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Using a Multi-Direction Reaching Approach to Investigate Fitts' Law and the Effect of Attentional Focus on Motor Learning

Charles R. Smith

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by

Charles R Smith

Bachelor of Science
The College of New Jersey, 2014

Master of Science
Lindenwood University, 2017

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Accepted by:

Jill C Stewart, Major Professor

Sheri P Silfies, Committee Member

Roozbeh Behroozmand, Committee Member

Shailesh Kantak, Committee Member

Tracey L. Weldon, Vice Provost and Dean of the Graduate School

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ABSTRACT

The Index of Difficulty value (ID) derived from Fitts' Law's speed-accuracy trade-off is commonly used to determine the difficulty of a targeted reaching movement and balance difficulty in sequence learning tasks. However, this value does not account for the mechanical difficulty of multi-directional movements which could affect both performance and learning. Where we direct our focus when completing a task/skill can also have an effect on how we perform and learn that task, however, the manner in which differing focus instructions affect learning a whole-arm reaching task is relatively unknown. The purpose of this dissertation was to examine 1) how Fitts' Law translates to multi-directional targeted reaching movements and 2) examine how differing focus of attention instructions affect the learning of a multi-directional, whole-arm sequence task. The first study found that while reaches to targets of increasing ID and same direction resulted in scaling of kinematic measures consistent with Fitts' Law, reaches between targets of the same ID but differing directions resulted in variations in movement time and other movement kinematic measures. These variations are likely the result of differences in mechanical difficulty due to changes in inertia and joint demands with direction. The results of Study 1 suggest that studies which use multi-directional, whole-arm reaching movements should either try to account for this effect and/or understand this limitation to Fitts' Law. The second study found that both External (EF) and Internal (IF) focus

instructions resulted in similar improvements in overall performance (Response Time) on the sequence task over practice but did so via different approaches. The EF instructions resulted in shorter hand paths indicating straighter hand trajectories during the task while the IF instructions resulted in higher peak velocities indicating higher movement speeds. The results of Study 2 suggest that both EF and IF instructions can be effective when learning a motor sequence task which requires both speed and accuracy but do so via differing control mechanisms. This finding suggests that instructions could be tailored to the task at hand and toward the control parameter (spatial, temporal) where change is most desired.

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CHAPTER 1

INTRODUCTION

Motor learning can be defined as a relatively permanent change in the ability to effectively execute a task or skill resultant from practice or experience. Where one places their focus during practice can have an influence on how motor skills are learned. Learning has been characterized by positive changes in task outcomes such as decreased reaction and execution times (Ariani & Diedrichsen, 2019; J. Baird & Stewart, 2018; de Kleijn, Kachergis, & Hommel, 2018; Ghilardi, Moisello, Silvestri, Ghez, & Krakauer, 2009; Nissen & Bullemer, 1987), improved accuracy (Ariani & Diedrichsen, 2019; Ghilardi et al., 2009; Nissen & Bullemer, 1987), straighter movement paths (Baird & Stewart, 2018; de Kleijn et al., 2018), and decreased interference from a secondary goal (Ghilardi et al., 2009; Nissen & Bullemer, 1987). Sequence learning, whereby a sequence is defined as a series of motor responses, has been predominantly studied using finger-pressing or joystick movement paradigms (Ariani & Diedrichsen, 2019; Boyd & Winstein, 2006; Lin et al., 2011; Nissen & Bullemer, 1987; Yokoi & Diedrichsen, 2019). While these studies allow for the investigation of sequence learning with a great amount of control over the task environment, their results may not be generalizable to tasks which involve

greater motor demands, such as whole-arm reaching (Wulf & Shea, 2002). Some studies have utilized more complex movements (e.g., whole-arm reaches) to examine sequence learning; however, these reaching movements are typically in two-dimensional workspaces and task difficulty is based on Fitts' Index of Difficulty (ID) (de Kleijn et al., 2018; Ghilardi et al., 2009; Perfetti et al., 2011; Perfetti et al., 2010; Sense & van Rijn, 2018).

Fitts' Law is defined by the speed-accuracy tradeoff whereby as either the distance between two targets increases, the size of the target decrease, or both the difficulty to accurately attain the target quickly increases logarithmically (Fitts, 1966; Fitts & Peterson, 1964). However, whole-arm reaching movements have varying inertial demands depending on the direction of movement which can influence not only kinematic outcomes like movement time and peak velocity (Gordon, Ghilardi, Cooper, & Ghez, 1994; Gordon, Ghilardi, & Ghez, 1994) but also the intersegmental dynamics between the shoulder and elbow (Dounskaia, Ketcham, & Stelmach, 2002; Gritsenko, Kalaska, & Cisek, 2011). These factors could, in turn, change the mechanical difficulty of the movement in a manner not accounted for by Fitts' Law. Also, many of the studies which have examined Fitts' Law and the effects of reach direction on reach control have not required the movement to be accurate to the target (Glazebrook, Kiernan, Welsh, & Tremblay, 2015; Gordon, Ghilardi, Cooper, et al., 1994; Gordon, Ghilardi, & Ghez, 1994; Heath, Weiler, Marriott, Elliott, & Binsted, 2011; Roberts et al., 2016; Sleimen-Malkoun, Temprado, Huys, Jirsa, & Berton, 2012; Takeda et al., 2019). However, endpoint accuracy is necessary in many whole-arm sequence tasks which often

balance task difficulty based upon Fitts' Law alone (Baird & Stewart, 2018; Meehan, Dao, Linsdell, & Boyd, 2011; Sense & van Rijn, 2018). **Therefore, the effect of reach direction on Fitts' Law in whole-arm reaches which require endpoint accuracy is not known and should be investigated in order to better understand how sequence and movement tasks can be better balanced for both task and mechanical difficulty.**

The OPTIMAL Theory of motor learning (Lewthwaite & Wulf, 2017; Wulf & Lewthwaite, 2016) proposes a model for the optimization of learning motor tasks and skills. Part of this theory describes how where we direct our attention when executing a task/skill can affect how we perform and learn it. Previous studies have linked external focus instructions, whereby attention is directed toward the goal/outcome of the task, with better performance accuracy (Beilock, Carr, MacMahon, & Starkes, 2002; Chua, Wulf, & Lewthwaite, 2018; Masters, 1992; Wulf, Chiviacowsky, & Drews, 2015; Wulf, Lauterbach, & Toole, 1999; Wulf, McConnel, Gartner, & Schwarz, 2002), greater jump height/distance (Becker & Smith, 2015; Porter, Ostrowski, Nolan, & Wu, 2010; Vidal, Wu, Nakajima, & Becker, 2018) and increased movement speed (Porter, Wu, Crossley, Knopp, & Campbell, 2015) compared to internally focused and non-instructed controls. However, internal focus cues which direct attention to the movement itself have at times have been linked with improved movement paths (Milanese, Cavedon, Corte, & Agostini, 2017; Schutts, Wu, Vidal, Hiegel, & Becker, 2017; Winchester, Porter, & McBride, 2009; Zentgraf & Munzert, 2009), which may indicate improved movement coordination. In fact, some studies have shown that when

internally focused instructions are relevant/salient to the task goal, the internally focused groups perform/learn at least as effectively as their externally focused counterparts (Mattes, 2016; Maurer & Munzert, 2013; Zachry, Wulf, Mercer, & Bezodis, 2005; Zentgraf & Munzert, 2009).

Many previous studies examining focus of attention have evaluated learning and performance effects using broad performance outcomes such as accuracy, distance, time, or speed (Becker & Smith, 2015; Beilock et al., 2002; Chua et al., 2018; Diekfuss et al., 2019; Halperin, Chapman, Martin, & Abbiss, 2017; Masters, 1992; Porter et al., 2015; Vaz, Avelar, & Resende, 2019; Vidal et al., 2018; Wulf et al., 2015; Wulf, Hoss, & Prinz, 1998; Wulf et al., 1999); however, these studies often lack detailed kinematic measures of movement (i.e., movement path and movement velocity) which could provide insight into how different focus instructions influence performance and learning. The learning of a whole-arm sequence task, as was used in Baird and Stewart (2018), requires movements to be fast, accurate and efficient (well-coordinated) in order to optimize performance and allows for the collection of detailed kinematic measures often lacking in previous focus of attention studies. **Therefore, the effect of different focus of attention instructions on a whole-arm sequence learning task that requires both fast, accurate, and efficient movements is not known.**

The dominant and non-dominant arms differ in the control and coordination of multi-joint reaching movements whereby the dominant right arm is more skilled at inter-joint coordination, as seen by straighter hand paths, while

the non-dominant arm is more skilled at attaining an accurate end point relative to the target (Sainburg & Kalakanis, 2000; Schabowsky, Hidler, & Lum, 2007; Schaffer & Sainburg, 2017; J. Wang & Sainburg, 2007). These differences in control may, in turn, impact learning of a whole-arm sequence task. Previous studies which compared the learning of a whole-arm sequence task between the arms found that while both the dominant right and non-dominant left arms effectively learned the sequence, as observed by decreased response times, they did so via different approaches. The dominant right arm improved in both spatial (hand path distance) and temporal (movement velocity) aspects of reach control thereby improving the overall efficiency of the motor pattern. The non-dominant left arm, however, improved predominantly in the spatial aspect of control with greater improvements in hand path distance over practice than the dominant right arm (Baird & Stewart, 2018; Baird et al., 2018; Smith et al., 2021a).

In previous studies where task performance largely depends on the effective completion of a specific movement pattern, internal focus instructions have been shown to be at least as effective as their external focused counterparts (Milanese et al., 2017; Neumann, Walsh, Moffitt, & Hannan, 2020; Schutts et al., 2017; Winchester et al., 2009; Zentgraf & Munzert, 2009). More specifically, when the cue is salient to the movement goal – such as hand movement in a juggling task (Zentgraf & Munzert, 2009) or snapping the wrist in a basketball shooting task (Maurer & Munzert, 2013; Zachry et al., 2005) – the internal focus cue elicits positive results. This diversion from the OPTIMAL

Theory may be because of how the cue is interpreted in the context of the task at hand. A study by Mattes (2016) discusses that externally focused instructions draw attention to how the movements interact with the environment and ultimately the task goal; the internally focused instructions commonly used in focus of attention studies, however, tend to increase awareness to how the body interacts with itself. Because of this dichotomy, Mattes suggests utilizing internal cues that promote "open monitoring" of the movement rather than constraining it to a specific component. These studies imply that internally focused instructions may have been commonly linked with negative task outcomes because the instructions were not salient to the task goal. **Therefore, because the two arms seem to learn this sequence task by improving differing areas of reach control, the addition of focus instructions may differentially affect how the two arms learn a whole-arm sequence task based upon the instruction's relevance/saliency with the limb's locus of control.**

The purpose of this dissertation was to 1) evaluate the effect of target direction on Fitts' Law during three-dimensional reaches and 2) evaluate the effect of external versus internal focus of attention instruction on the learning of a whole-arm implicit sequence task in both the dominant and non-dominant arms.

Specific Aim 1: To examine the interaction between Fitts' Law and target direction on whole-arm, three-dimensional reach performance with both the non-dominant left arm and the dominant right arm.

- *Hypothesis 1 (Effect of Difficulty)*: Reaches to targets along the same directional plane will increase in movement time as the inter-target

amplitude, and therefore Fitts' ID, increases (i.e., 5 to 1 and 1 to 5 compared to 5 to 9).

- *Hypothesis 2 (Effect of Direction)*: Reaches to targets with the same inter-target amplitude, and therefore the same Fitts' ID, will have varied movement times relating to differences in inertial demands due to reach direction whereby reaches directed along greater inertial planes (i.e., 1 to 9 or 5 to 9) will have a greater movement time than reaches directed along lesser inertial planes (i.e., 1 to 3 or 7 to 3).
- *Hypothesis 3 (Effect of Arm)*: Reaches with non-dominant left arm will show a greater effect of target direction on reach control to targets at the same Fitts ID than reaches with dominant right arm due to differences in inter-joint coordination between the two arms such that there will be a greater difference in movement time between reaches directed along greater inertial planes (i.e., 1 to 9 or 5 to 9) and those directed along lesser inertial planes (i.e., 1 to 3 or 7 to 3) in the non-dominant left arm than the dominant right arm.

Specific Aim 2: To investigate the effect of focus of attention instructions (internal vs. external) on the learning of an implicit whole-arm sequence task in both the non-dominant left and dominant right arms.

- *Hypothesis 1 (Focus on Learning)*: All groups will show a reduction in response time with practice.

- *Hypothesis 2 (Interaction between Focus and Arm on Control)*: There will be differences in how the focus instructions facilitate learning in the two arms.
    - *A:* Consistent with the OPTIMAL Theory (Lewthwaite & Wulf, 2017; Wulf & Lewthwaite, 2016), dominant Right arm will benefit most from the external focus instructions which facilitate automatic movement patterns seen through greater decreases in total hand path distance and increases in peak velocity than the internal focus instructions.
    - *B:* The non-dominant left arm would benefit more from the internal focus instructions by drawing attention to the arm and the coordination between joints thereby facilitating greater improvements in hand path where the left arm has the most to gain.

CHAPTER 2

REVIEW OF THE LITERATURE

2.1: Motor Learning: Defined

2.1.1: Motor Tasks & Motor Skills

In both sport and life, the ability to perform a variety of tasks and skills is necessary to optimize one's functionality in those arenas. Throughout our lives, beginning at birth, we begin to acquire and learn these tasks and skills as they are needed. Motor learning can be defined as a relatively permanent change in the ability to effectively execute a task or skill resultant from practice or experience. A task is the desired outcome, or goal, of a movement or series of movements (Shumway-Cook & Woolacott, 2012). Tasks can be categorized functionally or regulatorily. Functionally categorized tasks are defined by the action's goal. Such tasks could include transferring from a supine to a seated position while in bed, reaching and grasping a cup, standing up out of a chair, serving the ball in tennis or volleyball, catching a ball, running, etc. which denote various requirements to perform in daily life or sport (Shumway-Cook & Woolacott, 2012). These tasks can also be categorized regulatorily as either discrete or continuous dependent upon whether a defined beginning and endpoint exist in the task (Shumway-Cook & Woolacott, 2012). Many tasks of sport and daily life are discrete, meaning they have defined beginnings and

endings. When drinking, the task can begin when the reach for the cup is initiated and can end when the cup is placed to the lips. When serving a tennis ball, the task begins when the toss motion is initiated and ends when the follow-through of the racquet is completed. The same process can be applied to just about anything we do in daily life. Continuous tasks have endpoints that are arbitrarily defined by the performer or evaluator. In this manner, running and walking are continuous because though they have defined start points (that first toe-off) their endpoints are typically defined by the completion of some pre-determined distance (like a race) or time (like the six-minute walk test) rather than the motion having a specific termination point.

Tasks can be further dissected into their comprising skills which are the goal-directed movements involved in the execution of a task (Shumway-Cook & Woolacott, 2012). Accomplishing a task can require a single motor skill – such as a single targeted reach to press a doorbell – or a series of skills performed in coordinated, timed succession – such as reaching to grasp a drinking glass. In the former example, the only goal was to hit the target (the doorbell); whereas in the latter example, it is not enough to transfer the arm and hand to the glass as the hand must also open and close in order to grasp the glass. These two movements must be carefully coordinated to avoid knocking over the glass, crushing the glass, dropping the glass, or grasping an item that is not the glass. This means the successful task completion is contingent upon both the accuracy of the reach and proper scaling of the grasp.

2.1.2: Defining Learning in Research

Learning has been characterized by positive changes in task outcomes such as decreased reaction and execution times (Ariani & Diedrichsen, 2019; Baird & Stewart, 2018; de Kleijn et al., 2018; Ghilardi et al., 2009; Nissen & Bullemer, 1987), improved accuracy (Ariani & Diedrichsen, 2019; Ghilardi et al., 2009; Nissen & Bullemer, 1987), straighter movement paths (Baird & Stewart, 2018; de Kleijn et al., 2018), and decreased interference from a secondary goal (Ghilardi et al., 2009; Nissen & Bullemer, 1987). While these outcomes are helpful in defining that a task was learned, they do not clearly outline how the motor system adapted to improve performance.

Previous studies have shown that learning a skill can elicit positive changes in the movement itself. Learned movements should be well-coordinated and easily replicable to ensure each repetition elicits a similar or better outcome than the previous. Changes in inter-joint/inter-segment synchronies or variability in joint ranges of movement can create opportunities for errant outcomes. For example, changing the timing between hip and torso rotations can cause deviation from a golfer's normal swing plane resulting in an errant shot or a change in a pitcher's arm angle can change the pitch's trajectory, spin, velocity, and accuracy. Variability in these synchronies can be expected from novices as they are unfamiliar with the skill and are creating a new motor pattern for it; experts, however, have the skill well-learned and therefore will have more consistent movement patterns (Burdet, Osu, Franklin, Milner, & Kawato, 2001; Carson & Riek, 2001; Chapman, Vicenzino, Blanch, & Hodges, 2007; Hasson,

Caldwell, & van Emmerik, 2008) (Figure 2.1). The decrease in movement variability from learning can also correspond to improvements in inter-joint coordination (Chapman, Vicenzino, Blanch, & Hodges, 2009; Hasson et al., 2008; Kornatz, Christou, & Enoka, 2005), increased movement velocity (Kantak, Zahedi, & McGrath, 2017), and decreases in movement distance indicating a more effective motor strategy is being implemented.

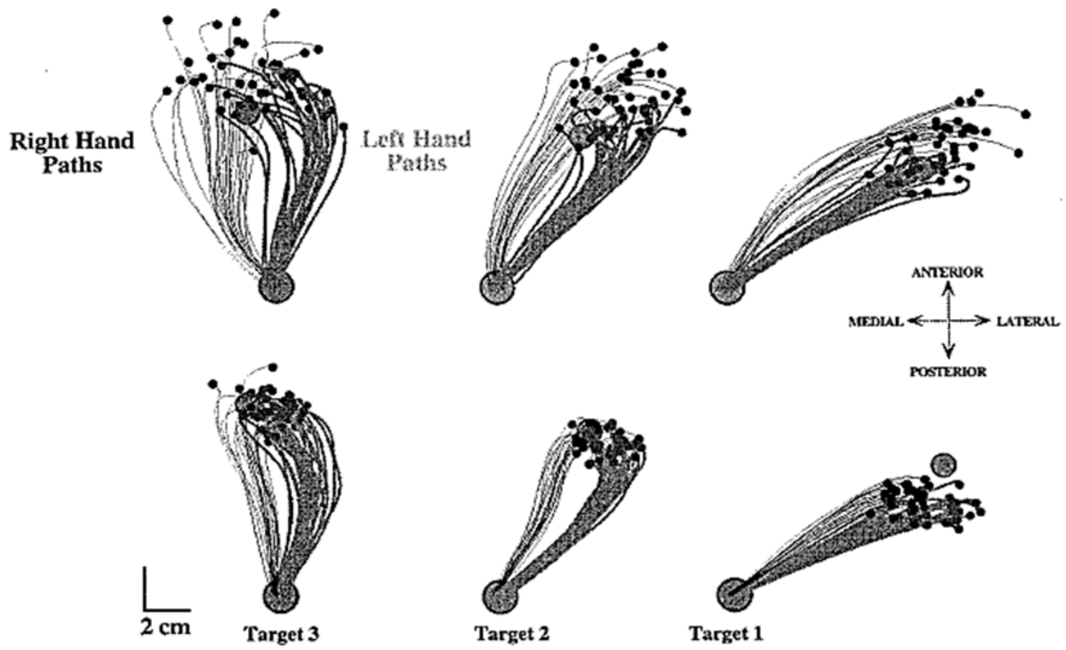

Figure 2.1. from *Chapman et al 2009.* displays improvements in joint motions with training; notice in **a** how the 95%CI of the joint displacements throughout the movements decrease in elite cyclists indicating a tighter, more consistent range from cycle to cycle; this consistency is reflected in **b** where we can see that the variability in the hip-ankle cycling is significantly lower in elite cyclists than in novices which would indicate a more coordinated movement pattern between the two joints.

Learning over multiple days can be evaluated in multiple contexts. Firstly, one can consider the overall learning effect, which can be classified as the change in performance metrics from the first block of the first practice session to the first block on the last practice session (Kantak & Winstein, 2012). This

provides insight into the general change over the practice time provided. Secondly, is the question of consolidation versus forgetting. Consolidation is defined as a continued improvement in performance from the last block of one practice session to the first block of the following practice session while forgetting would be the opposite (a decrease in performance) (Kantak & Winstein, 2012). Consolidation represents an increased stability in the memory of the task over time that is indicative of off-line learning while forgetting could indicate that more practice is needed for the changes in performance to become permanent (Kantak & Winstein, 2012). These are metrics define how well the memory of the task can be retrieved and re-implemented from one session to the next and tests the efficacy of the practice sessions and consolidation processes.

2.1.3: Implicit & Explicit Learning

Given the improvements in motor control and performance that accompany practice/experience, one can see how adept the motor system is at learning how to move to meet task demands. Can we rely on the motor system to only learn via trial and error (implicit learning), or does declarative knowledge of the specifications of the task – the sequence, how to move, how to manipulate an item – enhance the learning experience (explicit learning)? How tasks and skills are learned is not a simple discussion. Previous research has been able to parse out two different types of learning: implicit learning and explicit learning. Implicit learning is referred to as non-declarative learning because the skill was acquired through repetition of the motor system's automatic reaction to the task

presented whereas explicit learning is declarative in that the information regarding the task can be consciously recalled and implemented using attention, awareness, and higher cognitive processes (Shumway-Cook & Woolacott, 2012). These can also be referred to as "bottom-up" and "top-down" learning as implicit and explicit learning stem from subconscious feedback gained from previous attempts and conscious feedforward mechanisms aimed at controlling/regulating the impending attempt, respectively (Sun, Slusarz, & Terry, 2005). While these two processes seem to work independently from one another, they both process information to update and improve the motor plan for the execution of a movement or series of movements to optimize performance. Previous works have modeled that both forms of learning work in tandem with one another where motor skills are acquired and learned to varying degrees using both implicit and explicit components (Dale, Duran, & Morehead, 2012; Ghilardi et al., 2009; Sun et al., 2005).

2.2: Sequence Learning

2.2.1: Finger-Pressing Paradigms

In finger-pressing sequence tasks, a series of cues (number, shape, letter, color, etc.) coded to the fingers of the hand appear. After each cue appears, the participant presses a button/key with the corresponding finger. A series of cues makes up a predetermined n-length sequence where n = the number of cues in a sequence. Sequences can either be classified as either random – consisting of cues in no particular order – or repeated – consisting of a specific predetermined

cue order – and will be practiced over a single to multiple days. The changes in metrics like reaction time (the time from when the cue is presented to the time where the finger moves), response time (the time from when the cue is presented to the time where the button is pressed), total time (the time it takes to complete the sequence), and error (pressing the incorrect button in response to the cue) are typically used to classify learning. A "learned" sequence would show decreases in all of these metrics over practice and time (Ariani & Diedrichsen, 2019; Boyd & Winstein, 2006; Lin et al., 2011; Nissen & Bullemer, 1987; Yokoi & Diedrichsen, 2019).

Memory is gained through both implicit and explicit processes. The inclusion of both random and repeated sequences in practice has been used to further elucidate implicit and explicit contributions to learning. The improvements in the random sequence trials shows improvement in the implicit processes of recognizing to the cue and making an accurate response (Boyd & Winstein, 2006; Nissen & Bullemer, 1987); further improvement in the repeated sequence trials would then indicate that there is a component of the learning that was specific to sequence type whereby the repeated sequence may be subconsciously (or consciously) recognized and anticipated. If the learner can recall the sequence after all practice is completed, it would be determined that there was an explicit learning component to the task; if not, then learning likely occurred predominantly from implicit processes.

2.2.2: Whole-Arm Paradigms

The use of whole-arm paradigms has recently become of particular interest. In general, learning in these tasks is observed and interpreted in a similar manner as during finger-pressing tasks with decreased reaction time, response time, and total time (Baird & Stewart, 2018; de Kleijn et al., 2018; Ghilardi et al., 2009; Sense & van Rijn, 2018); however, the principles of learning garnered from simple motor tasks, like a button pressing sequence, may not necessarily be generalizable to learning more complex motor skills, like reaching with the whole arm (Wulf & Shea, 2002). Whole-arm paradigms may be more applicable to daily living because most functional tasks using the upper extremities require the coordinated movement of the entire arm, not just the hand. Aside from the increased movement demands, what makes these tasks particularly different from finger-pressing paradigms is that whole-arm tasks can also have target accuracy requirements whereby error is not just relative to movement selection (an incorrect response) but also relative to a target. Many whole-arm paradigms also have an accuracy demand whereby the learner not only reaches in response to a cue but also reaches with the goal of hitting a target in response to that cue (de Kleijn et al., 2018; Ghilardi et al., 2009; Sense & van Rijn, 2018). Therefore, learning in a whole-arm paradigm could include decreased error relative to the target.

The addition of movement error relative to a target increases the difficulty of the task at hand. This new level of difficulty can be observed through the context of Fitts' Law describing the speed-accuracy trade-off. Fitts' Law states

the difficulty of hitting a target increases as distance to the target increases, size of the target decreases, or both in a logarithmic manner (Fitts, 1966; Fitts & Peterson, 1964). Due to this, sequence tasks using whole-arm movements are typically balanced based upon the index of difficulty (ID) of the various reach movements calculated based off the speed-accuracy relationship (Baird & Stewart, 2018; Ghilardi et al., 2009; Perfetti et al., 2011; Perfetti et al., 2010). Even though the sequences are balanced based upon difficulty as defined by Fitts' ID, the sequences often require multidirectional movements. Previous research has shown that reaches to equally sized and spaced targets but in different directions do not have the same biomechanical demands (Gordon, Ghilardi, Cooper, et al., 1994; Gordon, Ghilardi, & Ghez, 1994).

As can be seen in Figure 2.2, the directions with greatest inertia tend to have the lowest acceleration values which corresponded to lower movement velocities (Gordon, Ghilardi, Cooper, et al., 1994; Gordon, Ghilardi, & Ghez, 1994). The same can be said of movement extent whereby peak acceleration, peak velocity, and movement extent decrease as inertia increases (Gordon, Ghilardi, Cooper, et al., 1994; Gordon, Ghilardi, & Ghez, 1994). Without the aid of visual or proprioceptive feedback, center-out movements made in low inertial directions tended to have larger errors in extent – or on-axis error along the targeted direction – than higher inertial directions (Gordon, Ghilardi, & Ghez, 1995); however, high inertia reaches tended to have greater radial error – or off-axis error deviating from the targeted direction – toward a point of lower inertia (Gordon et al., 1995). In a center-out paradigm where all targets have the same

Fitts' ID, these differences in velocity, acceleration, and error could be attributed to the inertial differences of the reaches. However, when visual feedback was added to the center-out paradigm, target error decreased across all directions but the differences in velocity and acceleration remained (Ghez, Gordon, & Ghilardi, 1995). Such outcomes indicate that while the quantified difficulty based on target size and distance are the same (i.e., via Fitt's Law), the physical difficulty of the reaches may be different because of the inertial demands of the reach.

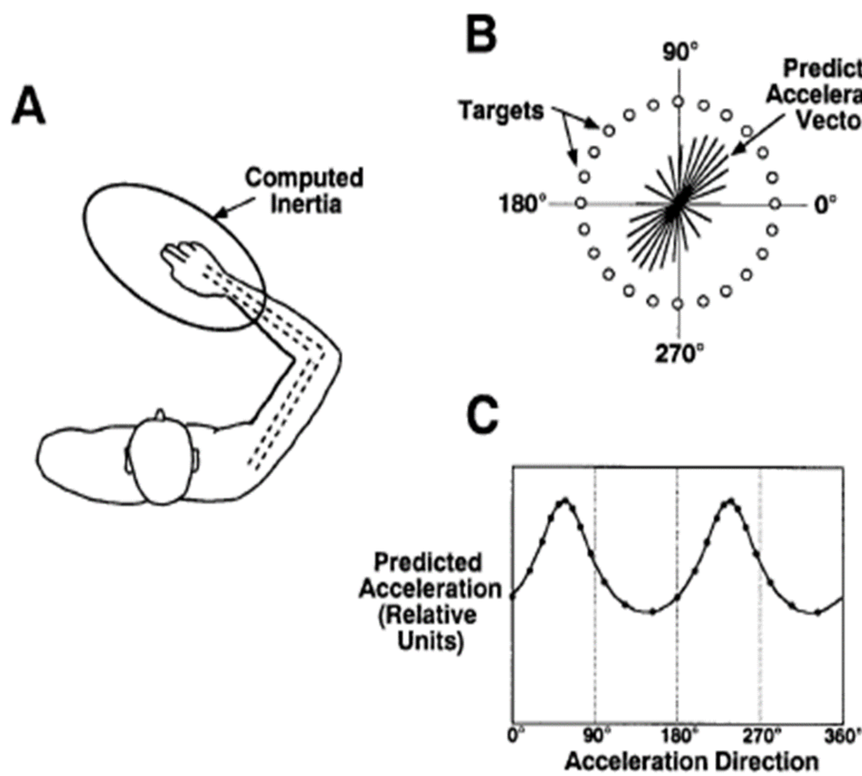

Figure 2.2. from *Gordon, Ghilardi & Ghez 1994.* **A** shows the inertial vectors for the different reach directions while **B** and **C** show the predicted movement acceleration vectors and peaks, respectively, for the different reach directions.

Reach directionality can also influence the joint demands of the reach. These differences in joint movement and coordination are seen in the results from Dounskaia et al. (2002) (Figure 2.3). Looking at four different movements –

vertical (a straight, forward-backward movement), horizontal (a straight medial-lateral movement), resistive (along a 45° diagonal toward the ipsilateral workspace), and assistive (along a 45° diagonal toward the contralateral workspace) – differences in inter-joint roles can be seen through differences in the magnitudes and directions of muscle and interaction torques at each joint (Figure 2.3b). For example, the resistive reach seemed to be heavily dominated by the muscle torque at the elbow and what little muscle torque occurs at the shoulder is counteracted by the interaction torque from the elbow; the assistive reach, however, has a large amount of muscle torque at the shoulder which creates an interactive torque that dominates the elbow movement. This inter-

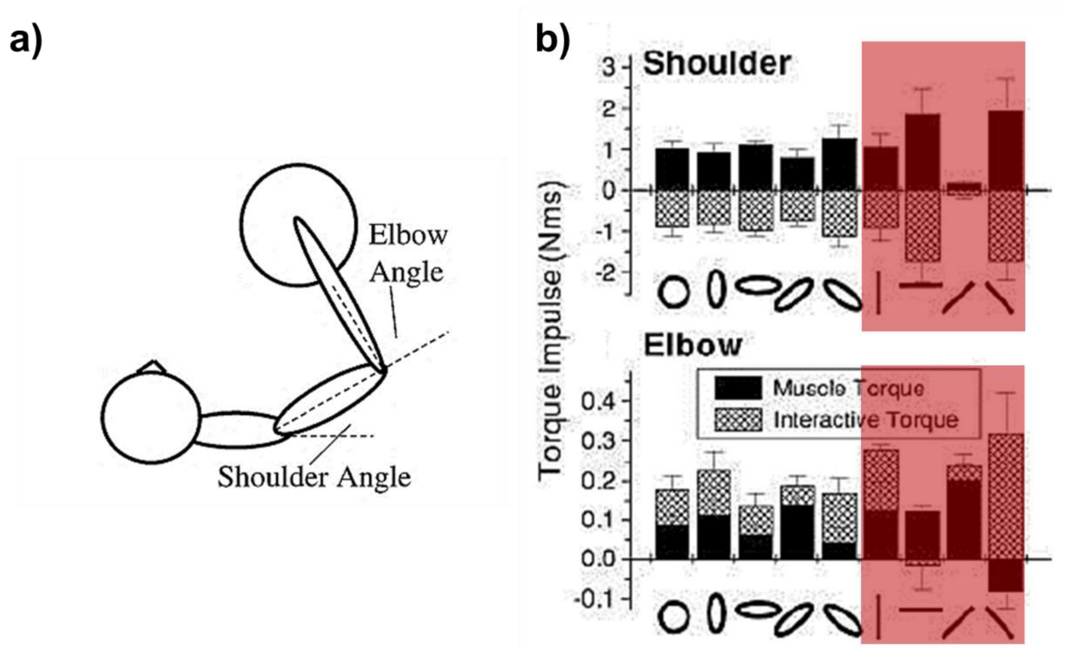

Figure 2.3. from *Dounskaia, et al 2002.* **a)** displays the experimental setup for their task to examine shoulder-elbow coordination in multi-directional reaches with the hand and arm in the initial start position; **b)** displays the contributions of muscle and interactive torques to the net torque at each joint; movements highlighted by the **red** box correspond to those described in-text in order vertical, horizontal, resistive, assistive; Nms = Newton meter seconds; data mean±sd

joint relationship is consistent with that seen in Gritsenko et al. (2011), which is where the “assistive” and “resistive” terminology is taken. The horizontal and vertical reaches appear to have torque profiles which are relatively similar to the resistive and assistive reaches, respectively, but with varying degrees of shoulder-elbow interaction. Dounskaia et al. (2002) showed similar results when examining the joint excursions and relative phases of the reaches whereby the resistive reach had relatively low total joint excursion and a relative phase indicating the movement is predominantly elbow-generated while the assistive reach had high total joint excursion and a relative phase indicating a split-control between the shoulder and elbow with the horizontal and vertical movements lying in between. This ordering in inter-joint demands – resistive, horizontal, vertical, assistive – also mirrors the increasing order of the directional inertias of the reaches, as described in Gordon, Ghilardi, and Ghez (1994), which could indicate that higher inertia reaches may also be more complex due to the amount of joint movement and inter-joint coordination required to effectively execute the reach.

2.2.3: Dominant vs Nondominant Arm

Reach control is also influenced by the arm with which the reach is performed, dominant or nondominant. Previous studies have described that reaches with the dominant arm are typically controlled using a feedforward, motor planning-based strategy while the nondominant arm typically tends to utilize a control strategy using predominantly sensory feedback loops to create

fast and accurate movements (Goble, Lewis, & Brown, 2006; Sainburg, 2005; Sainburg & Schaefer, 2004; Wang & Sainburg, 2007). Nondominant limb movements tend to have multipeaked velocity profiles (Bagesteiro & Sainburg, 2002; Sainburg & Kalakanis, 2000) which suggests that the reach comprised of an initial movement from the motor plan and a secondary movement carried out based on sensory feedback. Nondominant reaches also tend to have increased directional errors but have lower final position errors (Bagesteiro & Sainburg, 2002; Mutha, Haaland, & Sainburg, 2013; Sainburg & Kalakanis, 2000; Tomlinson & Sainburg, 2012) and covers a greater proportion of the total movement distance in the deceleration phase (Duff & Sainburg, 2007). This movement strategy indicates that the initial movement may not necessarily be accurate but instead serve to simply break inertia and get the limb out into the workspace, and the secondary movement acts to hone in on the final position.

The inter-joint coordination patterns between the dominant and nondominant limbs are also different (Bagesteiro & Sainburg, 2002; Sainburg & Kalakanis, 2000; Schaffer & Sainburg, 2017; Tomlinson & Sainburg, 2012). The difference in coordination is reflected through differences in hand paths between the two arms where the dominant arm tends to take a soft medial to lateral curvature toward the target while the nondominant arm tends to curve lateral to medial (Figure 2.4) (Bagesteiro & Sainburg, 2002; Duff & Sainburg, 2007; Sainburg & Kalakanis, 2000). The dominant arm’s medial-lateral curvature corresponds to the shoulder initiating and driving the movement while the elbow moves predominantly due to the interactive torque from the shoulder (Bagesteiro

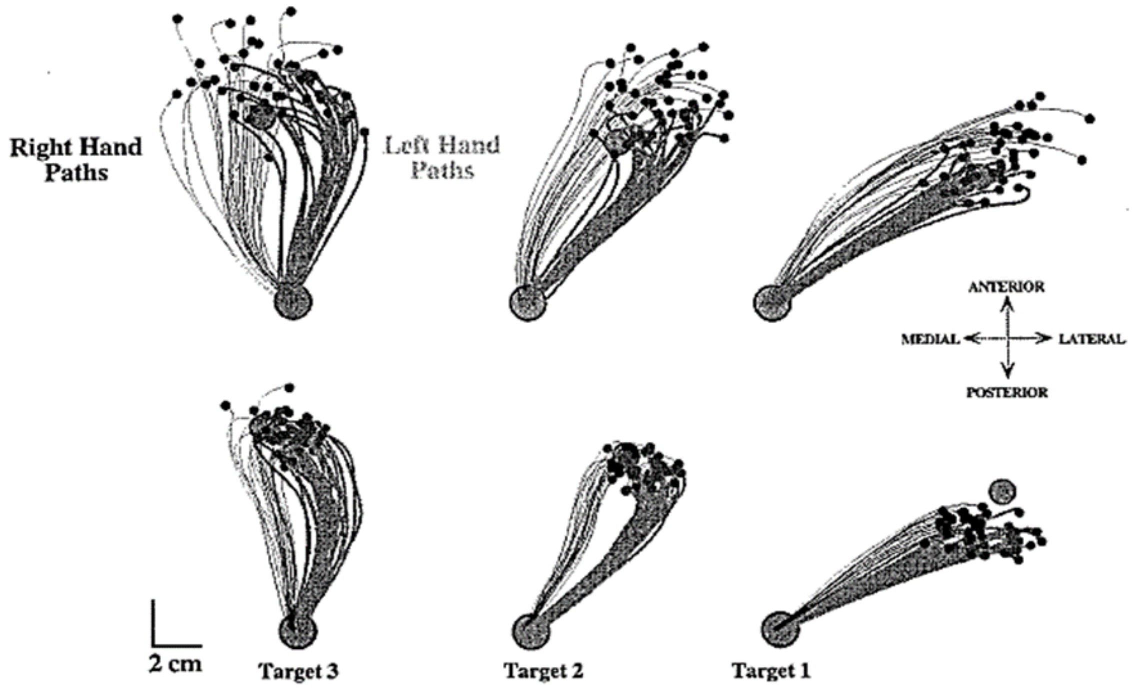

Figure 2.4. from *Sainburg & Kalakanis 2000.* shows the hand path curvatures of targeted reaches with both the dominant right and non-dominant left arms; notice how the laterally directed movements (to Target 1) have fairly straight paths regardless of hand while as the targeted direction moves more medially, the left arm paths become increasingly more curved; this change in shape seems to correspond to an increase in inter-joint demands as the reaches to Target 1 would correspond to a predominantly elbow-centric and low inertia movement while the reaches to Target 1 would correspond to a greater shoulder-elbow interaction and a greater inertial value in the movement (see Dounskaia et al 2002; Gordon et al 1994a).

& Sainburg, 2002; Sainburg & Kalakanis, 2000). This pattern of the shoulder being the driver of upper extremity movement is consistent with the "lead joint hypothesis" whereby the musculature at "leading joint" (often the proximal one) creates the movement's foundation whereby the "subordinate joint" (often the distal one) is moved passively through interaction torque and uses its musculature to terminate and adjust the movement (Dounskaia, 2010; Dounskaia et al., 2002). The nondominant arm's lateral-medial curvature, however, could be linked to the earlier onset of elbow excursion than the dominant arm

(Sainburg & Kalakanis, 2000) and the increased involvement of elbow muscle torques on both the shoulder and elbow joints in the early stages of movement (Bagesteiro & Sainburg, 2002; Sainburg, 2005; Sainburg & Kalakanis, 2000).

2.2.3: Summary

As was discussed before, much of the sequence learning literature has utilized finger-pressing paradigms. While these paradigms are advantageous because they are simple and can be implemented in tandem with fMRI data collection, they are not very functional to daily life, and no kinematic outcomes can be collected from these tasks. Joystick paradigms have been used because they too can be implemented with fMRI and can include targeted movements, like whole-arm paradigms, and therefore incorporate a speed-accuracy component; however, joystick movements are still limited to hand and wrist motion. Whole-arm sequence paradigms provide an opportunity to better understand how tasks are learned and their comprising movements controlled in a manner that is more akin to that of daily activities, but such tasks make up the least amount of the literature, and fewer still are set in a three-dimensional workspace. However, whole-arm sequence studies to date have not addressed the limitation that multidirectional reaches have varying biomechanical demands which may influence the difficulty of said reaches beyond the Fitts' ID. Additionally, whole-arm sequence studies have predominantly examined learning in the dominant right arm. Given the nondominant left arm displays a different control strategy than the dominant right arm over whole-arm movements,

investigation of not only how/if the left arm learns differently than the right arm but also if the nondominant left arm's differing motor control strategy changes reach directionality's possible influence on Fitts' ID.

2.3: The OPTIMAL Theory of Motor Learning

The OPTIMAL Theory of motor learning (Lewthwaite & Wulf, 2017; Wulf & Lewthwaite, 2016) seeks to give instruction as to how motor learning can be maximized. This theory has garnered a great amount of attention by researchers and clinicians alike who seek to maximize the learning capability and performance of people, especially as it pertains to learning a new skill or relearning a skill.

2.3.1: External Focus of Attention

Where we direct our attention during learning can have a profound influence in how we learn. External focus instructions, focusing on the goal/outcome of the task or movement, have been linked with improved balance (Diekfuss et al., 2019; McNevin, Shea, & Wulf, 2003; Vaz et al., 2019; Wulf et al., 1998; Wulf, McNevin, & Shea, 2001; Wulf, Shea, & Park, 2001), better target accuracy (Beilock et al., 2002; Chua et al., 2018; Masters, 1992; Wulf et al., 2015; Wulf et al., 1999; Wulf et al., 2002), greater jump height/distance (Becker & Smith, 2015; Porter et al., 2010; Vidal et al., 2018), increased movement speed (Porter et al., 2015), and greater force production and power (Halperin et al., 2017; Halperin, Williams, Martin, & Chapman, 2016; Makaruk, Porter,

Dlugolecka, Parnicka, & Makaruk, 2015; Zarghami, Saemi, & Fathi, 2012). Internal focus instructions, focusing on the movement or a specific movement component, and non-instructed controls generally present much smaller degrees of improvement, if any, in these tasks. Enhanced performance and learning from externally focused instruction have been attributed to improved movement efficiency as measured by decreased co-contraction of antagonist and synergist muscles (Lohse & Sherwood, 2012; Lohse, Sherwood, & Healy, 2011; Zachry et al., 2005) with little change in agonist EMG compared to controls (Lohse & Sherwood, 2012; Lohse et al., 2011; Marchant & Greig, 2017; Vance, Wulf, Tollner, McNevin, & Mercer, 2004; Wulf, Dufek, Lozano, & Pettigrew, 2010; Zachry et al., 2005). These changes in EMG seem to indicate improved muscle sequencing and movement coordination and therefore better neuromuscular control, similar to what's linked with the positive outcomes from motor learning. Externally focused movements also show greater amounts of movement entropy and variability indicating more automatic and reaction-like patterns from the motor system (Kal, van der Kamp, & Houdijk, 2013; van Ginneken et al., 2018; Vidal et al., 2018).

Internally focused instructions, however, tend to increase EMG signals for all involved muscles (Lohse & Sherwood, 2012; Lohse et al., 2011; Marchant & Greig, 2017; Vance et al., 2004; Wulf et al., 2010; Zachry et al., 2005) and freeze movement about the point of focus (van Ginneken et al., 2018; Vidal et al., 2018) compared to both external focus and control instructions. These apparent inefficiencies of internally focused instructions have been used to define the

“Constrained Action Hypothesis” which proposes that using an internal focus interferes with automatic control processes regulating the movement while adopting an external focus reinforces automatic processing and allows the motor system to naturally organize and execute the movement (McNevin et al., 2003; Wulf, McNevin, et al., 2001; Wulf & Prinz, 2001; Wulf, Shea, et al., 2001). Therefore, by constraining and consciously controlling the movement, internally focused instructions are thought to elicit less efficient and coordinated movement patterns than their externally focused counterparts. Given the internal versus external focus comparison thus far, this hypothesis would appear to be supported by the current body of literature.

Through these outcomes, the OPTIMAL Theory proposes using an external focus of attention to enhance goal-action coupling and prevent impedances to performance, and therefore learning, provided by internal foci as described by the “Constrained Action Hypothesis”.

2.3.2: Summary

The goal of the OPTIMAL Theory is to provide a framework assisting in the optimization of the conditions for learning. Utilizing an external focus of attention increases goal-action coupling and does not constrain the movement to the same degree as an internal focus of attention. This “freedom” to move increases the utilization of automatic/reactionary control processes and gives the learner control to approach the task with only the goal in mind. In doing so, an external focus may also support autonomy in the learning environment by further

promoting the exploration for a “correct” solution and self-regulation strategies. The success from the external focus then breeds future success and then improved learning due to more positive conditions. The results listed above indicate that an external focus of attention may function via implicit learning processes. However, as mentioned before, learning occurs on a spectrum between implicit and explicit processes (Dale et al., 2012; Ghilardi et al., 2009; Sun et al., 2005) meaning explicit, internally focused instruction may be similarly effective in some contexts.

2.4: Challenges to the Benefits of External Focus of Attention

While using an external focus of attention tends to yield better outcomes as it relates to performance metrics, internally focused cues have shown to be advantageous in certain circumstances. Such situations would include when looking at the kinematics of the resultant movement – particularly when internally focused instructions are salient to the task, familiar to the learner, and the skill is novel to the learner.

2.4.1: Movement Kinematics

Internal cues have been shown to constrain movements by freezing degrees of freedom of the joint of focus (van Ginneken et al., 2018; Vidal et al., 2018). There may be some instances where this response is positive. Most times, performance or learning changes due to focus of attention are evaluated using tasks that have outcome measures that are independent of the movement

themselves (Becker & Smith, 2015; Masters, 1992; Wulf et al., 2010; Wulf & Shea, 2002). For example, in many accuracy tasks – such as throwing, darts, golf, basketball – there are multiple possible movement solutions that could result in a successful outcome (Beilock et al., 2002; Masters, 1992; Wulf et al., 2015; Wulf et al., 1999; Zachry et al., 2005). Such tasks are inherently biased because the externally focused instructions are most relevant to the task at hand while the internally focused instructions might not be optimal for each individual. However, when the task at hand is contingent upon effective completion of a specific movement pattern, or a single movement solution, internal focus cues have elicited similar or better outcomes to external focus cues (Milanese et al., 2017; Neumann et al., 2020; Schutts et al., 2017; Winchester et al., 2009; Zentgraf & Munzert, 2009). In fact, when learning or performing a complex movement, like the power snatch in weightlifting, using internally focused feedback led to bar paths closer to the body and movement phase positions that allowed greater balance and control of the weight compared to non-instructed controls or purely externally focused cues (Milanese et al., 2017; Schutts et al., 2017; Winchester et al., 2009).

Neumann et al. (2020) examined the effects of focus instructions on performance in a 6 min rowing time trial on a rowing ergometer and found that the internal cues elicited greater total row distances and row distance per 30 sec epoch along with greater power than the externally focused group. Since the participants were coached in maintaining a stroke rate of 28 to 30 strokes per minute, which was maintained during data collection, one reason for the

difference in performance may have been due to more efficient movement paths and better movement component coupling in the internal group than the external group. The authors did postulate though that increased muscle effort could have resulted in the observed outcomes over increased efficiency (Neumann et al., 2020). However, Neumann et al. (2020) did not collect any kinematic data to support or refute these claims. Unfortunately, this is often the case with much of the focus of attention literature – performance outcome data is collected with little to no kinematic data to examine how the desired outcome (performance or learning) was accomplished.

2.4.2: Cue Saliency & Familiarity

One of the biggest criticisms of the focus of attention literature thus far is that of cue saliency and familiarity. Typically, whatever has been instructed using internally focused verbiage is often the location of positive and negative results. When instructions focus on a specific joint's movement in a dynamic task, that joint's movement gets frozen, possibly for stabilization purposes (van Ginneken et al., 2018; Vidal et al., 2018). However, the movement component in focus often is not what would be considered "critical" to the movement outcome, such as focusing on knee extension in a jumping task rather than hip extension (Ducharme, Wu, Lim, Porter, & Geraldo, 2016; Gokeler et al., 2015). When the cue is salient to the movement goal – such as hand movement in a juggling task (Zentgraf & Munzert, 2009) or snapping the wrist in a basketball shooting task (Maurer & Munzert, 2013; Zachry et al., 2005) – the internal focus cue elicits

positive results. For example, in the juggling task, the internal focused cue caused similar performance and learning of the juggling while eliciting hand paths similar to the experts; in comparison, the external focus cue lead to ball paths that were similar to the experts (Zentgraf & Munzert, 2009). Thus, saliency can be an important factor in the efficacy of internal focus instructions.

Maurer and Munzert (2013) showed that cue familiarity may be more important than cue content because there were no differences in basketball shooting accuracy between internal and external instructions so long as the instructions used familiar verbiage. The "mind-muscle connection" proposes that by drawing focus to a specific muscle or movement component a person can increase specific muscle recruitment and intensify feedback via local sensory organs, thereby increasing kinesthetic awareness of their body (Calatayud et al., 2016; Calatayud et al., 2017; Schoenfeld & Contreras, 2016; Snyder & Fry, 2012). In doing so, familiarity with internal cues might be increased and the decrements of internal cues abated. The issue of cue familiarity is further outlined by Mattes (2016) who discusses how internal and external focus instructions work into a new mindfulness-based intervention to sport and training. This narrative outlines a tug-of-war between internal (explicit) and external (implicit) foci and learning. External cues increase awareness to how movements interact with the environment and ultimately the movement goal. Internal cues, however, can increase awareness to how the body interacts with itself or the implement in hand. External cues are relatively easy to understand whereas internal cues often use verbiage that is very specific to a certain component of movement

which constrains the movement to that specific element. Mattes' new approach proposes that internal cues be geared more toward "open monitoring" and how the movement feels, thereby freeing it, rather than doing the movement "correctly", and constraining it (Mattes, 2016).

2.4.3: Novices versus Experts

Novices tend to respond more positively to internal cues, as they are just learning a new movement, than experts, who may already have automated processes for the movement (Beilock et al., 2002). While not all studies have directly compared novices with experts, some studies have utilized novices as their subject pool. Overall, some studies have found that internal focus cues produce similar or better learning or performance than external focus or control groups in tasks such as rowing (Neumann et al., 2020; Parr & Button, 2009), juggling (Zentgraf & Munzert, 2009), the power snatch (Milanese et al., 2017; Schutts et al., 2017; Winchester et al., 2009), and soccer dribbling (Beilock et al., 2002) in novices. While these results seem promising for the utilization of internal focus cues, Wulf (2013) has noted that such studies have inherent methodological flaws. For example, "skill focused" instructions, or focus on the task itself or an element of the task at hand rather than a direct focus to the movement or movement component, could create data variability because these cues might induce either an internal or external focus depending on the subject's interpretation or their context related to the task (Wulf, 2013) (e.g., "focus on straight club motion" during putting would elicit an external focus response as the

club is not part of the movement per se but is manipulated by the movement which could, in turn, elicit some internal focus strategy via kinesthetic sense of body position relative to the club). There is also criticism over cue content and that the focus cues are often too dissimilar from each other where there is no information processing overlap between the two foci (i.e., visual information is encouraged with external cue but not in internal) (Wulf, 2013). This further highlights that attentional focus instructions between studies are varied and that the verbiage of many internal cues may either be overly constraining or constraining the non-critical components of the movement. Therefore, it may be that we do not yet understand how learning occurs under different, relevant focus cues well enough to effectively evaluate differences between novices and experts; or we may need to delve more deeply into the comparison between novices and experts to evaluate if and how internal focus cues aid in the early learning phase of a new skill.

2.4.4: Limitations

Most of the focus of attention studies to date have primarily been evaluated using a crude performance metric such as balance, accuracy, distance, time, and speed (Becker & Smith, 2015; Beilock et al., 2002; Chua et al., 2018; Diekfuss et al., 2019; Halperin et al., 2017; Masters, 1992; McNevin et al., 2003; Porter et al., 2015; Vaz et al., 2019; Vidal et al., 2018; Wulf et al., 2015; Wulf et al., 1998; Wulf et al., 1999; Wulf, McNevin, et al., 2001; Wulf, Shea, et al., 2001). The few studies that did assess movement kinematics did so by

examining either movement paths or movement variability (Gokeler et al., 2015; Milanese et al., 2017; Schutts et al., 2017; van Ginneken et al., 2018; Vidal et al., 2018; Winchester et al., 2009; Zentgraf & Munzert, 2009). Few studies have examined joint motion and coordination patterns (Gokeler et al., 2015; Vidal et al., 2018), and these studies do not go beyond a cross-sectional observation to evaluate changes over a single day of acquisition, and therefore did not assess learning. Therefore, in-depth kinematic analyses of how different focus instructions influence changes in joint kinematics while learning motor skills is needed.

CHAPTER 3

INVESTIGATING THE APPLICABILITY OF FITTS' LAW TO MULTI-DIRECTIONAL, THREE-DIMENSIONAL TARGETED REACHING MOVEMENTS[1]

3.1: Introduction

Fitts' Law describes a speed-accuracy trade-off whereby as the distance between two points (target amplitude) increases and/or the size of the target (target width) decreases, the difficulty of attaining the target quickly and accurately increases logarithmically (Fitts, 1966; Fitts & Peterson, 1964). While this relationship is commonly used to determine the difficulty of targeted reaching movements, some exceptions have been described. Movement speed and/or accuracy are not simply related to the target size or distance but also related to the relative location of a target when viewed as part of a target group (Glazebrook et al., 2015), movement of additional degrees of freedom from other body segments (i.e., trunk and arm vs. arm alone) (Bonnetblanc, 2008), availability of online visual feedback (Heath et al., 2011), movement in lower extremity-based tasks (Danion, Duarte, & Grosjean, 1999; Juras, Slomka, & Latash, 2009), or whether the movement was discrete or cyclical in nature

(Smits-Engelsman, Van Galen, & Duysens, 2002). Additionally, most studies have investigated Fitts' Law using movements along a single direction or plane (Danion et al., 1999; Glazebrook et al., 2015; Heath et al., 2011; Jax, Rosenbaum, & Vaughan, 2007; Roberts et al., 2016; Robinson & Leifer, 1967; Rosenbaum & Gregory, 2002; Sleimen-Malkoun et al., 2012; Smits-Engelsman et al., 2002). Therefore, while the speed-accuracy trade-off described by Fitts' Law has been observed in various task environments, the applicability of Fitts' Law to a task involving multi-directional reaching movements has not been clearly defined.

Previous studies have shown that different movement directions impart different inertial demands which affect not only movement time but also movement kinematic measures such as peak acceleration and movement distance (Gordon, Ghilardi, Cooper, et al., 1994; Gordon, Ghilardi, & Ghez, 1994; Gordon et al., 1995). Differences in movement direction also result in different joint demands such that movements aimed in one direction can be accomplished using predominantly a single degree of freedom or a single joint while movements aimed in other directions may require simultaneous control over multiple degrees of freedom across multiple joints (Dounskaia, 2005; Dounskaia et al., 2002; Dounskaia & Wang, 2014; Gritsenko et al., 2011). These differences in inertia and joint coordination demands could, in turn, affect the movement's control and kinematic outcomes. While previous studies have used multidirectional reaches to examine Fitts' Law, they either lacked detailed

kinematic measures (Murata & Iwase, 2001) or did not examine the differences between the directions (Takeda et al., 2019).

Many of the task paradigms used for examination of Fitts' Law do not require the target to be captured (i.e., no accuracy demands), instead instructing the mover to attain the target by moving as quickly and accurately as possible (Glazebrook et al., 2015; Heath et al., 2011; Roberts et al., 2016; Sleimen-Malkoun et al., 2012; Takeda et al., 2019). However, activities of daily living often require a movement to terminate at a specific endpoint whereby inaccuracy can result in movement errors (i.e., knocking over a glass rather than grasping it or hitting the wrong button on an elevator panel). Therefore, it is relatively unknown how well Fitts' Law translates to movements for which end-point accuracy is required rather than simply encouraged.

Therefore, the purpose of this study was to examine the applicability of Fitts' Law in multi-directional, three-dimensional (3D) targeted reaching movements that have an endpoint accuracy requirement. It was hypothesized that reaches in the same direction but with increased inter-target distance, and therefore increased difficulty as determined by Fitts' Law, will have greater movement times, peak accelerations, and joint excursions than targeted reaches with lower difficulty (Fitts, 1966; Fitts & Peterson, 1964; Smith, Hetherington, Silfies, & Stewart, 2021; Stewart, Gordon, & Winstein, 2013, 2014). It was also hypothesized that these kinematic outcomes will vary for targeted reaches in different directions but with the same inter-target distance, and therefore the same difficulty as determined by Fitts' Law, which will coincide with the

differences in inertia and joint demands (Ghez et al., 1995; Gordon, Ghilardi, Cooper, et al., 1994; Gordon, Ghilardi, & Ghez, 1994; Gordon et al., 1995).

3.2: Methods

3.2.1: Experimental Procedure

This study was completed using a within-subject, cross-over design. Participants completed 10 reciprocating reaches for all defined target combinations in a randomized order with both arms. The arm completed first was counter-balanced across participants (dominant right arm or non-dominant left arm) with the process repeated with the opposite arm after a 20 min break.

3.2.2: Participants

To be eligible for participation, individuals had to be right-hand dominant as determined by the Edinburgh Handedness Questionnaire (Oldfield, 1971), older than 18 years of age, have no current or recent neurological symptoms as determined by a general symptom checklist, and report no pain in the upper extremities. Ten non-disabled, neurologically intact adults (5 female, 27.1±3.4 yrs) completed the targeted reach task. Pilot data collected using a similar paradigm as the one used in the current study found a large effect of direction on response time (η^2 of 0.255). A power analysis run using G*Power 3.1 and assuming a large effect size of $f = 0.5$, $\alpha = 0.05$, and 80% power indicated a minimum sample size of 8 was required. All participants provided informed consent prior to enrollment in the study. The study was conducted in accordance

with the Declaration of Helsinki, and all aspects of the study were approved by the Institutional Review Board (IRB) at the University of South Carolina.

3.2.3: Experimental Task

For the targeted reach task, participants completed a series of reciprocal reach movements between targets along varying directional axes. Briefly, participants sat facing a virtual display (Innovative Sport Training Inc., Chicago, IL) where the task was projected down into the workspace directly in front of them. The participants wore stereoscopic glasses to allow for 3D visualization of the targets. An electromagnetic marker placed on the index finger was used to both indicate position in the virtual display (cursor, 25mm white sphere) and collect position data throughout movement. Participants were instructed to reach to the individually projected target (28 mm red sphere) “as quickly as possible”. Once the center of the cursor was within 5 mm of the center of the target for >500 msec, the target was considered “hit” and would disappear as the next target appeared. Online visual feedback of the cursor and target position was present throughout. Prior to task completion, participants were exposed to the nine-target circular array (Fig 1) where they were able to explore the virtual environment, reach to the different target locations, and become familiarized with the process of placing the cursor into the target.

Participants completed a series of reciprocal reaches between twelve pairs of targets in the circular planar array. Targets were first classified based on Index of Difficulty (ID) as calculated by $log_2(A/_W)$ where A = the inter-target

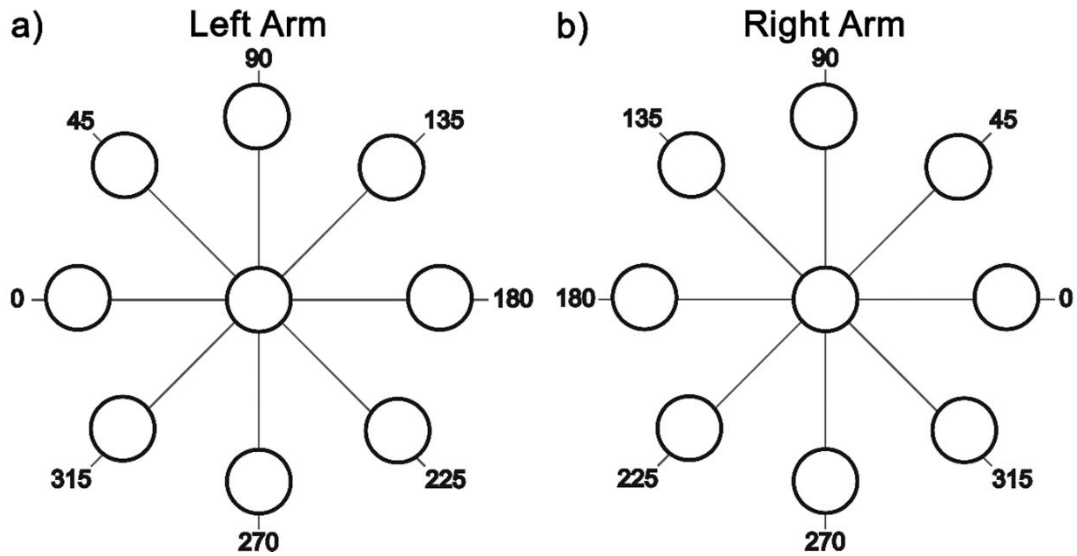

Figure 3.1. Target Arrays. Overhead view of the target arrays and the directional axes for the **a)** Left and **b)** Right arms. Note that the directions between the two arms were mirror images of each other in order to ensure the joint demands for each reach direction were the same between the two arms.

amplitude and W = the target's diameter (Fitts, 1966; Fitts & Peterson, 1964). The first set of target pairs comprised of reaching movements between the target at the center of the array and those on the periphery (10 cm reach distance, ID of 2.78). These movements were then subclassed into two different categories – Center-Out which were from the central target to the periphery and Out-Center which were from the periphery to the central target. These categories had the same ID (i.e., same target distance) but different initial joint positions. The second set of target pairs comprised of reaching movements between targets on the periphery along the diameter of the array (i.e., between two targets opposite each other on the array) which had longer inter-target amplitudes (20 cm) and a higher calculated ID of 3.78 (Long/Diameter).

3.2.4: Kinematic Analysis

All data were collected using the MotionMonitor system (Innovative Sport Training Inc., Chicago, IL). Electromagnetic sensors (Flock of Birds, Ascension Technology Corp, Shelburne, VT) were attached to the nailbed of the index finger, the midpoint of the dorsal aspect of the forearm, midpoint of the lateral aspect of the upper arm, and dorsal aspect of the scapular acromion process of the arm used along with the C7 spinous process. All landmarks were digitized using a stylus to build local coordinate systems for each arm segment (hand, forearm, upper arm, scapula, and thorax) using International Society of Biomechanics (ISB) recommendations (Wu et al., 2005). The index finger sensor was used to indicate hand/cursor position in the 3D workspace. Joint degrees of freedom were defined based upon a ZX'Y" Euler sequence outlined by Senk & Cheze (2006). Joint motions were defined based upon the movements characterized in the ISB recommendations (Wu et al., 2005). Shoulder flexion was defined as positive elevation of the upper arm segment relative to the thorax with 0° being with the upper arm in anatomical neutral at the participant's side and 90° being the upper arm perpendicular to the thorax. Shoulder adduction was defined as a positive planar rotation (towards the thorax) of the upper arm segment relative to the thorax with 0° being with the upper arm in anatomical neutral in-line with the thorax. Shoulder internal rotation was defined as a positive axial rotation (medial rotation) of the upper arm segment relative to the thorax with 0° being with the upper arm in anatomical neutral. Elbow extension was defined as negative elevation of the forearm segment relative to the upper arm

segment with 0° being the forearm in-line with the upper arm and 90° being the forearm perpendicular to the upper arm. Positional data was sampled at a rate of 120 Hz.

Data were analyzed using a customized script in MATLAB (Mathworks Inc., Natick, MA). Position and joint angle data were filtered using a low-pass Butterworth filter (2nd order, 10Hz cutoff). All kinematic variables were calculated using the filtered data. Velocity was defined as the first derivative of the movement trajectory and calculated by dividing the instantaneous change in 3D linear trajectory by the change in time (Winter, 2005). Acceleration was defined as the first derivative of the movement velocity and calculated by dividing the instantaneous change in velocity by the change in time. To find movement onset, we searched backward in time from the time of peak velocity until movement velocity dropped below 5 cm/sec and either changed direction (i.e., began to increase again) or the change in velocity was considered low (<3 cm/sec). Movement offset was defined as the time when the target was “hit” (defined above). Movement time (sec) was defined as the time between movement onset and movement offset. Peak acceleration was defined as the highest acceleration value between movement onset and movement offset. Total hand path distance (cm) was defined as the sum of the of the total distance moved from movement onset to movement offset (or the total distance the hand traveled in space from movement onset until the cursor “hit” the target). Joint excursions (deg) were defined as the change in joint angle about a degree of freedom from movement onset to movement offset.

3.2.5: Statistical Analysis

All statistical analyses were completed using SPSS v.28 (IBM Corp., Armonk, NY). Data from the five reaches for each target combination for each participant were averaged and used for analysis. The overall effects of Condition (Center-Out, Out-Center, and Long/Diameter) and Direction (0, 45, 90, …, 315) were analyzed using a 3 X 8 (Condition X Direction) repeated measures analysis of variance (ANOVA). Directions were defined as described in Table 3.1 such that similarly directed movements occurred along the same axis of the target array and had similar joint combinations (i.e., a Center-Out reach from the center target to 90 would be considered in the same direction as an Out-Center reach from 270 to the center target and a Long/Diameter reach from the 270 to 90) to ensure the comparison of like movements. For analysis purposes, joint excursions were expressed as the absolute value about a degree of freedom to accurately compare the magnitude of the movement about that degree of freedom between directions. Significant main effects were followed-up with Bonferroni-corrected paired t-tests for multiple comparisons. The dominant right and non-dominant left arms were analyzed separately due to the well described differences in performance and control between the two arms (Bagesteiro & Sainburg, 2002; Mutha et al., 2013; Sainburg & Kalakanis, 2000; Tomlinson & Sainburg, 2012). All analyses were completed with significance set at $p<0.05$. Partial eta squared (η^2) was used to estimate the effect sizes of any differences (η^2 of 0.01 – 0.059 = small effect; η^2 of 0.06 – 0.139 = medium effect; $\eta^2 \geq 0.140$ = large effect) (Cohen, 1988).

Table 3.1 Target Combinations & Directions Defined

		Difficulty		
Direction	**Inertia**	**Center-Out**	**Out-Center**	**Long/Diameter**
0	Mod	Center – 0	180 – Center	180 – 0
45	Low	Center – 45	225 – Center	225 – 45
90	Mod	Center – 90	180 – Center	270 – 90
135	High	Center – 135	315 – Center	315 – 135
180	Mod	Center – 180	0 – Center	0 – 180
225	Low	Center – 225	45 – Center	45 – 225
270	Mod	Center – 270	90 – Center	90 – 270
315	High	Center – 315	135 – Center	135 – 315

Target combinations used in this study categorized by both Direction and by Difficulty. “Center” references the target at the center of the target array; numbered values correspond to those pictured on the periphery of the array in Figure 3.1. Combinations are described as the starting point first followed by the ending point. The Center-Out and Out-Center movements are the two component movements that make up the corresponding Long/Diameter movement. Target combinations are the same for both arms (see Fig. 3.1). Predicted inertial demands are also provided as Low, Moderate (Mod), and High as previously defined by Gordon et al (1994).

3.3: Results

3.3.1: Movement Time

Target Direction had a significant effect on movement time for both the Right ($p = 0.051$, $\eta^2 = 0.246$; Figs 3.2 a-c) and Left arms ($p = 0.01$, $\eta^2 = 0.357$; Figs 3.3 a-c). Reaches in the 0 and 180 directions tended to have the fastest movement times while reaches in the 90, 270, and 315 directions tended to have the slowest movement times. Reach Condition also had a significant effect on

movement time in both arms (Right: $p<0.001$, $\eta^2 = 0.860$; Left: $p<0.001$, $\eta^2 = 0.721$) such that the reaches for target combinations with a longer inter-target amplitude and higher Fitts' ID (Long/Diameter) had greater movement times than those with a shorter inter-target amplitude and lower Fitts' ID (Center-Out and Out-Center) (Left & Right $p<0.05$). There was no significant difference in movement times for target combinations at the same Fitts' ID (Center-Out & Out-Center) ($p>0.1$).

3.3.2: Total Hand Path Distance

Target Direction had no effect on total hand path distance in either the Right ($p = 0.308$, $\eta^2 = 0.823$; Figs 3.2 d-f) or Left arms ($p = 0.121$, $\eta^2 = 0.914$; Figs 3.3 d-f). Total hand path distance did significantly differ by Condition in both arms (Right: $p<0.001$, $\eta^2 = 0.995$; Left: $p<0.001$, $\eta^2 = 0.988$). Similar to movement time, reaches for target combinations with a longer inter-target amplitude and higher Fitts' ID (Long/Diameter) had longer hand path distances than those with a shorter inter-target amplitude and lower Fitts' ID (Center-Out and Out-Center) (Left & Right $p<0.001$). However, the Center-Out reaches also had significantly shorter hand path distances than the Out-Center reaches in the Left arm (Mean Difference = 0.367±0.101 cm; $p<0.05$) but not the Right arm (Mean Difference = 0.089±0.066 cm; $p>0.1$) despite having identical Fitts' IDs.

3.3.3: Peak Acceleration

For reference, anticipated inertial values based upon direction, as defined by Gordon et al (1994) have been provided in Table 1. Target Direction had a

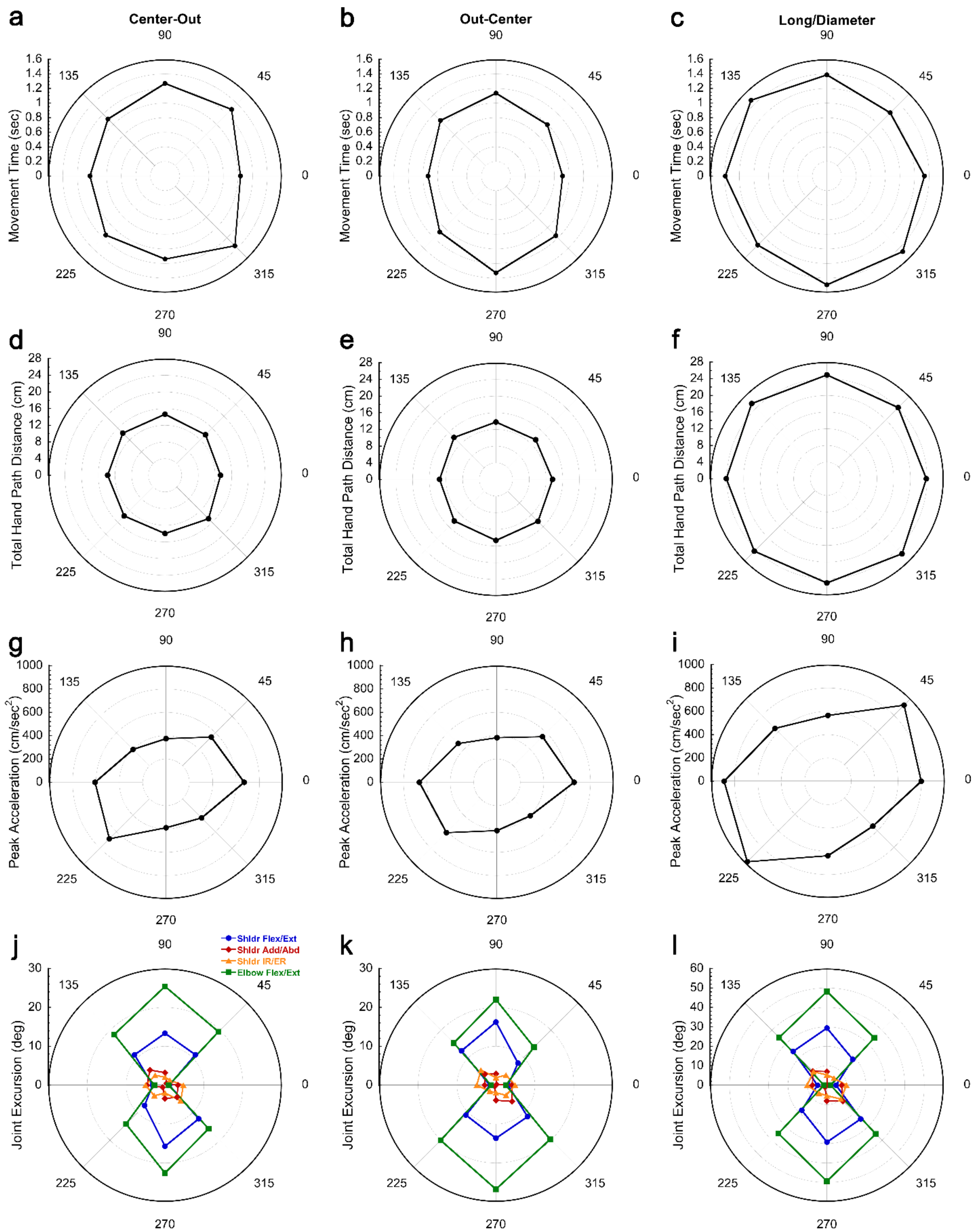

Figure 3.2. Right Arm Kinematics. Mean Right Arm outcomes for movement time (**a-c**), total hand path distance (**d-f**), peak acceleration (**g-i**), and joint excursions (**j-l**). Data are plotted by target direction. sec = seconds; cm = centimeters; deg = degrees; Shldr = shoulder; Flex = flexion; Ext = extension; Add = adduction; Abd = abduction; IR = internal rotation; ER = external rotation.

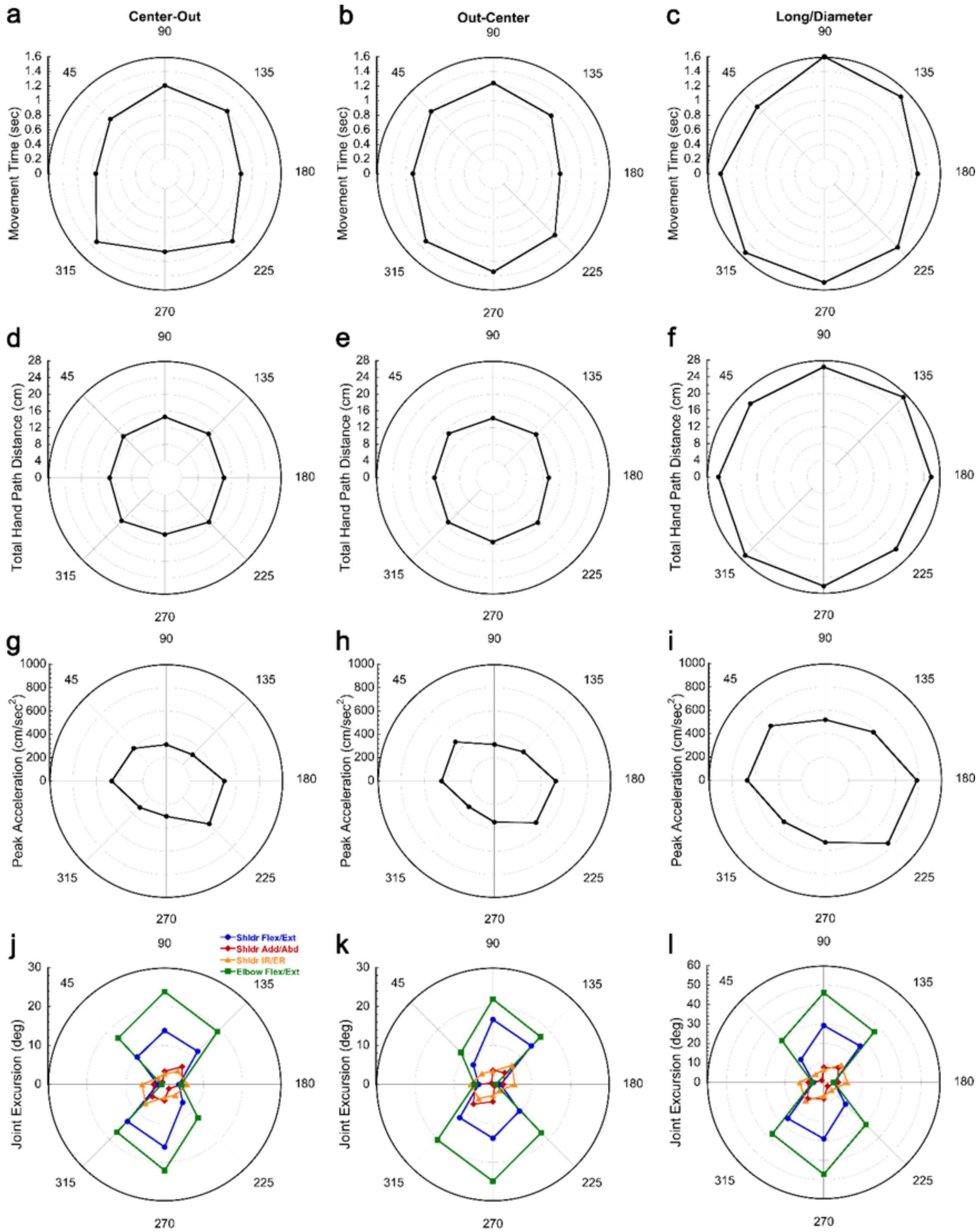

Figure 3.3. Left Arm Kinematics. Mean Left Arm outcomes for movement time (**a-c**), total hand path distance (**d-f**), peak acceleration (**g-i**), and joint excursions (**j-l**). Data are plotted by target direction. sec = seconds; cm = centimeters; deg = degrees; Shldr = shoulder; Flex = flexion; Ext = extension; Add = adduction; Abd = abduction; IR = internal rotation; ER = external rotation.

significant effect on peak acceleration in both the Right arm ($p = 0.003$, $\eta^2 = 0.534$; Figs 3.2 g-i) and Left arm ($p = 0.004$, $\eta^2 = 0.511$; Figs 3.3 g-i). Reaches in the 45 and 225 directions had the highest peak accelerations coinciding with the directions of lowest inertia and faster movement times while reaches in the 135 and 315 directions had the lowest peak accelerations coinciding with the directions of highest inertia and slower movement times. Condition also had a significant effect on peak acceleration in both the Right ($p<0.001$, $\eta^2 = 0.995$) and Left arms ($p<0.001$, $\eta^2 = 0.988$). Reaches for target combinations with a longer inter-target amplitude and higher Fitts' ID (Long/Diameter) had higher accelerations than those with a shorter inter-target amplitude and lower Fitts' ID (Center-Out and Out-Center) (Left & Right $p<0.001$). The Center-Out reaches also had significantly smaller peak accelerations than the Out-Center reaches in the Left arm (Mean Difference = 18.42±4.73 cm/sec^2; $p<0.05$) but not the Right arm (Mean Difference = 6.86±11.96 cm/sec^2; $p>0.1$) despite having identical inter-target amplitudes and Fitts' IDs.

3.3.4: Joint Excursions

Joint excursions for the Right and Left arms are displayed in Figs 3.2 j-l and 3.3 j-l, respectively, with statistical outcomes outlined in Table 2. Target Direction had a significant effect on joint excursions such that the amount of movement at the shoulder and elbow joints varied between directions for all four possible joint movements. Reaches directed in the fastest directions (0 & 180) had very little joint movement overall, and what movement does occur is predominantly accomplished via shoulder add/abduction and rotation. When

Table 3.2. Main Effects for Joint Excursions

Right Arm				
Effect	**Shldr Flex/Ext**	**Shldr Add/Abd**	**Shldr Int/Ext Rot**	**Elbow Flex/Ext**
Direction	p<0.001 (0.883)	p<0.01 (0.444)	p>0.05 (0.236)	p<0.001 (0.966)
Condition	p<0.001 (0.956)	p<0.001 (0.877)	p<0.001 (0.911)	p<0.001 (0.985)
Left Arm				
Effect	**Shldr Flex/Ext**	**Shldr Add/Abd**	**Shldr Int/Ext Rot**	**Elbow Flex/Ext**
Direction	p<0.001 (0.943)	p<0.001 (0.688)	p<0.01 (0.608)	p<0.001 (0.959)
Condition	p<0.001 (0.949)	p<0.001 (0.826)	p<0.001 (0.964)	p<0.001 (0.956)

Main effects from the ANOVAs for each joint movement in both the Right and Left arms; Shldr = shoulder; Flex /Ext = flexion/extension; Add/Abd = adduction/abduction; Int/Ext = internal/external; Rot = rotation; data presented as p-value(η^2).

examining reaches in the slowest directions (135 & 315), there was a large magnitude of movement about all the degrees of freedom examined, especially shoulder and elbow flexion/extension. Condition also had a significant effect such that reaches for target combinations with a higher Fitts' ID had greater joint excursions than those for target combinations with a lower Fitts' ID (all $p<0.05$). There were statistically significant differences in joint excursions between the Center-Out and Out-Center target combinations but only for shoulder flexion/extension (Mean Difference = 0.19±0.06 deg, $p<0.05$) and elbow

flexion/extension (Mean Difference = 0.31±0.11 deg, $p = 0.054$) in the Left Arm, however the magnitudes of these differences were relatively small. There were no differences between these two conditions in shoulder adduction/abduction (Mean Difference = 0.02±0.06 deg) or rotation (Mean Difference = 0.03±0.05 deg) in the Left arm (both $p>0.1$) or for any degrees of freedom in the Right arm ($0.073 \geq p \geq 1.00$).

3.4: Discussion

3.4.1: Summary

The purpose of this study was to examine the applicability of Fitts' Law in multi-directional, three-dimensional targeted reaching movements that have an endpoint accuracy requirement. While movement time increased based on increased task difficulty as expected based on Fitts' Law, there was an effect of target direction on reach performance. Reaches that had the same inter-target amplitude, and therefore same Fitts' ID, had varied movement times based upon the reach's directionality. Variances in peak acceleration and joint excursion in both arms corresponding to directional effects on movement time suggest reach performance was influenced by a combination of inertia and joint coordination demands. Differences in movement time between the Center-Out and Out-Center reaches in the non-dominant left arm also indicate that the initial configuration of the shoulder and elbow joints may influence reach performance even for targets with the same direction and inter-target distance but different starting points.

3.4.2: Effect of Target Distance

Previous studies examining the control of unconstrained, three-dimensional reaching movements have shown that increasing inter-target distances elicits a scaling effect whereby as inter-target distance increases, so too do movement times, peak velocities and joint excursions (Gordon, Ghilardi, Cooper, et al., 1994; Gottlieb, Corcos, & Agarwal, 1989; Gottlieb, Corcos, Agarwal, & Latash, 1990; Smith et al., 2022; Stewart et al., 2013, 2014). The increase in movement times, total hand path distances, peak accelerations, and joint excursions with increased inter-target distances, regardless of direction, observed in the present study is consistent with this previous work. Previous studies examining the influences of target amplitude and target width on movement outcomes have found that target amplitude has a greater influence on characterizing difficulty than target width (Heath et al., 2011; Hoffmann, 2016). Therefore, while varying both target amplitude and width both factor into the ID calculation, it would seem that variances in target amplitude may influence difficulty, and therefore movement time, to a greater degree than varying the width/size of the target.

3.4.3: Effect of Target Direction

The present study found variances in movement time based on target direction. The differences in movement time between directions may be related to the differences in inertia corresponding to the reach’s directionality, as defined

previously (Gordon, Ghilardi, Cooper, et al., 1994; Gordon, Ghilardi, & Ghez, 1994; Gordon et al., 1995) and exhibited by the differences in peak acceleration between directions. Reaches to targets with lower inertias (45 & 225) tended to have the greatest acceleration values while reaches to targets with higher inertias (135 & 315) tended to have the lowest acceleration values. Consequently, reaches in the low inertia directions had lower movement times than reaches in the high inertia directions which is consistent with the results of previous studies (Gordon, Ghilardi, Cooper, et al., 1994; Gordon, Ghilardi, & Ghez, 1994; Gordon et al., 1995). However, based on inertia alone, the 45 & 225 directed reaches should have had the lowest movement times. In the current study, the 0 and 180 directed reaches had the lowest movement times indicating additional factors beyond directional inertia influenced movement time.

Joint excursions also varied by direction also appeared to have an influence on movement time in addition to inertia. The directions with the fastest movement times (0 & 180) had relatively low but not the lowest inertia values and entailed movement which primarily required the medial-lateral translation of the upper arm via internal/external rotation and add/abduction of the shoulder joint with little movement in other joint motions. While the reaches with the lowest inertia (45 & 225) were still fast compared to other directions, they had greater amounts of elbow movement compared to the 0 and 180 directions, indicating a greater degree of shoulder-elbow coordination was required to complete these movements. The slowest reaches, unsurprisingly, had not only high inertia values but also the greatest overall joint excursions about all four degrees of

freedom measured indicating that effective execution of these movements required a significant amount of coordination between the shoulder and elbow joints. The movements of the shoulder and elbow joints found in the present study are consistent with previous studies which showed variations in inter-joint coordination in differently directed movements (Dounskaia et al., 2002; Dounskaia & Wang, 2014; Galloway & Koshland, 2002). Overall, these results suggest that the movement time of a reaching movement is related to a combination of the difficulty level, amount of joint movement, the degree of inter-joint coordination required, and directional inertia.

The conclusion that movement demand and execution vary by direction and are multifactorial is consistent with studies examining the directional biases of arm movements. These studies have suggested that arm movements are more commonly made in directions which not only have lower directional inertia but also minimize the need to control interactive torques from other joints (Dounskaia & Goble, 2011; Dounskaia, Goble, & Wang, 2011; Dounskaia, Wang, Sainburg, & Przybyla, 2014). In this manner, the motor system tends to employ the simplest control pattern whereby it utilizes the least amount of musculature and degrees of freedom to accomplish a movement to the minimal extent needed (d'Avella, Giese, Ivanenko, Schack, & Flash, 2015; Dounskaia, Shimansky, Ganter, & Vidt, 2020). It may be that movements along less preferred directional axes are more effortful and slower to execute because of their greater inertial values, and the greater excursions about multiple degrees of freedom incur a need to control greater interactive torques. Movements along more preferred

directional axes, however, may be easier and quicker to execute because of their lower inertial values, and they have very low overall joint excursions which means controlling lower interactive torques.

The lack of difference in total hand path distances between directions suggests that reaches to targets which have similar inter-target amplitudes, and therefore similar Fitts' IDs, elicit similarly length hand paths regardless of direction. This result would imply that the difference in movement times based upon direction were more related to differences in inertial and joint-related demands than to the straightness of the hand path.

While the task used in the present study was similar to that used previously (Gordon, Ghilardi, Cooper, et al., 1994; Gordon, Ghilardi, & Ghez, 1994) because comparisons between target directions were completed using center-out reaching movements, there are also some notable differences between these studies both in the paradigm and their applications. First, the present study involved fewer target directions but did not test exclusively center-out movements thereby incorporating a comparison examining the effect the initial position of the arm may have on reaching in such a task. Also, the series of studies examining the effects of reach direction were aimed at examining directional preferences in reaching (Gordon, Ghilardi, Cooper, et al., 1994; Gordon, Ghilardi, & Ghez, 1994) and how proprioception influences such outcomes (Ghez et al., 1995; Gordon et al., 1995). Therefore, those studies did not include online visual feedback or an endpoint accuracy requirement. The feedback provided and the accuracy requirements in the current study likely

impacted the overall effect of inertia on reach outcomes. Finally, the previous studies examined multi-direction reaching using two-dimensional reaching paradigms where the arm was supported. The present study examined three-dimensional reaching movements where the arm was free to move in space as needed thereby allowing for more practically applicable movement patterns.

3.4.4: Effect of Initial Position

We also observed differences in total hand path distance, peak acceleration, and shoulder and elbow flexion/extension between the Center-Out and Out-Center conditions but only in the non-dominant Left arm. While the differences were relatively small, they could be attributed to the differences in control between the dominant right and non-dominant left arms. Previous studies have shown that the non-dominant left arm is less skilled at inter-joint coordination than the dominant right arm (Sainburg, 2005; Sainburg & Kalakanis, 2000; Schaffer & Sainburg, 2017). Even though the Center-Out and Out-Center movements are along the same directional axis, have the same inertia, and have the same inter-target amplitude, they begin with different initial joint configurations. Because the non-dominant left arm is less skilled at effectively coordinating the shoulder and elbow joints, initiating a reach from different starting joint positions could cause differences in the movement pattern utilized to execute a reach. For example, the poorer coordination ability of the left arm could result in differences in inter-joint interactions which would, in turn, lead to the differences in joint excursion and hand path distance seen between the Center-

Out and Out-Center reaches. However, these apparent differences in coordination patterns did not result in differences in movement time between the Center-Out and Out-Center reaches. This similarity in movement time may have been the result of the Out-Center reaches having greater peak accelerations which could have been employed to overcome differences in coordination in the non-dominant Left Arm. Notably, these differences between the two conditions were not reflected in the dominant Right Arm as the dominant limb is quite adept at coordinating the shoulder and elbow joints (Sainburg, 2005; Sainburg, Ghez, & Kalakanis, 1999; Sainburg & Kalakanis, 2000; Wang & Sainburg, 2007) and, therefore, may not be as susceptible to changes in starting joint position.

3.4.5: Practical Implications

Previous studies have described other limitations to Fitts' Law (Bonnetblanc, 2008; Danion et al., 1999; Glazebrook et al., 2015; Heath et al., 2011; Juras et al., 2009; Smits-Engelsman et al., 2002). Studies examining the learning of sequential, multidirectional movements have used Fitts' Law as an approach to control for difficulty level (Baird & Stewart, 2018; Boyd & Winstein, 2003; Ghilardi et al., 2009; Moisello et al., 2009; Seidler, 2006). However, the impact of target direction and initial joint configuration are not always considered and may impact sequence learning. A recent study examining sequence learning noted differences in movement time and hand path curvature between reaches in the sequence which had different directions and starting positions (Liu & Block 2021). Therefore, future studies may consider target direction and initial joint

configuration when incorporating multi-directional reaches into experimental designs. Also, the effect of these factors related to reach direction may be magnified in clinical populations with reach control deficits (e.g., chronic stroke, Parkinson's, or cerebral palsy).

3.4.6: Limitations

Movements in the current study had accuracy demands in order to move on to the next target. Many studies that have investigated Fitts' Law have utilized tasks that did not include an accuracy requirement (Bonnetblanc, 2008; Danion et al., 1999; Glazebrook et al., 2015; Heath et al., 2011; Roberts et al., 2016; Sleimen-Malkoun et al., 2012; Takeda et al., 2019). Similarly, many of the studies which evaluated the effect of inertial demands on movement also did not include an accuracy requirement (Dounskaia & Goble, 2011; Dounskaia et al., 2011; Gordon, Ghilardi, Cooper, et al., 1994; Gordon, Ghilardi, & Ghez, 1994; Gordon et al., 1995). The results presented here should be interpreted in the context of the endpoint accuracy requirements.

While the present study evaluated joint movements as the absolute value of the joint's excursion via the difference between the starting and ending position of a degree of freedom, no explicit coordination metrics were included in the present analysis. Previous studies investigating coordination patterns in similar directions as those used in the present study have shown that reaching along these directions involves varied amounts of movement about multiple degrees of freedom (d'Avella et al., 2015; Dounskaia et al., 2011; Dounskaia et

al., 2002; Dounskaia & Wang, 2014; Dounskaia et al., 2014). However, unlike the movements of the present study, the reaches completed in these previous studies were neither fast nor accuracy-dependent, indicating future studies should explore the coordination between the shoulder and elbow joints during fast, multidirectional reaches where endpoint accuracy is required.

The present study examined movement in eight directions and two ID levels. These combinations were selected specifically because they all involved movement to or through the central target. This configuration allowed for consistency with previous center-out paradigms (Ghilardi et al., 2009; Gordon, Ghilardi, Cooper, et al., 1994; Gordon, Ghilardi, & Ghez, 1994; Gordon et al., 1995; Moisello et al., 2009) and meant that movements in the same direction were analogous to each other for direct comparison. However, the present study did not include as many directional variations as previous center-out tasks examining the effect of direction (Gordon, Ghilardi, Cooper, et al., 1994; Gordon, Ghilardi, & Ghez, 1994; Gordon et al., 1995) nor did it examine differing target widths or amplitude from the center target like many traditional Fitts' tasks (Danion et al., 1999; Glazebrook et al., 2015; Heath et al., 2011; Jax et al., 2007; Roberts et al., 2016; Robinson & Leifer, 1967; Rosenbaum & Gregory, 2002; Sleimen-Malkoun et al., 2012; Smits-Engelsman et al., 2002). While variances in target width and amplitude from the center should elicit changes in movement time corresponding to the increase or decrease in ID, future studies should expand upon this task paradigm by including more directions, varying target widths, and/or greater target amplitudes from the central target in order to better

understand not only the changes in movement time but also detailed kinematic measures of reach control.

3.4.7: Conclusion

Increased inter-target distances (target amplitudes) resulted in increased movement times, hand path distances, peak accelerations, and joint excursions in accordance with Fitts' law. However, movement time varied for reaches with the same inter-target amplitude but different target directions that could be attributed to differences in inertia and joint coordination demands. Future studies utilizing paradigms that include multi-directional reach movements should consider the results of the current study when defining difficulty level within and between conditions.

CHAPTER 4

THE EFFECT OF DIFFERING FOCUS OF ATTENTION INSTRUCTIONS ON THE LEARNING OF A WHOLE-ARM, THREE-DIMENSIONAL SEQUENCE TASK IN THE RIGHT AND LEFT ARMS

4.1: Introduction

The learning or relearning of functional tasks and skills is important for effective execution of tasks in daily life. The OPTIMAL Theory of motor learning (Lewthwaite & Wulf, 2017; Wulf & Lewthwaite, 2016) seeks to provide a model for how motor learning can be maximized. One element this theory addresses is that where we direct our attention during learning can have a profound influence on how we learn. External focus instructions place emphasis and focus on the goal/outcome of the task or movement whereas internal focus instructions place focus on the movement or a specific movement component. Previous studies have linked an external focus with improved balance (Diekfuss et al., 2019; McNevin et al., 2003; Vaz et al., 2019; Wulf et al., 1998; Wulf, McNevin, et al., 2001; Wulf, Shea, et al., 2001), better target accuracy (Beilock et al., 2002; Chua et al., 2018; Masters, 1992; Wulf et al., 2015; Wulf et al., 1999; Wulf et al., 2002),

greater jump height/distance (Becker & Smith, 2015; Porter et al., 2010; Vidal et al., 2018), increased movement speed (Porter et al., 2015), and greater force production and power (Halperin et al., 2017; Halperin et al., 2016; Makaruk et al., 2015; Zarghami et al., 2012) compared to internally focused and non-instructed control conditions. Internal focus instructions have been shown to freeze movement about their point of focus (van Ginneken et al., 2018; Vidal et al., 2018) compared to both external focus and control instructions. The freezing of movements along with other movement inefficiencies associated with internally focused instructions have been used to define the “Constrained Action Hypothesis” which proposes that using an internal focus interferes with automatic control processes regulating the movement while adopting an external focus reinforces automatic processing and allows the motor system to naturally organize and execute the movement (McNevin et al., 2003; Wulf, McNevin, et al., 2001; Wulf & Prinz, 2001; Wulf, Shea, et al., 2001).

Most of the focus of attention studies to date have primarily been evaluated using broad performance outcomes such as accuracy, distance, time, and speed (Becker & Smith, 2015; Beilock et al., 2002; Chua et al., 2018; Diekfuss et al., 2019; Halperin et al., 2017; Masters, 1992; Porter et al., 2015; Vaz et al., 2019; Vidal et al., 2018; Wulf et al., 2015; Wulf et al., 1998; Wulf et al., 1999). While these outcomes are useful for examining changes in overall task performance due to different focus instructions, the inclusion of kinematic measures of movement (i.e., movement path and movement velocity) can provide further insight into how the instructions may influence task

learning/performance. Whole-arm sequence paradigms provide a unique opportunity compared to other sequence tasks. Whole-arm sequence tasks require simultaneous, coordinated movement of multiple joints while moving against gravity thereby making them more demanding and complex than the commonly used finger-pressing tasks (Ambike & Schmiedeler, 2013; d'Avella et al., 2015; Dounskaia & Wang, 2014; Sande de Souza, Dionisio, Lerena, Marconi, & Almeida, 2009; Schaffer & Sainburg, 2017) and have been shown to be effective learning paradigms (Baird & Stewart, 2018; de Kleijn et al., 2018; Ghilardi et al., 2009; Sense & van Rijn, 2018). We previously investigated implicit sequence learning using a whole-arm 3D reaching task (serial target task) (Baird & Stewart, 2018). Importantly, this task paradigm allows the investigation of both spatial (hand path) and temporal (velocity) features of arm control over practice in addition to overall performance (time to complete the sequence). Previous studies have shown that this targeted reaching task can be effectively learned and can provide insight into changes of both spatial and temporal aspects of performance (Baird, 2017; Baird & Stewart, 2018; Smith et al., 2021b). While previous studies have examined the effect of focus of attention instructions on learning complex motor tasks using measures beyond task performance (Gokeler et al., 2015; Milanese et al., 2017; Schutts et al., 2017; van Ginneken et al., 2018; Vidal et al., 2018; Winchester et al., 2009; Zentgraf & Munzert, 2009), no study to date has examined how such instructions affect the learning of a sequence task using whole-arm targeted reaches.

Previous studies have shown interlimb differences in reach control between the dominant and non-dominant arms. Reaches with the dominant right arm tend to show relatively low initial direction error and straight hand paths, which indicates a high degree of inter-joint coordination between the shoulder and elbow and greater reliance on feedforward control (Bagesteiro & Sainburg, 2002; Mutha et al., 2013; Sainburg & Kalakanis, 2000; Tomlinson & Sainburg, 2012). In contrast, the non-dominant left arm tends to show increased initial direction errors and curved hand paths, indicating poorer inter-joint coordination, but lower final position errors, indicating greater end-point accuracy and reliance on feedback control (Bagesteiro & Sainburg, 2002; Mutha et al., 2013; Sainburg & Kalakanis, 2000; Tomlinson & Sainburg, 2012). These interlimb differences in reach control between the dominant and non-dominant arms may impact the manner in which a whole-arm movement sequence is learned using either limb. Studies using two-dimensional targeted reaching movements showed differences in the learning of reach movements between the dominant and non-dominant limbs which further emphasized the two limbs' reliance on feedforward and feedback control strategies, respectively (Bagesteiro, Lima, & Wang, 2021; Buchanan, 2004; Buchanan, Zihlman, Ryu, & Wright, 2007; Criscimagna-Hemminger, Donchin, Gazzaniga, & Shadmehr, 2003; Duff & Sainburg, 2007; Mutha, Haaland, & Sainburg, 2012; Mutha et al., 2013; Sainburg & Wang, 2002; Stockinger, Thurer, Focke, & Stein, 2015). Previous studies which compared the learning of a similar whole-arm sequence task between the arms found that while both the dominant right and non-dominant left arms effectively learned the

sequence, as observed by decreased response times, they did so via different approaches. The dominant right arm improved in both spatial (hand path distance) and temporal (movement velocity) aspects of reach control thereby improving the overall efficiency of the motor pattern. The non-dominant left arm, however, improved predominantly in the spatial aspect of control with greater improvements in hand path distance over practice than the dominant right arm (Baird & Stewart, 2018; Baird et al., 2018; Smith et al., 2021a). Using this whole-arm sequence learning task coupled with differing focus of attention instructions would allow the present study to not only examine the effects of those instructions on learning but also how those instructions may influence changes in the control patterns of the two limbs while learning.

In previous focus of attention studies where task performance largely depended on the effective completion of a specific movement pattern, internal focus instructions have been shown to be at least as effective as their external focused counterparts (Milanese et al., 2017; Neumann et al., 2020; Schutts et al., 2017; Winchester et al., 2009; Zentgraf & Munzert, 2009). More specifically, When the instruction has been salient to the movement goal – such as hand movement in a juggling task (Zentgraf & Munzert, 2009) or snapping the wrist in a basketball shooting task (Maurer & Munzert, 2013; Zachry et al., 2005) – the internally focus instruction elicited positive results at least similar to the externally focused instruction. This diversion from the OPTIMAL Theory may be because of how the cue is interpreted in the context of the task at hand. A study by Mattes (2016) discussed that externally focused instructions draw attention to how the

movements interact with the environment and ultimately the task goal; the internally focused instructions commonly used in focus of attention studies, however, tend to increase awareness to how the body interacts with itself. Because of this dichotomy, Mattes suggests utilizing internally focused instructions that promote “open monitoring” of the movement rather than constraining it to a specific component. These studies imply that the internally focused instructions which have been commonly linked with negative task outcomes may not have been completely salient to the task goal. Therefore, because the two arms seem to learn this sequence task by improving differing areas of reach control, the addition of focus instructions may differentially affect how the two arms learn a whole-arm sequence task based upon the instruction’s relevance/saliency with the limb’s locus of control.

Therefore, the purpose of this study was to investigate the effect of focus of attention instructions (internal arm-focused vs. external target-focused) on the learning of an implicit whole-arm sequence task in both the non-dominant left and dominant right arms. It was hypothesized that all groups would show a reduction in response time with practice, but there would be differences in how the focus instructions facilitated learning in the two arms. Consistent with the OPTIMAL Theory (Lewthwaite & Wulf, 2017; Wulf & Lewthwaite, 2016), it was hypothesized that the dominant right arm would benefit most from the external focus instructions which would facilitate automatic movement patterns seen through greater decreases in total hand path distance and increases in peak velocity than the internal focus instructions. However, it was hypothesized that the non-

dominant left arm would benefit more from the internal focus instructions which, by drawing attention to the arm and the coordination between joints, would facilitate greater improvements in hand path where the left arm has most to gain.

4.2: Methods

4.2.1: Participants

Forty-eight non-disabled, neurologically intact adults were recruited from the university community. To be eligible, individuals had to be 1) right-handed as determined by the Edinburgh Handedness Inventory (Oldfield, 1971), 2) be over the age of 18, 3) have no neurological conditions which could affect motor behavior/control as determined by a general neurological symptom checklist (e.g., ADHD, recent concussion, Multiple Sclerosis, etc.), and 4) have no current or history of pain in the upper extremities. Participants were block-randomized by gender into one of four groups: External Focus, Right Arm (EF Right); Internal Focus, Right Arm (IF Right); External Focus, Left Arm (EF Left); Internal Focus, Left Arm (IF Left). The study was conducted in accordance with the Declaration of Helsinki, and all aspects of the study were approved by the Institutional Review Board (IRB) at the University of South Carolina. An a priori power analysis was run using G*Power 3.1, a free power analysis software, assuming a moderate effect size with $f = 0.25$, $\alpha = 0.05$, and Power = 80% which indicated a sample size of 48 was required.

4.2.2: Experimental Task

The serial target task completed in this study was similar to that described in Baird & Stewart (2018). For the Left Arm group, the target array was mirrored such that inter-target movements were in the same direction relative to the person as they were for the right arm group (Figure 4.1). Briefly, participants sat facing a virtual display (Innovative Sport Training Inc., Chicago, IL) where the task was projected down into the workspace directly in front of them. The participants wore stereoscopic glasses to allow for 3D visualization of the targets (28 mm red sphere). An electromagnetic marker was placed on the index finger of the assigned arm to both indicate position in the virtual display (cursor, 25 mm white sphere) and collect position data throughout movement. Participants were then given one of two assigned focus instructions based upon their group. Participants in externally focused groups (EF Right and EF Left) were instructed

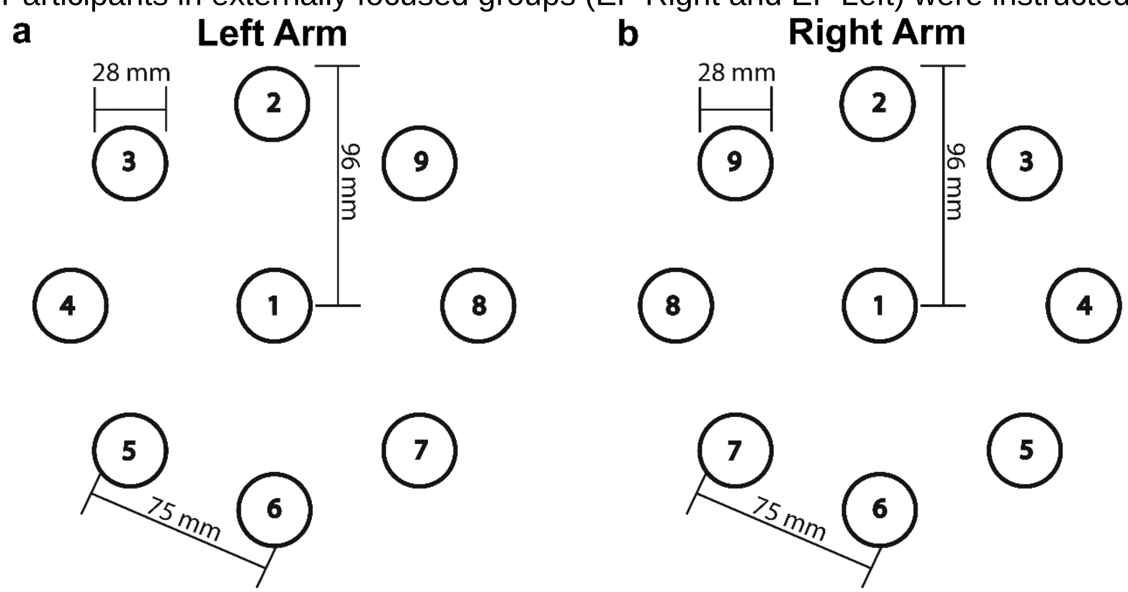

Figure 4.1. Target Arrays. Overhead view of the target arrays with the targes numbered for the **a)** Left and **b)** Right arms. The repeated sequence completed was 1-8-6-5-9-4-8-2. Note that the arrays were mirror images of each other in order to ensure the joint demands were the same between the two arms.

to “focus on moving the white sphere to the target sphere as fast as possible” while participants in the internally focused groups (IF Right and IF Left) were instructed to “focus on moving your arm to the target as fast as possible”. Once the center of the cursor was within 5 mm of the center of the target for >500 msec, the target was considered “hit” and would disappear as the next target appeared. Online visual feedback of the cursor and target position was present throughout.

The serial target task was comprised of two sequence conditions: repeated and random. Each sequence consisted of eight targets and were controlled for difficulty by matching the total straight-line inter-target distance traveled (93.8 cm). Individual movements between any two targets were assigned an Index of Difficulty (ID) value based on Fitts’ Law (Fitts, 1966; Fitts & Peterson, 1964; Meehan et al., 2011). Calculated values of each ID were 2.42, 2.78, 3.28, 3.66, and 3.78 in increasing order based on inter-target distance. To simplify, targets were assigned an ID value between 1 and 5 with 1 being the shortest movement (ID = 2.42) and 5 being the longest movement (ID = 3.78). Each sequence was assigned targets consisting of the same ID levels such that every eight-target sequence comprised of one movement at ID levels 1 and 4 and two movements at ID levels 2, 3, and 5. The repeated sequence (1 – 8 – 6 – 5 – 9 – 4 – 8 – 2) was the same across all trials. Random sequences were comprised of pseudorandomly assigned targets such that overall difficulty was the same as the repeated sequence. While the Random sequences were matched for difficulty based on Fitt’s law, they did not account for the effects of

directional inertia and inter-joint coordination demands. (Gordon, Ghilardi, Cooper, et al., 1994; Gordon, Ghilardi, & Ghez, 1994; Gordon et al., 1995; Smith et al., in prep). Therefore, only the Repeated sequences were used for our primary analysis. The Random sequences were included to help keep the Repeated sequence implicit.

All data were collected using the MotionMonitor system (Innovative Sport Training Inc., Chicago, IL). An electromagnetic sensor (Flock of Birds, Ascension Technology Corp, Shelburne, VT) was attached to the nailbed of the index finger of the arm used to complete the sequence. Positional data was sampled at a rate of 120 Hz and analyzed using a customized script in MATLAB (Mathworks Inc., Natick, MA). Consistent with previous studies using a similar task (Baird & Stewart, 2018; Brodie, Borich, & Boyd, 2014; Brodie, Meehan, Borich, & Boyd, 2014), total time to complete an eight-target sequence (response time) was the primary measure of task performance. To determine how performance changed over time, both spatial and temporal kinematic variables were evaluated. The spatial kinematic variable was the total length of the hand path (sum of total distance moved) when completing a sequence whereby a shorter total movement distance indicated straighter hand paths. The temporal kinematic variable was peak velocity which was calculated by dividing the change in the 3D linear movement trajectory by the change in time (Winter, 2005). The peak of velocity was extracted from each movement between two targets and averaged across each eight-target sequence. A higher peak velocity indicated faster movement speed.

4.2.3: Psychometric Measurements

Task-related motivation, efficacy, and effort were measured using the Interest/Enjoyment, Perceived Competence, and Effort/Importance subscales of the Intrinsic Motivation Inventory (IMI; Appendix A), respectively (Markland & Hardy, 1997; McAuley, Duncan, & Tammen, 1989; Ryan, 1982). In this inventory, participants rated the strength of a series of statements' truth to their feelings towards the task on a 7-point Likert scale where 1 = "not true at all" and 7 = "very true" whereby higher scores indicate a higher perceived degree of enjoyment, competence/self-efficacy, and effort when completing the task. The Psychobiosocial States – Trait Scale (PBS-ST; Appendix B) was used to assess the overall performance-related experience of the participants (Robazza, Bertollo, Ruiz, & Bortoli, 2016; Ruiz, Hanin, & Robazza, 2016). This questionnaire asked participants to rate the intensity of their association with 20 rows of 74 adjectives (3-4 per row forming an item) targeting 8 functional (+) and dysfunctional (-) modalities of a psychobiosocial state (i.e., affective, cognitive, motivational, volitional, bodily-somatic, motor-behavioral, operational, and communicative) on the modified Borg CR-10 scale ranging from 0 = "not at all" to 10 = "very, very much" (Borg, 1982). Dysfunctional modalities were reverse scored in such that a score of 10 (very, very much) became a score of 0 (not at all) and vice versa to allow for an overall sum score of each psychobiosocial state whereby a higher score indicated a functional, positive performance experience.

The cognitive load of the task was assessed using a Cognitive Load Questionnaire (CLQ; Appendix C) comprised of the naïve rating questionnaire developed by Klepsch, Schmitz, and Seufert (2017) where participants individually rated the truth of eight statements on a 7-point Likert scale where 1 = “completely wrong” and 7 = “completely right”. The CLQ also contained a ninth question, adopted from Paas (1992), where participants rated the “total invested mental effort” of the task on a 7-point Likert scale where 1 = “very low” to 7 = “very high”. This composite questionnaire also allowed for the differentiation between intrinsic (inherent to the complexity of the task), extraneous (caused by instructional design) and germane (from activities required of learner to facilitate learning) cognitive loads of the task allowing a more detailed comparison between the EF and IF groups. Higher scores on these items indicated that the participant perceived the task to be more mentally taxing.

Adherence to the focus instructions was measured via a Focus Adherence Questionnaire (Appendix D) which was comprised of six statements. The participants marked along a 100 mm visual analog scale how strongly they agreed or disagreed with each of six statements relating to the focus instructions. Three statements pertained to the external focus instructions and three statements pertained to the internal focus instructions. Agreement with each statement was determined by measuring how far along the scale participants marked whereby 0 mm = strongly disagree and 100 mm = strongly agree. The final measure of external and internal focus employed during the task was calculated as the average of their three respective statements.

4.2.4: Experimental Procedure

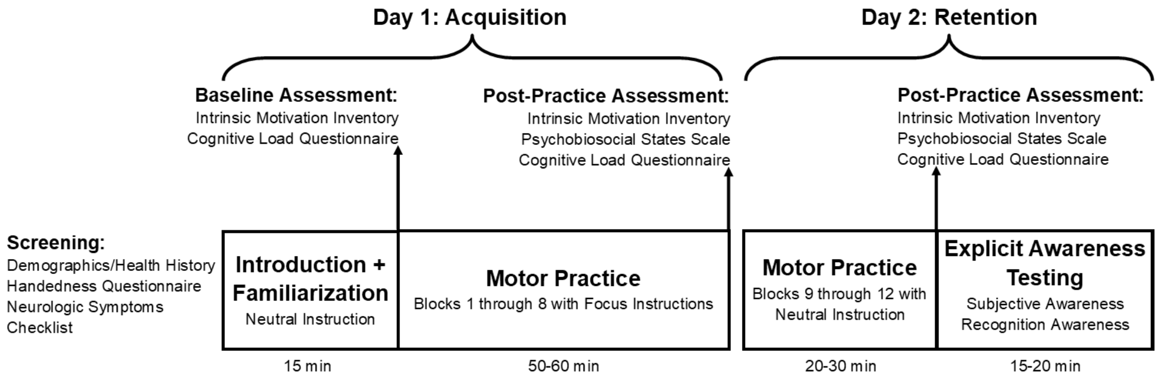

Figure 4.2. Schematic of Experimental Design*.* Graphic representation of Experimental Procedure. Participants were first screened for relevant information before completing a Familiarization trial under Neutral Instructions. Participants then completed Baseline assessments for the IMI and CLQ followed by 8 blocks of sequence practice with their designated Focus instructions. After the practice, participants completed another series of questionnaires. Participants then returned 24 hrs later for another 4 blocks of sequence practice under Neutral instructions followed by a final series of questionnaires and then Explicit Awareness testing.

The overall experimental procedure is graphically represented in Figure 4.2. Participants were first familiarized to the task by reaching to move the cursor representing hand position toward each target in the circular array. Next, participants completed three, eight-target Random sequences to become familiar with the task (Baseline). On Day 1 (Acquisition), individuals then practiced 144 total sequences (8 blocks of 18 sequences) in alternating random-repeated sequence order while receiving their assigned focus instruction prior to beginning each practice block. Participants were not made aware of the presence of the repeated sequence. Ten seconds of rest was provided after every third sequence and one minute rest after every 18 sequences. All participants returned on Day 2 (Retention) for retention testing whereby they completed an additional 72 alternating random-repeated sequences (4 blocks of 18 sequences) without any

specific focus instructions except to “attain the target as fast as possible”. All other procedures were identical to Day 1 (Acquisition).

After completion of the practice blocks on Day 2 (Retention), explicit awareness of the repeated sequence was assessed. First, participants were asked if they noticed the presence of a repeated sequence. If the individual responded “Yes”, he or she was asked to verbally recall the sequence while looking at an image of the target array. All participants then viewed six explicit awareness tests containing three eight-target sequences presented in the virtual environment. After each test, the participant was asked if the repeated sequence was present and, if so, which of the eight-target sequences contained the repeated sequence (beginning, middle or end). Three of the six tests contained the repeated sequence (positive test) while the remaining three tests contained a random sequence (negative test). Participants were classified as “aware” of the repeated sequence if they correctly identified the repeated sequence in two out of the three positive tests while also correctly identifying two out of the three negative tests.

Participants also completed a series of questionnaires aimed toward evaluating different aspects of their task/performance experience. Questionnaires included those aimed toward assessing the mental difficulty (Cognitive Load Questionnaire, CLQ), different aspects of motivation (Intrinsic Motivation Questionnaire, IMI), adherence to the focus instructions (Focus Adherence Questionnaire, Focus), and performance experience (Psychobiosocial States – Trait Scale, PBS-ST). The CLQ and IMI were

completed after the familiarization trial (Baseline), at the end of Day 1 practice and following Day 2 practice. The PBS-ST was completed at Day 1 and Day 2. Focus was only completed at Day 1. All questionnaires are described above.

4.2.5: Statistical Analysis

Due to the effect of reach direction on movement time whereby reaches along some axes of a circular target array are faster/slower because of directional inertia (Gordon, Ghilardi, Cooper, et al., 1994; Gordon, Ghilardi, & Ghez, 1994; Gordon et al., 1995; Smith et al., in prep), only the Repeated sequences were used in analyses as they were consistent throughout practice. All statistical analyses were completed using SPSS v.27 (IBM Corp., Armonk, NY) with significance set at $p<0.05$ for all tests.

Separate one-way analyses of variance (ANOVAs) were performed to determine if there were any between-group differences in age, handedness, Baseline kinematic outcomes (Response Time, Total Hand Path Distance, and Peak Velocity), number of targets correctly identified during Recall Awareness, and number of trials correctly identified during Recognition Awareness. A Chi-squared test for independence was also performed to examine any between group differences in occurrence of participants who recalled the presence of a repeated sequence during practice and between group differences in number participants who could be classified as attaining Recognition Awareness. Separate univariate general linear models (GLM) were used to assess changes in performance (Response Time) and reach control (Total Hand Path Distance

and Peak Velocity) over practice during Day 1 and Day 2. Fixed factors for Arm (Right and Left), Instruction (External Focus – EF and Internal Focus – IF), and Time (Blocks 1 – 8 and Blocks 9 – 12 for Days 1 & 2, respectively) were included in the models. Learning was defined as the degree of forgetting between the end of Day 1 (Block 8) and the beginning of Day 2 (Block 9). Univariate GLMs were used which included fixed factors for Arm, Instruction, and Time (Blocks 8 – 9) to assess if any kinematic outcomes changed over time. An improvement in outcomes from the end of Day 1 to the start of Day 2 was defined as consolidation while a worsening in outcomes from the end of Day 1 to the start of Day 2 was defined as forgetting.

Separate one-way ANOVAs were performed to determine if there were any between-group differences in the average External and Internal Focus scores collected from the Focus Adherence Questionnaire. Separate univariate GLMs with fixed factors for Arm, Instruction and Time (Baseline, End Day 1, End Day 2) were conducted to assess any differences in the subscales for the Cognitive Load Questionnaire and Intrinsic Motivation Inventory over time. A similar analysis was also run for the Psychobiosocial States Questionnaire with the only difference being that Time contained only the End of Day 1 and the End of Day 2.

Significant main effects found by the GLMs were evaluated by Bonferroni-corrected t-tests for multiple comparisons. For the CLQ and IMI subscales, significant Time effects were followed up specifically with Bonferroni-corrected paired t-tests comparing the changes in score from Baseline to the end of Day 1

(examine any change which may be related to the addition of focused instructions) and the end of Day 1 to the end of Day 2 (examine how perceptions changed from the end of Day 1 to the end of Day 2 practice when focused instructions were not present). Between-group differences as determined by the one-way ANOVAs were followed-up with Tukey's HSD test for multiple comparisons. Partial eta squared (η^2) was used to estimate the effect sizes of any differences (η^2 of 0.01 – 0.059 = small effect; η^2 of 0.06 – 0.139 = medium effect; $\eta^2 \geq 0.140$ = large effect) (Cohen, 1988).

4.3: Results

4.3.1: Participants

Participant information is displayed in Table 4.1. All forty-eight participants completed Day 1 data collection. However, three participants (1 EF Right, 2 EF Left) were not able to complete Day 2 data collection and one participant (IF Left) was excluded from Familiarization analyses due to technical difficulties. Significant differences were found for Age ($p<0.05$; $\eta^2 = 0.375$) and such that the EF Left group was older than the other groups. No significant between-group differences were detected for Baseline Response Time ($p>0.5$; $\eta^2 = 0.152$), Total Hand Path Distance ($p>0.2$; $\eta^2 = 0.215$), or Peak Velocity ($p>0.2$; $\eta^2 = 0.014$). When examining Explicit Awareness, there were no between-group differences in number of participants who recalled the presence of a repeated sequence ($\chi^2 = 3.203$; $p>0.3$), the number of targets those participants were able to recall ($p>0.8$; $\eta^2 = 0.102$), the number of correctly identified Recognition Awareness trials

($p>0.05$; $\eta^2 = 0.300$), and the number of participants who could be classified as attaining Recognition Awareness ($\chi^2 = 4.167$; $p>0.2$).

Table 4.1 Participant Information

	Right Arm		Left Arm	
Focus	***External***	***Internal***	***External***	***Internal***
Sex (F/M)	8/4	8/4	7/5	8/4
Age (yrs)	21.3±2.7	23.0±4.4	25.8±4.8*****	21.4±2.6
Baseline Response Time (sec)	28.47±2.36	24.44±2.00	26.58±2.38	25.21±1.81
Baseline Total Hand Path Distance (cm)	175.63±11.84	152.58±6.32	156.32±9.34	159.64±7.14
Baseline Peak Velocity (cm/sec)	39.06±3.11	37.06±1.82	38.31±3.37	38.64±2.05
External Focus Adherence (mm)	89.97±3.17	92.02 ±1.82	92.17±1.92	88.40±2.32
Internal Focus Adherence (mm)	77.79±8.09	85.94±5.08	70.97±7.28	86.49±2.72
Recall Sequence Presence? (n)	6	6	8	9
Number of Correct Targets Recalled (n)	0.83±0.31	0.83±0.31	0.83±0.31	0.83±0.31
Recognition Awareness (n)	4	2	0	3
Number of Correctly Identified Trials (n)	2.91±0.44	3.17±0.37	1.80±0.33	2.17±0.47

Participant demographic information, baseline kinematic measures from the Familiarization trial, focus measures, and explicit awareness; * = significantly different from other groups; F = female; M = male; yrs = years; sec = seconds; cm = centimeters; mm = millimeters; n = number/frequency; Data displayed as mean±SEM where relevant.

4.3.2: Focus Adherence

Focus adherence scores are also displayed in Table 1. No significant between-group differences were found for External Focus ($p>0.1$; $\eta^2 = 0.136$). While the Internal Focus scores appear to differ whereby the IF Right and IF Left groups had higher scores than their EF counterparts, analysis found these differences to be non-significant ($p>0.2$; $\eta^2 = 0.223$).

4.3.3: Response Time

Changes in Response Time over practice for the four groups are displayed in Figure 4.3 a&b for the Left and Right Arms, respectively. Response Time significantly decreased during Day 1 (Acquisition) practice ($p<0.001$; $\eta^2 = 0.316$) regardless of Arm or Focus instruction used. However, no differences were detected between Arm ($p>0.1$; $\eta^2<0.01$) or Focus ($p>0.5$; $\eta^2<0.01$). Response Time did not change from the end of Day 1 (Block 8) to the start of Day 2 (Block 9) ($p>0.5$; $\eta^2<0.01$) indicating no forgetting occurred regardless of Arm or Focus instruction. Similar to Day 1 (Acquisition), no differences were detected between Arm ($p>0.4$; $\eta^2<0.01$) or Focus ($p>0.2$; $\eta^2<0.01$). No significant interactions were found for Day 1 (Acquisition) or Learning. Response Time continued to decrease during Day 2 (Retention) practice ($p<0.01$; $\eta^2 = 0.070$) regardless of Arm or Focus instruction. However, an Arm X Focus interaction was detected ($p<0.01$; $\eta^2 = 0.044$) indicating that the Focus instructions had a differential effect between the arms whereby the EF instructions tended to have

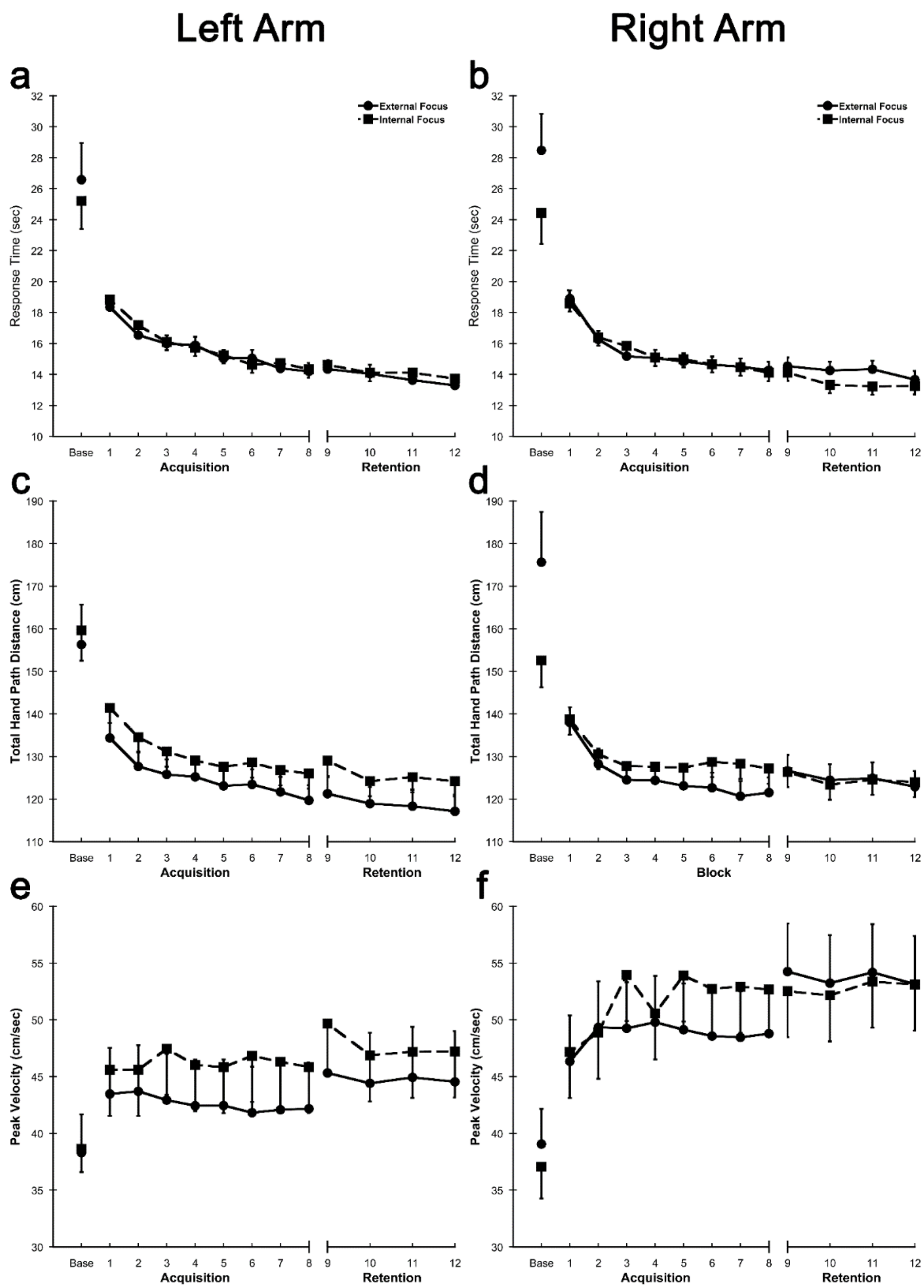

Figure 4.3. Kinematic Outcomes. Mean kinematic outcomes for the Left (**a,c,e**) and Right (**b,d,f**) arms. Figures display the average Response Time (**a,b**), Total Hand Path Distance (**c,d**), and Peak Velocities (**e,f**) from Baseline block-by-block to the end of practice on Day 2 (Retention) for the External Focus and Internal Focus groups in each arm; sec = seconds; cm = centimeters; Base = Baseline; data presented as mean±SEM.

lower response times than IF instructions in the Left Arm (mean diff = 0.315 sec) but higher times than IF instructions in the Right Arm (mean diff = 0.781 sec).

The analysis which excluded the outlier's Day 2 (Retention) data showed no findings which differed from those reported above.

4.3.4: Total Hand Path Distance

Changes in Total Hand Path Distance over practice for the four groups are displayed in Figure 4.3 b&c for the Left and Right Arms, respectively. Similar to Response Time, Total Hand Path Distance significantly decreased during Day 1 (Acquisition) ($p<0.001$; $\eta^2 = 0.120$) regardless of Arm or Focus instruction. However, an effect of Focus ($p<0.01$; $\eta^2 = 0.040$) indicated that the groups that received EF instructions had shorter hand paths than the groups that received IF instructions (mean difference = 4.82 cm). Arm had no effect during Day 1 (Acquisition) ($p>0.7$; $\eta^2<0.01$). Total Hand Path Distance, like Response Time, did not change from the end of Day 1 to the start of Day 2 ($p>0.3$; $\eta^2<0.01$) indicating no forgetting occurred regardless of Arm or Focus instruction. However, there was, again, an effect of Focus ($p = 0.05$; $\eta^2 = 0.044$) indicating the EF instructions continued to yield shorter hand paths than the IF instructions (mean difference = 4.85 cm). There was again no effect of Arm from the end of Day 1 to the start of Day 2 ($p>0.4$; $\eta^2<0.01$). Total Hand Path Distance did not change over practice during Day 2 (Retention) ($p>0.4$; $\eta^2 = 0.015$). While the EF instructions seemed to correspond to shorter hand paths than IF instructions in

the Left arm (mean difference = 6.74 cm) but not the right (mean difference = 0.16 cm), the Arm X Focus interaction was not significant ($p = 0.59$; $\eta^2 = 0.022$).

One participant was found to be an outlier on Day 2 (Retention) where their hand paths were on average 4 standard deviations greater than group average. Learning and Day 2 analyses were completed which excluded the outlier's Day 2 (Retention) data. Total Hand Path distance still did not change from the end of Day 1 to the start of Day 2 ($p>0.6$; $\eta^2<0.01$) with no effect for Arm ($p>0.8$; $\eta^2<0.01$). The effect of Focus remained significant ($p<0.05$; $\eta^2 = 0.073$) such that the EF instructions had shorter hand paths than the IF instructions (mean difference = 5.87 cm). During Day 2 (Retention), Total Hand Path Distance still did not change over Time ($p>0.3$; $\eta^2=0.022$) nor did it differ by Arm ($p>0.8$; $\eta^2<0.01$); however, Hand Path Distance did significantly differ by Focus ($p<0.01$; $\eta^2=0.073$) such that the EF groups had shorter hand paths than the IF groups (mean difference = 5.41 cm).

4.3.5: Peak Velocity

Changes in Peak Velocity over practice for the four groups are displayed in Figure 4.3 d&e for the Left and Right Arms, respectively. Overall, Peak Velocity did not significantly change during Day 1 (Acquisition) (p>; $\eta^2<0.01$). However, it did differ between Arms ($p<0.001$; $\eta^2 = 0.052$) such that the Right arm had higher peak velocities than the Left arm (mean difference = 5.75 cm/sec). Peak Velocity during Day 1 (Acquisition) also differed by Focus ($p<0.05$; $\eta^2 = 0.017$) such that the IF instructions yielded higher peak velocities than the

EF instructions (mean difference = 3.22 cm/sec). Peak Velocity did not change from the end of Day 1 to the start of Day 2 ($p>0.1$; $\eta^2 = 0.011$) indicating that no forgetting occurred regardless of Arm or Focus instruction. However, there was again an effect of Arm ($p<0.05$; $\eta^2 = 0.045$) which indicated that the Right arm continued to produce higher velocities than the Left arm (mean difference = 6.31 cm/sec). Peak Velocity remained relatively constant during Day 2 (Retention) ($p>0.1$; $\eta^2<0.01$) regardless of Arm or Focus instruction but continued to differ by Arm ($p<0.01$; $\eta^2 = 0.047$) whereby the Right arm produced higher velocities than the Left arm (mean difference = 6.98 cm/sec). No significant interactions were found.

One participant was found to be an outlier on Day 2 (Retention) with peak velocities that were more than 6 standard deviations greater than the group average. Learning and Day 2 analyses were completed which excluded the outlier's Day 2 (Retention) data. Peak Velocity still did not change from the end of Day 1 to the start of Day 2 ($p>0.6$; $\eta^2<0.01$) nor was there any effect for Arm ($p>0.05$; $\eta^2=0.032$ or Focus ($p>0.05$; $\eta^2=0.035$). During Day 2 (Retention), Peak Velocity still did not change over Time ($p>0.9$; $\eta^2<0.01$). While the Right arm continued to have higher peak velocities than the Left arm (mean difference = 3.21 cm/sec), the difference was not statistically significant ($p=0.055$; $\eta^2=0.023$). With the outlier excluded, Peak Velocity on Day 2 (Retention) also significantly differed by Focus ($p<0.01$; $\eta^2=0.049$) such that the IF instructions had higher peak velocities than the EF instructions (mean difference = 4.78 cm/sec).

4.3.6: Cognitive Load

Cognitive Load outcomes are displayed in Figure 4.4. Overall, Intrinsic Load had a significant effect for Time ($p<0.01$; $\eta^2 = 0.078$; Figure 4.4a). Pairwise comparisons between the timepoints showed that Intrinsic Load did not change from Baseline to End of Day 1 (mean difference = 0.2, $p>0.1$) which indicated no acute effect of providing focused instructions. However, Intrinsic Load significantly decreased from End of Day 1 to the End of Day 2 (mean difference = 1.4, $p<0.05$) which indicated a decrease in the perceived difficulty of the task on Day 2. Similarly, Extrinsic Load had a significant effect for Time ($p<0.05$ $\eta^2 = 0.049$; Figure 4.4b). Pairwise comparisons between the timepoints showed that Extrinsic Load did not significantly change from Baseline to the End of Day 1 (mean difference = 0.6, $p>0.1$) which indicated no acute effect of providing focused instructions. Extrinsic Load did significantly decrease from End of Day 1 to the End of Day 2 (mean difference = 1.2, $p<0.01$) which indicated a decrease in the perceived mental load incurred by items outside the task on Day 2. Neither Intrinsic or Extrinsic Loads had significant effects for Arm ($p>0.1$; $\eta^2<0.01$) or Focus ($p>0.1$; $\eta^2<0.01$). Germane Load also had a significant effect for Time ($p<0.05$; $\eta^2 = 0.069$; Figure 4.4c). Pairwise comparisons between the timepoints showed that Germane Load did not change from Baseline to End of Day 1 (mean difference = 0.04, $p>0.1$) which indicated no acute effect of providing focused instructions. However, Germane Load significantly decreased from the End of Day 1 to the End of Day 2 (mean difference = 1.4, $p<0.05$) which indicated a decrease in the perceived load from learning processes on Day 2. Germane

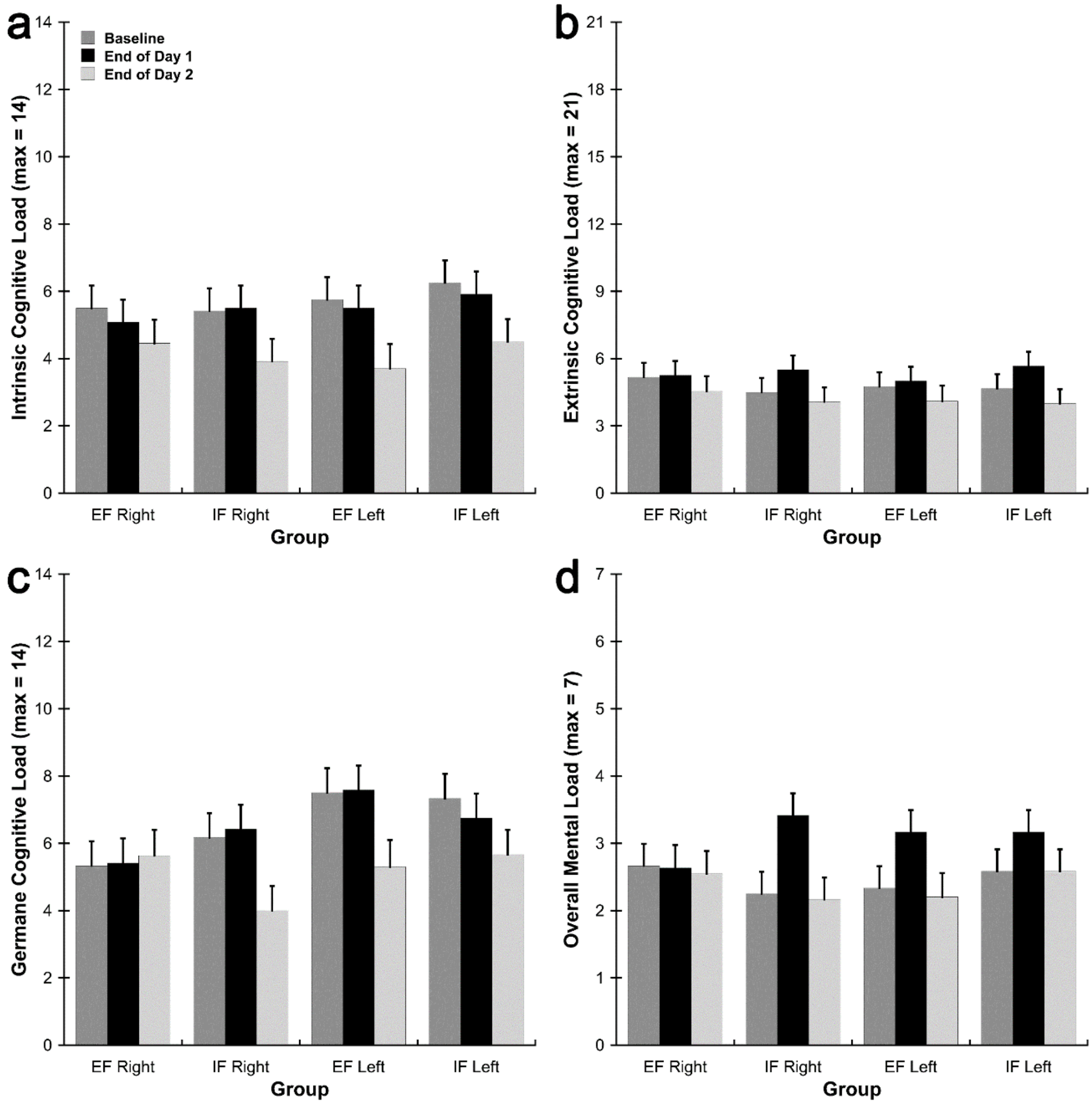

Figure 4.4 Cognitive Load. Average Cognitive Load scores taken at Baseline, End of Day 1, and End of Day 2 separated by Group for **a)** Intrinsic, **b)** Extrinsic, **c)** Germane, and **d)** Overall Mental loads. Notice that Y-axes differ between the graphs but are set to the maximum possible score for each metric; EF = External Focus; IF = Internal Focus; max = maximum; all data presented as mean±SEM.

Load also differed between the two Arms ($p<0.01$; $\eta^2 = 0.057$) such that, on average, the Right arm had lower scores than Left arm (mean difference = 1.2, $p<0.01$). Overall Mental Load significantly changed over Time ($p<0.01$; $\eta^2 = 0.082$; Figure 4.4d). Pairwise comparisons between the timepoints showed that

Overall Mental Load increased from Baseline to the End of Day 1 (mean difference = 0.6, $p = 0.02$) which indicated that the mental effort participants felt needed to be exerted on the task increased over practice on Day 1. However, Overall Mental Load decreased from the End of Day 1 to the End of Day 2 (mean difference = 0.7, $p<0.05$) which indicated that the overall perceived effort decreased on Day 2. There was no difference between Arms ($p>0.1$; $\eta^2<0.01$) or Focus instructions ($p>0.1$; $\eta^2<0.01$) for the Overall Mental Load nor were there any significant interactions for any Cognitive Load measure.

4.3.7: Motivation

Intrinsic Motivation outcomes are displayed in Figure 4.5. Enjoyment/Interest in the task had an effect for Time ($p<0.001$; $\eta^2 = 0.146$). Pairwise comparisons between the timepoints showed that Enjoyment/Interest decreased both from Baseline to the End of Day 1 (mean difference = 7.7, $p<0.001$) which indicated that participants, in general, lost interest or found the task less enjoyable over practice regardless of the presence of a focused instruction which did not change from the End of Day 1 to the End of Day 2 (mean difference = 1.9, $p>0.1$). There were no differences between Arms ($p>0.1$; $\eta^2<0.01$) or Focus instructions ($p>0.1$; $\eta^2 = 0.015$). While Perceived Competence appears to increase (Figure 4.5b) over practice, analyses found that Competence did not significantly change over Time ($p>0.1$; $\eta^2 = 0.029$) nor did it differ between Arm ($p>0.1$; $\eta^2<0.01$) or Focus instruction used ($p>0.1$; $\eta^2<0.01$). Effort/Importance placed on the task also had an effect for Time ($p<0.05$; η^2 =

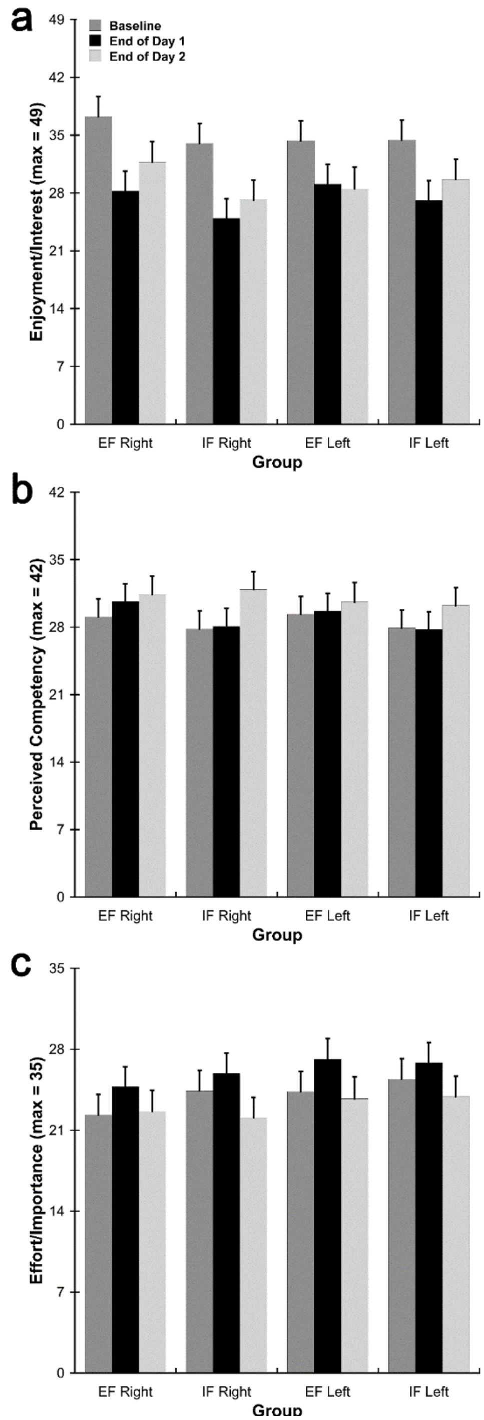

Figure 4.5 Intrinsic Motivation. Average scores for **a)** Enjoyment/Interest, **b)** Perceived Competency, **c)** Perceived Effort subscales of the Intrinsic Motivation Inventory (IMI) taken at Baseline, End of Day 1, and End of Day 2 separated by Group. Notice that Y-axes differ between the graphs but are set to the maximum possible score for each metric; EF = External Focus; IF = Internal Focus; max = maximum; all data presented as mean±SEM.

0.046; Figure 4.5c). While Effort/Importance appears to increase (Figure 4.5c), pairwise comparisons showed that Effort/Importance did not significantly change from Baseline to the End of Day 1 (mean difference = 2.0, $p>0.1$) which indicated that the perceived effort placed on doing the task well did not change over practice on Day 1. However, Effort/Importance did decrease from the End of Day 1 to the End of Day 2 (mean difference = 3.1, $p<0.05$) indicating that the effort placed on doing the task well decreased on Day 2. There were no differences between Arms ($p>0.1$; $\eta^2 = 0.017$) or Focus instructions ($p>0.1$; $\eta^2<0.01$). No significant interactions were found.

4.3.8: Psychobiosocial States

Psychobiosocial States outcomes are listed in Table 4.2. While Pleasant affect had no differences between Arms ($p>0.1$; $\eta^2 = 0.024$), there was a significant Focus X Time interaction ($p<0.05$; $\eta^2 = 0.071$) which indicated that Pleasant feelings during the task changed differently from the End of Day 1 to End of Day 2 based upon the Focus instructions given. Follow-up independent t-test comparing the change from the End of Day 1 to the End of Day 2 ($p<0.01$) between the two Focus instructions showed that, on average, EF's Pleasant affect slightly decreased (mean diff = 1.3) while IF's Pleasant affect slightly increased (mean diff = 0.880) over time. Feelings of Anger did not change over Time ($p>0.1$; $\eta^2<0.01$) nor did it differ between the two Arms ($p>0.1$; $\eta^2 = 0.028$), but it did differ between the two Focus instructions ($p<0.05$; $\eta^2 = 0.073$) such that, on average, those who received EF instructions had higher feelings of Anger

Table 4.2 Psychobiosocial States – Traits Outcomes

	Right Arm		Left Arm	
Focus	***External***	***Internal***	***External***	***Internal***
Pleasant (max = 20)‡				
End Day 1	11.0±0.5	9.3±0.5	9.9±0.5	9.2±0.5
End Day 2	9.8±0.5	10.3±0.5	9.2±0.6	10.0±0.5
Anger (max = 20)*				
End Day 1	13.9±0.7	11.3±0.7	12.1±0.7	11.4±0.7
End Day 2	12.9±0.8	11.4±0.7	11.7±0.8	11.1±0.7
Motor-Behavioral (max = 20)				
End Day 1	15.9±1.0	12.0±1.0	14.0±1.0	12.5±1.0
End Day 2	15.0±1.0	15.4±1.0	14.6±1.0	14.8±1.0
Cognitive (max = 20)				
End Day 1	14.4±1.0	12.0±1.0	14.7±1.0	13.8±1.0
End Day 2	14.9±1.0	14.2±1.0	14.8±1.1	13.5±1.0
Operational (max = 20)				
End Day 1	15.1±1.0	15.0±1.0	14.1±1.0	13.4±1.0
End Day 2	14.9±1.0	15.4±1.0	14.2±1.1	13.8±1.0
Communicative (max = 20)†				
End Day 1	12.3±1.1	9.5±1.1	10.3±1.1	11.0±1.1
End Day 2	13.3±1.2	13.2±1.1	13.3±1.3	13.8±1.8
Anxiety (max = 20)§				
End Day 1	9.4±0.5	11.3±0.5	10.8±0.5	10.2±0.5
End Day 2	9.6±0.5	10.2±0.5	10.3±0.6	10.4±0.5
Bodily (max = 20)†§				
End Day 1	10.5±1.1	7.7±1.1	8.7±1.1	8.9±1.1
End Day 2	13.3±1.2	11.0±1.1	11.3±1.3	12.7±1.1
Motivational (max = 20)				
End Day 1	13.8±1.1	11.6±1.1	12.7±1.1	13.8±1.1
End Day 2	13.9±1.2	13.2±1.1	13.3±1.3	14.1±1.1
Volitional (max = 20)				
End Day 1	15.8±0.9	14.3±0.9	14.9±0.9	15.2±0.9
End Day 2	14.8±1.0	14.7±0.9	14.6±1.1	14.2±0.9

The average scores for each performance-related Trait on the Psychobiosocial States – Trait (PBS-ST) Questionnaire for each group as they were measured at the End of Day 1 and the End of Day 2; Higher scores indicated greater positive feelings towards that trait; * = significant Effect of Focus; † = sig. Effect of Time. ‡

= significant Focus X Time interaction. § = significant Arm X Focus interaction; Data displayed as mean±SEM.

than those who received IF instructions (mean diff = 1.4). Positive feelings about Motor Behavior or movement quality increased over time (mean difference = 1.3), however, this change did not reach statistical significance ($p = 0.053$; $\eta^2 = 0.043$). Feelings about Motor Behavior, however, did not differ between the two Arms ($p>0.1$; $\eta^2<0.01$) or Focus instructions ($p>0.05$; $\eta^2 = 0.036$). Perceived Cognitive engagement did not change over Time ($p>0.1$; $\eta^2<0.01$) nor did it differ between the two Arms ($p>0.1$; $\eta^2<0.01$) or Focus instructions ($p>0.05$; $\eta^2 = 0.038$). Communicative traits of being free/less isolated had an overall effect of Time ($p<0.01$; $\eta^2 = 0.108$) such that these feelings increased from the End of Day 1 to the End of Day 2 (mean diff = 2.642, $p<0.01$) but did not differ between the two Arms ($p>0.1$; $\eta^2<0.01$) or Focus instructions ($p>0.1$; $\eta^2<0.01$). Feelings of Anxiety did not change over Time ($p>0.1$; $\eta^2<0.01$), however a significant Arm X Focus interaction ($p<0.05$; $\eta^2 = 0.052$) indicated that the EF instructions tended to yield lower feelings of Anxiety than the IF instructions in the Right arm (mean difference = 1.3) but not in the Left arm (mean difference = 0.3). Bodily traits of feeling energized/relaxed significantly increased with Time ($p<0.001$; $\eta^2 = 0.157$) regardless of Arm or Focus used. A significant Arm X Focus interaction ($p<0.05$; $\eta^2 = 0.049$) indicated that the EF instructions yielded greater feelings of energy/relaxation than the IF instructions in the Right arm (mean difference = 2.5) but not in the Left arm (mean difference = 0.8). Neither Motivational or Volitional feelings changed over Time ($p>0.1$; $\eta^2<0.01$) nor did they differ

between the Arms ($p>0.1$; $\eta^2<0.01$) and Focus instructions used ($p>0.1$; $\eta^2<0.01$).

4.4: Discussion

4.4.1: Summary

The purpose of this study was to examine how different focus of attention instructions influence the learning of a complex, whole-arm sequence task. Consistent with our initial hypothesis, task performance improved over practice, as was exhibited by decreases in Response Time, regardless of Arm or Focus instruction used. We also hypothesized that the Focus instructions would differentially affect how the task was learned in the two arms such that the External Focus (EF) instructions would facilitate learning to a greater degree than the Internal Focus (IF) instructions in the dominant right arm while the IF instructions would facilitate learning to a greater degree than the EF instructions in the non-dominant left arm. However, the Focus instructions did not differentially affect Response Time either during practice or learning but did influence the approach used to complete the sequence task. Regardless of the Arm used, the External Focus (EF) groups had consistently shorter hand paths than the Internal Focus (IF) groups while the IF groups had consistently higher movement velocities than the EF groups throughout practice. These results are contrary to our original hypothesis because while there were Focus-specific differences in the approach used to complete the task, the differences were not specific to the Arm used. There were no differences between Focus instructions

in Cognitive Loads, Enjoyment/Interest, Perceived Competence, or Effort/Importance in the task regardless of the Arm used. However, Cognitive Loads, Enjoyment/Interest, and Effort/Importance in the did decreased over Time regardless of Arm or Focus instruction. Positive performance affect in the Motor-Behavioral, Communicative, and Bodily performance traits, as measured by the PBS-ST, improved over Time regardless of Arm or Focus instruction. However, the EF groups seemed to have greater improvements in the Pleasant, Anger, and Anxiety trait scores regardless of Arm, higher Anxiety trait scores in the Right Arm, and Bodily trait scores in the Left arm than their IF counterparts. Together, these results show that Focus instructions may have also had a mild influence on how the participants felt about different aspects of their performance.

4.4.2: Effect of Focus Instruction

Regardless of the focus instruction employed, all participants effectively learned the sequence task. In many of the tasks used in previous studies, EF instructions elicited superior performance and learning responses than both IF instructions and non-instructed controls (Lewthwaite & Wulf, 2017; Wulf, 2013; Wulf & Lewthwaite, 2016). The results of the present study are not consistent with this previous work as no difference in Response Time over practice was found between the EF and IF instructed groups. In many of the previous studies which compared task performance between EF, IF, and non-instructed control over practice, the EF group was not the only group whose performance improved with practice. In fact, all groups often do improve performance with practice

except that the EF group tends to improve to a greater degree than the others (Becker & Fairbrother, 2019; Beilock et al., 2002; Chua et al., 2018; Masters, 1992; Wulf et al., 2015; Wulf et al., 1999; Wulf et al., 2002; Wulf & Prinz, 2001). Therefore, both Focus instructions eliciting improvements in task performance (Response Time) in the present study is consistent with previous findings. While the lack of difference between Focus instructions on task performance (Response Time) in the present study is counter to much of the previous literature, these results are not entirely unexpected. In many of the accuracy-based tasks – such as throwing, darts, golf, basketball – multiple possible movement solutions could result in a successful outcome (Beilock et al., 2002; Masters, 1992; Wulf et al., 2015; Wulf et al., 1999; Zachry et al., 2005). When the task at hand is contingent upon effective completion of a specific movement pattern, or a single movement solution, internal focus cues have elicited similar or better outcomes to external focus cues (Milanese et al., 2017; Neumann et al., 2020; Schutts et al., 2017; Winchester et al., 2009; Zentgraf & Munzert, 2009). The task used in the present study required participants to create both fast and accurate reaches to a targeted end point which can be accomplished through decreases in hand path distance, indicating an improved straightness in hand path, and/or increases in movement velocity (Baird, 2017; Baird & Stewart, 2018; Smith et al., 2021b). Previous studies have shown that when learning complex movement tasks which require straighter movement paths and increased movement velocity, IF instructions can be at least as effective as EF instructions

to improve task performance (Milanese et al., 2017; Schutts et al., 2017; Winchester et al., 2009; Zentgraf & Munzert, 2009).

While there were no differences in overall performance (Response Time) during Practice or Learning between the two Focus instructions, there were differences in the approach to improving performance based on Focus instructions. Specifically, those who received EF instructions had shorter hand path distances throughout, and therefore straighter hand paths, than those who received IF instructions; conversely, those who received IF instructions had higher movement velocities than those who received EF instructions. In other words, while all groups saw improved Response Times, Total Hand Path Distances, and Peak Velocities with practice, the EF group had consistently shorter hand paths while the IF group had consistently greater movement speeds. The observed effect of the Focus instructions on aspects of reach control may be related to the saliency, or relevance, of the cue to the task. The issue of cue/instruction saliency is not new to the focus of attention literature. Typically, the component of the movement to which the IF instructions draw attention is also the component of the movement in which either positive or negative changes in execution are observed (Ducharme et al., 2016; Gokeler et al., 2015; van Ginneken et al., 2018; Vidal et al., 2018). In other words, when the internally focused instructions are properly directed towards a movement component which is important for effective execution of the skill, internal focus instructions can elicit strongly positive learning outcomes similar to those of external focus (Milanese et al., 2017; Schutts et al., 2017; Winchester et al.,

2009; Zentgraf & Munzert, 2009). For example, in a study which examined novices learning how to juggle, the internal focused instructions (directed toward hand movements) elicited similar hand paths to that of experts while the external focus instructions (directed at ball trajectories) led to ball paths that were similar to the experts without any differences between the groups in overall juggling performance (Zentgraf & Munzert, 2009). In the present task, the EF instructions drew attention to moving the white cursor sphere to the target which could have corresponded to an increased emphasis on path straightness; similarly, the IF instructions drew attention to creating fast arm movements which could have corresponded to an increased emphasis on movement speed.

These results contrast what would be expected based upon previous focus of attention studies which found EF instructions to elicit consistently better performance than IF (Becker & Fairbrother, 2019; Beilock et al., 2002; Chua et al., 2018; Masters, 1992; Wulf et al., 2015; Wulf et al., 1999; Wulf et al., 2002; Wulf & Prinz, 2001). Also, we hypothesized that the Focus instructions would have differential effects on task performance and execution based upon the arm used. However, while the Focus instructions did cause a differential effect on task execution, they did not differently affect performance in the two arms. These contrasts may be related to how the instructions are received and interpreted in the context of the task itself. The OPTIMAL Theory emphasizes a characteristic called “goal-action coupling” which is defined by the idea that all variables in a learning environment (such as the focus instructions) should aim to tie the action of the participant to the desired outcome of that action (Lewthwaite & Wulf, 2017;

Wulf & Lewthwaite, 2016). The task used in the present study could be effectively learned and performed through three possible solutions – either move faster, move straighter, or both. While the Focus instructions were directed either toward the external task environment or the internal movement of the arm, they emphasized one of the two base solutions. The EF groups were instructed to "move the white sphere to the target as fast as possible" which aimed to draw attention to the cursor indicating hand position. The cursor was visible throughout the task which likely emphasized straighter movements (i.e., moving the cursor straight to the target) thereby creating straighter hand paths. The IF groups were instructed to "move their arm to the target as fast as possible". With the arm not being visible in the virtual environment, these instructions may have drawn attention more to simply moving fast and generating higher movement velocities. In this regard, the two Focus instructions may have been similarly effective for overall performance (i.e., Response Time) because they drew focus to one of the two possible solutions to the task at hand. However, these instructions may have only been interpreted in the manner described here as a result of the task environment.

4.4.3: Effect of the Task Environment

The task used in the present study is unique compared to those which have been used in previous focus of attention studies. Movement occurred in a virtual environment and was highly visually dependent. The Focus Adherence scores showed that participants had relatively high EF focus scores across all

groups indicating that they placed a great deal of focus on the location of the cursor regardless of the instruction provided. This almost “default” external focus may be due to the fact that the task is visually-based whereby the participants react to the visual stimulus of a target’s appearance, and the goal of the task is to get the cursor into the target for the next target to appear. While such a visually-based setup could make the task very inherently external, as suggested by the Adherence scores, the IF instructions did not interfere with task performance unlike other previous studies which had externally-based tasks (Beilock et al., 2002; Masters, 1992; Wulf et al., 2015; Wulf et al., 1999; Zachry et al., 2005). However, the tasks used in these studies goals were truly external to the movement itself in that the tasks entailed casting an implement toward a target (i.e., putting or throwing) which can have a variety of possible movement solutions all of which result in the desired outcome of hitting the target. In the present study, the cursor’s movement was entirely based upon hand position which relied upon coordinated simultaneous movement of the shoulder and elbow joints; therefore, while the task was external in nature whereby accuracy relative to a target was required, the task still had internally controlled elements because effective completion of the task required deft control of the arm to create a fast, accurate movement in order to successfully and efficiently reach to the target. This element was also reflected in the Adherence scores whereby all groups had some level of internally directed attention which did not differ between groups even though the IF groups tended to have higher scores. The lack of difference in Focus Adherence could be the result of the environment

itself, or the instructions may not have been specific or strong enough to elicit a strong differentiation in attentional focus during task execution between conditions. Future studies could further examine the influence of differently focused instructions on detailed kinematic measures of performance and measures of attentional focus.

It should be noted that the lack of difference between the Adherence scores could be due to the Focus instructions themselves in the context of the environment. While external in nature, the EF groups were asked to focus on the "white sphere" indicating hand position which is a relatively near landmark. Previous studies which have examined the effectiveness of EF instructions have found that as the EF instructions direct attention farther away from the movement effector, the greater the improvements in performance (Becker & Smith, 2015; McNevin et al., 2003; Singh & Wulf, 2020). Therefore, the similarities in overall performance seen in the present study may be due to the distance of the instruction from the effector (arm).

4.4.4: Effect of Focus on Psychometric Measures

Few studies have examined the effects of different focus of attention instructions on psychometric measures such as cognitive load, motivation, or performance experience. In this regard, the results seen in the present study are relatively novel. While previous studies and the Constrained Action Hypothesis suggest that IF instructions interfere with task performance and learning because of reduced automaticity in the movement pattern (McNevin et al., 2003; Wulf,

McNevin, et al., 2001; Wulf & Prinz, 2001; Wulf, Shea, et al., 2001), another possibility is the IF instructions created a dual-task environment as the focus on the movement itself draws attention away from the task goal. While this has not been explicitly examined in previous focus of attention studies, studies which have examined the acute effects of dual-task performance have shown decrements in primary task performance when the secondary task is being completed simultaneously with the primary task (Goh, Gordon, Sullivan, & Winstein, 2014; Moreira, Dieguez, Bredt, & Praca, 2021; Pashler, 1994; van Rooteselaar, Beke, & Gonzalez, 2020). If the IF instructions created a dual-task environment, an increase in perceived Cognitive Load would be expected because attention would have been divided between task execution and monitoring the movement itself. However, perceived cognitive load decreased over the course of practice regardless of Arm or Focus instruction used. Specifically, the decrease in Intrinsic Load indicated that the perceived mental difficulty due to elements inherent to the task itself decreased over time while decreases in Extrinsic Load indicated that the perceived mental difficulty due to the Focus instructions decreased over time. Decreases in Germane Load indicated that the perceived mental difficulty due to elements related to the learning processes from practice of the task decreased over time. More importantly, these values did not differ between the Focus instructions. Together these results indicate that the Focus instructions did not differentially affect how participants perceived task difficulty over practice. While there was a significant difference between the Arms on the Germane Load metric, the difference was

relatively small (less than one point). It also should be noted that all Cognitive Load scores were relatively low with all being less than half of the maximum possible score at all time points which would indicate that this task likely was not cognitively taxing.

The OPTIMAL Theory proposes that improved task performance leads to enhanced expectancies, or the expectation to replicate success, and increased motivation which, in turn, further facilitate successful task performance (Lewthwaite & Wulf, 2017; Wulf & Lewthwaite, 2016). Since EF instructions have been linked with improved task performance, it could be extrapolated that EF instructions would also yield improved motivation and self-efficacy. In fact, a recent study has shown that scores on the IMI are greater under practice conditions which include an external focus and autonomy-supporting language compared to during conditions which include an internal focus and more constraining language (Levac, Driscoll, Galvez, Mercado, & O'Neil, 2017). However, in the present study Enjoyment/Interest and Effort/Importance placed on the task both decreased over time while Perceived Competence remained relatively constant regardless of Arm or Focus instruction used. These results indicated that over the course of practice interest and enjoyment in completing the task waned while perceived effort put forth declined as well. The decrease in Effort would be expected with practice because as one becomes more familiar with a task, the ability to perform the task should become less effortful. However, this decline in Effort may be related to decreasing Enjoyment/Interest in the task. In other words, the participants may have become bored with the task and

therefore did not try as hard as practiced progressed. Perceived Competency also did not change over time; however, this may not have been related to either of the other Motivation subscales but more so due to the lack of performance-related feedback. Provision of performance feedback, specifically positive feedback, has been shown to not only increase self-efficacy in task performance but also motivation in general (Drews, Pacheco, Bastos, & Tani, 2021; Wright, O'Halloran, & Stukas, 2016; Wulf & Lewthwaite, 2016). However, it must be noted that regardless of these results, the scores on all Intrinsic Motivation subscales were relatively high overall (≥60% max possible score) which would indicate that the participants remained engaged and invested in performing the task to the best of their abilities throughout practice.

The examination of how participants felt about various different performance-related traits via the PBS-ST revealed some differences between the focus groups. While the IF instructions seemed to have more positive responses for the Pleasant (positive affect) and Anger traits, the EF instructions seemed to have more positive responses for the Anxiety and Bodily (energy/relaxed) traits. Also, all groups seemed to have more positive responses for the Motor Behavior and Communicative traits regardless of Focus instruction. While these results could indicate that the Focus instructions had differing effects on how participants perceived different aspects of their performance on the task, these outcomes should be viewed cautiously as many of the scores were close to 10/20 which would indicate that the participants had relatively ambivalent feelings as 0 = entirely negative and 20 = entirely positive performance

experience in each trait. Also, many of the differences over time and between groups were relatively small (~1 – 2 points) and had relatively small effect sizes indicating the differences may not be significant from a practical perspective. While the CLQ and IMI can provide insight about how the task and task environment were perceived, they do not provide information about how the participants felt about their performance abilities during the task where the PBS-ST does. The results of the present study show that both IF and EF instructions can provide positive performance experiences when the instructions are salient to the task and task outcome which is, in fact, consistent with the OPTIMAL Theory's emphasis on use of language which enhances autonomy and creates positive expectations toward performance (Lewthwaite & Wulf, 2017; Wulf & Lewthwaite, 2016).

While the results from the measures in the present study did not yield many significant findings when comparing between Focus instructions, future studies should continue to incorporate similar measures into their designs. Such measures can not only provide another metric by which task performance can be evaluated but also provide insight into the participants' perception of the task, their performance, and the instructions themselves, which is often missing from the current body of literature.

4.4.5: Effect of Arm on Task Performance and Learning

While studies have used two-dimensional targeted reaching movements to examine learning differences between the dominant and non-dominant limbs

(Bagesteiro et al., 2021; Buchanan, 2004; Buchanan et al., 2007; Criscimagna-Hemminger et al., 2003; Duff & Sainburg, 2007; Mutha et al., 2012, 2013; Sainburg & Wang, 2002; Stockinger et al., 2015), sequence learning using a whole-arm serial target task with the non-dominant and dominant limbs has not been thoroughly examined. In fact, previous studies which have examined sequence learning between the two limbs have often employed finger-pressing paradigms (Grafton, Hazeltine, & Ivry, 2002; Haaland, Elsinger, Mayer, Durgerian, & Rao, 2004; Kirsch & Hoffmann, 2010; Verwey & Clegg, 2005). In much of the reach control literature examining right-handed individuals, reaches with the dominant right arm tend to have straighter hand paths, indicating a higher degree of shoulder-elbow coordination, while reaches with the left arm tend to have more longer and more curved hand paths, indicating a lower degree of shoulder-elbow coordination (Bagesteiro & Sainburg, 2002; Mutha et al., 2013; Sainburg & Kalakanis, 2000; Tomlinson & Sainburg, 2012). These studies along with a previous analysis examining learning in the Right and Left arms using a similar task paradigm as the one used in the present study (Smith et al., 2021a,b) are what informed our original hypotheses. We hypothesized that the EF instructions would most benefit the Right arm because they would reinforce automatic control processes thereby eliciting greater decreases in total hand path distance and increases in peak velocity than the IF instructions; conversely, we hypothesized that the IF instructions would most benefit the Left arm by encouraging greater improvements in hand path distance where the Left arm has the most to gain. The present results showed, instead, no differences in task

performance (Response Time) or Learning between the arms and no differential effects of the Focus instructions on the arms. The lack of differences between the instructions on the arms may be in part because the task paradigm used here required the endpoint of the movement to be accurate to the target while many previous studies have not (Bagesteiro & Sainburg, 2002; Dexheimer & Sainburg, 2021; Goble et al., 2006; Sainburg & Kalakanis, 2000; Sainburg & Schaefer, 2004; Schaffer & Sainburg, 2017). However, our hypotheses were, in part, based upon a study which used a similar paradigm to that used in the present study which showed the Left arm had a greater degree of learning overall in large part due to changes in hand path distance while the Right arm improved both hand path distance and peak velocity (Smith et al., 2021a). Previous studies using this paradigm have also shown learning via a combination of improvements in both hand path distance and peak velocity (J. Baird & Stewart, 2018; J. F. Baird et al., 2018). Since both arms improved in both areas and to similar degrees in the present study, it may be that the Focus instructions used in the present study facilitated learning via the combined approach (i.e., improvements in both spatial and temporal performance). Also, the present study found that the Right arm had higher peak velocities than the Left arm which contrasts previous studies which have generally not shown differences in movement velocity between the two arms (Bagesteiro & Sainburg, 2002; Dexheimer & Sainburg, 2021; Goble et al., 2006; Sainburg & Kalakanis, 2000; Sainburg & Schaefer, 2004; Schaffer & Sainburg, 2017). However, movement times were often not reported in these studies making it difficult to draw comparisons to present results. Future studies

should further examine differences in learning whole-arm tasks between the two limbs.

4.4.6: Practical Application

Previous studies which have used internal cues focused on specific movement components that were often not key to the movement outcome have shown that IF cues negatively affect task performance and freeze movement about that point of focus (Ducharme et al., 2016; Gokeler et al., 2015; McNevin et al., 2003; van Ginneken et al., 2018; Vidal et al., 2018; Wulf, McNevin, et al., 2001; Wulf & Prinz, 2001; Wulf, Shea, et al., 2001). However, the present results add to a growing body of literature which indicate that the content of Focus instructions in the context of the task at hand seem to matter. Specifically, when the instructions are salient to the movement goal and are not overly constraining, IF instructions appear to elicit positive performance outcomes in a manner where changes in performance are driven by the aspect specific to the instruction (Mattes, 2016; Maurer & Munzert, 2013; Zachry et al., 2005; Zentgraf & Munzert, 2009). This is particularly important to clinicians as Physical Therapists, Sport Coaches, and Strength Coaches tend to utilize more internally focused instructions with their clientele (Diekfuss & Raisbeck, 2016; Johnson, Burridge, & Demain, 2013; B. J. Schoenfeld & Contreras, 2016). However, the OPTIMAL Theory encourages these professionals to forego IF and use only EF instruction (Lewthwaite & Wulf, 2017; Wulf & Lewthwaite, 2016). While more research into how focus instructions affect learning and performance is needed, the present

results indicate that IF instructions could play an important role in a training paradigm when incorporated in a manner where the instructions are specific to and salient with the desired outcomes. Future studies should look to expand upon the present work to further examine how differently focused instructions affect task performance and learning not only in laboratory but also in practical settings.

4.4.7: Limitations

This study was not without limitations. One such limitation was sample size. The present study only consisted of 48 participants across 4 groups which gave each group n = 12. However, an a priori power analysis calculated this to be a sufficient sample size for the present study design. Another limitation was loss of data due to technical difficulty. Three participants' data for Day 2 (Retention) could not be collected due to an error in the system which could not be reconciled prior to the end of their scheduled session. Also, due to the design of the experimental procedure, Day 2 could not be rescheduled for another day resulting in data loss for that day. While this would negatively affect our metrics for Day 2 and Learning analyses, their data was available and could be used to examine changes over the course of Day 1 keeping one of our primary analyses fully intact. Future studies should seek to employ a larger sample to avoid such issues. Age was significantly different between the groups. While many previous studies have primarily shown differences based on age when comparing younger (20 – 30 yrs) and older (>65 yrs) adults (Chaput & Proteau, 1996; Kwon, Chen,

Fox, & Christou, 2014; Seidler, 2006; Seidler et al., 2010; Walker, Philbin, & Fisk, 1997; Yan, Thomas, & Stelmach, 1998), a recent study did not show age-related declines in movement control until after age 40 (Wang, Williams, & Wilmut, 2020), and all participants in the present study were under age 35. Another possible limitation is that no performance-related feedback was provided during practice. While the provision of feedback in some form has been linked with increased task performance and motivation (Drews et al., 2021; Wright et al., 2016; Wulf & Lewthwaite, 2016) and is commonly provided in clinical settings, performance-related feedback was not provided in the present study because the task involved implicit learning of a sequence, a paradigm where the goal is to learn without the provision of feedback. Future studies should seek to incorporate feedback at least in the form of knowledge of results to better mirror practical settings.

4.4.8: Conclusions

In summary, both internal and external focus instructions elicited improvements in performance of a whole-arm, serial target task regardless of Arm used (dominant or non-dominant) whereby the EF instructions corresponded to shorter hand path distances and the IF instructions corresponded to higher movement velocities. These differences between foci in how they attained their response times appeared to be linked with the area to which the instructions drew attention. These results suggest that the saliency of the instructions to the task and the desired outcome may be relevant to task performance and learning

than the direction of the instruction's focus. There were minimal differences between focus instructions in cognitive load, motivation, and performance traits which indicate that both the IF and EF instructions elicited relatively similar task and performance experiences for the participants. These results can be helpful to practitioners when deciding what focus instructions to use during a training or rehabilitation program and how they may be most effective. Future studies should continue to provide detailed kinematic and psychometric analyses when comparing different focus instructions so that we may better understand how EF and IF can be best utilized to enhance performance and learning.

CHAPTER 5

CONCLUSION

This dissertation had two aims – to examine how Fitts' Law applied in a task environment which required fast, accurate whole-arm reaching movements across multiple directions and how differing focus of attention instructions would affect the learning of a whole-arm sequence task. In response to the first aim, the first study found that reaches to targets with increasing inter-target distance, and therefore increasing difficulty, but the same direction resulted in scaling of kinematic features of movement control consistent with the expectations of Fitts' Law. However, when targets were located at the same distance apart, and therefore same difficulty, but different directions, kinematic features of movement control varied with direction. Specifically, reaches which were in higher inertia directions and/or required greater amounts of joint movement in the shoulder and elbow were slower and took longer to complete than movements along lower inertia directions and/or required minimal amounts of movement at the shoulder and elbow joints. These results indicate that there is a mechanical difficulty for which Fitts' Law does not account. Target-based sequence tasks, like the one used in Study 2, often balance sequence difficulty based upon Fitts' Law. However, the results of the present study have added to the body of literature which has shown that there are task environments to which Fitts' Law does not translate (Bonnetblanc, 2008; Danion et al., 1999; Heath et al., 2011; Juras et al.,

2009). This can be of particular interest as many sequence tasks utilize Fitts' Law to balance for level of difficulty (Baird & Stewart, 2018; Ghilardi et al., 2009; Perfetti et al., 2011; Perfetti et al., 2010). The results of this dissertation along with those of previous studies suggest that Fitts' Law may not be a ubiquitous effect which is independent of modality. Further research is required to elucidate its applicability to other task environments and paradigms.

Study 2 found that both Internal (IF) and External (EF) focus instructions result in improved task performance (as seen by decreased Response Time) over practice. However, the gains in response time were achieved through different mechanisms. The EF groups had shorter hand path distances, a spatial feature of control, than the IF groups while the IF groups had higher peak velocities, a temporal feature of control, than the EF groups. These outcomes may have been the result of the instructions relevancy/saliency to the task and its outcomes. The EF instructions focused attention on moving the cursor quickly and, therefore, may have caused participants to place more emphasis on creating a linear path from one target to the next. In contrast, the IF instructions focused attention on moving the arm quickly, and, therefore may have cause participants to place more emphasis on creating fast movements at the sacrifice of some hand path straightness. These instructions also didn't have any effect on the perceived difficulty of the task, nor did they affect the participants' motivation to do the task or how they felt about their performance at the task. This is counter to much of the previous focus of attention literature which gives EF a distinct advantage over IF. These results would suggest that the context of the

instructions’ content in relation to the task may have a meaningful effect on task performance and learning. The ability to use both IF and EF instructions effectively would be important for clinicians and practitioners who have been shown to use both instructions in practice (Diekfuss & Raisbeck, 2016; Johnson et al., 2013; Schoenfeld & Contreras, 2016). A better understanding of how focused instructions affect performance and learning would help practitioners to better cue their clientele in a manner which is specific to their goals and desired performance outcomes. Per the OPTIMAL Theory, this should, in turn, further emphasize gains in performance and learning over time (Lewthwaite & Wulf, 2017; Wulf & Lewthwaite, 2016).

The two studies in this dissertation provide currently unknown information on areas key to motor training, Fitts’ Law and focus of attention. While other studies have hinted that Fitts’ Law may not apply in a multi-directional setting, no study to date has explicitly examined it nor have they done so in an environment where endpoint accuracy was required. Being able to complete accurate reaching movements in a three-dimensional, multi-directional environment are key to performance of tasks in daily living, but previous studies examining the applicability of Fitts’ Law had not emulated such an environment. Similarly, while much of the focus of attention literature has detailed focus instructions’ effects on performance and learning, these studies are often lacking in two key areas. First, they typically do not include kinematic measures of motor control which means much of the knowledge of how to use these instructions is based upon broad performance outcomes alone. Second, the instructions relevance to the desired

outcome is often in question, particularly for the IF instructions. Therefore, it’s relatively unknown whether the limits on performance typically seen with IF instructions are due to IF being a poorer instruction set or if the content of the instructions are simply not what is needed for that task. The present studies in this dissertation show that there are areas within these bodies of research which still require further investigation in order for there to be a greater understanding on how to 1) ensure tasks which require targeted movement are not biased due to mechanical difficulties of the movement and 2) how to provide instructions during tasks in a manner which is not only conducive to performance but also emphasizes the area of control or outcome where change is desired.

Greater understanding of the areas addressed in this dissertation would not only benefit researchers but also clinicians and practitioners. As was stated before, many tasks of daily living require fast, accurate movements in multiple directions. Having a greater understanding of how direction can affect elements of movement control can be helpful for not only designing more balanced task paradigms but also for those working with populations with motor deficits (e.g., Parkinson’s, stroke, Multiple Sclerosis). Because people with such conditions can have movement patterns which are either constrained, inefficient, and/or uncoordinated, understanding how factors such as direction interplay with movement control can help clinicians better understand these deficits and even how to structure a rehabilitation program to overcome them. Similarly, many clinicians, coaches, and trainers use a combination of EF and IF instructions in a variety of different contexts. Having a greater understanding of how those

instructions can affect performance and motor control would provide these professionals with information which could help them to incorporate those instructions optimally. In other words, practitioners would be able to tailor not only their programs to the clientele but also their instructions for the different tasks within the program to fit the desired goals/outcomes of each element of the program. In these ways, training and rehabilitation can be made more efficient and effective toward both patient/client and health/performance goals.

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APPENDIX A: COPY OF INTRINSIC MOTIVATION INVENTORY

For each of the following statements, please indicate how true it is for you, using the following scale:

1	2	3	4	5	6	7
Not true at all			Somewhat true			Very true

_____1. This activity was fun to do.

_____2. I put a lot of effort into this.

_____3. I was pretty skilled at this activity.

_____4. I am satisfied with my performance at this task.

_____5. I tried very hard on this activity.

_____6. I thought this was a boring activity.

_____7. After working at this activity for a while, I felt pretty competent.

_____8. It was important to me to do well at this task.

_____9. I thought this activity was quite enjoyable.

_____10. I think I did pretty well at this activity, compared to other students.

_____11. This activity did not hold my attention at all.

_____12. This was an activity that I couldn't do very well.

_____13. I didn't try very hard to do well at this activity.

_____14. I enjoyed doing this activity very much.

_____15. While I was doing this activity, I was thinking about how much I enjoyed it.

_____16. I didn’t put much energy into this.

_____17. I think I am pretty good at this activity.

______18. I would describe this activity as very interesting.

APPENDIX B: COPY OF THE PSYCHOBIOSOCIAL STATES – TRAIT QUESTIONNAIRE

Below are labels that athletes use to describe their performance-related experiences. Read all descriptors in each row carefully and circle the one that describes best how you feel; feel free to add your own adjectives to better describe your own experiences. Then, rate the intensity of that feeling on the following scale:

0 = nothing at all; 0.5 = very, very little; 1 = very little; 2 = a little; 3 = moderately; 5 = much; 7 = very much; 10 = very, very much; ● = maximum

1. Enthusiastic, confident, carefree, joyful	0	0.5	1	2	3	4	5	6	7	8	9	10	●
2. Fighting spirit, fierce, aggressive	0	0.5	1	2	3	4	5	6	7	8	9	10	●
3. Relaxed, coordinated, powerful, effortless movement	0	0.5	1	2	3	4	5	6	7	8	9	10	●
4. Distracted, overloaded, doubtful, confused	0	0.5	1	2	3	4	5	6	7	8	9	10	●
5. Effective, skillful, reliable, consistent task execution	0	0.5	1	2	3	4	5	6	7	8	9	10	●
6. Uncommunicative, withdrawn, alone, disconnected	0	0.5	1	2	3	4	5	6	7	8	9	10	●
7. Nervous, restless, discontented, dissatisfied	0	0.5	1	2	3	4	5	6	7	8	9	10	●
8. Vigorous, energetic, physically charged	0	0.5	1	2	3	4	5	6	7	8	9	10	●

9. Sluggish, clumsy, uncoordinated movement	0	0.5	1	2	3	4	5	6	7	8	9	10	●
10. Alert, focused, attentive	0	0.5	1	2	3	4	5	6	7	8	9	10	●
11. Unmotivated, uninterested, uncommitted	0	0.5	1	2	3	4	5	6	7	8	9	10	●
12. Overjoyed, complacent, pleased, satisfied	0	0.5	1	2	3	4	5	6	7	8	9	10	●
13. Ineffective, unskillful, unreliable, inconsistent task execution	0	0.5	1	2	3	4	5	6	7	8	9	10	●
14. Communicative, outgoing, sociable, connected	0	0.5	1	2	3	4	5	6	7	8	9	10	●
15. Purposeful, determined, persistent, decisive	0	0.5	1	2	3	4	5	6	7	8	9	10	●
16. Worried, apprehensive, concerned, troubled	0	0.5	1	2	3	4	5	6	7	8	9	10	●
17. Motivated, committed, inspired	0	0.5	1	2	3	4	5	6	7	8	9	10	●
18. Physically tense, jittery, tired, exhausted	0	0.5	1	2	3	4	5	6	7	8	9	10	●
19. Furious, resentful, irritated, annoyed	0	0.5	1	2	3	4	5	6	7	8	9	10	●
20. Unwilling, undetermined, indecisive	0	0.5	1	2	3	4	5	6	7	8	9	10	●

APPENDIX C: COPY OF COGNITIVE LOAD QUESTIONNAIRE

For each of the following statements, please indicate how true it is for you using the following scale:

1	2	3	4	5	6	7
Not true at all			Somewhat true			Very true

_____A. For this task, many things needed to be kept in mind simultaneously.

_____B. For this task, I had to highly engage myself.

_____C. The design of this task was very inconvenient for learning.

_____D. For this task, I had to think intensively on what things meant.

_____E. During this task, it was difficult to recognize and link the crucial information.

_____F. This task was very complex.

_____G. During this task, it was exhausting to find the important information.

Please rank the overall mental load of the task using the following scale (please circle your response):

1	2	3	4	5	6	7
Very Low			Moderate			High

APPENDIX D: COPY OF FOCUS ADHERENCE QUESTIONNAIRE

Please indicate on the line (below) the extent to which you agree/disagree with the following statements:

During the task, I was focused on moving the white sphere toward the red target sphere.

Strongly Disagree *Strongly Agree*

During the task, I was focused on moving my arm toward the red target sphere.

Strongly Disagree *Strongly Agree*

During the task, my intent was to get the white sphere into the red sphere quickly.

Strongly Disagree *Strongly Agree*

During the task, my intent was to move my arm in a fast yet coordinated manner.

Strongly Disagree *Strongly Agree*

During the task, my goal was to “hit” the red target sphere as quickly as possible.

Strongly Disagree *Strongly Agree*

During the task, my goal was to move my arm to the red target sphere as quickly as possible.

Strongly Disagree *Strongly Agree*