much for always being supportive and unreservedly providing brilliant ideas and suggestions on my thesis project.

Special thanks to Dr. Charles Shea and Dr. Carl Gabbard for your unlimited caring and encouragement as well as much help on coursework studies since I came to our Human Performance Labs. I will never forget your sincere words, especially when I was encountering a difficult time in life.

Many thanks are extended to my friends Joohyun Rhee, Yen-Ting Chen, Osmar Neto, Carol Marzullo, Attila Kovacs, Brittney Oliver, Deanna Kennedy, Jason Boyle, Ivan Pereira and Priscila Cacola, for their friendships and assistance on my graduate study in the United States. Special thanks to Joohyun Rhee for the many times he helped me by checking programing problems in the current study and to Attila Kovacs for providing the programs used in his study.

In addition, I would also like to thank Drs. Patricia Goodson, Gladys Ko, Tamy Frank-Cannon, and Michael Massett for their tutorings and kind suggestions, especially

when I got stuck in studying their courses. I would particularly like to thank Dr.

Goodson for her dedicated attitude in sharing her advice on the writing process.

My final thanks are extended to the support of the Department of Health and

Kinesiology and its awesome staff team during my three-year education at Texas A&M

University.

NOMENCLATURE

IMM	Immediate Group
SLEEP	Sleep Group
LA	Left Arm
RA	Right Arm
AC	Acquisition
FB	Feedback
NF	No-feedback
RMSE	Root Mean Square Error
SD	Standard Deviation
MCD	Mean Cycle Duration
FR	Frequency Ratio
AMP	Amplitude
RMS	Root Mean Square
SE	Standard Error

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CHAPTER I

INTRODUCTION

Consolidation

When playing a piano or playing the drums, the motor system must sequence together many individual movements (piano) and/or coordinate the arms with different rhythms. The acquisition of such complex motor skills requires the consolidation of action patterns with practice, a process referred to as motor learning. The process of motor skill learning must be inferred from a relatively permanent improvement in performance as a result of practice and experience (Magill, 2007). The improvements in performance can be generally categorized into two phases: (1) a within-practice-session phase; and (2) a time-dependent between-practice-session phase (Korman et al., 2007). *Memory consolidation*, a process of strengthening newly formed memories, often can be reflected by the latter phase (Korman et al., 2007). When consolidation of a motor skill has occurred, the performance of that skill will finally move to the automatic stage, which requires little attentional efforts (Doyon et al., 2009). Consolidation as a memory process may be broken down into two different behavioral phenomena. The first is the phenomenon of *enhancement or off-line improvement* in performance that occurs without any additional practice. The second is the phenomenon of *memory stabilization* that can be observed as resistance to interference from a similar task after acquisition of a novel skill (Goedert & Willingham, 2002; Robertson, Pascual-Leone, & Miall, 2004).

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This thesis follows the style of *Journal of Motor Behavior*.

The phenomena of enhancement and stabilization as part of the process of motor skill learning have been broadly examined through the use of sequential motor tasks in numerous learning studies (Goedert & Willingham, 2002; Walker, Brakefield, Hobson, & Stickgold, 2003; Walker, Brakefield, Morgan, Hobson, & Stickgold, 2002). A study by Korman et al. (2007) using a sequencing task demonstrated that an enhancement in sequence learning required sleep after training. The task required participants to use four fingers of the non-dominant hand – index, middle, ring and small finger represented as 1, 2, 3, 4 respectively – to tap a specific keyboard sequence (4, 1, 3, 2, 4). They practiced the sequence in the morning, and their performances were retested on the sequence eight or 22 hours later. The 22-hour retest included a normal overnight sleep period. A significant increase in the average number of correct sequences as compared to performance outcomes that tested immediately after the first training session was seen in the 22-hour retest group, but not in the eight-hour retest group. This off-line gain that appeared in the 22-hour retest group was taken as evidence that enhancement of the motor skill occurred without further practice following an overnight sleep period.

Korman et al. (2007) also demonstrated that the stabilization of the above-mentioned sequence (seq-A: 4, 1, 3, 2, 4) required at least two hours of wakefulness after initial training. Participants were trained with an opposite number-order sequence (seq-B: 4, 2, 3, 1, 4) eight hours or two hours after their initial practice with seq-A and then tested on seq-A after an overnight sleep. The results showed that a 24-hour off-line improvement in the performance of seq-A occurred when training on seq-B appeared eight hours after learning seq-A; but was abolished when training with seq-B appeared

two hours after learning seq-A. This indicates that during wakefulness, the motor memory for seq-A was in an unstable state at two hours after training, but was stabilized within eight hours after training. Thus, once the motor memory is stabilized, it will be resistant to interference allowing the acquired motor skill to be performed in spite of a long period of time without additional practice (Doyon et al., 2009). Moreover, it is well accepted that for sequence/discrete skills the phenomenon of stabilization often appears before the phenomenon of enhancement (Walker, 2005).

Discrete vs. Continuous Skills

How generalizable are the findings on enhancement and stabilization of a sequence motor skill to a rhythmic and continuous skill? Research has revealed differences between discrete-sequence motor skills and rhythmic-continuous motor skills in terms of kinematic and neurological characteristics. With regard to kinematic characteristics, rhythmic and continuous limb motion is smooth and harmonic, with acceleration peaks occurring as a limb reverses motion direction and velocity goes through zero (Buchanan, Park, & Shea, 2006; Buchanan, Park, Ryu, & Shea, 2003; Guiard, 1993, 1997; Mourik & Beek, 2004). In contrast, when you start or stop a discrete motion, or string together a series of discrete actions, acceleration and velocity approach zero simultaneously when the motion reaches a stop. Thus, the sequence/discrete skill is decomposable or segmented whereas a continuous/rhythmic skill is not. In addition, the use of energy in a continuous skill is typically very efficient in which energy stored in the skeletal muscle at the end of a cycle benefits the next cycle (Cavagna, 1977; Van Ingen Schenau, 1989).

In addition to the kinematic features, human functional neuroimaging (fMRI) techniques have identified that the cortical activation patterns of rhythmic-continuous movements are different from discrete-sequential movements suggesting unique control mechanisms (Schaal, Sternad, Osu, & Kawato, 2004). In an experiment by Schaal et al. (2004), participants produced wrist flexion-extension movements with one arm in either a rhythmic-continuous or discrete-sequential way. The fMRI results showed that the rhythmic-continuous movement was associated with contralateral activity in the primary sensorimotor cortex, premotor cortex, supplementary area, cingulate cortex and the ipsilateral side of the cerebellum. In contrast, the discrete-sequential movement was associated with bilateral activity in the above mentioned cerebral and cerebellar areas, along with activity in the dorsal premotor cortex, Broca's area, parietal cortex, and rostral cingulate zone. The additional activated brain areas for the discrete-sequential movement indicated that more motor planning was necessary because of the starts and stops associated with the discrete-sequencing actions (Schaal et al., 2004). Taken together, the kinematic and brain imaging findings suggest the differences in the control processes underlying the production of discrete-serial and rhythmic-continuous motor skills. This raises the question of whether or not enhancement and stabilization as processes indicative of motor skill learning will also emerge in continuous rhythmic tasks on the same time scale as in sequential motor tasks.

Bimanual Coordination Learning

In terms of learning rhythmic-continuous skills, there are a lot of studies that have used the bimanual coordination paradigm (Swinnen, Dounskaia, Walter, & Serrien,

1997; Swinnen, Lee, Verschueren, Serrien, & Bogaerds, 1997; Zanone & Kelso, 1992), but none were specially designed to study the process of consolidation in the same manner as examined by Korman et al. in sequencing tasks (2007). The underlying hypotheses for the bimanual work focused on motor learning in terms of the within-practice-session phase. The process of enhancement and stabilization as a function of sleep (between-practice-session phase), have yet to be studied within the rhythmic bimanual coordination learning paradigm.

Sequence skill requires the recurring motion of one arm or one set of fingers and can usually be learned in a single day of practice. In contrast, bimanual coordination requires the motions of both arms, and learning novel bimanual patterns usually takes 2 to 5 days of practice (Swinnen, Lee, et al., 1997; Zanone & Kelso, 1992). A recent study by Kovacs et al. showed that the rate of tuning a multi-frequency bimanual pattern can be accelerated by providing appropriate feedback and removing competing attentional resources (Kovacs, Buchanan, & Shea, 2010a). In the Kovacs et al. study, participants were able to tune a 1:2 pattern of bimanual coordination with only 5-minutes of practice when visual augmented feedback of the arms' motion was represented by a single dot tracing a Lissajous template of a perfect 1:2 pattern on a computer screen (Figure 1A). In this way, participants can easily detect error of their motion by comparing the distance between the dot and the goal Lissajous plot template. Kovacs and colleagues demonstrated that rapid tuning only occurred when movement pace was (1) self-controlled versus externally paced and (2) the arms were covered versus uncovered (Kovacs, Buchanan, & Shea, 2009a, 2010a). The conclusion was that competing

attentional factors in the form of metronomes and vision of the arms make it difficult to

produce multi-frequency patterns (Kovacs, Buchanan, & Shea, 2009a, 2010a).
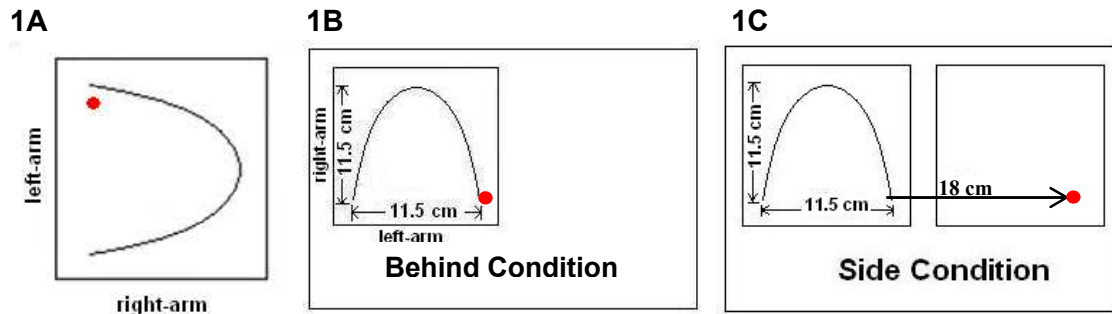
FIGURE 1. The feedback display in Kovacs et al. (2010a) (A). A comparison between the behind position feedback display (B) and side position feedback display (C).

However, there is a caveat of the Lissajous feedback display for learning a

bimanual coordination skill – participants' performance immediately deteriorates when

feedback is removed. Participants in Kovacs et al. (2009) could hardly perform the

pattern when feedback was removed, indicating that they did not actually learn the

bimanual coordination pattern but depended on the augmented visual feedback to guide

their movement. This can be explained by the "guidance hypothesis" which suggests that

when feedback is provided too often during the process of learning, performers begin to

depend on the feedback (Schmidt, Young, Swinnen, & Shapiro, 1989). The

overdependence on feedback during practice prevents performers from processing

important task-related information that may support the initial stabilization process.

Feedback benefits learning only when it is provided less frequently or less immediately

(Ho & Shea, 1978; Winstein & Schmidt, 1990). A recent study by Buchanan & Wang

(in-press) solved the problem of guidance following only 5 minutes of practice

(Buchanan & Wang, in-press). Participants in the Buchanan & Wang study were

assigned to two groups: One group used the same type of feedback as Kovcas et al.

(2010a) – a single dot representing the movement of two limbs superimposed on top of a

perfect 1:2 pattern template (behind group) (Figure 1B). The feedback display for the

behind group contains the same amount of perceptual information as Kovacs et al.

(2010a). For the other group, the same single dot representing the coordination between

two limbs was moved to the side of the template, with a 18 cm distance between the dot

and the template (side group) (Figure 1C). After five minutes of acquisition and

following a fifteen minute break, both behind and side groups were retested on the 1:2

pattern with and without the augmented visual feedback provided. When visual feedback

was presented, both groups showed significant improvement in performance in the test.

However, only the side group participants were able to perform the 1:2 pattern of

bimanual coordination when the visual feedback was removed. Similar to the results in

the Kovacs et al. (2009a) study, the behind group training lead to guidance, whereas the

side training protocol eliminated the guidance effect (Buchanan & Wang, in-press).

The findings that the side group participants in Buchanan & Wang (in-press)

were able to perform the bimanual coordination pattern when visual feedback was

removed opens a window to use the bimanual coordination paradigm to study the

process of consolidation in continuous skill learning. The improvement in performance

after the 15 minute break is similar to the *phenomena of enhancement* – an improvement

in performance without extra practice – which has been extensively reported in sequence

learning studies (Fischer, Hallschmid, Elsner, & Born, 2002; Walker et al., 2002). The differences between sequence motor skill learning and bimanual motor skill learning is that the phenomena of enhancement in sequence learning often appears on the second day and involves an overnight sleep (Walker et al., 2002), whereas in Buchanan & Wang (in-press) enhancement occurred within a 15-minute interval without sleep.

Consolidation in Bimanual Coordination

Let us go back to the question, 'Is the process of consolidation in sequence skill learning generalizable to continuous skill learning?'; the Buchanan & Wang (in-press) study provided some evidence of enhancement in bimanual coordination learning without sleep. However, extended research still needs to delineate the relationship between sleep and consolidation in rhythmic bimanual skill learning in order to answer the question on generalization. The present study was designed to determine if sleep will lead to enhancement following training on a rhythmic bimanual skill.

Purpose and Predictions

This current study will utilize the same experimental paradigm reported in Buchanan & Wang (in-press). The study has two independent variables: Group (immediate, sleep) and Feedback Position (behind, side). Performance for the sleep group (SLEEP) will be tested 24 hours later –involving an overnight sleep – after initial training on a new continuous bimanual skill, whereas performance for the immediate group (IMM) will be tested immediately after initial training. The variable Feedback Position (behind, side) represents the relationship between the cursor display and the template (Figure 1B, C). The current study has two goals: First, to examine if sleep

enhances the performance of a minimally trained 1:2 pattern of bimanual coordination in a manner that has been observed with sequencing skills, that is, performance significantly improves after an overnight sleep. Second, to test whether an overnight sleep may reduce the guidance effect associated with the behind feedback position as reported in Buchanan & Wang (in-press).

Accordingly, we have two predictions: First, performance will significantly improve after an overnight sleep, if enhancement is a process of consolidation underlying rhythmic bimanual skill learning. Second, we also predict that when learning is examined in the no-feedback condition, the behind group will perform equally to the side group after a night of sleep.

CHAPTER II

METHODS

Participants

Thirty-six (7 males, 29 females, average age = 20) Texas A&M undergraduate

students participated in this experiment for course credit. According to a four question

handedness evaluation (Coren, 1993), 34 were classified as right-arm dominate, 1 as left-

arm dominate and 1 as neither left- or right- arm dominate. The experiment protocol and

consent form were approved by the Texas A&M University IRB and all individuals

signed a consent form before participating.

Apparatus

Participants sat in a height-adjustable chair with their arms extended over a 0.7 m

tall table. The participants held two wooden pens and could move the pens anterior-

posterior and medial-lateral in the horizontal plane on the table. Attached to each pen

was an infrared emitting diode (IRED). The 3-D position of the IREDs was recorded

with an Optotrak 3020 camera (Figure 2A). The IREDs were used to provide a real-time

feedback display in the form of a cursor displayed as a red dot on a computer monitor

positioned 2.5 m in front of the participants at a height of 1.5 m. The red dot on the

screen reflected the horizontal motion of the participants' two arms as follows: When the

right arm moved from left to right, the dot moved up and down, and when the left arm

moved from left to right, the dot moved from left to right. Only arm movement in the

medial-lateral direction (x-axis) influenced the motion of the dot; arm movement in the

anterior-posterior direction on the table (z-axis) had no influence on the motion of the

dot. A wooden screen blocked the participants' sight of their arms, forearms and elbows (Figure 2A).

Groups and Procedure

The participants in this experiment were assigned to one of two groups ($N = 36$, 18 per group): One group performed test trials immediately following the completion of the acquisition trials (IMM); the other group (SLEEP) performed the test trials 24 hours later following a night of sleep. Participants in each group were assigned to one of two feedback positions ($N = 18$, 9 per position), a behind-template feedback position and a to-the-side feedback position. For the behind feedback position (Figure 1B), the cursor appeared in the same window with the 1:2 (LA:RA) Lissajous template; For the side feedback position (Figure 1C), the cursor appeared in a separate window such that the on-line feedback trace was 18 cm to right of the Lissajous template. For both feedback positions, the axes were equally scaled. The Lissajous template was 11.5 cm wide and 11.5 cm tall, requiring equal displacement with both arms.

The experimenter explained the task and demonstrated how to move the red dot on the screen to the participants. The experimenter also demonstrated the example of making the red dot trace the 1:2 Lissajous plot back and forth without the participants seeing the experimenter's arms move. Before starting, the experimenter gave participants a few practice trials to confirm they understood the experiment. Participants were given ten acquisition trials (30 sec each) to use either the behind or side cursor display to produce the 1:2 multifrequency pattern, and told to focus on the screen, not their arms, and move as fast as possible (Figure 2B). After practice, participants
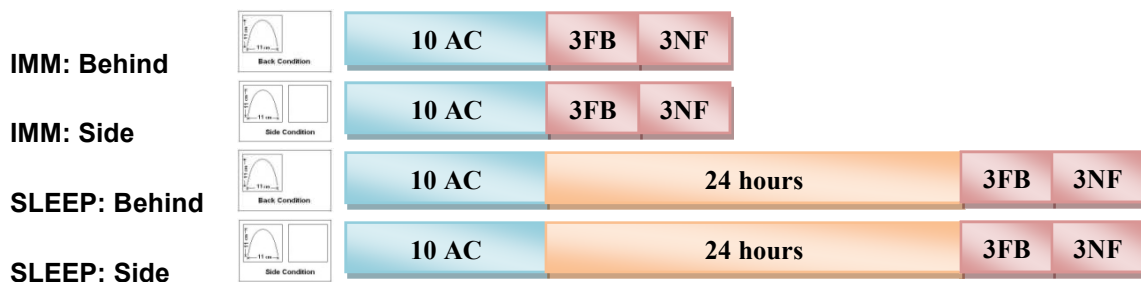
2A
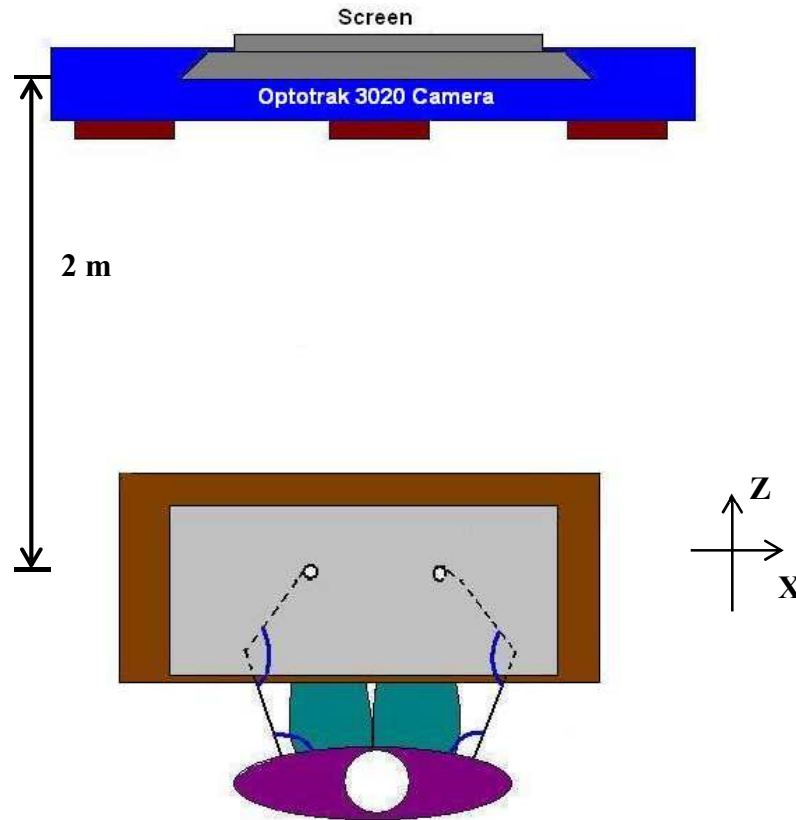
2B

FIGURE 2. The experiment apparatus in current work (A). Groups and procedure in current study (B). 10 AC, 3 FB and 3 NF represents ten acquisition trials, three feedback test trials and three no-feedback test trials respectively.

performed three test trials (30 sec each, trials 11, 12 and 13) with augmented visual

feedback and three test trials without visual feedback (30 sec each, trials 14, 15 and 16).

During the feedback trials, the cursor-display condition was the same as the one used in

the acquisition trials, whereas during the no-feedback trials, the LED screen was turned

off and visual feedback was not provided. For the IMM and SLEEP group, the six test

trials were performed immediately and 24 hours after their 10th acquisition trial

respectively.

Data Collection and Analysis

The IREDs attached to the wooden pens were sampled at 100 Hz and low-pass

filtered (Butterworth, 10 Hz) prior to computing any dependent measures. All dependent

measures were derived using Matlab 7.0 (Mathworks, Inc.).

Relative phase

For each trial, a continuous relative phase measure (ϕ_c) was computed to examine

the spatiotemporal coordination of the limbs during the task. The continuous relative

phase was computed from the x-axis displacement (x) and velocity ($\dot{x}$) time series of the

IREDs attached to the pens. The x and $\dot{x}$ time series were mean centered and rescaled to

the range -1 to 1. A phase angle (θ) for each limb (LA, RA) was computed for each

sampled point (i) as follows (Kelso et al., 1986):

$$\theta_i = tan^{-1}(\dot{x}_i/x_i).$$

The individual limb phase angles were unwrapped over every two cycle epoch of the RA

(faster moving limb) by locating absolute jumps $> 2\pi$ and adding the appropriate 2π

multiple to each data point after the jump. A continuous relative phase between the LA

and RA phase angles was computed for every two cycle epoch of RA motion. The continuous relative phase values over each epoch of RA motion were subtracted from a target relative phase representing a perfect 1:2 multi-frequency ratio between two sinusoidal oscillators, and a root mean square error of relative phase (ϕ_{RMSE}) was computed. The ϕ_{RMSE} values were averaged across a trial and the average provides a measure of goal attainment, with smaller values indicating more accurate performance. Relative phase variability (ϕ_{SD}) was computed as the standard deviation of the signed phase errors in each epoch with the epochs averaged over a trial, and this provides an estimate of the stability of bimanual coordination. Both of the above computations are consistent with those performed by Kovacs and colleagues in their studies (Kovacs, Buchanan, & Shea, 2009a, 2009b, 2010a, 2010b). The ϕ_{RMSE} and the ϕ_{SD} of the last three acquisition (AC) trials (trials 8-10), feedback (FB) test trials (trials 11-13), and no feedback (NF) test trials (trials 14-16) were averaged and analyzed as Blocks.

Mean cycle duration and frequency ratio

First, we calculated the number of cycles within each trial for each arm and report the number of right arm cycles (RA cycles). A mean cycle duration (MCD) for each arm was calculated over the 30-sec trial window (MCD = 30 sec / number of cycles). The mean cycle duration provides a measure of movement rate performance change with practice. The participants were instructed to increase their movement rate after every two trials. The MCD values of the LA and RA were used to compute a frequency ratio (FR) for each trial, FR = MCD_{RA}/MCD_{LA}. The frequency ratio provides a measure of adherence to the goal ratio of 0.5 for the 1:2 multi-frequency pattern.

X-axis and z-axis movement amplitude

For each trial and arm, a movement amplitude (AMP) was computed to examine the x-axis displacement of limbs during the task. Half-cycle peak-to-valley and valley-to-peak amplitudes were computed for each arm in each trial and averaged. The root mean square (RMS) for z-axis displacement was also computed to examine the anterior-posterior movement amplitude.

Statistics

All dependent measures were analyzed with ANOVAs. Independent sample or paired t-tests were performed when appropriate. The data were analyzed based on the following classification: acquisition performance (trials 1 and 10), feedback performance (trials 11, 12 and 13), and no-feedback performance (trials 14, 15 and 16). The specific ANOVAs are performed in the acquisition, feedback and no-feedback sections. The Group (IMM, SLEEP) and Feedback Position (behind, side) variables are between group factors. Trial (or Block) is a repeated measure variable in the ϕ_{RMSE}, ϕ_{SD}, RA cycles and frequency ratio calculations. Both Trial (or Block) and Arm (left, right) are repeated variables in the MCD, AMP and RMS calculations. For all the statistical tests, the significant level was set at $p < .05$. IBM SPSS statistics 20 software was used for all statistical analyses.

CHAPTER III

RESULTS

Acquisition Performance

Representative samples of the 1:2 pattern from the last acquisition trial for both the IMM and SLEEP groups are shown in Figure 3. The data from trials 1 and 10 were analyzed to determine if participants' performances improved within the five minutes of training. The ϕ_{RMSE}, ϕ_{SD}, frequency ratio (FR) and RA cycles were analyzed with a 2 Group (IMM, SLEEP) $\times$ 2 Feedback Position (behind, side) $\times$ 2 Trial (1, 10) ANOVA. The mean cycle duration (MCD), x-axis AMP and z-axis RMS values were analyzed with a 2 Group (IMM, SLEEP) $\times$ 2 Feedback Position (behind, side) $\times$ 2 Trial (1, 10) $\times$ 2 Arm (left, right) ANOVA.

Relative phase

The analysis of the ϕ_{RMSE} and the ϕ_{SD} data sets found a main effect of Trial [$F(1, 32) = 61.03, p < .001, F(1, 32) = 46.45, p < .001$], Feedback Position [$F(1, 32) = 7.90, p < .01, F(1, 32) = 8.62, p < .01$] and Trial $\times$ Feedback Position interaction [$F(1, 32) = 13.82, p < .01, F(1, 32) = 13.84, p < .01$] for both variables (Figure 4A, B). Tests of the interaction revealed that the ϕ_{RMSE} and ϕ_{SD} values for the behind position were larger than the side position on trial 1, with no significant difference between the feedback positions on trial 10. The ϕ_{RMSE} and ϕ_{SD} values decreased from trial 1 to trial 10 for both the behind and side feedback training positions. In addition, the Trial $\times$ Group $\times$ Feedback Position interaction [$F(1, 32) = 6.75, p < .05$] was also significant for the ϕ_{RMSE} data set.
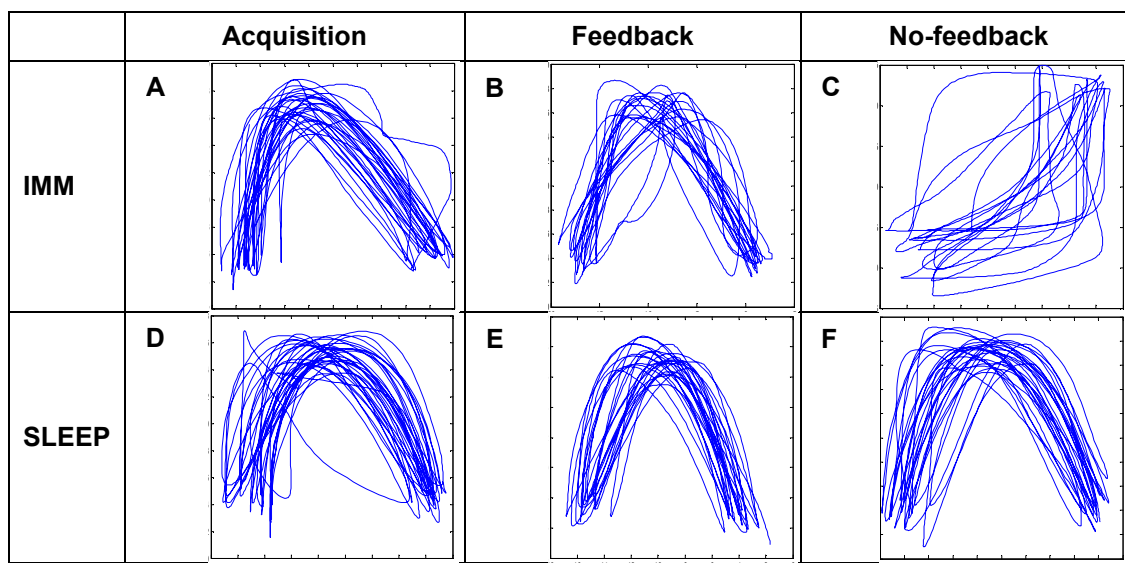
FIGURE 3. Displacement examples of the 1:2 pattern from an acquisition trial (A), a feedback trial (B) and a no-feedback trial (C) for a participant in the IMM group (behind cursor position). Displacement examples of the 1:2 pattern from an acquisition trial (D), a feedback trial (E) and a no-feedback trial (F) for a participant in the SLEEP group (side cursor position).

Frequency ratio

The required frequency ratio defined by the Lissajous plot was 0.5. The analysis of the FR data found a main effect of Trial [$F(1, 32) = 13.26, p < .01$] and Feedback Position [$F(1, 32) = 7.55, p < .05$]. In addition, the Trial $\times$ Feedback Position interaction was also significant [$F(1, 32) = 7.37, p < .05$] (Figure 4C). Tests of the interaction found that the FR values for the behind position were larger than the side position on trial 1, but found no difference in FR values between the behind and side cursor positions on trial 10. For both the behind and side feedback positions, the FR values decreased from trial 1 to trial 10. Independent sample t-tests found that the FR

values on trial 10 for the IMM_behind, IMM_side, SLEEP_behind, SLEEP_side groups

were not statistically different from the target ratio of 0.5 [$ts(8) > .61$, $ps > .05$].
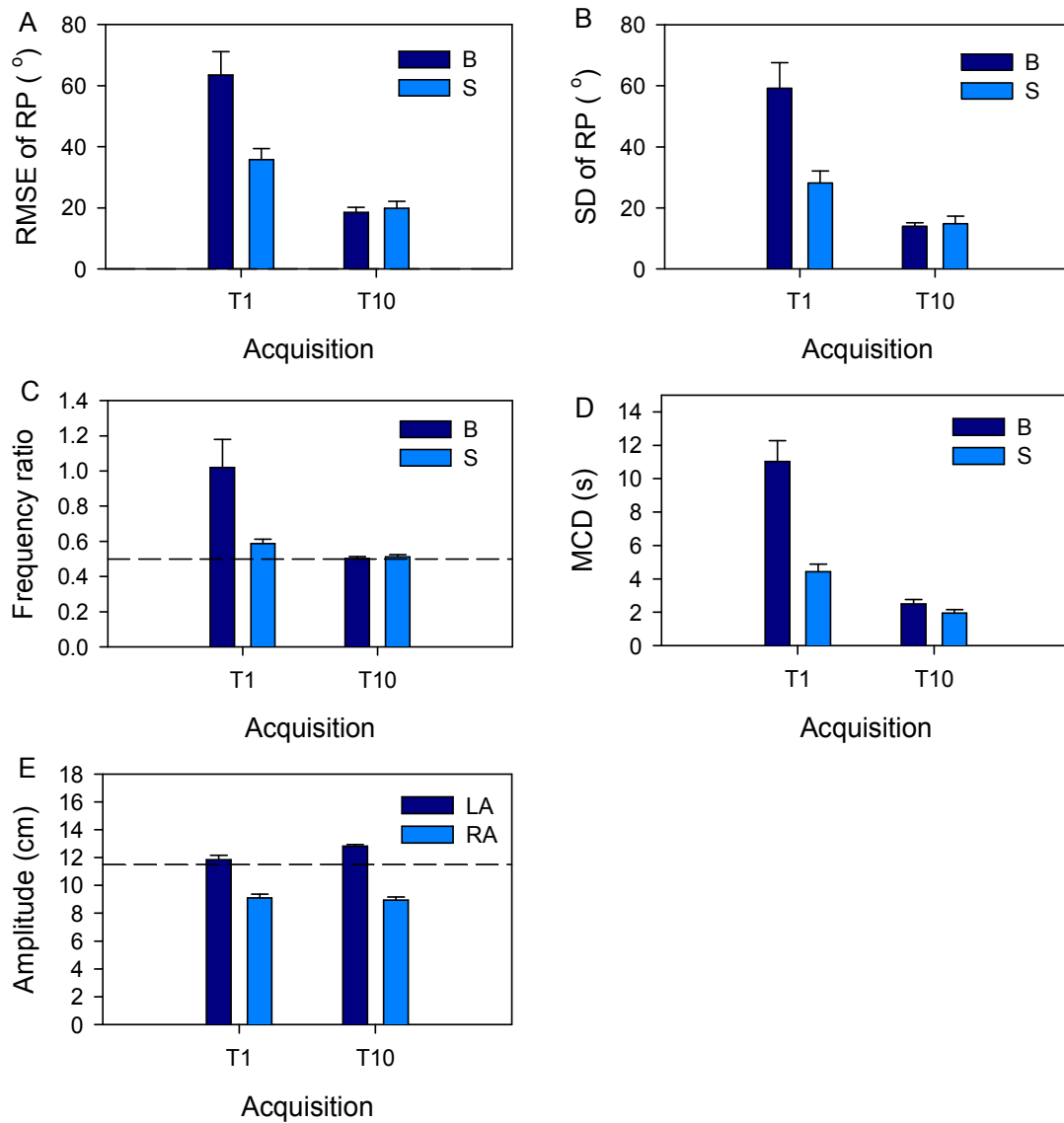
FIGURE 4. RMSE of relative phase (A), SD of relative phase (B), frequency ratio (C), mean cycle duration (D) and x-axis amplitude (E) from the 1st (T1) and 10th (T10) acquisition trials. The dashed line in the frequency ratio (C) and amplitude (E) figures represent the goal ratio of 0.5 (MCD_{RA} : MCD_{LA}) and the goal amplitude of 11.5 cm respectively. LA and RA represent the left arm and the right arm respectively. B and S represent the behind and side feedback training positions respectively. Error bars represent standard errors.

Mean cycle duration

The analysis of the MCD data revealed main effects of Trial [$F(1, 32) = 56.21$, $p < .001$], Arm [$F(1, 32) = 11.81$, $p < .01$] and Feedback Position [$F(1, 32) = 15.14$, $p < .001$]. The MCD values for the left arm ($M = 4.05$ s) were larger than the right arm ($M = 2.59$ s). In addition the Trial × Feedback Position interaction was also significant [$F(1, 32) = 17.12$, $p < .001$] (Figure 4D). Tests of the interaction revealed that the MCD values for the behind position were larger than the side position on trial 1, with no difference between the behind and side feedback positions on trial 10. For both the behind and side feedback positions, the MCD decreased from trial 1 to trial 10.

RA cycles

The analysis of the RA cycle data revealed main effects of Trial [$F(1, 32) = 106.65$, $p < .001$] and Feedback Position [$F(1, 32) = 7.71$, $p < .01$]. The number of RA cycles increased from trial 1 ($M = 8.19$) to trial 10 ($M = 24.35$), and this represents an increase in complete template traces from 4 to 12 on average. Overall, the average number of RA cycles for the behind position ($M = 17.67$) was smaller than the side position ($M = 24.58$), indicating that the side cursor position on average allowed participants to trace the template (12 traces) more often compared to the behind position display (8.5 traces).

Movement amplitude

The analysis of the x-axis amplitude data (AMP) found a main effect of Trial [$F(1, 32) = 6.04$, $p < .05$] and Arm [$F(1, 32) = 74.27$, $p < .001$]. In addition, the Trial × Arm interaction was also significant [$F(1, 32) = 10.63$, $p < .01$] (Figure 4E). Tests of

interaction revealed that the medial-lateral amplitude for the left arm increased from trial 1 to trial 10, whereas there was not a change in medial-lateral amplitude for the right arm from trial 1 to trial 10. T-tests revealed that the AMP for the left arm was larger than right arm on both trials 1 and 10.

The analysis of z-axis RMS data only found a main effect of Arm [$F(1, 32) =$ 9.56, $p < .01$]. The z-axis RMS for the left arm ($M = 3.63$ cm) was smaller than the right arm ($M = 4.29$ cm).

Feedback Performance

The purpose of the feedback (FB) test trials for comparison between SLEEP and IMM groups was to investigate the effect of sleep on performing a bimanual coordination skill. Representative samples of the 1:2 pattern from a feedback test trial for both the IMM and SLEEP groups are shown in Figure 3B, E. The data from the last three acquisition trials and the feedback test trials were taken and analyzed as blocks: AC (trials 8-10) and FB (trials 11-13). The ϕ_{RMSE}, ϕ_{SD}, frequency ratio (FR) and RA cycles were analyzed with a 2 Group (IMM, SLEEP) $\times$ 2 Feedback Position (behind, side) $\times$ 2 Block (AC, FB) ANOVA. The mean cycle duration (MCD), x-axis AMP and z-axis RMS values were analyzed with a 2 Group (IMM, SLEEP) $\times$ 2 Feedback Position (behind, side) $\times$ 2 Block (AC, FB) $\times$ 2 Arm (left, right) ANOVA.

Relative phase

The analysis of the ϕ_{RMSE} and ϕ_{SD} data sets found a main effect of Block for both variables [$F(1, 32) = 9.59$, $p < .01$, $F(1, 32) = 10.19$, $p < .01$]. In addition, the Block $\times$ Group interaction was also significant [$F(1, 32) = 4.66$, $p < .05$, $F(1, 32) = 4.87$, $p < .05$]

(Figure 5A, B). Tests of the interaction revealed that there was not a difference in ϕ_{RMSE} and ϕ_{SD} between IMM and SLEEP groups for both the AC and FB blocks. There was a significant decrease in ϕ_{RMSE} and ϕ_{SD} from the AC block to FB block for the SLEEP group, whereas there was no significant change from the AC block to the FB block for the IMM group.

Frequency ratio

The required frequency ratio defined by the Lissajous plot was 0.5. The analysis of the FR data found only a main effect of Block [$F(1, 32) = 5.59, p < .05$]. T-tests revealed that the FR values decreased from the AC block ($M = .53$) to the FB block ($M = .51$). Independent sample t-tests found that the FR values for AC block and FB block were larger than the required 0.5 target value [$t(35) = 4.02, p < .001, t(35) = 3.15, p < .01$].

Mean cycle duration

The analysis of the MCD data revealed main effects of Block [$F(1, 32) = 5.64, p < .05$], Arm [$F(1, 32) = 166.04, p < .001$] and Feedback Position [$F(1, 32) = 4.48, p < .05$]. The overall MCD values decreased from the AC block ($M = 2.47$ s) to the FB block ($M = 2.16$ s). The Arm $\times$ Feedback Position interaction was also significant [$F(1, 32) = 4.75, p < .05$] (Figure 5C). Tests of this interaction revealed that the MCD value for the left arm was larger than the right arm for both feedback positions, and the MCD value for the behind position was larger than the side position for both arms.
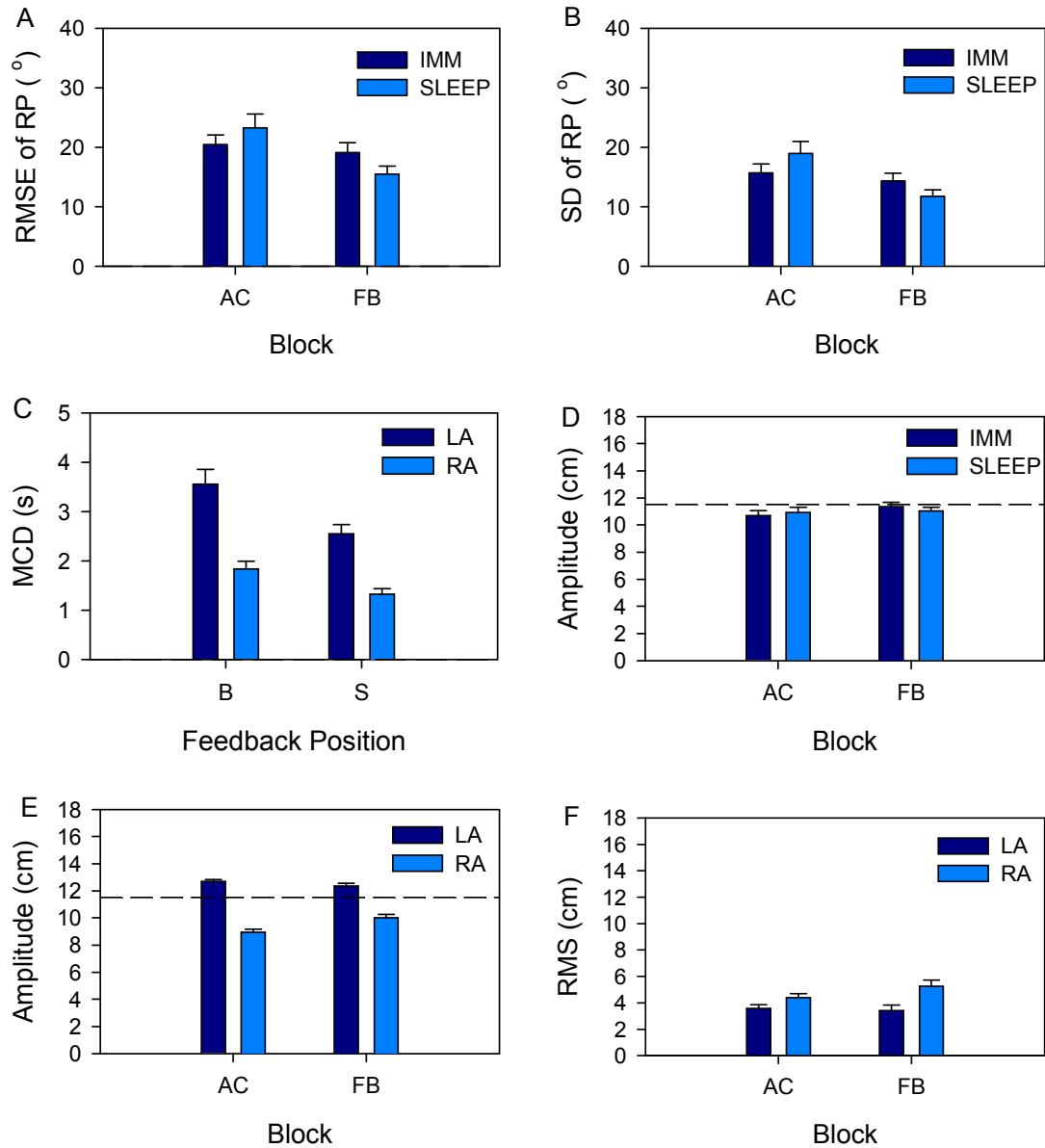
FIGURE 5. RMSE of relative phase (A), SD of relative phase (B), mean cycle duration (C), x-axis amplitude (D), x-axis amplitude (E) and z-axis amplitude (F) from the acquisition block (trial 8-10) and feedback block (trial 11-13). The dashed lines in the amplitude figures (D, E) represents the goal amplitude of 11.5 cm. LA and RA represent the left arm and the right arm respectively. B and S represent the behind and side feedback training positions respectively. Error bars represent standard errors.

RA cycles

The analysis of the RA cycle data revealed main effects of Trial [$F(1, 32) = 6.50$, $p < .05$] and Feedback Position [$F(1, 32) = 5.59$, $p < .05$]. The number of RA cycles increased from the AC block ($M = 22.78$) to the FB block ($M = 24.63$), representing an increase in complete template traces from 11 to 12 on average. The average number of RA cycles for the behind position ($M = 20.16$) was smaller than the side position ($M = 27.23$), indicating participants traced the template fewer times in the behind cursor position (10 traces) than the side cursor position (13 traces).

Movement amplitude

The analysis of the x-axis AMP data found a main effect of Block [$F(1, 32) = 8.27$, $p < .01$] and Arm [$F(1, 32) = 146.46$, $p < .001$]. In addition, the Block × Group [$F(1, 32) = 4.53$, $p < .05$] and Block × Arm [$F(1, 32) = 19.68$, $p < .001$] interactions were also significant. Tests of the Block × Group interaction failed to find a difference in medial-lateral amplitude between IMM and SLEEP groups for both the AC and FB blocks, but found the medial-lateral amplitude values for the IMM group increased from the AC to the FB block, with no change from the AC to the FB block for the SLEEP group (Figure 5D). Tests of the Block × Arm interaction revealed that the AMP values for the left arm were larger than the right arm for both the AC and FB blocks (Figure 5E). The AMP values for the right arm increased from the AC block to the FB block, whereas there was not a change from the AC block to the FB block for the left arm. The analysis of z-axis RMS data found a main effect of Arm [$F(1, 32) = 24.93$, $p < .001$]. The Block × Arm interaction was also significant [$F(1, 32) = 6.29$, $p < .05$]

(Figure 5F). The RMS value for the left arm was smaller than right arm for both the AC and FB blocks. Tests of the interaction found no change in z-axis RMS values from the AC block to FB block for either arm.

No-feedback Performance

The purpose of the no-feedback (NF) trials was to test for the guidance effect associated with the training position of the cursor. Representative samples of the 1:2 pattern from a no-feedback trial for both the IMM and SLEEP groups are shown in Figure 3C, F. The data from the last three acquisition trials and the no-feedback test trials were taken and analyzed as blocks: AC (trials 8-10) and NF (trials 14-16). The ϕ_{RMSE}, ϕ_{SD}, frequency ratio (FR) and RA cycles were analyzed with a 2 Group (IMM, SLEEP) × 2 Feedback Position (behind, side) × 2 Block (AC, FB) ANOVA. The mean cycle duration (MCD), x-axis AMP and z-axis RMS values were analyzed with a 2 Group (IMM, SLEEP) × 2 Feedback Position (behind, side) × 2 Block (AC, FB) × 2 Arm (left, right) ANOVA.

Relative phase

The analysis of the ϕ_{RMSE} and ϕ_{SD} data found a main effect of Block for both variables $[F(1, 32) = 9.08, p < .01, F(1, 32) = 10.40, p < .01]$, indicating a deterioration in overall performance accuracy and performance stability from acquisition to no-feedback trials (Figure 6A).

Frequency ratio

The analysis of the FR data found only a main effect of Block $[F(1, 32) = 10.32, p < .01]$. The FR values increased from the AC block ($M = .53$) to the NF block ($M = $

.62). Independent sample t-tests found that the FR values for AC block and NF block were larger than the required value of 0.5 [$t(35) = 4.02, p < .001, t(35) = 4.12, p < .001$].
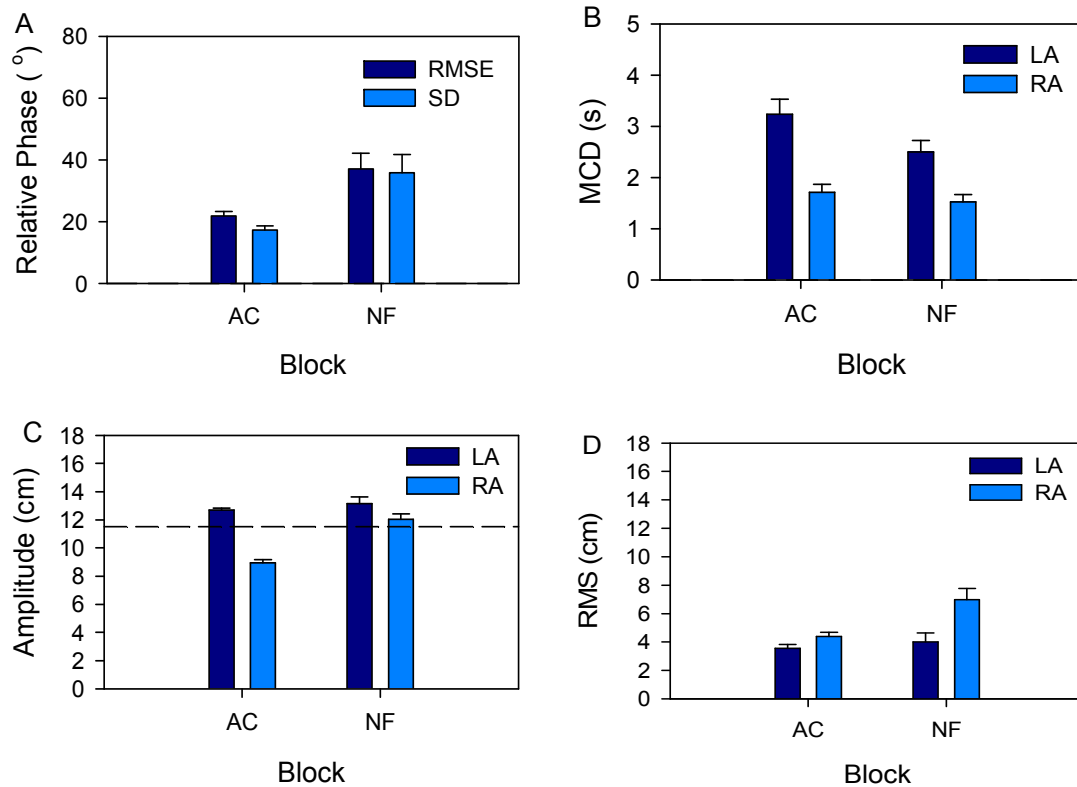
FIGURE 6. RMSE and SD of relative phase (A), mean cycle duration (B), x-axis amplitude (C) and z-axis amplitude (D) from the acquisition (trial 8-10) and no-feedback blocks (trial 14-16). The dashed line in the amplitude figures (C) represents the goal amplitude of 11.5 cm. LA and RA represent the left arm and the right arm respectively. Error bars represent standard errors.

Mean cycle duration

The analysis of the MCD data revealed main effects of Block [$F(1, 32) = 8.25, p < .01$], Arm [$F(1, 32) = 140.13, p < .001$] and Feedback Position [$F(1, 32) = 4.42, p < .05$]. The overall MCD values for the behind cursor position ($M = 2.63$ s) were larger

than the side position ($M = 1.86$ s). In addition the Block $\times$ Arm interaction was also significant [$F(1, 32) = 15.11, p < .001$] (Figure 6B). Tests of the interaction revealed that the MCD value for the left arm was larger than the right arm on both the AC and NF blocks. In addition, the MCD values decreased from the AC block to the NF block for the left arm, but there was not a change from the AC block to the NF block for the right arm.

RA cycles

The analysis of the RA cycle data revealed main effects of Block [$F(1, 32) = 5.83, p < .05$] and Feedback Position [$F(1, 32) = 5.11, p < .05$]. The number of RA cycles increased from the AC block ($M = 22.78$) to the NF block ($M = 25.69$), representing an increase in complete template traces from 11.5 to 13. The average number of RA cycles for the behind position ($M = 20.31$) was smaller than the side position ($M = 28.16$), indicating participants traced fewer times around the template when the cursor was behind the template (10 traces) than to the side of the template (14 traces).

Movement amplitude

The analysis of the x-axis AMP data found a main effect of Block [$F(1, 32) = 27.14, p < .001$] and Arm [$F(1, 32) = 66.84, p < .001$]. In addition, the Block $\times$ Arm [$F(1, 32) = 22.68, p < .001$] interaction was also significant (Figure 6C). Tests of the interaction revealed AMP values for the left arm were larger than the right arm for the AC block, with no difference between the two arms for the NF block. The AMP values

for the right arm increased from the AC block to the NF block, with no change from the

AC block to the NF block for the left arm.

The analysis of z-axis RMS data found a main effect of Block [$F(1, 32) = 7.89$, p

$< .01$] and Arm [$F(1, 32) = 23.26$, $p < .001$]. In addition, the Block $\times$ Arm interaction

was also significant [$F(1, 32) = 7.90$, $p < .01$] (Figure 6D). Tests of the interaction

revealed that the z-axis RMS for the left arm was smaller than right arm for both the AC

and NF blocks. The RMS values increased from the AC block to the NF block for the

right arm, with no change from AC block to the NF block for the left arm.

CHAPTER IV

DISCUSSION & CONCLUSION

Acquisition Performance

The feedback position of the cursor with respect to the Lissajous template, behind or side, did impact performance accuracy and performance stability at the beginning of training (trial 1), but the same level of performance was achieved by the end of acquisition (trial 10). Overall, both the IMM and SLEEP groups rapidly tuned-in the 1:2 bimanual pattern with only 5 minutes of practice. The acquisition performance in the current study was consistent with Kovacs et al. (2010a) and again shows the power of the Lissajous augmented visual feedback display with regard to training difficult multifrequency bimanual patterns.

Movement rate for the two arms was influenced by the Feedback Position of the cursor at the beginning of training. The mean cycle duration and frequency ratio for the behind cursor position was larger than the side cursor position on trial 1 but the difference between the two cursor positions disappeared on trial 10. The number of produced cycles for the right arm (RA) was also influenced by the position of the cursor during training. Participants trained with the side cursor position traced the temples more often than those who trained with the behind cursor position. Overall, both training conditions were associated with an increase in movement rate as well as an increase in performance accuracy and stability. A greater improvement in performance accuracy and variability was observed for the behind cursor position compared to the side cursor position.

The medial-lateral amplitude for the left arm slightly increased from trial 1 to trial 10 whereas the medial-lateral amplitude for the right arm was not change from trial 1 to trial 10. The left arm amplitude was larger than the right arm amplitude for both trials 1 and 10. It is very common in bimanual coordination studies that an increase in movement speed is associated with a decrease in movement amplitude (Peper & Beek, 1998; Young U Ryu & Buchanan, 2004). The anterior-posterior amplitude was not influenced by the cursor training position or by an overnight sleep.

Feedback Performance

When participants were re-tested after a night of sleep in the feedback condition, a decrease in ϕ_{RMSE} and ϕ_{SD} from AC to FB blocks was found. There was no change in ϕ_{RMSE} and ϕ_{SD} measures for the IMM group with continued practice. The finding that the delayed 24 hour interval improved participants' performance accuracy and stability in the current study is evidence of enhancement in this rhythmic bimanual coordination task and provides support for our first hypothesis. The position of the cursor (behind or side) with respect to the Lissajous template, however, did not influence performance accuracy and stability when visual augmented feedback was available. This is consistent with a previous bimanual coordination study in which performance with feedback was tested 15 minutes after initial training (Buchanan & Wang, in-press). Combining sleep with the Lissajous augmented visual feedback display as a training format resulted in an enhancement that has not been shown in bimanual coordination studies. However, different consolidation mechanisms may contribute to the enhancement in performance after sleep in the current study and the enhancement in performance after 15 minutes of

rest in the Buchanan & Wang (in-press) study. Although the phenomenon of enhancement in both studies resulted from practicing with the Lissajous augmented visual feedback display. the enhancement after only 15 minutes of rest may result from a temporary release of within-session practice induced fatigue, an effect described as reminiscence (Eysenck, 1977).

The overall movement rate and frequency ratio decreased from the AC block to the FB block, indicating an increase in performance accuracy and stability was achieved at a faster movement rate. Both arms moved faster for the side cursor position than the behind cursor position, although the difference in movement rate between the training cursor positions was more evident for the left arm than the right arm. The number of RA cycles produced was influenced by cursor training position when augmented visual feedback was available. Participants trained with the side cursor position traced the temple more often than those who trained with the behind cursor position. These results show that the side cursor position has an advantage of allowing participants to move at faster rates and trace the template more often and still maintain high levels of performance accuracy and stability (Buchanan & Wang, in-press).

We found a significant increase in medial-lateral amplitude from the AC block (10.69 cm) to the FB block (11.34 cm) for the IMM group, whereas there was no change from the AC block to the FB block for the SLEEP group. There was not a difference between the medial-lateral amplitude for the IMM and SLEEP groups for both AC and FB blocks, indicating that both the IMM and SLEEP medial-lateral amplitudes were close to the goal of 11.5 cm. The medial-lateral amplitude for the right arm increased

from the AC block to the FB block, whereas the medial-lateral amplitude for the left arm did not change from the AC block to the FB block. The medial-lateral amplitude for the left arm was larger than the right arm for both AC and FB blocks. Again the results indicate that the arm that moves faster produces smaller movement amplitudes than the arm that moves slower. This finding is consistent with other bimanual studies (Peper & Beek, 1998; Young U Ryu & Buchanan, 2004). The anterior-posterior amplitude was not influenced by the cursor training position or by sleep.

No-feedback Performance

Both performance accuracy and performance stability for the IMM and SLEEP groups deteriorated with removal of the visual feedback. Participants' performance in the no-feedback test condition might be evidence for early stabilization. In the Korman et al. (2007) study, the stabilization of a sequencing skill was tested by presenting a similar but difference sequence B (4,2,3,1,4) after initial learning with sequence A (4,1,3,2,4), and found that the stabilization phenomenon appeared between 2 hours and 8 hours after initial learning. Whereas in the current study, the stabilization of the 1:2 bimanual coordination pattern was tested by removing the feedback, and showed that the overall performance for both the IMM and SLEEP group participants deteriorated. It might take a longer period of time to stabilize a bimanual coordination skill (> 24 hours) than a sequencing skill (between 2 and 8 hours).

The result that cursor position had no impact on performance in the no-feedback test condition in the current study is different from Buchanan & Wang (in-press) which showed that when feedback was removed, the side group had an advantage. In the

current study, the same level of performance was observed between the behind-cursor-position and side-cursor-position participants. However, this result supports our second hypothesis – an overnight sleep reduced the guidance effect linked to the behind cursor position – and our second prediction that the behind group would perform equally to the side group after a night of sleep. However, performance accuracy and stability in the no-feedback test block still deteriorated compared to the acquisition block, indicating that the effect of an overnight sleep on overriding the guidance effect was limited in this experiment.

The overnight sleep and cursor training position had no impact on overall movement rate and the observed frequency ratio. However, there were two results in the no-feedback test condition that may provide an explanation for the lack of a sleep effect in the no feedback condition. First, the FR values for the NF block ($M = .62$) showed a relatively larger deviation from the goal ratio of 0.5 compared to the AC block ($M = .53$) and FB block ($M = .51$). Second, the group standard error of the mean ϕ_{RMSE} and mean ϕ_{SD} values for the NF block ($SE\phi_{RMSE} = 5.06°$, $SE\phi_{SD} = 5.91°$) was extremely large compared to the AC block ($SE\phi_{RMSE} = 1.41°$, $SE\phi_{SD} = 1.27°$) and FB block ($SE\phi_{RMSE} = 1.10°$, $SE\phi_{SD} = 1.27°$). The above differences led us to investigate if the loss of the side cursor position advantage in the current study was caused by one or more participants that were performing a 1:1 bimanual pattern. To look at the relationship between FR and sleep, we laid out a Relative Phase – FR distribution table in order to examine whether the difference in performance error and performance variability between the behind and side cursor position in the SLEEP group was masked by poor performance of 1 or 2

individuals or if every participant was performing poorly (Table 1). Table 1 shows that extremely large ϕ_{RMSE} and ϕ_{SD} values from one participant in the SLEEP-behind condition and two in the SLEEP-side condition as the result of producing a 1:1 pattern instead of the trained 1:2 pattern. The extremely large ϕ_{RMSE} and ϕ_{SD} values of the three participants most probably account for the loss of the cursor training position effect in the current study. If we exclude the participants that did not produce a FR close to the required 0.5, a similar advantage in the no-feedback condition for the side cursor position emerges.

TABLE 1. Comparison of FR Distribution in NF Block (trials 14-16) between the Behind and Side Cursor Positions in the SLEEP Group.

Feedback Position	RP \ FR	.40 - .50	.50 - .60	.60 - .70	.70 - .80	.80 - .90	.90 - 1.00
Behind	n	1	5	2	-	-	1
	RMSE	14.13	18.84	36.54	-	-	87.58
	SD	10.19	15.13	32.42	-	-	96.22
Side	n	4	3	-	-	-	2
	RMSE	12.62	21.96	-	-	-	100.44
	SD	9.16	16.79	-	-	-	111.86

To determine why the three participants in the SLEEP group did not produce a FR close to the required 0.5, we examined the individual number of RA cycles. We found that one participant in the behind cursor position traced the template more often (28.5 traces) than the behind-cursor-position group mean ($M = 21.5$ traces), and the two in the side cursor position traced template less often (21 traces, 7.5 traces) than the side-cursor-position group mean ($M = 31.5$ traces). A possible explanation for the one

participant in the behind-cursor-position group was that he moved so fast that he transitioned his bimanual coordination pattern to a more stable and easily performed 1:1 pattern. The two in the side-cursor-position who moved slower compared to the group mean may not have received enough practice during acquisition to stabilize their performance. For the rest of participants in the SLEEP group, those who trained with the side cursor position (FR range: .40 - .70) traced the templates more often ($M = 36.5$ traces) than those who trained with the behind cursor position (FR ranges: .40 - .60, $M =$ 20.5 traces) under the no-feedback test condition. Thus, the finding that more template traces was also shown for the side-cursor-position group in the current study is consistent with Buchanan & Wang (in-press).

The mean cycle duration for the left arm was larger than the right arm for both the AC and NF blocks. The MCD for the left arm decreased across the AC to NF blocks, whereas there was no change in the MCD for the right arm across the AC to NF blocks. The medial-lateral amplitude for the left arm was larger than the right arm for the AC block, but there was not a difference in the medial-lateral amplitude between the left and right arms for the NF blocks. There was no change in the medial-lateral amplitude across the AC to NF blocks for the left arm, whereas the medial-lateral amplitude for the left arm increased from the AC to NF block. Taking the MCD and medial-lateral amplitude findings together, the fact that the right arm amplitude increased with the removal of augmented feedback might have led to no further increase in movement rate from the AC to NF blocks for the right arm. The removal of the visually augmented feedback had a greater impact on movement rate and medial-lateral amplitude for the right arm than

the left arm. Again, the anterior-posterior amplitude was not influenced by sleep or cursor training position in the no-feedback test condition.

Conclusion

Two main conclusions may be drawn from the current results. First, sleep enhances the performance of a minimally trained 1:2 pattern of bimanual coordination in a manner that has been observed with sequencing skills – performance significantly improved after an overnight sleep. This improvement, however, was linked to the presence of the visual feedback display, the Lissajous-cursor plot. Second, the effect of sleep was not strong enough to override the guidance effect in the behind cursor position if we only take into account participants that attempted to do a 1:2 bimanual pattern.

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