THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF KINESIOLOGY

THE PERSISTENCE OF INTERLIMB COORDINATION DURING BIMANUAL MOVEMENTS

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Spring 2010

A thesis
submitted in partial fulfillment
of the requirements
for a baccalaureate degree
in Kinesiology
with honors in Kinesiology

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Abstract

Previous literature has shown that there are substantial interlimb differences in coordination during unimanual movements. The dominant arm is typically more efficient in controlling intersegmental dynamics and the nondominant arm has an advantage for maintaining limb posture. Some have suggested that bimanual movements may involve different control strategies than those that are used during unimanual movements. Additionally, research has shown that interlimb differences are less when bimanually congruent joint displacement movements are completed compared to those completed that require congruent hand displacement.

The purpose of this experiment was to observe if motor lateralization was affected during bilateral tasks. This was examined by comparing the coordination during unimanual and bimanual reaching movements. In this study, two hypotheses were proposed: 1) the effect of handedness would be reduced when moving bimanually compared to the movements made unimanually and 2) that bimanual movements that required congruent joint displacement would reflect less interlimb differences than those movements made with congruent hand displacement.

Subjects were asked to make rapid and concise unimanual and bimanual movements to various targets, each of which had different inertial requirements. Bimanual movements consisted of those which require either congruent joint displacement or congruent hand displacement.

Our results showed that interlimb differences in coordination were not changed under bimanual conditions. While we found some differences in coordination between joint congruent and hand congruent conditions, further comparison (outside of this current analysis) suggest that

these differences persist during matched unimanual comparison, and therefore cannot be attributed to bimanual movement conditions.

Based on our analysis, we suggest that the mechanisms which synchronize bimanual movements may occur upstream in the control process to the expression of motor lateralization and consequently, might not affect the expression of interlimb differences in coordination. This, in turn, indicates that bimanual coordination does not alter the mechanisms that determine intralimb coordination patterns. Additionally, our results challenged the conclusion of a difference in congruent joint displacement and congruent hand displacement movements; rather, the movements were similar in the amount of interlimb differences.

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Acknowledgments

There were many people who greatly helped attribute to the completion of this honors thesis. First, I would like to thank my supervisor, Dr. Robert Sainburg, for his continuous support throughout the past year and a half. I was able to learn the foundations of the scientific process through this research experience. I have gained a significant amount of respect for the development of a scientific study in a motor control laboratory.

Andrzej Przybyla PhD, co-supervisor, also deserves a very special thank you. I worked directly with Andrzej for my time in Dr. Sainburg's lab. Many of hours were spent working side by side with Andrzej on this project. It would not have progressed or even been close to completion without his help. Andrzej, despite all of my major stressing, I think it turned out 'verrrrrry niiiiiiiiice.'

Also to those in the lab who have been helping me since the beginning, especially Kati Wuebbenhorst PhD, Tucker Tomlinson, and Selcuk Akpinar, for putting up with my continuous stream of questions. And of course, for being there during any data processing crises.

Lastly and most importantly I would like to thank my family. My parents, Jeremiah and Louise, have showed me how to live life to the fullest through their example. I have learned from them how to stand in the face of challenges and I will be forever grateful for their love and support. And perhaps most importantly, they were always there for the phone calls.

My siblings, Jeremiah, Declan and Caitriona, also deserve a shout-out. My biggest hope for them is that they are able to have the same wonderful college experience as I was so fortunate to experience. Thanks to you three for just being there, despite probably having no idea why your older sister was slightly stressed about whatever a 'thesis' was.

Introduction

Motor lateralization, or handedness, is defined as the tendency to favor one hand for performance of unimanual tasks (Sainburg & Kalakanis 2000). People most commonly report their handedness based on which hand they use to write. Handedness becomes apparent during a child's toddler years, when drawing and writing activities begin. Whether handedness is a choice or if handedness depends on a biological determinant which is not under voluntary control, remains controversial. However, as early as 1905, the relationship between brain asymmetry and behavioral asymmetries had already been proposed. Based largely on the observation that left, but not right, hemisphere stroke could produce major language impairments, Hugo Leipmann proposed that the left hemisphere is the "major or master" hemisphere, while the right hemisphere is the "minor or slave" hemisphere (Liepmann, 1905). With regard to motor control, Liepmann proposed that the left hemisphere was specialized for motor control in right handed people. In fact, he predicted that stroke in the left hemisphere would produce greater motor deficits than right hemisphere stroke, a prediction that has not been supported by subsequent research (Schaefer, Haaland and Sainburg, 2007).

We now know from the foundational research of Michael Gazzaniga (Gazzaniga, 1998) that each hemisphere can be specialized for different aspects of a given function that might govern cognitive, perceptual, emotional, language, and motor aspects of behavior. For example, the left hemisphere is specialized for semantic and lexicon features of language and verbal and written communication (Milner, 1962; Zaidel, 1981 and 1985), while the right hemisphere is specialized for verbal prosody, intonation, and emotional expression and interpretation. The right hemisphere has also been shown to be specialized for certain cognitive-spatial manipulations

(Nebes, 1973; Corballis, 1999). Thus, a wide range of neurobehavioral functions have been associated with either right or left hemisphere specializations.

It is obvious, with the most casual level of consideration, that the right and left arms show differences in motor proficiency in the majority of individuals. However, until recently, little evidence connected this behavioral asymmetry to neural organization. It was previously known that certain neural structures such as the motor cortex (Amunts et al., 1996), cerebellum (Synder et al., 1995) and basal ganglia (Kooistra & Heilman, 1988), tended to be asymmetric in size and shape. In addition, a large number of studies have shown that use of the right and left arms evokes asymmetrical patterns of neural activation when recorded with EEG or fMRI (Dassonville et al., 1997; Viviani et al., 1998). While this suggested that certain motor control functions might be lateralized, the specific neurobehavioral functions remained largely speculative.

Recently, through a series of studies conducted in young healthy individual and patients with unilateral stroke, Robert Sainburg and colleagues proposed a hypothesis of neural lateralization that attributes different aspects of motor control to different cerebral hemispheres (Bagesteiro and Sainburg, 2002, 2003; Sainburg, 2002; Sainburg and Kalakanis, 2000; Sainburg and Wang, 2002; Schaefer et al., 2007, 2009a, 2009b)**.** This hypothesis states that the aspect of motor control that best differentiates dominant and nondominant arm movements is the control of limb dynamics. Recently, Schaefer et al. (2007) showed that this hypothesis may predict limb-specific insufficiencies after strokes occur in patients. This supported the idea that these control differences are associated with brain lateralization.

Sainburg and Kalakanis (2000) first investigated arm movement asymmetries in a study of targeted reaching movements performed by healthy and young adults. Six subjects reached to three targets that were designed to require different coordination patterns between the shoulder and elbow joints. Specifically, the design was to vary the amplitude of interaction torques evoked at the elbow joint. Interaction torque is produced when the end of one segment pushes on the end of an attached segment. In this study, the authors manipulated the amplitude of elbow joint interaction torques at the elbow by varying the amount of shoulder excursion required for each target. The most obvious results were the different trajectories taken by the right and left hands to reach the same targets. The authors proposed that different neural control mechanisms were used for the dominant and nondominant arm movements. It was also suggested that the interaction torque affected each hand path differently: the dominant path was unaffected by changes in interaction torque, whereas the nondominant trajectories were greatly deviated by the variations. These results verified those of Hore et al. (1996) which indicated in a ball throwing task that dominant arm movements reflected better coordination of finger extension for ball release with proximal arm motion in the dominant arm. They concluded that this was due to more accurate prediction of limb dynamics. It is plausible that such advantages might be the reason for the preference of one hand over the other for certain activities such as drawing, writing and throwing.

In 2002, Bagesteiro and Sainburg examined whether electromyographic recordings were consistent with the inverse dynamic analyses reported in previous studies (Sainburg, 2002; Sainburg and Kalakanis, 2000). The EMG results confirmed that dominant arm movements were associated with more efficient torque strategies, or better intersegmental coordination. These authors suggested that different neural control mechanisms have become specialized for different features of dominant and nondominant arm movements. The results led to the conclusion that the development of handedness arises due to these biological asymmetries.

Though it was apparent the dominant hand had its control advantages, there have also been studies examining if there were some advantages held by the nondominant hand. Wang and Sainburg (2002) studied brain lateralization by comparing limb performance under two different conditions: one in which the limb started from one fixed position and reached to three different targets, and the other with the limb starting from three different points and ending at one fixed target. The findings showed that the dominant arm was more accurate when starting at a fixed position and reaching to different targets. However, the nondominant limb had better accuracy when moving to a fixed target from different starting points. The authors concluded that both hemispheres are specialized for stabilizing various features of task performance. Motor control was concluded to be allocated across both hemispheres, each having a specific and complimentary function.

In summary, numerous studies have recently been produced with conclusions about the dominant and nondominant hand differences and specializations. The dominant limb employs more torque-efficient coordination patterns for movements made with similar speeds and accuracy to nondominant arm movements. It appears specialized for trajectory control, especially emphasizing advantages in coordinating multiple joints. Other research has lead to the conclusion that the nondominant arm might be specialized for maintaining stable limb positions (Bagesteiro and Sainburg, 2003; Duff and Sainburg, 2007). For instance, when one is hammering a nail into a wall, the dominant limb typically controls the dynamics of the hammer, or the swinging, and the nondominant limb holds the nail in a stable position.

All of the above research is based on studies in which either the dominant or nondominant arm moves alone, or unimanual movements. The fact that each arm appears to employ different coordination strategies, or at least proficiencies, leads to the question of how we coordinate these different limbs to work together during bimanual movements. It has been proposed that when two arms are used together to complete a bimanual task, movements become temporally synchronized which has suggested that the control of bimanual movements elicit unique control mechanisms than that of a unimanual movement. Most studies of bimanual coordination have concluded that our capability to independently manage both upper limbs simultaneously is fairly limited (Ivry, 2004).

One of the earliest researchers of bimanual coordination, Kelso (1979), suggested that there was a single, “superordinate” controller that delegates the control of both limbs during bilateral movements. Participants were instructed to complete a movement to three different targets relative to the body: lateral, medial and forward. Large differences in the movement times were apparent during unimanual movements. However, the differences were almost completely eliminated after the hands were required to work together to complete a bimanual task. These results led Kelso to suggest the concept of muscle linkage. He concluded that when the motor system was confronted with controlling multiple degrees of freedom, such as a bimanual task, the brain constrains the muscles in the limbs to act as a single unit, thus solving the ‘problem’ of the bimanual movement.

Spatial coupling is a possible interaction which has been studied during bimanual movements. Franz et al. (1991, 1996, and 1997) investigated bimanual movements and the effect of restriction of interlimb coordination due to this interaction. Participants drew continuous circles and lines, one task at a time or bimanually. The results of this task were that when completing the two tasks bimanually, there was a tendency for the lines to become more circle-like and for the circles to become more line-like. In other words, both hands produced elliptical trajectories. The authors concluded that the hands were these results that the spatial constraints (spatial coupling) has a large influence in the governance of bimanually coordinated movements. Additionally, the hands moved at the same times which caused the authors to believe the hands were 'tightly temporally locked.'

'Cross talk' is a term used by some researches when referring to this bimanual interaction. (Heuer, 1993; Heuer, Spijkers, Kleinsorge, van der Loo, & Steglich,1998; Spijkers & Heuer, 1995). This expression describes what may occur when bimanual reaching movements are planned. If it is a symmetric movement (one in which there was congruent joint displacement), cross-talk may reinforce planning, thus execution, of the movement. However, if it is asymmetric (a movement in which different amounts of joint displacement across limbs are required), the cross talk can lead to considerable intermanual hindrance. This was one explanation of Franz and colleague's interaction in their results when the hands simultaneously drew a line and circle, a movement considered asymmetric.

Various types of bimanual movements have been studied extensively. For this experiment two types of bimanual movements will be performed: those which require congruent joint displacement and those which are congruent in hand displacement. Semjen and his colleagues (1995) found that drawing circles with both hands in the symmetric fashion (one circle in the clockwise direction and the other in the counter-clockwise direction) was much more stable than when circles were made asymmetrically (both clockwise or both counterclockwise). In this case, the ‘symmetrical’ pattern requires the same types of joint displacement, as in our movement condition of congruent joint displacement. In 1997, Richard Carson and his colleagues also studied these two types of bimanual movements. Confirming the previously found results, Carson found that the spatiotemporal relationship between the two limbs was more precise and consistently maintained throughout the congruent joint displaced movements.

This study involved targeted reaching movements in both unimanual and bimanual conditions. Different targets were used to vary the joint excursions and the amount of intersegmental dynamics required for the movements. The first set of comparisons which were made were between unimanual and bimanual hand movements for three targets: lateral, medial and center. The second comparison was made between the two different types of bimanual movements. The first, which requires congruent hand displacement, does not involve congruent joint displacements. The second movement is congruent in joint displacement, but not congruent in hand displacement. These various conditions allowed us to see the changes in movement dynamics when moving the hands unimanually and bimanually. The center target was used for the experiment and will be analyzed for the first (unimanual and bimanual) comparison. However, because it requires both congruent hand and joint displacement, it was not analyzed for the bimanual comparisons, only the lateral and medial targets were examined for the bimanual comparison.

The purpose of this experiment was to observe if motor lateralization changed during bimanual tasks. If one controller is used for both hands the coordination of both of the hands may occur through three different possibilities: dominant hemisphere mechanisms, nondominant hemisphere mechanisms, or a mechanism reflecting neither dominant nor nondominant mechanisms. Alternatively, the mechanism may show the same for both bimanual and unimanual movements. These alternatives would indicate various mechanisms underlying bimanual coordination: either one or the other hemisphere co-opts control, lateralization occurs downstream to the mechanisms that coordinate movements, or finally, a unique controller is used during bimanual movements.

Our first hypothesis is that there will be an interaction of the bimanual condition on the interlimb differences, so these differences will not persist. This hypothesis is based upon previously described research on bimanual coordination. The second hypothesis has also been based upon earlier research: we predict that the movements will reflect less interlimb differences in the movements which require congruent joint displacement rather than those which congruent hand displacement. This study is set apart from previous research due to the detail of kinematics which will be examined. Additionally, unlike most previous work which has studied rhythmic movements, the motions in this study are more directed movements, which reflect a more practical example of most movements made throughout activities of daily living.

Methods

Subjects

Nine neurologically intact, right handed and young (ages 18-39) volunteers were recruited for this experiment. The participants consisted of four females and five males. Each volunteer gave his or her permission to participation by signing the consent form approved by the Institutional Review Board (IRB) of the Pennsylvania State University. Handedness was assessed using the extended version of the Edinburgh Inventory (Oldfield 1971). Finally, each subject received a payment of minimum wage for his or her participation.

Experimental Setup

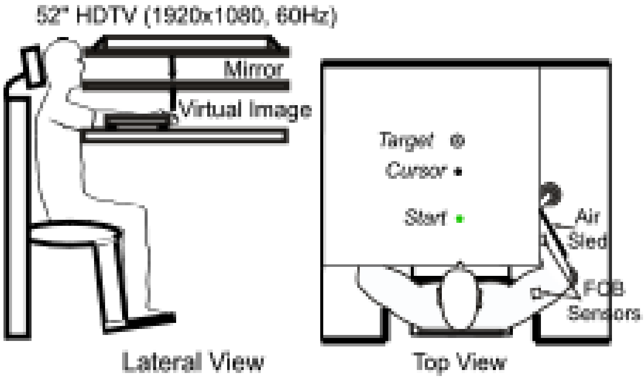

Figure 1: Figure 1 portrays the experimental setup used throughout the study. The lateral version on the left shows the participant in a seated position used for the experiment. The superior view on the right shows the volunteer seated however the top portion of the appartus was removed to see the target, cursor and start circles used in the study which will be discussed later.

The subjects' arms were positioned over a horizontal surface which was just below his or her shoulder height. This surface reduced the effects of both gravity and friction because it was an air jet system. The arms were constrained in an air sled to minimize the movements of the wrist and finger joints. Additionally, this sled dismissed arm fatigue as being a variable throughout the trial sessions. Above the arms, a horizontal projection (52" HDTV, Sony Electronic Inc) screen projected the images used for the reaching interactive game. The subject was able to see the projection with a mirror positioned above the arms and below the projection screen.

The positions and orientations of the arm segments were tracked using a Flock of Birds (Ascension Technology, USA) electromagnetic movement tracking system. Four 6 DOF sensors were placed on the body of the subjects; one was taped to both of the center dorsal hands and one was placed with a cuff midway down each upper lateral arm. These sensors were used to monitor the position and orientation of three the upper arm, forearm, and hand segments. However, because we were interested in examining the coordination between the upper arm and forearm, subjects wore a splint to immobilize joints distal to the elbow. Restriction of arm motion to the plane of the table surface allowed four degrees of freedom per arm: Shoulder x and y positions, arm flexion/extension and elbow flexion/extension. Various bony landmarks were digitized: two points to represent the finger, lateral and medial sides of the wrists, lateral and medial epicondyles of the elbow, and the acromioclavicular joint within the shoulder joints. The data were recorded at a frequency of 103 Hz for the first six subjects and 130 Hz for the final three subjects due to a system upgrade

Experimental Task/Design

The experimental set up pictured in Figure 1 was used for all participants throughout the study. Participants were in a seated position and remained so for the approximately 45 minute sessions. A start circle (d=2 cm) indicated to the subjects where to align prior to the start of the movement. A beep, which would sound after the cursor was in the start circle for 0.3 seconds, would indicate to the participant to begin the movement to the target circle (d=3.5 cm). The target circle distance from the start circle was .15 m. Subjects were instructed to make rapid, concise, and uncorrected movements and stopping as close to the target as possible. The range of required velocity was set to 0.8 to 1.2 meters per second. This high velocity requirement was required to elicit larger interlimb differences. Points were awarded based upon the accuracy of the final finger position to the center of the target, and only if the movement was within the required velocity. Specifically, points were allocated by increments of ten, three or one if the final position was within 3.5 cm, 4.5 cm or 5.5 cm of the target center, respectively. Positional feedback of the index finger was displayed before the go signal, for alignment purposes. It was then displayed as a circle for one second after each trial movement was ended. No visual feedback was given to the participant during the actual movement to the target.

The participants performed 225 trials of both unimanual and bimanual movements. There were 75 trials of each condition: right hand only, left hand only and bimanual movements. The type of movement was switched every fifteen trials. The participants were allowed to practice for about twenty trials prior to the start of the session. For analysis, the first block was excluded which was the first 45 trials. This was to ensure that a stabilized performance was to be evaluated.

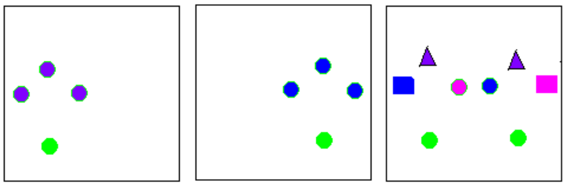

Figure 2: This figure displays the various possible targets for the experimental trial sessions. Green circles represent the start circle for all conditions. The box on the far left displays only left unimanual movements. The middle box displays the start circle and possible targets for the right unimanual movements. Finally, the box to the far right shows the possible movements for the bimanual conditions. Movements for this condition were made to the similar colored pairs (congruent hand displacement) or to the same shaped pairs (congruent joint displacement).

This experiment has one cursor representing the movement of each hand during the trials. The cursor represents the placement of the index fingers of each hand. The movements had three targets which were 30°, 90° and 150° relative to the starting position, which are shown in Figure 2. Start locations were based upon each participant's body sizes and was located after the shoulder angle was set to 35° and the elbow was set at 90°.

Data Analysis

There are several variables which were analyzed, in both temporal and spatial domains. Temporally, maximum velocity and movement duration were analyzed to make sure the movements were matched. Spatial variables were hand path curvature and final position error. Hand path curvature is the minor axis divided by the major axis of the hand path. The major axis is the largest distance between any two points in the path. The minor axis is the largest distance, perpendicular to the major axis, between any two points (Sainburg, 2002; Sainburg et al. 1993).

Final position error is the distance between the index finger location at the movement end and the target position. Hand path curvature and final position error were measured because these variables were expected to show interlimb differences due to previous studies (Bagesteiro and Sainburg, 2003; Duff and Sainburg, 2007). IgorPro was used to process the data and calculate the previously mentioned variables

Statistical analysis

The individual measures were analyzed in a separate analysis of variance (ANOVAs) in the JMP program. A three way-ANOVA was used for the statistical analysis. Significance was determined by an alpha value of .05.

Results

Unimanual vs. Bimanual

Our main hypothesis was that bimanual movement conditions will reduce interlimb differences in coordination, when compared with unimanual movement conditions. To test this, we compared dependent variables that have been shown to characterize motor lateralization between unimanual and bimanual movement conditions. As described earlier in the methods section, these measures included interlimb differences in both temporal and spatial domains. Note that our interlimb difference measures were calculated by subtracting the right from the left arm measurements for our dependent variables. Therefore, a positive value reflects that the right measure was smaller than the left, and vice versa for negative values. We have previously shown that the coordination differences between the right and left arms depend, to a large degree, on the inertial interactions between the limb segments (Sainburg and Kalakanis, 2000). Because these interactions vary with movement speed, we designed our task such that movement speed should be similar across movement conditions by providing velocity feedback. We used this feedback to require subjects to make movements with peak hand velocities that ranged between 0.80 meters per second and 1.2 meters per second. On average, our subjects' movements had peak velocities of 0.94±0.03 (MEAN±SE) meters per second across all subjects, hands and conditions. Differences between the hands were not significant, averaging only 0.02±0.03 meters per second and –0.02±0.02 meters per second for the unimanual and bimanual conditions, respectively, as shown in Figure 3.

At the bottom of Figure 3, interlimb differences in peak hand velocity are shown for each target. As expected, our ANOVA revealed a main effect of target on movement speed (ANOVA: $F_{(1,92)}=136.5$, $p<.0001$), which reflects the variations in inertia across the targets (Sainburg and Kalakanis, 2000). Because the movements to the lateral targets are almost completely single jointed (only elbow movement) and therefore are of lower inertia, the movement is completed at a higher velocity compared to movements to the other targets. However, there were no interactions with or main effects of either hand or experimental condition (unimanual, bimanual).

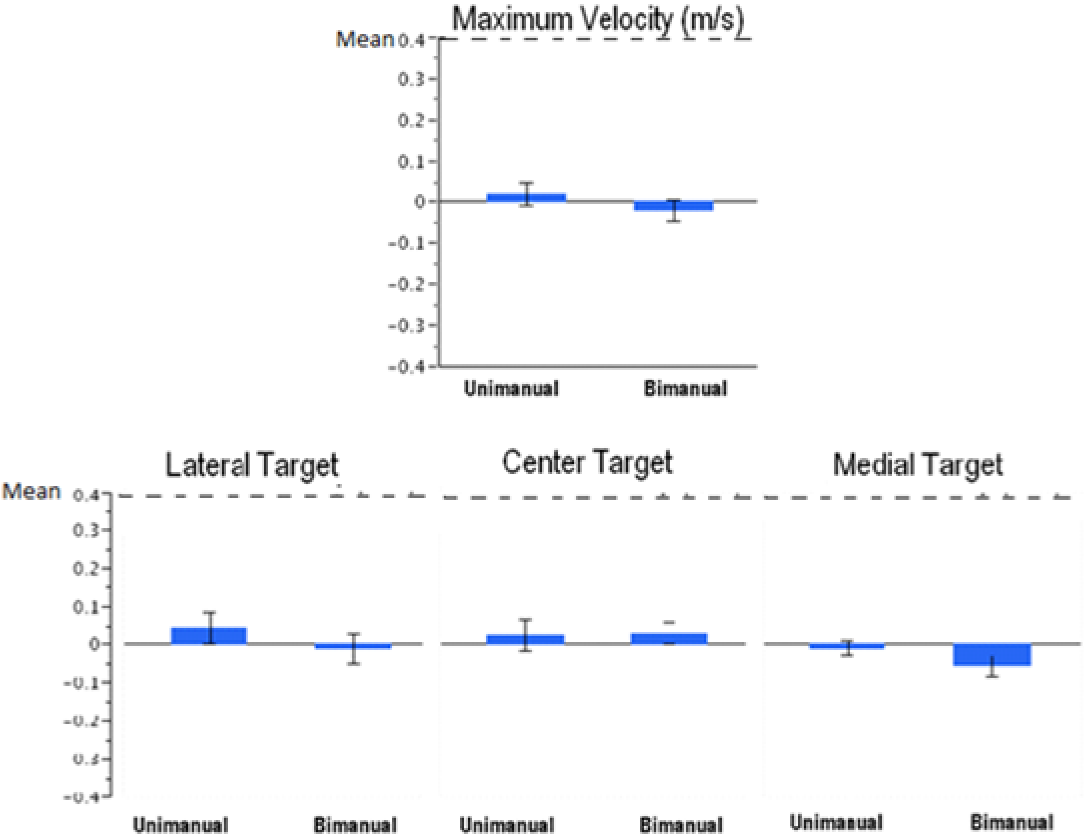

Figure 3: Interlimb differences in maximum velocity (meters per second) across all targets (top) and within targets (bottom). Note that all scales have been matched to the overall mean.

While peak speed is an important variable, movement timing can vary considerably for movements made under matched speed conditions (Sainburg and Schaefer, 2007). Therefore, we also measured movement durations, a parameter that has often been used to characterize interlimb coordination (Kelso, 1979). Across all movements and conditions, the average movement duration was 0.40±0.02 seconds. Interlimb differences in duration remained below 5% of this average, (0.01±0.01 and 0.02±0.01 seconds for unimanual and bimanual conditions, respectively). Figure 4 shows interlimb differences in movement duration, across targets and subjects for each experimental condition, as well as for each target separately. Surprisingly, our ANOVA revealed no interactions between condition (unimanual, bimanual), target or hand. (ANOVA: $F_{(1,92)}=0.08$, $p=.78$). We found a main effect of target on movement duration (ANOVA: $F_{(1,92)}=119.95$, $p<.0001$), which reflected the same direction dependent inertial effects that were described above for peak velocity. There was also significant main effect of condition ($F_{(1,92)}=5.35$, $p=.02$), such that bimanual movements had a slightly higher movement duration than unimanal movements. However, this effect did not vary with hand, such that bimanual movements were similarly longer in duration for both right and left arms.

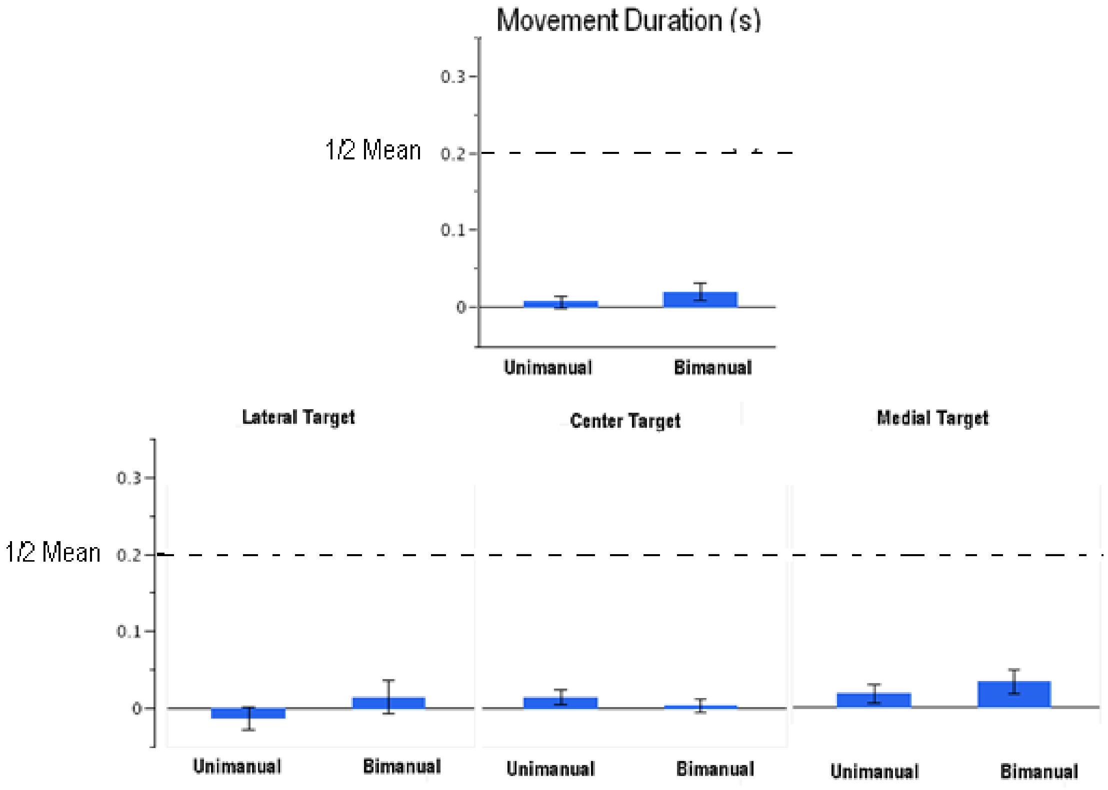

Figure 4: Interlimb differences in movement duration (seconds) across targets (top) and within target (bottom). Note that all scales have been matched to the overall mean.

In order to analyze the accuracy of the movements, final position error was also examined. Previous research has showed that reaching movements performed by the nondominant limb may achieve a more accurate final position compared to those performed by the dominant limb (Duff and Sainburg, 2006). Additionally, we predicted that there would be a relatively large final position error due to the high velocity requirements of the movements. On average, our subjects' movements had a final position error of 0.028±0.002 meters across all subjects, hands and conditions. Figure 6 shows the interlimb differences for this error, which remained below 3% of the average (-0.0007±0.003 and -0.0007±0.002 meters for the unimanual and bimanual conditions, respectively). Our ANOVA revealed a main effect of condition on the final position error (ANOVA: $F_{(1,92)}=4.55$, p=0.04) which was likely related to the more difficult perceptual task of reaching two targets with two cursors, as compared to reaching to one target with one cursor. In a follow up study, we will compare bimanual movements that move a single cursor to a single target, so that we can control for this complication.

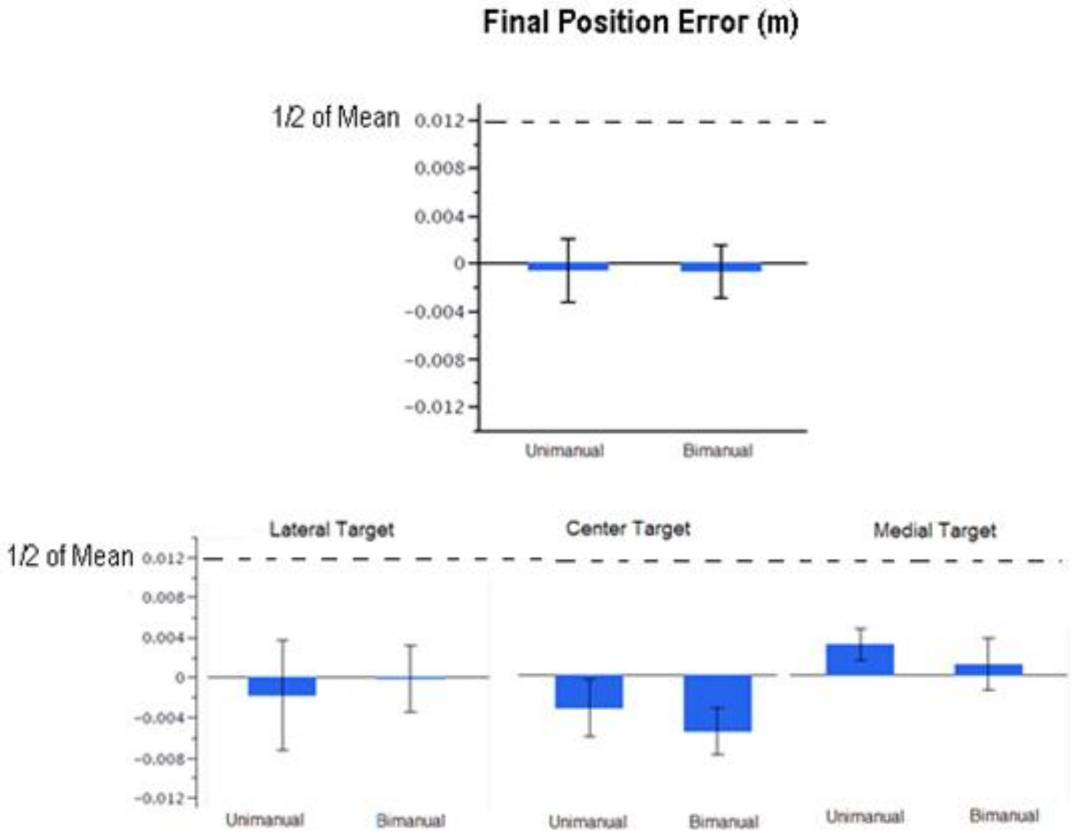

Figure 5: Interlimb differences in final position error (meters) across targets (top) and for each target (bottom). Note all scales have been matched to overall mean.

Hand path curvature was chosen as a variable because has previously shown differences between dominant and nondominant reaching movements. Earlier work in our lab has shown that nondominant hand paths typically show higher curvatures compared to movements of the dominant hand (Sainburg, 2002; Sainburg and Kalakanis, 2000). This has been attributed to the dominant system's more effective control of intersegmental dynamics. Across all movements and conditions, the average hand path curvature was 0.080±0.004. Interlimb differences in curvature, seen in Figure 6, were 0.014±0.003 and 0.008±0.006 for the unimanual and bimanual conditions, respectively. Additionally, Figure 6 shows the interlimb differences for each target. As expected, we found a main effect of hand (ANOVA: $F_{(1,92)}=5.22$, $p=0.02$) which reflects the previously found data that the nondominant hand is usually more curved than the dominant. There was also an effect of target (ANOVA: $F_{(1,92)}=6.28$, $p=.01$) which was also expected. As seen in Figure 6, movements to the lateral target had the least amount of interlimb difference. This is due to the inertial requirements for the lateral target being significantly lower than those requirements of the other targets. The center target in Figure 6 shows a trend, although not significant, in which interlimb differences were reduced during bimanual movements. However, movements to the medial target show the opposite trend. In order to better understand this, we performed additional analyses that were beyond the scope of this study. Those analyses revealed that a reduction in corrections to direction errors in the nondominant arm under bimanual conditions contributed to this trend. We believe this effect is related to attention factors associated with the fact that two targets and cursors were used during the bimanual task, but only one cursor and target were used during the unimanual task. Studies are currently underway to control for this complication.

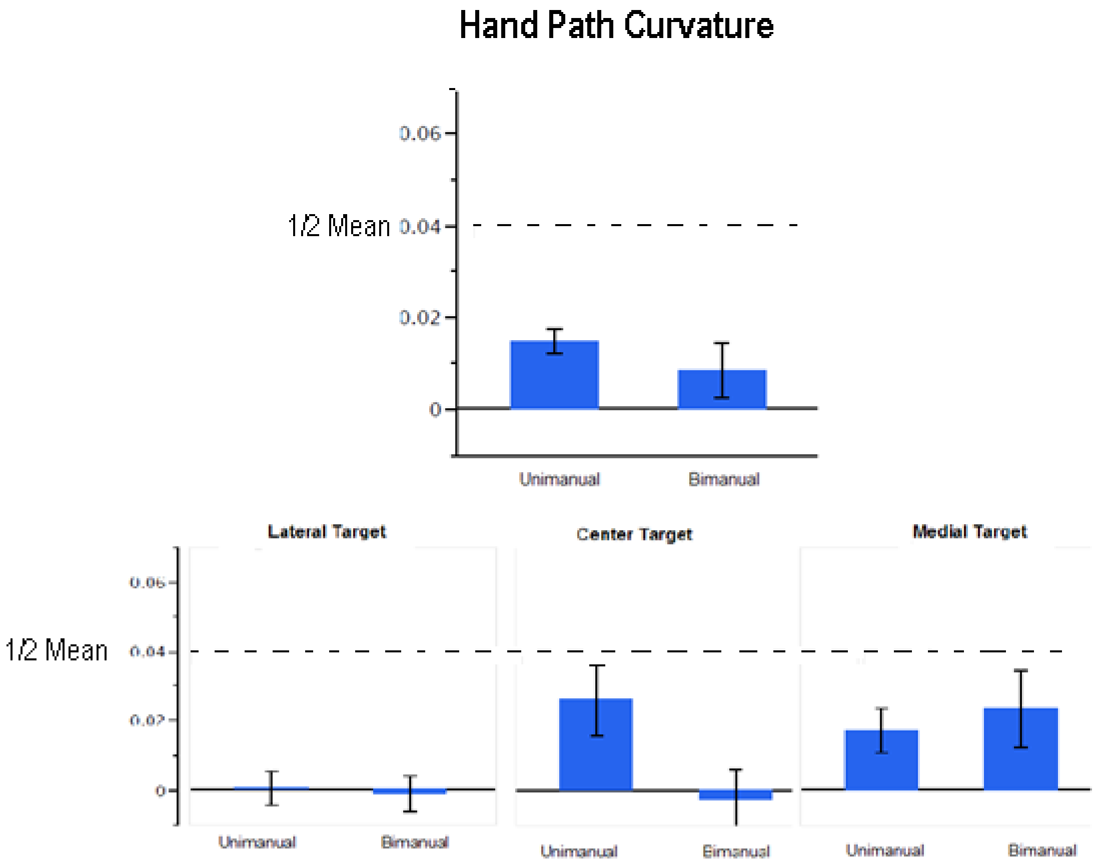

Figure 6: Interlimb differences in hand path curvature across targets (top) and within each target (bottom). Note that all scales have been matched to the overall mean.

Bimanual Hand vs. Bimanual Joint

The second prediction of this experiment was that bimanual movements made with congruent joint displacement will reflect less interlimb differences than those made with congruent hand displacement. This prediction is based on previous studies that have shown that movements which require the same joint displacement tend to be more similar to one another (Kelso, 1979; Carson, 1997). To test this hypothesis, we made a comparison between these two types of bimanual movements across targets. Note that for this section, the center target was not used for analysis, because this movement could not be categorized as either joint congruent or hand congruent. We thus separated our bimanual movements into two groups: joint congruent movements required the same joint displacements for each hand to reach the target, but required different direction hand movements. Hand Congruent movements required the same hand path directions and distances, but required both of the limbs to move through different joint displacements.

Figure 7 shows the comparison of bimanual movements for maximum velocity. Across subjects and targets, the interlimb differences were -0.05±.03 meters per second and -0.015±.024 meters per second for the congruent hand and congruent joint displacement movements, respectively. Both of these differences are below 6% of the total mean (0.94±0.03 meters per second). As expected, there was a main effect of target on movement speed (ANOVA: $F_{(1,128)}$=201.00, p<.0001) which reflects the previously mentioned inertial variations across targets. There was an interaction between movement condition and target (ANOVA: $F_{(1,128)}$=5.85, p=0.017). The medial target had greater interlimb differences in velocity during congruent hand displacement movements than those movements during congruent joint displacement movements.

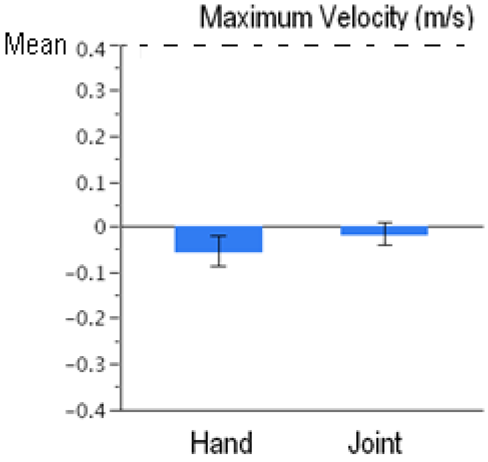

Figure 7: Average maximum velocity (meters per second) for congruent hand versus congruent joint displacement movements

The interlimb differences in movement duration were less than 10% of the mean (0.40±.02 seconds) being 0.04±0.02 s and 0.01±0.01 seconds, for hand and joint conditions respectively. These differences can be seen in Figure 8. ANOVA revealed a main affect of target on movement duration (ANOVA: $F_{(1,128)}$=116.6, p<.0001) which again, reflected the different inertial properties of the movements to the targets.

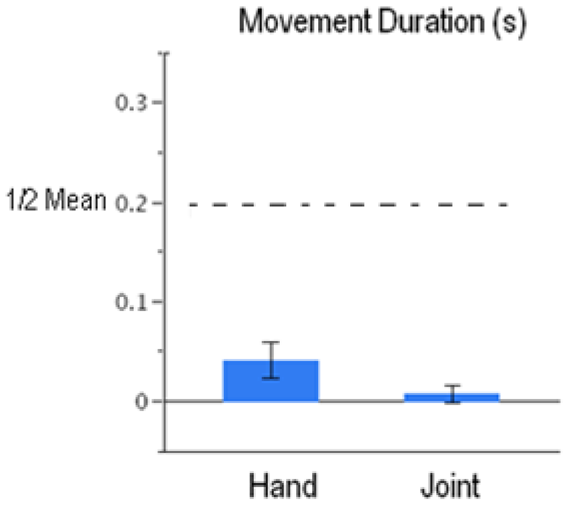

Figure 8: Average movement duration (seconds) for congruent hand versus congruent joint displacements

Final position error, which is pictured in Figure 9, was analyzed to compare the accuracy of the two different movement conditions. The interlimb differences, which were less than 10% of the mean (0.028±0.002 meters), were 0.001±0.004 and 0.002±0.002 meters for the hand and joint condition, respectively. There were no significant interactions or main effects found through ANOVA for final position error.

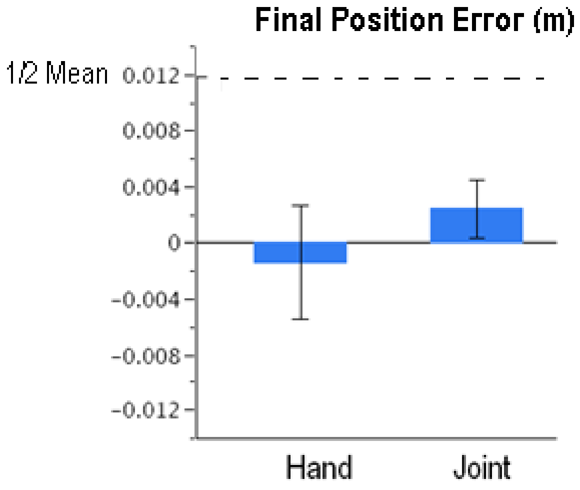

Figure 9: Average final position error (meters) for congruent hand versus congruent joint displacements

Interlimb differences for the bimanual movements in hand path curvature can be seen in Figure 10. Congruent hand displacement movements differed by 0.02±0.02 and congruent joint displacement movements differed by 0.003±0.01. As expected, we found a main effect of hand (ANOVA: $F_{(1,128)}=7.10$, $p=0.001$) and a main effect of target (ANOVA: $F_{(1,128)}=13.71$, $p=0.0003$). There was also an interaction between target and hand (ANOVA: $F_{(1,128)}=5.23$, $p=0.02$). Though the congruent joint displacement movements have a lower mean difference compared to those of the congruent hand displacements, this was not found to be significant. This was attributed to the large standard error bars which can be seen in Figure 10.

Overall, hand congruent conditions showed slightly higher interlimb differences in curvature and duration than joint congruent conditions. However, analysis beyond the scope of this report revealed that neither of these conditions were significantly different than the analogous comparisons of unimanual movements. These differences could, thus, be attributed to the differences in intralimb coordination between these movements, and was not related to interlimb differences in coordination.

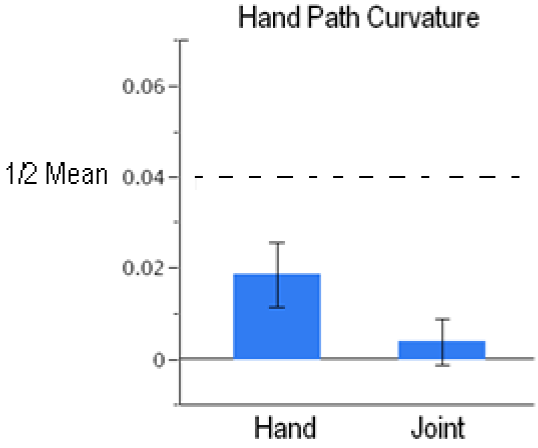

Figure 10: Average hand path curvature for congruent hand versus congruent joint displacements

DISCUSSION

Previous research has shown that there are differences between the dominant and nondominant arms when unimanual movements are performed (Sainburg and Kalakanis, 2000; Bagesteiro and Sainburg, 2002). Specifically, the dominant limb employs more torque-efficient coordination patterns for movements compared to those patterns of the nondominant limb. Other research has led to the conclusion that the nondominant arm might be specialized for maintaining stable limb positions (Bagesterio and Sainburg, 2003; Duff and Sainburg 2007).

Regarding bimanual coordination, it has been proposed that when two arms are used together to complete a bimanual task, movements become temporally synchronized and have suggested that the control of bimanual movements elicit unique control mechanisms than those of a unimanual movement (Kelso, 1979; Franz, 1991, 1996, 1997). Finally, previous research has shown that interlimb differences are less when bimanually congruent joint displacement movements are completed compared to those completed which require congruent hand displacement (Semjen, 1995; Carson, 1997).

In this study, two hypotheses were proposed: 1) the effect of handedness would be reduced when moving bimanually compared to movements made unimanually and 2) that bimanual movements which required congruent joint displacement will reflect less interlimb differences than those made with congruent hand displacement.

To test this prediction, subjects were asked to make rapid and concise unimanual and bimanual movements to various targets which required different amounts of inertial requirements in a virtual reality environment. Bimanual movements consisted of those which require either congruent joint displacement or congruent hand displacement.

Results showed that there was no significant interaction between hand, target and movement condition. Thus, interlimb differences in coordination were not changed under bimanual conditions. While we found some differences in coordination between joint congruent and hand congruent conditions, further comparison (outside our current analysis) suggest that these differences persist during matched unimanual comparison, and thus cannot be attributed to bimanual movement conditions.

Though many theories have been proposed which claim bimanual movements may have a unique control mechanism than unimanual movements, there were no differences found in this study. However, this dissimilarity with other studies may be due to a distinction in the type of movements which were tested. Two types of movements have been extensively studied in bimanual coordination: discrete movements and rhythmic movements. Discrete movements refer to goal-oriented movements, such as the reaching performed in this study which was specifically target-oriented. Conversely, rhythmic movements include a wide assortment of movements such as those that are continuous without breaks such as cyclic or repetitive movements (Hogan and Sternad, 2007).

Additionally, imaging studies have shown that rhythmic and discrete movements are controlled by different regions of the brain (Schaal et al., 2004; Yu et al., 2007) and specifically, that rhythmic movements tend to recruit more cerebellar activity (Ivry and Spencer, 2004; Ivry et al., 2002; Spencer et al., 2003). Nevertheless, Kelso’s seminal studies on bimanual coordination

(1979) were based on discrete reaching movements, and were among the first studies advocating separate control mechanisms for bimanual and unimanual movements.

The same reasoning may explain the results for the bimanual movement comparisons. Though previous research (Semjen, 1995; Carson, 1997) has concluded that ‘joint symmetric’ movements should produce more similar patterns compared to those which are ‘not symmetric,’ it should be noted that this previous research was completed by testing various rhythmic movements.

This distinction between discrete and rhythmic movements is one of great importance. Most activities which are performed in daily life are discrete movements, rather than continuous or repetitive movements. For example, reaching for a cell phone or performing a movement with the computer mouse are two instances of goal, or target, directed movements. With the exception of processes such as walking, we very rarely complete actions which are repetitive or a continuous action without a direct goal or aim.

Our results suggest that the mechanisms that synchronize bimanual movements may occur upstream in the control process to the expression of motor lateralization and consequently, might not affect the expression of interlimb differences in coordination. This, in turn, indicates that bimanual coordination does not alter the mechanisms that determine intralimb coordination patterns. Additionally, our results challenged the conclusion of a difference in congruent joint displacement and congruent hand displacement movements; rather, the movements were similar in the amount of interlimb differences.

Some limitations were present throughout this study. For example, the larger study which this project was a part of concluded that hand path curvature (the minor axis of the movement divided by the major axis of the movement) may not be the most efficient measurement for these movements. For example, it does not take into account if the subjects' movements were overshot, which would increase the major axis, and thus decrease the overall hand path curvature variable which would portray that a movement was less curved than it truly was. Though there were some small trends in interlimb differences between all conditions these were not statistically significant. Additionally, there were relatively large standard error bars. Perhaps a greater amount of subjects may have pronounced the interlimb differences to a greater degree and decreased the amount of standard error.

There are several future studies which could be developed as a follow up to this experiment. Though it was not published within this thesis project, a second experiment was completed which tested bimanual movements with one cursor rather than two. The cursor was shared between the index fingers of both hands during the movement (only congruent hand displacement movements could be performed). The conclusions from this second experiment could be very interesting and may make differences in coordination between unimanual and bimanual movements even more prominent.

Finally, many variables throughout this analysis showed that the center target portrayed interesting and different results compared to medial and lateral targets. It is a special case, in which bimanual movements to this target requires both congruent joint displacement and congruent hand displacement of the limbs, which may involve a totally different control mechanism. A future study which focuses primarily on limb movements made to this center target may reveal the possibility of another unique movement control mechanism.

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Child Care
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-Cared for the well being of up to three children (ages 1,2,4) at one time
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-Responsible for transportation to school, practices and other after school activities

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-Welcomed patients to the office, scheduled appointments.
-Measured blood pressure and pulses of the patients prior to therapy sessions
-Managed the auditing of all billing and clinical charts

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Brand Representative
April 2005-Present; Seasonal

-Interacted daily with the sales team and prospective clients
-Translated orders from customers into the internal The North Face portal system

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Pennsylvania Emergency Medical Technician, June 2008-present

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2008 Penn State Dance Marathon: Dancer for Women's Club Basketball
Women's Club Basketball: Member, player and Safety Officer
Intramural basketball, volleyball and soccer

Public Service:

A.I Nemours, DuPont Hospital

Emergency Department

May '07- August '07

- Duties included stocking rooms and care of the waiting room
- Acted as a liaison between patients and their doctors
- Assisted patients and their families by offering an extra hand during their time at the hospital.

Chester County Hospital

Hospital Transporter

May '06- September '06

- Remained on call to assist doctors and administrators when needed
- Transported patients to different parts of the hospital for their appointments

Pennsylvania Certified Emergency Medical Technician

Good Fellowship Ambulance Company, Station 55

June '08-Present

- Responsible for the primary assessment, treatment and transportation of patients in need emergency care
- Prepared ambulances before and after calls
- Continuing education was also required to keep up with the most modern medical techniques
- Accurate and full charting skills were necessary as EMTs must chart every call within a 24 hour time period