CHARACTERISTIC LAG & THE INTERMANUAL SPEED ADVANTAGE

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CHARACTERISTIC LAG & THE INTERMANUAL SPEED ADVANTAGE

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LIST OF SYMBOLS AND ABBREVIATIONS

AOI	Area of interest
CRP	Cross recurrence plot
CQRA	Cross-recurrence quantification analysis
GAF	Gaze-anchoring fixation
LAF	Look-ahead fixation
%REC	Percent recurrence
PRLA	Pre-Reach Look-Ahead
SGDMs	Simultaneous, goal-directed movements

SUMMARY

Previous research has found evidence for the intermanual speed advantage, wherein novice actors perform a visually-guided, two-handed task faster with one hand from each member of a dyad (i.e., intermanually) compared to when one actor completes the task with their own two hands (i.e., bimanually). The intermanual speed advantage is reversed or erased, however, after the task has been well-practiced by both actors bimanually. Furthermore, visuomotor coupling (i.e., coupling between eye and hand movements) has been found to underlie the presence of the intermanual speed advantage in novices and its erasure in experienced actors. This is due to a reduced reliance on visual input as the execution of the manual task becomes more fluent. Using secondary data, the present study seeks to further investigate how visuomotor coupling changes as a function of previous bimanual practice. This is done through a characteristic lag analysis, a dynamical systems metric that assesses how close in time and space the gaze and hands are while actors complete a simulated laparoscopic cutting task. Results suggest that the individual visuomotor coordination of the component actors impacts the execution of the task by the dyad in the intermanual condition, and that this change in coordination depends on previous bimanual practice. Specifically, findings show that the lag between the gaze and the hands of novice actors entrains to the partner with the longer lag (i.e., the less coupled partner) when acting in the intermanual trials. However, in experienced actors with previous bimanual practice, the dyad entrains to the actor with the shorter lag (i.e., the more coupled partner) imposing a ceiling on the dyad in intermanual trails and preventing them from uncoupling further. This pattern of results demonstrates how changes in visuomotor

coupling lag help account for the erasure of the intermanual speed advantage after previous bimanual practice.

CHAPTER 1. INTRODUCTION

An intimate understanding of the dynamic interaction between the visual and motor systems can provide valuable insight into the limitations and constraints operators face when work requires precise coordination between the two. Though many fields require detailed attention of the visuomotor system, we see particularly interesting issues arise when this precision work must not only be coordinated within an operator, but also between two or more operators jointly working to complete a task. For example, the fields of laparoscopic surgery and robotic teleoperation at times require operators to work in tandem to accomplish a goal, for example, with the case of laparoscopy, tying surgical knots (Zheng et al., 2005), or in the case of teleoperation, multiple operators controlling multiple robotic arms (Van Oosterhout et al., 2017). Select investigations have begun to depict the distinct coordination constraints of dyadic verses individual visuomotor control (Crites, 2018; Zheng et al., 2005), however more work is still needed to portray a complete understanding of its complexities.

One robust effect found in the interpersonal coordination literature is the Intermanual Speed Advantage. This speed advantage occurs when a visually-guided, two-handed task (e.g., surgical knot tying) is completed faster when that task is conducted with one hand from two different people (i.e., intermanually), as opposed to two hands from the same person (i.e., bimanually; e.g., Zheng et al., 2005). This "coordination mode effect" has been demonstrated to occur in novices in a variety of both basic and complex tasks: pursuit-rotor tracking (Reed et al., 2006; Wegner & Zeaman 1956); simulated laparoscopic cutting (Crites, 2018; Zheng et al., 2005); and teleoperation (Glynn and Henning 2000;

Gorman & Crites, 2013). However, recent investigations have shown reversal or elimination of the intermanual speed advantage when the task is well-practiced by individual members of the dyad (Crites 2018; Gorman & Crites, 2015).

In a study by Gorman and Crites (2015), the presence of the speed advantage was assessed in the completion of shoe tying—a well-practiced, if not automatic, task in their study population. The results showed, unsurprisingly, shorter completion times for the bimanual coordination mode, where participants tied a shoe-like apparatus on their own, over the intermanual condition, where they did so with a partner. The effect of practice on the intermanual speed advantage has since been explored further in a series of studies by Crites (2018), where, in addition to exploring this practice hypothesis, he sought to identify underlying behavioral factors that account for the intermanual speed advantage. In those studies, participants completed a simulated laparoscopic cutting task (in contrast to shoe-tying, this was a novel task for all participants) both bimanually and with a partner in an intermanual condition. Results were compared for participants who engaged in a bimanual practice phase prior to completing the task intermanually and those who were considered novices (i.e., those who did not complete a bimanual practice phase). Here, previous bimanual practice was shown to eliminate the speed advantage, suggesting interpersonal coordination patterns are influenced by the fluency with which an actor completes a task and more context dependent than previously suggested. The present study builds off of this later study by Crites to better understand how visuomotor coordination specifically is influenced by both previous bimanual practice and the joint-action of a dyad.

The addition of the present study to the literature serves to benefit multiple fields, given that specialized operators across disciplines rely on fluency in myriad manual skills.

In medicine, precision control of the visual and motor systems is necessary to effectively complete surgical tasks (e.g., Zheng et al., 2005). In human robot interaction (HRI), precise visual understanding of depth information is required to successfully remotely operate ground vehicles for life-saving search and rescue missions (e.g., Jones et al., 2011). In precision training, for domains like archery, combined visual and haptic feedback have been shown to distinguish expert from intermediate shooters (e.g., Monfared et al., 2019). In sum, a more complete understanding of visuomotor interactions can serve to benefit a broad array of applications, from robotic surgery to marksman level shooting. Additionally, as comparatively little work has been done to understand to interaction of two separate visuomotor systems (i.e., from two different people) in a manual task, the present work will help address how the two human systems impact each other, in comparison to a single system working to coordinate the execution of a task. This allows for the investigation of how the visuomotor system is constrained: to what degree is the visuomotor system bound by neuromuscular (i.e., internal) constraints compared to interpersonal spatiotemporal (i.e., external) constraints?

It is similarly important to study how previous experience impacts the coordination of the visuomotor system in two-handed tasks. As previously mentioned, practice has impacts on coordination that can distinguish expert operators from novices, as seen in such phenomena as the intermanual speed advantage. Since interpersonal coordination is required in safety-critical fields, an understanding of how coordination behaves between two experienced verses two inexperienced operators has important training implications. The purpose of the present study is to understand how both practice and different coordination modes (bimanual vs. intermanual) affect the dependent relationship between the visual and motor systems in visually-guided, two-handed tasks. The relationship between visual and motor systems is investigated using a characteristic lag analysis, which is explained in detail below after a review of visuomotor coordination research. This lag analysis is examined in the context of a simulated laparoscopic cutting task designed by Crites (2018) and utilizes data collected for the purposes of that 2018 work.

1.1 Visuomotor Coupling in Different Coordination Modes

Though extensive work has been conducted to explore the coordination of the visuomotor system within a single operator as they complete a diverse array of tasks (e.g., Land et al., 1999; Land & Furneaux, 1997; Mennie et al., 2007), there stands a knowledge gap of how dyads or teams of people coordinate two visuomotor systems. As the present work offers to build on current knowledge of interpersonal visuomotor coordination, below is a review of the perceptuomotor coordination literature as it relates to bimanual and intermanual tasks.

The present study investigates visuomotor coupling within and between individuals as they complete a visually-guided, interdependent two-handed task. Coupling is generally defined as systems or processes that interact during the course of an action or a series of actions (Gorman et al., 2017). In the context of the current study the coupled systems are the motor and visual systems of the actor(s) completing the task. These systems' combined action then make up the visuomotor system, which is investigated under the following definition of visuomotor coupling. As the present study builds off of and uses data collected as part of a Crites (2018) study, the same definition of visuomotor coupling is used here:

“visuomotor coupling is defined as the sequential, spatial and temporal dependencies that take place during manual coordination” (p. 58).

There is a rich body of literature that demonstrates the tight coupling between vision and motor actions involving the upper limbs, dating back to Woodworth’s (1899) work detailing the action of reaching for an object. His work and others since, have shown that at first, the hand moves quickly, in a ballistic manner, then after roughly two-thirds of the way into the duration of the movement time, a low-velocity stage is initiated as it receives precise input from the visual system to make an accurate landing and grasp the object (Jeannerod, 1984). It has since become known that a saccade typically precedes a goal-directed movement, with the saccade arriving to the target before the movement of the hand is either initiated or terminated (Hayoe et al., 2003; Land et al., 1999; Land & Furneaux, 1997; Mennie et al., 2007). This orienting saccade is referred to as a look-ahead fixation and is reviewed in depth below. Another important element of visuomotor coupling relevant to the present study is the necessity for the gaze to remain foveated on a target until and slightly after the motor action has been terminated (Neggers & Bekkering, 2000, 2002). This stabilizing fixation is referred to here as a gaze anchoring fixation and is subsequently detailed. These elements taken together begin to depict the sequential and time-sharing nature demanded by bimanual visuomotor coordination.

1.1.1 Bimanual Visuomotor Coupling

As mentioned, under bimanual coordination, an operator is required to time-share a variety of guiding fixations across the two hands. The sequential nature of the coordination between the hands and vision places constraints on how quickly a single operator can move to complete a serial task. A common observation in the requirements of visuomotor coordination is the look-ahead fixation (LAF; Land & Furneaux, 1997). LAFs are fixations made to an area of interest (AOI) associated with the *subsequent* step or subtask in a sequential task. For example, a study that assessed the eye movement patterns of participants as they built a wood model found that before a piece of the model was reached for, an LAF was made to foveate the piece of interest roughly 20% of the time (Mennie et al., 2007). Other studies have found LAFs present in a wide array of bimanual tasks, such as playing the piano, driving, making a cup of tea, and preparing a sandwich, where LAFs were made before the initiation of an associated motor action roughly one-third of the time (Hayoe et al., 2003; Land et al., 1999; Land & Furneaux, 1997). This aspect of visuomotor coupling demonstrates the intimacy of the connection between the visual and motor systems of an actor, as well as, the importance of the spatial information associated with distinct subtasks, referred to here as AOIs, in multi-step motor tasks.

A second seemingly compulsory fixation when coordinating a motor task is what is known as a gaze-anchoring fixation (GAF). A GAF is a steadying fixation that persists on a target after the hand has terminated its targeted movement (Neggers & Bekkering, 2000; Rand, 2014). There appears to be time inefficient perceptuomotor constraints within the GAF process. In the unimanual (i.e., one-handed) case, it has been shown that a saccade to a second target cannot be initiated until after the motor action (e.g., pointing) involving the first target has been completed (Neggers & Bekkering, 2000, 2002). Meaning, the gaze is uniformly coupled with the intended target of a hand in motion. Matched with the general requirement of an orienting saccade (i.e., a LAF) made prior to a move to a (second) target, this process becomes squarely stepwise and temporally inefficient (Mennie et al., 2006).

The costly nature of this process is then exacerbated when two hands must share one system of foveated vision in the bimanual coordination mode. Here, we begin to see how constraints on visuomotor coupling might underlie the intermanual speed advantage, such that the decoupling of the two visuomotor systems governing the two hands in the intermanual mode allows for faster, simultaneous movements, which are generally absent in intrapersonal coordination.

1.1.1.1 Bimanual Between-Hand Coupling

Other constraints are placed on the perceptuomotor system when working bimanually that stem strictly from the limitations of the motor system itself. Research into between-hand coupling has shown a general dependence between the two upper limbs. Between-hand coupling is the tendency for the two hands to align in space and time. Here, we talk exclusively of the constraints on the motor system itself, excepting the involvement of the visual system. A basic demonstration of this dependence can be seen when one tries to move one hand vertically up and down, while moving the other horizontally from left to right. It becomes immediately apparent that the motion of one hand introduces variability into the path of the other hand. This was empirically demonstrated by Franz (1997), where participants were able to continuously and accurately trace a circle simultaneously with both hands, but when the one hand was required to trace a straight line, while the other circled, the circle became more line-like, and the line more circle-like.

Another spatiotemporal constraint in between-hand coordination involves the speed of movement when the two hands each complete a simultaneous action. For example, when the two hands move simultaneously to point at two separate targets, they terminate their movements at the same time, even if the targets are of different distances (Kelso et al., 1979). The timing of two hands moving to two separate targets is anchored by the time it takes the hand reaching for the furthest target to arrive, therefore the movement of the hand to the closer target is delayed more so than it would be if the task were completed unimanually. Though these bimanual limitations can be overcome to some extent with practice, in unfamiliar tasks the motor system is believed to be constrained to act as a single unit, meaning a single top-down command is given to both limbs, as opposed to two separate commands intended for each limb. This is believed to be done to reduce the degrees of freedom (DOF) needed to be accounted for by the motor system (Kelso et al., 1979).

With the limitations introduced by both visuomotor coupling and between-hand coupling, we can begin to understand that there are multiple coupled systems working against the efficiency of a bimanual task. These nested, coupled systems also show how an uncoupling of the visuomotor system, as well as an uncoupling of the two hands can positively impact the efficiency of task completion. As will be discussed in later sections, a reduction in coupling can either unfold with practice or can be introduced when a task moves from the bimanual to the intermanual coordination mode (Crites, 2018).

1.1.2 Intermanual Visuomotor Coupling

Compared to the unimanual and bimanual coordination modes, there has been little research dedicated to intermanual coordination, and even less to intermanual *visuomotor* coordination. We can, however, glean insights from the investigation of unimanual coordination, as an intermanual task is essentially two unimanual tasks being coordinated between partners (Crites, 2018). In intermanual coordination we can expect to see select visuomotor constraints outlined in the bimanual discussion above persist; however, the uncoupling of the two hands and the addition of a second line of sight will likely alleviate some of those inefficiencies.

As mentioned, a key difference between visuomotor coupling in the bimanual mode and the intermanual mode is the addition of a second visual system. This additional gaze minimizes the timesharing requirement of the vision between the two hands (Crites, 2018). Though in the intermanual case the presence of a LAF before or during the hand's movement toward the target will remain (Mennie et al., 2006), as will the GAF, which steadies the gaze and confirms contact with the target after the hand has landed (Rand, 2014), these actions will now be able to be completed closer in time for sequential subtasks. Specifically, with the addition of another actor, guiding fixations can happen simultaneously for consecutive subtasks (Crites, 2018).

Though two fixations can be completed at any one time during intermanual completion, this does not necessarily mean that individual fixations will be of a shorter duration in the intermanual mode compared to bimanual mode. Regarding GAFs, Crites (2018) specifically proposed that GAFs would be shorter (i.e., gaze would not linger on a hand for long after the manual action had been terminated) in the *bimanual* coordination mode. This was thought to be due to the need to multitask in bimanual execution, and, to complete the task as quickly as possible, actors would need to quickly move onto the next LAF to keep the sequence of events in motion (Terrier et al., 2011). Conversely, since the pressure to dual task in the intermanual mode is loosened, actors could linger their gaze longer to ensure steadiness and accuracy of the hand while executing the task. Additionally, since the hand of the partner will only need to be monitored for task progress, as opposed to precise target contact, we can assume peripheral monitoring will suffice during intermanual execution. This peripheral monitoring will then allow the actor to jump ahead to prepare for the next step required of their hand, allowing the two hands to complete the sequential subtasks even closer in time, if not simultaneously, than could be managed bimanually.

Particularly influential work in unimanual coordination that predates studies of bimanual finger pointing (e.g., Kelso et al., 1979) was conducted by Fitts. Again, it is important to consider unimanual coordination in this context, as the intermanual mode is comprised of two actors engaged in jointly-executed, but coordinated, unimanual tasks. In a seminal finger pointing task, where participants were required to alternatingly tap a single finger between two targets, Fitts and Peterson (1964) established that the termination of a pointing action was determined by the distance (i.e., amplitude; A) and size (i.e., width; W) of the target, jointly referred to as the index of difficulty (ID). Specifically, it is stated that as ID increases (where either A increases or W decreases, or both) latency will also increase (Fitts, 1954). This is the simple relationship that we might expect to see in a task completed intermanually, as opposed to the more constrained relationship we see with distance and latency (and target size) in bimanual tasks, wherein the action of the limb navigating to the easier target entrains to the movement time of the more difficult target (Kelso et al., 1979). However, there is evidence that interference from completing a joint action alongside a partner influences one's ability to make truly independent movements. This concept is referred to as synchrony and is described in detail next.

1.1.2.1 Synchronization

Synchronization is defined as the spontaneous organization of two or more interacting systems in or across time (Strotgatz, 2003). Synchronization occurs in mechanical objects, such as the ticking of two clocks hung on the same wall (Bennett et al., 2002; Huygens, 1673), in nature with the blinking of firefly lights (Winfree, 1967), and in human behavior where audience members spontaneously applaud in unison (Néda et al., 2000). This phenomenon has been extensively studied in simple tasks completed by dyads. The mechanism for this spontaneous organization varies, but a coupling mechanism as simple as looking at another person's movements can cause a dyad's pattern of movements to align without intention or instruction to do so (Oullier et al., 2008). These findings have important implications for visuomotor coupling in intermanual coordination for visually-guided tasks, such as that of the present analysis.

In an extension of the original Fitts tapping study described above, Fine and Amazeen (2011) had participants complete the tapping oscillation task unimanually, as in the original study, bimanually, as in the Kelso and colleagues (1979) study, as well as alongside a partner. The results for the bimanual condition replicated Kelso and colleagues' (1979) findings that showed a delayed movement time to the easier target when the second hand was navigating to a difficult (i.e., smaller and more distant) target. The authors also found this effect, though to a slightly lesser extent, present in the intermanual condition, where participants completed the task with only one hand while a paired participant did the same alongside them with their opposing hand. These results suggest there is an aspect of visuomotor coupling that is due to external or bottom-up influence, and that it is not strictly due to neuromuscular (i.e., top-down) constraints. However, there still appears to be a greater tendency to couple movements in bimanual tasks, as compared to intermanual tasks. This is demonstrated in the greater delay participants had when arriving to easy targets in the bimanual trials, as compared to the intermanual trials (Fine & Amazeen, 2011).

As noted, though spontaneous synchronization with a partner can impact visuomotor coupling in intermanual tasks, there is evidence to show it poses less of a threat than the coupling constraints found in bimanual coupling. The body of research outlined in the sections above all point to an "uncoupling advantage", such that the less coupling present during the completion of a visually-guided, two-handed task, the more efficiently it will be completed. Specifically, visuomotor coupling and between-hand coupling appear to reduce the ability for an actor to make simultaneous, independent movements, placing intermanual coordination at a speed advantage over bimanual coordination (Crites, 2018). Ultimately, we can expect distinct visuomotor relationships to occur from one coordination mode (e.g., intrapersonal) to the other (e.g., interpersonal).

1.2 The Effect of Practice on Two-Handed Tasks

The attainment of fluency in perceptuomotor skills is marked by relatively discrete stages of skill acquisition. Fitts (1964) proposed the earliest stage to be marked by the establishment of the cognitive activities needed to execute the task, like understanding instructions. This Cognitive stage is generally short for simple tasks, and then quickly gives way to the Associative stage, which has fewer errors than the earliest stage, but still does not exhibit full performance. Performance in the Associative stage is still disjointed, however here, actors learn to adjust their actions to refine performance. Finally, in the Autonomous stage, little cognitive demand is required for continual accurate execution. It is also understood that this Autonomous stage continues and actors constantly improve upon their performance, even after thousands of trials, suggesting plateaus in performance are never truly achieved (Fitts, 1964; Keller, 1985).

Under this framework, we might see why two actors in the Cognitive or Associative stages of skill acquisition perform a novel two-handed task quicker when working together (i.e., intermanually), as opposed to working individually (i.e., bimanually). As mentioned, this effect has come to be known as the intermanual speed advantage. In these earlier stages of learning, more cognitive processing power (two thinking minds) and less responsibility for each (only one hand working per motor system) may account for the speed gains of the intermanual coordination mode. In other words, there is a reduced need to timeshare cognitive resources between the coordination of the two limbs. Similarly, this model of skill acquisition may also help explain why the intermanual speed advantage is not observed in well-practiced tasks (Crites, 2018; Gorman & Crites, 2015), as the Autonomous stage can accommodate more motor activity, given the diminished reliance on cognition and attention (Fitts, 1964). However, there are also visuomotor developments to consider as fluency of a task is achieved that complement the logic of the three-stage model. Below is a review of how the relationship between the visual and motor systems might evolve as an actor moves from one skill acquisition stage to the next.

1.2.1 How Practice Changes Visuomotor Coupling

The distinct patterns of perceptuomotor coordination of novices verses experts have been established across varied contexts. For example, tracking the trajectory of a ball in sports like tennis (Mallek et al., 2017), fixation patterns in juggling (Dessing et al. , 2012), and gaze behaviors in a laparoscopy training environment (Law et al., 2004) all differ between novices and experts. How do fixation requirements change as actors approach task fluency? Generally, tasks become less visually-guided as performance improves, where less visual feedback of motor actions is needed as the task is carried out (Franz, 1997; Sailer et al., 2005). This research also suggests that foveal vision is particularly important during early learning phases, but peripheral vision becomes sufficient as learning progresses, pointing to an uncoupling of the visual and motor systems over time (Sailer et al., 2005).

In studies comparing experienced verses novice surgeons in simulated laparoscopy environments, a common observation is that experts spend more time fixating the target of the tool they are manipulating, whereas novices tend to track the movement of the tool with their gaze as it maneuvers toward the target. This is then associated with a fewer number of fixations in experts overall, as well as fewer errors and shorter task completion times for this more experienced group (Law et al., 2004; Salier et al., 2005; Wilson et al., 2010). These observations have implications for how LAFs might differ between participants with sufficient practice at a sequential task, and those without practice. It is likely that LAFs occur earlier and less frequently in this group as compared to those relatively unfamiliar with a task. Additionally, given the greater deficit the bimanual coordination mode suffers due to visuomotor coupling, compared to the intermanual coordination mode, the effect of practice on visuomotor coupling is likely to be more pronounced (i.e., beneficial) in bimanual trials than in intermanual trials.

Another important metric to consider for the present study is gaze anchoring fixations and how they are impacted by practice. Crites (2018) argued that gaze anchoring fixations would be shorter in participants who had gone through a practice phase, citing that manual tasks become less visually dependent with repetition (Franz, 1997). There is little literature that specifically reviews the effect of experience on GAFs for manual tasks; however, as will be further explained below, Crites (2018) observed that gaze anchoring was reduced with practice across both coordination modes. This finding aligns with previous research that suggests there is a reduction in reliance on visual feedback to complete motor tasks over time (Franz, 1997). Overall, the decoupling of the visual and motor systems with practice enables actors to make more simultaneous movements, especially in bimanual conditions where visuomotor coupling is particularly detrimental to speed. A similar decoupling occurs in between-hand coordination as expertise is gained in a motor task. This line of work is reviewed below.

1.2.1.1 The Impact of Practice on Between-Hand Coupling

Similar to visuomotor coupling, an uncoupling of the movement of the two upper limbs emerges as a motor skill is acquired (Summers, 2002). Therefore, though the present study does not directly assess between-hand coupling, it is important to consider the motor constraints inherent within visuomotor coupling. The uncoupling effect has been studied in special populations, such as experienced musicians who have learned to overcome the between-hand tendency to align. For example, Shaffer (1981) observed that expert pianists seemed to manipulate their hands as two separate subsystems controlled independently in space and time, suggesting that, with practice and training, the hands can learn to move independently, releasing their coordination from the top-down joint-action command to move in unison (Summers, 2001; Kelso et al., 1979). This ability to manipulate the hands separately with practice also suggests that motor alignment is not neurologically constrained, or “hard-wired.” The process of learning to move the hands independent of each other is thought to unfold over time as a consequence of integration, or the “interleaving of the movements of the two hands” (Summers, 2001, p. 4).

The majority of the work done to understand the uncoupling process in regard to motor coordination has focused on the difficulty people have in executing polyrhythms, or nonharmonic rhythmic movements. For example, it is inherently challenging to tap a finger of the right hand along with a finger on the left hand in a 5:3 pattern (an example of a polyrhythm), where the right finger taps five times for every three taps of the left finger. It has been shown to be particularly difficult to achieve such tapping patterns even with extensive practice, as the hands’ natural coordination pattern settles in phase at 1:1 and is demonstrably challenging to override (Summers, 2001). Though there are not explicit rhythmic requirements of the task conducted in the present study, it is possible that adjacent or related constraints are at play in the Crites (2018) paradigm, where the variable timing and sequencing of the subtasks may impose motor limitations, especially in the bimanual coordination mode.

1.3 Introduction to Crites (2018)

The present study extends work completed by Crites (2018). Of central focus to Crites’ work was the intermanual speed advantage. As mentioned in the introduction, this speed advantage is found when novices complete a visually-guided, two-handed task faster in intermanual trials (i.e., with one of their hands and another from a partner) than in bimanual trails (i.e., alone). To better understand the speed advantage, across two studies Crites investigated hypothesized underlying factors that may account for the shorter trial times of the intermanual condition. These factors, explained further in the Method section, include: visuomotor coupling, between-hand coupling, and simultaneous, goal-directed movements (SGDMs). Across the two experiments these factors were investigated to not only assess their correlation with speed in a laparoscopic cutting task, but also their contribution to the elimination of the intermanual speed advantage when participants completed an extended bimanual practice phase before engaging in intermanual trials. Thus, in total, four factors were evaluated including visuomotor coupling, between-hand coupling, SGDMs, and practice, though only practice was manipulated in his study.

As mentioned in the introduction, robust effects of previous bimanual practice have been observed in studies of interpersonal coordination (Gorman & Crites, 2015). Of specific interest to the Crites work was the moderating effect of previous bimanual practice on the intermanual speed advantage. This moderating effect is such that when an individual practices a two-handed task to asymptote, where continued progress levels off in a practice stage, performance in an intermanual trial will *not* outperform the practiced bimanual trials in terms of speed. In contrast, when this same two-handed task is performed by novices, the intermanual trials will reliably be faster than the bimanual trials. The motivation behind the Crites (2018) study was twofold: 1) identify behavioral factors that help account for the intermanual speed advantage in unpracticed tasks (the four factors mentioned above), and 2) replicate findings from a prior study (Gorman & Crites, 2015), which showed a reversal of the intermanual speed advantage when actors were well-practiced at the bimanual execution of the task—in that case, shoe tying.

Crites' investigation of the underlying factors extended a study by Zheng and colleagues (2005) that employed a similar laparoscopic cutting task, where participants completed the task bimanually and intermanually, resulting in the finding of an intermanual speed advantage. In the Zheng and colleagues study, the experimental task simulated a laparoscopic suturing and cutting task, where the operator is required to grasp and pull a thread from a synthetic organ using a grasping tool, then cut the thread with laparoscopic scissors. Component subtasks where identified for both the grasper and scissors to calculate dependent measures and understand the pattern of movement for the two tools across the two conditions. In the Zheng experiment, the task was completed by novices in either bimanual or intermanual trails, resulting in shorter trial times for the intermanual condition. To explain this effect, the authors suggested that anticipatory (i.e., simultaneous) movements allowed the dyad to complete the task faster (e.g., the scissor could move to its next location before the grasper finished completing the current task), and that this asymmetric movement was not available to individuals in the bimanual condition. Furthermore, these anticipatory movements were suggested to emerge from the shared mental model of the actors as they completed the task.

Crites' (2018) extension of this 2005 study used a similar simulated laparoscopic task and sought to draw a more parsimonious conclusion about the underlying mechanism(s) of the speed advantage. Without having to infer weighty cognitive mechanisms such as shared mental models, the findings from Crites (2018) showed that the underlying behavioral factors he proposed accounted for the reduced trial time in intermanual trials. SGDMs (referred to as anticipatory movements in Zheng et al., 2005), visuomotor coupling, and between-hand coupling, were all significantly correlated with trial time for the unpracticed trials, providing support for more behavioral mechanisms underlying the observed effect. SGDMs were proposed to be the result of visuomotor and between-hand *un*coupling. In turn, results showed that the more SGDMs made, the less visuomotor and between-hand coupling was exhibited in the novice condition.

Crites (2018) also found support for the moderating effect of practice, which was an extension of a prior study (Gorman & Crites, 2015), wherein previous bimanual practice eliminated the intermanual speed advantage. Additionally, Crites examined how the three measured underlying factors (SGDMs, between-hand, and visuomotor coupling) contributed to the effect of previous bimanual practice on intermanual trials. Results for bimanually practiced versus bimanually unpracticed intermanual trials showed that visuomotor and between-hand coupling were reduced with bimanual practice, and this reduction in coupling was related to better (i.e., faster) performance. Overall, more SGDMs were associated with intermanual trails, whether the task had been previously practiced or not. Given the success of these metrics in accounting for the underlying behaviors that drive coordination mode and practice effects, the present study seeks to extend this work by investigating a fourth explanatory factor: characteristic lag in visuomotor coupling.

1.4 Characteristic Lag and the Present Study

Though aggregated metrics (used in this case to mean *averaged across time*) are often helpful in understanding group differences and sufficient for myriad scientific insights, they lack information that depicts how systems are organized in time. Analyses that deconstruct temporal information allow us to better understand how one subsystem might influence a neighboring subsystem, and the constraints that influence patterns of coordination between system elements (Coco & Dale, 2014). In the case of visuomotor coordination, temporal analyses have shown eye movements to precede associated motor actions, such as the LAFs described previously (e.g., Mennie et al., 2007). Furthermore, this line of work has revealed reliable estimations of the degree to which motor actions lag behind eye movements. For example, the current stream of visual information received by a driver is associated with course adjustments 800ms later, and fixations made to sheet music by pianists precede accompanying key depressions by roughly 1s (Land & Furneaux, 1997). In studies that aggregate behavior across time, these results are inaccessible.

The present study builds on a line of research that assesses leader-follower relationships in dynamic systems, similar to the examples described above. In these analyses, streams of timed-coded data are interrogated to see at which time lag they maximally align, revealing the degree to which one subsystem follows the other (Coco & Dale, 2014). It is proposed that the lag relationship between the gaze and hands in a visually-guided, two-handed task changes with practice and is unique to the coordination mode (i.e., bimanual versus intermanual) used to execute the task. The interacting effect of these two variables is also assessed in terms of its effect on lag behaviors. The specific motivation behind this analysis is to understand whether unique lag in the eye and hand relationship is an underlying factor that contributes to the erasure of the intermanual speed advantage after actors have had previous bimanual practice with the task. Broadly, this work comments on an underlying mechanism of human interaction and interpersonal coordination. This mechanism is hypothesized here to be visuomotor coordination.

Other such lag analyses have revealed unique insights of interpersonal coordination. Though many studies have focused on simple movements and motor coordination (e.g., Kelso et al., 1979), others have extended this more basic research to articulate the temporal structure of complex human behavior. For example, Richardson and

Dale (2005) showed that when describing a scene to another listener, the eye movements of a listener follow roughly two-seconds behind the eye movements of a speaker. Importantly, the more closely in time the listener's eye fixations followed the speaker's, the higher the listener scored on a comprehension test. Furthermore, Louwerse and colleagues (2012) demonstrated that synchronization between interlocutors extends beyond just eye movements, wherein facial expressions, gestures, and language all synchronized between the conversationalists. Here, a tight coupling was found between the interlocutors that suggested imitation, as the mirrored actions were so close in time (within a few seconds). These and other such analyses begin to reveal the extent to which our cognition and behaviors are influenced through interpersonal coordination. The present study extends the characteristic lag literature by investigating how partners' patterns of visuomotor coordination influence each other.

1.4.1 The Impact of an Individual's Coordination on the Dyad

Lag analyses and related synchronization studies have revealed interesting insights regarding interaction in motor tasks, many results of which scale up from intrapersonal coordination to interpersonal coordination (Fine and Amazeen, 2011; Lorås et al., 2019). These studies in particular tend to focus on oscillation speed or task completion times and are reviewed below. Though the present study specifically assesses lag, findings regarding speed provide an empirical basis from which the present hypotheses are built.

One particular phenomenon that is revealed in this line of work is a tendency for one subsystem to spontaneously synchronize with, or *entrain* to, another subsystem when they become coupled. Entrainment is generally defined as the tendency for a behavior of a system to spontaneously, temporally align with the existing behavior of a newly introduced second system (Strogatz, 2003). There are two hypothesized alternatives for how the newfound pattern of coordination is negotiated when a task moves from bimanual to intermanual execution. First, it is possible that the two newly coupled systems both forego their original coordination patterns for a unique, emergent pattern brought on by the interaction (Gipson, Gorman, & Hessler, 2016). A second possible scenario is that one system will forego its original or preferred coordination pattern for that of the other producing an additive relationship between the intermanual and bimanual trials (Oullier et al., 2008).

1.4.1.1 Coordination in Oscillatory Tasks

Largely, these synchronization patterns have been investigated in simple movements between and within human actors, as well as animals and objects. However, here we focus on human behavior. The typical paradigm for investigating these phenomena requires participants to swing an arm, rhythmically tap a finger, walk, sway, or engage in some other simple, repetitive action. A previously discussed study that examined a two-handed version of the Fitts' tapping task, wherein participants had to make simultaneous movements to targets using both hands, found that movements to an easy target exhibited a previously unobserved speed when coupled with a movement of the other hand to a difficult target (Kelso et al., 1979). The speed of movement to the easy target was emblematic of neither the movement to the hard target of the other hand, nor a unimanual movement to an easy target. Instead, a third speed was observed, showing an emergent temporal structure (Kelso et al., 1979). Does this pattern of results scale up from the intrapersonal to the interpersonal coordination mode, as well?

A study by Oullier and colleagues (2008) explicitly set out to understand how oscillatory patterns are influenced when visual coupling is introduced between two people. The experimental task was to rhythmically move the index finger of the right hand up and down at a comfortable speed. Preferred or natural oscillation rates were measured for each individual prior to being matched to a partner. The pairs were then matched based on their preferred oscillation rates, such that those with lower rates completed the interpersonal condition facing a partner with a high natural oscillation rate. Findings revealed that generally, after pairs became visually coupled, those with the naturally lower oscillation rates would speed up, but not quite to the speed of the quicker oscillator. Similarly, higher rate oscillators would slow down upon seeing their partner, but not enough to match the original speed of the slow oscillator. Along with the results from the Kelso and colleagues (1979) study described above, this shows that a third relationship is established both in moving from unimanual to bimanual and bimanual to intermanual coordination modes for oscillatory tasks.

1.4.1.2 Coordination in Complex Tasks

Many tasks that require coordination between two people are not of an oscillatory structure (Vial & Cornejo, 2022). Previously mentioned examples of non-rhythmic interpersonal coordination include laparoscopy, the focus of the present study, and teleoperation. Limited research has assessed how coordination patterns change with practice in these contexts, and similarly, how they change when moving from the bimanual to intermanual coordination mode. Two studies are reviewed below that begin to describe how task completion time for more complex tasks are impacted by practice and the coordination across actors.

Evidence to suggest that an emergent coordinated relationship is present in intermanual coordination between novices was found in a study by Reed and colleagues (2006). The task required two hands—whether from the same person or two different individuals—to rotate a disk so that it aligned with a target (i.e., a pursuit rotor task). Findings revealed that dyads were significantly faster at this task than even the faster actor in the bimanual condition. This notion is the essence of the intermanual speed advantage, which was previously introduced and has been assessed in numerous settings (e.g., laparoscopy; Zheng et al., 2005). Conversely, this effect has not been found in well-practiced tasks. In these familiar tasks, task completion speed is statistically equal in the two coordination modes (Crites, 2018). This latter relationship between performance in the two coordination modes shows that intermanual speed is representative of a previously observed bimanual speed in well-practiced dyads.

With practice, the execution of sequential motor actions can become rigid, where the bounds between initially discrete subtasks begin to blur. This occurs over time as the components of the task start to integrate with each other to form a continuous stream of action (Knight, 2004). As mentioned, this integration begets rigidity, wherein it becomes difficult to edit an established pattern of execution without having to edit the entire task procedure (Lee et al., 2008; Gorman & Crites, 2013). This serves as a possible explanation of the disappearance of the intermanual speed advantage with previous bimanual practice. It is proposed that experienced actors are more rigid in the execution of the task and are therefore unable to establish a compromising, or emergent, pattern of coordination when asked to complete that task as dyad. With the integration of all the subtasks into a single flow of action, they are unable to improve upon their execution even when more cognitive resources are added (i.e., another person) because they cannot effectively integrate their previously established patterns of coordination.

The goal of the present study is to extend our knowledge of the underpinnings of coordination patterns when a task moves from one coordination mode to another, and how previous bimanual practice impacts that transition. Specifically, the present study will assess if visuomotor lag, an assumed underlying factor in the intermanual speed advantage, is unique to the intermanual condition (i.e., the emergence hypothesis), or emblematic of one of the two partner's bimanual trials in the intermanual condition (i.e., the entrainment hypothesis). Furthermore, practice effects will be examined to assess whether visuomotor lag is a contributing factor to the moderating effect of practice found in the intermanual speed advantage. It is hypothesized that a pattern of entrainment (i.e., additivity) to one partner is observed in dyads with previous bimanual practice, while a novel (i.e., emergent) lag coordination pattern is observed in novice dyads. Since both processes—additivity and emergence—have been observed in past research regarding speed in two-handed tasks, differences in lag patterns would help account for the moderating effect of practice and connect these findings to potentially help resolve why both have been previously found.

1.5 Hypotheses

There are two alternatives to how visuomotor coupling lag will compare between the bimanual trials and the intermanual trials: 1) the lag value observed in the intermanual trial is different from both of the component bimanual trials, or 2) the lag value observed in the intermanual trial is equal to one of the lag values found in the bimanual trials. As mentioned, both alternatives have been found previously in studies investigating patterns of speed in two-handed tasks. Alternative 1 is referred to as the Emergence Hypothesis and is expected to be observed only in novice participants—the group wherein the intermanual speed advantage is found. Alternative 2 is referred to as the Entrainment Hypothesis and is expected to be observed only in participants with previous bimanual practice—the group wherein the intermanual speed advantage is not found. Thus, it is expected that whether we observe emergence or entrainment will be moderated by the effect of practice. This pattern of results would lend itself to a more parsimonious understanding of why both additivity and emergence have been found in past studies.

Hypothesis 1 (Emergence Hypothesis): When novices complete a motor task bimanually, their pattern of visuomotor coordination, defined here as characteristic lag between gaze fixations and accompanying manual actions, is distinct from when this task is completed in the intermanual coordination mode. Specifically, the characteristic lag in the intermanual trials should be longer than the longest lag of the respective bimanual trials. This suggests that in the intermanual trial, participants' visual and motor systems are even further decoupled than the more decoupled of the constituents' bimanual trials. This pattern of results generally mirrors what is observed in the task completion speed of novices in the intermanual speed advantage (e.g., Zheng et al., 2005); however here, the advantage is hypothesized to be seen in the degree of decoupling in the intermanual trials.

Hypothesis 2 (Entrainment Hypothesis): Conversely, when two actors with previous bimanual practice complete a task intermanually, the characteristic lag of the intermanual trials should show entrainment of the dyad's coordination to that observed in bimanual trials. This is expected to occur given that bimanually well-practiced tasks do not show performance differences between the bimanual and intermanual conditions (Crites, 2018; Gorman & Crites, 2015). The entrainment will be such that the partner who exhibited more visuomotor coupling (i.e., a shorter lag value) will be attracted to the coordination pattern of the originally more decoupled partner, but the originally decoupled partner will remain at their original (i.e., bimanual) degree of coupling. The intermanual trials will be effectively constrained by the visuomotor coordination of the more decoupled of the two constituents and will not be able to further decouple in the intermanual mode. This additive effect in the lag metric reflects Crites' (2018) finding regarding speed in practiced tasks, where bimanual speed was emblematic of intermanual speed.

CHAPTER 2. METHOD

The present study sought to understand how coordination of the gaze and hands changes 1) with previous bimanual practice, 2) from bimanual to intermanual trials, and 3) with the interaction of previous bimanual practice and coordination mode in the execution of a complex motor task. Changes in the visuomotor relationship were quantified using Cross Recurrence Quantification Analysis (CRQA) and defined under a lag variable that depicts how far in time motor movements follow or lead associated gaze fixations. CQRA is explained in detail below, after a description of the experimental task and procedure designed by Crites (2018). The present study reports on an archival analysis which analyzes data collected by Crites.

2.1 Crites (2018) Experimental Method

2.1.1 Experiment 1

The purpose of Experiment 1 in the Crites (2018) study was to assess how the three, previously introduced, hypothesized factors (between-hand coupling, visuomotor coupling and SGDMs) contributed to the intermanual speed advantage in *novices*.

2.1.1.1 Participants

Twenty-four Georgia Tech undergraduate students (12 dyads) participated in Experiment 1 for partial course credit. Participants' mean age was 20.71 (SD = 2.28), and 21% were female. The prevalence 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).

2.1.1.2 Experimental Design

To assess coordination mode effects, a within-subjects Mode variable was defined with two levels: Bimanual and Intermanual. In the Bimanual condition participants completed the task with their left and right hands as an individual. In the Intermanual condition, participants completed the task with either their left or right hand, alongside a partner doing the same with the opposing hand. Order of the conditions was counterbalanced, with half the participants completing the bimanual trials before the intermanual trials, and the other half in the reverse order. Order was defined as a between-subjects variable in the original study, resulting in a 2 (Mode: Bimanual, Intermanual) x 2 (Order: Bimanual First, Intermanual First) mixed design. No main effects of Order were found, therefore the Order variable is not discussed further in the present study. Ten trials were completed for both levels of Mode.

2.1.1.3 Apparatus

Previous research that observed the intermanual speed advantage employed tasks that shared the following attributes, which were also implemented in the Crites (2018) task. The task was designed to be interactive across the hands, such that one or more subtasks were dependent on action from both hands. The task also needed to be agonistic, meaning the utilization of both hands to complete interactive subtasks would be advantageous, over just using one hand (Jarrassé et al., 2012; Van Oosterhout et al., 2017). Furthermore, the task was designed to exploit the hypothesized underlying factors contributing to the speed advantage, meaning it was required to be visually-guided and to rely on simultaneous, asymmetric movement of the limbs (Crites, 2018).

The task had two component parts, each enacted by one of the opposing hands. In every trial, the index and middle fingers of the right hand served as the “scissor tool”, and those of the left hand served as the “grasper tool.” Fingers were used instead of actual tools, as in the Zheng and colleagues (2005) study, to allow for a more direct assessment of the motor system, not impacted by the need to coordinate tools (Crites, 2018). An overview of the task is shown in Figure 1. Generally, participants were required to move a straw-like object and a short pipe from their starting locations and insert the straw through the pipe. Then they “cut” the straw before returning both items to their starting locations.

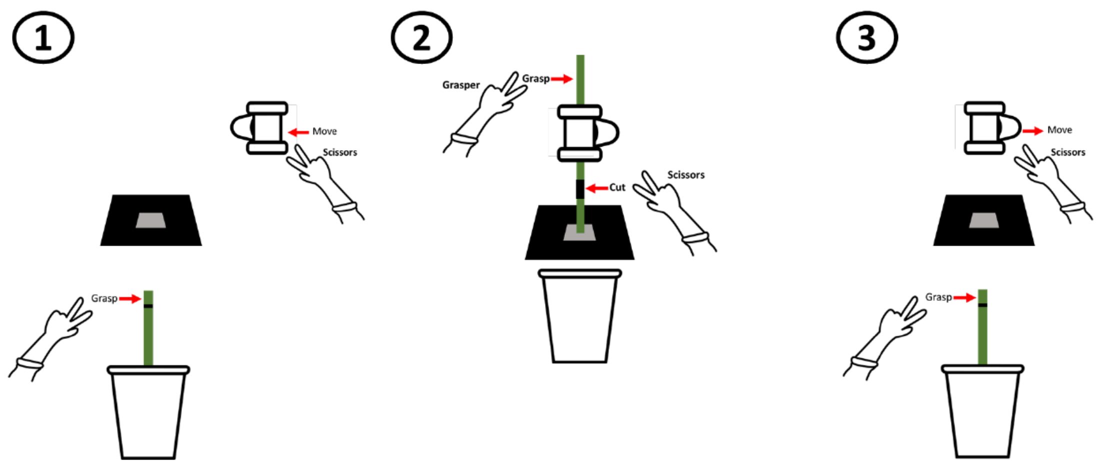


Figure 1 – Participants were asked to move a pipe to a particular area, place a straw-like object through the pipe, and simulate a cutting action at a particular place on the object. Graphic copied from Crites (2018).

The task structure was broken down into six discrete subtasks for each hand (i.e., for both the grasper and the scissor). This was done to allow for a level of analysis that is appropriate for assessing coordination patterns in two-handed tasks (Land et al., 1999;

Land & Hayhoe, 2001; Hayhoe & Ballard, 2005). Specifically, the identified subtasks provided clear start and end points for each motion that are prevalent in the visuomotor coordination literature (e.g., Fitts, 1954). A summary of the subtasks is provided in Table 1.

Table 1 – Each grasper and scissor task needed to complete the simulated cutting task. Adapted from Crites (2018).

Grasper	Scissors
Grasp object	Grasp object
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. These subtasks apply to conditions using both the bimanual and intermanual coordination modes.

The steps of the grasper tool are depicted in Figure 2 from Crites (2018). Starting from the home key, the grasper tool (the left hand) was required to (1) pinch and hold the top of a straw-like object (i.e., the object) with the index and middle fingers. Then, (2) the grasper lifted the object to the location of a pipe and inserted the bottom of the object through the opening. Step (3) required the grasper to rest the object on a gray square at the base of the apparatus, *at which point the scissors would then make a 'cut' to the bottom of the object*. Then the grasper (4) lifted the object from the pipe and (5) returned the object to its starting location. Step (6) was to return the fingers to the home key.

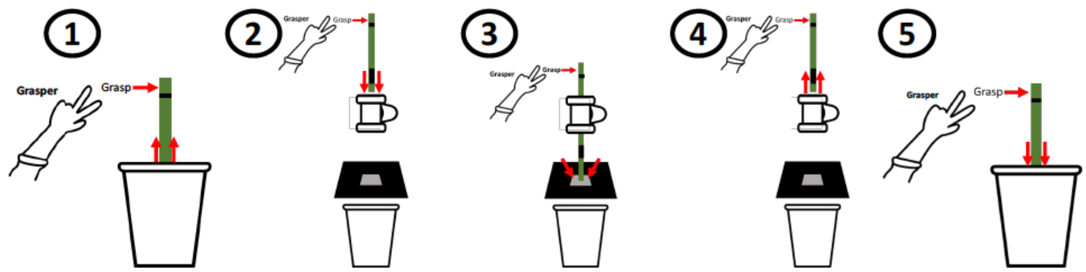


Figure 2 – Steps of the grasper tool (the index and middle fingers of the left hand). Step 6 was to return the finder to the home key. Graphic from Crites (2018).

The steps of the scissor tool are depicted in Figure 3 from Crites (2018). Starting from the home key, the index and middle fingers of the right hand, (1) pinched the pipe. Next, the scissors (2) moved the pipe to hover over the gray square. *Once the straw-like object was inserted by the grasper*, (3) the scissors made a 'cut' to the bottom of the straw. Then the scissors (4) moved the fingers back to the pipe, and, *after the straw had been removed by the grasper*, (5) returned the pipe to its starting position. Lastly, (6) the scissors returned to the home key.

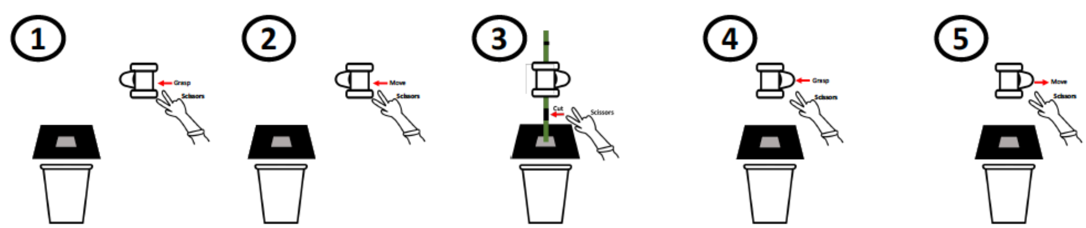


Figure 3 – Steps of the scissor tool (the index and middle finders of the right hand). Step 6 was to return the fingers to the home key. Graphic from Crites (2018).

Multiple views of the apparatus can be seen in Figure 4. This same apparatus was used for both Experiments 1 and 2, for both the intermanual and bimanual conditions.

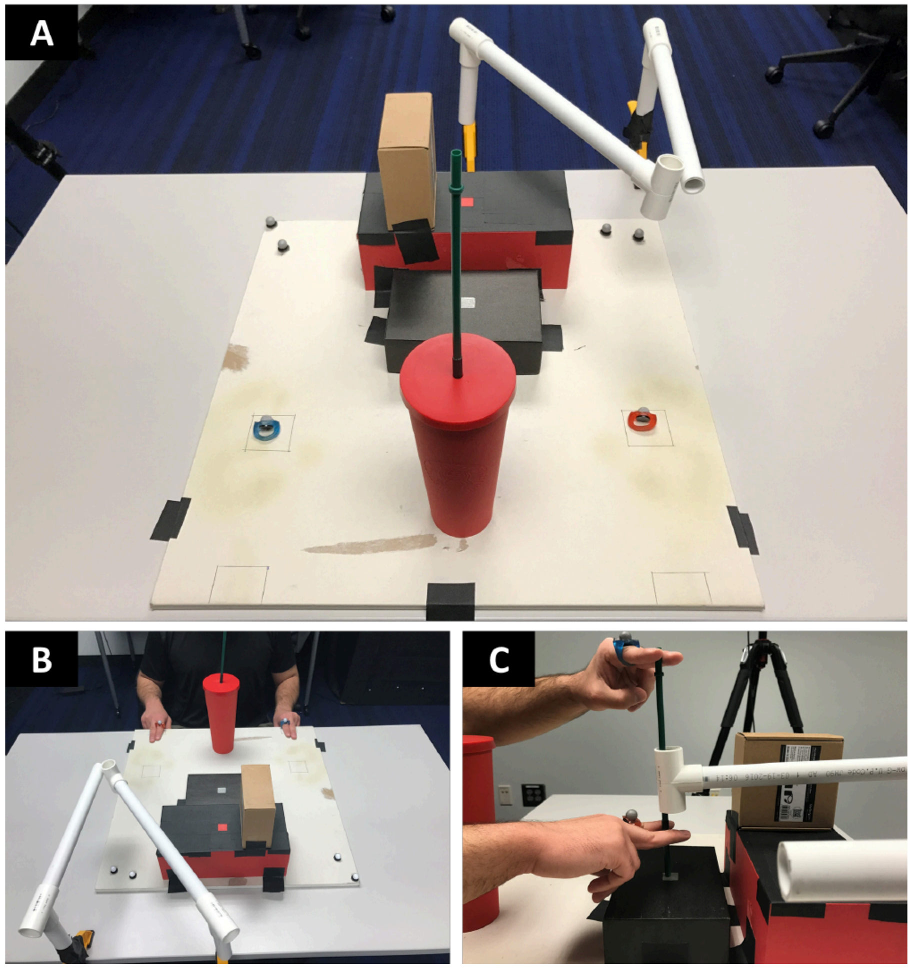


Figure 4 – Copied from Crites (2018). (A) A participant's view of the apparatus, with all object in their starting locations. (B) A view of a participant with both hands at the starting location (home keys) in the bimanual condition. (C) View of a participant completing cutting action in the bimanual condition.

To capture eye-tracking data, a wearable eye-tracking system by Ergoneers (Dikablis Eye-Tracking Glasses Professional) was calibrated for each participant (Ergoneers, 2014). The system sampled data at 60 Hz via binocular eye cameras and tracked pupil detection at 0.05°, glance direction at 0.1-0.3° with a 40-90° viewing angle. The glasses featured an outward facing scene camera above the bridge of the nose, collecting video data from the participants' perspective. Prior to the first trial, each participant had the system calibrated to align the inward facing binocular eye cameras to the outward facing scene camera in D-Lab. The D-Lab 3.4 software package (Ergoneers, 2014) was used for data collection and analysis. A screenshot of the D-Lab software is seen in Figure 5, taken from Crites (2018).

The eye tracking system was set up in such a way as to define the areas of interest (AOIs) that would later be used to calculate the visuomotor coupling metrics employed by Crites (2018). AOIs were defined in the original study as “physical locations in three-dimensional space containing task-relevant information” (Crites, 2018, p. 50). These AOIs mapped onto the subtasks for each tool described above.

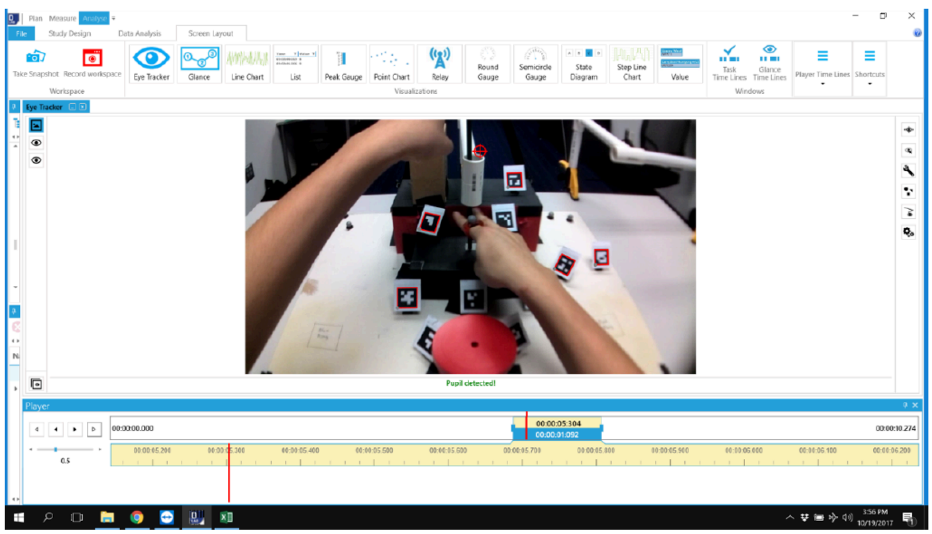


Figure 5 - Screenshot and caption from Crites (2018) of the D-Lab software package of a trial recording. “The video in the center is a still frame from the view of a participant completing the task using the bimanual coordination mode. The red crosshair illustrates where the participant is looking. The 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.” p. 50.

To capture movement data in the Crites (2018) study, the room was outfitted with a ten-camera Vicon Vantage 5 motion capture system with a sampling rate of 100 Hz.

Data was collected using reflective markers attached to rubber rings, which participants wore on their index fingers, as seen in Figures 4b and 4c.

2.1.1.4 Measures

Here, measures implemented by Crites (2018) to capture visuomotor and between-hand coupling are detailed, as they provide important context for the present study. Measures of speed (TrialTime), variability and SGDMs are also briefly explained.

Visuomotor Coupling Measures. Visuomotor coupling was operationalized as two separate measures of motor actions to respective eye fixations. The first measure was termed "Pre-Reach Look-Ahead" by Crites and aligns with the look ahead fixations (LAFs) describe earlier. LAFs in Crites' work were a calculation of the difference in time between looking at an AOI and reaching for it or starting a similar manual action. Gaze anchoring fixations (GAFs) were the second measure of visuomotor coupling used in Crites' (2018) study. GAFs were a calculation of the difference in time between grasping in an AOI (or making a similar manual action) and looking away from it.

These measures both relayed eye movement and hand movement information, as such eye-tracking and hand movement video data where used in their calculation. The subtasks, previously explained, all corresponded with a start and stop reaching or grasping action that were used to assess the eye fixations and hand movements (See Table 2 for Grasper subtask start and stop actions; Table 3 for those of the scissor). Each subtask mapped on to an AOI on the task apparatus. AOIs were used to calculate the time of initiation or termination of an eye or hand movement. Therefore, the start of a task-specific eye movement occurred when the eye fixated on an AOI associated with a manual action to that same AOI and stopped when the eye first looked away from the AOI. The result of this structure created data points representing LAFs and GAFs for every subtask of both of the tools/hands.

Table 2 – Each grasper subtask broken down by start and stop movements. Copied from Crites (2018).

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 area of the box
	Stop: Once the object first touches the grey box
Remove object from the pipe	
	Start: Once the object is removed from the area of the grey 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 condition using the bimanual and intermanual coordination mode.

Table 3 – Each scissor subtask broken down by start and stop movements. Copied from Crites (2018).

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 closed on the top of the pipe
Move pipe over to grey area of box (second position)	
	Start: Once the pipe starts movements toward 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
Remove fingers to pipe	
	Start: Once both fingers start to open/release grasp on object
	Stop: Once both fingers complete grasp the pipe
Return pipe back to first position (first position)	
	Start: Once the pipe begins motion toward 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.

The calculation of these two metrics required the start and stop times of both the hands and the eyes to be recorded for each AOI. As described by Crites (2018), the start time of the eye movement was when the eye fixated on the AOI (Eye_AOI Start Time), and the stop time of the eye was when the fixation left the AOI (Eye_AOI Stop Time). Similarly, the start time of the hand movement was when the hand started to move to the AOI (Hand_AOI Start Time), and the stop time was when the hand reached the AOI (Hand_AOI Stop Time). Equations for the LAFs and GAFs metrics can be seen in

Equations 1 and 2, respectively. Visualizations of these calculations can be seen in Figure 6 as depicted by Crites (2018).

$$LAF = EYE_{AOI\ Start\ Time} - Manual_{AOI\ Start\ Time} \tag{1}$$

$$GAF = EYE_{AOI\ Stop\ Time} - Manual_{AOI\ Stop\ Time} \tag{2}$$

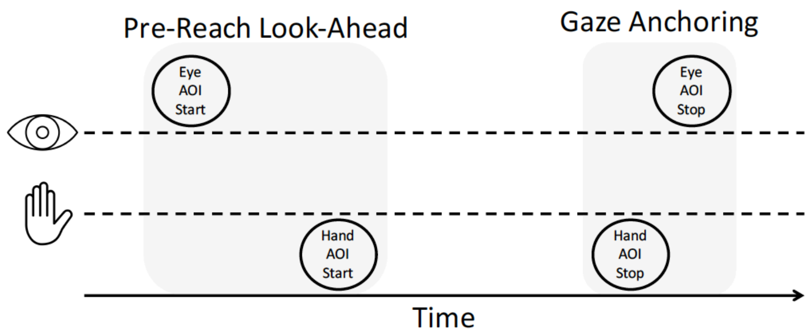


Figure 6 – Visual representation of the calculations used to measure LAFs (termed pre-reach look-ahead in Crites study) and GAFs. Graphic from Crites (2018).

Between-hand coupling measures. In the original Crites (2018) work, a related analysis to that which is investigated here to evaluate characteristic lag was conducted to measure between-hand coupling. In this method of analysis, referred to as Cross Recurrence Quantification Analysis (CQRA), two streams of time-coded data are plotted against one another in a Cross Recurrence Plot (CRP; Shockley, Butwill, Zbilut & Webber, 2002). The CRP is a visualization of the times at which two dynamical systems share a location within the threshold of a determined radius (Riley & Van Orden, 2005). To construct the CRP in the Crites (2018) study (see Figure 7 for example), the continuous motion capture data from the left and right hands were plotted along the opposing axes. In a CRP, a dot (i.e., a recurrent point) is plotted anytime the two streams of data share a position (defined by the extent of the radius) in their joint dynamical space (i.e., phase space). The more dots filled in on a CRP, the more coupling the system exhibits. To further quantify coupling, a measure termed percent recurrence (%REC; Equation 3) is then calculated by dividing the number of plotted recurrence points by the total number of possible recurrence points (i.e., the total area of the CRP). %REC then determines what percent of the time the systems share a position in phase space.

$$\%REC = \frac{Total\ \#\ Recurrent\ Points}{Total\ \#\ Possible\ Recurrent\ Points} * 100 \tag{3}$$

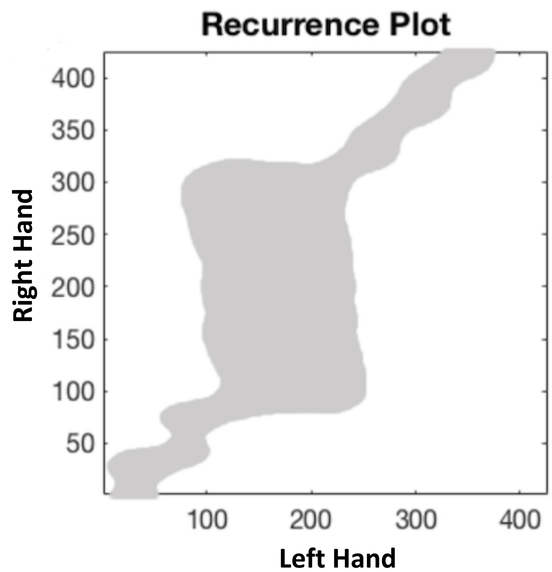


Figure 7 – An example recurrence plot from Crites (2018), depicting the movement of the left hand being followed by the movement of the right hand during the simulated cutting task.

Simultaneous, goal-directed movements (SDGMs). Video analysis from trained research assistants was used to measure SGDMs. Per Crites (2018), coders were to denote a SGDM as such under 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)" (p. 63). Six such SGDMs were possible for any given trial. SGDMs were distinguished from simultaneous movements that were not goal oriented. Such ancillary movements were considered products of bimanual coupling or intermanual synchrony and were not counted as SGDMs by coders.

Speed. Motion-capture data was used to determine the speed of each trial (i.e., trial time). An area of the three-dimensional task space was determined in pilot testing to indicate the start and stop of a trial. This area was 60mm above each home key. The start time was indicated as the first time the hands entered the area, after just leaving the home keys from the starting position. The stop time was indicated as the return of the hands to this area before arriving at the ending location, where the hands were returned to the home keys. Trial time was then calculated as the difference between the stop and start times. This procedure was used to ensure only task-relevant information was included in the trial time calculations (Crites, 2018).

Variability. This metric was used to capture the stability of the hands as they completed the task. Lower variability is an indication of a more skilled actor, meaning this metric helped assess task fluency (Crites, 2018; Gorman & Crites, 2015; Thelen et al., 1993). Variability was computed using the motion-capture data, where the determinant of the variance-covariance matrix between the left and right hand of a particular dimension in three-dimensional space served as the variability for each trial.

2.1.1.5 Procedure

After obtaining informed consent, participants where shown the apparatus and given an overview of the two different coordination modes they would engage in. In Experiment 1, the coordination modes were counterbalanced, such that half of the participants completed the bimanual trails first, while others completed the intermanual trails first. Participants were not allowed to speak with each other at any point during the experimental session. While one participant completed the bimanual trial, the other would complete a demographics questionnaire and the Edinburgh Handedness Inventory (Oldfield, 1971) in a separate room.

An experimenter instructed the participants "to complete the task as quickly and accurately as possible," "to complete the task as fast as possible while still accurately completing the task," and "if the trial is performed incorrectly, then it will not count" (Crites, 2018, p. 65). Participants placed the motion capture marker rings on their index fingers, and assumed the "ready position" (placing fingers on the home key) before each trial. The trial began with a "Go" signal from one of two experimenters in the room. Prior to this signal the experimenters started both the eye-tracking and motion-capture systems. A trial was determined complete once the participant(s) spoke the word "Done" with both hand back on the home keys. The eye-tracking and motion-capture systems were then stopped by the experimenters.

Example images of bimanual and intermanual starting positions are provided in Figure 8, as originally shown in Crites (2018). In bimanual trials, the single participant was instructed to sit centered to the apparatus, with the first two fingers of their right hand on the right home key, and those of the left hand on the left home key (Figure 8a). In the intermanual trials, one participant sat to the side of the other. The participant on the right side placed the first two fingers of the right hand on the right home key (in front of them), and the participant on the left side place the two fingers of their left hand on the left home key (in front of them; Figure 8b). The right hand in both conditions completed the scissor portion of the task, while the left hand completed the grasper portion of the task.

Before participants began the experimental trials they completed a short series of practice trials in both of the coordination modes, which lasted roughly one minute, to ensure they were acquainted with the task requirements. The practice trials were not to be completed with speed as a priority, but instead it was emphasized they be completed correctly. Following the practice trials, participants were randomly assigned to complete one of the coordination modes prior to the other, and randomly assigned to a role within their dyad. Experimental sessions lasted roughly 1.5 hours, wherein ten trials in each coordination mode were completed per participant (Crites, 2018).

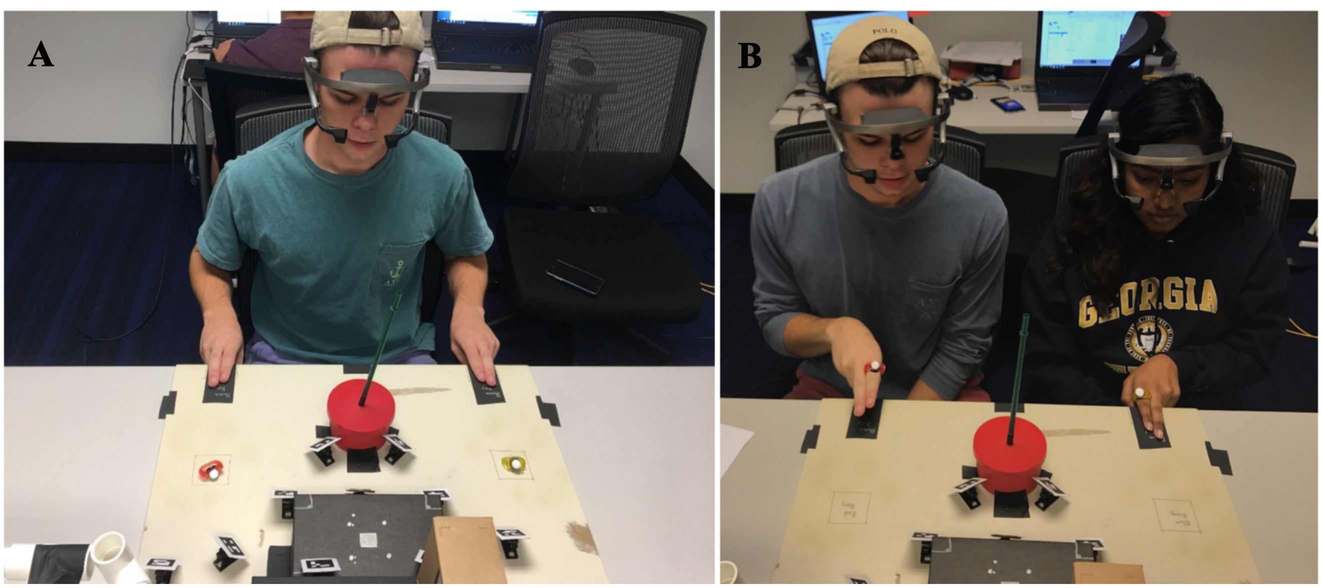


Figure 8 – (A) A participant is shown in the starting position of the bimanual condition with the apparatus in front of them. (B) The two participants are shown with their respective hands in the starting position before they begin an intermanual trial. Images taken from Crites (2018).

2.1.2 *Experiment 2*

The purpose of Experiment 2 in the Crites (2018) study was to assess how previous bimanual practice impacts the intermanual speed advantage. The three originally hypothesized underlying factors (between-hand coupling, visuomotor coupling and SGDMs) were also assessed in Experiment 2 to understand their contribution to the hypothesized reversal of the speed advantage in bimanually familiar tasks.

2.1.2.1 Participants

Twenty-four Georgia Tech undergraduate students (12 dyads) were recruited from the posting of flyers in the psychology building to participate in Experiment 2 for monetary compensation ($45). Participants' mean age was 23.58 (SD = 4.30), and 50% were female. Six dyads were mixed gender, three were all male, and three were all female. To be eligible, participants were required to be right-handed. Right-handedness was assessed using the Edinburgh Handedness Inventory (Oldfield, 1971).

2.1.2.2 Experimental Design

To ensure participants were well-practiced at the bimanual execution of the task, over the course of two consecutive days, each participant completed 100 trails per day. The next (third) day participants were again brought into the lab to complete both the bimanual and intermanual experimental trials that would be used to assess coordination mode effects. Per Crites (2018), the number of practice trials was selected based on prior studies that demonstrated the achievement of performance asymptote in motor tasks after fewer than the number of trials used here (e.g., Joseph et al., 2013). On the third day of the experiment, the procedure followed that of Experiment 1, where the order in which the participants completed the two coordination modes was counterbalanced.

2.1.2.3 Apparatus

The same simulated cutting task and apparatus, motion-capture and eye-tracking devices were used in Experiment 2, as in Experiment 1. There was however an instrumentation failure with the eye-tracking device, which prevented the collection of eye-tracking data for the last six dyads to complete the experimental trials. To maintain consistency in experimental procedures, the last six dyads still wore the eye tracking device (Crites, 2018).

2.1.2.4 Measures

Measures remained the same from Experiment 1, however an additional measure was collected to assess the effectiveness of the bimanual practice phase in bringing participants to performance asymptote. To assess whether the task had been sufficiently practiced, the performance curves of the practice sessions were fitted to power and exponential curves. If a participant's performance curve after day 2 was aligned with that of the power function, the participant was considered to be sufficiently practiced at the bimanual execution of the task (Newell & Rosenbloom, 1981). Conversely, if their performance was better fitted to the exponential function, skill acquisition was believed to still be in progress (Crites, 2018; Heathcote et al., 2000).

Additionally, as the eye-tracking device failed for the second half of Experiment 2 experimental trails, measures of LAFs and GAFs were only calculated for six of the 12 dyads.

2.1.2.5 Procedure

For the practice phase of Experiment 2 in the Crites (2018) study, participants arrived at the lab individually to complete the 100 bimanual trials for two consecutive days. Prior to completing the practice trials participants were informed of experimental procedures and gave consent to participate. As in Experiment 1, the apparatus was shown and a general overview of the task requirements was outlined. For the practice phase, only the bimanual coordination mode was used. Task instructions and procedures remained the same from Experiment 1. Even during the practice phase, eye-tracking and motion-capture devices were started by the experimenters for each trial. However, during the practice phase, as it consisted of many more trials than Experiment 1, participants were given a 1-2 minute break after every 25th trial to mitigate fatigue effects. The two practice sessions lasted roughly one hour each.

Procedures on day three were the same as in Experiment 1, where members of the dyad arrived to the lab in pairs. The day three experimental session again lasted 1.5 hours.

2.2 Analysis Conducted in the Present Study

The present study analyzed data collected in the two experiments from Crites (2018) described above to answer a novel research question. Specifically, data used to calculate visuomotor coupling measures was assessed in a new CQRA analysis to calculate characteristic lag between the gaze and hands during task completion. The CQRA analysis of the present study diverges from the one conducted to assess between-hand coupling in Crites (2018), both in procedure and in the end-goal of the analysis. The motor information used to quantify between-hand coupling in Crites (2018) was continuously sampled. Conversely, the visuomotor coupling data analyzed here is discrete in nature, since they were collected in reference to task-relevant AOIs. Thus, the analyses diverge in their execution. “Discrete” in this instance refers to the “timestamp” nature of the visuomotor coupling data, which is described in detail below. Additionally, the CRQA conducted in the Crites study assessed %REC on the trial overall, whereas the present study seeks to understand characteristic lag, which instead assesses the value of %REC only along the individual diagonals of the CRP. These procedures are explained in detail below.

2.2.1 Method

2.2.1.1 <u>Participants</u>

Demographic information on participants can be found in participants descriptions above for the Crites (2018) study. Data from a total of 17 dyads were used for the characteristic lag analyses of the present study. Though data from 24 dyads were collected in the Crites (2018) procedures, eye tracking data from six of those dyads (from Experiment 2) are missing due to instrumentation failure. One additional dyad (Team 1 from Experiment 2) had an instrumentation failure with only one participant for both the bimanual and intermanual trials. This made it necessary to remove this team from the analysis, as the bimanual trials from the viable participant could not be assigned to a condition, and only half of the intermanual trials had usable data.

2.2.1.2 Apparatus & Materials

The apparatus and materials remain the same from those described above and in Crites (2018).

2.2.1.3 Experimental Design

Planned comparisons of characteristic lag (i.e., lag) evaluated the lag metric across three different levels of a between subjects variable, Visuomotor Lag. The lag values associated with the two bimanual trials, wherein the participants comprise the dyad of the associated intermanual trial, were organized such that the participant with the shorter lag value was denoted as Bi_Shorter, whereas the participant with the longer lag value was denoted as Bi_Longer. Intermanual lag values will be denoted as INTER. Of note, shorter lag values indicate a tighter coupling between the gaze and hands, whereas longer lag values indicate more decoupling of the visual and motor systems. This results in three levels of Visuomotor Lag: Bi_Shorter, Bi_Longer and INTER.

Additionally, characteristic lag was assessed separately for the Unpracticed and Practiced trials across two analyses. The Unpracticed analysis corresponded to data from Experiment 1 in Crites (2018), where individuals and dyads completed the task without extensive previous bimanual practice. The Practiced analysis corresponded to data from Day 3 of Experiment 2 in Crites (2018), wherein individuals first completed two days of bimanual practice, then participated in both bimanual and intermanual trials on the third day. Analyses occurred separately across the two levels of practice.

2.2.1.4 Discrete CQRA Procedures & Measures

CRQA methods have traditionally utilized continuous data, referred to broadly as *time series data* within the non-linear dynamics literature. However, the discrete recurrence approach was developed to analyze data that are in some way segmented, such that they are not continuous across time (Gorman et al., 2012). In analyses on continuous data, recurrence points are noted when the two streams of time-coded data occupy the same location in phase space, where "same location" is defined within a certain distance threshold (i.e., radius). The procedures of threshold determination are not required for discrete analyses, and thus are not detailed here, however a description of these methods and how they are employed can be found in Crites (2018). In the discrete case, the CRP and its recurrence points are dictated by the codes ascribed to the data, as opposed to threshold calculations (Gorman et al., 2012). The procedure is explained in the following paragraphs.

Previous discrete CQRAs have evaluated team communication dynamics to better understand how team members reorganize over time in simulated task environments. These analyses use coded communication data (e.g., text-chat dialogues between team members) to understand the variability in communication patterns and establish how team interactions change in dynamic environments. These analyses are noteworthy because they can be implemented for real-time analyses of team interactions that unravel how individual inputs (e.g., single actors) impact the behavior of the system (e.g., team) as a whole (Demir et al., 2021; Gorman et al., 2012 & 2020). Though the present study examines area-specific eye fixations and hand placements, as opposed to communication patterns, it also reveals how an individual's coordination impacts that of the overall system. This was accomplished by a comparison between the characteristic lag of the bimanual verses intermanual coordination modes, and the practiced verses unpracticed dyads.

The discrete recurrence analysis begins with the construction of the discrete CRP. This instantiation of the CRP is similar to that of the continuous version described previously, where two streams of data are plotted along the opposing axes. However, in the discrete case, the data streams are made up of nominal codes (Gorman et al., 2012). For example, in a study by Gorman and colleagues (2020) transcripts from surgical teams completing training simulations were coded for turn-taking behaviors, with utterances by each team member denoted by a different number in the code (or a zero if no one was speaking). The goal was to understand which team members' communications contributed to significant reorganizations in the team's interaction. To construct the discrete simple recurrence plot the nominal code of turn-taking behaviors was plotted against itself. (Note: here the plot is a simple, as opposed to cross-, recurrence plot, since only one time series is analyzed.) An example recurrence plot from this study is provided below. As the same coded time series has been plotted against itself, the main diagonal is fully comprised of recurrent points and the upper triangle mirrors the lower triangle. Of note are the diagonal lines that occur off the main diagonal, as those reflect speech patterns that recur throughout the course of the experimental session. Each diagonal in a recurrence plot represents a distinct time lag, where the two time series are offset by a single unit (Richardson & Dale, 2005). In Figure 9 the neighboring diagonals are delayed in increments of 1 Hz as they recede from the main diagonal to either the upper left or lower right.

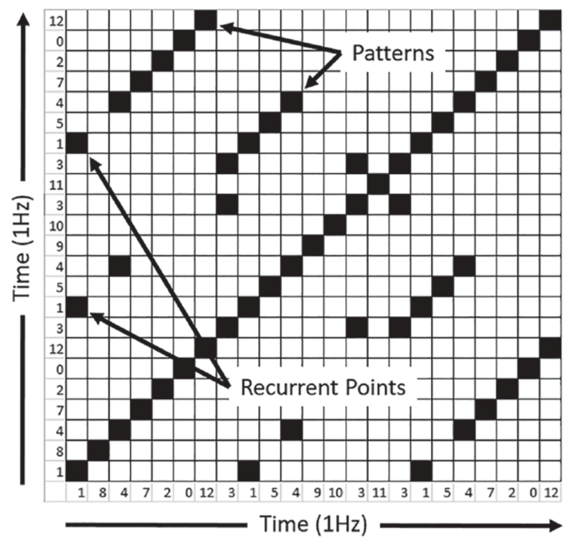


Figure 9 – An example discrete recurrence plot from Gorman et al., 2020. The line along the main diagonal is a product of the time series being plotted against itself. The lines off the main diagonal reflect patterns of coordination (here, speaking order) that are repeated throughout the simulated task.

It is not a requirement of the two time series along the X and Y axes to be identical in a recurrence plot. Alternatively, the recurrence plot could be constructed with two separate streams of data to see how they overlap at different time lags, as was done in the current study, and was the procedure for a 2005 study by Richardson and Dale, previously introduced. In that work, speakers' eye movements were recorded as they described a scene from a common television program (either *Friends* or *The Simpsons*). Participants then listened to the voice recording of a speaker while viewing the same scene as the one being described. Listeners' eye movements were recorded, and the nominal time series created to represent the order of eye fixations was coded to correspond with AOIs within the scene (e.g., Ross, Rachel, Homer, etc.) for both speakers and listeners. Paired speaker-listener dyads had their respective, nominally coded, fixation location time series plotted against each other, which created CRPs, like the example published by Richardson and Dale (2005) and reproduced below in Figure 10. The 'scarf plots' to either side of the CRP depict the recurrence levels of the eye fixations at two different time lags. The scarf plot to the left shows the eye fixation recurrence in real-time (lag of 0 s), whereas the plot to the right shows how more recurrence is present when the listener's fixations are lagged 2 s behind the speaker's fixations.

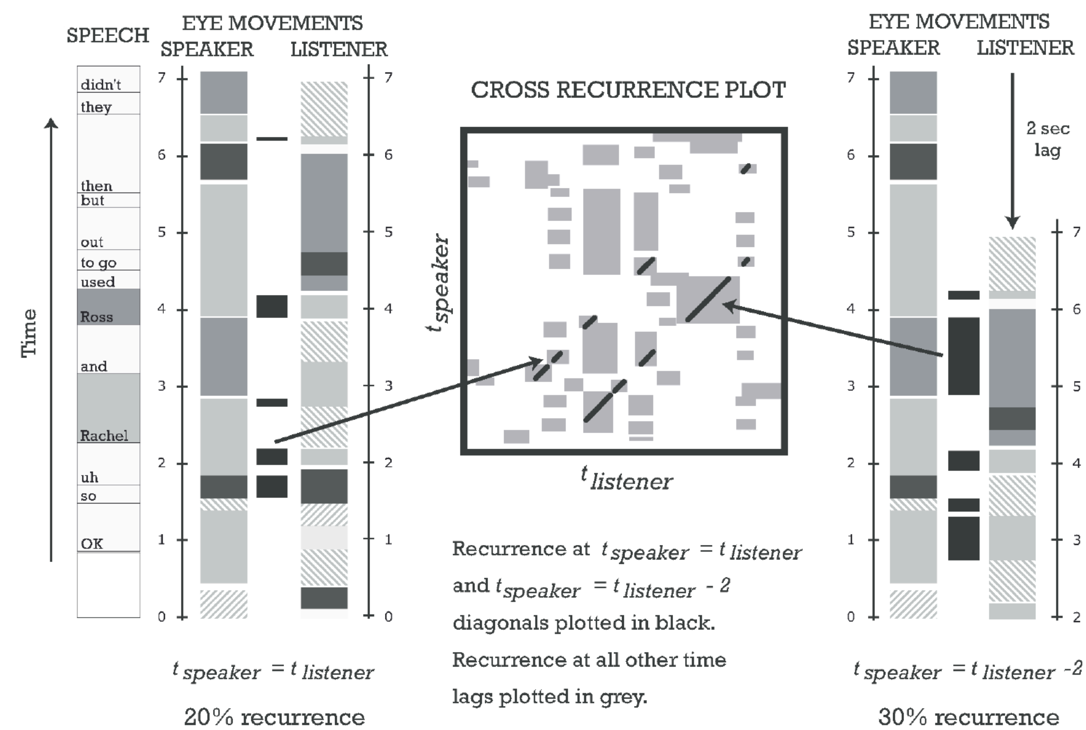


Figure 10 - Visualizations of how a discrete CRP was used to determine characteristic lag in eye movements of speaker-listener pairs in Richardson and Dale (2005).

Similar to the Richardson and Dale (2005) procedure described above, to code the data for the present study, AOIs were mapped onto those collected by Crites (2018) to capture LAFs. Different nominal codes were used here to indicate the different AOIs on the experimental apparatus. An example of the data structure devised by Crites to analyze the two measures of visuomotor coupling in the 2018 study is provided in Figure 11. Here, we can see the timestamp nature of the data, where the time (in seconds) at which the hands and the eyes arrive to and leave an AOI are noted for each of the six subtasks for both the grasper and scissor tools.

Time at which gaze of grasper operator arrives to first AOI.

Time at which hands of grasper operator arrive to first AOI.

A

Grasper	AOI	Object	Object	Pipe_2	Pipe_2	Grey	Grey	Pipe_2	Pipe_2	Cup	Cup	Home	Home
	Eye_Time	0.932	1.915	3.088	4.375	4.394	4.834	5.323	6.098	7.045	8.541	9.207	
	Movement	Start	Stop	Start	Stop	Start	Stop	Start	Stop	Start	Stop	Start	Stop
	Hand_Time	1.175	1.992	2.977	4.133	4.167	4.779	5.935	6.394	6.428	8.043	8.553	9.233
		1	2	3	4	5	6	7	8	9	10	11	12
Scissors	AOI	Pipe_1	Pipe_1	Grey	Grey	Black	Black	Pipe_2	Pipe_2	Pipe_1	Pipe_1	Home	Home
	Eye_Time	1.966	2.833	3.026	3.062	4.853	5.31	5.323	6.098	6.137	6.96	8.53	
	Movement	Start	Stop	Start	Stop	Start	Stop	Start	Stop	Start	Stop	Start	Stop
	Hand_Time	2.088	2.734	2.836	3.771	4.728	5.289	5.306	6.241	6.275	7.363	7.805	8.995

B

Each grasper task broken down by start and stop movements.

Grasper	
Object = Grasp object (1-2)	
	Start: Once the entire hand has left the home key
	Stop: Once fingers completely close on object
Pipe_2 = Insert object through top of the pipe (3-4)	
	Start: Once object begins moving up
	Stop: Once object is occluded by the pipe
Grey = Rest object on grey area of the box (5-6)	
	Start: The next motion frame from previous step
	Stop: Once object first touches grey box and doesn't move
Pipe_2 = Remove object from the pipe (7-8)	
	Start: Once object leaves contact with grey box
	Stop: Once object is successfully out of the pipe
Cup = Return object back to resting position (9-10)	
	Start: Next motion frame from previous step (unless they pause)
	Stop: Object is **about** to be successfully inserted in hole
Home = Return fingers to home key (11-12)	
	Start: Once fingers begin to release grasp on object
	Stop: Once any part of the hand has made contact with the home key

C

Each scissors task broken down by start and stop movements.

Scissors	
Pipe_1 = Grasp pipe (the pipe is located in its starting, first position) (1-2)	
	Start: Once the entire hand has left the home key
	Stop: Once fingers have completely closed around the pipe
Grey = Move pipe over to grey area of box (second position) (3-4)	
	Start: Once movement starts towards the grey area of the box
	Stop: Once the hand seems to arrive at the position
Black = Simulate cutting action (5-6)	
	Start: Once fingers have been removed from the pipe and are no longer grasped around
	Stop: Once fingers are grasping the object
Pipe_2 = Return fingers to pipe (pipe is located at the second position) (7-8)	
	Start: Once fingers start to open/release grasp on object
	Stop: Once fingers completely grasp the pipe
Pipe_1 = Return pipe back to first position (first position) (9-10)	
	Start: Once pipe begins motion towards resting position
	Stop: Once pipe is close to the resting position
Home = Return fingers to home key (11-12)	
	Start: Once fingers have let go of the pipe
	Stop: Once any part of the hand has made contact with the home key

Figure 11 – (A) Data for a bimanual trial representing the time at which both the gaze and hands arrive at AOIs for each of the two tools. (B) The corresponding key for the grasper tool explaining the distinct AOIs and their correspondence to subtasks. (C) The corresponding key for the scissor tool explaining the distinct AOIs and their correspondence to subtasks.

To generate the discrete time series for the present study each of the four visuomotor components (Eye-Grasper, Hand-Grasper, Eye-Scissor, Hand-Scissor), a nominal code was assigned for each AOI—numbered 1 through 6. The four time series are comprised of nominal codes that are associated with times from 0 ms to the stop time associated with the final subtask (e.g., 9233 ms for the grasper of the trial in Figure 11).

The coded time series were denoted with a 0 any time the eyes/hands were *not* in an AOI, and a non-zero number (1-6) when the eyes/hands occupied an AOI. Recurrent points were not counted when both time series expressed a 0—only non-zero matched pairs qualified as recurrent points (e.g., 1-1 or 5-5). Custom MATLAB (MathWorks, 2020) code was used to format the nominal time series in this way. After the creation of the time series, the eye data was plotted against the hand data for each tool (e.g., Eye_Grasper vs. Hand_Grasper) using the *drpfromts* function in the *CRQA* R-package (Coco & Dale, 2012). This resulted in two lag metrics per trial, one for grasper and one for scissors, regardless of whether the trial was conducted under the bimanual or intermanual coordination mode. From each latent CRP assessed through the *drpfromts* function, characteristic lag was determined based on which diagonal in the latent CRP had the highest degree of %REC (Equation 3; Richardson & Dale, 2005). Each diagonal represented a lag unit of 1 ms to retain the sampling rate in the original data.

Figure 12 shows example lag profiles generated using the *drpfromts* function for an Experiment 1 team. Lag values were generated for the two members of the dyad and one of their intermanual trials for both tools. The tallest spike in these graphs, noted with a vertical blue line, marks the maximum lag for that trial. To generate these graphs, a window size of 3,000 +/- was set for each trial, which calculated lag values across 6,000 diagonals of the latent CRP, as the *drpfromts* function does not output an actual CRP. A maximum lag at zero would indicate the gaze and hands were maximally aligned in real time. A negative lag, to the left of the zero marker, indicates the hands were leading the eyes (i.e., the eyes needed to be lagged in order to fall in step with the hands). A positive lag indicates the eyes were leading the hands. As is evident in these graphs, maximum lag tended to be negative, which was in conflict with theoretical expectations, but is in alignment with Crites' (2018) findings. This issue is addressed in detail in the Discussion section.

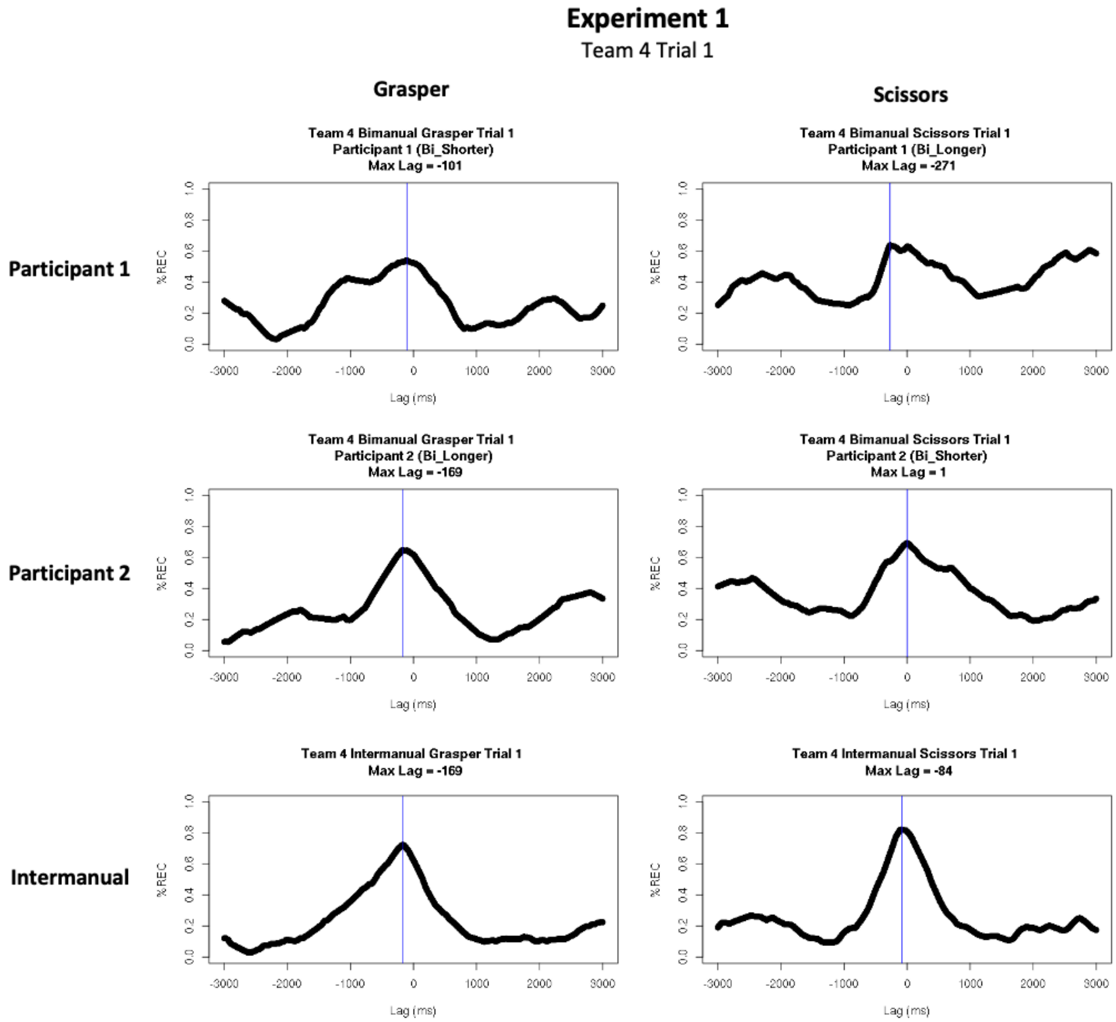
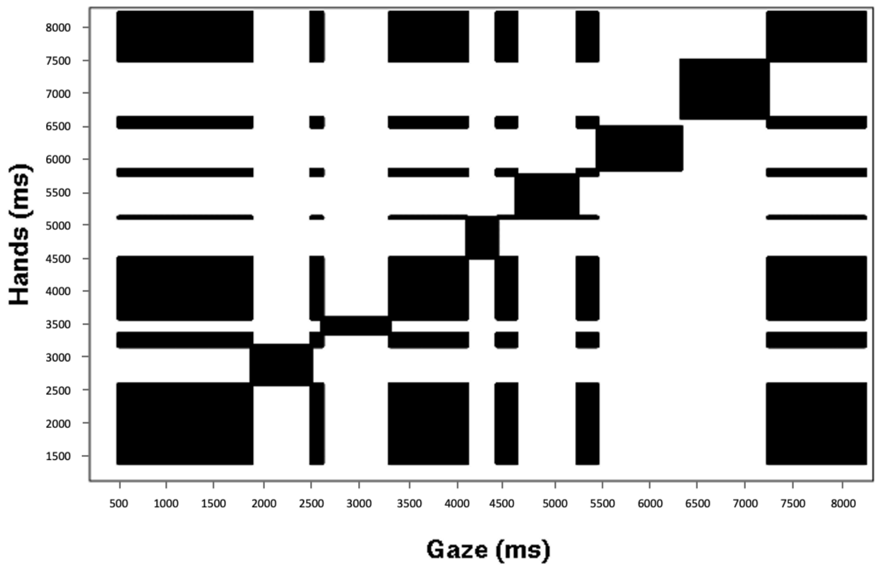


Figure 12 – Lag profiles generated using the *drpfromts* function in the *CRQA* R package (Coco & Dale, 2012). This function was used to calculate maximum lag for the present study. The blue vertical lines indicate maximum lag for each trial. These plots were created for Team 4 of Experiment 1 for each participant and the dyad for both tools.

For every trial this *drpfromts* function generated two characteristic lag values—one for the gaze and hands of the grasper role (Lag_Grasper) and the other for the gaze and hands of the scissor role (Lag_Scissor). Dyads completed the task ten times each, both in the bimanual and intermanual coordination modes, resulting in 30 trials per dyad (ten for both participants in the bimanual condition and ten for the intermanual condition; Crites 2018). Nine out of the 30 trials were assessed for each team in the Crites (2018) study (trial numbers 1, 5 and 10 for both bimanual trials and the intermanual trials), which was adopted for the current study, as well.

Below are example CRPs generated from two of the trials displayed in the lag profile graphs in Figure 13. These were generated using the *plotRP* function in the *CRQA* R package (Coco & Dale, 2012). We see in the intermanual trial, which displayed a very peaked lag profile, that consistent coupling appears only surrounding the main diagonal. For the participant 2 trial, which produced a more jagged lag profile, that large sections of coupling appear both surrounding the main diagonal and further from it.

Experiment 1
Team 4 Trial 1
Intermanual Scissors



Experiment 1
Team 4 Trial 1
Participant 2 Scissors

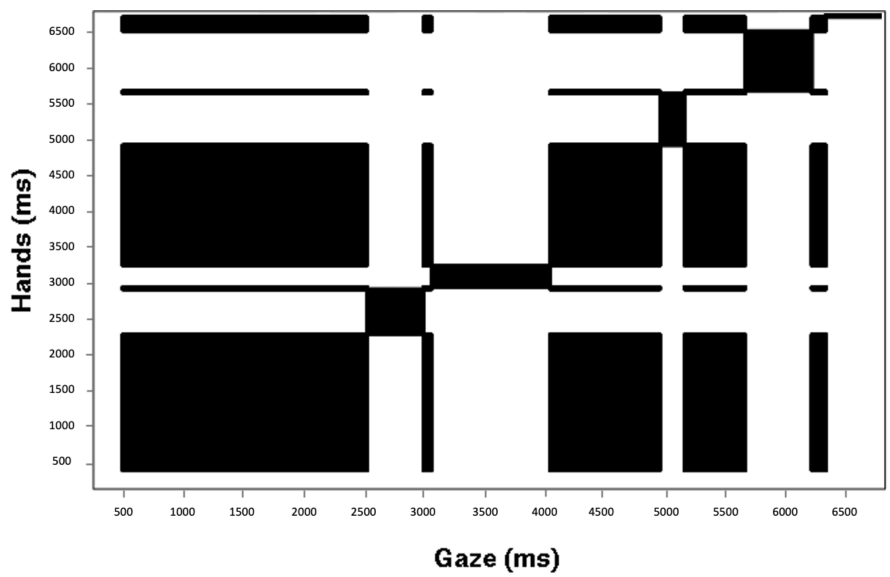


Figure 13 – Two example cross-recurrence plots from an Experiment 1 team. The top plot from the intermanual trial demonstrates a concentration of coupling along and near the main diagonal, while the bottom plot shows more consistent coupling at lags both near and distant form the main diagonal.

CHAPTER 3. RESULTS

3.1 Recovering Missing Data from Crites (2018)

Prior to proceeding with the calculation of lag values, we attempted to recover missing data from the original Crites (2018) datasets. The data missing from the original data sheets was largely due to unexpected patterns of activity within the task environment. Generally, these missing data occurred if the gaze or hands followed an unexpected pattern of movement throughout the task's AOIs. Many times this indicated a decoupling of the two modalities within the task environment (e.g., while the hands were in AOI 2, the gaze shifted to AOI 4). To ensure these patterns of decoupling were reflected in the dataset used in the present study, as they would have a direct impact on lag values, two research assistants blind to the hypotheses of the study reviewed the raw data for trials that had cells with missing time values. These raw data were video files taken from the perspective of the participants' head-mounted, outward-facing, eye-tracking cameras. The pupil was tracked within the scene of the task and AOIs were noted within the software such that AOIs would become shaded in when the pupil occupied that area of the task. To assess the positioning of the hands during task completion, their physical position with regard to the task apparatus was noted.

Specific instructions for each directive followed the coding scheme implemented by Crites (2018), with one exception that attempted to address the missing data. To maintain the original structure of the data, nominal codes were defined to indicate if the eyes or hands were in an unexpected AOI. Again, this was the cause of a majority of the missing data. An example is provided below in Figure 14 that illustrates how nominal codes were assigned when the modalities attended to AOIs in an unexpected pattern. In sum, the tool (indicated by a G or S) and number of the AOI within that tool (a number one through six) preceded the time at which the modality occupied that AOI. This allowed the data to reflect the nature of the decoupling occurring in these formerly empty cells. These were important data to include as they were implicated in the lag metric.

Grasper	AOI	Object	Object	Pipe_2	Pipe_2	Grey	Grey	Pipe_2	Pipe_2	Cup	Cup	Home	Home
	Eye_Time	0.908	1.435	2.251	2.948	2.965	3.39	3.796	4.221	4.459	6.329	6.38	6.805
	Movement	Start	Stop	Start	Stop	Start	Stop	Start	Stop	Start	Stop	Start	Stop
	Hand_Time	1.316	1.724	1.979	2.744	2.795	3.254	3.949	4.136	4.187	6.091	6.193	6.652
		1	2	3	4	5	6	7	8	9	10	11	12
Scissors	AOI	Pipe_1	Pipe_1	Box	Box	Black	Black	Pipe_2	Pipe_2	Pipe_1	Pipe_1	Home	Home
	Eye_Time	1.503	1.911	2.115	2.234	3.407	3.779	3.796	4.221	G7: 3.796	G8: 4.221	6.958	7.213
	Movement	Start	Stop	Start	Stop	Start	Stop	Start	Stop	Start	Stop	Start	Stop
	Hand_Time	1.418	1.979	2.013	2.659	3.356	3.611	3.711	3.949	4.017	4.578	4.765	5.343

Figure 14 – Example of how unexpected patterns of movement were denoted in the review of missing data. Here, we see the gaze attend to the Grasper Pipe_2 AOI instead of attending to the Scissor Pipe_1 AOI. The numbers that follow G7 (Grasper 7) and G8 (Grasper 8)

The two research assistants were blind to the hypotheses and randomly assigned to review selected trails. They were first introduced to the instructions and code book, then coded the trials of the first team together to ensure they were using roughly the same criteria for noting the times in each AOI. Both research assistants reviewed 20% of the trials to allow for a calculation of inter-rater agreement. It is worth noting that the nature of these formerly missing data were inherently more ambiguous than cells that had been identified by the Crites (2018) research group. Thus, there is likely more interrater variability in these cells than in the data wherein the modalities followed their expected patterns, though Crites (2018) did not report interrater reliability metrics.

Out of the trials that two research assistants both independently coded, there were 107 cells in the data sheets with missing values. Out of these 107 cells, both RAs reported numerical values for 92 of them. The remaining 15 cells had numerical values reported by only one research assistant, wherein the other noted the modality never visited that AOI or both research assistants reported the modality never visited that AOI. To assess interrater reliability of the 92 cells with numerical data, an interclass correlation coefficient was calculated. To calculate this value, any nominal codes reported by the researchers were ignored (the agreement of the nominal codes is discussed below). The ICC estimate was calculated using SPSS (IMB Corp., 2017) based on mean-rating (k = 2), absolute-agreement and a one-way random effect model (Koo & Li, 2016). A high degree of reliability was found between the two coders by this metric, $ICC = 0.99$, $F(91, 92) = 125.26$, $p < .001$. To reconcile discrepancies with the numerical data, the average discrepancy was first calculated across the data set. Any pair of data points that fell above the average discrepancy was reviewed by a third reviewer who made a final decision after reassessing the raw data (i.e., the video files). For those cells that differed less than average, their average was taken and served as the final data point for that cell.

To assess the interrater reliability of the nominal codes (e.g., G8) for the dataset, Cohen's Kappa was calculated using SPSS (IBM Corp., 2017). Fourteen data points were excluded from the Kappa calculation, as one of the research assistants applied a wider array of nominal codes to their data than the other. Thus, the included data points were comprised of those associated with nominal codes both of the research assistants applied to their sets of data. A stand-in nominal code of "*no decoupling noted"* was applied to the cells where no nominal code was applied (i.e., when the research assistants reported that the modalities followed their predicted trajectory through the task environment). There was moderate-to-strong agreement between the two raters' judgements, $\kappa = .795$, $p < .001$. To reconcile discrepancies with the nominal codes, a third rater reviewed the videos (the raw data) to assess which rater was more accurate.

3.2 Correlations between the Grasper and Scissor Lag Values

To understand if it was appropriate to average the lag values of the two tools for each trial and, thus, include them in a single analysis, a Pearson's *r* correlation was assessed for both the Experiment 1 (Unpracticed) and Experiment 2 (Practiced) datasets. If the lag value of the two tools were significantly correlated ($p < .05$), the two tools would have been averaged in all subsequent analyses. However, the tools were not significantly correlated (Experiment 1: $r = -0.08$, $p = 0.40$; Experiment 2: $r = 0.24$, $p = 0.11$) and thus analyses proceeded separately for the grasper values and the scissors values across the two experiments.

3.3 ANOVAs

As mentioned in the Experimental Design section, the lag values associated with the two bimanual trials, wherein the participants comprise the associated intermanual trial, were organized such that the participant with the shorter average lag value was denoted as Bi_Shorter. The participant with the longer average lag value was denoted as Bi_Longer. Intermanual lag values were denoted as INTER. This resulted in three levels of Visuomotor Lag: Bi_Shorter, Bi_Longer and INTER.

Lag values from the Unpracticed (Experiment 1) and Practiced (Experiment 2) trials remained separate across all analyses. However, the same planned comparisons were run on the three levels of Visuomotor Lag for the Practiced and Unpracticed trials to address Hypotheses 1 and 2, respectively. Recall here that Practiced refers to previous *bimanual* practice. Data from Unpracticed trials correspond with Crites' (2018) Experiment 1, and data from Practiced trials correspond with Day 3 of Experiment 2. Four one-way, between-subjects ANOVAs were run on data from the Unpracticed and Practiced trials, with Scissor and Grasper analyses kept separate, to determine if there was a difference in lag values across the three levels of Visuomotor Lag (Bi_Shorter, Bi_Longer, INTER) within each practice condition and tool. A between-subjects design was chosen since there were different participants at each level of the Visuomotor Lag variable. Though there is some overlap in within-subject variance between the individual bimanual conditions and the intermanual condition, there is no overlap in variance between the two bimanual conditions thus a between-subjects design was selected. Planned comparisons to assess both hypotheses evaluate the difference between Bi_Shorter and INTER, and Bi_Longer and INTER.

3.3.1 Data Excluded from ANOVAs

3.3.1.1 Outliers

Outliers, which were defined to be 3 standard deviations above or below the mean, were determined for each experiment separately, as ANOVAs were conducted separately for the two data sets. In Experiment 1, two values (one from the Grasper tool and one from the Scissor tool) fit this criteria and were removed from analysis. For Experiment 2, two Grasper values were excluded and one Scissor value was excluded due to their extreme values. Outliers were a result of trials that were either relatively long in length or missing data in the AOI data sheets due to eye-tracker calibration issues.

3.3.1.2 Eye Tracker Calibration Issues

After revisiting the raw, video data, missing data still persisted due to eye tracker calibration issues. For select trials from Teams 2 and 3 in Experiment 1, data could not be recovered for the eye data streams. This resulted in seven lag values that could not be calculated—two from Team 2 and five from Team 3.

Related to the larger equipment failure reported by Crites (2018) that effected the Experiment 2 sample size, Team 1 was excluded from the Experiment 2 analysis, as previously mentioned.

3.3.1.3 Final Data Points

With the removal of outliers and missing or incomplete data for the Experiment 1 trials, the final data set included 103 Grasper lag values and 104 Scissor lag values, for a total of 207 data points out of the possible 216. For the five teams in Experiment 2, a total of 87 data points (43 Grasper values; 44 Scissor values) were included out of the original 90 lag values once the three outliers were removed.

With this final set of data each bimanual participant was sorted into either the Bi_Shorter or Bi-Longer condition of the Visuomotor Coupling variable. This was determined through a comparison of the average lag value for each participant when they completed the trials bimanually. The participant with the shorter average lag value, in absolute value if the lags were in opposing directions, was assigned to the Bi_Shorter condition. The participant with the longer average lag value was assigned to the Bi_Longer condition.

3.3.2 ANOVA Results

Four separate between subjects one-way ANOVAs were run on the Visuomotor Coupling variable, which had three levels: Bi_Shorter, Bi_Longer, and INTER. One analysis for each of the two tools was conducted for the two experiments.

3.3.2.1 Experiment 1

For the analysis of the Grasper lag values in Experiment 1 there was a significant effect, $F(2, 100) = 8.09$, $p = .001$, $\eta^2 = 0.14$. Results from planned comparisons show the Bi_Shorter condition ($M = -120.42$, $SD = 84.47$) was significantly shorter than the INTER condition ($M = -206.68$, $SD = 115.76$), which was in agreement with predictions that Bi_Shorter would have a shorter lag than the INTER condition, $p = 0.001$. Bi_Longer was also predicted to have a shorter lag than the INTER condition, however, the Bi_Longer ($M = -214.09$, $SD = 122.94$) and INTER conditions did not significantly differ, $p = 0.78$. Though not implicated in the hypotheses, the Bi_Shorter and Bi_Longer conditions also significantly differed, $p = 0.001$.

For the Scissor values, there was not a significant effect, $F(2, 101) = 2.90$, $p = 0.06$, $\eta^2 = 0.05$. See Figure 15 for the pattern of results from Experiment 1 from both tools.

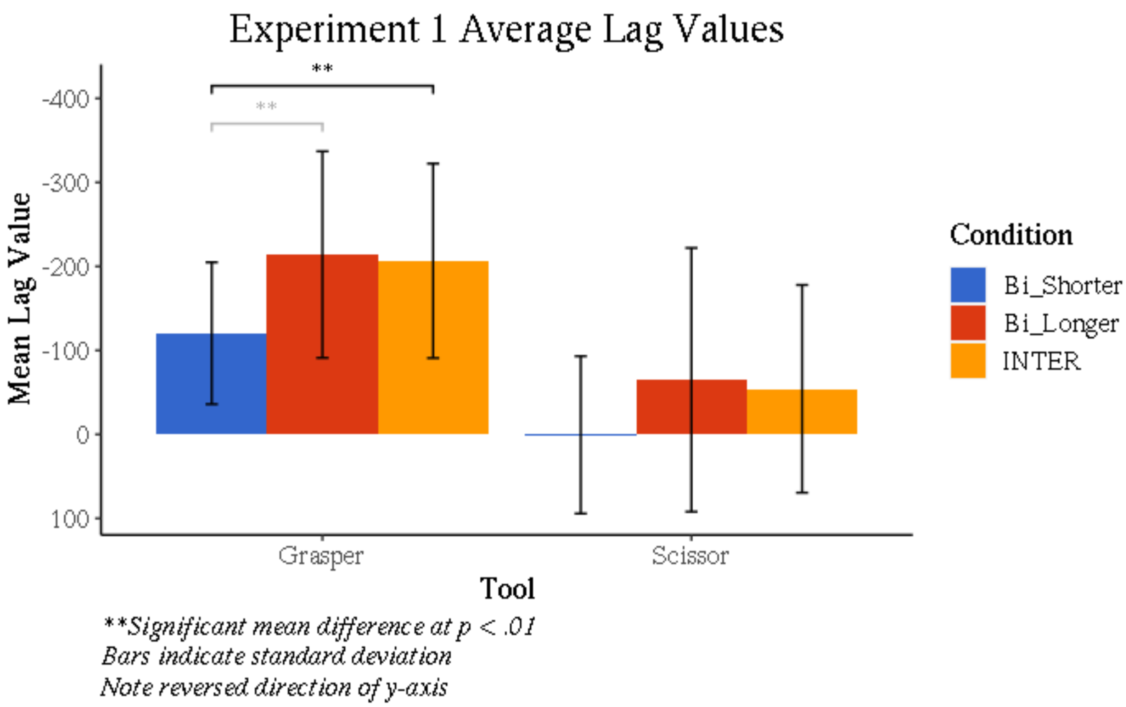


Figure 15 – Results from Experiment 1 ANOVA.

3.3.2.2 <u>Experiment 2</u>

For the analysis of the Grasper lag value in Experiment 2, there was a significant effect, $F(2, 40) = 5.37$, $p = 0.01$, $\eta^2 = 0.21$. The lag values of the Bi_Longer condition (M = -165.36, SD = 58.58) were significantly longer than the INTER condition (M = -95.21, SD = 90.95), which contradicted the hypothesis that the Bi_Longer and INTER conditions would not differ, $p = 0.02$. The Bi_Shorter condition (M = -72.67, SD = 85.40) did not significantly differ from the INTER condition, which contradicted the prediction that the lag of the INTER condition would be longer than the Bi_Shorter lag, $p = 0.51$. Though not implicated in the hypotheses, the Bi_Shorter and Bi_Longer conditions also significantly differed, $p = 0.003$.

For the analysis of the Scissor lag value in Experiment 2, there was a not significant effect, $F(2, 41) = 2.286$, $p = 0.12$, $\eta^2 = 0.10$. See Figure 16 for the pattern of results from Experiment 2 from both tools.

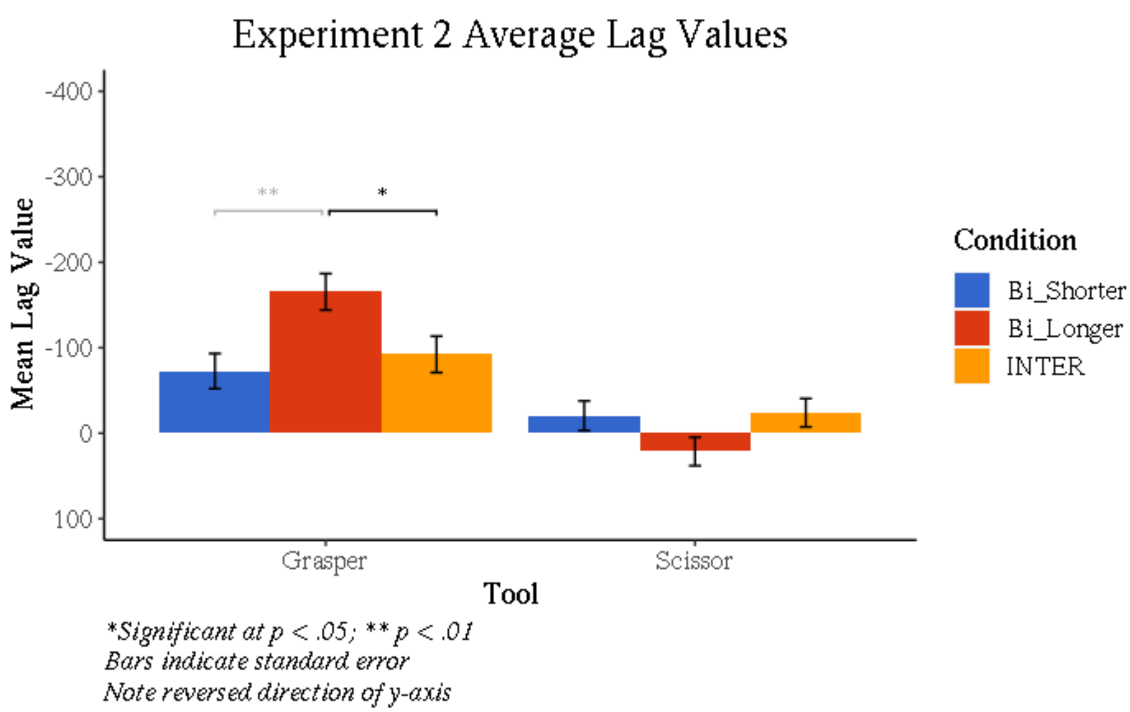


Figure 16 – Results from Experiment 2 ANOVA.

CHAPTER 4. DISCUSSION

4.1 Summary of Results

The emergence hypothesis associated with the Experiment 1 data, proposed that the lag values found in the intermanual trials would be longer than the lag values of both of the bimanual conditions. This pattern of results was to suggest a further decoupling in the intermanual condition, wherein the eyes and hands moved relatively independently of each other. These predictions were partially supported by the Experiment 1 findings. Though the intermanual condition did not statistically differ from the Bi_Longer condition, the Bi_Shorter condition was significantly shorter than the INTER condition for the Grasper trails. There were no significant findings in the Scissor trials due to high variability of the lag values associated with this tool; however, the pattern of means for each coupling condition was consistent with the Grasper results.

The entrainment hypothesis associated with the Experiment 2 data proposed that the lag values found in the intermanual trials would be longer than the Bi_Shorter condition but not differ with the Bi_Longer condition. This hypothesis was to suggest entrainment of the coordination pattern of the dyad to that of the more uncoupled partner. These results were not supported by the data. Instead, the pattern of results suggests the dyad entrained to the coordination pattern of the more coupled partner (i.e., the partner with the shorter bimanual coupling lag). Like in Experiment 1, these results were only statistically significant for the Grasper trials.

These results can be better understood as two different entrainment patterns. For Experiment 1, we see the dyad entrain to the more decoupled partner—the intermanual trials have a similar lag to the Bi_Longer trials. This finding provides further support for how coupling underlies the intermanual speed advantage, such that more *de*coupling (i.e., longer lag values) in the intermanual coordination mode with unpracticed dyads is associated with faster performance when compared to bimanual execution of a task (Crites, 2018). These results suggest that one mechanism for establishing a less coupled pattern of task execution in the intermanual coordination mode is for the dyad to assume the previously established visuomotor coordination pattern of the more uncoupled partner.

In Experiment 2 we also see entrainment, however here, the dyad entrains to the more coupled partner, where the intermanual lag values are similar to the Bi_Shorter trials. These findings are consistent with the erasure or reversal of the intermanual speed advantage in practiced dyads (Crites 2018; Gorman & Crites, 2015). These results suggests that there is tighter visuomotor coupling in intermanual trials for practiced dyads compared to unpracticed dyads. This provides further support for how coupling underlies speed in manual tasks, such that more coupling impedes performance. In the present study, we see more coupling in the intermanual trials of practiced dyads, which prevents the dyad's performance from winning out over individual performance.

In comparing lag values across the two experiments, we see more coupling overall (i.e., shorter lag values) in Experiment 2, despite faster trial times (Crites, 2018). This finding is reflected in Crites' results regarding LAFs. He observed that the hands and gaze could proceed closer in step after the task had been practiced with no cost to speed. The task had been so well practiced that actors required less input from the gaze to coordinate manual action (Crites, 2018). This is similarly observed in the results of the present study where the two modalities are more coupled in Experiment 2 results, but speed of execution is still superior to Experiment 1 trials times. As is shown in the Grasper values for the two experiments in Figure 17, we see that shorter lag values are indicative of shorter coupling.

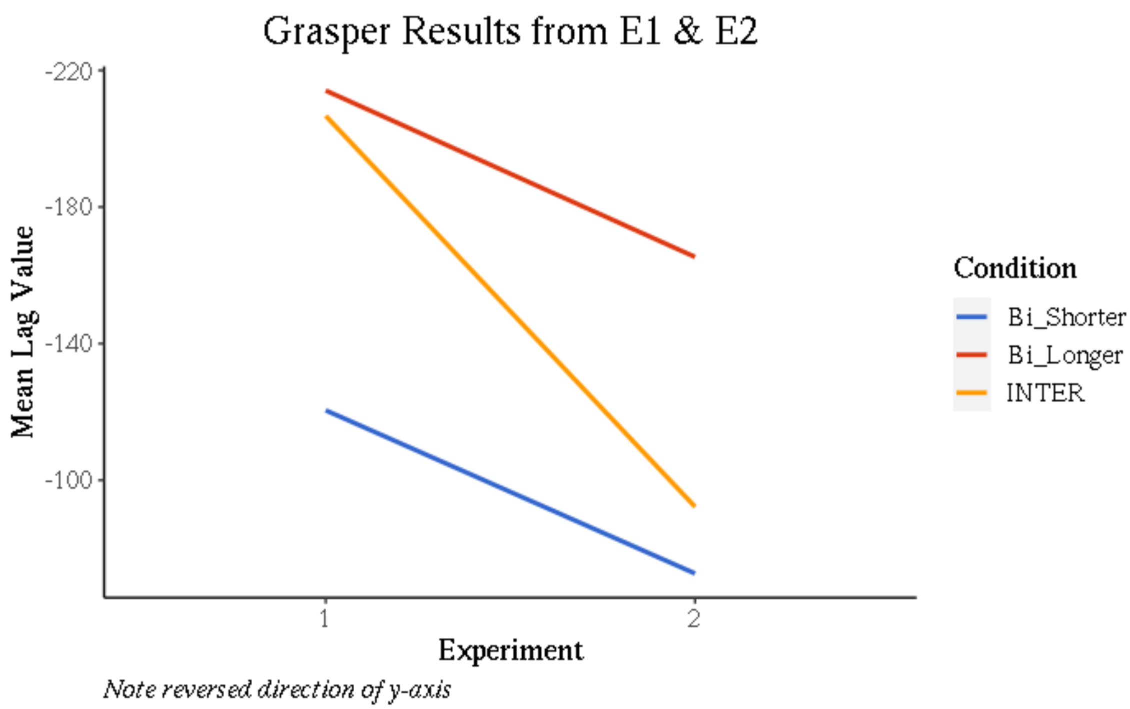


Figure 17 - Grasper lag values across the two experiments indicate coupling tightens with practice. This result was also reported in Crites (2018).

4.2 Lag Observed in Unexpected Direction

Past work in the visuomotor coordination literature has found that a saccade typically precedes a goal-directed manual movement (Hayoe et al., 2003; Land et al., 1999; Land & Furneaux, 1997; Mennie et al., 2007). Thus, the direction of the lag found in the present study was presumed to confirm this finding such that the gaze preceded the hands in entering and leaving an AOI. This result was not found in the present study. Instead, we see average lag values in a negative direction, which indicates that the hands tended to lead the eyes. This is presumed to be a product of the discrete nature of the data structure. Had both data streams been continuously sampled, lag values may have been in the theoretically plausible direction.

Though the on-average negative lag values are in conflict with theoretical predictions, they align with Crites (2018) findings regarding LAFs and GAFs, for which calculations relied on the same data used in the present study. Though Crites' interpretation focused on mean comparisons across experiments and coordination modes, his results suggest the hands led the eyes, such that LAF and GAF values tended to be positive. Equations 1 and 2 show that the times at which the hands were in an AOI were subtracted from the times at which the eyes were in that same AOI. Since these values tended to be positive in Crites' findings, it is evident that—through this operationalization—the hands were ahead of the eyes. Since the hands had smaller/faster time values than the eye times, LAFs and GAFs were positive on average. Again, this may be a product of the discrete nature of the data used for both studies, and future research is needed to determine this issue.

With the exception of eight data points, all of the lag values associated with the Grasper tool were in the negative direction, where the hands led the eyes. However, there was substantially more variability in the direction of the lag of Scissor tool. Though a majority of the lag values were negative, roughly 40% of the trials produced lag values where the eyes led the hands. This variability between the tools suggests that visuomotor coupling lag behavior may be task dependent. In the cutting task explored in the present study, the actions of the Scissor tool, generally had to follow those taken by the partner operating the Grasper tool. This type of following behavior may be the source of the higher degree of variability in the lag values of the Scissor tool.

To better understand how the direction of the lag values were influencing the mean differences reported in the present study, analyses on the absolute values of the lag metric were conducted. Generally the results using absolute lag values held from what was reported in the Results section, with one exception. In Experiment 2, with the transformation of lag values to their absolute values, mean differences were found between the Bi_Longer and INTER conditions and the Bi_Shorter and Bi_Longer conditions for the Scissor tool. This is the pattern of results observed in the Grasper tool for Experiment 2. This suggests that the variability in the direction of Scissor lag values hindered the detection of significant effects only marginally for the Scissor tool. This was to be expected, as the Grasper tool had a reasonably homogenous lag direction, thus was impacted little by an absolute value transformation.

4.3 Strengths, Limitations and Future Directions

The present study adopted a novel approach to operationalizing visuomotor coordination. Past work has employed the lag metric to assess gaze patterns (Richardson & Dale, 2005), facial expressions, and communication patterns of interlocutors (Louwerse et al., 2012), but those analyses did not investigate cross-modality effects. The present study extends the application of the lag metric to assess entrainment between dyads in visuomotor coordination. This work also extends the interpersonal motor coordination literature, which historically has been assessed in simple coupled oscillator tasks (e.g., Fine & Amazeen, 2011).

To address the limitations in this work, specifically regarding the discrete nature of the data, future studies should rely on continuous data streams to model the two modalities. This would require equivalent sampling rates to be taken from eye tracking devises and motion capture cameras. The synchronization of physiological and movement sensors such as these is an ongoing challenge in psychological research, though emerging technologies may make continuously sampled data more amenable to coordinate across streams (e.g., The Observer XT). We believe the discrete nature of the data in the present study is responsible for the unpredicted direction of visuomotor coupling lag, where the hands were shown to lead the eyes. Future work with continuous data could be done to confirm or deny this prediction.

This work may also benefit from a multilevel statistical analysis, as opposed to traditional analysis of variance. Due to the dependencies in the data points, such that lag values are nested within tools, tools are nested within participants, participants within dyads, and dyads within teams, the independence assumption of the current analysis was likely violated. Thus, future work should structure data into the framework of a multilevel modelling analysis. This type of multilevel analysis was beyond the scope of my training at the time this work was proposed, but future publications associated with this work will assess results with regard to the nested structure of the data. Though there is some concern over the dependence in these data, *p*-values were relatively small suggesting the chance of making a Type I error was low.

4.4 Conclusion

The present study extends the interpersonal coordination literature, such that entrainment behavior in intermanual visuomotor coupling lag is dependent on previous bimanual practice. The erasure of the intermanual speed advantage in well-practiced dyads appears to be, in part, the result of the dyad assuming the visuomotor coordination pattern of the more coupled member of the dyad. This places a ceiling on how quickly they are able to perform the task, as less simultaneous goal-directed movements are able to be made as the level of coupling increases (Crites, 2018). In unpracticed dyads, the visuomotor coordination pattern of the team entrains to the more decoupled partner, thus allowing the dyad to make more simultaneous movements than the individual members on average and, ultimately, complete the task faster as a team.

Though this pattern of results diverges from hypothesized results, findings are consistent with previous coordination patterns reported in the literature, wherein coupled dyads have been shown to entrain coordination between partners, though entrainment is generally only observed in experienced teams (Cites, 2018; Reed et al., 2006; Zheng et al., 2005). A novel finding of the present study is that entrainment is present in novice teams, as well, as was seen in the visuomotor coupling lag metric.

Ultimately, this work adds to our understanding of how novices versus experienced operators interact within a manual task, and how that interaction is influenced by the addition of a partner. Results may implicate entrainment training paradigms used for such domains as laparoscopic surgery and teleoperation, wherein the work environments frequently require intermanual coordination (Crites, 2018). These results suggest that characteristic lag accounts for differences between novice and experienced actors collaborating intermanually in such fields.

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