Speed Differences during Two-Handed Tasks:

Bimanual versus Intermanual Coordination and the Effect of Practice

by

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Abstract

Prior research has shown that some two-handed tasks are completed faster when using the dyadic, intermanual coordination mode (two people each using one hand to complete a two-handed task) compared to the normal, bimanual coordination mode (one person using two-hands). However, this so-called "intermanual speed advantage" has been found to disappear after bimanual practice. Research suggests that these performance differences may depend on fundamental characteristics of each coordination mode that facilitate or impede speed during two-handed tasks. To investigate underlying human factors that affect speed, a task was constructed to exploit ostensible bimanual limitations: between-hand coupling and visuomotor coupling. Additionally, it was hypothesized that speed during two-handed tasks is associated with simultaneous, goal-directed movements (SGDMs) of the limbs, and that the bimanual limitations restrict the ability to make these movements during unpracticed task performance. It was further hypothesized that the intermanual speed advantage would disappear following bimanual practice. Indeed, the intermanual speed advantage found in prior literature was replicated during an unpracticed task and was not present following bimanual practice. Results suggest that the explanatory measures (between-hand coupling, visuomotor coupling, and SGDMs) provide a simple explanation of speed during two-handed tasks as compared to previously offered explanations based on shared task knowledge. Furthermore, previous bimanual practice increased performance (as evidenced by speed and results for most of the explanatory measures), which was consistent with hypotheses. The findings have implications for theories of motor control and applications that require individual and cooperative manual coordination, such as teleoperation and laparoscopy.

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List of Abbreviations

AMI – Average Mutual Information

AOI – Area of Interest

CAD – Computer-Aided Design

CRP – Cross Recurrence Plot

CRQA – Cross Recurrence Quantification Analysis

DOF – Degrees of Freedom

FNN – False Nearest Neighbors

GMP – Generalized Motor Program

HCI – Human-Computer Interaction

HHI – Human-Human Interaction

HRI – Human-Robot Interaction

ID – Index of Difficulty

MNS – Mirror Neuron System

PRP – Psychological Refractory Period

PSP – Phase Space Reconstruction

RAs – Research Assistants

SGDM(s) – Simultaneous Goal-Directed Movements

SMM – Shared Mental Model

SOA – Stimulus Onset Asynchrony

Chapter I

Introduction

Successful manual coordination is required in many aspects of life (Land & Tatler, 2009). Prior research has investigated different types of manual coordination tasks, such as one-handed tasks (e.g., Adams, 1981; Fitts, 1954; Woodworth, 1899), two-handed tasks (e.g., Franz, 1997; Kelso, 1981; Mechsner, Kerzel, Knoblich, & Prinz, 2001), and manually coordinating with another person to complete a task (e.g., van der Wel, Knoblich, & Sebanz, 2011; Reed et al., 2006). Importantly, some two-handed tasks are completed faster with a partner compared to completing the task alone (Glynn & Henning, 2000; Gorman & Crites, 2013; Reed et al., 2006; Van Oosterhout, Heemskerk, de Baar, van der Helm, & Abbink, 2017; Wegner & Zeaman, 1956; Zheng, Verjee, Lomax, & MacKenzie, 2005). For example, when teleoperating a rover around a track, participants completed the task faster when two people simultaneously operated the rover compared to a single operator (Gorman & Crites, 2013). Similar differences in performance have been observed during other teleoperation tasks (e.g., Glynn & Henning, 2000), pursuit-rotor tasks (e.g., Wegner & Zeaman, 1956), and laparoscopic tasks (e.g., Zheng et al., 2005).

The majority of manual coordination research has focused on simple tasks, such as individual one-handed line drawing tasks (Adams, 1952; Snoddy, 1926), individual two-finger oscillations tasks (Kelso, 1995), and dyadic finger oscillations tasks (Oullier, De Guzman, Jantzen, Lagarde, & Kelso, 2008). This dissertation extends the current understanding of manual coordination by examining how one versus two people complete complex manual movements that require visual input when completing a series of interdependent subtasks across the hands. Specifically, this dissertation examined previously observed differences in speed when people completed two-handed tasks alone compared to completing the task as a dyad. Furthermore, this dissertation examined how practice affects observed differences in speed during two-handed tasks.

Understanding how people complete manual coordination tasks has implications for a variety of domains, such Human Computer Interaction (HCI) (e.g., design of virtual manipulation systems; Hinckley, Pausch, Goble, & Kassell, 1994), Human Robot Interaction (HRI) (e.g., smart robotic surgical systems; Liu, Kobayashi, Zhang, & Fujie, 2014), training (e.g., manual coordination improvement; Ganesh, Takagi, Osu, Yoshioka, Kawato, & Burdet, 2014), and medicine (e.g., laparoscopy; Zheng et al., 2005). Additionally, from a theoretical perspective, the results of this dissertation have implications for understanding how people complete visually-guided two-handed tasks individually and with a partner. These practical applications along with theoretical applications are discussed in the General Discussion section.

The way people carry out manual coordination tasks (e.g., one-handed, two-handed, etc.) are referred to as manual "coordination modes" (Gorman & Crites, 2013). This dissertation discusses unimanual (i.e., one-handed), bimanual (i.e., two-handed), and intermanual (i.e., different peoples' hands) coordination with particular focus on the latter two coordination modes. Figure 1.1 shows an example of all three coordination modes being used when completing the aforementioned teleoperated task (Gorman & Crites, 2013).

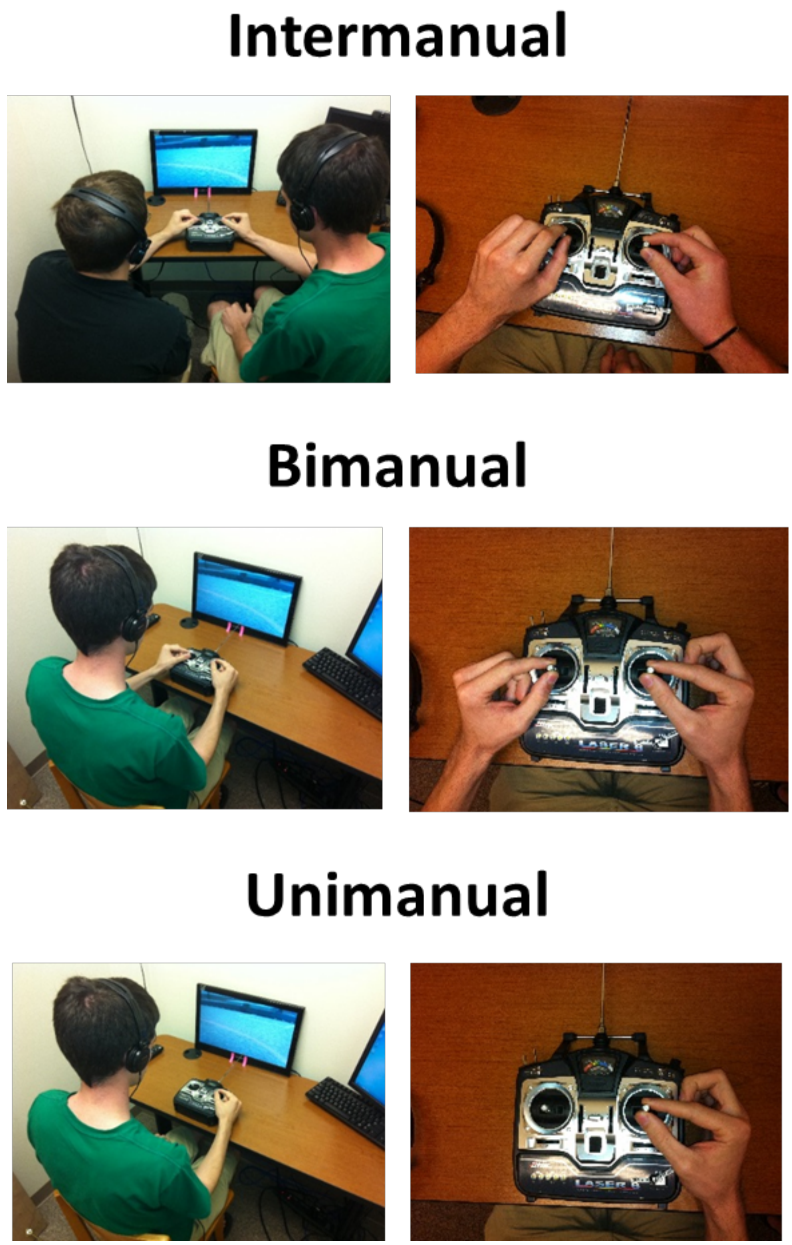

Figure 1.1. Example of all three coordination modes where participants controlled the steering and acceleration of a teleoperated rover. Unimanual (lower): Unimanual control of steering and acceleration collapsed across a single joystick. Bimanual (middle): Bimanual control of steering with the left hand and acceleration with the right hand across two joysticks. Intermanual (top): Intermanual control with one participant controlling steering with their left hand and another participant controlling acceleration with their right hand.

When using these coordination modes, with what is the hand(s) coordinating? When completing a task unimanually, one must coordinate internal and external spatiotemporal properties, in addition to adhering to any potential task demands. Playing the piano with one hand, for example, requires the coordination of the eyes, arm, hand, fingers, etc. when tapping the correct key(s) at the correct time. When completing a task bimanually, many of the same spatiotemporal coordination aspects that exist in the unimanual case are involved; however, there is now another hand that requires coordination (Srinivasan, Martin, & Reed, 2013). The addition of the second hand in some respects may help, such as when playing the piano or tying your shoelaces (e.g., Furuya & Kinoshita, 2008; Gorman & Crites, 2015); however, in other cases, the addition of the second hand can hurt performance, such as when completing two simultaneous left and right hand pointing tasks (e.g., Kelso, Goodman, & Southard, 1979). When completing a task intermanually, the spatiotemporal properties now extend to coordinating with another individual who is also coordinating with themselves. Interestingly, certain unpracticed tasks are easier for novices to complete with a partner compared to completing the same task alone. Continuing the piano example, it may be easier for two novices to play a song that requires two hands. For example, each person can focus on their respective role for each hand during intermanual piano playing (Furuya & Kinoshita, 2008), but must still unimanually coordinate their internal actions spatially and temporally while still coordinating with their partner. Compared to the bimanual coordination mode, the addition of the second hand from another person may help, such as when completing a laparoscopic cutting task (e.g., Zheng et al., 2005); however, in other cases the addition of the second hand from another person can hurt performance, such as when tying shoelaces (Gorman & Crites, 2015).

As mentioned previously, some two-handed tasks are completed faster with a partner (i.e., intermanually) compared to completing the task alone (i.e., bimanually) (e.g., Gorman & Crites, 2013). Researchers investigating the coordination modes have shown that bimanual versus intermanual speed may be dependent on previous bimanual practice (Gorman & Crites, 2015). Additionally, the observed differences in speed may be due to perceptual-motor characteristics when completing a two-handed task using the bimanual coordination mode that may not have as much of an effect regarding intermanual performance (Fine & Amazeen, 2011; Kelso, et al., 1979). The purpose of this dissertation seeks to understand these previously observed differences in speed during two-handed tasks. More specifically, one of the known underlying factors—practice—as well as hypothesized factors that may affect speed during bimanual and intermanual coordination are examined. Before introducing these factors, a brief overview of the three coordination modes is introduced. A more detailed review of the literature can be found in Appendix A (extended literature review section).

Manual Coordination Modes

The three manual coordination modes are described below to establish an understanding regarding the factors that are hypothesized to underlie speed during two-handed tasks. For this dissertation, the focus is on speed as opposed to other performance metrics because previous research observed differences in speed during bimanual and intermanual performance; however, additional explanatory variables will be introduced. Although the bimanual and intermanual coordination modes are of direct importance for this dissertation, an understanding of the research investigating one-handed tasks is included to provide context for the two-handed coordination modes. Therefore, a brief overview of research related the unimanual, bimanual, and intermanual coordination is presented below.

Unimanual. Woodworth (1899) described how a unimanual task consists of an initial, unregulated ballistic phase that is followed by regulatory precision control influenced via eye-hand coordination. That is, the hand quickly moves toward the target and then slows down based on visual and proprioceptive feedback regarding where the hand is located relative to the desired target (Jeannerod, 1984). When reaching for a phone, for example, the hand quickly moves towards the device before slowing down to ensure grasping accuracy. This example demonstrates how the eye is required both before a manual action (e.g., to locate an object) and during the manual action (e.g., external feedback) (Land & Hayhoe, 2001).

Some of the most influential manual coordination research was provided by Fitts (1954), who investigated unimanual pointing and aiming movements. Fitts showed that the time it takes to complete a visually-guided unimanual movement is a function of target size and distance (Fitts, 1954; Fitts & Peterson, 1964). Specifically, the time it takes to reach a target is influenced by its index of difficulty (ID), which is defined by the target size, or width (W), and the distance traveled to the target, or amplitude (A). The ID increases as A increases and/or W decreases; consequently, increases in ID are associated with increases in time to complete the task (Figure 1.2). This finding is important in the context of this dissertation because it shows how task time is influenced by W and A.

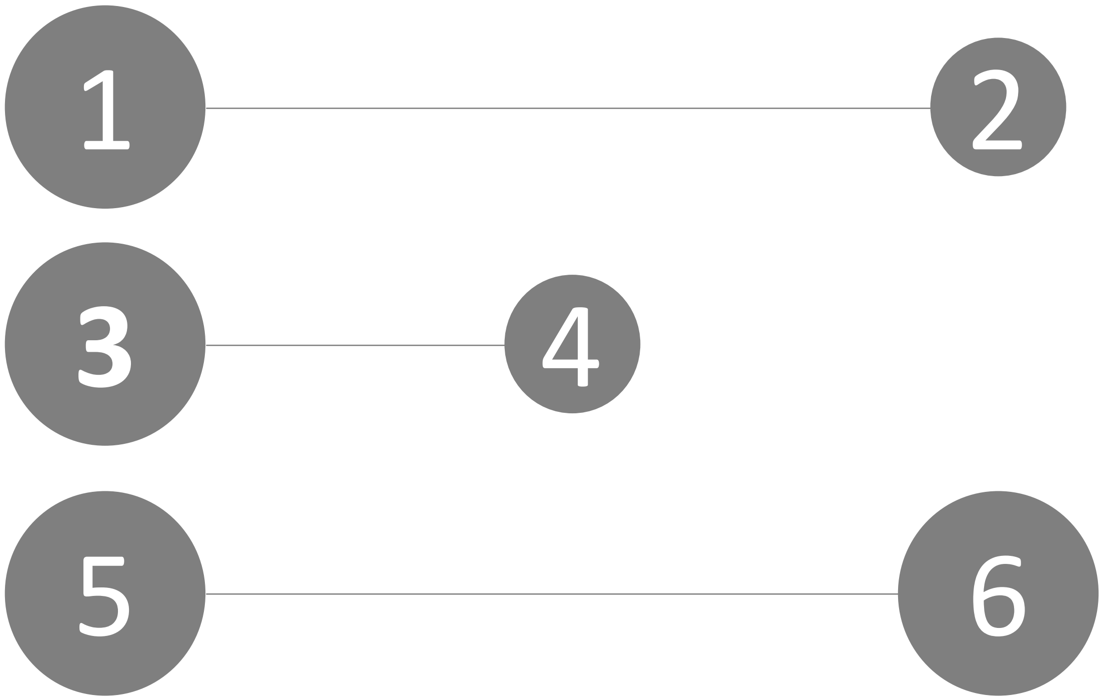

Figure 1.2. An example of Fitts' Law during unimanual pointing. Moving from circles 1 → 2 will take longer than moving from circles 3 → 4 and circles 5 → 6. The differences in time are because moving from circles 1 → 2 has a larger ID than the other two sets of circles. The larger ID is due to a longer target distance (compared to circles 3 → 4) and a smaller target size (compared to circles 5 → 6).

This research showed that smaller targets require more precise movements and take more time to complete. Additionally, this research suggests that it will take more time when completing sequential, precise manual movements with multiple subtasks compared to manual movements with larger target sizes. For example, overall task time would be shorter (faster) if all the circles in Figure 1.2 were larger and overall task time would be increased (slower) if all the circles were smaller.

Furthermore, research shows that immediately before starting a manual action (e.g., reaching for an object), a guiding fixation first locates the object to guide initial manual movement (Mennie, Hayhoe, & Sullivan, 2006). After the manual action has been initiated (i.e., the hand starts to move), the eye stays focused on the object until the hand arrives (or is close to arriving) (Rand & Stelmach, 2010). In this context, the gaze is used to stabilize movement during manual tasks and is referred to as gaze anchoring (Rand, 2014).

Taken together, a typical visually-guided unimanual task has two components: (1) a guiding fixation towards the to-be manipulated object and (2) a gaze ‘anchored’ on the object until the hand arrives at the object (Mennie et al., 2006; Rand, 2014). The time it takes to complete the task is affected by target size and distance. If the target size is extremely large and/or target distance is extremely short, then the initial guiding fixation and subsequent gaze anchoring do not play as much of a role when compared to the opposite situations (Rand & Stelmach, 2010). Thus, unimanual tasks can be said to be made up of the following eye-handed coordination components: guiding fixations and gaze anchoring, which are affected by target size and distance.

Bimanual. The bimanual coordination mode has the most extensive research when compared to the other two coordination modes (Kelso, 1995). Using the bimanual coordination mode has both costs and benefits. For example, handwriting is easier when using your other hand as a frame of reference (Guiard, 1987); typing with a standard keyboard is easier using two fingers from separate hands than using two fingers from the same hand (e.g., typing b-y is faster than m-y; Rosenbaum, Kenny, & Derr, 1983); and tying one’s shoelaces using both hands is easier compared to using only one hand. Interestingly, the examples described above show that one hand is able to move relatively independent from the other and that each task has been previously practiced (e.g., handwriting). In contrast, bimanual coordination has disadvantages under certain conditions when both hands are forced to move simultaneously during task performance (at least early on during motor skill acquisition; Gorman & Crites, 2015). Specifically, temporal and spatial coupling constraints, such as relative phase, amplitude, and direction have been shown to influence bimanual coordination, such that task bimanual performance is negatively influenced compared to completing the same task unimanually (Kelso et al., 1979; Shea, Buchanan, & Kennedy, 2016; Swinnen & Wenderoth, 2004; Xia, Irani, & Wang, 2007).

Finger oscillation tasks illustrates the temporal and spatial *coupling* constraints inherent in bimanual coordination. In general, coupling is defined as two or more processes having some form of interaction with each other (Gorman, Dunbar, Grimm, & Gipson, 2017). For example, when oscillating the index fingers of both hands back and forth, humans have a tendency to move either in-phase or anti-phase (Figure 1.3). The in-phase and anti-phase preference is said to be more perceptual-spatial in nature than biomechanical and is temporally influenced, such that movement frequency influences phase (Mechsner et al., 2001). For example, simultaneous finger oscillations following an anti-phase pattern naturally transition to the in-phase pattern when the oscillation frequency is increased, which demonstrates the body's natural tendency for the two hands to synchronize in space and time. This phenomenon and its negative impact on two-handed performance are described in more detail below, under Between-Hand Coupling.

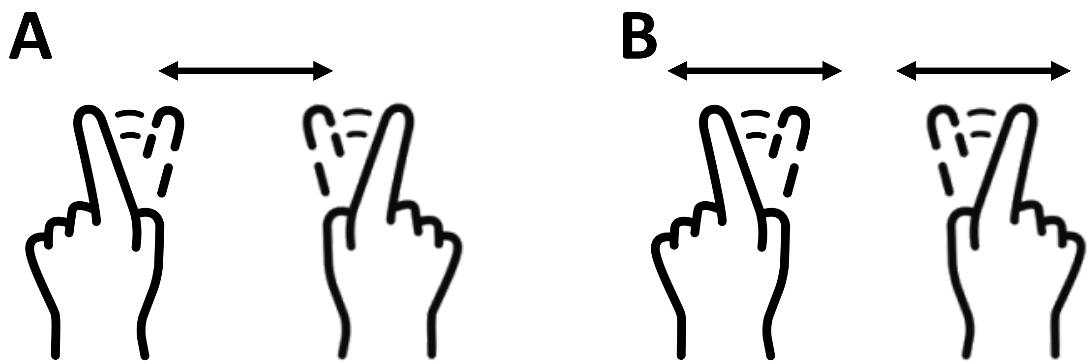

Figure 1.3. (A) In-phase movement; the fingers move towards and away from each other in unison. (B) Anti-phase movement; the fingers move to the right and left in unison.

As with unimanual coordination, bimanual coordination requires a similar eye-hand sequential process when completing visually-guided tasks, including, but not limited to, guiding fixations and gaze anchoring, which are affected by target size and distance. When completing a bimanual task that requires simultaneous movement, however, the eyes and hands must now time-share across both unimanual portions of the task. Specifically, the eyes and hands are only physically able to complete one visually-guided subtask at the same time under most task conditions. This sequential process and time-sharing requires individuals to split up bimanual coordination tasks that require simultaneous movement and has been shown to slow performance (Neggers & Bekkering, 2000, 2002; Rand & Stelmach, 2010). Furthermore, in addition to temporal coupling when completing a task bimanually, the movement of one hand affects the other hand in space (Chan & Chan, 1995). For example, even when the hand attempts to move without visual guidance, the concomitant movement of the other hand has been shown to influence the movement of the other hand in terms of speed and variability (Franz, 1997).

Intermanual. The intermanual coordination mode has very little research relative to the other coordination modes; however, early work showed initial interest investigating basic manual control tasks using the intermanual coordination mode (e.g., pursuit-rotor tasks; Wegner & Zeaman, 1956) with a more recent surge regarding more applied domains (e.g., laparoscopy; Bao, He, & Zeng, 2018). Some authors studying bimanual versus intermanual coordination have only required participants to complete the task using their dominant hand. For example, during Zheng and colleagues' (2005) laparoscopic cutting task, participants were asked to manipulate laparoscopic grasper and scissors using both hands in the bimanual condition and their dominant hand in the intermanual condition. In this regard, participants simultaneously completed two unimanual tasks with their preferred or dominant hand during intermanual performance. However, for this dissertation, intermanual coordination consists of two people simultaneously completing two-handed tasks, where one participant uses their right hand and the other participant uses their left hand. In this case, the intermanual coordination mode is effectively splitting the roles of the bimanual coordination task across the body to be completed unimanually. Studying intermanual coordination with this paradigm allows for a direct comparison of coordination modes without the need for hand dominance inconsistencies across the body (Goodale, Meenan, & Bulthoff, 1994; Gonzales, Ganel, & Goodale, 2006).

For this dissertation, it is proposed that intermanual coordination follows a sequential eye-hand coordination process similar to unimanual and bimanual coordination (i.e., guiding fixations and gaze anchoring, which are influenced by target size and distance). However, unlike the bimanual coordination mode, which may force individuals to timeshare tasks across the hands, the intermanual coordination mode can utilize each participants' visuomotor system when completing the two-handed task. Thus, each unimanual subtask required during the two-handed task can be completed relatively in isolation aside from having to interact with a partner. For example, each person is still able to complete their guiding fixation and establish gaze anchoring for various target sizes and distances, but they are not forced to divide the task across each hand as much as they would when completing the task using the bimanual coordination mode. Thus, regarding speed during two-handed task, completing each unimanual subtask simultaneously during intermanual performance may increase overall task performance (as opposed to sequentially during bimanual performance).

Mode Effects

Differences in performance among coordination modes are referred to as “mode effects.” A mode effect is defined when any coordination mode (e.g., intermanual) outperforms another coordination mode (e.g., bimanual) when completing the same task (e.g., teleoperation) while using the same measure (e.g., speed) for comparison (Gorman & Crites, 2013). Most of the research investigating mode effects has involved a direct comparison of the bimanual and intermanual coordination modes. One finding has consistently been observed: The Intermanual Speed Advantage (Glynn & Henning, 2000; Gorman & Crites, 2013; Reed et al., 2006; Van Oosterhout et al., 2017; Wegner & Zeaman, 1956; Zheng et al., 2005). The intermanual speed advantage is the term used when a two-handed task is performed faster when using the intermanual coordination mode compared to the bimanual coordination mode (i.e., an intermanual mode effect of speed). Interestingly, the so-called intermanual speed advantage is not present when the task has been previously practiced using the bimanual coordination mode (e.g., bimanual versus intermanual shoe-tying; Gorman & Crites, 2015). In this instance, participants, unsurprisingly, completed the task faster using the familiar, bimanual coordination mode (i.e., a bimanual mode effect of speed), which will be described in more detail when discussing The Effect of Practice and Between-Hand Coupling.

Speed During Two-Handed Tasks

Comparing the coordination modes has provided a greater understanding of what underlies speed during two-handed tasks, regardless of coordination mode. Regarding the development of manual coordination, Fitts (1964) argued that performers go through various stages during skill acquisition, such as the Cognitive, Associative, and Autonomous Stages (Fitts, 1964). At the start of manual skill development, the Cognitive stage characterizes error-ridden and inefficient task performance with rapid performance gains. On the other end of the spectrum, the Autonomous stage is characterized with automatic performance with very few errors (Davids, Button, & Bennett, 2008). With this viewpoint, completing a novel two-handed task using the bimanual coordination mode may require perceptual feedback on each individual movement of each hand when compared to someone who is has plenty of practice (e.g., novice piano playing; Furuya & Kinoshita, 2008). In this way, isolating the movement of each limb during a two-handed task may slow performance. However, if the task is divided across two people, where each person can focus on their individual part of the task (i.e., the unimanual subtasks that make up the entire intermanual task), then they may be able to circumvent negative characteristics associated with the Cognitive stage of motor skill acquisition. This viewpoint can be illustrated when learning a new skill. When learning to play the guitar, for example, someone may isolate the movement of each limb, hand, or finger. The performer may focus attention on the chord and not strum the strings correctly or vice versa. However, if two people learning to play a two-handed instrument only focused on one of those tasks, then they may be able to perform better completing the task intermanually compared to bimanually.

Researchers that observed the intermanual speed advantage asked participants to complete specific types of two-handed tasks with three overlapping characteristics (Glynn & Henning, 2000; Gorman & Crites, 2013; Reed et al., 2006; Wegner & Zeaman, 1956; Zheng et al., 2005). First, the tasks had at least one movement that required asymmetric movement of the limbs when completed simultaneously (Van Oosterhout et al., 2017). For example, Glynn and Henning (2000) asked participants to simultaneously move joysticks in opposite directions during certain subtasks while navigating a teleoperated maze. Secondly, the tasks required an interactive component across the limbs (Van Oosterhout et al., 2017). For example, Reed and colleagues (2006) asked participants to physically coordinate with each other during a visually-guided task, where the movement of one person effected the movement of the other. Third, the tasks were comprised of multiple subtasks where each subtask helped (as opposed to hurt) the overall goal (referred to as agonistic; Jarrassé, Charalambous, & Burdet, 2012). For example, Wegner and Zeaman (1956) asked participants to complete a pursuit rotor task in where participants worked together to maintain a metal stylus on a path embedded in a rotating turntable. Taken together, the common three task demands outline the type of tasks used when the intermanual speed advantage has been observed (Jarrassé et al., 2012; Van Oosterhout et al., 2017).

What underlies these speed differences during two-handed tasks? Zheng and colleagues (2005) suggested that participants developed a “shared mental model” (SMM;

Cannon-Bowers, Salas, and Converse, 1993), which allowed them to anticipate each other's task-related needs during intermanual performance that circumvented bimanual limitations. Zheng and colleagues (2005) asked participants to complete a laparoscopic cutting task using either the bimanual or intermanual coordination mode. Using a laparoscopic grasper and laparoscopic scissors, Zheng and colleagues' (2005) cutting task required participants to move each laparoscopic tool from a starting area, cut a piece of thread, and then return the tools to their original positions. During this task, the participant controlling the grasper tool was asked to grasp the thread and move it to the cutting area where the participant controlling the scissors tool was supposed to cut the thread. Importantly, both laparoscopic tools started at locations separate from the cutting area. Thus, both the grasper tool and scissors tool had to be relocated to the cutting area to complete the task.

In the context of their laparoscopic cutting task, Zheng and colleagues (2005) suggested that participants who completed the cutting task using the intermanual coordination mode were able to make more two-handed anticipatory movements than participants who completed the task using the bimanual coordination mode. For example, when using the intermanual coordination mode, one participant was able to focus on grasping and moving the thread to the cutting location while the other participant was able to focus on moving the scissors to the cutting location (Zheng et al., 2005). In the bimanual case, a single participant needed to complete each portion of the task sequentially. For example, the participant may have waited to grasp and move the thread over to the cutting area, and then move the scissors to the cutting area to cut the thread.

Zheng and colleagues (2005) suspected that the difference in time could be accounted for by more simultaneous, anticipatory movements made during the intermanual condition.

Zheng and colleagues (2007) explored this hypothesis by reanalyzing video data from their (2005) experiment. Results showed that more anticipatory movements were observed when participants completed the laparoscopic cutting task using the intermanual coordination mode compared to the bimanual coordination mode. Particularly, the hand controlling the laparoscopic cutting tool (i.e., scissors) would move to the cutting location while the hand controlling the laparoscopic grasping tool (i.e., grasper) was moving the thread to the cutting area. Zheng and colleagues (2007) suggested that due to eye-hand coordination task constraints during bimanual coordination, such as visually attending to one hand at a time, bimanual participants completed the task more sequentially with less anticipatory movements. It was concluded that completing the two-handed task using the intermanual coordination mode allowed participants to circumvent constraints inherent to the bimanual coordination mode in the form of simultaneous anticipatory movements that were facilitated by a SMM (Zheng et al., 2007). Additional information related to the Zheng and colleagues' experiments is provided in the Extended Literature Review section.

Gorman and Crites (2013) agreed that the intermanual mode effect was likely due to anticipatory movements. However, due to using novice participants, combined with the novelty and simplicity of their two-handed tasks (like the Zheng et al., 2005 cutting task), the explanation of the development of shared task knowledge or a SMM may not be the primary source of anticipatory movements. Specifically, we argued that the requirements for successful performance of simple, unpracticed intermanual tasks may be based more on organizing bottom-up, perceptual–motor interactions and timing behaviors rather than top-down, knowledge-driven processes (Bingham et al., 2008; Kelso et al., 1979). For example, participants' movement during bimanual performance may have been slowed due to inherent characteristics of bimanual coordination. When completing the task intermanually, participants were not slowed by such characteristics and were able to move freely as a function of the real-time information that was coming in, rather than on a stored representation within their body.

Regardless of the competing explanations proposed by Zheng and colleagues (2007) and by Gorman and Crites (2013), it was suggested that anticipatory movements facilitate speed during two-handed tasks, regardless of coordination mode, and that the intermanual coordination mode seemed to produce more anticipatory movements. One aim of this dissertation is to specifically understand some of the factors that underlie these simultaneous anticipatory movements, which are hypothesized to facilitate speed during two-handed coordination tasks. When compared to intermanual coordination, there are certain aspects of bimanual coordination that may restrict the ability to make anticipatory movements.

Limitations of bimanual coordination. For this dissertation, it is suggested that there are at least two behavior-based limitations that offers a simpler explanation (as opposed to using a SMM) for the intermanual speed advantage: bimanual coupling and bimanual visuomotor coupling.

Bimanual coupling. Bimanual coupling is best described with a simple example of moving the hands unimanually versus bimanually. Unimanually, it is easy to move the left hand vertically or the right hand horizontally and performance is not affected, as long as both tasks are not completed simultaneously. However, if one hand moves vertically while the other hand moves horizontally (i.e., a simultaneous, bimanual task), then the task becomes slower and more variable (Franz, 1997). The movement of one hand affecting the movement of the other is an example of between-hand coupling. Research shows that at least two things typically happen as a result of between-hand coupling during bimanual coordination (i.e., bimanual coupling). One, the movement of one hand affects the movements of the other while both hands simultaneously complete the task (Kelso et al., 1979). In this situation, the task still proceeds with simultaneous movement of each hand; however, the hand that requires more movement time (due to a larger ID) slows the movement of the other hand. Second, the actor chooses to isolate each limb by completing each bimanual subtask unimanually, which will slow down overall task performance compared to completing the task simultaneously (Bingham et al., 2008; Neggers & Bekkering, 2002). Figure 1.4 describes three examples of bimanual coupling.

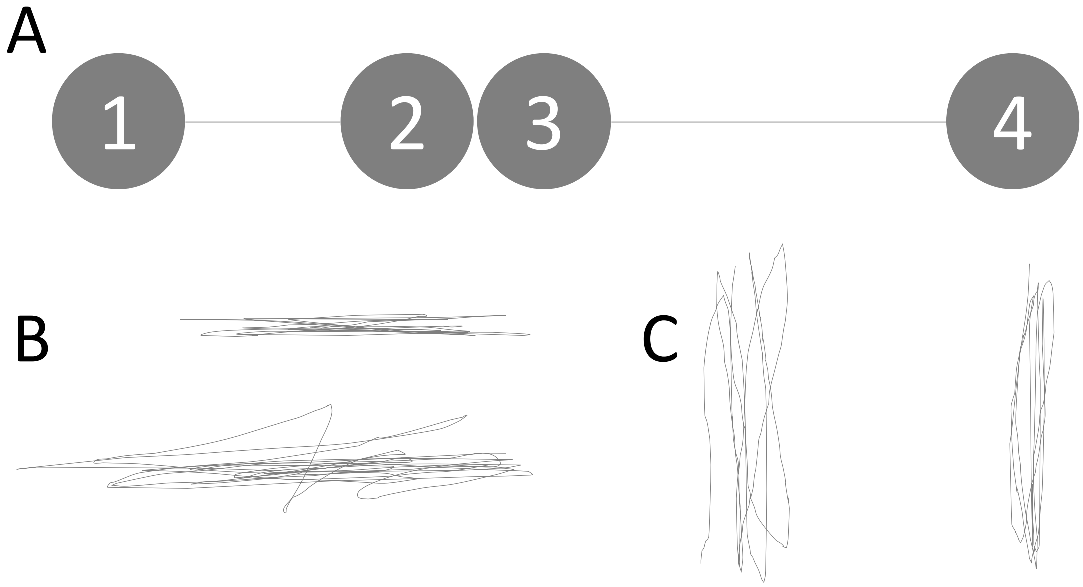

Figure1. 4. Examples of bimanual coupling. (A) Unimanually moving from circle 1 → 2 with the left index finger may take one second to complete and unimanually moving from circle 4 → 3 with the right index finger may take two seconds to complete; however, research shows that completing each unimanual task bimanually (simultaneously) results in similar movement times, such that speed during the shorter unimanual movement time (1 → 2) is reduced (e.g., both fingers complete the task in two seconds; Kelso et al., 1979). (B) Unimanual horizontal mouse movement of the right hand (top) contrasted with bimanual horizontal mouse movement of the right hand with simultaneous vertical movement with the left hand (bottom). (C) Unimanual vertical mouse movement of the right hand (right) contrasted with bimanual vertical mouse movement of the right hand with simultaneous horizontal movement with the left hand (left) (Franz, 1997).

A formal definition outlining the theoretical mechanisms underlying bimanual coupling has yet to be presented. However, Kelso and colleagues (1979), using a series of experiments and building off previous theoretical accounts (e.g., Bernstein, 1967), have suggested that bimanual coupling is due in part to simplifying a motor system that is faced with controlling multiple degrees of freedom (DOF). When completing a two-handed task, the motor system solves the DOF problem by constraining the limbs to act as a single unit. Importantly, Kelso and colleagues (1979) go on to say how the performer is able to overcome the multiple DOF constraint with practice, which can be demonstrated by observing one of the numerous motor tasks that require independent movement of the limbs. Furthermore, because a single motor command, rather than different motor commands, are issued for each hand of the movement, the bimanual coupling phenomenon is thought to have a physiological basis (Turvey, Fitch, & Tuller, 1982).

Bimanual visuomotor coupling. Similar to bimanual coupling, bimanual visuomotor coupling is best described using a simple example of moving the hands unimanually versus bimanually. Unimanually, it is simple to use the left index finger to strike the “J” key or use the right index finger to strike the “F” key on an unfamiliar keyboard. However, if both tasks are completed simultaneously (i.e., bimanually), then research shows that one visually-guided action (e.g., left index finger striking the “J” key) must be completed before the other visually-guided action (e.g., right index finger striking the “F” key) can be completed (Neggers & Bekkering, 2002). The sequential steps required during one subtask of the visually-guided task (e.g., the eyes locate the “J” key, the left index finger moves toward the “J” key, and the left index finger arrives at the key and then presses it) delaying or slowing the other subtask is an example of visuomotor coupling during bimanual coordination (i.e., bimanual visuomotor coupling). Research shows that at least two things happen as a result of visuomotor coupling, regardless of coordination mode. First, a guiding fixation first locates the object for manual interaction (Mennie et al., 2006). Second, the eyes stay anchored on the object until manual interaction is completed (Rand, 2014). When completing a unimanual task, these two sequential steps of eye-hand coordination are viewed as necessities and do not seem to negatively affect performance. However, when completing a bimanual task that requires simultaneous, visually-guided movement with multiple subtasks, the sequential subtasks negatively affect performance Bingham et al., 2008). The negative performance seems to be largely due to the movement of one hand delaying the movement of the other hand during bimanual coordination, which may be due to guiding fixations and gaze anchoring (Mennie et al., 2006). Specifically, one visually-guided task must be completed before starting the next visually-guided task. (See Figure 1.5 for examples of bimanual visuomotor coupling.)

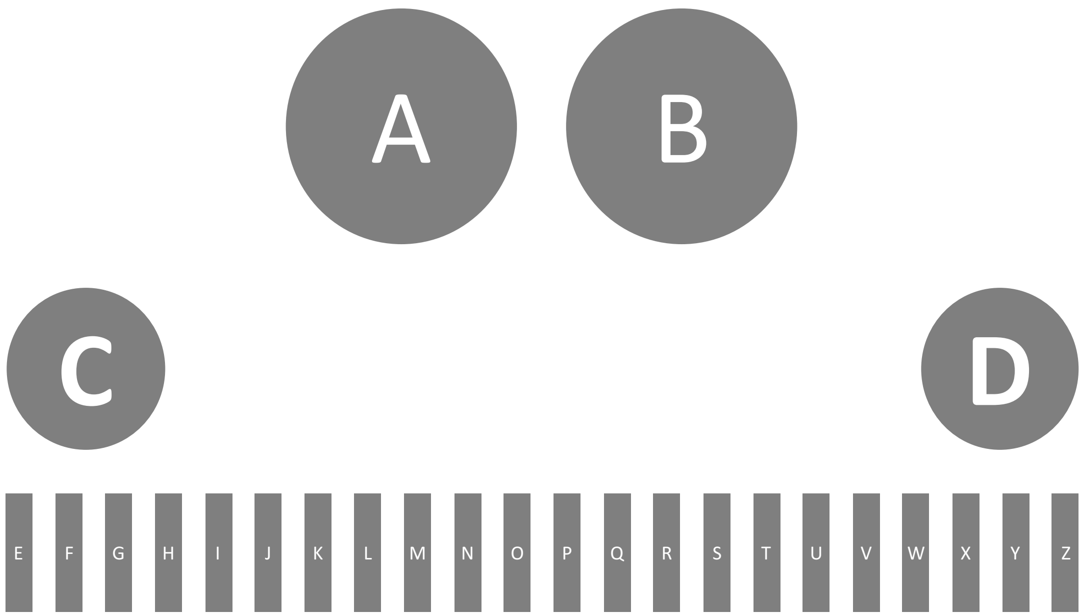

Figure 1.5. An example illustrating the varying degrees of bimanual visuomotor coupling relative to target distance and target size. The more a manual task requires precision, the more bimanual visuomotor coupling will slow performance. Simultaneously pressing circles A and B with the left and right index fingers may be possible. However, simultaneously pressing circles C and D due to their smaller size and distance may cause one subtask to be completed (e.g., pressing circle C with the left index finger) before the other task can be started or completed (e.g., pressing circle D with the right index finger). Furthermore, simultaneously pressing keys G and T may not be possible due to their smaller sizes, distances, and spatial resolution; however, these effects may be reduced, to a degree, with practice (Intriligator & Cavanagh, 2001).

Interestingly, the negative consequences of bimanual visuomotor coupling only seem obvious when comparing bimanual and intermanual coordination. For example, when completing the exercises in Figure 1.5 intermanually, the movement times of the left or right index fingers should arrive at the targets at approximately the same time. However, when completing the task using the bimanual coordination mode, it is easy to see how guiding fixations and gaze anchoring delay overall performance time. Lastly, it is important to note that visuomotor coupling occurs during unimanual, bimanual, and intermanual coordination. However, bimanual performance seems to be most affected during two-handed tasks that require simultaneous movement of the limbs, especially if the task requires a discrete number of subtasks for both hands.

The Effect of Practice and Between-Hand Coupling

When investigating speed during two-handed tasks, it is important to keep in mind that people typically complete two-handed tasks bimanually and one may assume that the typical, bimanual coordination mode would outperform the previously unpracticed intermanual coordination mode. However, as described above, intermanual has outperformed bimanual in a variety of tasks (e.g., Zheng et al., 2005). Additionally, the majority of research that investigated bimanual versus intermanual coordination used novice participants completing a previously unpracticed task. Taken together, these points suggest that the intermanual speed advantage may be dependent on previous practice using the familiar, bimanual coordination mode. Therefore, the effect of previous bimanual practice may be an underlying factor that affects speed during two-handed tasks, especially in the context of applying these findings to skilled tasks (e.g., laparoscopy; Zheng et al., 2005). Gorman and Crites (2015) investigated this hypothesis by utilizing a previously practiced bimanual task, shoe-tying.

As mentioned above, Gorman and Crites (2015) found that bimanual shoe-tying was faster than intermanual shoe-tying. Identifying the reason for this reversed mode effect is of particular interest. Because behavior is an inherently dynamic process, it is important to implement analyses that show how it evolves over time. Thus, in addition to the standard summary metrics investigating performance (e.g., speed), Gorman and Crites (2015) also measured between-hand coupling during bimanual and intermanual task performance to examine if speed differences were qualified by dynamic patterns unique to each coordination mode. Between-hand coupling was measured using an approach called Cross Recurrence Quantification Analysis (CRQA) (Riley & Van Orden, 2005).

CRQA is a method for assessing nonlinear coupling between any two dynamical systems (Shockley, Butwill, Zbilut & Webber, 2002). CRQA starts by constructing a Cross Recurrence Plot (CRP). A CRP is a graphical representation of the times at which two dynamical systems (e.g., let *X* and *Y* be two dynamical systems) are in the same state by plotting a dot whenever those systems inhabit the same location of a shared dynamical space (Riley & Van Orden, 2005). The state of any dynamical system can be described using one or more parameters, for example, velocity and position. Plotting velocity and position of a dynamical system can be used to describe the system within dynamical space. Any single observation within this dynamical space is referred to the system state.

To create a CRP, time series generated by each system (e.g., let *x* and *y* be time series generated by *X* and *Y*) are first plotted in a shared dynamical space, and a dot is plotted in the CRP for all pair-wise combinations of points in the shared space that are sufficiently close within a threshold (i.e., a radius). The plotted points are called recurrent points, and the amount and relative spacing of recurrent points in the CRP allows for assessment of coupling between two dynamical systems by calculating measures from the recurrent points. The measure of coupling, %REC, is the number of recurrent points divided by the possible number of recurrent points in a CRP and is used to quantify the degree to which two systems are coupled (Shockley et al., 2002).

For illustrative purposes, Figure 1.6 provides example CRPs constructed from coupled vs. uncoupled *x* and *y* time series generated by mouse movements in the *X*-*Y* plane. Figure 1.6A shows the CRP of coupled mouse movements along the *X* and *Y* dimensions during circle drawing that resulted in %REC = 7%. Figure 1.6B shows the CRP of uncoupled mouse movements along the *X* and *Y* dimensions during random drawing that resulted in %REC = 0.1%, which indicates a weaker coupling. The computation of the CRQA measures are described in more detail below but note here that, as demonstrated in Figure 1.6, the CRP will be generally more filled in, and the values of dynamic coupling indicates generally greater for coupled time series.

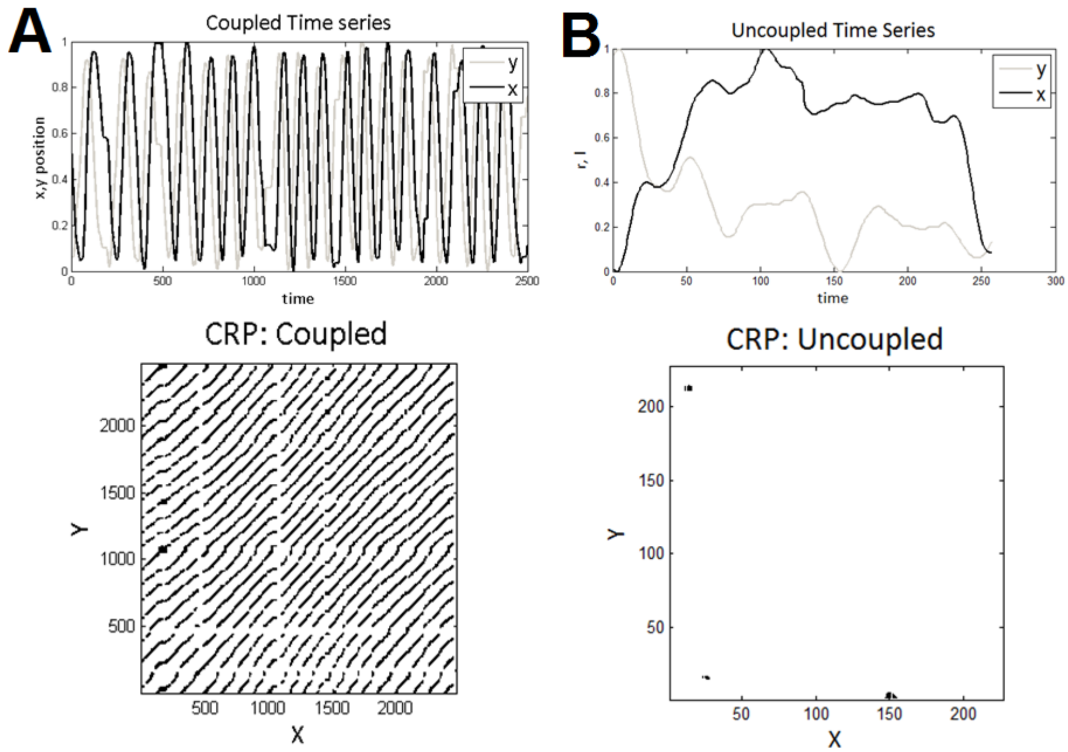

Figure 1.6. Example time series and cross-recurrence plots for coupled (A) vs. uncoupled (B) time series: (A) shows *x* (black) and *y* (grey) time series from mouse movements in the *X*-*Y* plane during circle drawing; and (B) shows *x* and *y* time series from mouse movements in the *X*-*Y* plane during random drawing. The recurrent points in the uncoupled CRP are clearly visible (%REC = 7%); however, the recurrent points in the coupled CRP are barely visible (%REC = 0.1%)

Gorman and Crites (2015) analyzed dynamic coupling measures as a function of coordination mode during shoe-tying using CRPs. A CRP was constructed to represent the times at which the two dynamical systems (i.e., hands) were in a shared dynamical space (e.g., let *L* and *R* be two dynamical systems representing the left- and right-hand, respectively). Participants' left and right hands during shoe-tying were plotted on a shared dynamical space to quantify coupling in terms of percent recurrence (%REC). Gorman and Crites (2015) observed more between-hand coupling during shoe-tying performance when participants completed the task using the unpracticed intermanual coordination mode compared to the previously practiced bimanual coordination mode (Figure 1.7).

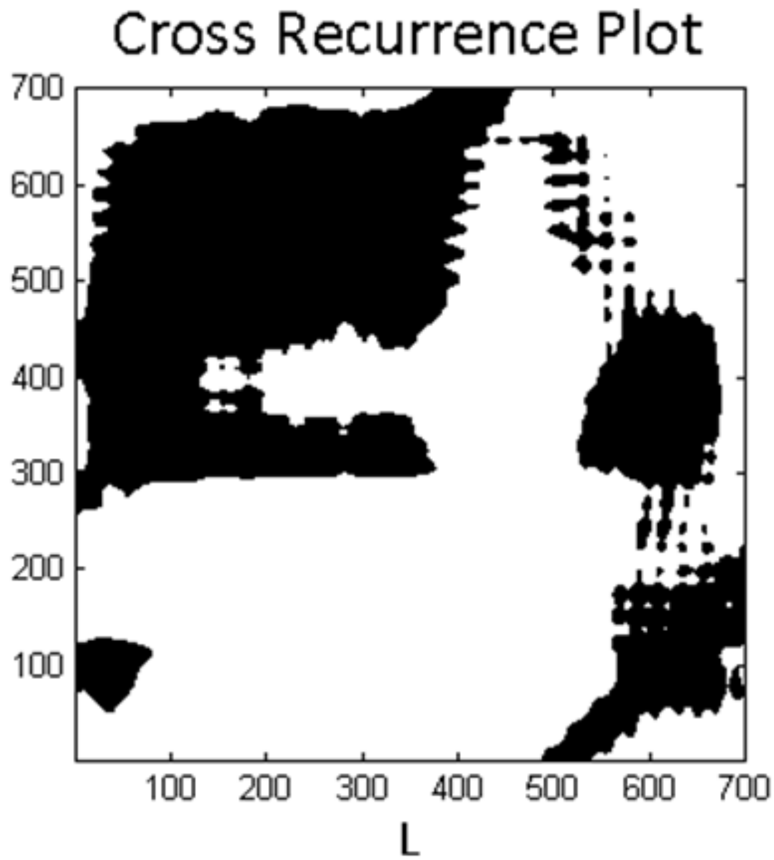

Figure 1.7. Example CRP from Gorman and Crites (2015). The CRP is based on right and left hand mediolateral (x-axis) time series from one intermanual trial. The recurrent pattern in the top-left portion of the cross-recurrence plot corresponded to left-handed followed by right-handed knot formation during intermanual shoe-tying (%REC = 37%).

Thus, contrary to the previously observed intermanual speed advantage using novices (e.g., teleoperation; Gorman & Crites, 2013), Gorman and Crites (2015) found that intermanual shoe-tying was slower than bimanual shoe-tying (i.e., a bimanual speed advantage) and these differences in performance were associated with lower between-hand coupling. Subsequent analyses showed that between-hand coupling was significantly correlated with speed, such that lower measures of between-hand coupling was associated with faster shoe-tying, regardless of coordination mode (i.e., bimanual was faster with less between-hand coupling, and intermanual was slower with more between-hand coupling). Gorman and Crites (2015) argued that independent, decoupling of the hands is what produced faster tying performance. Specifically, the data suggested that participants were able to independently move the limbs during bimanual performance in a similar manner suggested by Zheng and colleagues' (2005) regarding anticipatory movements intermanual performance.

Anticipatory movements. As with the anticipatory movement effect (Zheng et al., 2005, 2007), participants during the Gorman and Crites (2015) study must have learned to move each hand independently of the other when completing the shoe-tying task bimanually. Gorman and Crites (2015) suggested that, because decoupling is important for effective performance during both coordination modes and can be readily observed, it provides a more parsimonious explanation of skill development than the development of shared task knowledge. Additionally, we argued that faster speed during two-handed tasks may be due to the lack of between-hand coupling. Furthermore, the previously observed differences in speed when using the intermanual coordination mode may be attributable to independent movement of the limbs as opposed to shared task knowledge, such that independent movement of the limbs allows for potential anticipatory movements (i.e., people are able to make anticipatory movements because decoupled hands are free to move independently).

Summary of findings. Table 1.1 shows a summary of the literature regarding bimanual versus intermanual findings with respect to speed. The table highlights the differences between whether or not the task has been previously practiced using the bimanual coordination mode. Thus, "Practiced" refers to a task that has been previously practiced using the bimanual coordination mode (i.e., bimanual shoe-tying) and "Unpracticed" refers to tasks that were not previously practiced using either coordination mode. The missing data fields, anticipatory movements during a previously practiced bimanual task and between-hand coupling during an unpracticed task, were observed and measured in this dissertation.

Table 1.1

Known Effects by Measure

		Speed (Time)	Between-Hand Coupling (%REC)	Simultaneous Goal-Directed Movements
Practiced	Bimanual	Faster[1]	Lower[1]	-
	Intermanual	Slower[1]	Higher[1]	-
Unpracticed	Bimanual	Slower[2]	-	Fewer[3]
	Intermanual	Faster[2]	-	More[3]

Note. Simultaneous, goal-directed movements were referred to as anticipatory movements by Zheng and colleagues (2007).
[1](Gorman & Crites, 2015); [2](Glynn & Henning, 2000; Gorman & Crites, 2013; Reed et al., 2006; Van Oosterhout et al., 2017; Wegner & Zeaman, 1956; Zheng et al., 2005); [3](Zheng et al., 2007)

Chapter II

The Current Study

The purpose of this dissertation was to investigate the intermanual speed advantage over bimanual performance (Glynn & Henning, 2000; Gorman & Crites, 2013; Reed et al., 2006; Wegner & Zeaman, 1956; Zheng, Verjee, Lomax, & MacKenzie, 2005) and how previous bimanual practice affects this difference in speed (Gorman & Crites, 2015). Experiment 1 evaluated mode effects when completing an unpracticed simulated cutting task. Experiment 2 used the same task to further evaluate mode effects after participants have undergone a bimanual practice phase. Thus, the goal of Experiment 2 was to determine if the intermanual speed advantage disappears after bimanual practice, such that the hypothesized negative aspects of bimanual coordination are no longer detrimental to performance. During both experiments, the underlying factors hypothesized to be affecting speed during two-handed tasks (e.g., between-hand coupling) were measured.

Hypotheses

The hypotheses for Experiments 1 and 2 will now be offered to explain speed differences during two-handed tasks. Prior to listing the set of hypotheses, a summary for each factor hypothesized to affect speed during two-handed tasks is presented.

Bimanual coupling. Due to bimanual coupling, people are typically unsuccessful when trying to simultaneously move both limbs independently from one another (e.g., bimanual circle drawing, Verschueren, Swinnen, Cordo, & Dounskaia, 1999; bimanual tapping tasks, Kelso, Southard, & Goodman, 1979). In almost every case, either some form of mutual synchronization tendencies is observed. However, research has shown that people can decouple their movements with enough practice (Kelso & Zanone, 2002; Zanone & Kelso, 1992, 1997), similar to what was observed during previously practiced bimanual shoe-tying (Gorman & Crites, 2015). For this dissertation, bimanual coupling is operationally defined as the lack of spatial and temporal independence of the hands during an individual, visually-guided two-handed task. Between-hand coupling using the bimanual coordination mode (bimanual coupling) and intermanual coordination will be measured using %REC, and is described in more detail under Measures.

Bimanual visuomotor coupling. During manual tasks, reaching and grasping is a visually-guided action (Fitts & Peterson, 1964). Visually-guided tasks typically follow a sequential pattern, such that 1) the eye first fixates on an object, the hand starts to move towards the object, 2) the eye stays focused on the object while the hand makes corrective actions in route to the object, and 3) the eye terminates the fixation when the hand arrives at the object (Jeannarod, 1984; Rand, 2014, Woodworth, 1899). Thus, when completing a two-handed task using the bimanual coordination mode, the visually-guided subtask of one hand must first be completed before the other hand is available to guide manual movement (Pelz, Hayhoe, & Loeber, 2001). It is hypothesized that the initial guiding fixation and subsequent gaze anchoring slow performance during simultaneous bimanual tasks (Bingham et al., 2007; Bowman et al. 2009). However, tasks that have been practiced over an extended period do not need to be as visually guided compared to a novel task (Franz, 1997). Thus, the negative aspects associated with visuomotor coupling during bimanual coordination may be overcome with practice, to a degree. For this dissertation, bimanual visuomotor coupling is operationally defined as the sequential dependence of a visually-guided action during an individual two-handed task.

Visuomotor coupling using the bimanual coordination mode (bimanual visuomotor coupling) and intermanual coordination will be measured by analyzing guiding fixations (referred to as Pre-Reach Look-Ahead) and gaze anchoring (the terms and measurements are described in more detail, under Measures).

Simultaneous, goal-directed movements. Zheng and colleagues (2005) hypothesized that anticipatory movements were one of the underlying factors that facilitate the intermanual speed advantage. Subsequent analyses showed that more of these anticipatory movements were observed when participants completed their laparoscopic cutting task using the intermanual coordination mode compared to the bimanual coordination mode (Zheng et al., 2007). Zheng and colleagues (2007) posited that fewer bimanual movements were due to lack of simultaneous, independent movement of the limbs during their laparoscopic cutting task. Specifically, it was proposed that participants using the bimanual coordination mode were unable to complete as many anticipatory movements due to a lack of independence across the limbs and participants using the intermanual coordination mode were able to complete more anticipatory movements due to the development of a SMM (Zheng, et al., 2007).

The anticipatory movements observed during intermanual performance may only be possible when the limbs are able to move independently or when bimanual performance has reached the “level of independent hand function to achieve operational efficiency” (p. 938, Zheng et al., 2007). Therefore, more anticipatory movements should be observed when using the intermanual coordination mode for an unpracticed task or during the bimanual coordination mode for a previously practiced bimanual task (i.e., allowing for independent, decoupled movement of the limbs (Gorman & Crites, 2015;

Zanone & Kelso, 1992, 1997). In this regard, lower between-hand coupling and lower visuomotor coupling are hypothesized to be a prerequisite for more anticipatory movements. For this dissertation, the term "simultaneous goal-directed movements" (SGDMs) will be used instead of anticipatory movements, and will be operationally defined as the initiation and follow through of a goal-directed movement of one hand while the other hand is simultaneously completing another portion of the task (the rationale for using a different term and measurement description is described in more detail, under Measures). In short, SGDMs were used to evaluate subtasks that may not seem directly anticipatory, but contribute to overall task performance at a larger timescale.

Summary of hypotheses. For a previously *un*practiced bimanual task, it is hypothesized that bimanual coupling and bimanual visuomotor coupling negatively impact performance when completing a two-handed task using the bimanual coordination mode compared to the intermanual coordination mode. Additionally, bimanual coupling and bimanual visuomotor coupling restrict the movement of the limbs, which is hypothesized to limit SGDMs, regardless of coordination mode. Furthermore, these between-hand coupling and visuomotor coupling do not play as much of a role when completing the task using the intermanual coordination mode. For a previously *practiced* bimanual task, it is hypothesized that previous bimanual practice allows participants to overcome bimanual coupling and, to a degree, overcome the effect of bimanual visuomotor coupling. Due to the lessened degree of bimanual coupling and bimanual visuomotor coupling, the independent movement of the limbs should facilitate more SGDMs when using the bimanual coordination mode.

Theoretically, the intermanual speed advantage (as compared to bimanual performance) may be due to the limiting effects of bimanual coupling and bimanual visuomotor coupling, which limits the ability to make SGDMs. The main hypothesis is that these effects, which are assumed to be present for unpracticed tasks performed using the bimanual coordination mode, are not present (or play a smaller role) when performed using the intermanual coordination mode. Furthermore, these effects disappear when the task has been previously practiced using the bimanual coordination mode. Based on the information described above, the following sets of hypotheses are offered.

Hypothesis one (H1). Bimanual coordination during an unpracticed task is limited by coupled, dependent movement of the limbs (e.g., bimanual coupling) and visually attending to one hand at a time (e.g., bimanual visuomotor coupling). Additionally, the dependent movement of the limbs and visually attending to one hand at a time will limit the ability to make SGDMs.

Hypothesis two (H2). Intermanual coordination during an unpracticed task is facilitated by decoupled, independent movement of the limbs (i.e., lower between-hand coupling) and visually attending to two visually-guided actions at a time (i.e., lower visuomotor coupling). Additionally, this ability for both independent movement of the limbs and visually attending to two hands at a time will also permit the ability to make more SGDMs.

Hypothesis three (H3). Bimanual coordination during a previously practiced bimanual task is facilitated by decoupled, independent movement of the limbs (i.e., overcoming bimanual coupling). However, visual coordination will still be limited by visually attending to one hand at a time (i.e., bimanual visuomotor coupling), but the degree in which it will affect performance should be reduced relative to an unpracticed task. Additionally, this ability for independent movement of the limbs will permit the ability to make more SGDMs.

Hypothesis four (H4). Intermanual coordination during a previously practiced bimanual task is facilitated by the same aspects as intermanual coordination during an unpracticed task. Specifically, intermanual coordination during a previously practiced bimanual task is facilitated by decoupled, independent movement of the limbs (i.e., lower between-hand coupling) and visually attending to two hands at a time (i.e., lower visuomotor coupling). Additionally, this ability for both independent movement of the limbs and visually attending to two hands at a time will continue to permit the ability to make more SGDMs.

The hypotheses are summarized in Table 2.1. These hypotheses will be evaluated by measurement and manipulations, and will be described in more detail in the following sections.

Table 2.1

Hypotheses Described by the Factors Limiting and Facilitating Bimanual and Intermanual Coordination

	Unpracticed			Practiced		
Hypotheses	Coupling	Visuomotor Coupling	Simultaneous Goal-Directed Movements	Coupling	Visuomotor Coupling	Simultaneous Goal-Directed Movements
H1: Bimanual is limited by	Limited	Limited	Limited	-	-	-
H2: Intermanual is facilitated by	Facilitated	Facilitated	Facilitated	-	-	-
H3: Bimanual is facilitated by	-	-	-	Facilitated	Limited[1]	Facilitated
H4: Intermanual is facilitated by	-	-	-	Facilitated	Facilitated	Facilitated

Note. It is hypothesized that these factors, limiting or facilitating, affect bimanual and intermanual coordination in terms of speed. [1]This effect is hypothesized to still be present, but with a lower degree due to previous bimanual practice compared to an unpracticed task.

The Simulated Cutting Task

To investigate speed differences during bimanual and intermanual coordination, a task was constructed to exploit two hypothesized bimanual limitations that theoretically underlie mode effects during a previously unpracticed task. To exploit these hypothesized limitations, the task needed to include visually-guided simultaneous, asymmetric movement of the limbs. Additionally, in order to follow similar patterns of two-handed tasks that observed the intermanual speed advantage, the task needed to be interactive across the hands (i.e., at least one subtask completed by one hand required interaction with a subtask completed by another hand) and must be agonistic in nature (i.e., completion of subtasks by each hand helps, as opposed to hurts, the overall task goal) (Jarrassé et al., 2012; Van Oosterhout et al., 2017).

Participants were asked to complete a two-handed simulated cutting task using the bimanual and intermanual coordination mode. During this simulated cutting task, participants were asked to pretend that their left hand was a grasper and their right hand was a pair of scissors. Fingers were selected in place of tools to avoid the additional cognitive demand that occurs during compatible and incompatible tool transformations (Massen & Sattler, 2010). Additionally, using only the hands provided a direct evaluation of the manual coordination modes without the requirement for intermediary equipment. Furthermore, constructing the task in this way allowed for a comparison to previous research (e.g., Zheng et al., 2005) without the actual equipment to show that the result was a property of the motor system and cannot be attributed to the equipment. An overview of the task is shown in Figure 2.1.

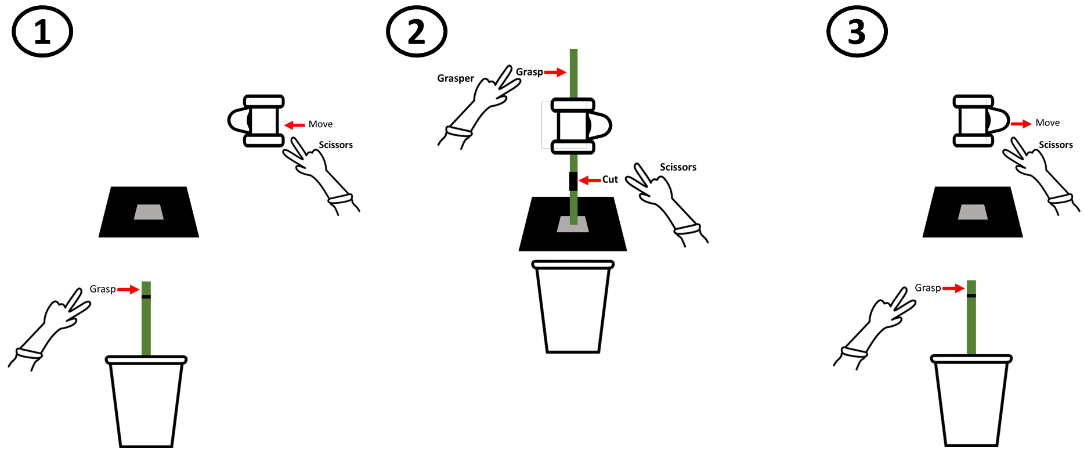

Figure 2.1. Participants were asked to move a pipe to a particular area, place an object through the pipe, and simulate a cutting action at a particular place on the object.

In general, participants were asked to move an object and a pipe to a particular area, place the object through the pipe, rest the object on a particular area on a box, simulate a cutting action at a particular place on the object, and then return the object and pipe to their original positions (Figure 2.1). Table 2.2 shows how the task for each hand consists of six subtasks. It is important to note that the current task could be broken down into further, more specific subtasks at different spatial scales and time scales; however, this level of analysis is appropriate for analyzing the task (Kirwan & Ainsworth, 1992). Additionally, analyzing the task at this level allowed for establishing clear starting and ending points that are characteristic of visually-guided manual tasks with multiple subtasks (Fitts, 1954). Furthermore, this approach followed a similar protocol and analyses of previous eye-hand coordination research investigating two-handed tasks (Land, Mennie, & Rusted, 1999; Land & Hayhoe, 2001; Hayhoe & Ballard, 2005). The subtasks relative to the left hand (grasper) and right hand (scissors) will now be described in more detail. The grasper's subtasks will first be described, followed by the scissors.

Table 2.2

Each Grasper and Scissor Task Needed to Complete the Simulated Cutting Task

Grasper	Scissors
Grasp object	Grasp pipe
Insert object through top of the pipe	Move pipe over to grey area of box
Rest object on grey area of the box	Simulate cutting action
Remove object from the pipe	Return fingers to pipe
Return object back to resting position	Return pipe back to first position
Return fingers to home key	Return fingers to home key

Note. This breakdown applies to both the conditions using the bimanual and intermanual coordination mode.

Grasper subtasks. The grasper portion of the task will now be described in a series of six subtasks. Using only two fingers and starting from the home key, (1) the left hand (grasper) removed their fingers from the home key and grasped the top portion of the object. Next, (2) the grasper removed the object from its resting position and inserted the bottom of the object through the top of the pipe. Next, (3) the grasper rested the bottom tip of the object on the grey area of the box. Next, *after a cut was simulated by the scissors*, (4) the grasper removed the object from the pipe. Next, (5) the grasper returned the object to its original resting position. Finally, (6) the grasper returned their fingers to the home key (Figure 2.2).

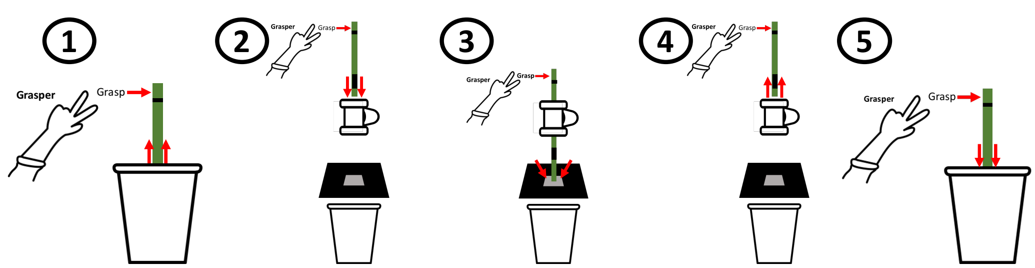

Figure 2.2. Grasper portion of the task shown in five subtasks. The sixth subtask (returning to the home key) is not shown.

Scissors subtasks. The scissor portion of the task will now be described in a series of six subtasks. Using only two fingers and starting from the home key, (1) the right hand (scissors) removed their fingers from the home key and grasped the pipe. Next, (2) the scissors moved the pipe to the area above the grey area of the box. Next, once the bottom tip of the object was resting on the grey area of the box, (3) the scissors simulated a cutting action on the black portion of the object. Next, (4) the scissors returned their fingers to the pipe. Next, *after the object was removed from the pipe*, (5) the right hand (scissors) returned the pipe to its resting position. Finally, (6) the scissors returned their fingers to the home key (Figure 2.3).

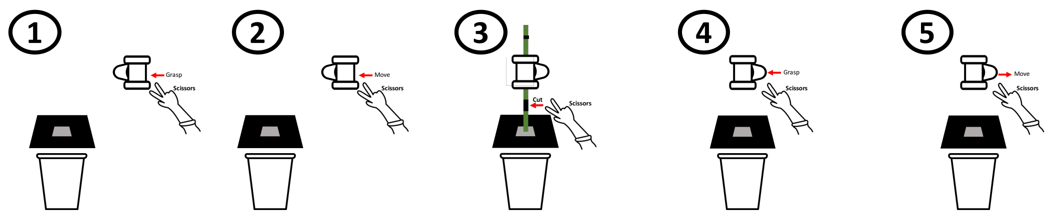

Figure 2.3. Scissor portion of the task shown in five subtasks. The sixth subtask (returning to the home key) is not shown.

Bimanual versus intermanual simulated cutting. When completing the simulated cutting task using the bimanual coordination mode, participants used their left hand and their right hand to complete the grasper and scissors subtasks, respectively. When completing the simulated cutting task using the intermanual coordination mode, two participants completed the task as a dyad, where each used one hand. Specifically, the intermanual coordination mode required one participant to only use their left hand to complete the grasper portion of the task and required the other participant to only use their right hand to complete the scissors portion of the task.

When completing the task using either coordination mode, the simulated cutting task consisted of asymmetric subtasks requiring simultaneous input from each hand, which was designed to exploit bimanual coupling. For example, the first grasper subtask required the left hand to move from the left to the right, and the first scissors subtask required the right hand to move forward. When completed simultaneously, these two asymmetric actions theoretically induced bimanual coupling. Thus, bimanual coupling was either induced or the participant decided to complete each subtask sequentially (unimanually).

When completing the task using either coordination mode, the simulated cutting task required visually-guided manual coordination. Each subtask included a precise visually-guided component, which was designed to exploit bimanual visuomotor coupling. For example, the grasper was required to grasp a specific portion at the top object that measures 2.5 cm high and 0.7 cm wide, and the scissors were required to simulate a cutting action at a specific portion on the object that measures 2 cm high and 0.7 cm wide. Due to bimanual visuomotor coupling, one visually-guided subtask was theoretically needed to be completed with one hand before the next visually-guided subtask could be completed with the other hand.

When completing the task using the intermanual coordination mode, the two hands were interdependent with each other’s movement (i.e., interacted with each other) for three of the grasper subtasks (two, three, and four) and three of the scissors subtasks (three, four, and five). For example, for the second grasper subtask, the scissors must have already moved the pipe from its original position before the grasper could insert the bottom tip of the object into the top of the pipe. Additionally, for the third scissors subtask, the grasper must have already rested the bottom tip of the object on the grey area of the box before the scissors could simulate a cutting action. Furthermore, successful completion of one subtask was dependent on successful completion of another subtask. Thus, the task was agonistic. These interdependencies across the hands and the collaborative nature inherent when completing the subtasks illustrate the interactive, agonistic requirements of the simulated cutting task relative to previous tasks that observed the intermanual speed advantage (Jarrassé et al., 2012; Van Oosterhout et al., 2017).

Bimanual coupling and the simulated cutting task. It is proposed that the quickest way to complete most two-handed tasks is for both hands to move simultaneously (as opposed to sequentially). For example, as opposed to first grasping the object with the grasper (subtask one) and then grasping the pipe with the scissors (subtask one), it would be faster to grasp the object and pipe simultaneously. With this reasoning, it is proposed that simultaneous subtask completion would minimize overall task time. As previously mentioned, due to bimanual coupling, at least two situations may arise: (1) people may isolate the movement of each limb (i.e., move one hand at a time) or (2) people may move each limb in a similar manner, which causes the shorter movement times of one hand to be constrained by the longer movement times of the other hand (Kelso et al., 1979) (see Figure 2.4).

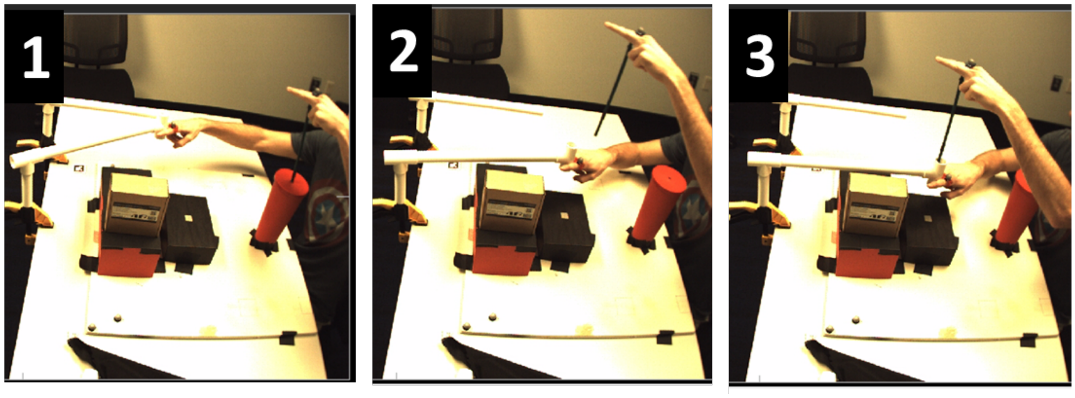

Figure 2.4. A bimanual example of the participant's hands moving sequentially when completing the simulated cutting task. (Frame 1) The participant grasped the object with their left hand (grasper) and did not continue on to the next subtask until after the right hand (scissors) grasped the pipe. (Frame 2) The participant then moved the pipe to the area over the grey area of the box using the scissors before starting the grasper subtask of inserting the object into the top of the pipe (Frame 3).

It was hypothesized that using the intermanual coordination mode to complete the simulated cutting task may circumvent either bimanual limitation that is brought about by bimanual coupling. Specifically, when the simulated task is divided across two visuomotor systems, each participant can focus solely on each unimanual subtask. For example, it was hypothesized that one participant would use their left hand to grasp the top portion of the object while the other participant simultaneously used their right hand to grasp the pipe when using the intermanual coordination mode. Additionally, research has shown that people can decouple their movements with enough practice (Kelso & Zanone, 2002; Zanone & Kelso, 1992, 1997), similar to what was observed in the highly-practiced shoe-tying task (Gorman & Crites, 2015). Therefore, practicing the simulated cutting task using the bimanual coordination mode may reduce bimanual coupling, which may facilitate more SGDMs and increase task performance as measured by speed.

Bimanual visuomotor coupling and the simulated cutting task. As previously established, to complete the simulated cutting task as fast as possible, the participants should to simultaneously visually guide the grasper (left hand) to grasp the top of the object and visually guide the scissors (right hand) to grasp the pipe. However, bimanual visuomotor coupling may cause participants to wait for one visually-guided subtask to be completed with one hand before starting a separate visually-guided subtask with the other hand (e.g., Land et al., 1999; Hayhoe, 2000). It was hypothesized that using the intermanual coordination mode to complete two-handed tasks may circumvent the negative aspects related to the sequential dependence inherent in bimanual visuomotor coupling. When completing the task intermanually, participants are essentially completing two separate unimanual actions with separate visuomotor systems. Therefore, they should be able to complete two visually-guided subtasks simultaneously (see Figure 2.5). Additionally, tasks that have been practiced over an extended period do not need to rely as much on vision (Franz, 1997). Therefore, practicing the simulated cutting task using the bimanual coordination mode may reduce bimanual visuomotor coupling, which may increase task performance as measured by speed. However, due to the physical constraints imposed by the ingle visuomotor system, bimanual visuomotor coupling should still affect performance to some degree.

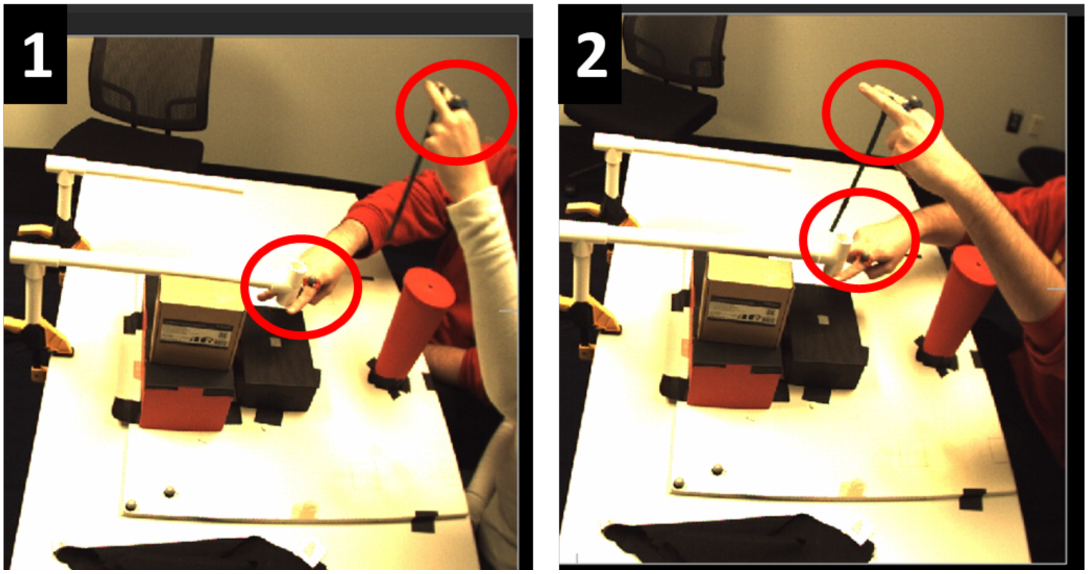

Figure 2.5. An intermanual example of the participant's hands independently moving simultaneously from each other. (Frame 1) The participant completing the task as the scissors (right hand) has already removed their hand from the home key, grasped the pipe, and moved the pipe to the area above the grey area of the box. (Frame 2) The participant completing the task as the grasper (left hand) can immediately insert the object into the top of the pipe.

Simultaneous goal-directed movements and the simulated cutting task. One of the previously observed benefiting aspects of the intermanual speed advantage is SGDMs (i.e., anticipatory movements; Zheng et al., 2007). It was previously hypothesized that the underlying speed advantage during two-handed tasks (regardless of coordination mode) is facilitated by independent, decoupled movements of the limbs (Gorman & Crites, 2015). Along these lines, SGDMs observed during intermanual performance may be enhanced when the limbs can move independently (i.e., are not inhibited by bimanual coupling and bimanual visuomotor coupling). Therefore, more SGDMs should be observed intermanual performance for an unpracticed task and during bimanual performance for a previously practiced task (i.e., allowing for independent, decoupled movement of the limbs) (Gorman & Crites, 2015; Kelso & Zanone, 2002; Zanone & Kelso, 1991).

Summary. In summary, the simulated cutting task was created to exploit the limitations during bimanual coordination (Kelso et al., 1979; Mennie et al., 2007; Rand, 2014). It was hypothesized that bimanual coupling and bimanual visuomotor coupling both restrict the movement of individual two-handed tasks, which reduce the ability to complete SGDMs when completing a task using the bimanual coordination mode. As described in the examples above, regarding the first subtask for grasper and scissor movement, these two hypothesized bimanual limitations create a sequential back-and-forth aspect that decreases performance as measured by speed. It was hypothesized that due to these limitations, the hands are not able to move independent from one another and fewer SGDMs will occur.

Chapter III

Experiment 1

The purpose of Experiment 1 was to replicate the intermanual speed advantage while investigating mode effects and relations among between-hand coupling, measures of visuomotor coupling, and SGDMs.

Method

Participants. Pilot data revealed a relatively large effect size from an ANOVA of the repeated measures, within-between subjects interaction ($\eta^2 = .84$; Cohen, 1988). A power analysis was performed for sample size estimation. With alpha (α) = .05 and power ($1 - \beta$) = 0.80, G*Power (Faul, Erdfelder, Lang, & Buchner, 2007) estimated the sample size needed to be approximately eight dyads ($N = 8$) for this design. However, given the low sample size, it was proposed to use a larger sample size of twelve teams ($N = 24$) for Experiment 1 to account for task differences and establish a similar comparison of groups across experiments. Specifically, differences in sample size estimations across experiments was observed ($N = 6$ was estimated for Experiment 2).

Twenty-four undergraduates (12 dyads) from Georgia Tech participated for partial course credit. Participants were recruited via online recruiting tool. Participants' mean age was $M = 20.71$ ($SD = 2.28$), and 21% were female. The preponderance of males was unplanned. Seven dyads were all male, five were mixed gender. To be eligible, participants were required to be right-handed. Right-handedness was assessed using the Edinburgh Handedness Inventory (Oldfield, 1971).

Experimental design. To address the question of mode effects, a within-subjects variable, Mode, was manipulated with two levels: Bimanual (Bi) and Intermanual (Inter).

During the Bi condition, participants individually completed the task using two hands (i.e., bimanually). During the Inter condition, participants completed the task as a dyad, where each participant used only one hand (one participant used their left hand to complete the task, and the other participant used their right hand to complete the task). To examine practice across coordination modes (i.e., counterbalance), a between-subjects variable, Order, was manipulated with two levels: Bimanual-to-Intermanual (Bi → Inter) and Intermanual-to-Bimanual (Inter → Bi). During the Bi → Inter condition, participants first completed the task bimanually, then intermanually. During the Inter → Bi condition, participants completed the task intermanually first, then bimanually. Participants completed 10 trials at each Mode level. Ten trials were used to prevent participants from reaching a performance plateau or asymptote during pilot testing (Gray & Lindstedt, 2016). In summary, Experiment 1 was a 2 (Mode) × 2 (Order), mixed-subjects design.

Apparatus and materials. A single apparatus was constructed to meet the needs of the task for both experiments (Figure 3.1). The apparatus was constructed to create simultaneous, asymmetric, two-handed movements that required precise eye-hand coordination when reach, grasping, aiming, and pointing actions were being conducted. Participants used the apparatus to complete the simulated cutting task in a motion capture room that featured a ten-camera Vicon Vantage 5 motion capture system sampled at 100 Hz; Vicon Nexus 1.7 software was used to capture participants' movements as they completed the task (Vicon, Oxford, UK) (Figure 3.1A). Data was collected using reflective markers attached to flexible rubber rings, which participants wore on their index fingers (Figure 3.1C).

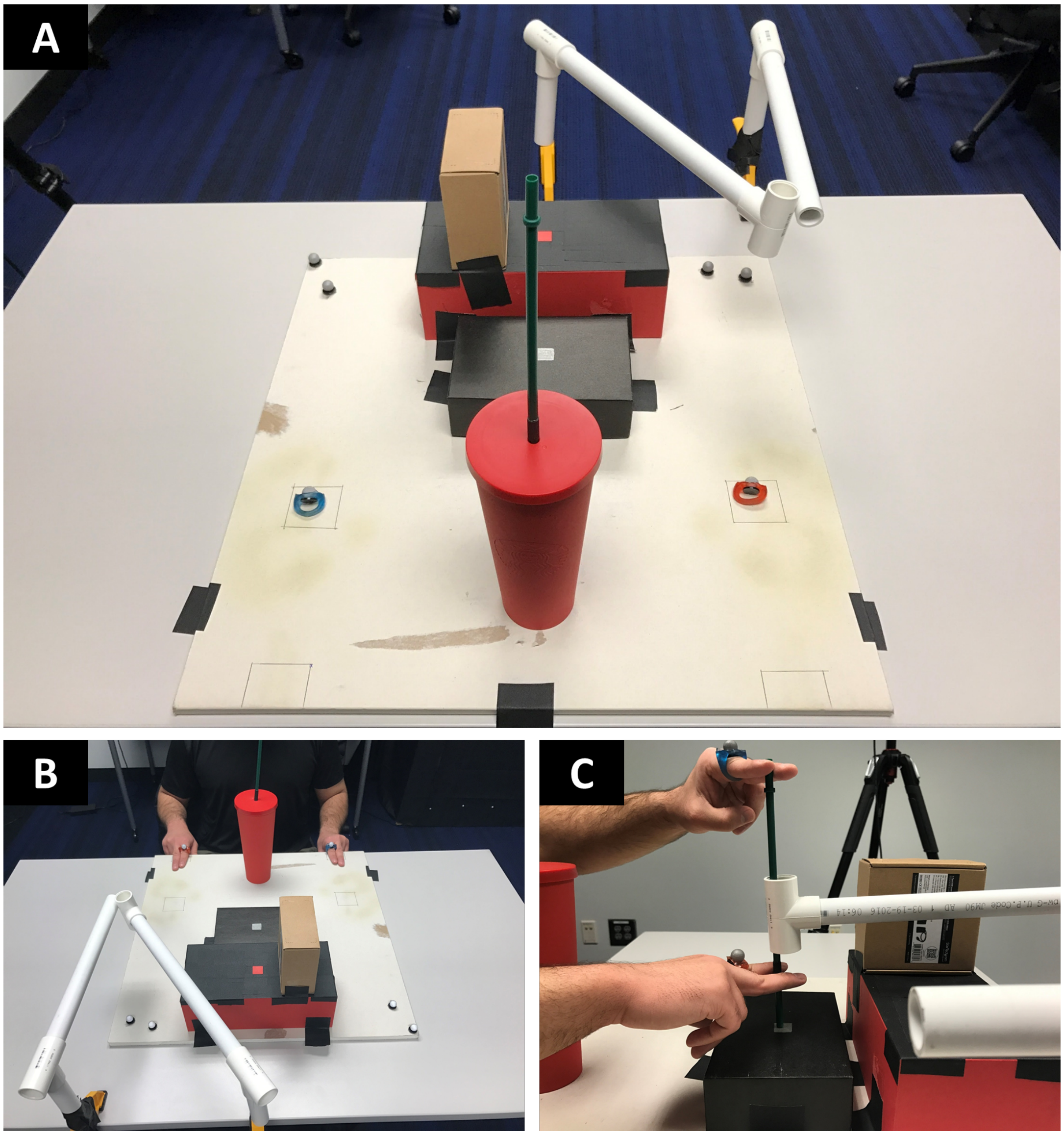

Figure 3.1. (A) Apparatus from the participant's point of view during pilot testing. (B) An example of a participant in the Bimanual condition. (C) An example of a participant completing the simulated cutting action during the Bimanual condition.

To obtain eye-tracking information, participants donned a wearable eye-tracking system – Ergoneers' Dikablis Eye-Tracking Glasses Professional (Figure 3.2), which captured eye-tracking data sampled at 60 Hz via binocular eye cameras (Ergoneers, 2014). The Ergoneers Dikablis Eye-Tracking system tracked pupil detection at 0.05°, glance direction at 0.1° – 0.3°, and a 40° – 90° camera viewing angle.

Figure 3.2. Dikablis Eye-Tracking Glasses Professional.

The Dikablis Eye-Tracking Glasses feature an outward facing scene camera located above the bridge of the nose, which collected video data from the participants' perspective. Prior to trial performance, calibration was performed for each participant using the inward facing binocular eye cameras and the outward facing scene camera in D-Lab (Ergoneers, 2014). The D-Lab 3.4 software package (Ergoneers Inc, Manching, Germany) was used for data collection and analysis on a separate computer for each eye tracker used per dyad (i.e., a separate eye tracker and computer was used for each participant). An example of the eye-tracking data is overlaid on the video scene data in D-Lab (Figure 3.3).

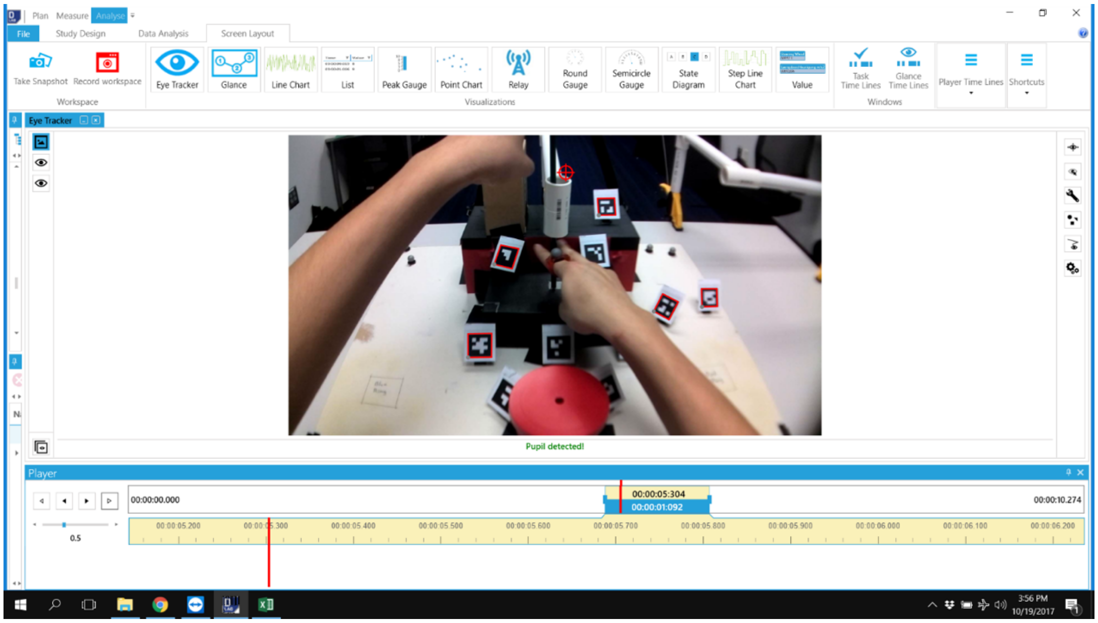

Figure 3.3. A screenshot of the D-Lab software package of a trial recording. The video in the center is a still frame from the view of a participant completing the task using the bimanual coordination mode. The red crosshair illustrates where the participant is looking. The still image shown is a participant who just finished the simulated cutting subtask and is looking back to the pipe in order to guide the next subtask.

The information obtained from the eye-tracking data was used to test the hypotheses and associated predictions. Additionally, eye-tracking metrics (e.g., fixations, fixation duration, saccades, and saccade duration) were calculated to assess differences in Mode and to examine possible correlations with speed. Additionally, eye-tracking data was used to define areas of interest (AOIs), which are physical locations in three-dimensional space containing task-relevant information (Wickens et al., 2013).

Measures. Information regarding the measures for both Experiment 1 and Experiment 2 are provided below. Additional information regarding select the measures of visuomotor coupling and SGDMs and how they are calculated can be found in Appendix B (extended measures section).

Speed. Movement data was collected using the mediolateral (X), sagittal (Y), and transverse (Z) dimension of the motion capture space (Figure 3.4).

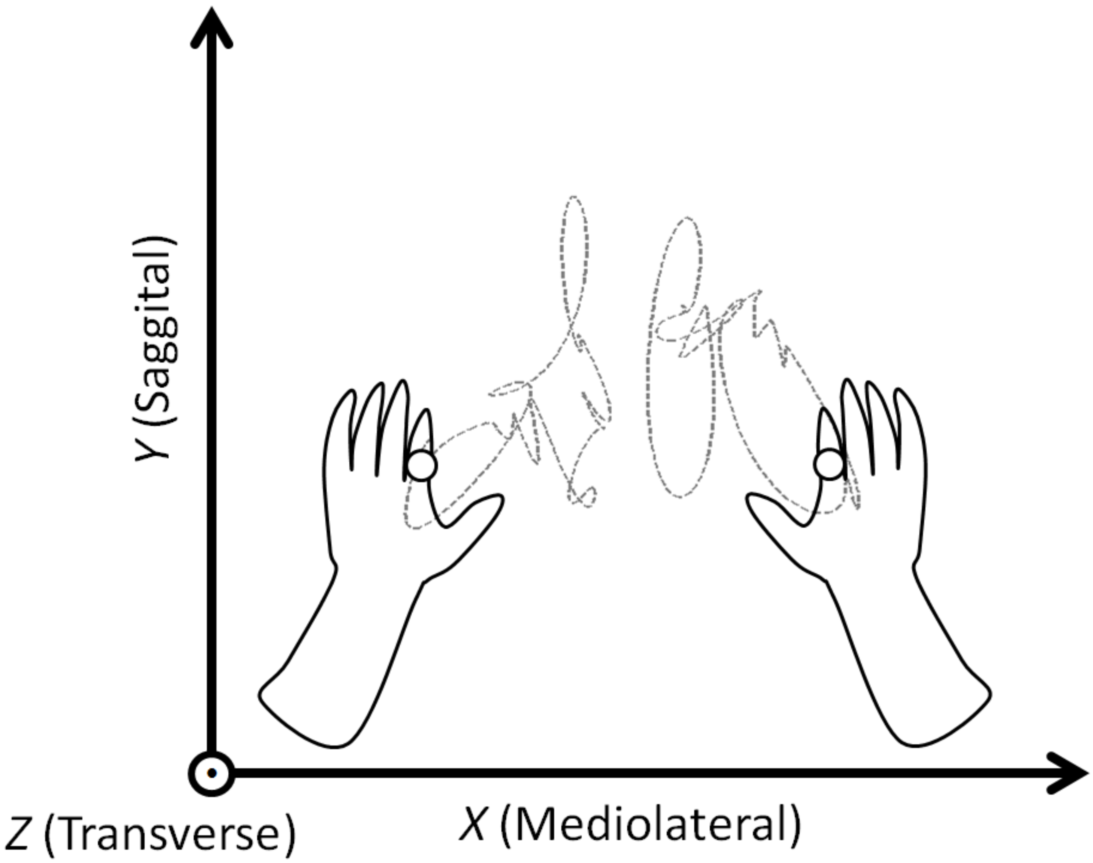

Figure 3.4. Orientation of the laboratory coordinate system from Gorman and Crites (2015) showing example movement data (dashed lines) from a single trial plotted in the mediolateral-sagittal (x, y) plane.

Speed was measured using a predetermined volume of space to start and stop each trial. The exact location of the start/stop volume was determined during pilot testing (60mm above the home keys). The start/stop volume was used to identify the onset and offset of movement duration for each trial, such that movement onset occurred when the first hand entered the volume (signaling task start) and offset occurred when the last hand exited the volume (signaling task completion). Trial time (TrialTime) was measured in seconds as the difference between offset and onset time. Additionally, trial times were used to truncate the movement data by removing samples at the beginning and end of each trial when participants' hands were stationary, which eliminated non-task-related information from all subsequent movement data (e.g., Coupling) analyses. TrialTime was averaged across participants for the bimanual trials for comparison with intermanual trials.

Variability. When movements are skilled, the hands are less variably related to one another (Gorman & Crites, 2015). In this case, lower variability during a manual coordination tasks reflects a higher skill level, with faster trial-to-trial performance correlated with lower trial-to-trial variability (i.e., there is a positive correlation between task completion time and variance; Gorman & Crites, 2015; Thelen et al., 1993). Variability was computed for each trial as Generalized Variance (GenVar), which is the determinant of the covariance matrix between the left- and right-hand along a particular dimension for that trial (Equation 1). In terms of variability during task performance, the sagittal dimension contained the most simulated cutting information across both hands; however, analyses were performed using all three axes and the same pattern of results was observed for all three axes.

$$GenVar = \begin{vmatrix} Var(right) & Cov(right, left) \\ Cov(right, left) & Var(left) \end{vmatrix}$$
$$= Var(right)Var(left) - Cov(right, left)^2 \qquad (1)$$

Whereas the covariance matrix separately describes the spread and relation of scores along the dimensions of a multivariate distribution, GenVar provides a scalar index of the multivariate scatter of scores (Wilks, 1960). GenVar was calculated between the left and right hands at each trial for movement duration determined by TrialTime.

Similar to the measure of speed, GenVar scores were averaged across participants for the bimanual trials for comparison with intermanual trials.

Between-hand coupling. To analyze between-hand coupling, movement data was analyzed from participants' left and right hands during simulated cutting using Cross Recurrence Quantification Analysis (CRQA) (Shockley, Butwill, Zbilut & Webber, 2002). Between-hand coupling was measured using %REC and MAXLINE. %REC is the number of recurrent points divided by the possible number of recurrent points in a CRP and was used to quantify the degree to which two systems are coupled. MAXLINE quantifies the stability to which two systems are coupled (Shockley et al., 2002). MAXLINE was included as a complementary measure of coupling, and analyses are included in the Extended Results section; however, the same pattern of results was observed.

Prior to creating the CRP, Phase Space Reconstruction (PSR) was performed on each time series (i.e., trial). PSR is used to unfold a scalar time series into its appropriate dynamical space using an embedding dimension that corresponds to the underlying dynamical degrees of freedom (i.e., position, velocity, etc.) of the system that generated the time series (Abarbanel, 1996). However, prior to PSR, parameters used during the reconstruction process were estimated (Shockley et al., 2002).

PSR solutions result in parameters (time delay, τ, and embedding dimension, d_E, described below) for reconstructing vectors in the dynamical space from the observed time series; these vectors correspond to the unknown state variable of the dynamical system. The state of the system at any time is given by a τ-scaled d_E-element vector, where τ is a time delay that separates time series observations, such that they are maximally independent, and d_E is the embedding dimension that specifies the number of coordinates needed to describe position in the dynamical space (Takens, 1981). In summary, the d_E vector components are time-delayed (by a constant time delay, τ) observations of the time series. For example, after reconstructing the dynamics of a system R (right hand) from its time series r (sagittal dimension), the state of R at time t can be specified by the d_E-element vector $\mathbf{r}(t) = [r(t), r(t + \tau), r(t + 2\tau)\ldots, r(t + d_E - 1)\tau)]$.

Using the standard PSR approach (Abarbanel, 1996), τ was chosen as the first minimum of the average mutual information (AMI) function for each hand. τ corresponds to the time delay at which the movement time series from each hand becomes maximally unrelated (i.e., uncorrelated) with itself. For specifying independent dynamical dimensions (Fraser & Swinney, 1986), d_E was chosen as the number of time-delayed dimensions at which the false nearest neighbor (FNN) function for each hand reaches zero, which specifies the number of independent dynamical dimensions (i.e., dynamical degrees of freedom) needed to account for the system dynamics (Kennel, Brown, & Abarbanel, 1992; Rhodes & Morari, 1997). Following recommendations for CRQA analysis, all movement data was normalized and rescaled using maximum-distance rescaling prior to PSR (Shockley, 2005; Webber & Zbilut, 2005).

By analyzing ten randomly-selected trials for common τ and d_E values, the shared dynamical space for all trials was estimated as having $\tau = 47$ and $d_E = 5$. With five phase space dimensions, five dynamical degrees of freedom were accounted for (i.e., displacement, velocity, acceleration, jerk, and snap; Eager, Pendrill, & Reistad, 2016) at each hand in the sagittal dimension during simulated cutting. In terms of variability during task performance, the sagittal dimension contained the most simulated cutting information across both hands. The reconstructed phase space is not identical to the actual, unknown phase space, but it is isomorphic to it (Takens, 1981). In other words, they are not structurally exact when plotted, but are statistically identical when analyzed (Shockley, 2005). Hence, though exact positions cannot be known, the PSR coordinates can be used to identify when two systems (e.g., the left [L] and right [R] hands) are in the same dynamical state (i.e., coupled). As previously mentioned, a dot is plotted in the CRP for all pair-wise combinations of points in the shared space that are sufficiently close within a threshold (i.e., a radius).

The radius is defined as the distance between units required to count (x, y) as a recurring point. However, if dimensions are greater than one, then windows are used and the threshold at which that Euclidean distance is small enough is specified by a radius value (Marwan, Carmen Romano, Thiel, & Kurths, 2007). For this dissertation, the radius is the value that determined the points in time during which both hands shared the same state in the reconstructed dynamical space. For example, if the distance between vectors $\mathbf{l}(415)$ and $\mathbf{r}(132)$ in the dynamical space was less than the value of the radius, then a dot was plotted at location {415, 132} in the CRP. The size of the radius refers to a percentage of the maximum distance between observed points in the reconstructed dynamical space. For behavioral data, Shockley (2005) recommends a radius between 20% and 40%. That rule is meant to ensure that the CRP is neither completely flooded with, nor devoid of, recurrent points (for this dissertation, a radius of 30% was selected). Figure 3.5 shows a CRP for an example bimanual simulated cutting trial constructed using the PSR parameter values $\tau = 47$ and $d_E = 5$.

Once a CRP was constructed for each trial, %REC and MAXLINE were calculated from each plot. As noted previously, %REC quantifies the level of coupling between any two nonlinear dynamical systems, in this case between left and right-hand movements during simulated cutting, and it is computed as the total number of recurrent points in a CRP divided by the total number of possible recurrent points, expressed as a percentage (Equation 2).

$$\%REC = \frac{Total\ \#\ Recurrent\ Points}{Total\ \#\ Possible\ Recurrent\ Points} * 100 \qquad (2)$$

The %REC of the example CRP shown in Figure 3.5 is 23.95%. If the CRP were more filled in, then that percentage would have been higher. MAXLINE quantifies the stability of coupling between the two systems and is computed as the longest continuous diagonal of recurrent points in the CRP. The MAXLINE of the CRP shown in Figure 3.5, an example bimanual trial, is 262, which corresponds to left and right bimanual coupling that occurred early and late, respectively, during the simulated cutting trial.

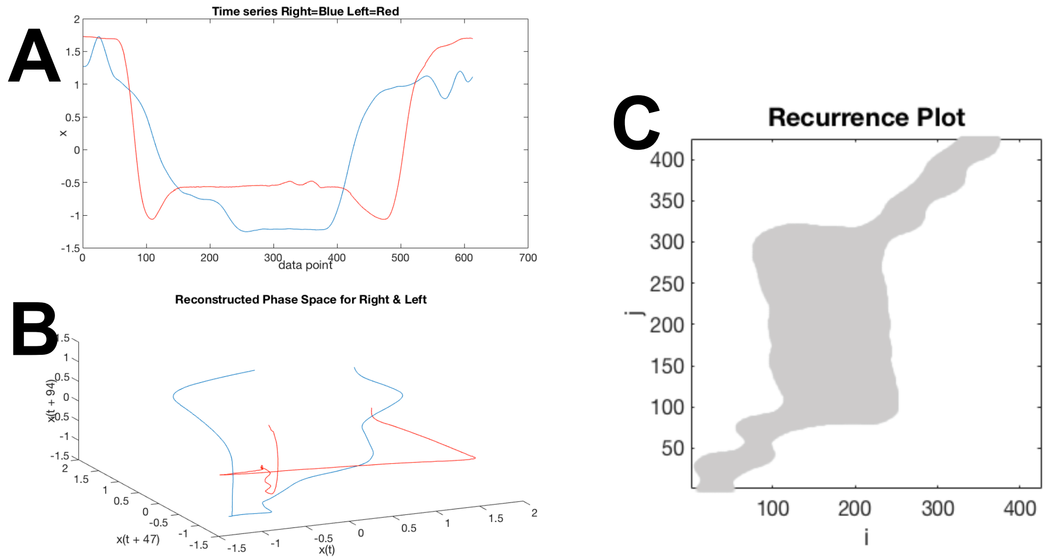

Figure 3.5. (A) right (*r* [blue]) and left (*l* [red]) hand sagittal time series from one trial (bimanual); (B) phase space reconstruction of that trial ($\tau = 47$ and $d_E = 5$; only three-dimensions are shown for illustrative purposes); and (C) cross-recurrence plot for that trial (radius = 30%). The recurrent pattern in the center portion of the cross-recurrence plot corresponds to left-handed followed by right-handed bimanual simulated cutting formation.

Values of %REC are independent of order and higher values index the degree in which the two hands were coupled in space and time throughout task performance (Shockley, 2005). Values of MAXLINE are time-dependent and higher values index the degree in which the two hands were coupled throughout a particular time during task performance (Shockley et al., 2003).

In summary, higher values of %REC indicate more between-hand coupling and higher values of MAXLINE indicate the degree of between-hand coupling. Measures of between-hand coupling was calculated between the left and right hands at each trial for movement duration determined by TrialTime. Thus, between-hand coupling was only analyzed on task-relevant data. Similar to the measure of Speed and Variability, coupling measures were averaged across participants for the bimanual trials for comparison with intermanual trials.

Visuomotor coupling. Visuomotor coupling is defined as the sequential, spatial, and temporal dependencies that take place during manual coordination. The measurement of visuomotor coupling consists of both “Pre-Reach Look-Ahead” (i.e., a guiding fixation) and “Gaze Anchoring,” which are hypothesized to be underlying processes that facilitate eye-hand coordination during visually-guided reaching and grasping. Pre-Reach Look-Ahead is operationally defined as the difference in time between looking at an AOI and reaching for it (e.g., reaching for the pipe) or starting a similar manual action (e.g., removing the object from its resting position). Gaze Anchoring is operationally defined as the difference in time between looking away from an AOI and grasping it (e.g., grasping the pipe) or completing a similar manual action (e.g., inserting the object into the pipe).

The measures of visuomotor coupling have a visual component and a manual component, which were collected via eye-tracking data and hand movement video data, respectively. All eye-movement and hand-movement data were collected with respect to pre-defined start and stop subtasks while participants completed the two-handed simulated cutting task. Subtasks were broken down according to reaching and grasping hand movements, and pointing and aiming hand movements that were a goal-directed with observable starting and finishing points (Land et al., 1999). Tables 3.1 and 3.2 show the start and stop components broken down for each grasper and scissor subtask, respectively.

Table 3.1

Each Grasper Subtask Broken Down by Start and Stop Movements

Grasp object	
	Start: Once both fingers have left the home key
	Stop: Once both fingers completely closed on the top of the object
Insert object through top of the pipe	
	Start: Once the object begins moving toward the top of the pipe
	Stop: Once the object is inserted into the pipe
Rest object on grey area of the box	
	Start: Once the object starts moving toward the grey are of the box
	Stop: Once the object first touches grey box
Remove object from the pipe	
	Start: Once the object is removed from the grey area of the box
	Stop: Once the object is successfully out of the pipe
Return object back to resting position	
	Start: Once the object starts moving toward the cup
	Stop: Once the object is successfully inserted into the hole of the cup
Return fingers to home key	
	Start: Once both fingers begin to release grasp on the object
	Stop: Once both fingers arrive at the home key

Note. This breakdown applies to both the conditions using the bimanual and intermanual coordination mode.

For both eye movements and hand movements, AOIs related to each subtask were identified and used to classify when eye and hand movements started and stopped. For example, the grasper must first leave the home key (starting position) and then grasp the top portion of the object. During this subtask, the top of the object is classified as a grasper-specific AOI during the two-handed simulated cutting task. Therefore, the start of a task-related eye movement occurred when the eye fixated on an AOI that was used to guide a manual action and stopped when the eye first looked away from the AOI. Each grasper and scissors subtask yielded a data point representing Pre-Reach Look-Ahead and a data point representing Gaze Anchoring.

Table 3.2

Each Scissor Subtask Broken Down by Start and Stop Movements

Grasp pipe (the pipe is located in its starting, first position)	
	Start: Once both fingers have left the home key
	Stop: Once both fingers completely close on the top of the pipe
Move pipe over to grey area of box (second position)	
	Start: Once the pipe starts movement towards the grey area of the box
	Stop: Once the pipe arrives at the position over the grey area of the box
Simulate cutting action	
	Start: Once both fingers have been removed from the pipe
	Stop: Once both fingers are grasping the object
Return fingers to pipe	
	Start: Once both fingers start to open/release grasp on object
	Stop: Once both fingers completely grasp the pipe
Return pipe back to first position (first position)	
	Start: Once the pipe begins motion towards resting position
	Stop: Once the pipe arrives at the resting position
Return fingers to home key	
	Start: Once both fingers begin to release grasp on the pipe
	Stop: Once both fingers arrive at the home key

Note. This breakdown applies to both the bimanual and intermanual coordination mode.

To calculate Pre-Reach Look-Ahead and Gaze Anchoring, the start and stop of eye movements and start and stop of hand movements relative to grasper and scissor subtasks were identified and recorded. The data needed to calculate a Pre-Reach Look-Ahead was the “Eye-AOI Start Time” (e.g., when the participant first looked at the top of the object) and the “Manual-AOI Start Time” (e.g., when the participant first started to reach towards the object). The data needed to calculate Gaze Anchoring was “Eye-AOI Stop Time” (e.g., when the participant stopped looking at the top of the object) and “Manual-AOI Stop Time” (e.g., when the participant grasped the top of the object) (Figure 3.6).

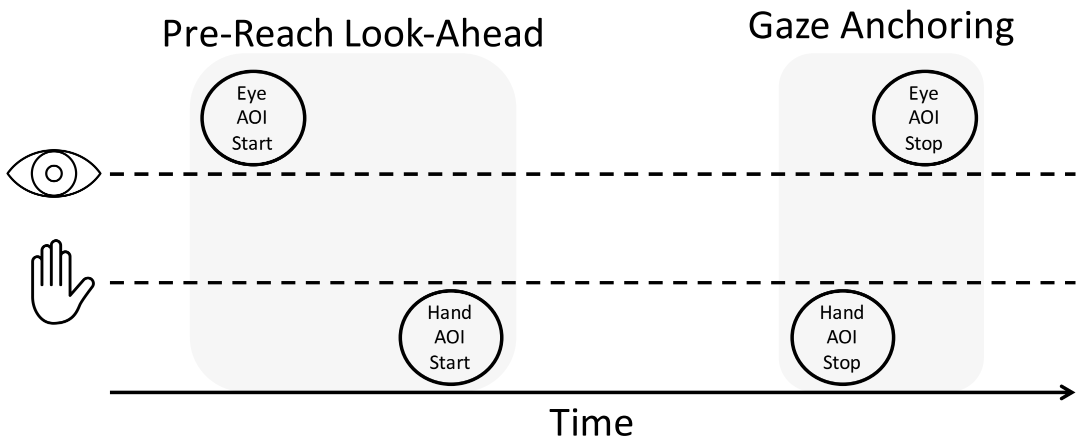

Figure 3.6. Example outlining hypothesized bimanual data used to calculate both Pre-Reach Look-Ahead and Gaze Anchoring. Pre-Reach Look-Ahead is calculated subtracting Eye-AOI Start Time from Manual – AOI Start Time. Gaze Anchoring is calculated by subtracting Eye-AOI Stop Time by Manual – AOI Stop Time.

Eye-tracking and hand movement video data were analyzed frame-by-frame within D-Lab and manually recorded into spreadsheets in a series of start and stop movements. Relative to the simulated cutting task, the start time of the Eye-AOI movement was recorded as when the eye fixated on the AOI (e.g., the pipe) and the stop time of the Eye-AOI movement was recorded as when the eye left the AOI (e.g., moving to the next AOI or any task irrelevant fixation). The start time of the Manual-AOI movement was recorded as when the hand started to move to the AOI and the stop time of the Manual-AOI movement was recorded as when the hand reached the AOI (e.g., moving to the next AOI or any task irrelevant task fixation). Custom MatLab code (MathWorks, Inc.) was used to calculate Pre-Reach Look-Ahead and Gaze Anchoring for each subtask using Equation 3 and Equation 4, respectively.

$$\text{Pre\_Reach Look\_Ahead} = \text{Eye\_AOI Start Time} - \text{Manual\_AOI Start Time} \tag{3}$$

$$\text{Gaze Anchoring} = \text{Eye\_AOI Stop Time} - \text{Manual\_AOI Stop Time} \tag{4}$$

It was hypothesized that visuomotor coupling delays overall movement time when completing a two-handed task using a single visuomotor system (i.e., bimanually) compared to completing the two-handed task using two separate visuomotor systems (i.e., intermanually). Specifically, visuomotor coupling restrains behavior due to the sequential, spatial, and temporal dependencies that take place during bimanual coordination and these negative characteristics do not play as much of a role when the task is completed intermanually. Regarding Pre-Reach Look-Ahead, the eye may have to look at the to-be manipulated object longer before starting the manual action. It has been suggested that this is an artifact of completing a previous manual action with the other hand (Neggers & Bekkering, 2000). Regarding Gaze Anchoring, the eye may have to stay focused on the object for a shorter period of time before moving to the next portion of the task (i.e., the next subtask) during bimanual performance compared to intermanual performance, which has been suggested that this is an artifact of needing to complete another manual action with other hand (Terrier et al., 2011). During intermanual performance, the eye is able to stay focused on the object longer since there is no timesharing across the hands. Moreover, the sequential, visually-guided components that make up bimanual visuomotor coupling cause a sequential, back-and-forth timesharing across the hands when completing a two-handed task bimanually. Visuomotor coupling measures eye-hand time differences during different sub-tasks, which were used to assess how much visuomotor coupling restrains behavior when simultaneously completing a two-handed task – bimanually and intermanually. Therefore, it was predicted that the eye-hand dependence caused by visuomotor coupling should result in longer times as measured by Pre-Reach Look-Ahead and shorter times as measured by Gaze Anchoring. Pre-Reach Look-Ahead and Gaze Anchoring scores were calculated for each subtask for each trial.

Similar to the measure of Speed, Variability, Coupling, and SGDMs, Visuomotor Coupling measures were averaged across participants for the bimanual trials for comparison with intermanual trials.

Simultaneous, goal directed movements. The measure of simultaneous goal-directed movements (SGDMs) followed a protocol similar to that of Zheng and colleagues (2007). Video recordings of the simulated cutting task were reviewed and rated by two undergraduate research assistants (RAs). RAs were trained to rate an SGDM using the following definition: "Simultaneous goal-directed movements are operationally defined as the initiation and follow-through of a grasper/scissor goal-directed movement while the other hand is actively completing a grasper/scissor goal-directed movement (i.e., initiation *and* follow-through of a goal-directed movement of one hand while the other hand is simultaneously completing another portion of the task)." A total of six SGDMs were possible for any given trial—one for each of the six subtasks during simulated cutting—regardless of coordination mode.

Importantly, Zheng and colleagues (2007) asked participants to complete a simulated laparoscopic cutting task and used an operational definition of anticipatory movements that allowed for only one possible anticipatory movement per trial. To include a broader range of potential movements during the simulated cutting task for this dissertation, a new term and definition was created – SGDMs. As previously mentioned, Zheng and colleagues' (2007) definition dictates that all anticipatory movements are SGDMs; however, all SGDMs are not directly anticipatory. In the context of the simulated cutting task, for example, simultaneously grasping the object with the left hand and the pipe with the right hand would be considered a SGDM; however, this movement is not directly anticipatory at the single subtask timescale. In the context of the entire task of simulated cutting, however, these movements are anticipatory.

It is important to note that not all grasper and scissor movements that happen before the completion of the complementary grasper and scissor subtask are constituted a SGDM. For example, when participants were using the bimanual coordination mode to complete simulated cutting, the movement of one hand may have incidentally moved due to concurrent movement of the other hand (i.e., ostensibly due to bimanual coupling). A specific case of this was observed during the first grasper/scissor subtask. Immediately after the signal to start the task, the scissors started to move in the upwards direction while the grasper moved towards the object (or vice versa). This example shows simultaneous movement; however, this type of movement was classified as unintended. Therefore, this movement was not classified as an SGDM because the unintentional movement was not goal-directed (i.e., the movement was merely incidental and possibly due to bimanual coupling, and was not part of subsequent object manipulation). Alternatively, simultaneous movement for this subtask may indeed be goal-directed. For example, when participants were using the intermanual coordination mode to complete simulated cutting immediately after the signal to start the task, the scissors may start to move upwards towards the pipe (a goal-directed movement) while the grasper is moving towards the object (a goal directed-movement). In this case, both movements were intentional and directed toward a goal (grasp object while simultaneously moving to grasp the pipe). Thus, this movement would be considered a SGDM.

Procedure. Participants were asked to complete a simulated cutting task specifically constructed to analyze bimanual and intermanual coordination. At the beginning of the experimental session, informed consent was obtained. Following Georgia Tech IRB protocol, the experimenter assessed whether the participants were sufficiently informed, comprehended what was expected of them, and were still willing to continue the study. Participants were shown the apparatus and were given a general overview of the two coordination modes in which they were to complete the task. Depending on the order of conditions (Bi → Inter or Inter → Bi), participants either completed the first set of trials bimanually or intermanually. At times when one participant was completing the task using the Bi condition, the other participant was in a separate room completing a demographic questionnaire and the Edinburgh Handedness Inventory (Oldfield, 1971) (Appendix D). Participants were not allowed to talk to each other before, during, or in between trials.

Participants were instructed to “complete the task as quickly and accurately as possible” and “to complete the task as fast as possible while still accurately completing the task” and “if a trial is performed incorrectly, then it will not count.” Two trained experimenters observed all trials to ensure accuracy. All participants were instructed to place the marker rings on their index fingers and to put their hands in the “ready position,” with their fingers “as still and as flat as possible” before each trial (Figure 3.7).

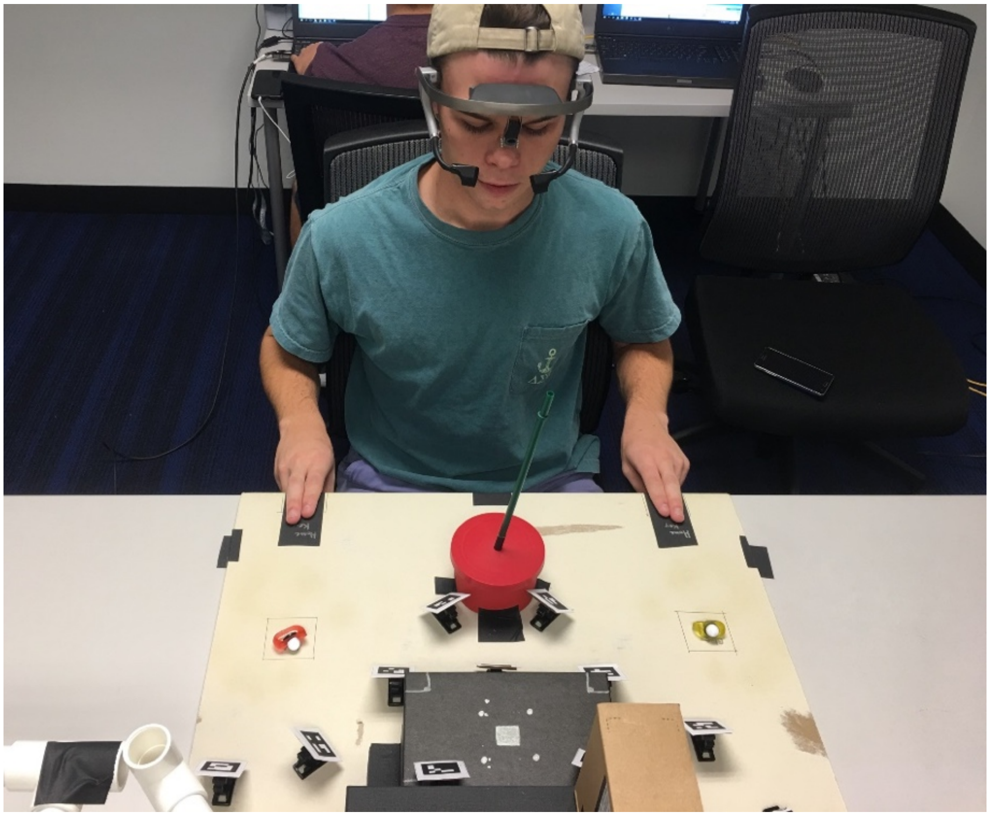

Figure 3.7. A research assistant posing as a participant in the "Ready Position" prior to completing the task using the bimanual coordination mode.

Before each trial, one experimenter started the motion-capture data collection, and another experimenter started the eye-tracker data collection. Participants were instructed to start a trial when hearing a "Go" signal. Upon completing each trial, participants indicated to the experimenters that they were finished by saying "Done" after both hands were back at the home keys; at this time, the experimenters stopped the motion-capture data and eye-tracker data recordings for that trial. For the Bi condition, participants completed the task using both their left and right hands (Figure 3.7). For the Inter condition, one participant was instructed to sit on the right side of the apparatus and to complete the task with his or her right hand (i.e., complete the scissors portion of the task), and the other participant was instructed to sit on the left side of the apparatus and to complete the task with his or her left hand (i.e., complete grasper portion of the task) (Figure 3.8).

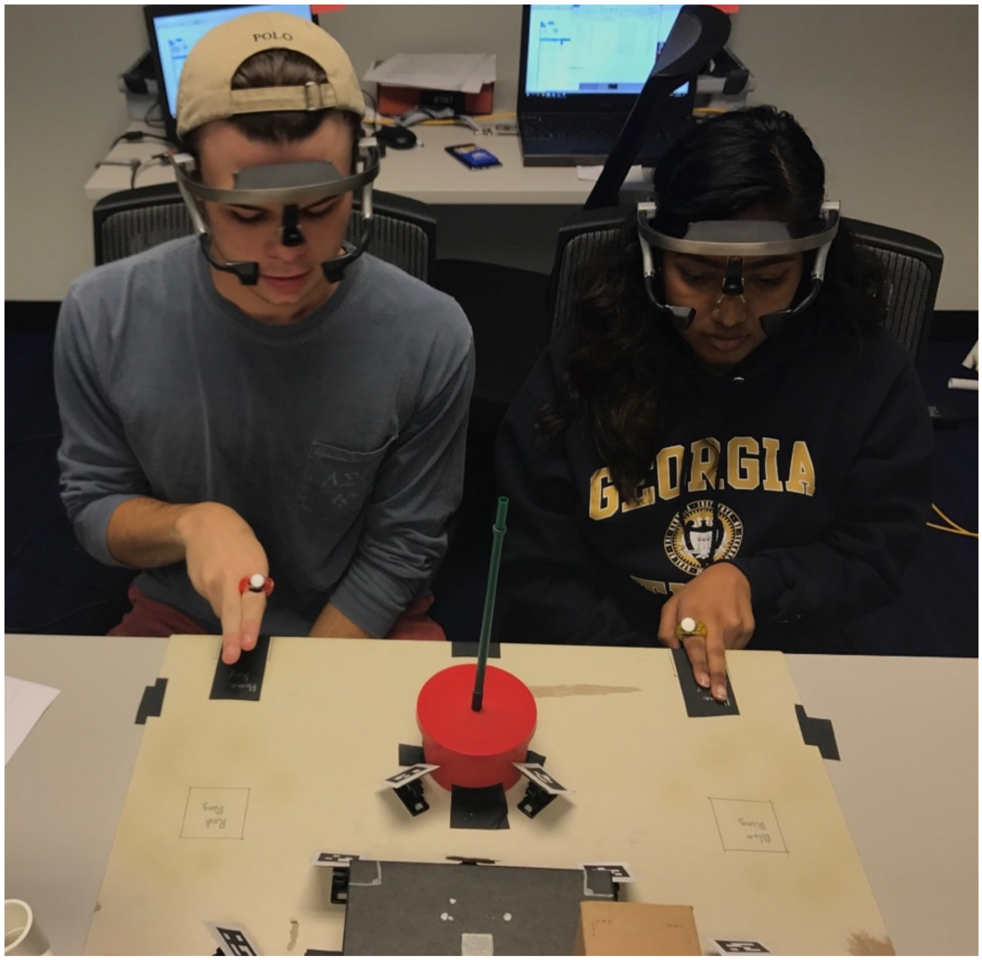

Figure 3.8. Two research assistants posing as participants in the "Ready Position" prior to completing the task using the intermanual coordination mode.

Before starting the trials, participants performed practice trials to demonstrate that they knew how to complete the task for each level of Mode. During practice trials, participants were instructed to focus on accuracy and not to focus on speed at this time. Practice lasted approximately one minute and participants did not complete any additional trials once they demonstrated they could complete the task accurately. Once the participant(s) demonstrated they could complete the task accurately, the experimental trials started. All assignments related to Mode, Order, and role during the Inter condition were randomized (i.e., participants were randomly assigned to the role of grasper or scissors). Each experimental session lasted approximately 1.5 hours per dyad.

Predictions

H1 stated that speed during bimanual coordination for an unpracticed task is limited by bimanual coupling and bimanual visuomotor coupling, which inhibits the ability to perform SGDMs. If this hypothesis is supported, then bimanual performance should be associated with higher TrialTime, higher %REC, higher Pre-Reach Look-Ahead, lower Gaze Anchoring, and fewer SGDMS relative to intermanual performance.

H2 stated that speed during intermanual coordination for an unpracticed task is facilitated by a lack of bimanual coupling and a lack of bimanual visuomotor coupling, which increases the opportunity to perform SGDMs. If this hypothesis is supported, then intermanual performance should be associated with lower TrialTime, lower %REC, lower Pre-Reach Look-Ahead, higher Gaze Anchoring, and more SGDMS relative to bimanual performance. Results that would support these predictions are summarized in Table 3.3.

Additional support for H1 and H2 would be obtained from significant correlations involving TrialTime and the explanatory variables: %REC, Pre-Reach Look-Ahead, Gaze Anchoring, and SGDMs. Finally, because H1 and H2 posit that between-hand coupling and visuomotor coupling inhibit or permit the ability to make SGDMs, it would be predicted that %REC, Pre-Reach Look-Ahead, and Gaze Anchoring will be significantly correlated to SGDMs.

Table 3.3

Experiment 1 Predictions Relative to Dependent Variables

Dependent Variable	Coordination Mode	
	Bimanual	Intermanual
TrialTime	Higher	Lower
%REC	Higher	Lower
Pre-Reach Look-Ahead	Higher	Lower
Gaze Anchoring	Lower	Higher
SGDMs	Less	More

Results

The primary purpose of Experiment 1 was to investigate speed differences during two-handed tasks. Accordingly, speed (i.e., TrialTime) was analyzed to assess for a possible mode effect. In order to further understand any potential mode effects for speed, the associated explanatory dependent variables were analyzed (e.g., %REC). Effect sizes reported are partial eta-squared and Cohen's *d* (Cohen, 1992; Keppel & Wickens, 2004). Descriptive statistics for Experiment 1 are presented in Table 3.4.

Table 3.4

Summary of Results for Experiment 1

Dependent Variable	Coordination Mode	
	Bimanual	Intermanual
TrialTime (s)	7.90 (1.83)	6.54 (1.26)
%REC	16.86 (6.26)	9.92 (2.92)
Pre-Reach Look-Ahead (s)	0.28 (0.18)	0.08 (0.07)
Gaze Anchoring (s)	0.03 (0.08)	0.18 (0.07)
SGDMs	3.12 (0.37)	4.88 (0.55)

Note. Means are presented with standard deviations in parentheses.

Repeated contrasts on TrialTime were first analyzed to assess whether each dyads' performance was still improving in each coordination mode (i.e., had not reached plateau or asymptote). Fourteen contrasts were significant for Bi (Trial 1 vs. Trial 8; Trial 1 vs. Trial 9; Trial 1 vs. Trial 10; Trial 2 vs. Trial 3; Trial 2 vs. Trial 5; Trial 2 vs. Trial 6; Trial 2 vs. Trial 7; Trial 2 vs. Trial 8; Trial 2 vs. Trial 9; Trial 2 vs. Trial 10; Trial 4 vs. Trial 6; Trial 4 vs. Trial 8; Trial 4 vs. Trial 9; Trial 4 vs. Trial 10) and 14 contrasts were significant for Inter (Trial 1 vs. Trial 6; Trial 1 vs. Trial 7; Trial 1 vs. Trial 8; Trial 1 vs. Trial 9; Trial 1 vs. Trial 10; Trial 2 vs. Trial 7; Trial 2 vs. Trial 8; Trial 2 vs. Trial 9; Trial 2 vs. Trial 10; Trial 3 vs. Trial 9; Trial 3 vs. Trial 10; Trial 4 vs. Trial 9; Trial 4 vs. Trial 10; Trial 5 vs. Trial 10). These patterns of results for Bi and Inter indicate that trial time continued to decrease throughout the experiment (see Figure 3.9) and that performance was still improving (asymptote or plateau was not reached) for this unpracticed task for both coordination modes (Gray & Lindstedt, 2016). Therefore, the task was considered to be previously unpracticed using either coordination mode.

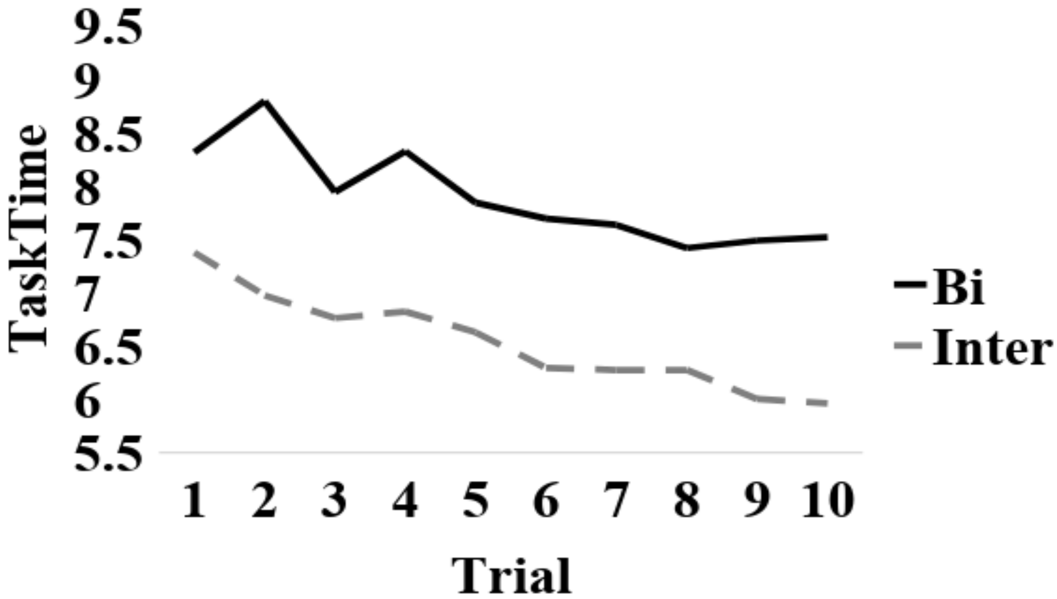

Figure 3.9. Mean trial times as a function of trial, indicating performance asymptote not was reached for both the bimanual (Bi) and intermanual (Inter) coordination modes.

While trials were not significantly different past trials four (bimanual) and five (intermanual), one cannot confirm performance asymptote was reached during Experiment 1. Importantly, one may not be convinced performance asymptote was not reached and the task should be considered practiced. However, using data from the bimanual practice phase during Experiment 2, it can be demonstrated that performance theoretically would have continued to improve after Trial 10 when using the bimanual coordination mode for Experiment 1 (see Figure 3.10). Therefore, it is theoretically confirmed that performance was still improving (asymptote or plateau was not reached) for the bimanual coordination mode.

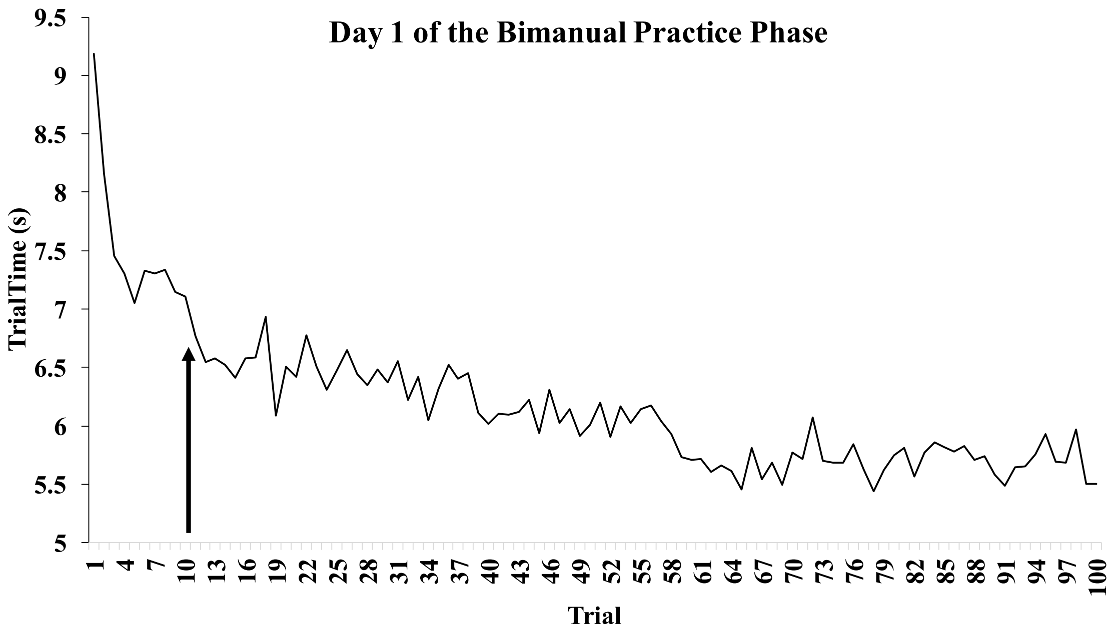

Figure 3.10. Participants' mean trial times for Day 1 of the Bimanual Practice Phase during Experiment 2. The data theoretically demonstrates that participants' performance would have continued to improve past Trial 10 during Experiment 1. Therefore, the task is considered unpracticed during Experiment 1.

Speed. In order to examine practice effects across coordination modes, TrialTime was analyzed using a 2 (Mode) × 2 (Order) mixed-subjects ANOVA. The Mode × Order interaction on mean TrialTime was not significant, $F(1, 10) = 0.51$, $p = .494$, $\eta^2 = .05$, indicating the main effect of Mode was independent of a brief practice phase and mode switching effects. Additionally, the main effect of Order on mean TrialTime was not significant, $F(1, 10) = 0.07$, $p = .797$, $\eta^2 = .01$, indicating that any subsequent main effects of Mode are independent of the order in which participants completed the tasks. The main effect of Mode was significant, $F(1, 10) = 34.60$, $p < .001$, $\eta^2 = .78$. As depicted in Figure 3.11, TrialTime was significantly shorter when participants completed the task using the Inter Mode (M = 6.54 s, SD = 1.26 s) compared to the Bi Mode (M = 7.90 s, SD = 1.83 s). Consequently, an intermanual mode effect for speed was observed, which is consistent with predictions.

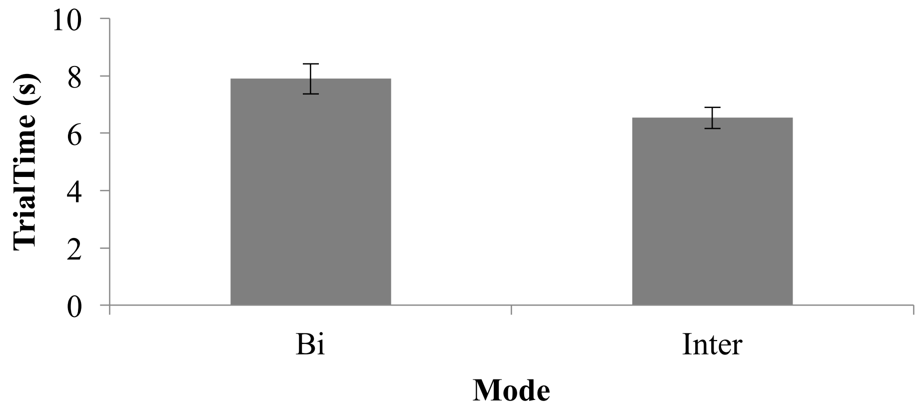

Figure 3.11 Mean trial time (TrialTime) for bimanual trials (Bi) and intermanual trials (Inter). Error bars represent ± 1 standard error of the mean.

In order to examine speed-accuracy tradeoffs, correlations between speed and variability were analyzed. Movement variability (operationally defined as GenVar) was measured in mm using the sagittal (*Y*) dimension. Supplementary analyses using variability along the other two axes produced similar patterns of results. As shown in Table 3.5, GenVar was not significantly correlated to TrialTime when participants completed the task using the bimanual coordination mode (r = -0.46, p = .14, r^2 = 0.21; power [$1 - \beta$] = 0.32) or the intermanual coordination mode (r = 0.11, p = .73; r^2 = 0.01; power [$1 - \beta$] = 0.06).

Table 3.5

*Correlations Between Speed (TrialTime) and Variability (*GenVar*)*

	Bi	Inter
	GenVar	GenVar
TrialTime	-0.46[1]	0.11

Note. N = 12; Bi = Bimanual Trials and Inter = Intermanual Trials.
[1]Denotes medium effect (Cohen, 1992).

Between-hand coupling. To examine differences underlying mode effects, coupling was assessed using %REC. A 2 (Mode) × 2 (Order) mixed-subjects ANOVA on %REC indicated that the Mode × Order interaction was not significant, $F(1, 10) = 0.01$, $p = .929$, $\eta^2 = .001$. Additionally, the main effect of Order was not significant, $F(1, 10) = 1.81$, $p = .208$, $\eta^2 = .15$, showing that any subsequent main effects of Mode on %REC are independent of the order in which participants completed the tasks. The main effect of Mode was significant, $F(1, 10) = 14.23$, $p = .004$, $\eta^2 = .59$. As illustrated in Figure 3.12, %REC was significantly lower when participants completed the task using the Inter Mode (M = 9.92%, SD = 2.92%) compared to the Bi Mode (M = 16.86%, SD = 6.26%). Consequently, an intermanual mode effect for coupling was observed, which is consistent with predictions.

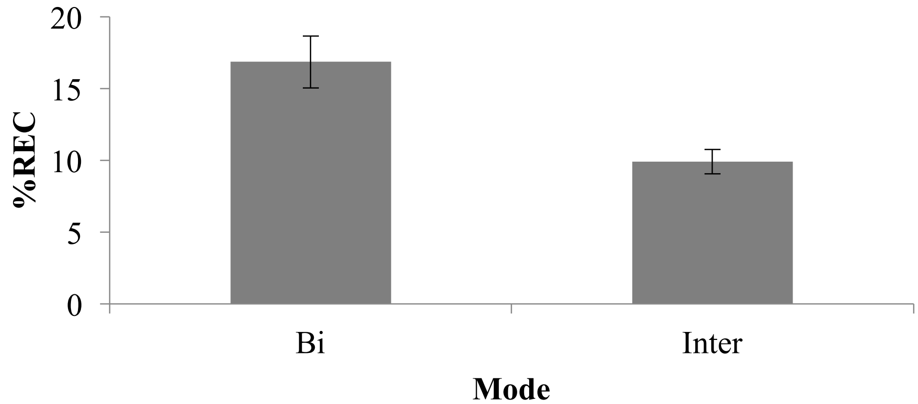

Figure 3.12. Mean percent recurrence (%REC) for bimanual trials (Bi) and intermanual trials (Inter). Error bars represent ± 1 standard error of the mean.

Visuomotor coupling. In order to examine visuomotor coupling, Pre-Reach Look-Ahead and Gaze Anchoring were analyzed for each Mode. For each measure, means were calculated across all grasper and scissor subtasks, respectively; these means were then averaged to produce a single measure for each Mode. Further analyses of this data are provided in Appendix C (Extended Results Section).

Pre-reach look-ahead. A 2 (Mode) × 2 (Order) mixed-subjects ANOVA on mean Pre-Reach Look-Ahead indicated that the Mode × Order interaction was not significant, $F(1, 10) = 4.60$, $p = .058$, $\eta^2 = .32$. Additionally, the main effect of Order was not significant, $F(1, 10) = 1.27$, $p = .286$, $\eta^2 = .11$, showing that any subsequent main effects of Mode on mean Pre-Reach Look-Ahead are independent of the order in which participants completed the tasks. The main effect of Mode was significant, $F(1, 10) = 19.85$, $p = .001$, $\eta^2 = .68$. As illustrated in Figure 3.13, Pre-Reach Look-Ahead was significantly higher when participants completed the task using the Bi Mode ($M = 0.28$ s, $SD = 0.18$ s) compared to the Inter Mode ($M = 0.08$ s, $SD = 0.07$ s). Consequently, an intermanual mode effect for coupling was observed, which is consistent with predictions.

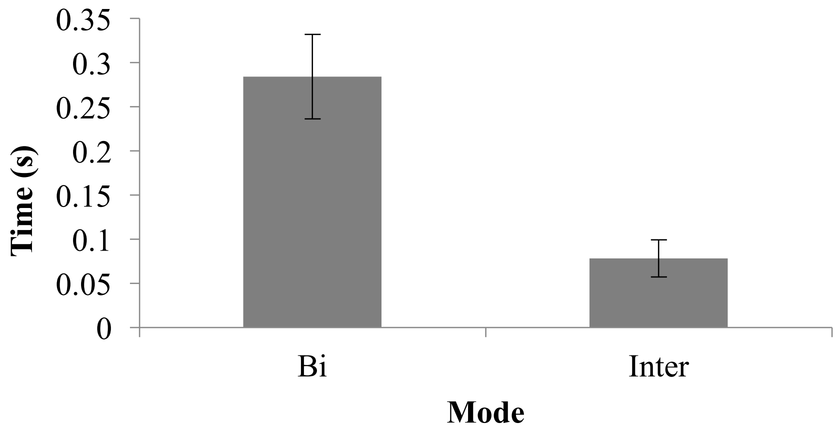

Figure 3.13. Mean Pre-Reach Look-Ahead averaged across subtasks and hands for bimanual trials (Bi) and intermanual trials (Inter). Error bars represent ± 1 standard error of the mean.

Gaze anchoring. A 2 (Mode) × 2 (Order) mixed-subjects ANOVA on mean Gaze Anchoring indicated the Mode × Order interaction was not significant, $F(1, 10) = 0.04$, $p = .850$, $\eta^2 = .004$. Additionally, the main effect of Order was not significant, $F(1, 10) = 0.09$, $p = .773$, $\eta^2 = .01$, showing that any subsequent main effects of Mode on mean Gaze Anchoring are independent of the order in which participants completed the tasks relative. The main effect of Mode was significant, $F(1, 10) = 63.46$, $p < .001$, $\eta^2 = .86$. As illustrated in Figure 3.14, Gaze Anchoring was significantly higher when participants completed the task using the Inter Mode ($M = 0.18$ s, $SD = 0.07$ s) compared to the Bi Mode ($M = 0.03$ s, $SD = 0.08$ s). Consequently, an intermanual mode effect for visuomotor coupling was observed, which is consistent with predictions.

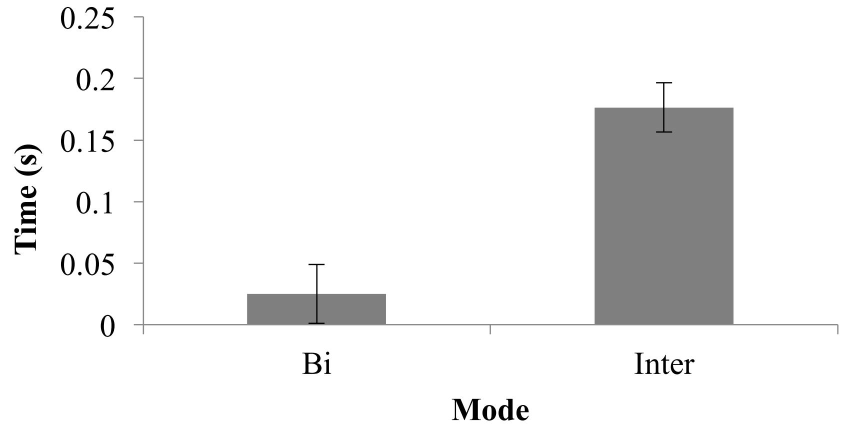

Figure 3.14. Mean Gaze Anchoring averaged across subtasks and hands for bimanual trials (Bi) and intermanual trials (Inter). Error bars represent ± 1 standard error of the mean.

SGDMs. To examine differences underlying mode effects, SGDMs were analyzed. Prior to analysis, Cohen's kappa was calculated on the randomly sampled set of overlapping trials rated by the trained RAs. Cohen's kappa indicated sufficient inter-rater agreement of whether or not a SGDM occurred within a given trial (Cohen, 1968) (percent agreement = 91.05%), $\kappa = 0.815$, $p < 001$.

A 2 (Mode) × 2 (Order) mixed-subjects ANOVA on mean SGDMs indicated the Mode × Order interaction was not significant, $F(1, 10) = 0.75$, $p = .408$, $\eta^2 = .07$. Additionally, the main effect of Order on mean SGDMs was not significant, $F(1, 10) = 0.27$, $p = .873$, $\eta^2 = .003$, showing that any subsequent main effects of Mode are independent of the order in which participants completed the tasks. The main effect of Mode was significant, $F(1, 10) = 115.60$, $p < .001$, $\eta^2 = .92$. As illustrated in Figure 3.15, more SGDMs were observed when participants completed the task using the Inter Mode ($M = 4.88$, $SD = 0.55$) compared to the Bi Mode ($M = 3.16$, $SD = 0.52$). Consequently, an intermanual mode effect for SGDMs was observed, which is consistent with predictions.

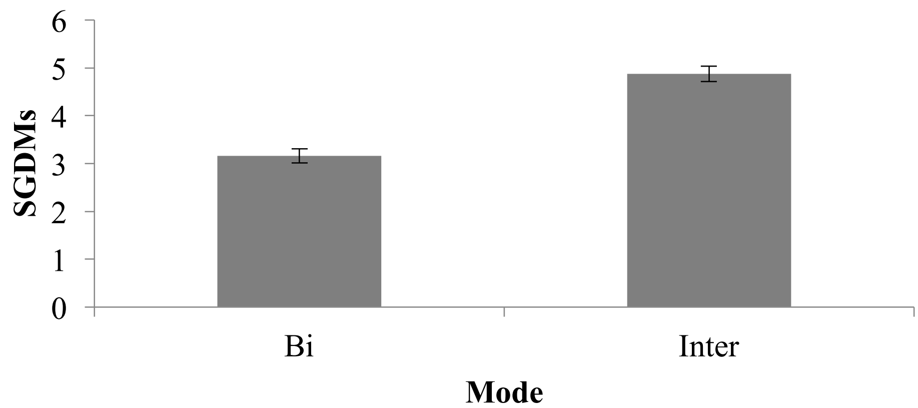

Figure 3.15. Mean number of total SGDMs for bimanual trials (Bi) and intermanual trials (Inter). Error bars represent ± 1 standard error of the mean.

Correlations. To examine the relationship between speed and the explanatory variables, correlations between speed and each dependent variable were analyzed at each level of Mode.

Bimanual. As shown in Table 3.6, when participants completed the task using the bimanual coordination mode TrialTime was significantly correlated with %REC (r = 0.96, $p < .01$; $r^2 = 0.92$; power [$1 - \beta$] = 0.99), Pre-Reach Look-Ahead ($r = 0.77$, $p = .041$; $r^2 = 0.59$; power [$1 - \beta$] = 0.86), Gaze Anchoring ($r = 0.60$, $p = .041$; $r^2 = 0.36$; power [$1 - \beta$] = 0.55), and SGDMs ($r = -0.78$, $p = .003$; $r^2 = 0.61$; power [$1 - \beta$] = 0.88). These findings are consistent with predictions.

Correlations between the explanatory dependent variables were analyzed at each level of Mode to examine whether between-hand coupling and visuomotor coupling measures were significantly correlated with SGDMs when using the bimanual coordination mode. As shown in Table 3.6, when participants completed the task using the bimanual coordination mode, %REC (r = -0.66, p = .019; r^2 = 0.44; power [1 – β] = 0.66) was significantly correlated with SGDMs, which is consistent with predictions. However, Pre-Reach Look-Ahead and Gaze Anchoring (r = -0.57, p = .054; r^2 = 0.32; power [1 – β] = 0.53) were not significantly correlated with SGDMs (r = -0.31, p = .334; r^2 = 0.10; power [1 – β] = 0.16).

Analyses on the remaining variables indicated %REC was significantly correlated with Pre-Reach Look-Ahead (r = 0.84, p = .001; r^2 = 0.71; power [1 – β] = 0.96). However, %REC was not significantly correlated with Gaze Anchoring (r = 0.57, p = .052; r^2 = 0.32; power [1 – β] = 0.46) or GenVar (r = -0.55, p = .066; r^2 = 0.37; power [1 – β] = 0.45). Pre-Reach Look-Ahead was significantly correlated with Gaze Anchoring (r = 0.61, p = .036; r^2 = 0.37; power [1 – β] = 0.56) and GenVar (r = -0.61, p = .034; r^2 = 0.37; power [1 – β] = 0.32). However, Pre-Reach Look-Ahead was not significantly correlated with SGDMs (r = -0.31, p = .334; r^2 = 0.10; power [1 – β] = 0.16). Finally, SGDMs was not significantly correlated with GenVar (r = 0.05, p = .878; r^2 < 0.01; power [1 – β] = 0.05). No predictions were made regarding these correlations.

Table 3.6

Correlations Between the Dependent Variables at the Bimanual Level of Mode

	%REC	Pre-Reach	Gaze	SGDMs	GenVar
TrialTime	0.96**	0.77**	0.60*	-0.78**	-0.46[1]
%REC		0.84**	0.57[2]	-0.66*	-0.55[2]
Pre-Reach			0.61*	-0.31[1]	-0.61*
Gaze				-0.57[2]	-0.30
SGDMs					0.05

Note. N = 12; * p < .05, ** p < .01; [1]Denotes medium effect, [2]denotes medium effect (Cohen, 1992).

Intermanual. As shown in Table 3.7, when participants completed the task using the intermanual coordination mode TrialTime was significantly correlated with Pre-Reach Look-Ahead (r = 0.63, p = .03; r^2 = 0.40; power [1 – β] = 0.60), Gaze Anchoring (r = 0.68, p = .014; r^2 = 0.46; power [1 – β] = 0.705), and SGDMs (r = -0.62, p = .033; r^2 = 0.38; power [1 – β] = 0.59). These findings are consistent with predictions. However, inconsistent with predictions, TrialTime was not significantly correlated with %REC (r = 0.39, p = .216; r^2 = 0.15; power [1 – β] = 0.24).

Correlations between the explanatory dependent variables were analyzed at each level of Mode to examine whether between-hand coupling and visuomotor coupling measures were significantly correlated with SGDMs when using the intermanual coordination mode. %REC (r = -0.39, p = .210; r^2 = 0.15; power [1 – β] = 0.24) and Pre-Reach Look-Ahead (r = -0.32, p = .310; r^2 = 0.10; power [1 – β] = 0.17) were not significantly correlated with SGDMs, which is inconsistent with predictions. However, Gaze Anchoring was significantly correlated with SGDMs (r = -0.67, p = .018; r^2 = 0.45; power [1 – β] = 0.68). This finding was consistent with predictions.

Analyses on the remaining variables indicated %REC was not significantly correlated with Pre-Reach Look-Ahead (r = 0.26, p = .410; r^2 = 0.07; power [1 – β] = 0.13), Gaze Anchoring (r = 0.25, p = .429; r^2 = 0.06; power [1 – β] = 0.12), or GenVar (r = 0.12, p = .717; r^2 = 0.01; power [1 – β] = 0.07). Additionally, Pre-Reach Look-Ahead was significantly correlated with Gaze Anchoring (r = 0.59, p = .042; r^2 = 0.35; power [1 – β] = 0.53). However, Pre-Reach Look-Ahead was not significantly correlated with GenVar (r = 0.09, p = .774; r^2 = 0.01; power [1 – β] = 0.06). Furthermore, Gaze Anchoring was not significantly correlated with GenVar (r = -0.14, p = .658; r^2 = 0.02;

power [1 – β] = 0.07). Finally, SGDMs was not significantly correlated with GenVar (r = 0.32, p = .308; r^2 = 0.10; power [1 – β] = 0.17). No predictions were made regarding these correlations.

Table 3.7

Correlations Between the Dependent Variables at the Intermanual Level of Mode

	%REC	Pre-Reach	Gaze	SGDMs	GenVar
TrialTime	0.39[1]	0.63*	0.68*	-0.62*	0.11
%REC		0.26	0.25	-0.39[1]	0.12
Pre-Reach			0.59*	-0.32[1]	0.09
Gaze				-0.67*	-0.14
SGDMs					0.32[1]

Note. N = 12; * p < .05; [1]denotes medium effect, [2]denotes medium effect (Cohen, 1992).

Appendix C contains (extended results section) analyses of the visuomotor coupling measures for each hand and at each subtask, and SGDMs at each subtask. Supplementary results are provided for the between-hand coupling measure, MAXLINE. Additionally, correlations are presented for GenVar at each axis for all dependent variables. Furthermore, eye-tracking statistics (e.g., number of fixations at each level of Mode) are presented.

Discussion

Experiment 1 investigated bimanual versus intermanual mode effects for a previously unpracticed bimanual task. In order to understand speed differences during these two-handed tasks, explanatory dependent variables were measured and analyzed.

The results of Experiment 1 relative to the hypotheses are described below. Further discussion of these findings is presented in the General Discussion.

Consistent with predictions, Experiment 1 revealed an intermanual speed advantage during a previously unpracticed task, and participants exhibited a higher degree of between-hand coupling, a higher degree of visuomotor coupling, and fewer SGDMs when using the bimanual coordination mode. Thus, H1 was supported. Additionally, Experiment 1 revealed that between-hand coupling and visuomotor coupling measures were significantly correlated with SGDMs when using the bimanual coordination mode, providing further support for H1.

Consistent with predictions, participants exhibited a lower degree of between-hand coupling, a lower degree of visuomotor coupling, and more SGDMs when using the intermanual coordination mode for a previously unpracticed task. Thus, H2 was supported. Additionally, Experiment 1 revealed that visuomotor coupling measures were significantly correlated with SGDMs when using the intermanual coordination mode, which offers further support for H1. However, between-hand coupling was not significantly correlated with SGDMs when using the intermanual coordination mode.

Speed. Participants completed the simulated cutting task faster with a partner compared to working alone (a mode effect). Thus, the previously observed intermanual speed advantage was replicated for a previously unpracticed bimanual task.

Between-hand coupling. Participants exhibited a greater degree of between-hand coupling when they completed the task using the bimanual coordination mode compared to the intermanual coordination mode, suggesting task performance is facilitated by lower levels of between-hand coupling. This finding was corroborated with a significant speed-coupling correlation, suggesting that decoupling movement of the limbs may facilitate speed during bimanual and intermanual tasks. Additionally, these results show that the simulated cutting task evoked bimanual coupling as intended.

Visuomotor coupling. Significant differences were observed for both measures of visuomotor coupling (Pre-Reach Look-Ahead, Gaze Anchoring). Results for these measures are discussed in turn.

Pre-Reach look-ahead. There was a longer offset between glancing at an object and starting a manual action when completing the task using the bimanual coordination mode compared to the intermanual coordination mode. This finding was corroborated with a significant correlation between speed (TrialTime) and Pre-Reach Look-Ahead, such that decreases in Pre-Reach Look-Ahead were associated with longer trial times. This finding suggests that visuomotor coupling may compromise speed during two-handed tasks for the bimanual coordination mode. Specifically, it suggests participants needed more time between looking at something and unimanually interacting with it when completing the task bimanually, which negatively affected performance.

Gaze anchoring. There was a longer offset between terminating a glance and completing a manual action intermanually compared to the bimanually. This finding indicates that bimanual eye-hand coupling at the end of the task was terminated faster than intermanual eye-hand coupling, which is consistent with predictions. Additionally, subsequent correlation analyses indicated that longer trial times (TrialTime) were associated with lower degrees of visuomotor coupling (Gaze Anchoring). This finding suggests that visuomotor coupling may compromise speed during intermanual performance, which is inconsistent with predictions. It also suggests participants terminated their gaze and/or unimanual movement faster when completing the task bimanually. Thus, bimanual simulated cutting ostensibly required participants to quickly finish manual subtasks when using the bimanual coordination mode.

SGDMs. Participants exhibited a greater number of SGDMs when using the intermanual coordination mode (compared to the bimanual coordination mode), suggesting that SGDMs facilitate task performance. This finding was corroborated with a significant speed-SGDM correlation, which suggests that SGDMs may facilitate speed during two-handed tasks. Furthermore, bimanual coupling was significantly correlated with SGDMs, which suggests that decoupled movement of the limbs facilitates SGDMs when completing the task using the both coordination modes.

Chapter IV

Experiment 2

The purpose of Experiment 2 was to evaluate the effect of previous bimanual practice on subsequent mode effects and relations among between-hand coupling, measures of visuomotor coupling, and SGDMs.

Method

Participants. Previous research by Gorman and Crites (2015) reported a relatively large effect size from an ANOVA of the repeated measures, within-between subjects interaction (η^2 = .65; Cohen, 1988). A power analysis was performed for sample size estimation. With alpha (α) = .05 and power ($1 - \beta$) = 0.80, G*Power (Faul, et al., 2007) estimated the sample size needed to be approximately six dyads (N = 12) for this design. However, given the low sample size, it was proposed to use a larger sample size of twelve teams (N = 24) for Experiment 2. Therefore, a larger sample size was used to account for task differences and to establish a similar comparison of groups across experiments. Specifically, differences in sample size estimations across experiments was observed (N = 8 was estimated for Experiment 2).

Twenty-four undergraduates (12 dyads) from Georgia Tech participated for monetary compensation ($45). Participants were recruited using flyers (Appendix D) posted in and around the psychology building. Participants' mean age was M = 23.58 (SD = 4.30), and 50% were female. Six of the dyads were mixed gender, three were all male, and three were all female. As in Experiment 1, participants were required to be right-handed. Right-handedness was assessed using the Edinburgh Handedness Inventory (Oldfield, 1971).

Experimental design. For each dyad, Experiment 2 lasted over a consecutive, three-day period. To address the question of bimanual practice affecting subsequent mode effects, participants separately completed 100 trials per day for two consecutive days prior to analyzing mode effects on day three. The precise number of 100 trials during the two consecutive practice days was based on a previous motor learning experiments that obtained performance plateau or asymptote using a fewer number of trials (e.g., Joseph, Adam, King, & Newell, 2013), which was validated in Experiment 2 (see, Experiment 2 Results). Following the bimanual practice phase, the design of Experiment 2 followed the same design as Experiment 1 by having the same between-subjects manipulation of Order (Bi → Inter and Inter → Bi) and the same within-subjects manipulation of Mode (Bi and Inter). Therefore, after the bimanual practice phase, Experiment 2 had a 2 (Order) × 2 (Mode), mixed-subjects design.

Apparatus and materials. Experiment 2 used the same apparatus and materials described in Experiment 1. However, the eye-tracking software used to collect and analyze data from both of the Dikablis Eye-Tracking Glasses Professional (D-Lab) failed to collect data after the sixth dyad. Due to the instrument error, which could not be fixed, additional teams were unable to be added to the experiment. Therefore, data was analyzed on a smaller sample size ($N = 6$) for all subsequent eye-tracking data (i.e., visuomotor coupling measures). To ensure experimental consistency, all participants still donned the eye-tracking glasses and went through the same procedure as prior participants whose data were able to be collected.

Measures. The visuomotor coupling measures, Pre-Reach Look-Ahead and Gaze Anchoring, were affected by technical difficulties, thus reducing the sample size ($N = 6$).

Importantly, only the visuomotor coupling measures were affected by this issue. Thus, speed, variability, between-hand coupling, and SGDMs utilized the full sample size for all analyses (*N* = 12).

Experiment 2 used the same measures described in Experiment 1 with the addition of performance curve analysis. Functions of performance curves were also included as a manipulation check regarding the bimanual practice phase. The performance curves were fitted with power versus exponential performance curves to ensure the simulated cutting task was sufficiently practiced with the bimanual coordination mode before reporting mode effects. Thus, examining whether or not the task was previously unpracticed or practiced using the bimanual coordination mode. In short, performance data that is better fit using a power law function suggests that learning is “slowing down” (Newell & Rosenbloom, 1981, p. 18) and an exponential function suggests skill acquisition is still in process (Heathcote, Brown, & Mewhort, 2000).

Therefore, if Day 1 and Day 2 bimanual TrialTime data is better fit using a power law function, then the task will be said to be previously practiced using the bimanual coordination mode. However, if bimanual TrialTime data that is better fit using an exponential function, then skill acquisition may still be in process (Heathcote, Brown, & Mewhort, 2000). Additional rationale and background regarding this perspective is provided below.

The motor skill acquisition literature suggests that a power function is the general learning function (A. Newell & Rosenbloom, 1981), which is due largely to seminal works early in the field of motor learning that studied performance curves as an average function over learners (e.g., Crossman, 1959; Snoddy, 1926). However, power function performance curves have been shown to be a result from averaging different individuals' outcome performance data over their multiple timescales of skill acquisition (i.e., averaging over trials, as opposed to analyzing each trial individually) (K. M. Newell, Mayer-Kress, & Liu, 2001). Reanalyzing learning trial series of outcome performance (e.g., trial time of task performance) on an individual-by-individual basis has revealed that an exponential function is a better fit for transient fluctuations in performance that occur on a single timescale when acquiring a new motor skill, and a power function is a better fit for persistent learning across multiple timescales (Stratton, Liu, Hong, Mayer-Kress, & K. M. Newell, 2007; K. M. Newell et al., 2001). Hence, whether individual trial series are better fit by exponential versus power functions corresponds to underlying, qualitative differences in the time scaling characteristics of early transitory (exponential; single timescale) vs. persistent (power; multiple timescales) motor skill acquisition.

Procedure. During the two-consecutive day bimanual practice phase, participants arrived at the lab individually (as opposed to as a dyad as in Experiment 1). At the beginning of the experimental session, informed consent was obtained. Following Georgia Tech IRB protocol, the experimenter assessed whether the participant was sufficiently informed, comprehended what was expected of him or her, and was still willing to continue the study. Participants were shown the apparatus and were given a general overview of the coordination mode (bimanual) in which they used to complete the task.

Similar to Experiment 1, participants were instructed to "complete the task as quickly and accurately as possible" and "to complete the task as fast as possible while still accurately completing the task" and "if a trial is performed incorrectly, then it will not count." Two trained experimenters observed all trials to ensure accuracy. All participants were instructed to place the marker rings on their index fingers and to put their hands in the "ready position" with their fingers "as still and as flat as possible" prior to each trial.

Prior to each trial, the experimenters started the motion-capture data collection and eye-tracker data collection. Participants were instructed to start a trial when hearing a "Go" signal. Upon completing each trial, participants indicated they are finished by saying "Done" when both hands are back in a flat position over the home keys; at this time, the experimenters stopped the motion-capture data and eye-tracker data recordings for that trial. In order to reduce fatigue, participants were provided with a 1-2 minute break after 25 trials (i.e., participants were provided three breaks per day during the bimanual practice phase). After the bimanual practice phase, Experiment 2 used the same procedure described in Experiment 1. Days 1 and 2 each lasted approximately one hour per participant. Day 3 lasted approximately 1.5 hours per dyad. Thus, each dyad participated approximately 5.5 hours in total over the consecutive, three-day period.

Predictions

H3 stated that speed during bimanual coordination for a practiced task is facilitated by reduced bimanual coupling and bimanual visuomotor coupling, which increases the opportunity to perform SGDMs. If this hypothesis is supported, then bimanual performance should be associated with lower TrialTime and lower %REC as compared to intermanual performance. However, due to the physical constraints inherent in bimanual coordination, hit should still be associated with higher Pre-Reach Look-Ahead and lower Gaze Anchoring (as in Experiment 1).

H4 stated that intermanual coordination during a previously practiced bimanual task is facilitated by the same aspects as intermanual coordination during an unpracticed task. However, due to previous bimanual practice and lack of intermanual practice, intermanual performance will be slower than bimanual performance. Moreover, the associated explanatory dependent variables should indicate decreased task performance with the intermanual, relative to bimanual, coordination mode. SGMDs are predicted to be equal for the two coordination modes because bimanual practice has overcome bimanual coupling and, to a degree, bimanual visuomotor coupling and intermanual coordination should still be reflecting the same behavior that facilitates SGDMs. Results that would support these predictions are summarized in Table 4.1.

Table 4.1

Experiment 2 Predictions Relative to Dependent Variables

Dependent Variable	Coordination Mode	
	Bimanual	Intermanual
TrialTime	Lower	Higher
%REC	Lower	Higher
Pre-Reach Look-Ahead	Higher	Lower
Gaze Anchoring	Lower	Higher
SGDMs	Equal	Equal

Additional support for H4 and H4 would be obtained from significant bimanual correlations involving TrialTime and the explanatory variables: %REC, Pre-Reach Look-Ahead, Gaze Anchoring, and SGDMs. Finally, because H3 and H4 posit that between-hand coupling and visuomotor coupling inhibit or permit the ability to make SGDMs, it would be predicted that %REC, Pre-Reach Look-Ahead, and Gaze Anchoring will be significantly correlated to SGDMs.

Results

The primary purpose of Experiment 2 was to investigate how bimanual practice affects previously observed mode effects involving speed. Results for the dependent measures in Experiment 2 are presented in the same order as Experiment 1. Descriptive statistics for Experiment 2 are presented in Table 4.2. Effect sizes reported are partial eta-squared and Cohen's *d* (Cohen, 1992; Keppel & Wickens, 2004).

Table 4.2

Summary of Results for Experiment 2

Dependent Variable	Coordination Mode	
	Bimanual	Intermanual
TrialTime (s)	5.27 (0.61)	5.36 (0.61)
%REC	10.05 (4.27)	6.44 (2.15)
Pre-Reach Look-Ahead (s)	0.11 (0.06)	0.04 (0.12)
Gaze Anchoring (s)	-0.01 (0.04)	0.14 (0.05)
SGDMs	3.79 (0.24)	4.45 (0.28)

Note. Means are presented with standard deviations in parentheses.

Repeated contrasts on TrialTime were first analyzed to assess whether each bimanual performance was still improving in each coordination mode (i.e., have reached performance plateau or asymptote). None of the contrasts were significant for Bi and ten contrasts were significant for Inter (Trial 1 vs. Trial 4; Trial 1 vs. Trial 5; Trial 1 vs. Trial 8; Trial 2 vs. Trial 4; Trial 3 vs. Trial 4; Trial 3 vs. Trial 4; Trial 3 vs. Trial 6; Trial 3 vs. Trial 7; Trial 3 vs. Trial 8; Trial 4 vs. Trial 10). These patterns of results indicate that performance reached asymptote when using the bimanual coordination mode (Gray & Lindstedt, 2016), but continued to improve beyond Trial 4 for the intermanual coordination mode (see Figure 4.1). Consequently, the task was considered to be previously practiced when using the bimanual coordination mode, but not when using the intermanual coordination mode (i.e., learning was still occurring).

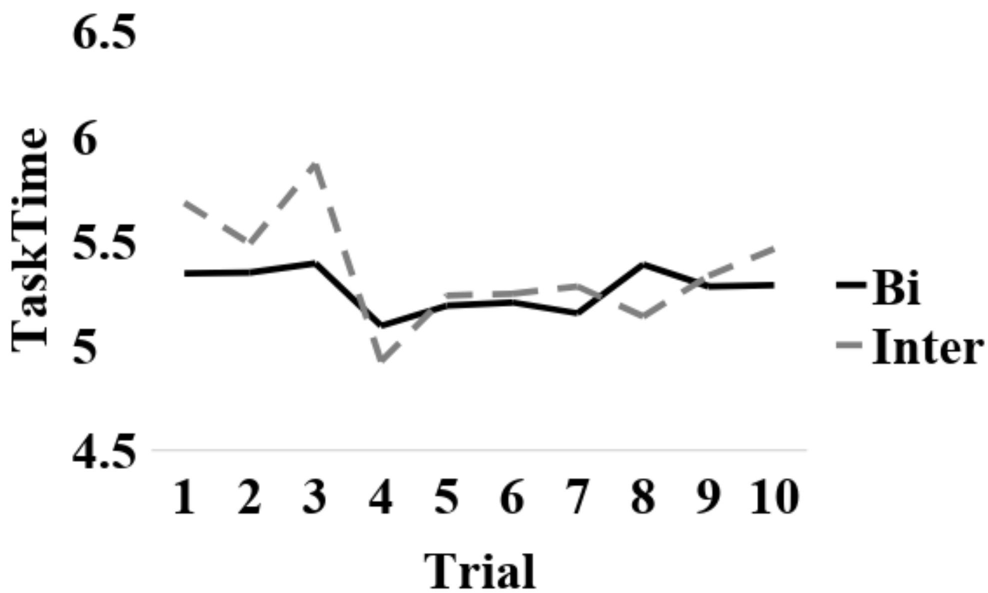

Figure 4.1. Mean trial times as a function of trial, indicating performance asymptote was reached for the bimanual coordination mode (Bi) but learning was still potentially occurring with the coordination model (Inter).

To ensure performance had reached performance asymptote or plateau, practice was further assessed with performance curves. Specifically, exponential and power law functions were fit to the data to examine whether skill acquisition was still underway (Stratton et al., 2007; K. M. Newell et al., 2001). Two paired-samples *t*-tests on individual (as opposed to average) speed data for the bimanual practice phase were calculated to compare the fit of the two functions for Day 1 and Day 2. As shown in

Figure 4.2, the power law function fit the data better (*M* = 0.43; *SD* = 0.08) than an exponential function (*M* = 0.35; *SD* = 0.09) for Day 1, $t(11) = -6.05$, $p < .001$, $d = -1.78$. Similarly, a power law function fit the data better (*M* = 0.11; *SD* = 0.06) than an exponential function (*M* = 0.09; *SD* = 0.05) for Day 2, $t(11) = -2.67$, $p = .022$, $d = -0.14$. Thus, skill acquisition with the bimanual coordination mode exhibited timescales characteristic of individuals who are no longer learning and have reached performance plateau or asymptote (Gray & Lindstedt, 2016; Stratton et al., 2007). This finding is consistent with predictions.

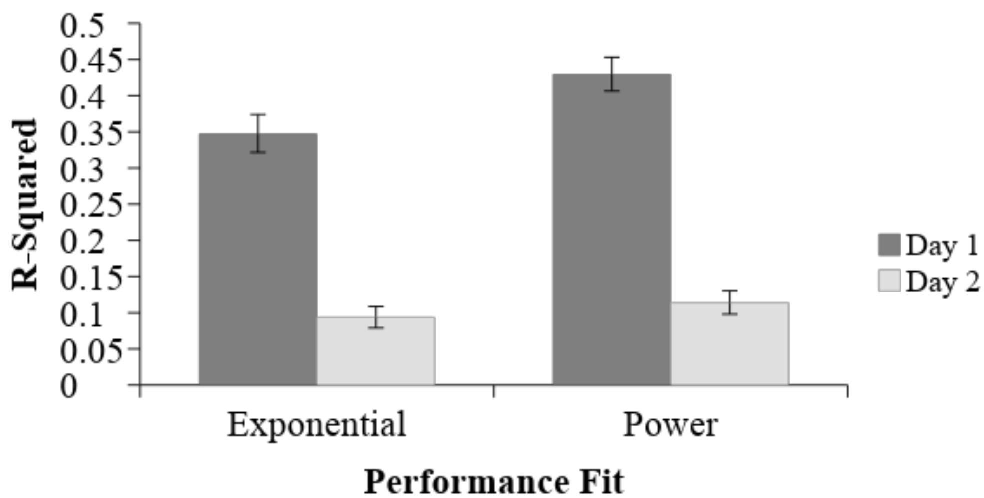

Figure 4.2. Mean R-squared for trials fitted to exponential performance curves and power law performance curves for Day 1 and Day 2 of the bimanual practice phase. Error bars represent ± 1 standard error of the mean.

Speed. In order to examine practice effects across coordination modes, mean TrialTime was analyzed using a 2 (Mode) × 2 (Order) mixed-subjects ANOVA. The Mode × Order interaction was not significant, $F(1, 10) = 0.92$, $p = .360$, $\eta^2 = .08$. Additionally, the main effect of Mode was not significant, $F(1, 10) = 0.81$, $p = .388$, $\eta^2 = .08$. This finding is inconsistent with predictions. However, the main effect of Order was significant, $F(1, 10) = 5.70$, $p = .038$, $\eta^2 = .36$. As illustrated in Figure 4.3, mean TrialTime was significantly lower when participants completed the task using the Bi → Inter Order (M = 4.98 s, SD = 0.51 s) compared to the Inter → Bi Order (M = 5.65 s, SD = 0.50 s). Thus, overall, participants were faster when starting with the familiar, previously practiced coordination mode as opposed to the unfamiliar, novel coordination mode.

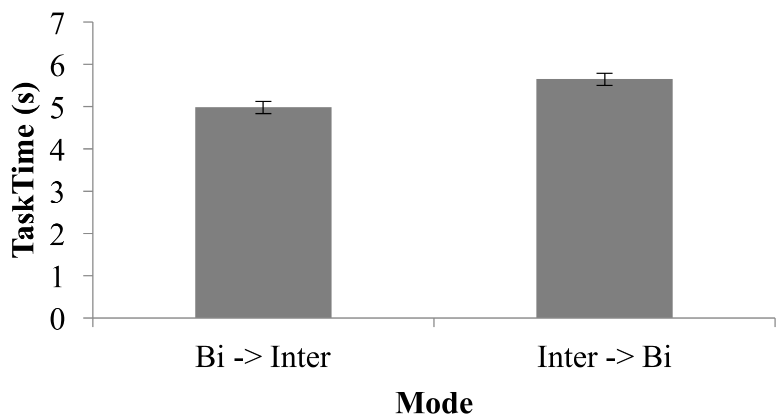

Figure 4.3. Mean trial time (TrialTime) for trials in which participants started with the bimanual coordination mode first (Bi → Inter) and trials in which they started with the intermanual coordination mode (Inter → Bi). Error bars represent ± 1 standard error of the mean.

In order to examine speed-accuracy tradeoffs, correlations between speed and variability were analyzed. Just as in Experiment 1, movement variability (operationally defined as GenVar) was measured in mm using the sagittal (Y) dimension. Supplementary analyses using variability along the other two axes produced similar patterns of results. As shown in Table 4.3, GenVar was not significantly correlated to TrialTime when participants used the bimanual coordination mode ($r = -0.20$, $p = .528$; r^2

= 0.04; power [1 – β] = 0.09) or the intermanual coordination mode (r = -0.51, p = .093; r^2 = 0.26; power [1 – β] = 0.39).

Table 4.3

*Correlations Between Speed (TrialTime) and Variability (*GenVar*)*

	Bi	Inter
	GenVar	GenVar
TrialTime (s)	-0.20	-0.51[1]

Note. N = 12; Bi = Bimanual Trials and Inter = Intermanual Trials.
[1]Denotes large effect (Cohen, 1992).

Between-hand coupling. To examine differences underlying mode effects, coupling was assessed using %REC. A 2 (Mode) × 2 (Order) mixed-subjects ANOVA on mean %REC indicated that the Mode × Order interaction was not significant, $F(1, 10)$ = 1.44, p = .258, η^2 = .13. However, the main effect of Mode was significant, $F(1, 10)$ = 7.76, p = .019, η^2 = .44. As illustrated in Figure 4.4, mean %REC was significantly lower when participants completed the task using the Inter Mode (M = 6.44%, SD = 2.15%) compared to the Bi Mode (M = 10.05%, SD = 4.27%). Consequently, an intermanual mode effect for coupling was observed, which is inconsistent with predictions.

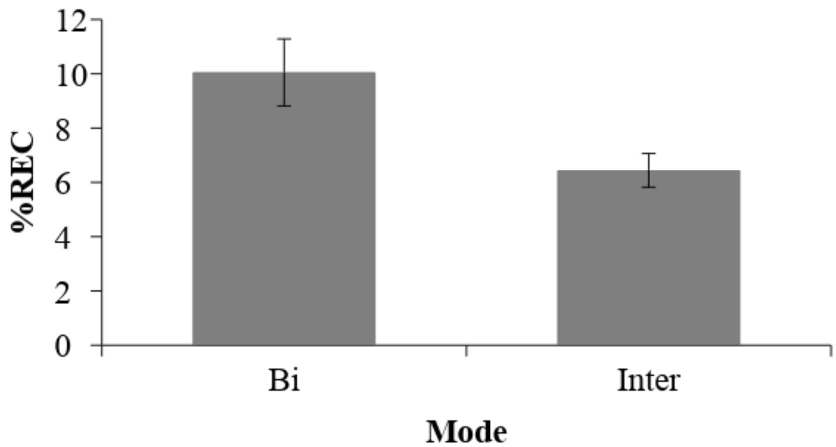

Figure 4.4. Mean percent recurrence (%REC) for bimanual trials (Bi) and intermanual trials (Inter). Error bars represent ± 1 standard error of the mean.

Additionally, the main effect of Order on mean %REC was significant, $F(1, 10) = 12.44$, $p = .005$, $\eta^2 = .55$. As illustrated in Figure 4.5, mean %REC was significantly lower when participants completed the task using the Bi → Inter Order ($M = 6.47\%$, $SD = 2.15\%$) compared to Inter → Bi Order ($M = 10.02\%$, $SD = 4.27\%$). Thus, overall, participants decoupled their limbs more when starting the mode effect experiment with the familiar, previously practiced coordination mode as opposed to the unfamiliar, novel coordination mode.

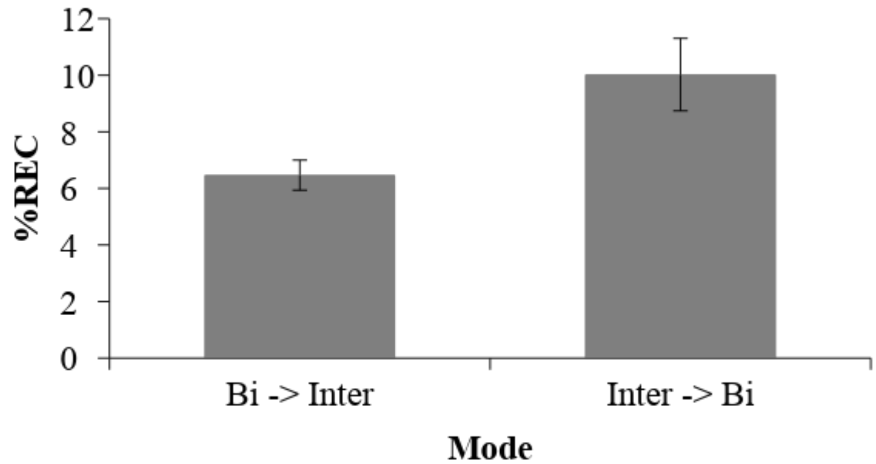

Figure 4.5. Mean percent recurrence (%REC) for trials where participants started with the bimanual coordination mode first (Bi → Inter) and trials where participants started with the intermanual coordination mode (Inter → Bi). Error bars represent ± 1 standard error of the mean.

Visuomotor coupling. In order to examine visuomotor coupling, Pre-Reach Look- Ahead and Gaze Anchoring were analyzed for each Mode. Just as in Experiment 1, for each measure, means were calculated across all grasper and scissor subtasks, respectively; these means were then averaged to produce a single measure for each Mode.

Pre-reach look-ahead. A 2 (Mode) × 2 (Order) mixed-subjects ANOVA on mean Pre-Reach Look-Ahead indicated that the Mode × Order interaction was not significant, $F(1, 3) = 0.01$, $p = .942$, $\eta^2 = .002$. Additionally, the main effects of Order, $F(1, 3) = 0.27$, $p = .638$, $\eta^2 = .08$, and Mode, $F(1, 3) = 0.89$, $p = .416$, $\eta^2 = .23$, were not significant. As illustrated in Figure 4.6, Pre-Reach Look-Ahead values were similar for Bi ($M = 0.11$ s, $SD = 0.06$ s) compared to Inter ($M = 0.04$ s, $SD = 0.12$ s). However, the general pattern of results is consistent with predictions and results of Experiment 1.

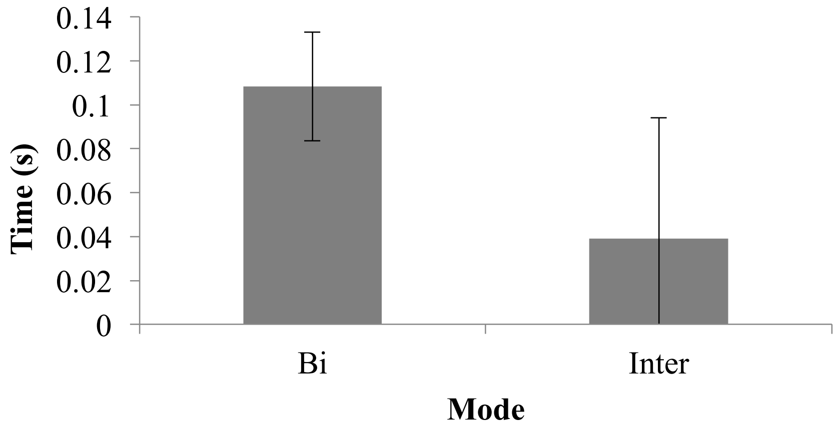

Figure 4.6. Mean Pre-Reach Look-Ahead averaged across subtasks and hands for bimanual trials (Bi) and intermanual trials (Inter). Error bars represent ± 1 standard error of the mean.

Gaze anchoring. A 2 (Mode) × 2 (Order) mixed-subjects ANOVA on mean Gaze Anchoring indicated the Mode × Order interaction was not significant, $F(1, 3) = 0.12$, $p = .748$, $\eta^2 = .04$. Additionally, the main effects of Order, $F(1, 3) = 1.09$, $p = .373$, $\eta^2 = .27$. and Mode, $F(1, 3) = 10.05$, $p = .050$, $\eta^2 = .77$, on mean Gaze Anchoring were not significant. As illustrated in Figure 4.7, Gaze Anchoring values were similar for Bi (M = 0.02 s, SD = 0.08 s) compared to Inter (M = 0.18 s, SD = 0.07 s). However, the general pattern of results is consistent with predictions and results of Experiment 1.

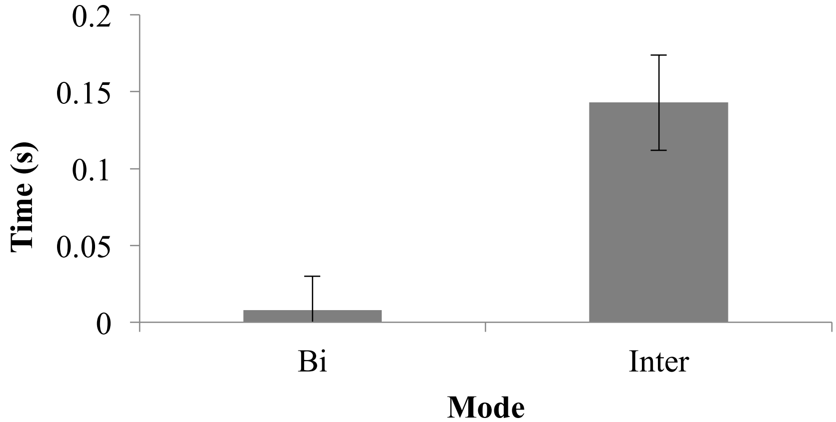

Figure 4.7. Mean Gaze Anchoring averaged across subtasks and hands for bimanual trials (Bi) and intermanual trials (Inter). Error bars represent ± 1 standard error of the mean.

SGDMs. To examine differences underlying mode effects, SGDMs were analyzed. Similar to Experiment 1, prior to analysis, Cohen's kappa was calculated on the randomly sampled set of overlapping trials rated by the trained RAs. Cohen's kappa indicated sufficient inter-rater agreement of whether or not a SGDM occurred within a given trial (Cohen, 1968) (percent agreement = 92.13%), $\kappa = 0.823$, $p < 001$.

A 2 (Mode) × 2 (Order) mixed-subjects ANOVA on mean SGDMs indicated the Mode × Order interaction was not significant, $F(1, 10) = 4.09$, $p = .074$, $\eta^2 = .31$. Additionally, the main effect of Order was not significant, $F(1, 10) = 0.01$, $p = .928$, $\eta^2 = .001$. The main effect of Mode was significant, $F(1, 10) = 76.77$, $p < .001$, $\eta^2 = .90$. As illustrated in Figure 4.8, more SGDMs were observed when participants completed the task using the Inter Mode ($M = 4.45$, $SD = 0.28$) compared to the Bi Mode ($M = 3.79$, $SD = 0.24$). Consequently, an intermanual mode effect for SGDMs was observed, which is inconsistent with predictions.

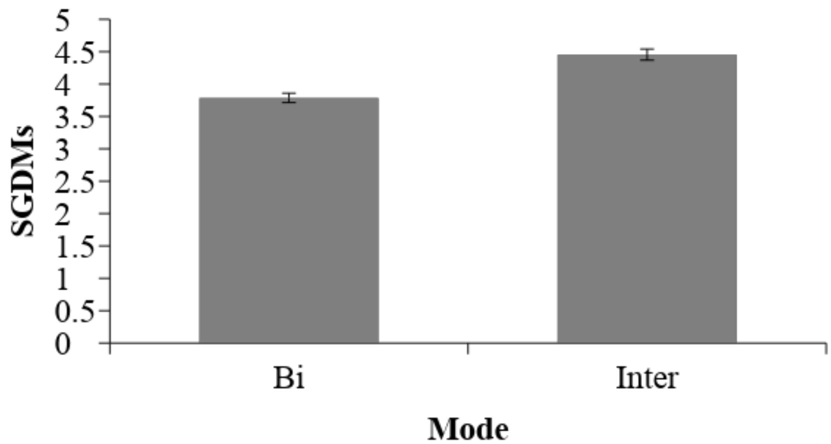

Figure 4.8. Mean number of total SGDMs for bimanual trials (Bi) and intermanual trials (Inter). Error bars represent ± 1 standard error of the mean.

Correlations. To examine the relationship between speed and the explanatory variables, correlations between speed and each dependent variable were analyzed at each level of Mode.

Bimanual. As shown in Table 4.4, when participants completed the task using the bimanual coordination mode, TrialTime was significantly correlated with %REC (r = 0.81, p = .002; r^2 = 0.66; power [1 – β] = 0.92), which is consistent with predictions. However, TrialTime was not significantly correlated with Pre-Reach Look-Ahead (r = 0.26, p = .041; r^2 = 0.59; power [1 – β] = 0.07), Gaze Anchoring (r = -0.21, p = .685; r^2 = 0.04; power [1 – β] = 0.07), or SGDMs (r = 0.31, p = .328; r^2 = 0.10; power [1 – β] = 0.16). These findings are inconsistent with predictions.

Correlations between the explanatory dependent variables were analyzed at each level of Mode to examine whether between-hand coupling and visuomotor coupling measures were significantly correlated with SGDMs when using the bimanual coordination mode. As shown in Table 4.4, when participants completed the task using the bimanual coordination mode, %REC (r = .25, p = .439; r^2 = 0.06; power [1 – β] =

0.12), Pre-Reach Look-Ahead (r = -0.04, p = .934; r^2 < 0.01; power [1 – β] = 0.05), and Gaze Anchoring (r = -0.06, p = .912; r^2 < 0.01; power [1 – β] = 0.05) were not significantly correlated with SGDMs. These findings are inconsistent with predictions.

Analyses on the remaining variables indicated %REC was not significantly correlated with Pre-Reach Look-Ahead (r = 0.10, p = .899; r^2 = 0.01; power [1 – β] = 0.05), Gaze Anchoring (r = -0.04, p = .946; r^2 = 0.06; power [1 – β] = 0.05), or GenVar (r = -.37, p = .235; r^2 = 0.14; power [1 – β] = 0.21). Furthermore, Pre-Reach Look-Ahead was not significantly correlated with Gaze Anchoring (r = 0.39, p = .448; r^2 = 0.15; power [1 – β] = 0.11) or GenVar (r = -0.64, p = .168; r^2 = 0.41; power [1 – β] = 0.26). Moreover, Gaze Anchoring was not significantly correlated with GenVar (r = -0.65, p = .162; r^2 = 0.42; power [1 – β] = 0.27). Finally, SGDMs was not significantly correlated with GenVar (r = -0.43, p = .167; r^2 = 0.18; power [1 – β] = 0.13). No predictions were made regarding these correlations.

Table 4.4

Correlations Between the Dependent Variables at the Bimanual Level of Mode

	%REC	Pre-Reach[1]	Gaze[1]	SGDMs	GenVar
TrialTime	0.81**	0.26	-0.21	0.31[2]	-0.20
%REC		0.07	-0.04	0.25	-0.37[2]
Pre-Reach			0.39[2]	-0.04	-0.64[3]
Gaze				-0.06	-0.65[3]
SGDMs					-0.44[2]

Note. N = 12 ([1]N = 6); * p < .05, ** p < .01; [2]Denotes medium effect, [3]Denotes large effect (Cohen, 1992).

Intermanual. As shown in Table 4.5, none of the other correlations were significant for the intermanual coordination mode. TrialTime was not significantly correlated with %REC (r = 0.38, p = .221; r^2 = 0.14; power [1 – β] = 0.22), Pre-Reach Look-Ahead (r = -0.16, p = .804; r^2 = 0.03; power [1 – β] = 0.06), Gaze Anchoring (r = 0.36, p = .554; r^2 = 0.13; power [1 – β] = 0.10), or SGDMs (r = 0.01, p = .967; r^2 < 0.01; power [1 – β] = 0.05). These findings are inconsistent with predictions. %REC was not significantly correlated with Pre-Reach Look-Ahead (r = -0.12, p = .854; r^2 = 0.01; power [1 – β] = 0.06), Gaze Anchoring (r = -0.72, p = .168; r^2 = 0.52; power [1 – β] = 0.35), SGDMs (r = 0.03, p = .934; r^2 < 0.01; power [1 – β] = 0.05), or GenVar (r = -0.42, p = .170; r^2 = 0.18; power [1 – β] = 0.27). Pre-Reach Look-Ahead was not significantly correlated with Gaze Anchoring (r = -0.09, p = .884; r^2 < 0.01.09; power [1 – β] = 0.12), SGDMs (r = -0.26, p = .667; r^2 = 0.07; power [1 – β] = 0.07), or GenVar (r = -0.30, p = .630; r^2 = 0.09; power [1 – β] = 0.08). Gaze Anchoring was not significantly correlated with SGDMs (r = -0.67, p = .218; r^2 = 0.45; power [1 – β] = 0.29) or GenVar (r = 0.11, p = .864; r^2 = 0.01; power [1 – β] = 0.05). Finally, SGDMs was not significantly correlated with GenVar (r = 0.04, p = .901; r^2 < 0.01; power [1 – β] = 0.05).

Table 4.5

Correlations Between the Dependent Variables at the Intermanual Level of Mode

	%REC	Pre-Reach[1]	Gaze[1]	SGDMs	GenVar
TrialTime	0.38[2]	-0.16	0.36[2]	0.01	-0.51[3]
%REC		-0.12	-0.72[3]	0.03	-0.42
Pre-Reach			-0.09	-0.27	-0.30
Gaze				-0.67[3]	0.11
SGDMs					0.04

Note. N = 12 ([1]N = 5); [2]Denotes medium effect, [3]Denotes large effect (Cohen, 1992).

Appendix C contains (extended results section) analyses of the visuomotor coupling measures for each hand and at each subtask, and SGDMs at each subtask. Supplementary results are provided for the between-hand coupling measure, MAXLINE. Additionally, correlations are presented for GenVar at each axis for all dependent variables. Furthermore, eye-tracking statistics (e.g., number of fixations at each level of Mode) are presented.

Discussion

Experiment 2 investigated bimanual versus intermanual mode effects for a previously practiced bimanual task. In order to understand speed differences during these two-handed tasks, explanatory dependent variables were measured and analyzed. The results of Experiment 2 relative to the hypotheses are described below. Further discussion of these findings is presented in the General Discussion.

H3. Experiment 2 revealed no differences in coordination mode during a previously practiced bimanual task, which was partially inconsistent with predictions. Specifically, participants exhibited a higher degree of both between-hand coupling and visuomotor coupling, and fewer SGDMs, when using the bimanual coordination mode. Thus, H3 was not supported. Additionally, Experiment 2 revealed that between-hand coupling was significantly correlated with SGDMs when using the bimanual coordination mode, which offers partial support for H3. However, visuomotor coupling measures were not significantly correlated with SGDMs when using the bimanual coordination mode.

H4. Consistent with predictions, participants exhibited low degrees of between-hand coupling and visuomotor coupling, and a greater number of SGDMs, when using the intermanual coordination mode for a previously practiced bimanual task. Thus, H4 was supported. However, Experiment 2 revealed that between-hand coupling and visuomotor coupling measures were not significantly correlated with SGDMs when using the intermanual coordination mode.

Speed. Prior to analyses of mode effects, performance curves were analyzed to ensure the task was previously practiced after 200 trials with the bimanual coordination. Indeed, results revealed that an exponential performance curve better-fit the data (in terms of variability accounted for), which is consistent with predictions. Therefore, learning using the bimanual coordination mode seemed to have reached either performance plateau or asymptote (Gray & Lindstedt, 2016; K. M. Newell et al., 2001).

There was not a significant difference between mean task times using the different coordination modes with a previously practiced bimanual task. Thus, the intermanual speed advantage that was observed during a simulated cutting for Experiment 1 was not reversed (Gorman & Crites, 2015); however, the effect disappeared. This finding indicates that previous bimanual practice may eliminate any potential mode effects that existed prior to bimanual skill acquisition. In an effort to further understand what underlies this absence of a mode effect on speed from a behavioral perspective, additional behavioral variables were collected and analyzed. These measures are discussed below.

Between-hand coupling. The pattern of results for Coupling were similar to that in Experiment 1. Participants exhibited a greater degree of between-hand coupling when they completed the task using the bimanual coordination mode compared to the intermanual coordination mode; however, this mode effect was not paired with a significant mode effect of speed. Additionally, this a significant speed-coupling correlation was observed when completing the task using the bimanual coordination mode, suggesting that decoupling movement of the limbs may be more important during bimanual performance than intermanual. Thus, it seems the simulated cutting task continued to evoke bimanual coupling after the bimanual practice phase.

Visuomotor coupling. Significant mode effects (using the adjusted alpha) were observed for Gaze Anchoring, but not for Pre-Reach Look-Ahead. This pattern of results further suggests that bimanual and intermanual coordination modes are distinguishable. Additionally, while speed-visuomotor correlations were not present in Experiment 2, the small sample paired with the pattern of results from Experiment 1 suggest that both measures of visuomotor coupling are associated with speed during two-handed tasks, regardless of coordination modes.

Pre-reach look-ahead. There was a lack of significant difference between the two coordination modes on Pre-Reach Look-Ahead (the time between glancing at an object and starting a manual action). However, examination of Figure 4.6 shows the pattern of results was the same during Experiment 1. This finding was not associated with a significant speed-pre-reach-look-ahead correlation.

Gaze anchoring. The pattern of results for Gaze Anchoring were similar to that of Experiment 1. Specifically, there was a longer offset between terminating a glance and completing a manual action when performing the task with the intermanual coordination mode compared to the bimanual coordination mode. However, this finding was not corroborated with a significant speed-gaze-anchoring correlation. As with Pre-Reach Look-Ahead, significant mode effects of visuomotor coupling illustrate the differences across coordination modes. Specifically, these results demonstrated eye-hand behavioral differences during two-handed tasks where one of the coordination modes is able to utilize different visuomotor systems.

SGDMs. Participants exhibited a greater number of SGDMs when using the intermanual coordination mode (compared to the bimanual coordination mode), suggesting that SGDMs facilitate task performance. This finding replicates the results of Experiment 1; however, this was not accompanied by a mode effect of speed in Experiment 2. Therefore, SGDMs may not be a critical mechanism underlying the speed differences that occur between bimanual and intermanual coordination in a previously practiced bimanual task.

Chapter V

Statistical Comparison of Experiments

In order to examine the effect of previous bimanual practice, the results for Experiment 1 and Experiment 2 were compared statistically. Effect sizes reported are partial eta-squared and Cohen's *d* (Cohen, 1992; Keppel & Wickens, 2004). A summary of the results for Experiments 1 and Experiment 2 is presented in Table 5.1.

Table 5.1

Summary of Results for Experiment 1 and 2

Dependent Variable	Experiment			
	Experiment 1		Experiment 2	
	Bimanual	Intermanual	Bimanual	Intermanual
TrialTime (s)	7.90 (1.83)	6.54 (1.26)	5.27 (0.61)	5.36 (0.61)
%REC	16.86 (6.26)	9.92 (2.92)	10.05 (4.27)	6.44 (2.15)
Pre-Reach Look-Ahead (s)	0.30 (0.18)	0.07 (0.07)	0.11 (0.06)	0.04 (0.12)
Gaze Anchoring (s)	0.02 (0.08)	0.18 (0.07)	-0.01 (0.04)	0.14 (0.05)
SGDMs	3.12 (0.37)	4.88 (0.55)	3.79 (0.24)	4.45 (0.28)

Note. Means reported. Standard deviations in parentheses.

Speed. Mean TrialTime was analyzed using a 2 (Mode) × 2 (Experiment) mixed-subjects ANOVA. The Mode × Experiment interaction on mean TrialTime was significant, $F(1, 22) = 33.92$, $p = .001$, $\eta^2 = .607$. The main effect of Mode was significant, $F(1, 22) = 25.47$, $p < .001$, $\eta^2 = .537$. Additionally, the main effect of Experiment was significant, $F(1, 22) = 16.91$, $p = .001$, $\eta^2 = .426$, indicating that the bimanual practice phase influenced subsequent task times (see Figure 5.1).

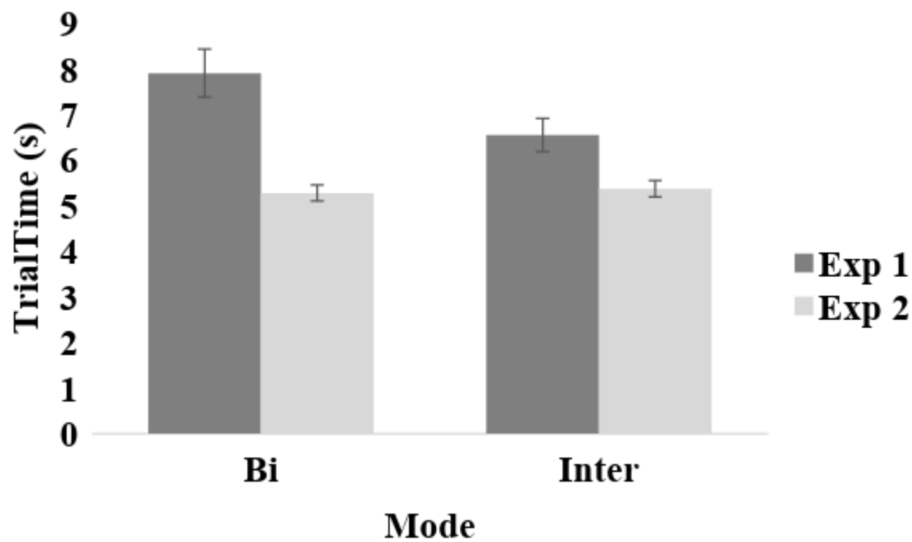

Figure 5.1. Mean trial time (TrialTime) for bimanual trials (Bi) and intermanual trials (Inter) for Experiment 1 and Experiment 2. Error bars represent ± 1 standard error of the mean.

In order to examine the effect of previous bimanual practice during Day 1 and Day 2 of Experiment 2, the simple effects of Experiment on mean TrialTime were assessed at each level of Mode using independent-samples *t*-tests ($\alpha_{\mathrm{Bon}} = .05/2 = .025$). As illustrated in Figure 5.1, mean TrialTime when participants completed the task using the Bi Mode was significantly higher during Experiment 1 ($M = 7.90$ s; $SD = 1.83$ s) than Experiment 2 ($M = 5.27$ s; $SD = 0.61$ s), $t(13.40) = 4.72$, $p < .001$, $d = 1.93$; this finding is consistent with predictions. Additionally, mean TrialTime when participants completed the task using the Inter Mode was significantly higher in Experiment 1 ($M = 6.53$ s; $SD = 1.16$ s) than Experiment 2 ($M = 5.36$ s; $SD = 0.61$ s), $t(22) = 4.72$, $p = .008$, $d = 1.26$. This finding is inconsistent with predictions.

Between-hand coupling. A 2 (Mode) × 2 (Experiment) mixed-subjects ANOVA indicated that the Mode × Experiment interaction on mean %REC was not significant, $F(1, 22) = 2.31$, $p = .143$, $\eta^2 = .10$. However, there were significant main effects of Mode,

$F(1, 22) = 23.07$, $p < .001$, $\eta^2 = .51$, and Experiment, $F(1, 22) = 15.25$, $p = .001$, $\eta^2 = .41$, on mean %REC, indicating that the bimanual practice phase influenced subsequent coupling (see Figure 5.2). This finding is consistent with predictions.

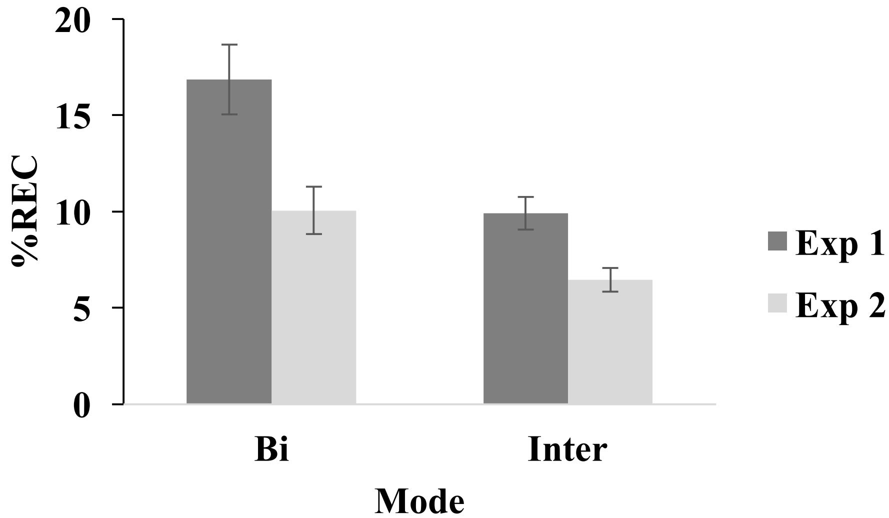

Figure 5.2. Mean percent recurrence (%REC) for bimanual trials (Bi) and intermanual trials (Inter) for Experiment 1 and Experiment 2. Error bars represent ± 1 standard error of the mean.

In order to examine the effect of previous bimanual practice during Day 1 and Day 2 of Experiment 2, the simple effects of Experiment on mean %REC were assessed at each level of Mode using independent-samples *t*-tests ($\alpha_{Bon} = .05/2 = .025$). As illustrated in Figure 5.2, participants' mean %REC when completing the task using the Bi Mode was significantly higher in Experiment 1 ($M = 16.86\%$; $SD = 6.26\%$) than Experiment 2 ($M = 10.05\%$; $SD = 4.27\%$), $t(22) = 3.11$, $p = .011$, $d = 1.27$. This finding is consistent with predictions. Additionally, participants' mean %REC when completing the task using the Inter Mode was significantly higher during Experiment 1 ($M = 9.92\%$; *SD*

= 2.92%) than Experiment 2 (*M* = 6.44%; *SD* = 2.15%), $t(22) = 3.32$, $p = .003$, $d = 1.36$. This finding is inconsistent with predictions.

Pre-reach look-ahead. A 2 (Mode) × 2 (Experiment) mixed-subjects ANOVA on mean Pre-Reach Look-Ahead indicated that the Mode × Experiment interaction was not significant, $F(1, 15) = 2.46$, $p = .137$, $\eta^2 = .14$. There was a significant main effect of Mode, $F(1, 15) = 9.94$, $p = .007$, $\eta^2 = .51$ (see Figure 5.3), as mean Pre-Reach Look-Ahead was greater when completing the task using the Bi Mode (*M* = 0.28 s; *SD* = 0.18 s) than the Inter mode (*M* = 0.11 s; *SD* = 0.05 s). The main effect of Experiment was not significant, $F(1, 15) = 4.40$, $p = .053$, $\eta^2 = .23$. This finding is consistent with predictions.

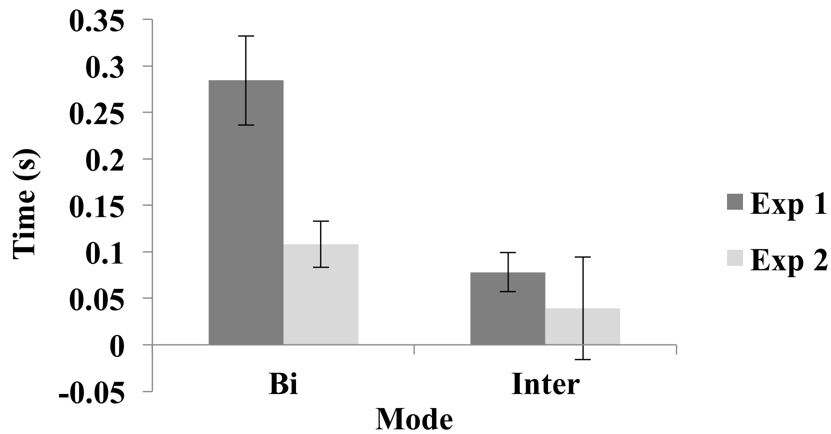

Figure 5.3. Mean Pre-Reach Look-Ahead averaged across subtasks and hands for bimanual trials (Bi) and intermanual trials (Inter) for Experiment 1 and Experiment 2. Error bars represent ± 1 standard error of the mean.

Gaze anchoring. A 2 (Mode) × 2 (Experiment) mixed-subjects ANOVA on mean Gaze Anchoring indicated that the Mode × Experiment interaction was not significant, $F(1, 15) = .048$, $p = .829$, $\eta^2 = .003$. There was a significant main effect of Mode on mean Gaze Anchoring, $F(1, 15) = 74.94$, $p < .001$, $\eta^2 = .83$, such that participants exhibited greater mean gaze anchoring using the Inter Mode (*M* = 0.02 s; *SD* = 0.07 s) than the Bi Mode (*M* = 0.16 s; *SD* = 0.07 s) (see Figure 5.4). The main effect of Experiment was not significant, $F(1, 15) = 1.34$, $p = .265$, $\eta^2 = .08$. This finding is inconsistent with predictions.

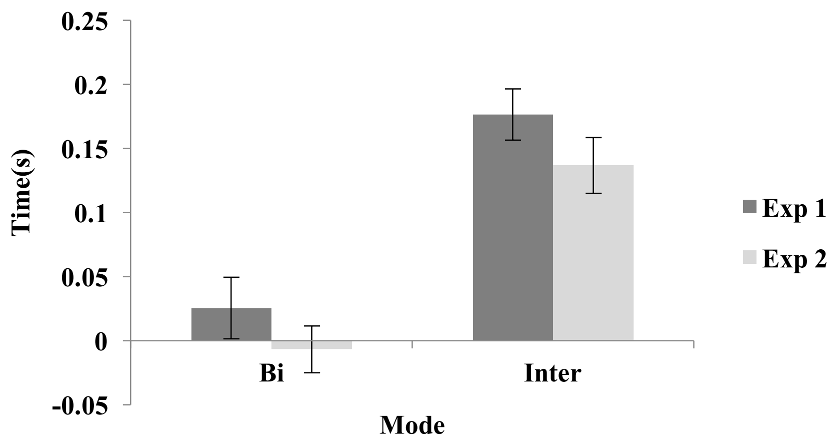

Figure 5.4. Mean Gaze Anchoring averaged across subtasks and hands for bimanual trials (Bi) and intermanual trials (Inter) for Experiment 1 and Experiment 2. Error bars represent ± 1 standard error of the mean.

SGDMs. SGDMs were analyzed using a 2 (Mode) × 2 (Experiment) mixed-subjects ANOVA. The Mode × Experiment interaction on mean SGDMs was significant, $F(1, 22) = 33.13$, $p < .001$, $\eta^2 = .60$. Additionally, the main effect of Mode was significant, $F(1, 22) = 181.62$, $p < .001$, $\eta^2 = .89$. However, the main effect of Experiment was not significant, $F(1, 22) = 0.29$, $p = .597$, $\eta^2 = .013$, indicating that the bimanual practice phase did not influence the subsequent number of observed SGDMs (see Figure 5.5).

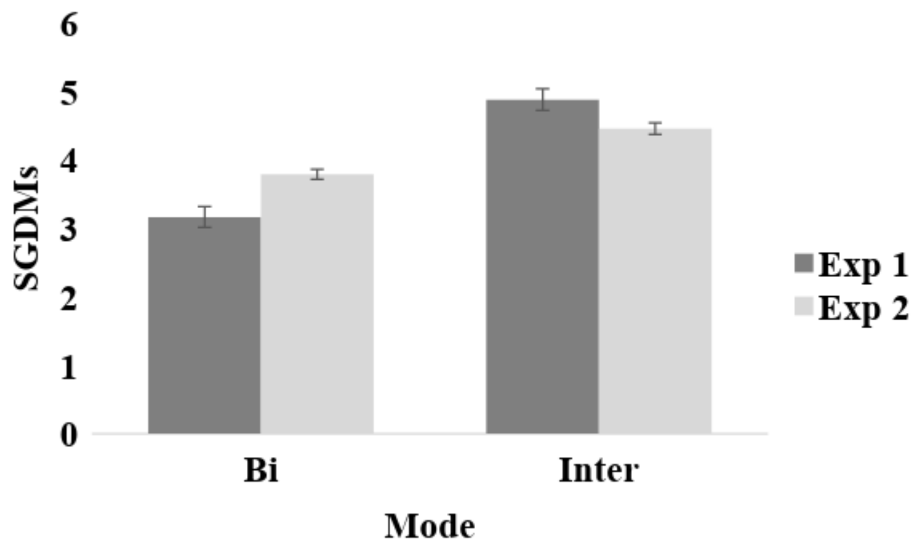

Figure 5.5. Mean number of total SGDMs for bimanual trials (Bi) and intermanual trials (Inter) for Experiment 1 and Experiment 2. Error bars represent ± 1 standard error of the mean.

In order to examine the effect of previous bimanual practice during Day 1 and Day 2 of Experiment 2, the simple effects of Experiment on mean SGDMs were assessed at each level of Mode using independent-samples *t*-tests (α_{Bon} = .05/2 = .025). As illustrated in Figure 5.5, participants' mean SGDMs when completing the task using the Bi Mode was significantly lower in Experiment 1 (M = 3.16; SD = 0.52) than Experiment 2 (M = 3.75; SD = 0.25), $t(15.94) = -3.53$, p = .003, d = 1.45. This finding is consistent with predictions. Additionally, participants' mean SGDMs when completing the task using the Inter Mode was significantly higher in Experiment 1 (M = 4.88; SD = 0.55) than Experiment 2 (M = 4.44; SD = 0.27), $t(22) = 3.32$, p = .023, d = 1.02. This finding is inconsistent with predictions.

Discussion

In order to examine the effect of bimanual practice on subsequent bimanual versus intermanual performance, the results of Experiment 1 were analyzed against

Experiment 2 after the bimanual practice phase. In general, it participants' performance improved at most levels for both coordination modes following the bimanual practice phase. Some of the important findings relative to the hypotheses are described below. Further discussion of these findings is presented in the General Discussion.

Speed. Participants in Experiment 2 completed the simulated cutting task significantly faster than participants in Experiment 1 when performing the simulated cutting task using either the bimanual or intermanual coordination modes. Thus, the bimanual practice phase appears to have facilitated skill transfer from one coordination mode to the other. It was predicted that bimanual speed would increase and intermanual speed would remain relatively stable from Experiment 1 to Experiment 2; this prediction was partially supported.

Between-hand coupling. Participants in Experiment 2 exhibited a significantly lower amount of between-hand coupling than participants in Experiment 1 when performing the simulated cutting task using either coordination mode. Previous bimanual practice of the simulated cutting task appears to have reduced bimanual coupling and between-hand intermanual coupling. Thus, consistent with the findings for speed, the bimanual practice phase appears to have facilitated skill transfer from one coordination mode to the other.

Visuomotor coupling. Visuomotor coupling results revealed the same pattern of results in Experiment 2 compared to Experiment 1 with respect to mode effects.

Pre-reach look-ahead. Compared to Experiment 1, participants in Experiment 2 took a significantly shorter amount of time between glancing at an object and starting a manual action when in the simulated cutting task—this occurred for both the bimanual and intermanual coordination modes. Thus, as predicted, smaller values of Pre-Reach Look-Ahead are associated with skilled performance.

Gaze anchoring. The pattern of results indicate that gaze anchoring was decreasing for both coordination modes across both Experiment 1 and Experiment 2. This pattern of results suggests that a smaller—as opposed to a larger—value of gaze anchoring may be associated with reduced visuomotor coupling. This finding is inconsistent with predictions. Interestingly, previous mode effects of Gaze Anchoring paired with the mode effects of speed suggested large values may facilitate speed.

SGDMs. Relative to participants in Experiment 1, participants in Experiment 2 completed more SGDMs when performing the simulated cutting task using the bimanual coordination mode; this finding is consistent with predictions. However, participants in Experiment 2 completed fewer SGDMs than participants in Experiment 1 when using the intermanual coordination mode. This finding is inconsistent with predictions, and is revisited in the General Discussion.

Chapter VI

General Discussion

The results of Experiment 1 indicated an intermanual speed advantage for an unpracticed task and revealed additional mode effects regarding between-hand coupling, visuomotor coupling, and SGDMs. All explanatory variables exhibited positive relationships with speed, which suggests these factors may be contributing mechanisms underlying speed during an unpracticed two-handed task, regardless of coordination mode. The results of Experiment 2 showed that the intermanual speed advantage disappeared after the task had been practiced using the bimanual coordination mode. Similar to Experiment 1, mode effects were observed for all explanatory variables. Unlike Experiment 1, however, the explanatory variables were not significantly correlated with speed (with the exception of between-hand coupling during bimanual coordination). While these findings did not yield significant results using conventional hypothesis testing, it might be premature to dismiss these associations due to the amount of variance accounted for was relatively good for this type of research (i.e., interpersonal coordination research; Gorman & Crites, 2015). Additionally, the medium-to-large effect sizes in combination with the pattern of results across experiments encourage the explanatory variables' relevance when describing speed during bimanually practiced two-handed tasks, regardless of coordination mode. The comparison of results for Experiment 1 and 2 indicated that bimanual practice enhanced all elements proposed to underlie two-handed task performance (with the exception of SGDMs during intermanual performance). Therefore, between-hand coupling and visuomotor coupling, through their effects on the ability to make SGDMs, appear to account for previously observed speed differences during two-handed tasks (Glynn & Henning, 2000; Gorman & Crites, 2013; 2015; Reed et al., 2006; Van Oosterhout et al., 2017; Wegner & Zeaman, 1956; Zheng et al., 2005; 2007). The results for mode effects relative to the predictions and hypotheses are summarized in Tables 6.1 and 6.2, respectively.

Table 6.1

Summary of Experiments 1 and 2

Dependent Variables	Experiment 1		Experiment 2	
	Bimanual	Intermanual	Bimanual	Intermanual
TrialTime	Slower[1]	Faster[1]	Equal	Equal
%REC	Higher[1]	Lower[1]	Higher	Lower
Pre-Reach	Longer[1]	Shorter[1]	Longer[1]	Shorter[1]
Gaze Anchoring	Shorter[1]	Longer[1]	Shorter[1]	Longer[1]
SGDMs	Less[1]	More[1]	Less	More

Note. [1]Denotes consistent with predictions.

Table 6.2

Supported Hypotheses for Experiment 1 and Experiment 2

	Experiment 1			Experiment 2		
Hypotheses	Between-Hand Coupling	Visuomotor Coupling	Simultaneous Goal-Directed Movements	Between-Hand Coupling	Visuomotor Coupling	Simultaneous Goal-Directed Movements
H1: Bimanual is limited by	Limited[1]	Limited[1]	Limited[1]	-	-	-
H2: Intermanual is facilitated by	Facilitated[2]	Facilitated[1]	Facilitated[1]	-	-	-
H3: Bimanual is facilitated by	-	-	-	Facilitated	Limited[1]	Facilitated
H4: Intermanual is facilitated by	-	-	-	Facilitated[1]	Facilitated[1]	Facilitated[1]

Note. [1]Denotes hypothesis was supported; [2]Denotes hypothesis was partially supported.

Mode Effects

As predicted, Experiment 1 revealed an intermanual mode effect of speed over bimanual during a previously unpracticed task. Thus, the previously observed intermanual speed advantage was replicated (Glynn & Henning, 2000; Gorman & Crites, 2013; Reed et al., 2006; Van Oosterhout et al., 2017; Wegner & Zeaman, 1956; Zheng et al., 2005). However, the results of Experiment 2 were inconsistent with those previously reported in Gorman and Crites (2015), as the observed mode effect in Experiment 1 disappeared (but did not reverse) in Experiment 2. The absence of a bimanual speed advantage may be due to skill transfer and a floor effect in task performance.

The bimanual practice phase seemed to have transferred skill to the intermanual coordination mode, and bimanual speed may have never been able to surpass intermanual speed due to limitations imposed by the task and/or insufficient practice. This notion is supported by the findings that bimanual and intermanual speed were both faster during Experiment 2 compared to Experiment 1. The improvement of both coordination modes from previous bimanual practice could imply that skill acquisition was no longer possible for either coordination mode. Additionally, the results revealed that previous bimanual practice increased subsequent bimanual performance to a larger magnitude relative to subsequent intermanual performance, such that the difference in speed across experiments was greater for bimanual simulated cutting than for intermanual simulated cutting. If this pattern of results continued without the ostensible floor effect of performance, then the faster timescale of bimanual skill acquisition may have led to a bimanual speed advantage as predicted.

Figure 6.1 illustrates the predicted performance across both experiments. It was initially predicted that previous bimanual practice would only improve bimanual task performance relative to stagnant intermanual performance, such that data for Experiment 2 Day 3 would reveal a bimanual speed advantage. It was further predicted that the intermanual speed advantage would reverse as a result of bimanual speed increasing while intermanual speed remained relatively unchanged. However, both bimanual and intermanual speed increased after bimanual practice. Future research should investigate tasks that present longer bimanual practice phases and offer greater opportunity for improvement, regardless of possible intermanual improvement, and therefore further explore the potential for skill transfer to the intermanual mode following bimanual practice.

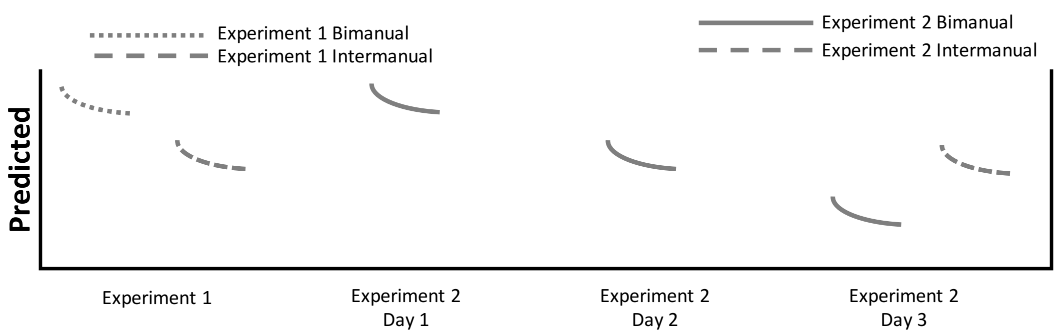

Figure 6.1. Initial predicted performance for Experiment 1 and Experiment 2.

Additionally, the lack of a bimanual speed advantage in Experiment 2 may be due to the inadequate length of the bimanual practice phase. Gorman and Crites (2015) asked participants to complete a perceptual-motor skill that participants had been completing for years (i.e., shoe-tying). Consequently, participants in Experiment 2 of the current study may have been unable to reach levels of expertise similar to those in Gorman and Crites (2015) due to the sheer frequency of shoe-tying across an individuals' lives. Performance data collected in the current study suggest that a performance asymptote was reached; however, this may actually reflect a performance plateau (Gray, 2017). Research indicates that individuals exhibit performance plateaus for a variety of tasks before settling into a performance asymptote (Gray & Lindstedt, 2016). It is not until individuals reach a critical time during skill acquisition that they are released from the performance plateau and continue improving until reaching the next plateau (this process can be conceptualized as a staircase of performance; Crossman, 1959). Plateaus in skill acquisition may be due to a shift in strategy or a sudden new understanding of the task (Davids, Button, & Bennett, 2008). As the theory and past findings indicate, depending on the task and the person, individuals may demonstrate a few or many performance plateaus before finally arriving at an actual (final) performance asymptote (Gray, 2017). Practically speaking, unless there are physical constraints on space and time (e.g., limits in movement from one place to another), researchers may never be entirely sure that an individual has reached performance asymptote (Adams, 1987). Accordingly, it is difficult to determine when a two-handed task has been sufficiently practiced using the bimanual coordination mode (or any coordination mode). For this study, the participants may have settled into a bimanual performance plateau, or the task reached floor performance due to physical constraints in space and limits in practice time.

The significant effect of Order observed during Experiment 2 further suggests that participants may have still been learning. Specifically, overall, the Bi → Inter Order was associated with faster performance than the Inter → Bi Order (this pattern of results was also observed for coupling). The suggestion that participants were still learning is based on the work of Adams' (1952) "warm-up decrement" later expanded upon by Newell and colleagues (2001), to contend that short-term learning effects reflect transient changes attributable to "warm-up" against a backdrop of long-term, persistent motor skill acquisition. Participants in the Bi → Inter condition started Day 3 of the mode effects portion of the experiment by completing the task using the previously practiced bimanual coordination mode and were able to quickly settle into their performance plateau (i.e., subsequent intermanual performance occurred after participants were able to practice with their familiar coordination mode). Participants in the Inter → Bi condition started Day 3 of the experiment by completing a previously practiced task using an unfamiliar intermanual coordination mode. Because participants who used the intermanual mode first were unable to settle into a performance plateau, it may have negatively affected performance for both coordination modes. Importantly, these types of effects attributable to warm-up decrement and performance plateau disappear as the persistent level of skill increases (Newell et al., 2001), suggesting that bimanual learning may still have been taking place during Experiment 2. Together with the proposed performance plateau explanation, it may be that it was still too early in learning to observe a bimanual speed advantage.

Finally, participants reaching performance plateau (as opposed to true asymptote) suggests they may have been in the associative stage versus the automatic stage of skill development (Fitts, 1964). An automatic stage implies that one can perform at a high, or relatively fast, error-free level even when dual-tasking or under attentional load (Heuer, 1991). Furthermore, performance can plateau during attentional underload in the associative stage of skill acquisition (Detweiler & Schneider, 1999). Given the unfamiliar nature of completing the task using the intermanual coordination mode, it is expected that participants' previous bimanual experience negatively affected intermanual performance (i.e., automaticity affected concurrent performance; Brown & Carr, 1989). This suggests that the role of previous bimanual and intermanual practice should be experimentally manipulated.

Speed During Two-Handed Tasks

What facilitates speed differences during two-handed tasks? It was initially proposed that SGDMs during two-handed tasks leads to faster performance and that independent movement of the limbs increased the likelihood of making a SGDM (Gorman & Crites, 2015; Zheng et al., 2007). Except for intermanual SGDMs, the pattern of results of the current study revealed that task performance improved for all dependent variables measured across both experiments. Each explanatory variable will be described in turn relative to speed.

Between-hand coupling. The results of Experiment 1 indicated that participants were exhibiting bimanual coupling during simulated cutting and that higher levels of between-hand coupling were associated with slower performance. Additionally, while participants' speed differences across coordination modes disappeared during Experiment 2, their degree of bimanual coupling was still significantly correlated with speed. Furthermore, bimanual coupling was significantly correlated to SGDMs, such that lower levels of between-hand coupling were associated with more SGDMs. Thus, as observed in Gorman and Crites (2015), decoupling of the limbs was associated with faster performance and more SGDMs (i.e., a speed-coupling tradeoff). However, coupling was not directly manipulated in the current study. Therefore, additional research is required to further understand this mechanism's contribution to speed during two-handed tasks.

The present results are consistent with prior research indicating that bimanual coupling negatively affects task performance as measured by speed (Kelso et al., 1979; Franz, 1997; Shea et al., 2016; Swinnen & Wenderoth, 2004). This dissertation was the first theoretical extension of between-hand coupling research in the context of manual coordination task performance. Previous research paradigms were not directly comparable to typical tasks, which reduced their generalizability to more applied domains. For example, bimanual tapping tasks and circle tasks do not have obvious practical implications (Kelso et al., 1979; Franz, 1997). However, recent research suggests that investigating underlying principles inherent in two-handed tasks is being conducted more frequently in the context of more applied domains, such as laparoscopic surgery (e.g., Zheng et al., 2009; Hajari, Cheng, Zheng, & Basu, 2016). For example, Hajari and colleagues (2016) applied the CRQA method for analyzing dyads behavior in the context of laparoscopy to understand differences between good- versus poor-performing teams.

Interestingly, coupling decreased from Experiment 1 to Experiment 2 for both coordination modes. These observed differences suggest there may be a higher degree of intermanual coupling than initially hypothesized, but that bimanual practice leads to decreases in between-hand coupling regardless of coordination mode. Intermanual coupling can be described by the theory of visually-linked dyads (Ouiller et al., 2008). When people complete a two-handed task as a dyad, their limbs are putatively visually-coupled and exhibit a tendency to synchronize movement with respect to the other limb.

Hence, dyads using the intermanual coordination mode may be drawn towards the natural tendency to “sync” their movement patterns with one another (Strogatz, 2003). This “mirroring” phenomenon has been observed in a variety of interpersonal settings. For example, spontaneous synchrony is observed between two people completing leg oscillations (Schmidt, Carello, & Turvey, 1990), finger oscillations (Gipson et al, 2016; Gorman, Amazeen, Crites, & Gipson, 2017; Ouiller et al., 2008), and rocking side-by-side in rocking chairs (Richardson et al., 2007). In all cases, each member of the dyad must be visually attending to the other person (or must have some other informational source for coupling; e.g., auditory coupling; Gipson et al., 2016).

Using the example of a bimanual Fitts’ task described in the Extended Literature Review (Kelso et al., 1979), an intermanual Fitts’ task reveals similar results, which may have direct bearing on the current study (i.e., two people each used one hand to simultaneously complete the two-handed Fitts’ tapping task with varied target sizes and movement distances) (Fine & Amazeen, 2011). Fine and Amazeen (2011) asked participants to complete the Fitts’ tapping task unimanually, bimanually, and intermanually. For the bimanual task, their results replicated that of Kelso and colleagues (1979); however, similar movement times were also observed intermanually (Fine & Amazeen, 2011). The pattern of results reported by Fine and Amazeen (2011) reveal similar two-handed coupling tendencies for both coordination modes for a two-handed, visually-guided task. Thus, this finding suggests that two-handed coupling may be more perceptual-spatial in nature than the purely biomechanical constraints eluded to in this study (Franz, 1997; Kelso, 1995; Mechsner et al., 2001). However, Fine and Amazeen (2011) and other studies (e.g., Gipson et al., 2016) compared coupling with informationally-linked dyads to bimanual coupling and indicate that the coordination tendencies (e.g., information-mediated synchronization) are stronger when using the bimanual mode compared to the intermanual mode, which is consistent with the findings of the current study (Fine & Amazeen, 2011; Jung et al., 2011; Richardson et al., 2008; Schmidt et al., 1990). Thus, the degree to which two individuals' hand movements are coupled is theoretically lower than individual between-hand coupling, at least initially (Gorman & Crites, 2015).

Visuomotor coupling. The results of Experiment 1 and 2 indicate that participants were exhibiting different levels of visuomotor coupling during simulated cutting across coordination modes, as measured by Pre-Reach Look-Ahead and Gaze Anchoring. The measures of visuomotor coupling (Pre-Reach Look-Ahead and Gaze Anchoring) are well rooted in theory and prior literature (e.g., Land & Hayhoe, 2001; Rand, 2014). Importantly, this is the first study to investigate these measures within the intermanual paradigm. Experiment 1 indicated that both measures of visuomotor coupling were significantly related to speed, but this effect disappeared in Experiment 2. The lack of significant correlations may be attributable to the low sample size for these measures in Experiment 2 that resulted from instrumentation failure. However, with the exception of intermanual SGDMs, the pattern of results across experiments suggests that bimanual practice improved all explanatory variables including both measures of visuomotor coupling. Additionally, in terms of traditional effect size guidelines (e.g., Cohen, 1992), many of these relationships had at least medium effect sizes in both experiments that are comparable to research investigating interpersonal coordination (e.g., Gorman & Crites, 2015). Therefore, the smaller sample size, the improvement across experiments with other variables, and the medium-to-large effect sizes suggest the results regarding both measures of visuomotor coupling should not be dismissed, but taken under consideration as explanatory mechanisms underlying two-handed tasks. Future research should investigate these variables with a larger sample size.

Regarding Gaze Anchoring, the hypotheses predicted that a shorter value (i.e., a longer time between terminating a manual action and terminating gaze) would be observed for individuals when using the bimanual coordination mode relative to the intermanual coordination mode. When completing a two-handed task using the bimanual mode, the individual is essentially multitasking across the hands to complete their subtasks. When the individual is attempting to complete the task as quickly as possible, the actions may be more simultaneous, creating the need for dual-tasking. The hypothesized shorter value of Gaze Anchoring was predicted in part because participants need to terminate the manual coordination act in order to advance to the next subtask in this dual-tasking situation (Terrier et al., 2011). When using the intermanual coordination mode, subjects are not as rushed, and can focus longer on each subtask to better utilize Gaze Anchoring to maintain stability and accuracy (Mennie et al., 2007; Neggers & Bekkering, 2000). Importantly, the pattern of results across Experiments 1 and 2 suggest that task performance increased across all dependent variables measured. Thus, for both coordination modes, Gaze Anchoring *decreased*, which suggests that a shorter anchoring actually implies a *lack* of visuomotor coupling. Thus, the observed mode effects of Gaze Anchoring suggest that visuomotor coupling may be sacrificing speed during intermanual performance, ostensibly in part to the lack of the dual-tasking demand present in bimanual performance.

SGDMs. Experiment 1 revealed more SGDMs during intermanual performance than bimanual performance, conceptually replicating the previously observed finding related to SGDMs (i.e., anticipatory movements; Zheng et al., 2007). Additionally, a greater number of SGDMs was associated with faster performance in Experiment 1 using either coordination mode, which implies that the simultaneous completion of subtasks reduces task time. Experiments 1 and 2 showed that participants exhibited more SGDMs when completing the task using the intermanual coordination mode compared to the bimanual mode, suggesting that intermanual performance is more conducive to simultaneous movements; however, previous bimanual practice may reduce this effect. Furthermore, fewer SGDMs were observed during Experiment 2 than Experiment 1, which suggests that previous bimanual practice influenced participants' abilities to make SGDMs.

Prior research assessed simultaneous movements during bimanual and intermanual performance in the context of anticipatory movements. Zheng and colleagues (2007) offered their anticipatory movement hypothesis using cognitive mechanisms to explain teamwork in the form of shared task knowledge (SMM; Cannon-Bowers et al., 1993). For example, during Zheng and colleagues' (2007) simulated laparoscopic cutting task, participants could develop shared, overlapping task knowledge. Specifically, it was theorized that each participant knew their role and responsibilities as well as their partner's role and responsibilities. Thus, each participant could focus on their own portion of the task. It was argued that participants' overlapping knowledge was used to form a SMM that facilitated task performance, such that each participant knew where their hand should be with respect to their partner's hand when completing the laparoscopic cutting task. However, a SMM was not measured, and such measurement techniques can be problematic (Cooke, Gorman, Myers, & Duran, 2013; Gorman et al., 2010). For example, DeChurch and Mesmer-Magnus (2010) showed that higher levels of SMM is not always indicative of greater task performance.

Instead, the current study evaluated more parsimonious explanations for why bimanual performance is slower than intermanual performance in an unpracticed task. As predicted, both experiments showed that SGDMs were significantly correlated (or exhibited a substantial effect size) with between-hand coupling and visuomotor coupling measures for both coordination modes. These findings, taken together with the finding that SGDMs were significantly correlated with speed in Experiment 1, further support the notion that these explanatory measures underlie speed during two-handed tasks.

To summarize this section, this dissertation offers a different explanation that focuses on why bimanual performance is *slower* than intermanual performance for an unpracticed task rather than why intermanual performance is *faster* for an unpracticed task. Specifically, bimanual coordination is constrained by fundamental characteristics inherent to the coordination mode (e.g., bimanual coupling and bimanual visuomotor coupling) and the same characteristics do not inhibit performance as much during intermanual coordination. The simulated cutting task used in the current study was designed to exacerbate two known characteristics of task performance that slow down bimanual coordination under the appropriate circumstances (asymmetric movements and simultaneous visually-guided tasks). Based on the results of Experiment 1, one can surmise that bimanual coordination is limited by pre-reach look-ahead (in the form of guiding fixations and bimanual coupling) in ways that intermanual coordination is not. It was further predicted that after a sufficient amount of bimanual practice, participants would reach the level of skill where these limitations would not play as large of a role, and that bimanual speed would surpass intermanual speed. While this was not found, it is important to note that bimanual practice led to improvements in *all* of the explanatory variables, regardless of coordination mode (with the exception of intermanual SGDMs), as well as speed relative to Experiment 1. It is possible to interpret the results of Experiment 2 as strengthening the conclusion that there is a perceptual-motor basis of bimanual coupling and visuomotor coupling that lies at the heart of bimanual and intermanual coordination and the differences in how these modes are performed.

Alternative Explanations

In addition to the behavioral explanations provided above (i.e., bimanual coupling, bimanual visuomotor coupling, and SGDMs), a potentially-complementary cognitive explanation should be considered. The psychological refractory period (PRP) is a possible alternative explanation to perceptual-motor factors constraining bimanual performance. The PRP refers to the observation that when two stimuli are displayed in close succession and each requires a rapid response, the response to the second stimulus is affected (delayed) by the processing of the first stimulus (Telford, 1931; Davids, 1959) (see Figure 6.2). Moreover, as the stimulus onset asynchrony (SOA; period of time between onsets of the two stimuli) is reduced, response times tend to increase.

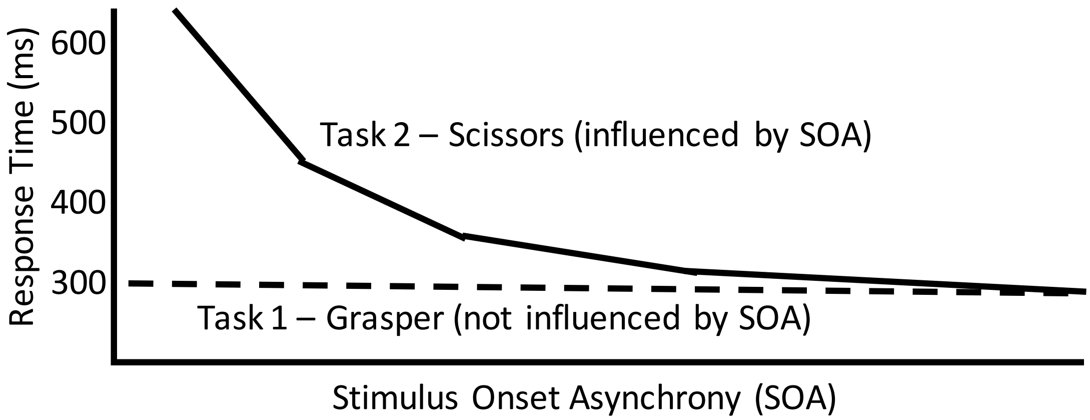

Figure 6.2. Psychological refractory period in the context of the simulated cutting task.

The simulated cutting task is made up of a series of subtasks that must be completed using two hands. As described in earlier sections of this dissertation, it is faster to complete two subtasks simultaneously than to complete each subtask sequentially. When completing the task bimanually, all stimuli are available to the participant simultaneously, and they must select and execute a manual action with the right or left hand (either simultaneously or sequentially). Due to the inherent limitation of having only one visuomotor system, an individual using the bimanual coordination mode must select which manual action to initiate first (the right-hand subtask or the left-hand subtask). Specifically, the participant must perceive each option, decide which subtask to complete first, and then execute a motor command (i.e., input → response selection → response execution). Considering this input → processing → output (IPO) framework of the information processing sequence in conjunction with the PRP can explain why two visuomotor perceptual systems (i.e., intermanual) may be preferred over one visuomotor system (i.e., bimanual). Specifically, structural interference (only having one set of eyes) and delays associated with simultaneous central processing (the PRP effect) could both help explain limitations in the bimanual mode.

Essentially, there may be a refractory period between responding/completing the first subtask and moving on to the next subtask. If the SOA is decreased, then the response time of the first task remains unaffected, but the response time of the second subtask increases. The explanations for this effect involve the IPO framework, suggesting that there is a bottleneck when response selection is required from two simultaneously performed tasks, which negatively affects performance. Interestingly, practice has been shown to reduce the magnitude of the PRP effect, but it cannot eliminate it (Van Selst, Ruthruff, & Johnston, 1999). Therefore, similar to structural interference inherent in visuomotor coupling (i.e., the eyes and hands can only be at one place at a time), the PRP suggests that cognitive mechanisms may also be important factors underlying time-sharing in visuomotor coupling. Furthermore, even if the two stimuli were close enough in the visual field to be perceived simultaneously (i.e., visually-guided), the response selection component of each subtask would be expected to slow performance.

Interestingly, when the two stimuli are displayed close to each other (or simultaneously, like the simulated cutting task), the stimuli are perceptually grouped. This grouping effect leads to a longer reaction time for both stimuli (Welford, 1968). Thus, for the simulated cutting task, either both stimuli are perceptually grouped and reaction times to both stimuli are increased, or there is an asynchrony (SOA) and the second reaction time is increased. In either situation, the sequential multi-task nature of bimanual coordination is delayed at each subtask. Furthermore, completing the subtasks more quickly is analogous to reducing SOAs, which paradoxically has the potential to produce greater interference (i.e., due to the PRP). Furthermore, the fact that both stimuli are presented simultaneously suggests that more processing could occur (Schmidt & Lee, 2011). Therefore, this effect may be enhanced with speed across subtasks (Figure 6.3).

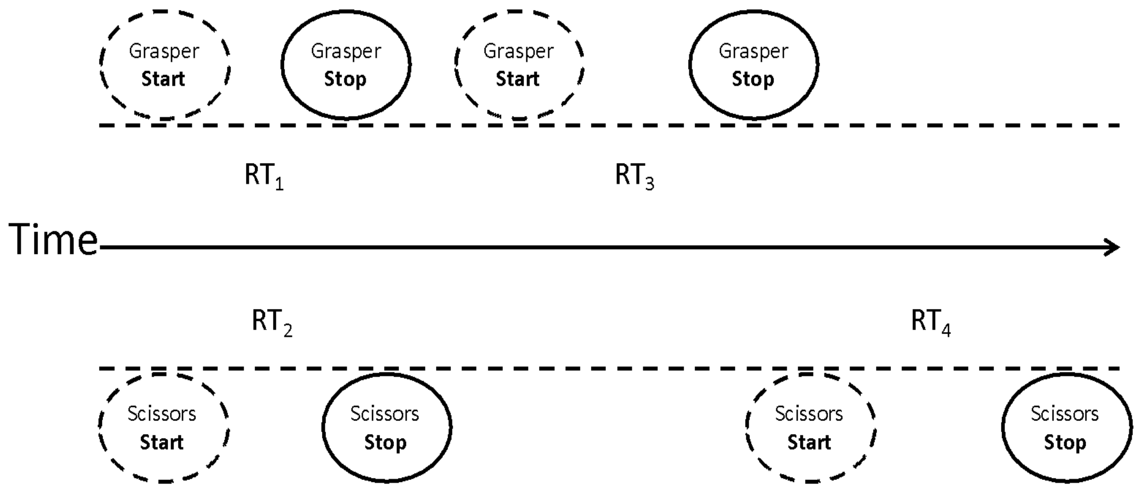

Figure 6.3. Illustration showing how the psychological refractory period may have increased overall bimanual trial time one subtask at a time.

Theoretical Implications

The results from these experiments have several theoretical implications. The observed mode effect of between-hand coupling was the first demonstration of its kind for an unpracticed task when investigating bimanual and intermanual coordination. Similar to previous research observing two-handed coordination, participants' hands were naturally coupled in space and time when using the bimanual coordination mode (Kelso et al., 1979; Franz, 1997; Shea et al., 2016; Swinnen & Wenderoth, 2004). Participants may have been unintentionally settling into a naturally-coupled state based on the characteristics of the task (e.g., participants were instructed to complete the tasks as "quickly and accurately as possible") (Mechsner et al., 2001).

When completing a bimanual task, non-visual forms of communication between the two hands may be beneficial when completing specific tasks (Kelso, 1995). For example, one hand can be used as a reference point to the other hand when completing a bimanual task without visual input (Norman & Shallice, 1986; Wiesendanger & Serrien, 2004). However, this cross-talk between the limbs has been shown to negatively affect performance in certain contexts (Franz, 1997); for example, simultaneously drawing a circle with one hand and a line with the other hand (Franz et al., 1991). Nevertheless, similar to prior research findings, the effects of between-hand coupling on simulated cutting was overcome, to a degree, with previous bimanual practice (Gorman & Crites, 2015). Thus, the results of the current study have shown how the harmful effects of cross-talk when completing a bimanual task can be reduced with practice.

Regarding between-hand coupling, research has shown that simultaneously completing a two-handed task influences bimanual coupling both spatially (Franz, 1997) and temporally (Kelso, 1995). While bimanual coupling has been studied during a variety of simple tasks, it has yet to be applied as a mechanism to explain speed during more applied tasks with multiple subtasks. With bimanual coupling, it is easy to see how the movement of one hand affects the other negatively impacts performance. When completing the same two-handed task using the intermanual coordination mode, the between-hand coupling does not negatively affect performance as compared to the bimanual coordination mode for the unpracticed task.

The pattern of results also indicates that guiding fixations (as measured by Pre-Reach Look-Ahead) require more of a lead time when completing an asymmetric bimanual task where the hand two hands are not manipulating objects in a nearby visual field. Dividing attention across the hands may seems to have caused the participants to complete the task sequentially (as opposed to simultaneously), which aligns with previous research (e.g., Bowman et al., 2009). Although the tasks are shared across visuomotor systems, the present results suggest participants were able to focus visual attention on their individual subtasks, thus, circumventing the bimanual limitation. This finding, however, suggests that participants were not visually attending to one another as in other studies investigating dyadic behavior (Gipson et al., 2017). Therefore, other explanations for the degree of between-hand coupling during intermanual performance may have greater weight (e.g., cognitive coupling; Gorman et al., 2017). Future research should explore the degree to which dyads are coupling during two-handed tasks and manipulate the underlying mechanism. For example, clocks swinging on the same wall have their pendulums sync up due to physical connection to the wall (Huygens, 1673). Peoples' fingers sync up when they are looking at one another, but this effect disappears when visual information is removed (Oullier et al., 2008). During the present study, participants were not visually attending to one another except during interdependent subtasks; however, the reduction and degree of between-hand coupling across experiments suggest the participants were still physically coupled in space and time. Therefore, participants may have been coupled together with respect to some other underlying mechanism. This finding is consistent with previous research measuring participants' postural sway synchronizing in space and time (as measured by %REC) when communicating and not visible to one another (Shockley et al., 2003).

From a theoretical perspective, how does an individual coordinate his or her actions with another person? Research has shown that simultaneously completing two subtasks working toward a common goal may facilitate speed via "anticipatory movements" (Zheng et al., 2007). While anticipatory movements were supposedly facilitated via shared task knowledge in the form of a SMMs, SGDMs are supposedly facilitated via decoupled movement of the limbs, and are described as a function of visuomotor coupling during a two-handed task. While both anticipatory movements and simultaneous goal-directed movements can both be observed and measured (i.e., counted), the underlying mechanisms differ. Anticipatory movements use underlying cognitive mechanisms related to "anticipation" and knowledge structures, whereas SGDMs are a function of the constraints, or lack thereof, of the perceptual-motor system. Therefore, it is proposed that instead of using SMMs to explain the intermanual speed advantage, the advantage is better explained with low-level perceptual motor variables.

The current findings as a whole support the key concepts in the dynamical systems literature, that behavior can be described at a more fundamental level as opposed to solely relying on cognitive mechanisms (Guastello, 2013). Importantly, it is the author's view that it is not an either-or situation and that cognitive mechanisms (e.g., SMM, attentional bottleneck) are useful when describing behavior. However, a simpler approach may be to first effectively describe how the behavior is unfolding before alluding to underlying cognitive mechanisms.

Practical Implications

There are several practical implications to be drawn from the present findings. First, this research may undermine the intuitive assumption that most people prefer to perform all two-handed tasks alone using both of their own hands. Specifically, there are a number of constraints that may shape how, when, and why one coordination mode will be preferred over another. For example, in some cases physical injury (e.g., loss of limb function due to paralysis, or loss of limb due to amputation) is the cause of loss of bimanual ability. In other cases, a limb or hand may simply be occupied with another task. In either case, the individual may perform the task unimanually or seek out the aid of another person or agent to complete the task intermanually.

An example of the latter case is when a surgeon is holding something in place with one hand while simultaneously attempting to complete another task that requires two hands. Regardless of the underlying motivation for using the intermanual mode, the same internal and external coordination requirements underlying unimanual performance by a single individual apply, but with the additional coordination requirement presented as a result of interacting with a partner. Importantly, people are generally able to coordinate with one another with ease (Gorman, Amazeen, & Cooke, 2010; Knoblich, Butterfill, & Sebanz, 2011; Schmidt & Richardson, 2008; Sebanz, Bekkering, & Knoblich, 2006), which suggests intermanual applications may be possible in a variety of domains.

Although participants in the current study were able to reduce bimanual coupling and increase speed relative to participants in the unpracticed experiment, more between-hand coupling was present during bimanual performance compared to intermanual performance across experiments. This persistent effect of bimanual coupling has particular implications for tasks that require simultaneous, asymmetric movement of the limbs. For example, teleoperated tasks involving the manipulation of heavy payloads (e.g., tasks during oil rig repairs and maintenance of fusion plants) require simultaneous, asymmetric control of robotic arms (Madrid & Matson, 2014; Rolfe, 1997). Van Oosterhout and colleagues (2017) compared bimanual and intermanual teleoperation in this domain and found that participants completing the task using the intermanual coordination mode were faster than those using the bimanual coordination mode (unimanual was examined, and performed worse out of the three coordination modes, similar to Gorman & Crites, 2013).

Additionally, the present findings have practical implications for tasks that do not necessarily involve a pure intermanual component, such that the intermanual paradigm could be used in situations where distributing mental resources is beneficial. For example, Zheng and colleagues (2005) manipulated camera rotation during a teleoperation task, which has been shown to increase mental workload, and argued that dyads had a “larger capacity to absorb the impact of camera rotation than single individuals performing bimanually” (Zheng et al., 2005, p. 1394). Specifically, it was proposed that dual-task constraints present in bimanual coordination tasks impose a higher degree of cognitive load due to a limited amount of processing resources available and that the intermanual coordination mode requires fewer processing resources (Norman & Bobrow, 1975). Furthermore, research has shown that there are shortages of operators for some tasks that are typically performed alone (e.g., teleoperation in urban search and rescue; Murphy & Burke, 2010).

Along these lines, Van Oosterhout and colleagues (2017) tested a mental workload hypothesis during their teleoperation task using a subjective measure of workload (i.e., NASA-TLX; Hart & Staveland, 1988) and did not find a significant difference between coordination modes. However, as in other experiments investigating two-handed coordination (e.g., Crites & Gorman, 2013; Zheng et al., 2005), Van Oosterhout and colleagues (2017) used novice participants completing an unpracticed task. To the extent that novelty of the task could account for the lack of differences in mental workload, the intermanual coordination mode may be practically beneficial for previously practiced tasks (in terms of mental workload reduction). However, the present study suggests that previous practice leads to the disappearance of the intermanual speed advantage.

The results of the present study could motivate the development of training methods to improve subsequent manual task performance in the context of rehabilitation and training. Research has shown that human-human interaction (HHI) of manual tasks increases ensuing individual task performance (Sawers & Ting, 2014). Sawyers and Ting (2014) have suggested how HHI at the sensorimotor level promote rehabilitation using rehabilitation robots, such that designing a robot based on HHI principles promotes more interactions (e.g., between-hand coupling at the bimanual and intermanual levels). Furthermore, Ganesh and colleagues (2014) implemented a unique HHI research paradigm in which participants learned a novel two-handed task by first working with a partner. It was proposed that unconscious haptic feedback during dyadic interactions promoted learning. Participants were instructed to complete an intermanual task that required them to unconsciously interact with one another by implementing haptic feedback outside of conscious awareness. Using this training paradigm, Ganesh and colleagues (2014) were able to improve bimanual coordination independent of cognitive interactions that could arise when working with a partner. Interestingly, the pattern of results observed by Ganesh et al. (2014) were discordant with those of the present study, in which bimanual practice increased subsequent performance when participants completed the task using the novel intermanual coordination mode. Results revealed that physical connection with a partner improved task performance. Additionally, similar results have been observed in previous research (Gorman and Crites, 2015; Triplett, 1898): working with a faster partner improved subsequent performance. In the Gorman and Crites (2015) study, slower participants significantly increased task performance when working with a faster partner. Future research should investigate subsequent mode effects using this HHI paradigm while also measuring the explanatory variables measured in the current study. It would be particularly interesting to examine whether dependent variables increased (as they did in the current study with the exception of intermanual SGDMs).

The HHI component observed in this dissertation could be used to inform design decisions related to HRI. Understanding how people perform and learn a manual task with an external aid, such as another person's hand (i.e., HHI), has implications for learning and the coordination of performance with an external agent (i.e., HRI). Research on the design of robotic interactions might apply the current work to, for instance, a surgical context. Specifically, smart surgical robotic systems that incorporate eye-hand coordination for surgical assistance may apply the HHI component of this research to augment surgeons' trust in automated robotic arms designed to mimic qualities of both bimanual and intermanual behavior (Bainbridge, 1983; Liu et al., 2014).

Additionally, the present results suggest that visually-guided bimanual task performance required participants to divide visual attention across their body. This distribution of attention across the body when splitting up a two-handed task across a single visuomotor system has implication for the design of user interfaces that require two-handed responses (Balakrishnan & Hinckley, 2000). Specifically, issues may arise when using large bimanual interfaces that require simultaneous input, such as for computer-aided design (CAD). The results of the current study suggest that when two AOIs become sufficiently separated in space and time, visual attention is shared across the hands and results in sequential (as opposed to simultaneous) movements, which causes a decrement in bimanual performance.

Along these lines, Hinkley, Pausch, Proffitt, and Kassell (1998) argued that two-handed user interface design can be superior to one-handed design and that a common-sense approach to the design of such systems is to facilitate simultaneous object manipulation. In order to design and implement a two-handed interface, the human behavioral principles investigated in this dissertation must be introduced in the design process. Specifically, the design of any two-handed user interface must should to the following behavioral principles. One, the presence of between-hand coupling during bimanual and intermanual performance will reveal higher amounts of bimanual coupling. Two, between-hand coupling can be reduced with previous bimanual practice for either coordination mode. Three, bimanual visuomotor coupling dictates that dual-task performance when manipulating two objects is typically completed sequentially when the objects are a sufficient distance apart. Four, guiding fixations have longer lead times and gaze anchoring of objects are terminated more quickly during bimanual performance due to timesharing across the hands. Five, previous bimanual practice can reduce the length of both guiding fixations and gaze anchoring.

Limitations and Future Directions

This dissertation describes an original set of experiments that were used to investigate speed differences during two-handed tasks and the effect of previous bimanual practice on subsequent mode effects. There are several limitations in this study. Each limitation has been specified below with suggestions for future directions of research.

First, the explanatory variables were observed as opposed to manipulated. The explanations described above were based on observed mode effects and correlations. A direction manipulation of between-hand coupling, visuomotor coupling measures, and SGDMs would provide stronger evidence that these variables underlie speed during two-handed tasks as opposed to being associated with them. Future directions should directly manipulate these explanatory variables, in addition to practice.

Second, the present study only manipulated previous practice for the bimanual coordination mode. While this reasoning underlying the experimental design was based on extending the current line of research (e.g., Gorman & Crites, 2015), the logical next step is to investigate intermanual practice in a similar manner. The results of Ganesh and colleagues (2014) suggests that a similar pattern of results to the present study may be observed. However, the study by Ganesh and colleagues' (2014) did not implement a practice phase to the degree the present study did.

Third, there may have been a floor effect of task performance. The rationale and reasoning for a potential floor effect has been extensively described earlier in the General Discussion. Importantly, one main focus when constructing the simulated cutting task was to create a visually-guided task with multiple subtasks so learning would occur during the bimanual practice phase without any floor effects. Future directions should investigate tasks with more room for improvement in addition to longer bimanual practice phases.

Fourth, different task characteristics should be considered in future research. The present study examined a two-handed task that required simultaneous, asymmetric actions with an interactive component that was agonistic in nature. Manipulating additional task conditions, such as movement type (e.g., reaching and grasping versus pointing), size and distance between two, size and distance of targets, symmetric versus asymmetric tasks, and non-interactive tasks should all be considered. Specifically related to the size and distance of targets, future research should investigate the coordination modes while manipulating visual attention. If visual attention depends on the size of the visual field, then it may not equally apply to all fields. For the present study, the measures of visuomotor coupling did not address visual attention. Along these lines, future research should investigate the effect of planning eye movements when prior to intermanual task performance (Pelz & Canosa, 2001).

Finally, future research should investigate mental workload in the context of previously practiced bimanual tasks and previously practiced intermanual tasks. While Van Oosterhout and colleagues (2017) investigated mental workload using the intermanual paradigm, they used novice participants completing a novel task. The majority of bimanual versus intermanual research struggles to have more direct applications. Specifically, the coordination modes should be compared using participants who are expert at their craft (e.g., payload operators) completing actual tasks (e.g., teleoperation tasks similar to the Van Oosterhout experiment).

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Appendix A

Extended Literature Review

Any two-handed task, whether it's making a sandwich or tying shoelaces, requires the cooperation and coordination of multiple systems (Land & Tatler, 2009), and may include coordinating with another person. Interestingly, some two-handed tasks are faster when working with a partner when compared to completing the task alone (Glynn & Henning, 2000; Gorman & Crites, 2013; Reed et al., 2006; Wegner & Zeaman, 1956; Zheng, Verjee, Lomax, & MacKenzie, 2005). For example, participants performed a two-handed laparoscopic cutting task faster as a team when compared to individuals who completed the task individually (Zheng et al., 2005). However, this effect disappeared if the task had been previously practiced individually (Gorman & Crites, 2015). *Intra*personal and *inter*personal *manual* coordination tasks (i.e., manual coordination within and across individuals) were the primary focus of this dissertation. Specifically, this dissertation investigated speed differences during two-handed tasks completed by a single person ("bimanual" coordination), and tasks using different peoples' hands ("intermanual" coordination). Throughout this dissertation, bimanual and intermanual coordination tasks were referred to as distinguishable manual "coordination modes" (Gorman & Crites, 2013, 2015). A third coordination mode was included for descriptive purposes for understanding the two primary coordination modes: tasks completed with one hand ("unimanual" coordination). Figure A1 shows an example of all three coordination modes during a teleoperation task.

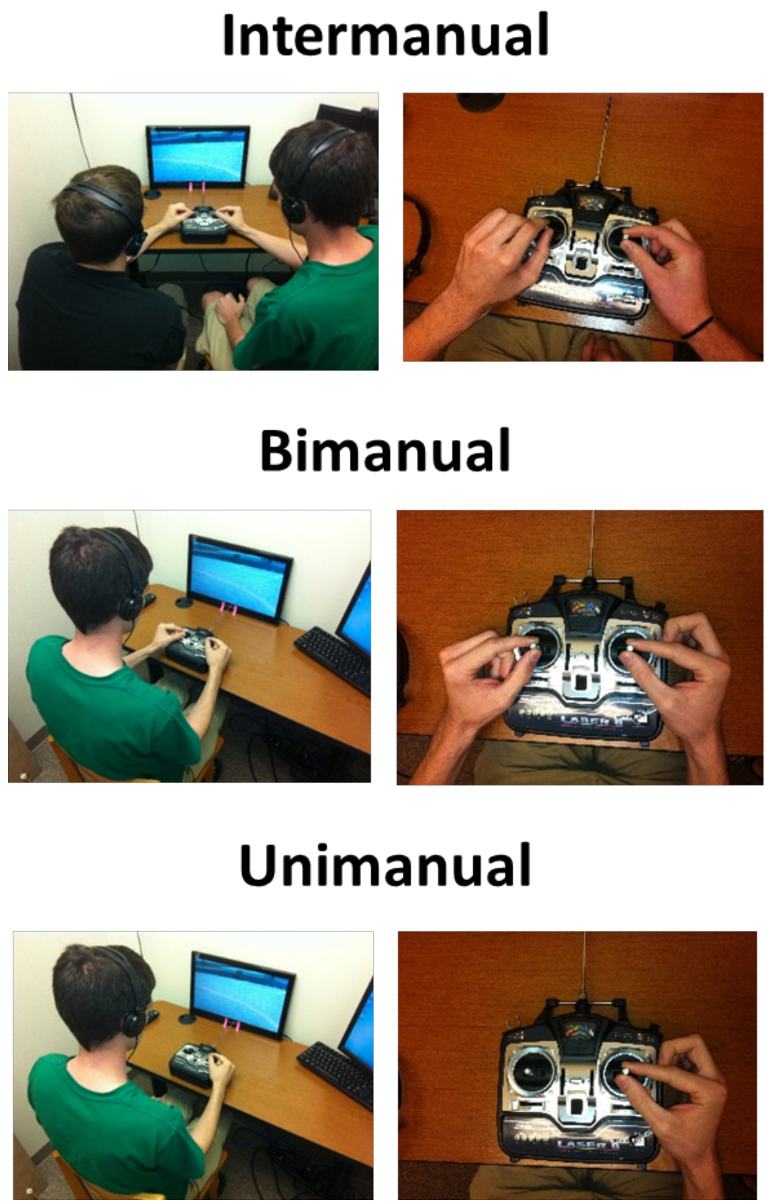

Figure A1. Example of all three coordination modes, where participants controlled the steering and acceleration of a teleoperated rover. Unimanual (lower): Unimanual control of steering and acceleration collapsed across a single joystick. Bimanual (middle): Bimanual control of steering with the left hand, and acceleration with the right hand across two joysticks. Intermanual (top): Intermanual control with one participant controlling steering with their left hand, and another controlling acceleration with their right hand.

One may assume that most people would prefer to perform all two-handed tasks alone, bimanually. However, there are a variety of situations that shape how, when, and why people use one coordination mode over another. In one instance, physical injury (e.g., loss of limb function due to paralysis or loss of limb due to amputation) may be the root cause for the lack of bimanual ability. In another instance, a limb or hand may simply be occupied with another task. In either case, the individual may complete the task unimanually, or seek out the aid of another person or agent to complete the task intermanually. For example, a surgeon may be holding something in place with one hand while still needing to complete a task that requires two hands. As a result, the surgeon may seek the aid of a surgical assistant, or interact with some kind of pre-built apparatus or robotic arm (Liu, Kobayashi, Zhang, & Fujie, 2014). Finally, the intermanual coordination mode may be preferred due to performance differences, or to reduce cognitive resources to focus on another task or another portion of the task (Zheng et al., 2005; Van Oosterhout, Heemskerk, de Baar, van der Helm & Abbink, 2017).

Knowing the differences in performance between coordination modes has major ramifications in applied domains, such as medicine (e.g., surgical knot tying; Murphy, 2001; controlling a robotic arm; Piccigallo et al., 2010) and teleoperations (Shull & Gonzalez, 2006). For example, expert medical operators (e.g., surgeons tying knots) learn to complete the same task using multiple manual coordination modes (Murphy, 2001). Little is known about what enables speed during two-handed tasks, which is important because many tasks require fast and accurate performance.

Coordination modes

The majority of *intra*personal manual coordination research focuses on an individual completing simple movement tasks, such as drawing a line, pointing, and grasping (Adams, 1952, 1961, 1964, 1971, 1987; Bernstein, 1967, 1996; Fitts, 1954; Fitts

& Peterson, 1964; Kelso, 1995; Rosenbaum et al., 1990; Woodworth, 1899). Investigating coordination in this way has allowed researchers to identify basic principles that underlie unimanual and bimanual movements, which, for this dissertation, were used to hypothesize about intermanual movements. Additionally, there is an extensive amount of *inter*personal manual research. However, the majority of this research, similar to that of bimanual coordination, focused on rhythmic tasks (e.g., dyadic finger oscillations; Ouiller, Guzman, Jantzen, Lagarde, & Kelso, 2008).

The following sections briefly review the relevant literature for the unimanual, bimanual, and intermanual coordination modes. As mentioned above, there is an extensive amount of both *intra*personal and *inter*personal research. Therefore, the literature reviewed in the following sections have been specifically selected to further the understanding of speed differences during bimanual and intermanual coordination.

The unimanual coordination mode. Unimanual research dates back to Woodworth (1899), who was one of the first to examine how individuals moved their hand from one area to another (i.e., discrete movements that have a clear beginning and end; Schmidt & Lee, 2011). Psychologist Paul Fitts (1954) advanced the study of unimanual coordination by having participants complete one-handed transfer (e.g., moving disks and pins from one location to another) and tapping tasks with varying movement distances and target sizes (Figure A2). This research led to Fitts' Law: the observation that movement time (speed) can be quantified as a function of target width and target amplitude (Fitts, 1954; Fitts & Peterson, 1964). Important to this dissertation, is that Fitts' Law is not limited to the rapid pointing task shown in Figure A2, but may also be applied to unimanual aiming movements (Fitts and Peterson, 1964) and unimanual peg transfer tasks (Annet, Golby & Kay, 1958). Additionally, it should be noted that while Fitts' Law does have many applications, it breaks down (i.e., a lack of prediction) with very small movement distances and target sizes (Klapp, 1975).

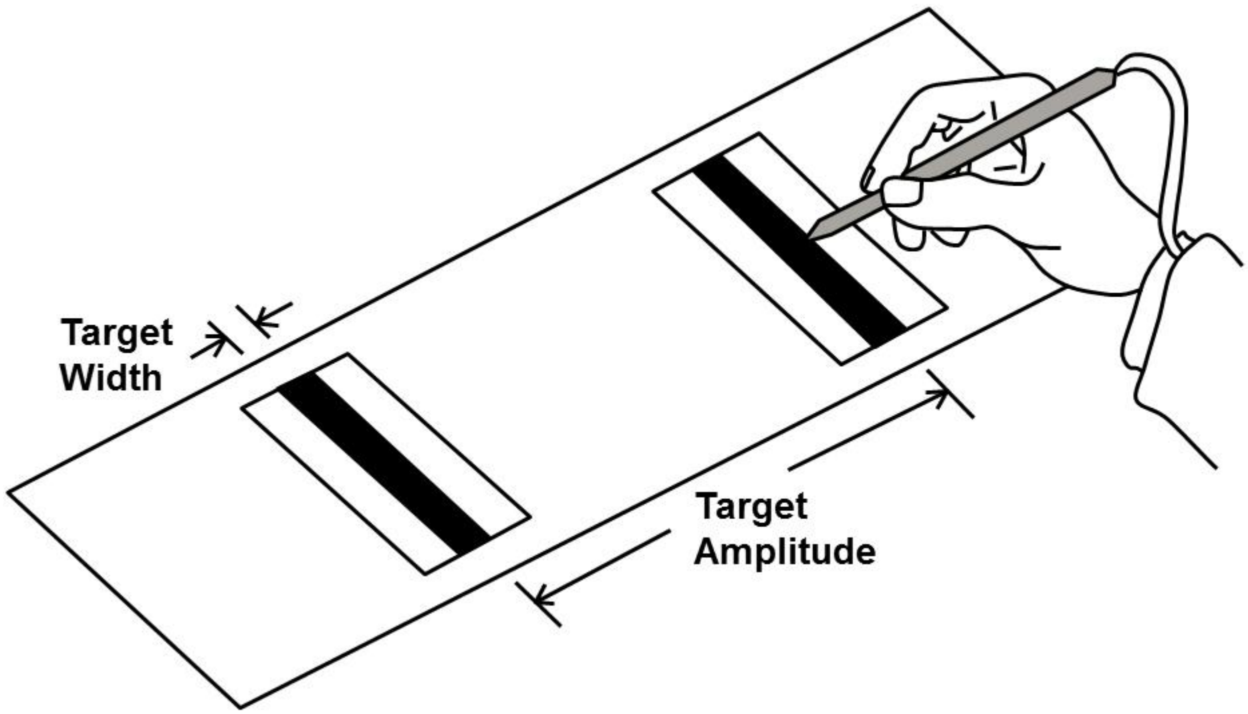

Figure A2. An illustration of the tapping task used by Fitts (1954). Movement time can be quantified as a function of target width and target amplitude. As target width and/or target amplitude increase, movement time increases.

Compared to bimanual coordination, unimanual coordination may be less mentally demanding due to dual task interference present when simultaneously manipulating both limbs during bimanual coordination (Norman & Barrow, 1975; Pashler & OBrien, 1993). However, this may be task specific (Koeneke et al., 2004; Rosenbaum, Kenny, & Derr, 1983). For example, during a two-finger cursor navigation task, unimanual is slower because it is associated with increased cortical demands (Koeneke et al., 2004). Similarly, people naturally type two-handed letter sequences faster than one-handed letter sequences on a standard keyboard (e.g., typing “b-y” is faster than typing “m-y”; Rosenbaum, Kenny, & Derr, 1983). In the b-y case, a skilled typist uses their left index finger to hit the “B” key, and then uses the right index finger to hit the “Y” key almost immediately following the previous keystroke. Alternatively, in the m-y case, the typist must wait for the right index finger to hit the “M” key before the right index fingers navigates to across the keyboard to then hit the “Y” key. Therefore, there seems to be a sequential dependence on finger movement during the unimanual case that is not present in the bimanual case. This visuomotor finding was extended to bimanual and intermanual coordination further in the document.

These task-dependent characteristics of unimanual versus bimanual coordination are helpful when applied to the intermanual coordination mode. These two examples show that some tasks benefit when using two hands when compared to only using one, even though there are negative aspects when using the bimanual coordination mode (e.g., dual task interference). However, it is important to note that interference during the bimanual tasks exists, and was revisited in the Negative Aspects of Bimanual Coordination section.

Eye-hand coordination during unimanual tasks. The eye-hand coordination required during all three coordination modes was of particular interest for this dissertation. Therefore, it is important to review the available and relevant literature regarding eye-hand coordination. In unfamiliar settings, unimanual reaching and grasping is a visually-guided action (Fitts & Peterson, 1964), and vision is critical for accurate performance (Fisk & Goodale, 1988). Prior to a unimanual action, people initiate an anticipatory eye movement towards the to-be-manipulated object (i.e., a “guiding fixation," Mennie, Hayhoe, & Sullivan, 2006). Once a unimanual action has been initiated to manipulate the object (i.e., the hand starts to move), the eye stays focused on the object until the hand arrives (or is close to arriving) (i.e., "gaze anchoring," Bowman et al. 2009; Rand & Stelmach 2010). Additionally, if a task requires two sequential actions (i.e., manipulating one object and then another), then the eyes must wait for the first unimanual action to reach completion (or near-to-completion) until the second unimanual action can start (Rand, 2014).

The bimanual coordination mode. Bimanual coordination is the fundamental paradigm for studying manual coordination (Kelso, 1995). The majority of bimanual research focused on rhythmic movement during finger oscillation tasks (Semjen, Summers, & Cattaert, 1995; Swinnen & Wenderoth, 2004; Turvey, Rosenblum, Schmidt, & Kugler, 1986). A bimanual finger oscillation task requires individuals to continuously oscillate both index fingers simultaneously (up-and-down or side-to-side). Figure A3 shows examples of in-phase and anti-phase finger oscillation movements (side-to-side). The consistent finding within this line of research is that people tend to unintentionally synchronize their movements. For example, when completing a side-to-side finger oscillation task, the fingers naturally move in a temporally coupled manner in either the in-phase or in anti-phase, with the in-phase pattern being the preferred phase by humans (Mechsner, Kerzel, Knoblich, & Prinz 2001).

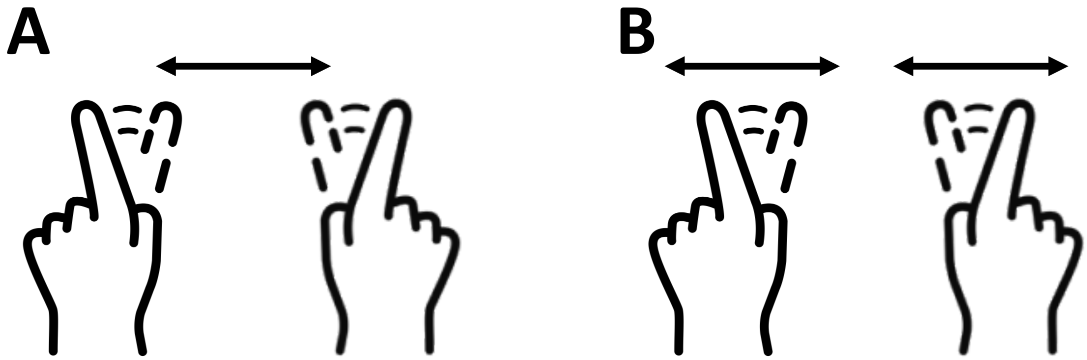

Figure A3. (A) In-phase movement; the fingers move towards and away from each other in unison. (B) Anti-phase movement; the fingers move to the right and left in unison.

Mechsner and colleagues (2001) experimentally induced naïve participants to successfully complete a difficult bimanual task: coordinating ones' limbs in a 4:3 movement ratio (e.g., four movements of the right arm for every three movements of the left arm). Completing such a task is important because moving the limbs in a 4:3 frequency ratio is "practically impossible" (Mechsner et al., 2001, p. 72) for most people to perform. In order to accomplish this task, participants followed a simple visual pattern. Mechsner and colleagues (2001) asked participants to rotate two flags in symmetric (in-phase or anti-phase) patterns using hand cranks hidden under a table (Figure A4).

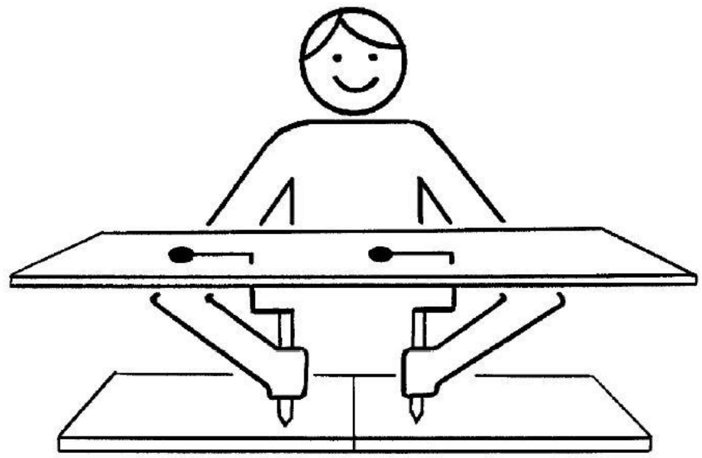

Figure A4. Participants rotated two flags in symmetric (in-phase or anti-phase) patterns using hand cranks (Mechsner et al., 2001).

Using a gearing mechanism, participants' hands were circling in a 4:3 rotation underneath the table while the flags were moving at a simple, 1:1 ratio above the table. Visually, participants were keeping the flags in a simple in-phase 1:1 ratio. However, because of the gears, their hands were maintaining the 4:3 ratio. Thus, by following the simple visual pattern, participants were able to oscillate their limbs in the "practically impossible" 4:3 ratio. This experiment showed how manual coordination may be governed more by visual information, and not just the biomechanical linkages that exist throughout the body. In particular, this research showed that participants were able to overcome the ubiquitous tendency for people to temporally synchronize the movements of their hands (Kelso, 1995).

Eye-hand coordination during bimanual tasks. Eye-hand coordination during bimanual coordination has been investigated in a variety of settings (Land, 2006; Land & Hayhoe, 2001), such as making a cup of tea (Land, Mennie, & Rusted, 1999), and making a peanut-butter-and-jelly sandwich (Hayhoe, 2000). Similar to unimanual coordination, anticipatory eye movements (i.e., guiding fixations) are also present during bimanual coordination (Mennie et al., 2006). Important to the discussion and comparison of coordination modes, gaze anchoring (Rand & Stelmach, 2010) present during unimanual coordination is also present during bimanual coordination, and has been shown to be detrimental to performance as measured by speed (Bingham et al., 2007). This is because eye-hand coordination during bimanual tasks is sustained by delaying hand movements until the eye is available for guiding movement (Pelz, Hayhoe, & Loeber, 2001). Thus, if a bimanual task requires simultaneous reaching and grasping, then one visually-guided subtask has to be completed with one hand before starting a separate visually-guided subtask with the other hand (Bingham et al., 2007), which makes the person complete the previously intended simultaneous action sequentially.

The intermanual coordination mode. Some researchers have argued that intermanual coordination is simply two people simultaneously completing unimanual tasks with a common goal. However, each person has to coordinate their actions with one another in time and space (Zheng et al., 2005). When comparing bimanual and intermanual coordination research, intermanual coordination mode may be easier to perform due to dual-task interference present in bimanual coordination (Norman & Barrow, 1975; Pashler & OBrien, 1993), since bimanual is empirically inferior intermanual (due to possible dual-task interference). However, it should be noted that the research comparing these coordination modes was limited. Most of the research regarding the intermanual coordination mode was investigated using applied tasks and were discussed in the Mode Effects section. However, research paradigms used to study intrapersonal coordination (e.g., finger oscillations) have been extended to interpersonal coordination, which were to understand some aspects of intermanual coordination.

Interestingly, the same in-phase and anti-phase temporal synchronization observed during intrapersonal coordination was also observed across individuals (Fine & Amazeen, 2011; Jung, Hollander, Muller, & Prinz, 2011; Ouiller et al., 2008; Schmidt, Carello, & Turvey, 1990). Specifically, when one individual completed a bimanual finger oscillation task, the same results were observed when two individuals completed the same task as a dyad (Gipson, Gorman, & Hessler, 2016) (Figure A5).

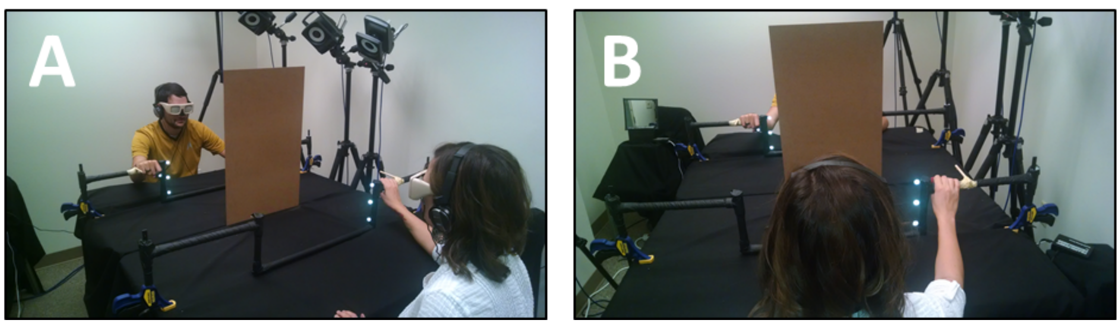

Figure A5. Experimental setup of Gipson and colleagues (2016). Participants sitting across from each other completed the typical bimanual finger oscillation task with two people. Visual information was manipulated using visual occlusion spectacles.

In the case of a single individual, the participant relied on internal biomechanical linkages between their hands, in addition to external perceptual information (Kelso, 1995). However, in the interpersonal case, the two people were linked solely through perceptual (e.g., visual) information (Gipson et al., 2016; Ouiller et al., 2008). These findings further suggested that the information needed for manual coordination may be more perceptual-spatial in nature, as opposed to strictly neural/physiological (Mechsner et al., 2001).

Eye-hand coordination during intermanual tasks. Eye-hand coordination during intermanual coordination has yet to been specifically investigated. However, one can use the previously described unimanual and bimanual research as a starting point to understand the underlying visual aspects of intermanual coordination. Using this line of reasoning, it was surmised that the same visual aspects during unimanual coordination may also apply during intermanual coordination, with the inclusion of the social/team component (Zheng et al., 2005). From a social perspective, research showed that the visual system played a significant role during action observation of another person's goal-directed action (Grdeback & Falck-Ytter, 2015). For example, when participants observed another person reaching towards a to-be-manipulated object, the observer moved their eyes towards the same object (i.e., anticipatory eye movements; Flanagan & Johansson, 2003; Grdeback & Falck-Ytter, 2015). Along these lines, anticipatory guiding fixations and gaze anchoring observed during unimanual and bimanual situations may also apply to intermanual situations, which was investigated in this dissertation.

Important to the discussion and comparison of coordination modes, the detrimental effect guiding fixations and gaze anchoring present during bimanual coordination (Bingham et al., 2007) should not play as much of a role during the intermanual coordination mode. Using the intermanual coordination mode to complete two-handed tasks may be one way to circumvent the negative aspects related to eye-hand coordination during bimanual tasks. For example, if an intermanual task requires simultaneous grasping, then each visually-guided subtask can be completed simultaneously (rather than sequentially, which must be done when completing the task bimanually) since the intermanual coordination mode has a separate visuomotor systems (person) for each hand.

Negative Aspects of Bimanual Coordination

When compared to intermanual coordination, there are certain aspects of bimanual coordination that may impede task performance, speed in particular. Based on past research, it seemed that two main phenomena outline the intermanual speed advantage: bimanual coupling and bimanual visuomotor coupling. These two aspects of bimanual coordination were discussed in the following sections.

Bimanual coupling. If you pretend there are two cups in front of you at separate distances (one closer and one further away) and complete two separate unimanual grasping tasks, then you would probably conclude that it would take you less time to grasp the cup that is closer to you than the cup that is further from you (Figure A6). However, if you attempt this task bimanually (i.e., complete these two separate unimanual actions simultaneously), then you would probably grasp the objects at approximately the same time (e.g., Kelso et al., 1979; Kunde & Weigelt, 2005).

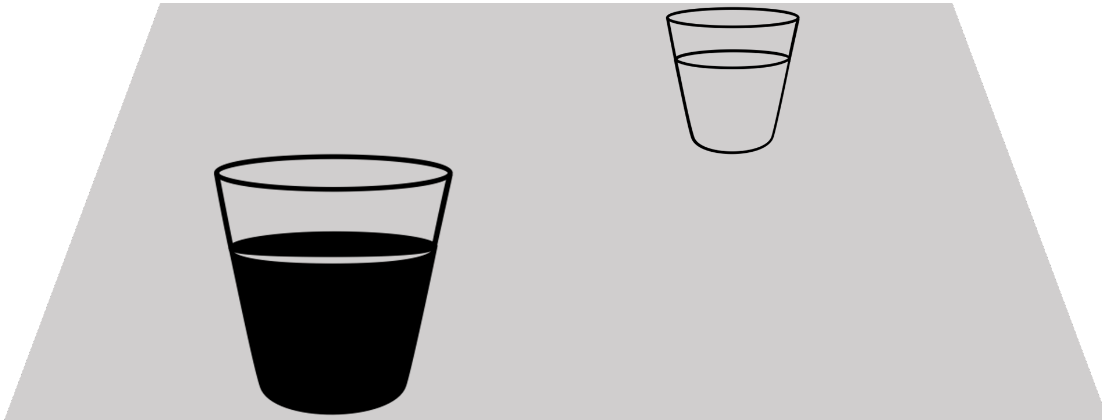

Figure A6. Two cups placed on a desk at separate distances. Unimanually grasping the further cup should take longer than grasping the closer cup. When completing the task bimanually, the time it takes to simultaneously grasp both cups is approximately the same.

This was an example of the bimanual coupling, which is the lack of spatial and temporal independence of the hands during an individual two-handed task. Bimanual coupling has been reported to happen temporally (Semjen et al., 1995; Turvey et al., 1986) and spatially (Franz et al., 1991). The cup exercise was an example of temporal bimanual coupling, which was introduced earlier (e.g., homologous and non-homologous muscle movement of the fingers during a bimanual finger oscillation task tend to sync up; Kelso, 1995). In addition to temporal bimanual coupling, there was also spatial bimanual coupling, which occurred when simultaneous, incongruent movement during a bimanual task caused a higher degree of movement variability when compared to completing the task unimanually (Franz, 1997). For example, simultaneously drawing a square with one hand and a circle with the other hand will cause performance to suffer (Figure A7).

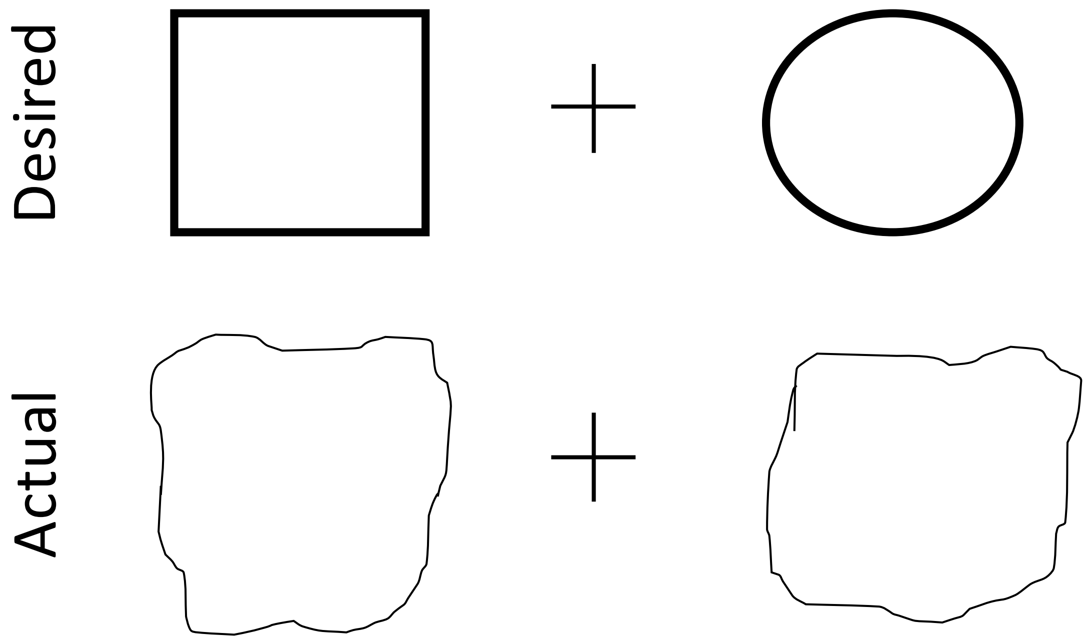

Figure A7. An example of spatial bimanual coupling similar to what was observed during Chan and Chan (1995).

As mentioned earlier, when bimanual coupling is present, the movement of one hand interferes the movement of the other hand. When this happens, people tend to isolate the movement of each limb (which causes them to sequentially complete the task) or tend to move each limb in a similar manner (which may negatively impact performance) (Kelso et al., 1979). Paul Fitts' unimanual research showed that as target size decreases and/or target distance increases, the time it takes to arrive at that target (movement time) increases (i.e., Fitts' Law; Fitts, 1954). However, when completing a bimanual Fitts' Law task with two separate targets at different distances, Fitts' Law can no longer predict task time for each limb. During a bimanual Fitts' Law task, the two hands move together as a single motor unit, and arrive at each target at approximately the same time (i.e., bimanual coupling). Specifically, the hand that is supposed to travel to the further target constrains the movement of the hand that is supposed to travel to the closer target (see Figure A8; Kelso et al., 1979).

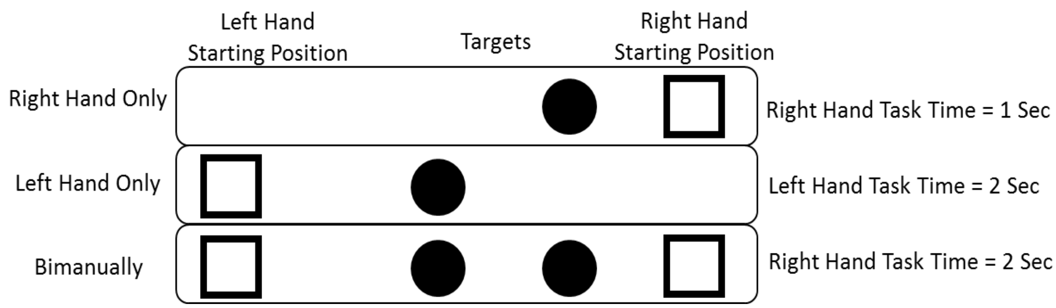

Figure A8. When completing the task using only one hand, the distance-to-target can predict movement time. However, this prediction does not apply during the bimanual case (the hand that moves to the further target affects movement time of the other hand).

Importantly, bimanual coupling disappears, to a degree, with extended practice (Kelso & Zanone, 2002; Zanone & Kelso, 1992, 1997). Musicians, for example, are able to overcome both the spatial and temporal effects of bimanual coupling (Shaffer, 1981). For example, in the early phases of learning to play the piano, the hands will spontaneously synchronize and move together. However, after extended practice, the hands are able to move independently (but still have coordinated movements) to create the desired musical notes (Furaya & Kinoshita, 2008; Furaya & Soechting, 2012).

Interestingly, using the intermanual coordination mode to complete two-handed tasks may be one way to circumvent the negative aspects related to the bimanual coupling. This is because the intermanual coordination mode does not have the same internal neural/physiological linkages present during bimanual coordination. However, as explained in the introduction, the same intrapersonal temporal and spatial coupling are also observed interpersonally (Fine & Amazeen, 2011; Jung, Hollander, Muller, & Prinz, 2011; Schmidt, Carello, & Turvey, 1990). However, this effect goes away with the removal of mutual visual information (i.e., not attending to the other hand) (Gipson et al., 2016; Ouiller et al., 2008).

Bimanual visuomotor coupling. Extending the cups example from above, pretend the cups are now of equal distance from you (one to the left and one to the right), and now each cup has two circular marks at the top of each cup (Figure A9). In this example, you are only allowed to use your middle finger and your thumb to grasp each cup, and you are only allowed to grasp the areas that have circular marks. If you were to complete two separate unimanual grasping tasks, then you would probably (correctly) conclude that the time it would take for you to grasp each cup by the circular marks would be approximately the same. However, if you were to attempt this task bimanually (i.e., complete these two separate unimanual actions simultaneously), then you would have to wait for one visually-guided subtask to be completed with one hand (e.g., whichever cup you chose to grasp first) before starting a separate visually-guided subtask with the other hand (e.g., grasping the second cup) (Bingham, Hughes, & Mon-Williams, 2008; Rand, 2014).

Figure A9. During a bimanual coordination task that requires simultaneous reaching and grasping from both hands, the visual system is physically only able to focus on one visually-guided action at a time. In this hypothetical example, the goal is to simultaneously grasp both cups by the blue circular marks. Due to bimanual visuomotor coupling, you may only be able to successfully visually guide one of the hand at a time, which could be detrimental to performance.

During a bimanual task that requires simultaneous reaching and grasping from both hands, the visual system is only physically able to focus on one visually-guided action at a time (i.e., the task essentially becomes two separate unimanual tasks due to this sequential dependence) (Bingham, et al., 2008). Bimanual visuomotor coupling present during any manual task may negatively affect task time during bimanual coordination. Having to wait for one visually-guided subtask to be completed with one hand before starting a separate visually-guided subtask with the other hand will take longer than completing both tasks simultaneously with both hands (Bowman et al. 2009; Neggers and Bekkering 2000; Rand and Stelmach 2010; Rand, 2014).

It is important to note that the distances between the two objects should play a role, such that the sequential bimanual dependence brought about from visuomotor coupling may be a function of object distance. For example, what if the two cups in the previous example were so close together that you could visually attend to both objects at the same time? Would you still think that you would have to wait for one visually guided action to be completed with one hand before moving to the other- action? One may assume that performance should decline as target distance increases and target size decreases (or a related function). However, Bingham and colleagues (2008) found that sequential looking during a bimanual reach-to-grasp task still affected behavior when objects were only 20 cm apart. Unfortunately, Bingham and colleagues (2008) did not report viewing distance or participants' visual angle.

Unimanual and bimanual visuomotor coupling plays more of a role when completing an unpracticed task in an unfamiliar environment (compared to a previously practiced task in a familiar environment) (Land & Tatler, 2009). For relatively unpracticed tasks, the eyes play more of a role in searching for the next target (Abernethy, 1990). However, tasks that have been practiced over an extended period of time, such as tying one's shoelaces, do not need to be visually guided; thus, bimanual visuomotor coupling should not play as much of a role after extended bimanual practice (Franz, 2003). Additionally, similar to circumventing the negative effect during bimanual coupling, using the intermanual coordination mode to complete two-handed tasks may be a way to circumvent the negative aspects related to bimanual visuomotor coupling during simultaneous bimanual actions, at least when the task is not a previously practiced bimanual task.

Mode Effects

The aforementioned differences in performance comparing coordination modes will be referred to as "mode effects." A "mode effect" may be classified as when any coordination mode (e.g., intermanual) outperforms another coordination mode (e.g., bimanual) when completing the same manual task (e.g., teleoperation) while using the same measure (e.g., speed) for comparison (Gorman & Crites, 2013). Most of the intermanual research (Glynn & Henning, 2000; Gorman & Crites, 2013, 2015; Zheng et al., 2005, 2007) involved a direct comparison of the bimanual and intermanual coordination modes. In these settings, one particular finding was consistently observed: The Intermanual Speed Advantage. The intermanual speed advantage was observed during following tasks: a laparoscopic cutting task (Zheng et al., 2005, 2007), teleoperation tasks (Glynn & Henning, 2000; Gorman & Crites, 2013), and pursuit-rotor tasks (Reed et al., 2006; Wegner & Zeaman, 1956).

The intermanual speed advantage. As mentioned before, research investigating the bimanual and intermanual coordination modes is limited, but the intermanual speed advantage has been replicated in a handful of studies. The intermanual speed advantage is the observation that performance is faster when completing a task using the intermanual coordination mode, compared to completing the same task using the bimanual coordination mode (Gorman & Crites, 2013). Reed and colleagues (2006), Wegner and Zeaman (1956), and Glynn and Henning (2000) did not offer any specific explanation of the intermanual speed advantage. As a result, these studies were not specifically reviewed.

Laparoscopic cutting task. Zheng and colleagues (2005) observed the intermanual speed advantage during a laparoscopic cutting task. In this task, participants completed the cutting task either individually (bimanually) or as a dyad (intermanually). Figure A10 shows a graphic of the apparatus they used.

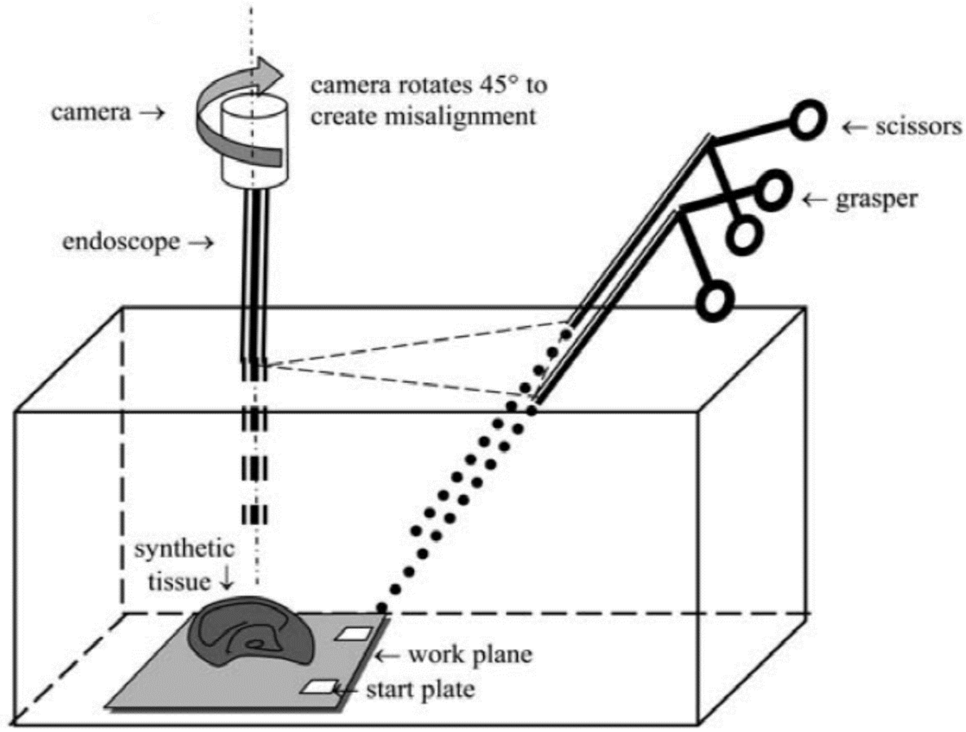

Figure A10. Endoscopic training box used in the Zheng et al. (2005) experiment. The camera rotation was used to manipulate participants' workload and had little effect on dyadic performance.

Results revealed that participants performed the task faster intermanually (Zheng et al., 2005). What underlies the intermanual speed advantage? Zheng and colleagues (2005) posited that participants depended on shared task knowledge in the form of a "shared mental model" (SMM; Cannon-Bowers, Salas, and Converse, 1993). A SMM is a knowledge structure, held by individuals and team members, that forms an accurate task representation and understanding, and facilitates coordination with other team members (Cannon-Bowers et al., 1993). Zheng and colleagues (2005) suggested that the SMM is what allowed participants to predict each other's movements. However, this hypothesis was not directly analyzed. Specifically, they argued that shared task knowledge led participants to develop expectancies about where their hand and their partner's hand should be on a moment-to-moment basis, such that participants were able to anticipate their partner's movements to complete the task faster (Zheng et al., 2005).

In order to assess this anticipatory movement hypothesis, Zheng and colleagues (2007) reanalyzed data from the original Zheng and colleagues (2005) study, and observed more anticipatory movements during the intermanual condition than there were in the bimanual condition. The authors concluded that the intermanual mode effect was due to anticipatory movements (i.e., one participant's hand anticipated the movements of the other participant), which were not observed when individuals completed the task using the bimanual coordination mode (Zheng et al., 2007). Therefore, anticipatory movements, via shared task knowledge in the form of a SMM, was offered as the contributing factor underlying the intermanual speed advantage.

Teleoperation task. Gorman and Crites (2013) replicated the intermanual speed advantage in a teleoperation task. In this task, participants remotely navigated a rover around a track using the unimanual, bimanual, and intermanual coordination modes. Figure A11 shows the control modes and apparatus used in the study.

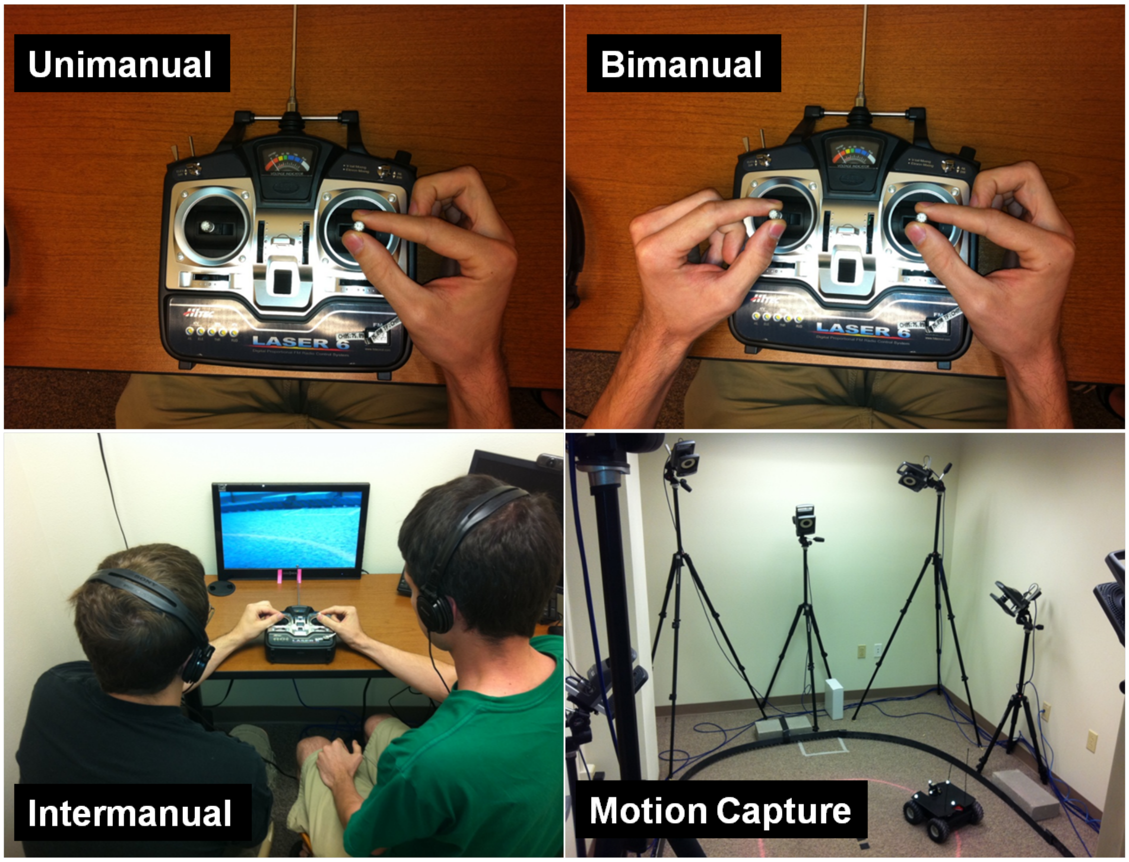

Figure A11. Manual coordination modes and experiment apparatus used in the Gorman and Crites (2013) experiment.

The results similarly revealed that participants completed the task faster intermanually compared to bimanual and unimanual control (as expected, unimanual was slowest; Gorman & Crites, 2013). Thus, the intermanual speed advantage was replicated using a different task; however, the explanation of this mode effect offered by Gorman and Crites (2013) contrasted with that of Zheng and colleagues (2005, 2007).

Gorman and Crites (2013) agreed that the intermanual mode effect was likely due to anticipatory movements. However, due to use of novice participants, and the novelty and simplicity of the task (like the Zheng et al., 2005 task), the explanation of the development of shared task knowledge or a SMM may not be the primary source to develop anticipatory movements. Specifically, it was argued that the requirements for successful performance of these simple and unpracticed intermanual tasks may be based more on organizing bottom-up, perceptual–motor interactions and timing behaviors, rather than on top-down (i.e., shared knowledge) processes. In this sense, the participants were reacting more to the real-time information that is coming in, rather than the stored representation within their body.

The effect of task familiarity. One limitation of the Zheng and colleagues (2005, 2007) study and the Gorman and Crites (2013) study is that the researchers used novice participants (college students) who were performing unfamiliar, previously unpracticed tasks – laparoscopy and teleoperation. Thus, even though intermanual mode effects were observed and replicated in these and other studies (e.g., Reed et al., 2006), one cannot establish their generalizability to previously practiced manual tasks (e.g., surgery), where knowledge and previous practice may be more relevant factors. Thus, previous practice using the bimanual coordination mode was another key factor to investigate the underlying factors related to this mode effect of speed.

Mode effects during a highly-practiced task. Gorman and Crites (2015) sought to further investigate the intermanual speed advantage by using a previously practiced bimanual task: shoe-tying. In this task, participants tied a shoe-like apparatus using both the bimanual and intermanual coordination mode. Figure A12 shows participants completing the task in the intermanual condition.

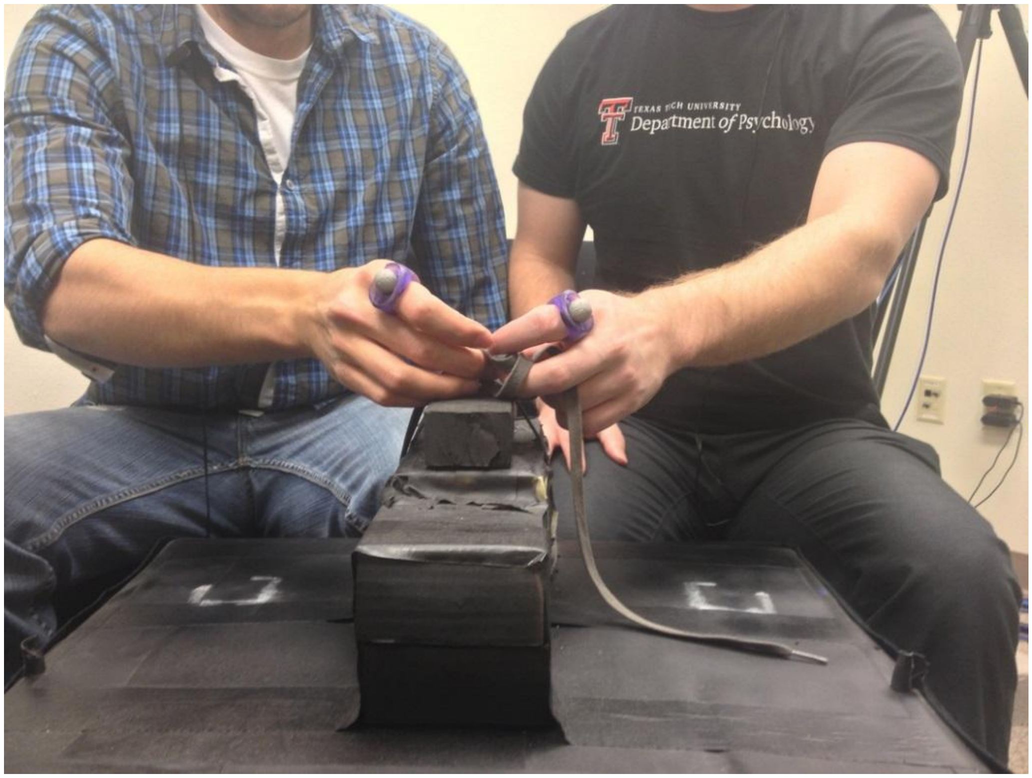

Figure A12. Example of the intermanual condition during the Gorman and Crites (2015) study. For all intermanual conditions, participants sitting to the left of the "shoe" used their left hand, while participants sitting to the right of the "shoe" used their right hand.

This shoe-tying paradigm was ideal for studying highly-practiced ("automatic") manual tasks, because participants from typical research pools (i.e., undergraduate university students) were ostensibly shoe-tying experts. In this setting, the intermanual coordination mode was the only previously unpracticed aspect of the task, as opposed to unfamiliar tasks (e.g., teleoperation), where both the bimanual and intermanual coordination modes were previously unpracticed. This grounded the previous claims of the intermanual speed advantage into a more realistic, comparable setting.

Contrary to the observed intermanual speed advantage using novices, Gorman and Crites (2015) found, unsurprisingly, that intermanual shoe-tying was slower than bimanual shoe-tying (i.e., a bimanual speed advantage). Hence, the intermanual mode effect was not present when using a previously practiced bimanual task. At first glance, this finding seems trivial, but it may have important implications for manual skills, such as bimanual and intermanual surgical tasks (Zheng et al., 2005, 2007).

So, why did the intermanual speed advantage disappear? Gorman and Crites (2015) suggested that the prior experience and life-long development of bimanual shoe-tying interfered with performance using the new, unpracticed intermanual coordination mode. Along these lines, researchers have argued that manual coordination tasks go through various stages during skill acquisition; such as the Cognitive, Associative, and Autonomous Stages (Fitts, 1964). At the start of manual skill development, the Cognitive stage characterizes error-ridden and inefficient task performance with rapid performance gains. On the other end of the spectrum, the Autonomous stage is characterized with automatic performance with very few errors (Davids, Button, & Bennett, 2008). With this viewpoint, bimanual and intermanual shoe-tying during the Gorman and Crites (2015) study were in the Autonomous and Cognitive stages, respectively. Given the unfamiliar nature of completing the task using the intermanual coordination mode, it is expected that participants' previous bimanual experience negatively affected intermanual performance (i.e., automaticity interfered with concurrent performance; Brown & Carr, 1989). This suggests that the role of previous bimanual practice should be experimentally manipulated.

Measuring coupling. The previous discussion of research findings focused exclusively on the measure of performance/speed (e.g., the intermanual speed advantage). However, speed is merely one measure of performance that can specify a mode effect. In addition to speed, other measures have been used to research performance differences between the bimanual and intermanual coordination modes. Primarily, movement variability has been used alongside speed, such that speed-variability correlations are used to assess skill level (Elliott et al., 2010). When movements are skilled, the hands are less variably related to one another (Gorman & Crites, 2015). In this case, lower variability during manual coordination tasks reflect a higher skill level, with faster trial-to-trial performance correlated with lower trial-to-trial variability (i.e., a positive correlation between task completion time and variance; Gorman & Crites, 2015; Thelen et al., 1993). However, this dissertation was not only concerned with the speed/variability performance, but also how performance unfolds. In this way, this dissertation sought to describe bimanual and intermanual movement *over time*. To investigate this, between-hand *coupling* measures based on dynamical systems theory analyzed the relationship between the hands during manual performance, in addition to traditional speed/variability measures and correlations.

Coupling measures. Coupling, in the physical sense, was originally observed in the 1600s by Christiaan Huygens, who noticed that two or more pendulums of a clock would end up swinging in synchrony when mounted in the same clock box (Huygens, 1673). The common board these clocks were mounted on created a physical link that coupled the pendulums, allowing them to eventually swing in synchrony (i.e., they had to be physically coupled to move together). This example describes coupling, which is formally defined as “the study of mutual dependency among relatively independent components” (Shockley, Butwill, Zbilut & Webber, 2002, p. 59). Interestingly, this idea of coupling and synchronicity is not limited to physical objects, such as clocks coupled through a piece of wood, but is also seen in biological systems throughout nature, including perceptually-coupled humans (Gipson, Gorman, & Hessler, 2016; Strogatz, 2003).

Unlike speed and variability, coupling measures are less prominent in the history of manual coordination research. Whereas traditional measures provide the researcher with a summative “snapshot” of task performance (e.g., averaging performance across movement trials), coupling measures employ techniques that allow us to gauge how a process unfolds over time throughout the trial (Riley & Van Orden, 2005). When researching coupling between the hands, various methods must be employed to successfully describe the hands as a dynamical system. The approach described below outputs multiple measures that quantify and describe how coupled the hands are.

Cross Recurrence Quantification Analysis (CRQA) is a method for assessing the degree of coupling between two time series generated by two components of a dynamical system (Shockley, Butwill, Zbilut & Webber, 2002). For manual coordination, the CRQA method provides measures of how coupled two hands are as they move through space and time during task performance. The two measures of coupling used in this dissertation were percent recurrence (%REC) and the longest diagonal segment of recurrent points (MAXLINE) (e.g., Shockley, Baker, Richardson, & Fowler, 2007; Shockley, Santana, & Fowler, 2003). %REC quantifies the degree to which the hands are coupled, and MAXLINE quantifies the stability of that coupling (Shockley et al., 2002). The concept of the stability of a system is not easily defined nor described, so a few examples are provided next.

The stability of a coupled system can be thought of as a system of parts constrained to move together through time, governed by a similar set of rules (Guastello,

2013) – when one part moves in a certain way, the other part must eventually follow. However, it is simpler to think of the stability of a coupled system at a more abstract level. For example, you can hear the stability of a coupled system when you listen to an orchestra, watch a team row crew, or feel the smooth ride in a high-end vehicle. When a coupled system is not stable or moves away from stability, the orchestra "sounds off," the team rowing crew is not moving in unison, or the car seems to shake when braking. In all accounts, there is something chaotic about the system – something is "off." When a system is not stable (i.e., low MAXLINE), the parts of the system are not coupled or only weakly; they are working/moving independently. To summarize, the coupling measures can describe how coupled the parts are (%REC) and how stable that coupling is (MAXLINE).

Coupling measures in bimanual and intermanual coordination. In addition to speed and variability, Gorman and Crites (2015) used these coupling measures to compare the bimanual and intermanual coordination modes during familiar task performance (i.e., shoe-tying). They found the intermanual coordination mode had significantly higher values of %REC and MAXLINE compared to bimanual. Thus, when completing a familiar task using the bimanual coordination mode, participants exhibited lower between-hand coupling and stability than when completing the task intermanually. Hence, bimanual tying was associated with the hands moving independently, and intermanual tying was associated with the hands becoming synchronized, similar to the findings observed during the intrapersonal (Mechsner et al., 2001) and interpersonal (Gipson et al., 2016) temporal coupling.

Additionally, Gorman and Crites (2015) observed that lower between-hand coupling was correlated with faster, more skilled performance, which suggests that decoupling the hands (i.e., the two hands working independently) may be a part of highly-practiced tying performance, and is presumably learned from an early age. Interestingly, this finding was consonant with previous research that examined the stability of relatively simple finger oscillatory movements as a function of movement frequency (speed). In particular, Kelso (1995) observed that participants' movement stability during in-phase finger tapping (moving both fingers up and down simultaneously) varied as a function of speed, such that, as participants tapped their fingers faster, the coordination of movements across the fingers became less stable. Interestingly, the relatively complex shoe-tying task revealed that differences in overall speed (i.e., bimanual faster than intermanual) may be associated with the stability of coupling across the participant's hands (Gorman & Crites, 2015).

Furthermore, Gorman and Crites (2015) argued that the decoupling of the hands is what produced faster tying performance. As with the anticipatory movement effect (described before), participants learned to move each hand independently of the other when completing this bimanual task. This is an interesting finding, because typical bimanual coordination tasks show how spatially and temporally linked the two hands are to one another (i.e., bimanual coupling). In almost every bimanual coupling case, some form of mutual synchronization tendencies is observed (e.g., Kelso et al., 1979). However, some research has shown that people can decouple their movements with enough practice (Zanone & Kelso, 1991), similar to what we see in the highly-practiced shoe-tying task (Gorman & Crites, 2015). Thus, the fact that participants are able to decouple their hands, consequently allowing them to circumvent typical bimanual coupling constraints, permits participants to complete the task faster than tasks where they have not reached that level of practice.

The independent movements observed during bimanual tasks may be comparable to anticipatory movement effects observed during intermanual performance (Zheng et al., 2007). Thus, whether tasks are completed bimanually or intermanually, independent (decoupled) movements of the limbs may characterize high task performance as measured by speed. Taken together, it seems that complementary, opposed to synchronized, movement timings are associated with higher levels of performance in the highly-practiced shoe-tying task. If this is the case, then in order to achieve higher task performance, individuals should steer away from the unintentional tendency that naturally forces individuals into “sync” when they are coupled (Strogatz, 2003).

Summary of findings. The current state of the literature suggests that the intermanual speed advantage may depend on bimanual practice (Gorman & Crites, 2015). However, additional measurement approaches (e.g., dynamic coupling) and theoretical limitations inherent in bimanual coordination (i.e., bimanual coupling and bimanual visuomotor coupling) may be able to extend the understanding within this line of research. Integrating these measures are beneficial because speed as the sole performance criterion of mode effects does not reveal the underlying process differences between these coordination modes. Table A1 shows a summary of known bimanual versus intermanual findings, highlighting the differences between whether or not the task has been previously practiced.

Table A1

Known Effects by Measure

		Speed (Time)	Between-Hand Coupling (%REC)	Anticipatory Movements
Practiced	Bimanual	Faster[1]	Lower[1]	-
	Intermanual	Slower[1]	Higher[1]	-
Unpracticed	Bimanual	Slower[2]	-	Fewer[2]
	Intermanual	Faster[2]	-	More[2]

Note. [1](Gorman & Crites, 2015); [2](Glynn & Henning, 2000; Gorman & Crites, 2013; Reed et al., 2006; Van Oosterhout et al., 2017; Wegner & Zeaman, 1956; Zheng et al., 2005, 2007)

Appendix B

Extended Measures Section

Visuomotor Coupling

How will visuomotor coupling data be collected? After reviewing the visuomotor literature, researchers either collect eye-tracking and hand movement data using the same system or have to simultaneously collect both sources of data and then manually combine them along a standard timeline. Due to technological limitations, the second approach was utilized.

Multimodal scoresheets. Based on the work of Holsanova (2001), Holmqvist and colleagues (2011) suggest building a multimodal score-sheet to combine eye-tracking and hand movement data. A multimodal score-sheet allows for the analysis of several tiers of temporal data along a common timeline (Holmqvist et al., 2011). Holsanova (2001) manually synchronized speech data and eye-movement data using a multimodal score-sheet. To do this, Holsanova (2001) and others (e.g., Johansson et al., 2006) analyzed eye-tracking data in the form of fixation sequences (analyzed frame-by-frame to construct scan paths) along with the development of speech units over time. Holmqvist and colleagues (2011) define a scan path as "the route of oculomotor events through space within a certain timespan" (p. 254).

Land, Mennie, and Rested (1999) used multimodal score-sheets to analyze gross body movements, targets of visual fixation actions, and manipulations (actions) of the hands along the same timeline while participants made a cup of tea (Figure B1). For this dissertation, the inclusion of gross body movements (i.e., trunk movements) such as "walk towards sink" (Land & Tatler, 2009; p. 87) did not apply since participants were in a seated position and every object is within arm's reach.

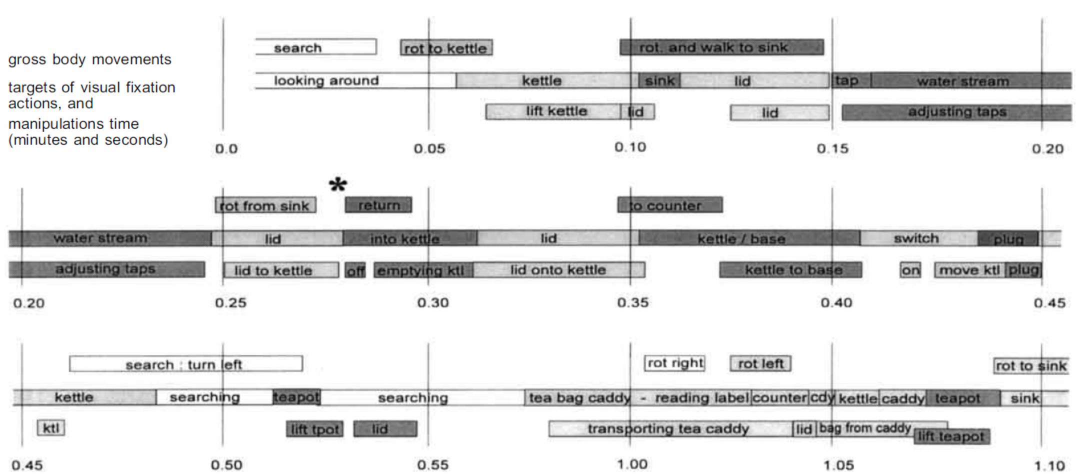

Figure B1. Example of a multimodal scoresheet based on the sequence of gross body movements, eye movements, and hand movements during a segment of the task used in the Land and colleagues (1999) experiment.

Hayhoe and colleagues (2003) conducted a similar research study based on Land and colleagues (1999). Opposed to making tea, Hayhoe and colleagues asked participants to make a peanut butter and jelly sandwich. Using fixation sequences, the researchers were able to temporally record the order of when participants were looking at a particular object and create a scan path (Figure B2).

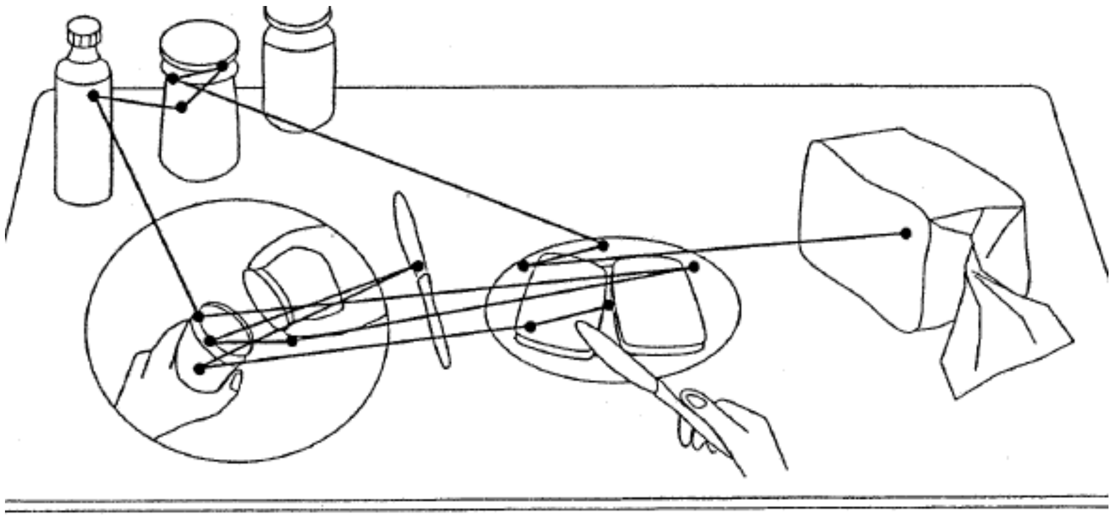

Figure B2. Example of a scan path created from a multimodal scoresheet from Land and Hayhoe (2001).

Based on frame-by-frame fixation sequences, Hayhoe and colleagues (2003) created multimodal score-sheets similar to Land and colleagues (1999) to combine the eye-tracking fixation data with left and right-hand manipulations (Figure B3).

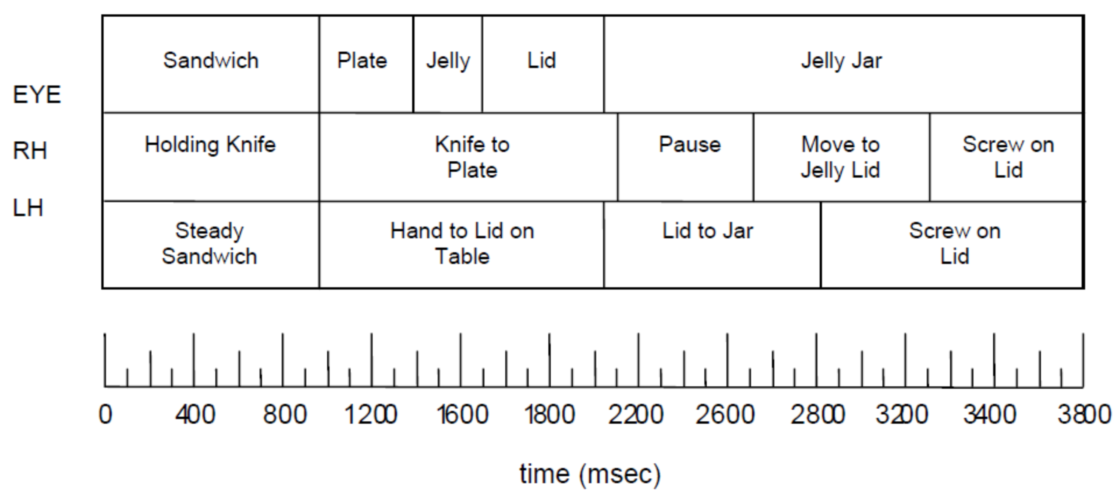

Figure B3. Example of a multimodal scoresheet based on the sequence of eye and hand movements during a segment of the task used in the Hayhoe and colleagues (2003) experiment.

Taken together, these studies provided the basis for obtaining data to measure Visuomotor Coupling by calculating Pre-Reach Look-Ahead and Gaze Anchoring (Hayhoe et al., 2003; Holsanova, 2001; Land et al., 1999). Specifically, the multimodal scoresheets used for this dissertation were directly based on the Hayhoe and colleagues (2003) study, but includes two fixation sequences due to the AOI-based analysis for each grasper/scissor subtask. Thus, for both the bimanual and intermanual coordination modes, there were two tiers (i.e., rows) related to eye-tracking data and two tiers related to the hand movements. Using the data sources available, scan paths in the form of fixation sequences were recorded into multimodal scoresheets, which were then used to calculate the two metrics needed to measure Visuomotor Coupling. Specifics related to the creation of the multimodal scoresheet will be described below followed by the calculations of Pre-Reach Look-Ahead and Gaze Anchoring.

Creating the multimodal scoresheet. Based on the works of Hayhoe and Land (2001), Hayhoe and colleagues (2003), and Land and colleagues (1999), the following steps will be followed to create the multimodal scoresheet for the measures of visuomotor coupling:

- Manual component
  - Define each subtask of grasper (left hand) and scissor (right hand) movement when completing the simulating cutting task.
  - Identify and define when each subtask starts and stops.
  - Record the start and stop of each subtask into the multimodal scoresheet.
- Visual component
  - Define each Area of Interest (AOI) relative to each manual subtask when completing the simulating cutting task.
  - Record fixation sequences to identify start and stop of glances within and outside of AOIs.
  - Record the start and stop of each eye movement into the multimodal scoresheet.

Each aspect of these steps is described in the order listed above.

Defining the manual subcomponents. In order to collect the data for the multimodal scoresheet, all visual and manual actions during the task were defined spatially and temporally. Each subtask related to the left hand (grasper) and the right hand (scissors) is shown in Table B1. Each subtask was reduced to the level of analysis to identify a clear start and stop for each reaching and grasping, and pointing and aiming movement completed during the two-handed simulated cutting task.

Table B1

Each Grasper and Scissor Task Needed to Complete the Simulated Cutting Task

Grasper	Scissors
Grasp object	Grasp pipe
Insert object through top of the pipe	Move pipe over to grey area of box
Rest object on grey area of the box	Simulate cutting action
Remove object from the pipe	Return fingers to pipe
Return object back to resting position	Return pipe back to first position
Return fingers to home key	Return fingers to home key

Note. This breakdown applies to both the conditions using the Bimanual and Intermanual coordination mode.

Identifying manual start/stop. Each subtask needed a clear definition of a beginning and an end. The start and stop times of these subtasks are referred to as temporal markers. Land and Tatler (2009) describe how “the best temporal marker to use to define the beginning of each act was the saccade that combined head-and-eye movement. This provided a ‘defining movement’ against which the timing of the other components of the action could be measured.” (p.86). Each start/stop task related to the left hand (grasper) in Table B2 and the right hand (scissors) is shown in Table B3.

Table B2

Each Grasper Subtask Broken Down by Start and Stop Movements

Grasp object	
	Start: Once both fingers have left the home key
	Stop: Once both fingers completely closed on the top of the object
Insert object through top of the pipe	
	Start: Once the object begins moving toward the top of the pipe
	Stop: Once the object is inserted into the pipe
Rest object on grey area of the box	
	Start: Once the object starts moving toward the grey are of the box
	Stop: Once the object first touches grey box
Remove object from the pipe	
	Start: Once the object is removed from the grey area of the box
	Stop: Once the object is successfully out of the pipe
Return object back to resting position	
	Start: Once the object starts moving toward the cup
	Stop: Once the object is successfully inserted into the hole of the cup
Return fingers to home key	
	Start: Once both fingers begin to release grasp on the object
	Stop: Once both fingers arrive at the home key

Note. This breakdown applies to both the conditions using the Bimanual and Intermanual coordination mode.

Recording the start and stop of each manual action. Video analysis of the start and stop times of each manual subtask were recorded into the multimodal scoresheet as two separate tiers: Grasper (left hand) and Scissors (right hand). The video data was collected at 30Hz and raw frame-rate-based time are converted into standard time of seconds (s) and milliseconds (ms) so as to have a common timeline for comparison with the eye movement data. An example of the video data is shown below in Figure B4.

Table B3

Each Scissor Subtask Broken Down by Start and Stop Movements

Grasp pipe (the pipe is located in its starting, first position)
Start: Once both fingers have left the home key
Stop: Once both fingers completely close on the top of the pipe
Move pipe over to grey area of box (second position)
Start: Once the pipe starts movement towards the grey area of the box
Stop: Once the pipe arrives at the position over the grey area of the box
Simulate cutting action
Start: Once both fingers have been removed from the pipe
Stop: Once both fingers are grasping the object
Return fingers to pipe
Start: Once both fingers start to open/release grasp on object
Stop: Once both fingers completely grasp the pipe
Return pipe back to first position (first position)
Start: Once the pipe begins motion towards resting position
Stop: Once the pipe arrives at the resting position
Return fingers to home key
Start: Once both fingers begin to release grasp on the pipe
Stop: Once both fingers arrive at the home key

Note. This breakdown applies to both the Bimanual and Intermanual coordination mode.

Defining the AOIs. In order to record the data for the multimodal scoresheet, all visual movements during the simulated cutting task were defined at the same spatial and temporal level of analysis as the manual movements. Therefore, the same subtasks used to define grasper (left hand) and scissors (right hand) manual movements were used for defining the eye movements. Holmqvist and colleagues (2011) suggests that manual analysis fixation patters include finding fixations within AOIs (i.e., glances). For this dissertation, specific AOIs were already established relative to each subtask and were easily viewed within gaze-overlaid scene videos (Figure B4).

Identifying eye-movement start/stop. As mentioned above, the start and stop of each subtask related to the grasper (left hand) and the scissors (right hand) used for hand movements were the same for eye movements. Figure B1 shows an example of a scan path of a pilot participant completing the task using the bimanual coordination mode. A scan path is used to illustrate the sequence of fixations; however, actual analysis did not use a scan path. This was because the scan path software masks fixations on a movement-to-moment basis. Therefore, the lowest level of analysis allowed by the software, 0.017s (a default of the software used, D-Lab), was used to collect the data for the visual component, frame-by-frame.

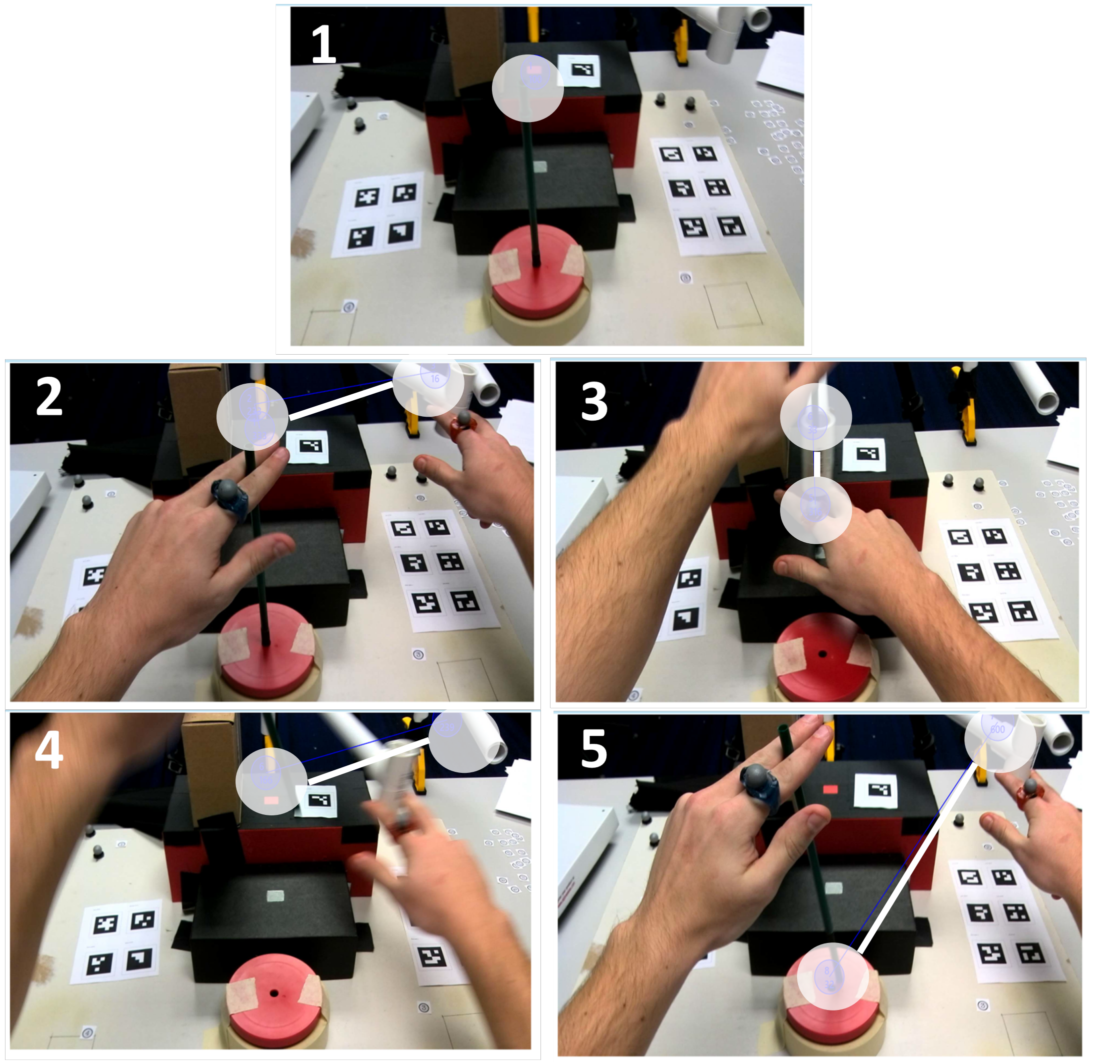

Figure B4. Example of a scan path of a pilot participant completing the task using the bimanual coordination mode. White circles have been overlaid on the images so the reader can view the scan path.

During this example, it is easy to see that the participant first looks at the top of the to-be manipulated object (Figure B4[1]). Next, the participant (while still grasping top portion of the object, then directs their eye gaze to toward the to-be manipulated pipe (Figure B4[2]). Then, after guiding the bottom of the object through the top portion of the pipe, the participant looks at the black portion of the object to complete the simulated cutting action (Figure B4[3-4]). Next, the participant returns the pipe and object back to their respective resting positions (Figure B4[5]).

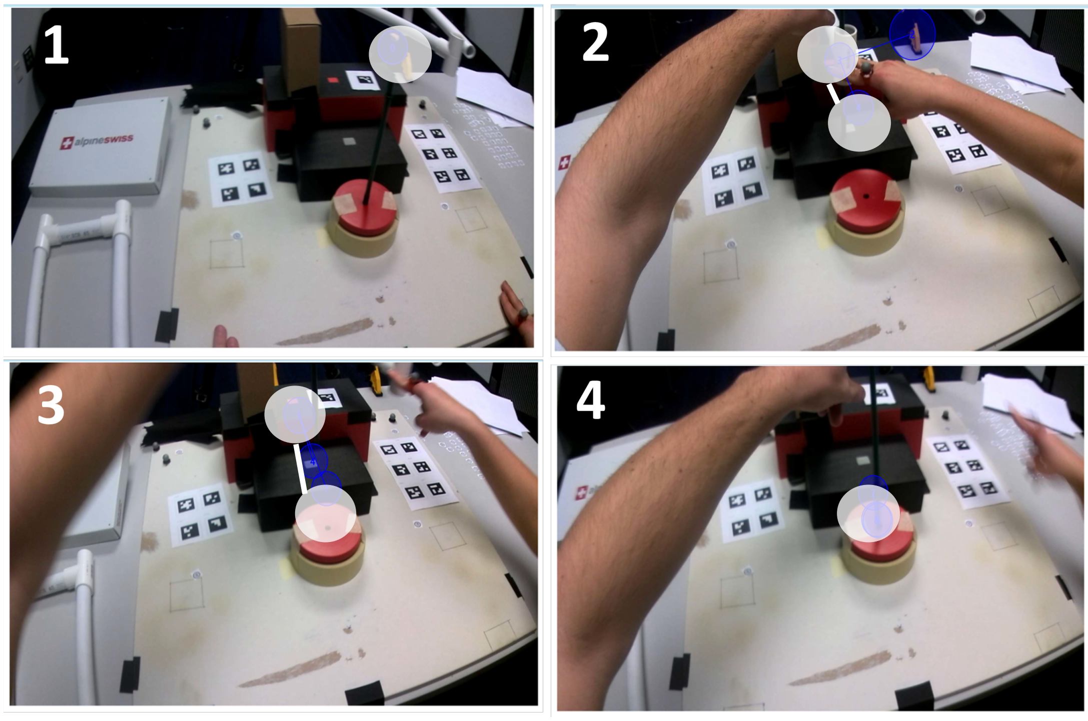

Figure B5. Example of a scan path of participants completing the task using the intermanual coordination mode from the grasper's perspective. White circles have been overlaid on the images so the reader can view the scan path.

Figure B5 shows an example of a scan path of participants completing the task using the intermanual coordination mode from the grasper's (left hand) perspective. During this example, it is easy to see that the participant first looks at the top of the to-be manipulated object (Figure B5[1]). Next, the participant (while still grasping top portion of the object) directs their eye gaze toward the pipe while it is resting above the grey area of the box (Figure B5[2-3]). Finally, the participant returns the object back to its resting position after a cut has been simulated by the scissors (Figure B5[4]).

Recording the start and stop of each eye-movement. Video analysis of the start and stop times of each eye movement were then put into the multimodal scoresheet. For both the bimanual and intermanual conditions, there were two tiers (rows) of eye-tracking data – one row specifically for the grasper-related AOIs and one row specifically for the scissor-related AOIs. Unlike the 30Hz sampling rate used for the hand movement data, the eye-tracking data was collected at 60Hz. Raw frame-rate-based time will be converted into standard time of seconds (s) and milliseconds (ms) so as to have a common timeline for comparison with the hand movement data.

Calculations of pre-reach look-ahead and gaze anchoring. As described above, for each subtask, the grasper and scissor eye and hand data were recorded into spreadsheets. A specific example of the data recorded into a single spreadsheet is provided below. The example below is from pilot data; specifically, Participant 1 from Team 7 completing the task using the Bimanual coordination mode during their first trial. The data from this trial was recorded into a multimodal score sheet based on the following rules:

- Eye-AOI
    - Start = when the eye arrives in the AOI
    - Stop = when the eye leaves the AOI
- Manual-AOI
    - Start = when the hand starts to move towards the AOI
    - Stop = when the hand arrives at the AOI

The recorded data of each subtask is shown in Figure B6.

Grasper	**AOI**	**Object**		**Pipe**		**Box**		**Pipe**		**Cup**		**Home**	
	Start/Stop	**Start**	**Stop**	**Start**	**Stop**	**Start**	**Stop**	**Start**	**Stop**	**Start**	**Stop**	**Start**	**Stop**
	Eye_Time	2.082	2.371	2.728	4.712	4.746	6.310	6.939	7.789	8.733	10.756	11.589	11.725
	Manual_Time	1.989	2.422	2.592	4.525	4.559	5.835	7.585	7.959	7.993	10.535	11.079	11.793

Scissors	**AOI**	**Pipe**		**Grey**		**Black**		**Pipe**		**Pipe**		**Home**	
	Start/Stop	**Start**	**Stop**	**Start**	**Stop**	**Start**	**Stop**	**Start**	**Stop**	**Start**	**Stop**	**Start**	**Stop**
	Eye_Time	0.034	1.513	1.564	2.065	6.361	6.786	6.803	6.820	8.461	8.648	11.062	11.130
	Manual_Time	0.935	1.555	1.606	2.286	6.259	6.786	6.922	7.432	8.061	9.821	10.212	11.165

Figure B6. Example of recorded pilot data into an Excel spreadsheet during the Bimanual condition.

The following example is now provided to show the calculation of Pre-Reach Look-Ahead and Gaze Anchoring when the Grasper is completing the subtask of putting the bottom part of the object through the top of the pipe when the pipe is in the second position (i.e., “Insert object through top of the pipe”). Subtask subtask starts “once object begins moving toward the top of the pipe” and stops “once the object is inserted into the pipe” (see Table B3). After the data was recorded into the spreadsheet (Figure B6), the data was then calculated to find Pre-Reach Look-Ahead and Gaze Anchoring. For Pre-Reach Look-Ahead, the following data was used: Eye-AOI Start Time; Manual-AOI Start Time. Which is used in the calculation of Pre-Reach Look-Ahead:

$$\text{Pre\_Reach Look\_Ahead} = Eye\_AOI\ Start\ Time - Manual\_AOI\ Start\ Time$$

This specific data used is highlighted in Figure B7.

Grasper	**AOI**	**Pipe**	
	Start/Stop	**Start**	**Stop**
	Eye_Time	2.728	4.712
	Manual_Time	2.592	4.525

Figure B7. Example of pilot data during the Bimanual condition. The grey cells are the data used for the calculation of Pre-Reach Look-Ahead (Eye-AOI Start Time = 2.728; Manual-AOI Start Time = 2.592).

Based on the example provided, the following calculations are then performed using the following data: Eye-AOI Start Time = 2.728s; Manual-AOI Start Time = 2.592s. Which is used in the calculation of Pre-Reach Look-Ahead:

$$0.136\text{s} \ = 2.728\text{s} - 2.592\text{s}$$

Next, the data must be calculated to find Pre-Reach Look-Ahead and Gaze Anchoring. For Pre-Reach Look-Ahead, the following data is used: Eye-AOI Stop Time; Manual-AOI Start Time. Which is used in the calculation of Pre-Reach Look-Ahead:

$$\text{Gaze Anchoring } = Eye\_AOI\ Stop\ Time - \ Manual\_AOI\ Start\ Time$$

This specific data used is highlighted in Figure B8.

Grasper	AOI	Pipe	
	Start/Stop	Start	Stop
	Eye_Time	2.728	**4.712**
	Manual_Time	2.592	**4.525**

Figure B8. Example of pilot data during the Bimanual condition. The grey cells are the data used for the calculation of Gaze Anchoring (Eye-AOI Stop Time = 2.728; Manual-AOI Stop Time = 2.592).

Based on the example provided, the following calculations are then performed using the following data: Eye-AOI Start Time = 4.712s; Manual-AOI Start Time = 4.535s. Which is used in the calculation of Pre-Reach Look-Ahead:

$$0.362\text{s} = 4.712\text{s} - 4.535\text{s}$$

For this example, the calculation of Pre-Reach Look-Ahead resulted 0.136 seconds and Gaze Anchoring resulted in 0.362 seconds. The result of Pre-Reach Look-Ahead shows that there was a 0.136s difference between when the participant looked at the pipe and then reached for the pipe. The result of Gaze Anchoring shows that there was a 0.362s difference between when the participant stopped looking at the pipe and when their hand arrived at the pipe. This example outlined the Grasper completing the subtask of putting the bottom part of the object through the top of the pipe when the pipe is in the second position. It is important to note that this was just one subtask. Pre-Reach Look-Ahead and Gaze Anchoring was calculated for each subtask for a given trial for both grasper and scissor data. Data will be analyzed at each subtask level. Additionally, overall trial data was calculated by averaging across each subtask and across each hand.

SGDMs

Two undergraduate research assistants (RAs) first went through an initial training phase, which consisted of understanding the overall task, the subtasks, the definition of SGDMs, and what may or may not be an SGDM. The assistants were not informed of the goal of the study, hypotheses, predictions, or anything that may influence their ratings in any way. Additionally, the two assistants did not participate in lab meetings to ensure their ratings were not sullied with influencing information. After the initial training phase, the assistants then individually rated a small subset of randomly sampled pilot data. The pilot data included participants completing the task using both coordination modes. Next, the assistants and researcher reviewed the ratings for each subtask for every trial (Hallgren, 2012). Percentage of agreement between raters was not calculated at this time. This process of individually rating a small subset of pilot data and then reviewing as a team was completed a total of three times before moving on to the experimental data. The percentage of agreement between raters was calculated on the third time (91%), which was high enough to move on to experimental data (Gwet, 2014).

For Experiment 1, the two trained raters individually rated a randomly sampled subset of data. 30% of the data was sampled. Due to the higher number of bimanual trials (1:2 ratio of intermanual to bimanual), a larger number of bimanual trials were rated. After the two raters individually completed their overlapping subset of trials, both raters reviewed disagreements and updated the final ratings for that subset of data. Once the agreement level was calculated and shown to be sufficient, the remaining 70% of the trials were randomly split among the two assistants to be individually rated (i.e., each assistant rated the remaining 35% of the trials). This same process occurred for Experiment 2 Days 1 and 2, and Experiment 2 Day 3. Experiment 2 was split up due to the large difference in the number of trials and the fact that Experiment 2 Days 1 and 2 only had bimanual trials.

Inter-rater reliability was used to assess the consensus of the raters (Hallgren, 2012). Cohen's kappa was used to assess inter-rater reliability (Cohen, 1968). Prior to analysis, the assumptions required for Cohen's kappa were evaluated: data was scored on a nominal scale (SGDM: yes/no), the observations were paired (assistants rated the same observations), the same number of categories were evaluated (2x2 crosstabulation responses of a dichotomous scale), independence of raters (all known precautions were taken to ensure assistants completed all ratings independently), and both assistants rated all observations used when calculating Cohen's kappa (Cohen, 1968). Additionally, it should be noted that Cohen's kappa was selected because it adheres to all five assumptions listed above.

For Experiment 1, Cohen's kappa was calculated to determine if there was agreement between two research assistants' judgments as to whether or not a SGDM occurred within a given trial. There was high agreement between the two research assistants' judgments (percent agreement = 91.05%), $\kappa = 0.815$, $p < 001$. For Experiment 2, Days 1 and 2, Cohen's kappa was calculated to determine if there was agreement between two research assistants' judgments as to whether or not a SGDM occurred within a given trial. There was high agreement between the two research assistants' judgments (percent agreement = 94.25%), $\kappa = 0.884$, $p < 001$. For Experiment 2, Day 3, Cohen's kappa was calculated to determine if there was agreement between two research assistants' judgments as to whether or not a SGDM occurred within a given trial. There was high agreement between the two research assistants' judgments (percent agreement = 92.13%), $\kappa = 0.823$, $p < 001$. A summary of the inter-rater reliability metrics is provided in Table B4. SGDMs were averaged between participants for the bimanual trials for comparison with intermanual trials.

Table B4

Summary of Inter-Rater Reliability Metrics

Experiment	Agreement	Kappa	*p*-value
Experiment 1	91.05%	0.815	$p < .001$
Experiment 2 Days 1 and 2	94.25%	0.884	$p < .001$
Experiment 2 Day 3	92.13%	0.823	$p < .001$

Note. Kappa was computed for phases of SGDM analysis.

Appendix C

Extended Results Section

Analyses not specifically addressing the hypotheses, manipulation checks, and exploratory analyses are included in this section. Additional analyses were performed on eye-tracking metrics, speed, variability, coupling measures, visuomotor coupling measures, and SGDMs. Data is analyzed for each mode effect experiment, Experiment 1 and Experiment 2 Day 3, as well data from the bimanual practice phase, Experiment 2 Day 1 and Day 2.

Experiment 1

Eye-tracking metrics. In addition to manually recording data to calculate Pre-Reach Look-Ahead and Gaze Anchoring, it was suggested to consider further eye-tracking metrics. Therefore, the following additional and relevant eye-tracking metrics are included. While these additional eye-tracking metrics do not directly address specific hypotheses, each of these groups of metrics were analyzed by coordination mode (Table C1) and correlational analyses are applied with other speed in correlation tables below (Tables C2 and C3). AOI-related analyses were not possible due to technical difficulties with the D-Lab software.

Table C1

Eye-Tracking Metrics at Each Level of Mode for Experiment 1

	Bimanual	Intermanual
Fixation Duration	407.53 (133.33)	454.10 (139.57)
Fixations[1]	23.35 (13.55)	18.97 (10.49)
Saccade Duration	100.88 (50.60)	106.85 (71.422)
Saccades[1]	23.06 (12.89)	18.41 (9.90)

Note. [1]Denotes a significant difference between coordination modes (alpha 0.05).

As shown in Table C1, a paired-samples *t*-tests revealed participants exhibited significantly more fixations using the bimanual coordination mode ($M = 23.35$; $SD = 13.55$) compared the intermanual coordination mode ($M = 18.97$; $SD = 10.49$), $t(11) = 2.252$, $p = .046$, $d = 0.72$. Additionally, participants exhibited significantly more saccades using the bimanual coordination mode ($M = 23.06$; $SD = 12.89$) compared the intermanual coordination mode ($M = 18.41$; $SD = 9.90$), $t(11) = 2.25$, $p = .046$, $d = 0.71$.

Table C2

Eye-Tracking Metrics with TrialTime during Bimanual Performance

	Fixation Duration	Fixations	Saccade Duration	Saccades
TrialTime	-0.20	0.74**	-0.09	0.76**
Fixation Duration		-.78**	.71*	-0.75**
Fixations			-0.57	0.99**
Saccade Duration				-0.545
Saccades				

Note. $N = 12$; * $p < .05$, ** $p < .01$,

Table C3

Eye-tracking Metrics with TrialTime during Intermanual Performance

	Fixation Duration	Fixations	Saccade Duration	Saccades
TrialTime	-0.12	0.62*	-0.08	0.62*
Fixation Duration		-.77**	0.27	-0.78**
Fixations			-0.50	0.99**
Saccade Duration				-0.47
Saccades				

Note. $N = 12$; * $p < .05$, ** $p < .01$,

Correlation tables. Correlations of all explanatory variables and speed including GenVar at all three axes (X, Y, and Z) are presented below for bimanual (Table C4) and intermanual (Table C5) performance data.

Table C4

Experiment 1 Bimanual Correlations of All Dependent Variables Including GenVar and Coupling Measures at all Three Axes

	GenVar (Y)	GenVar (X)	GenVar (Z)	%REC	MAX	SGDM	Pre-Reach	Gaze
TrialTime	-0.455	-0.313	-0.332	.962**	.991**	-.777**	.771**	.595**
GenVar (Y)		0.499	.759**	-0.546	-0.492	0.050	-.613*	-0.304
GenVar (X)			.637*	-0.267	-0.314	0.081	-0.342	-0.150
GenVar (Z)				-0.290	-0.296	0.068	-0.355	-0.093
%REC					.972**	-.664*	.851**	0.528
MAX						-.751**	.787**	.588*
SGDM							-0.321	-0.493
Pre-Reach								.607*

Note. $N = 12$; * $p < .05$, ** $p < .01$.

Table C5

Experiment 1 Intermanual Correlations of All Dependent Variables Including GenVar and Coupling Measures at All Three Axes

	GenVar (Y)	GenVar (X)	GenVar (Z)	%REC	MAX	SGDM	Pre-Reach	Gaze
TrialTime	0.111	0.035	-0.036	0.385	.879**	-.615*	.661*	.682*
GenVar (Y)		0.008	-0.052	0.117	0.213	0.322	0.162	-0.183
GenVar (X)			0.546	.720**	0.196	-0.250	0.066	0.127
GenVar (Z)				0.317	-0.232	-0.189	-0.056	-0.044
%REC					.607*	-0.390	0.314	0.238
MAX						-0.518	0.566	0.516
SGDM							-0.308	.-.665*
Pre-Reach								.628*

Note. $N = 12$; * $p < .05$, ** $p < .01$.

Between-hand coupling. To examine differences underlying mode effects, coupling was analyzed using MAXLINE. MAXLINE was analyzed using a 2 (Mode) × 2 (Order) mixed-subjects ANOVA. The Mode × Order interaction was not significant, $F(1, 10) = 0.02$, $p = .894$, $\eta^2 = .002$. Additionally, the main effect of Order was not significant, $F(1, 10) = 0.19$, $p = .676$, $\eta^2 = .02$, showing that any subsequent main effects of Mode are independent of the order in which they completed the tasks relative to Coupling. The main effect of Mode was significant, $F(1, 10) = 21.29$, $p = .001$, $\eta^2 = .68$. As illustrated in Figure C, MAXLINE was significantly lower when participants completed the task using the Inter Mode Inter ($M = 115.73$, $SD = 35.62$) compared to the Bi Mode ($M = 212.97$, $SD = 93.19$). This finding is consistent with predictions.

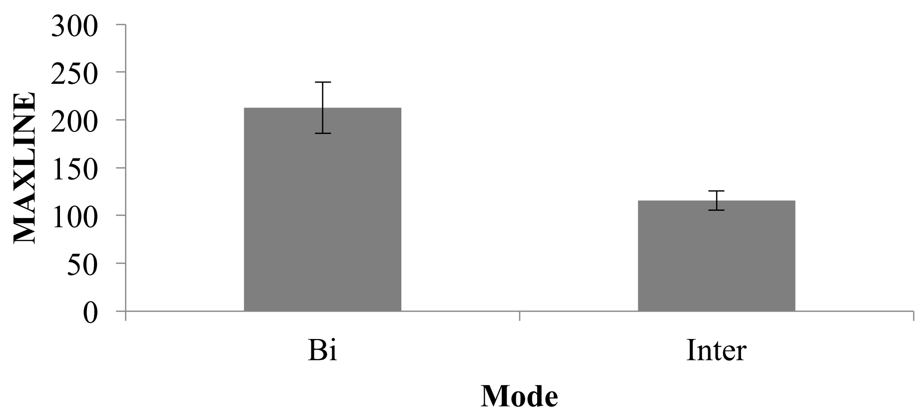

Figure C1. Mean longest diagonal segment (MAXLINE) for bimanual trials (Bi) and intermanual trials (Inter). Error bars indicate standard error of the mean.

Visuomotor coupling. Subsequent analyses were performed on Pre-Reach Look-Ahead at each subtask for each hand to determine which specific subtasks yielded significant differences at each level of Mode.

Pre-reach look-ahead. In order to assess the effect of visuomotor coupling, Pre-Reach Look-Ahead was analyzed at each level of Mode for both the left hand (Grasper) and right hand (Scissors) during task performance. As shown in Figure C2A, a paired-samples *t*-tests revealed that Bi Grasper Pre-Reach Look-Ahead was significantly higher ($M = 0.23$; $SD = 0.11$) when compared to Inter Grasper Pre-Reach Look-Ahead ($M = 0.08$; $SD = 0.11$), $t(11) = 4.12$, $p = .002$, $d = 1.27$. Additionally, as shown in Figure C2B, Bi Scissors Pre-Reach Look-Ahead was significantly higher ($M = 0.34$; $SD = 0.28$) when compared to Inter Scissors Pre-Reach Look-Ahead ($M = 0.08$; $SD = 0.10$), $t(11) = 2.91$, $p = .014$, $d = 0.99$.

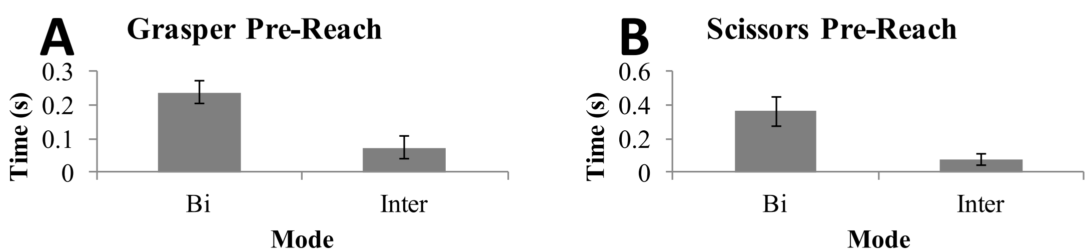

Figure C2. Mean Grasper (A) and Scissors (B) Pre-Reach Look-Ahead across all subtasks for bimanual trials (Bi) and intermanual trials (Inter). Error bars indicate standard error of the mean.

Grasper pre-reach. Paired-samples *t*-tests were calculated to assess Grasper Pre-Reach Look-Ahead at each level of mode for each subtask. As shown in Figure C3, a paired-samples *t*-tests revealed that Grasper Pre-Reach Look-Ahead was significantly higher during the Bi Mode ($M = 0.65$; $SD = 0.35$) when compared to Inter Mode ($M =$

0.24; *SD* = 0.16) for subtask two $t(10) = 3.50$, $p = .006$, $d = 1.13$. Additionally, Grasper Pre-Reach Look-Ahead was significantly higher during the Bi Mode (*M* = 0.49; *SD* = 0.28) when compared to Inter Mode (*M* = 0.17; *SD* = 0.22) for subtask five $t(10) = -3.22$, $p = .008$, $d = 0.94$. Finally, Grasper Pre-Reach Look-Ahead was significantly higher during the Bi Mode (*M* = 0.49; *SD* = 0.22) when compared to Inter Mode (*M* = 0.31; *SD* = 0.14) for subtask six $t(8) = 2.56$, $p = .034$, $d = 0.90$.

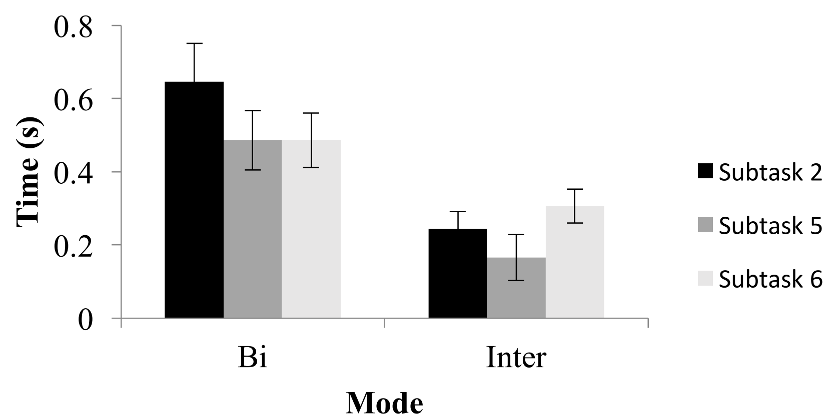

Figure C3. Mean Grasper Pre-Reach Look-Ahead for bimanual trials (Bi) and intermanual trials (Inter) for subtasks two, five, and six. Error bars indicate standard error of the mean.

Subtasks one ($t(11) = 2.19$, $p = .051$, $d = 0.65$), three ($t(10) = -1.91$, $p = .085$, $d = -0.63$), and four ($t(9) = -1.54$, $p = .158$, $d = -0.78$) were not significant.

Scissors pre-reach look-ahead. Paired-samples *t*-tests were calculated to assess Scissors Pre-Reach Look-Ahead at each level of mode for each subtask. As shown in Figure C4, a paired-samples *t*-tests revealed that Scissors Pre-Reach Look-Ahead was significantly higher during the Bi Mode (*M* = 0.09; *SD* = 0.11) when compared to Inter Mode (*M* = 0.32; *SD* = 0.20) for subtask one $t(11) = 5.61$, $p < .001$, $d = 1.66$.

Additionally, Scissors Pre-Reach Look-Ahead was significantly higher during the Bi Mode (M = 0.60; SD = 0.69) when compared to Inter Mode (M = 0.24; SD = 0.19) for subtask five $t(11) = -2.01$, $p = .069$, $d = 0.78$. Finally, Scissors Pre-Reach Look-Ahead was significantly higher during the Bi Mode (M = 1.29; SD = 1.12) when compared to Inter Mode (M = 0.18; SD = 0.15) for subtask six $t(8) = 3.04$, $p = .016$, $d = 0.91$.

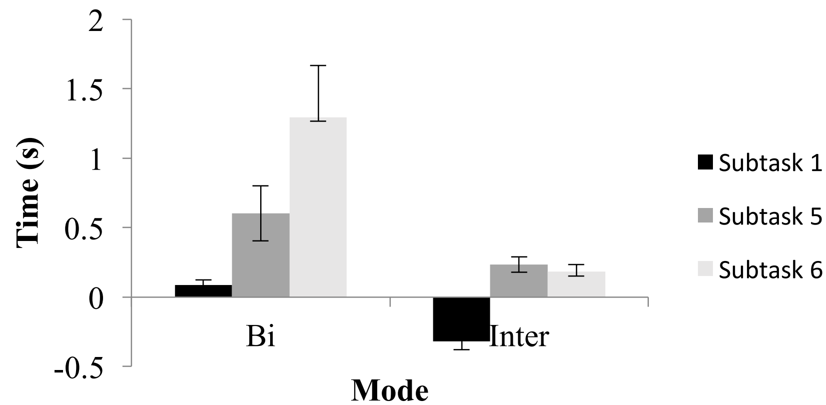

Figure C4 Mean Scissors Pre-Reach Look-Ahead for bimanual trials (Bi) and intermanual trials (Inter) for subtasks one, five, and six. Error bars indicate standard error of the mean.

Subtasks two ($t(11) = 0.80$, $p = .439$, $d = 0.23$), three ($t(11) = -1.66$, $p = .126$, $d = -0.55$), and four ($t(11) = -1.05$, $p = .314$, $d = -0.31$) were not significant.

Gaze anchoring. In order to assess the effect of visuomotor coupling, Gaze Anchoring was analyzed at each level of Mode for both the left hand (Grasper) and right hand (Scissors) during task performance. As shown in Figure C5, a paired-samples *t*-tests revealed that Bi Grasper Gaze Anchoring was significantly lower (M = 0.15; SD = 0.07) when compared to Inter Grasper Gaze Anchoring (M = 0.27; SD = 0.07), $t(10) = -5.36$, $p < .001$, $d = -1.61$. Additionally, as shown in Figure C5B, Bi Scissors Gaze Anchoring was significantly lower (*M* = -0.11; *SD* = 0.14) when compared to Inter Scissors Gaze Anchoring (*M* = 0.08; *SD* = 0.12), *t(*10) = -4.06, *p* = .002, *d* = -1.57.

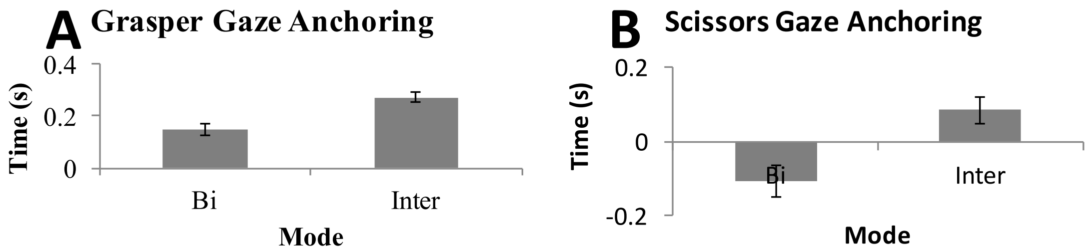

Figure C5. Mean Grasper (A) and Scissors (B) Gaze Anchoring across all subtasks for bimanual trials (Bi) and intermanual trials (Inter). Error bars indicate standard error of the mean.

Grasper gaze anchoring. Paired-samples *t*-tests were calculated to assess Grasper Gaze Anchoring at each level of mode for each subtask. As shown in Figure C6, a paired-samples *t*-tests revealed that Grasper Gaze Anchoring was significantly lower during the Bi Mode (*M* = -0.12; *SD* = 0.14) when compared to Inter Mode (*M* = 0.09; *SD* = 0.14) for subtask one *t*(10) = -3.52, *p* = .006, *d* = -1.06. Additionally, Grasper Gaze Anchoring was significantly lower during the Bi Mode (*M* = 0.18; *SD* = 0.04) when compared to Inter Mode (*M* = 0.43; *SD* = 0.22) for subtask three *t*(10) = -3.63, *p* = .005, *d* = -1.27. Finally, Grasper Gaze Anchoring was significantly lower during the Bi Mode (*M* = -0.05; *SD* = 0.19) when compared to Inter Mode (*M* = 0.09; *SD* = 0.14) for subtask four *t*(9) = -3.05, *p* = .014, *d* = -1.04.

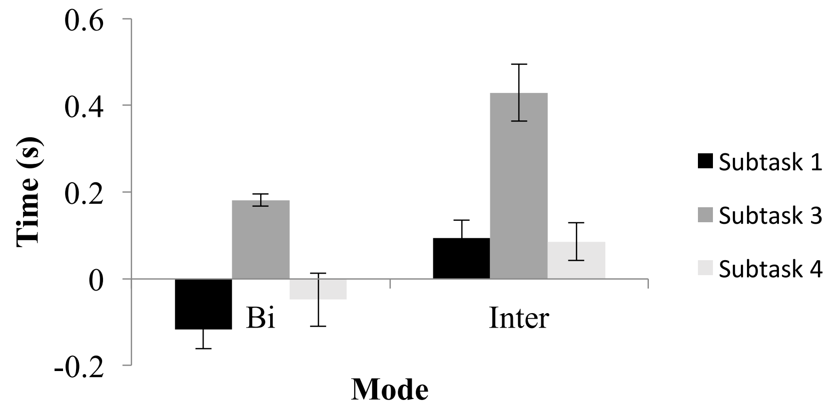

Figure C6. Mean Grasper Gaze Anchoring for bimanual trials (Bi) and intermanual trials (Inter) for subtasks one, three, and four. Error bars indicate standard error of the mean.

Subtasks two ($t(10) = -1.63$, $p = .135$, $d = -0.55$), five ($t(11) = 1.05$, $p = .316$, $d = 0.31$), and six ($t(8) = -0.59$, $p = .570$, $d = -0.20$) were not significant.

Scissors gaze anchoring. Paired-samples *t*-tests were calculated to assess Scissors Gaze Anchoring at each level of mode for each subtask. As shown in Figure C7, a paired-samples *t*-tests revealed that Scissors Gaze Anchoring was significantly lower during the Bi Mode ($M = -0.69$; $SD = 0.22$) when compared to Inter Mode ($M = -0.10$; $SD = 0.22$) for subtask two $t(11) = -6.29$, $p < .001$, $d = -1.82$. Additionally, Scissors Gaze Anchoring was significantly lower during the Bi Mode ($M = 0.18$; $SD = 0.04$) when compared to Inter Mode ($M = 0.43$; $SD = 0.22$) for subtask five $t(10) = -2.65$, $p = .022$, $d = -1.00$.

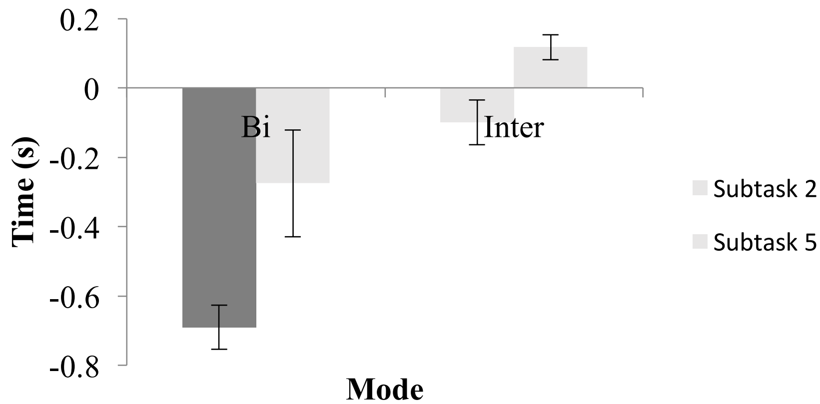

Figure C7. Mean Scissors Gaze Anchoring for bimanual trials (Bi) and intermanual trials (Inter) for subtasks two and five. Error bars indicate standard error of the mean.

Subtasks one ($t(11) = -1.09$, $p = -0.31$, $d = -0.63$), three ($t(11) = -0.35$, $p = .733$, $d = -0.10$), four ($t(11) = -1.19$, $p = .258$, $d = -0.36$), and six ($t(7) = 1.54$, $p = .167$, $d = 0.76$) were not significant.

SGDMs. Subsequent analyses were performed on SGDMs at each subtask to determine which specific subtasks yielded significant differences at each level of Mode. Paired-samples *t*-tests were calculated to assess SGDMs at each level of mode for each subtask. As shown in Figure C8, more SGDMs were observed when participants completed the task using the Inter Mode ($M = 1.00$; $SD = 0.00$) when compared to the Bi Mode ($M = 0.70$; $SD = 0.29$) for subtask one $t(11) = -3.59$, $p = .004$, $d = 1.46$. Additionally, more SGDMs were observed when participants completed the task using the Inter Mode ($M = 0.63$; $SD = 0.34$) when compared to the Bi Mode ($M = 0.37$; $SD = 0.26$) for subtask four $t(11) = -2.90$, $p = .043$, $d = 0.71$. Finally, more SGDMs were observed when participants completed the task using the Inter Mode ($M = 0.98$; $SD = 0.04$) when compared to the Bi Mode ($M = 0.13$; $SD = 0.16$) for subtask six $t(11) = -19.15$, $p < .001$, $d = -6.59$. Subtasks two ($t(11) = -1.603$, $p = .137$, $d = -0.63$), three ($t(11)$

= -1.09, p = .300, d = -0.36), and five ($t(11)$ = -1.95, p = .078, d = 0.80) were not significant.

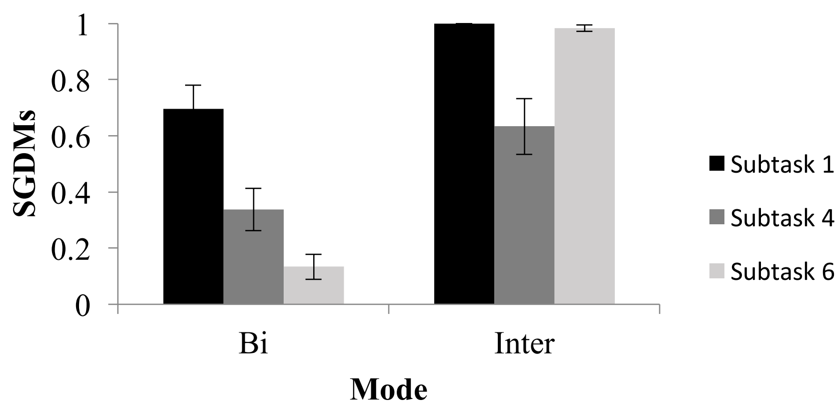

Figure C8. Mean number of total SGDMs for bimanual trials (Bi) and intermanual trials (Inter) for subtasks one, four, and six. Error bars indicate standard error of the mean.

Table C6

Significant Grasper and Scissor Subtasks

Grasper	**Scissors**
Grasp object	Grasp pipe (the pipe is located in its first position)
Remove object from the pipe	Return fingers to pipe (first position)
Return fingers to home key	Return fingers to home key

Note. This breakdown applies to both the conditions using the Bimanual and Intermanual coordination mode.

Experiment 2

Eye-tracking metrics. The same eye-tracking metrics calculated during Experiment 1 were also calculated for Experiment 2 (Tables C9 and C10). Additionally, Days 1 and 2 were calculated (Tables C7 and C8).

Table C7

Eye-tracking Metrics at Each level of Mode for Experiment 2 Days 1 and 2

	Day 1	Day 2
Fixation Duration	503.30 (102.13)	487.43 (104.38)
Fixations	13.13 (2.39)	10.26 (0.66)
Saccade Duration	129.98 (46.40)	123.54 (38.06)
Saccades	14.27 (3.14)	11.11 (1.40)

Note. No significant differences were observed (alpha 0.05).

Table C8

Eye-tracking metrics at each level of Mode for Experiment 2 Day 3

	Bimanual	Intermanual
Fixation Duration	468.06 (84.58)	482.87 (70.87)
Fixations[1]	9.94 (1.50)	9.59 (0.89)
Saccade Duration	143.31 (58.81)	152.98 (32.60)
Saccades[1]	10.49 (0.83)	9.68 (0.83)

Note. [1]Denotes a significant difference between coordination modes (alpha 0.05).

Table C9

Eye-tracking Metrics with TrialTime During Bimanual Performance

	Fixation Duration	Fixations	Saccade Duration	Saccades
TrialTime	0.803	-0.447	0.11	-0.746
Fixation Duration		-0.024	-0.336	-0.533
Fixations			-0.685	0.74
Saccade Duration				-0.583
Saccades				

Note. $N = 6$; * $p < .05$, ** $p < .01$,

Table C10

Eye-Tracking Metrics with TrialTime During Intermanual Performance

	Fixation Duration	Fixations	Saccade Duration	Saccades
TrialTime	.930**	-0.251	-0.186	-0.459
Fixation Duration		0.02	-0.502	-0.192
Fixations			-0.379	.957**
Saccade Duration				-0.373
Saccades				

Note. $N = 6$; * $p < .05$, ** $p < .01$,

Correlations. Correlations of all explanatory variables and speed including GenVar at all three axes (X, Y, and Z) are presented below for bimanual (Table C11) and intermanual (Table C12) performance data.

Table C11

Experiment 2 Intermanual Correlations of all Dependent Variables Including GenVar and Coupling Measures at All Three Axes

	GenVar (Y)	GenVar (X)	GenVar (Z)	%REC	MAX	SGDM	Pre-Reach[1]	Gaze[1]
TrialTime	-0.507	-0.273	0.162	0.382	.849**	0.013	-0.155	0.358
GenVar (Y)		0.189	-0.023	-0.423	-0.440	0.040	-0.295	0.107
GenVar (X)			0.504	0.258	-0.220	-0.207	-0.567	-0.243
GenVar (Z)				0.018	-0.113	-0.260	-0.689	0.291
%REC					.678*	0.027	-0.115	-0.722
MAX						0.046	-0.076	-0.569
SGDM							-0.264	-0.668
Pre-Reach								-0.091

Note. $N = 12$ ($^{1}N = 5$); * $p < .05$, ** $p < .01$.

Table C12

Experiment 2 Bimanual Correlations of All Dependent Variables Including GenVar and Coupling Measures at All Three Axes

	GenVar (Y)	GenVar (X)	GenVar (Z)	%REC	MAX	SGDM	Pre-Reach[1]	Gaze[1]
TrialTime	-0.202	0.073	0.383	.807**	.979**	0.309	0.258	-0.213
GenVar (Y)		-0.083	0.349	-0.371	-0.150	-0.427	-0.643	-0.651
GenVar (X)			.610*	0.224	0.091	0.052	-0.026	.820*
GenVar (Z)				0.292	0.390	-0.142	0.038	0.246
%REC					.860**	0.247	0.068	-0.036
MAX						0.232	0.105	-0.201
SGDM							-0.044	-0.058
Pre-Reach								0.387

Note. $N = 12$ ($^1N = 6$); * $p < .05$, ** $p < .01$.

Between-Hand Coupling. To further examine differences underlying mode effects, coupling was analyzed using MAXLINE. MAXLINE was analyzed using a 2 (Mode) × 2 (Order) mixed-subjects ANOVA. The Mode × Order interaction was not significant, $F(1, 10) = 2.32$, $p = .158$, $\eta^2 = .19$. Additionally, the main effect of Order was not significant, $F(1, 10) = 4.92$, $p = .051$, $\eta^2 = .33$, showing that any subsequent main effects of Mode are independent of the order in which they completed the tasks relative to Coupling. The main effect of Mode was significant, $F(1, 10) = 5.78$, $p = .037$, $\eta^2 = .37$. As illustrated in Figure C9, MAXLINE was significantly lower when participants completed the task using the Inter Mode Inter ($M = 74.08$, $SD = 25.80$) compared to the Bi Mode ($M = 89.74$, $SD = 31.56$).

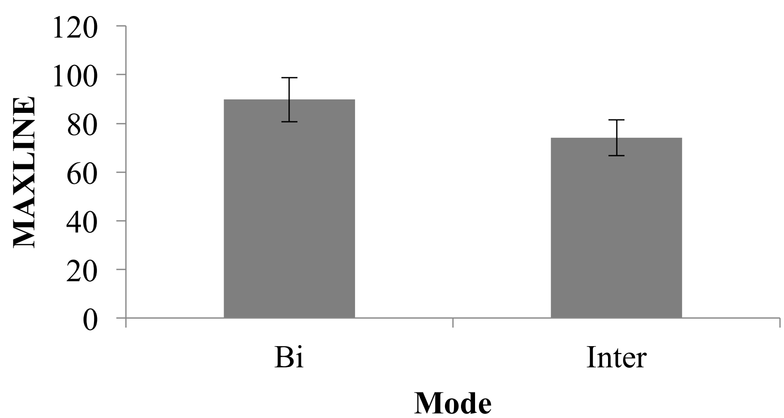

Figure C9. Mean longest diagonal segment (MAXLINE) for bimanual trials (Bi) and intermanual trials (Inter). Error bars indicate standard error of the mean.

Visuomotor Coupling.

Pre-Reach Look-Ahead. In order to assess the effect of visuomotor coupling, Pre-Reach Look-Ahead was analyzed at each level of Mode for both the left hand (Grasper) and right hand (Scissors) during task performance. As shown in Figure C10A, a paired-samples *t*-tests revealed that Bi Grasper Pre-Reach Look-Ahead was not significantly different (M = 0.12; SD = 0.10) when compared to Inter Grasper Pre-Reach Look-Ahead (M = -0.01; SD = 0.07), $t(4)$ = 2.47, p = .069, d = 1.12. Additionally, as shown in Figure C10B, Bi Scissors Pre-Reach Look-Ahead was not significantly different (M = 0.10; SD = 0.05) when compared to Inter Scissors Pre-Reach Look-Ahead (M = 0.09; SD = 0.19), $t(4)$ = 0.13, p = .904, d = 0.18.

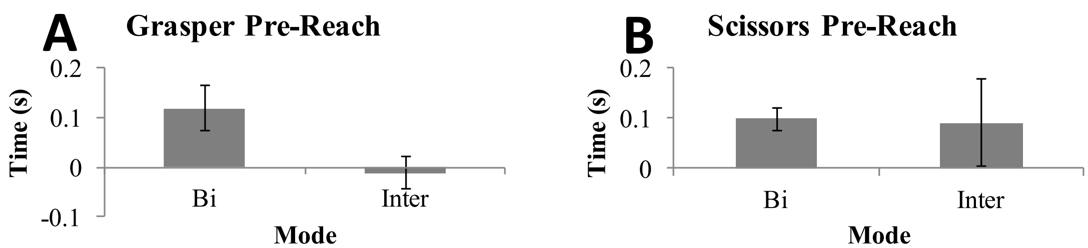

Figure C10. Mean Grasper (A) and Scissors (B) Pre-Reach Look-Ahead across all subtasks for bimanual trials (Bi) and intermanual trials (Inter). Error bars indicate standard error of the mean.

Grasper pre-reach look-ahead. Paired-samples *t*-tests were calculated to assess Grasper Pre-Reach Look-Ahead at each level of mode for each subtask. As shown in Figure C11, a paired-samples *t*-tests revealed that Grasper Pre-Reach Look-Ahead was significantly higher during the Bi Mode (M = 0.31; SD = 0.10) when compared to Inter Mode (M = 0.05; SD = 0.16) for subtask five $t(4)$ = 4.19, p = .014, d = 2.01.

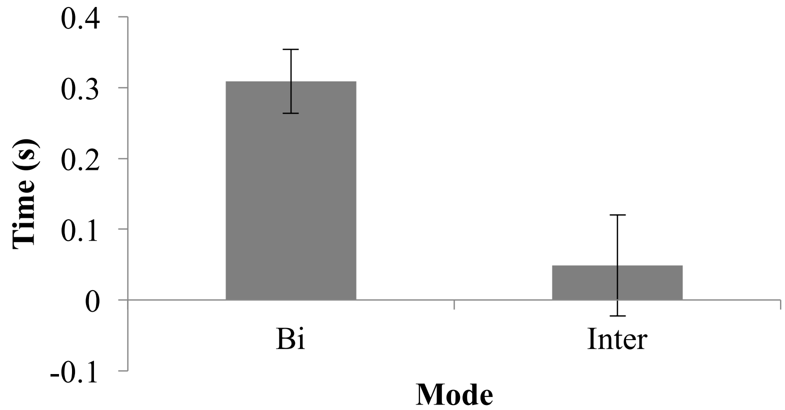

Figure C11. Mean Grasper Gaze Anchoring for bimanual trials (Bi) and intermanual trials (Inter) for subtasks five. Error bars indicate standard error of the mean.

Subtasks one ($t(4) = 0.20$, $p = .848$, $d = 0.09$), two ($t(4) = 1.50$, $p = .208$, $d = 0.69$), three ($t(4) = -0.86$, $p = .436$, $d = 0.48$), four ($t(3) = -1.89$, $p = .156$, $d = -0.95$), and six ($t(2) = 1.11$, $p = .384$, $d = 0.74$) were not significant.

Scissors pre-reach look-ahead. Paired-samples *t*-tests were calculated to assess Scissors Pre-Reach Look-Ahead at each level of mode for each subtask. As shown in Figure C12, a paired-samples *t*-tests revealed that Scissors Pre-Reach Look-Ahead was significantly higher during the Bi Mode ($M = 0.26$; $SD = 0.21$) when compared to Inter Mode ($M = -0.25$; $SD = 0.14$) for subtask one $t(4) = 4.10$, $p = .015$, $d = 1.85$. Additionally, Scissors Pre-Reach Look-Ahead was significantly lower during the Bi Mode ($M = -0.13$; $SD = 0.05$) when compared to Inter Mode ($M = 0.04$; $SD = 0.08$) for subtask two $t(4) = -3.85$, $p = .018$, $d = -1.75$. Furthermore, Scissors Pre-Reach Look-Ahead was significantly lower during the Bi Mode ($M = -0.01$; $SD = 0.05$) when compared to Inter Mode ($M = 0.15$; $SD = 0.08$) for subtask five $t(4) = -3.45$, $p = .026$, $d = -1.58$. Finally, Scissors Pre-Reach Look-Ahead was significantly higher during the Bi

Mode (*M* = 0.54; *SD* = 0.32) when compared to Inter Mode (*M* = 0.21; *SD* = 0.15) for subtask six $t(3) = 3.501$, $p = .039$, $d = 4.84$.

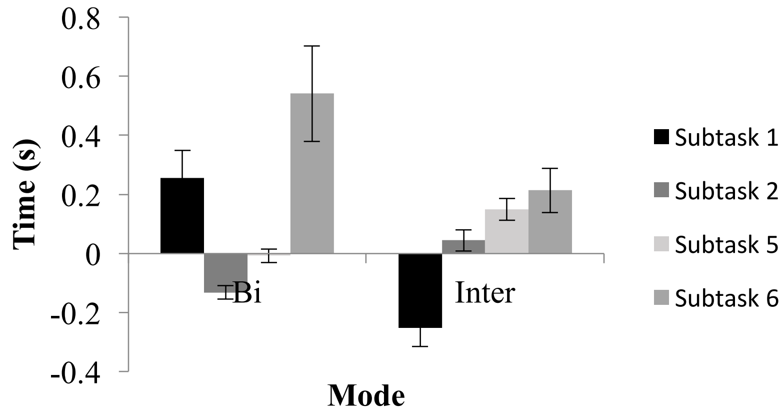

Figure C12. Mean Scissors Gaze Anchoring for bimanual trials (Bi) and intermanual trials (Inter) for subtasks one, two, five, and six. Error bars indicate standard error of the mean.

Subtasks three ($t(4) = -0.77$, $p = .485$, $d = -0.40$) and four ($t(3) = -1.86$, $p = .160$, $d = -1.16$) were not significant.

Gaze anchoring. In order to assess the effect of visuomotor coupling, Gaze Anchoring was analyzed at each level of Mode for both the left hand (Grasper) and right hand (Scissors) during task performance. As shown in Figure C13A, a paired-samples *t*-tests revealed that Bi Grasper Gaze Anchoring was not significantly different (*M* = 0.12; *SD* = 0.09) when compared to Inter Grasper Gaze Anchoring (*M* = 0.18; *SD* = 0.09), $t(4) = -1.36$, $p = .246$, $d = -0.61$. However, as shown in Figure C13B, Bi Scissors Gaze Anchoring was significantly different (*M* = -0.13; *SD* = 0.06) when compared to Inter Scissors Gaze Anchoring (*M* = 0.09; *SD* = 0.07), $t(4) = -12.03$, $p < .001$, $d = -5.54$.

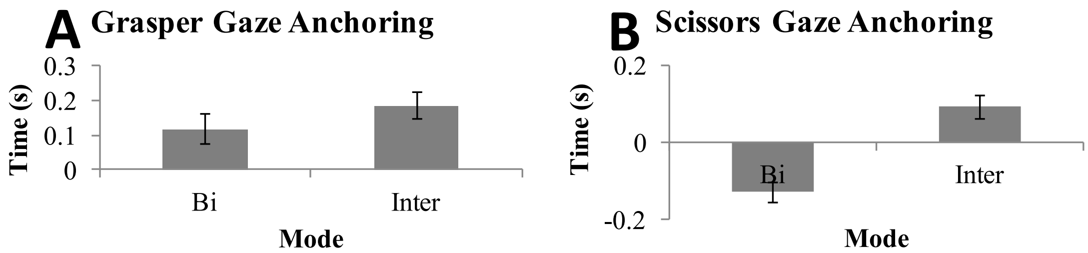

Figure C13. Mean Grasper (A) and Scissors (B) Gaze Anchoring across all subtasks for bimanual trials (Bi) and intermanual trials (Inter). Error bars indicate standard error of the mean.

Grasper gaze anchoring. Paired-samples *t*-tests were calculated to assess Grasper Gaze Anchoring at each level of mode for each subtask. As shown in Figure C14, a paired-samples *t*-tests revealed that Grasper Gaze Anchoring was significantly lower during the Bi Mode (M = -0.17; SD = 0.08) when compared to Inter Mode (M = 0.06; SD = 0.15) for subtask one $t(4)$ = -2.92, p = .043, d = -1.36. Additionally, Grasper Gaze Anchoring was significantly lower during the Bi Mode (M = 0.04; SD = 0.11) when compared to Inter Mode (M = 0.14; SD = 0.13) for subtask six $t(2)$ = -8.63, p = .013, d = -5.42.

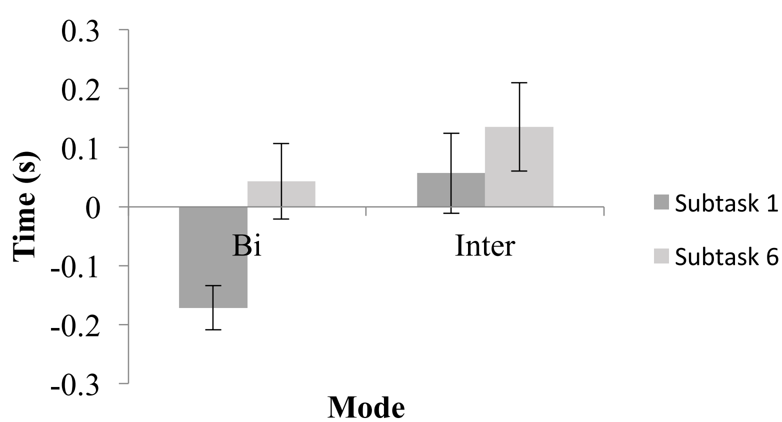

Figure C14. Mean Grasper Gaze Anchoring for bimanual trials (Bi) and intermanual trials (Inter) for subtasks one and six. Error bars indicate standard error of the mean.

Subtasks two ($t(4) = -0.11$, $p = .921$, $d = -0.06$), three ($t(4) = -0.47$, $p = .664$, $d = -0.21$), four ($t(3) = -1.63$, $p = .202$, $d = -0.81$), and five ($t(4) = 0.39$, $p = .717$, $d = 0.18$) were not significant.

Scissors gaze anchoring. Paired-samples *t*-tests were calculated to assess Scissors Gaze Anchoring at each level of mode for each subtask. As shown in Figure C15, a paired-samples *t*-tests revealed that Scissors Gaze Anchoring was significantly lower during the Bi Mode ($M = 0.12$; $SD = 0.07$) when compared to Inter Mode ($M = 0.18$; $SD = 0.08$) for subtask three $t(4) = -2.92$, $p = .043$, $d = -1.31$. Additionally, Scissors Gaze Anchoring was significantly lower during the Bi Mode ($M = 0.06$; $SD = 0.07$) when compared to Inter Mode ($M = 0.51$; $SD = 0.35$) for subtask five $t(4) = -7.35$, $p = .002$, $d = -4.44$.

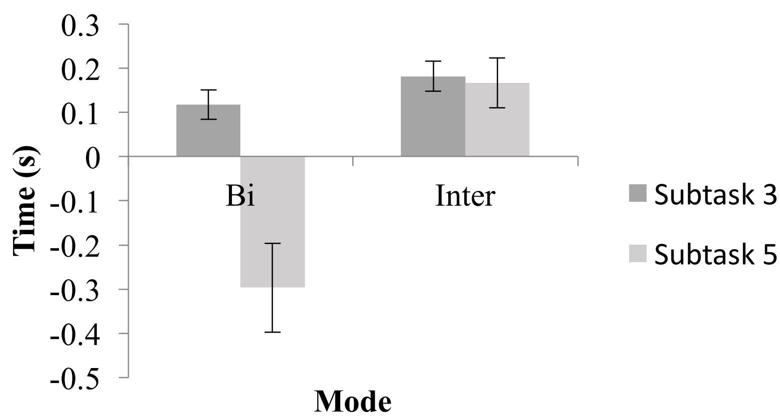

Figure C15. Mean Scissors Gaze Anchoring for bimanual trials (Bi) and intermanual trials (Inter) for subtasks three and five. Error bars indicate standard error of the mean.

Subtasks one ($t(4) = 1.62$, $p = .181$, $d = 0.73$), two ($t(4) = -2.61$, $p = .059$, $d = -1.18$), four ($t(3) = -2.78$, $p = .069$, $d = -2.06$), and six ($t(3) = -1.91$, $p = .152$, $d = -0.96$) were not significant.

SGDMs. Subsequent analyses were performed on SGDMs at each subtask to determine which specific subtasks yielded significant differences at each level of Mode. Paired-samples *t*-tests were calculated to assess SGDMs at each level of Mode for each subtask. As shown in Figure C16, more SGDMs were observed when participants completed the task using the Inter Mode ($M = 0.96$; $SD = 0.07$) when compared to the Bi Mode ($M = 0.88$; $SD = 0.29$) for subtask one $t(11) = -2.324$, $p = .040$, $d = 0.37$. Additionally, more SGDMs were observed when participants completed the task using the Inter Mode ($M = 0.94$; $SD = 0.07$) when compared to the Bi Mode ($M = 0.82$; $SD = 0.10$) for subtask two $t(11) = -3.45$, $p = .005$, $d = 1.04$. Finally, more SGDMs were observed when participants completed the task using the Inter Mode ($M = 0.79$; $SD = 0.11$) when compared to the Bi Mode ($M = 0.34$; $SD = 0.14$) for subtask six $t(11) = -9.19$, $p < .001$, $d = 2.94$. Alternatively, subtasks three ($t(11) = -0.67$, $p = .517$, $d = 0.23$), four ($t(11) = -0.549$, $p = .594$, $d = -0.146$), and five ($t(11) = -1.77$, $p = .105$, $d = -0.54$) were not significant.

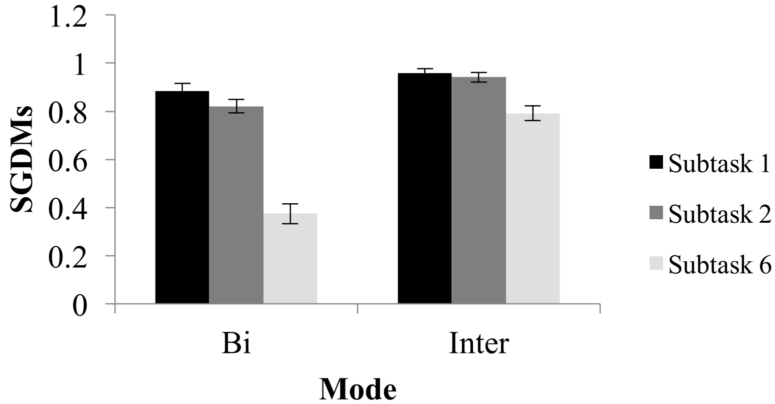

Figure C16. Mean number of total SGDMs for bimanual trials (Bi) and intermanual trials (Inter) for subtasks one, four, and six. Error bars indicate standard error of the mean.

Appendix D

Surveys and Questionnaires Section

Demographics Survey

Team #________ Participant 1 ____ 2 ____

Demographics Survey

1. Gender: Male____ Female____

2. Dominant hand: Left____ Right____

3. Age ______

4. Race/ethnicity:

□ American Indian or Alaska Native

□ Hawaiian or Other Pacific Islander

□ Asian or Asian American

□ Black or African American

□ Hispanic of Latino

□ Non-Hispanic White

□ Other:______________

7. Do you know the other participant in this experiment? Yes____ No____

7a. If yes, then how many months? ______

Edinburgh Handedness Inventory

Team #________

Participant 1 ____ 2 ____

Part. # ________

Edinburgh Handedness Inventory

Please indicate your preferences in the use of hands in the following activities *by putting a check in the appropriate column.* Where the preference is so strong that you would never try to use the other hand, unless absolutely forced to, *put 2 checks.* If in any case you are really indifferent, *put a check in both columns.*

Some of the activities listed below require the use of both hands. In these cases, the part of the task, or object, for which hand preference is wanted is indicated in parentheses.

Please try and answer all of the questions, and only leave a blank if you have no experience at all with the object or task.

	Left	Right
1. Writing	⌜ ⌜	⌜ ⌜
2. Drawing	⌜ ⌜	⌜ ⌜
3. Throwing	⌜ ⌜	⌜ ⌜
4. Scissors	⌜ ⌜	⌜ ⌜
5. Toothbrush	⌜ ⌜	⌜ ⌜
6. Knife (without fork)	⌜ ⌜	⌜ ⌜
7. Spoon	⌜ ⌜	⌜ ⌜
8. Broom (upper hand)	⌜ ⌜	⌜ ⌜
9. Striking Match (match)	⌜ ⌜	⌜ ⌜
10. Opening box (lid)	⌜ ⌜	⌜ ⌜

Research Participation Flyer

Research Volunteers Needed

Participants Will Receive $45

We are looking for volunteers to complete two-handed tasks over a three-day period. Days 1-2 will last approximately 1 hour. Day 3 will last approximately 1.5 hours. In appreciation of your time, you will receive $45.

Exclusion/Inclusion Criteria:

Anyone capable of tying their own shoes with two hands, have normal dexterity, are right-handed, and have normal to corrected-to-normal vision can participate in this study. Those with any problems with their arms or hands that would not allow them to complete the manual, dexterous tasks may not be in this study. Those who are left-handed and have bad vision are not able to participate in this study.

If you are interested and would like more information, then please inquire here.

Thank you!

This study has been reviewed and approved by the
Research Ethics Review Board, Georgia Institute of Technology

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