Bimanual Coupling and the Intermanual Speed Advantage

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This study investigated previously observed differences in speed when completing a two-handed task either *bimanually* (i.e., the normal, two-handed mode) or *intermanually* (i.e., when such tasks are performed with different peoples' hands). When comparing these two manual "coordination modes," a phenomena referred to as the intermanual speed advantage has been observed. While various research domains have reported the intermanual speed advantage (i.e., a "mode effect"), recent research suggests that the observed difference in performance may depend on fundamental bimanual limitations that are not observed when using the intermanual coordination mode. To investigate the intermanual speed advantage, a task was constructed to exploit a hypothesized bimanual limitation that may underlie this mode effect: bimanual coupling. Results showed a replication of the intermanual speed advantage and higher between-hand coupling during bimanual performance. Subsequent analyses suggests that speed during two-handed tasks may be facilitated by decoupled movement of the limbs, regardless of coordination mode.

INTRODUCTION

Whether it's making a cup of tea or tying your shoelaces, manual coordination requires internal and external cooperation and coordination (Land & Tatler, 2009). Interestingly, some two-handed tasks are faster when working with a partner when compared to completing the task alone (Glynn & Henning, 2000; Gorman & Crites, 2013; Reed et al., 2006; Wegner & Zeaman, 1956; Zheng, Verjee, Lomax, & MacKenzie, 2005). When completing a two-handed task alone, it is commonly referred to as bimanual coordination (Kelso, 1995). An interpersonal alternative to the bimanual coordination mode is the intermanual coordination mode, which refers to the situation when two people work together to complete a two-handed task, where each person uses only one hand (Gorman & Crites, 2013, 2015). In the strict sense of the term, the intermanual coordination mode requires one person to only use their left hand and one person to only use their right hand (effectively splitting the standard bimanual coordination mode across two visuomotor systems), but in some instances only the dominant hand of each contributing effector has been used (e.g., Zheng et al., 2005).

These differences in performance comparing coordination modes will be referred to as "mode effects." A mode effect may be classified as when any coordination mode (e.g., intermanual) outperforms another coordination mode (e.g., bimanual) when completing the same task (e.g., teleoperation) while using the same measure (e.g., speed) for comparison (Gorman & Crites, 2013). Most of the research investigating mode effects involved a direct comparison of the bimanual and intermanual coordination modes. In these settings, one particular finding has consistently been observed: The Intermanual Speed Advantage. The intermanual speed advantage is the term used for when a two-handed task is performed faster when using the intermanual coordination mode compared to the bimanual coordination mode (i.e., an intermanual mode effect of speed). The intermanual speed advantage has been observed across a variety of task situations: a laparoscopic cutting task (Zheng et al., 2005); teleoperation tasks (Glynn & Henning, 2000; Gorman & Crites, 2013); and pursuit-rotor tasks (Reed et al., 2006; Wegner & Zeaman, 1956).

What underlies the intermanual speed advantage? Zheng and colleagues (2005) posited that participants depend on shared task knowledge in the form of a "shared mental model" (SMM; Cannon-Bowers, Salas, and Converse, 1993). Specifically, they argued that shared task knowledge may lead participants to develop expectancies about where their hand and their partner's hand should be on a moment-to-moment basis, such that participants are able to anticipate their partner's movements and complete the task faster (Zheng et al., 2005). In order to assess this anticipatory movement hypothesis, Zheng, Swanström, and Mackenzie (2007) reanalyzed data from their original study and, indeed, found that more anticipatory movements were made during the intermanual condition than the bimanual condition.

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

The aim of this experiment was to understand what underlies the intermanual speed advantage from a more *fundamental* level, *behaviorally*. When compared to intermanual coordination, there are certain aspects of bimanual coordination that may impede task performance, speed in particular. Specifically, it seems that one contributing factor that may underlie the intermanual speed advantage is bimanual coupling.

Bimanual Coupling

Bimanual coupling will be defined as the lack of spatial and temporal independence of the hands during an individual two-handed task. Bimanual coupling will be described using an example of grasping two cups. If you pretend there are two cups in front of you at separate distances (one closer and one further away) and you were to complete two separate unimanual (one-handed) grasping tasks, then you would probably conclude that it would take you less time to grasp the cup that is closer to you than the cup that is further from you (Figure 1). However, if you attempt this task bimanually (i.e., complete these two separate unimanual actions simultaneously), then research shows that you would most likely grasp the objects at approximately the same time (e.g., Kelso et al., 1979).

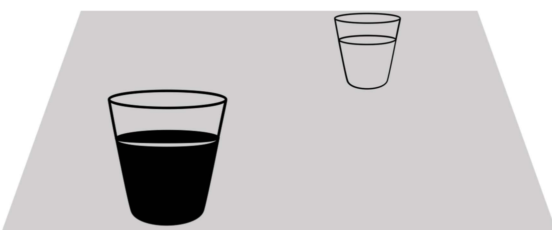

Figure 1. Two cups placed on a desk at separate distances. Unimanually, grasping the further cup should take longer than grasping the closer cup. When completing the task bimanually, the time it takes to simultaneously grasp both cups is approximately the same.

Bimanual coupling has been reported to happen temporally (Kelso, 1995) and spatially (Franz, 1997). The cup exercise is an example of temporal bimanual coupling. Spatial bimanual coupling occurs when simultaneous, incongruent movement during a bimanual task results in a higher degree of movement variability when compared to completing the task unimanually (Franz 1997). For example, simultaneously drawing a square with one hand and a circle with the other hand will cause performance of each component task to suffer (Semjen, Summers, & Cattaert, 1995).

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

Interestingly, using the intermanual coordination mode to complete two-handed tasks may be one way to circumvent the negative aspects of bimanual coupling. This is because the intermanual coordination mode does not have the same internal neural/physiological linkages present during bimanual coordination. However, the same intrapersonal temporal and spatial coupling are also observed interpersonally (Fine & Amazeen, 2011; Jung, Hollander, Muller, & Prinz, 2011), but this effect goes away with the removal of mutual visual information (i.e., not having to attend to the other hand) (Gipson et al., 2016). One of the specific measurement techniques used to assess coupling will be described below, under Measures.

The Current Study

The purpose of this experiment was to investigate the intermanual speed advantage by directly measuring both speed and bimanual coupling. As previously mentioned, bimanual coupling may negatively impact bimanual performance as measured by speed. To investigate this, a task has been constructed to exploit bimanual coupling during a two-handed task.

METHOD

Participants

Twenty undergraduates (10 dyads) from Georgia Tech participated for partial course credit. Participants' mean age was $M = 20.05$ ($SD = 1.47$), and 55% were female. Two of the dyads were all male, three were all female, and five were mixed gender. All participants were required to be right-handed.

Experimental Design

To address the question of mode effects, a within-subjects variable, Mode, was manipulated with two levels: Bimanual (Bi) and Intermanual (Inter). During the Bi condition, participants individually completed the task using two hands (i.e., bimanually). During the Inter condition, participants completed the task as a dyad, where each participant used only one hand (one participant only used their left hand and the other participant only used their right hand). In order to assess for possible practice across coordination modes (i.e., counterbalance) and control for possible transfer effects (i.e., mode switching), a between-subjects variable, Order, was manipulated with two levels: Bimanual-to-Intermanual (Bi → Inter) and Intermanual-to-Bimanual (Inter → Bi). During the Bi → Inter condition, participants first completed the task bimanually and then completed the task intermanually. During the Inter → Bi condition, participants first completed the task intermanually and then completed the task bimanually. Participants completed 10 trials for each level of Mode. The precise number of 10 trials was used so participants would not reach learning/performance plateau or asymptote, which was based on the number of trials required to reach a performance asymptote during pilot testing.

Apparatus

An apparatus was constructed to meet the needs of the task (Figure 2). Participants completed the task in a motion capture room. A ten-camera Vicon Vantage 5 motion capture system captured participants' movements (100Hz) as they completed the task. Data was collected from reflective markers attached to flexible rubber rings, which participants wore on their index fingers.

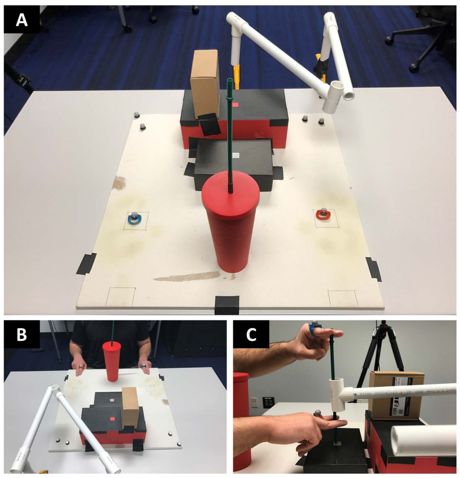

Figure 2. (A) The apparatus from the participant's view. (B) An example of a participant in the Bi condition. (C) An example of a participant completing the simulated cutting action during the Bi condition.

Measures

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

Coupling. In order to assess between-hand coupling, Cross Recurrence Quantification (CRQ) analysis was conducted on the movement data. CRQ is a method for assessing nonlinear coupling between the hands (Shockley, 2005). CRQ analysis proceeds by first constructing a Cross Recurrence Plot (CRP). A CRP is a graphical representation of the times at which two dynamical systems are in the same state by plotting a dot whenever those systems inhabit the same location of a shared phase space. Time series generated by each system are first plotted in a shared phase space, and a dot is plotted in the CRP for all pair-wise combinations (similar to plotting points on the x-axis and y-axis to plot a line) of points in the shared space that are sufficiently close within a threshold (i.e., a radius). The plotted points are called recurrent points, and the amount and relative spacing of recurrent points in the CRP allow us to assess dynamic coupling between the two systems (hands).

Following standard CRQ approaches, the movement time series generated by participants' hands during task performance was plotted on a CRP to quantify coupling in terms of percent recurrence (%REC) (Shockley, Butwill, Zbilut, & Webber, 2002). %REC is the number of recurrent points divided by the possible number of recurrent points in a CRP, and it quantifies the degree to which two systems are coupled.

Task Overview

An overview of the task is shown in Figure 3. During this simulated cutting task, participants pretend that their left hand is a grasper and their right hand is a pair of scissors. Fingers were selected in lieu of tools to avoid the additional bimanual interference that occurs during compatible and incompatible tool transformations (Massen & Sattler, 2010). This provides a more direct evaluation of the manual coordination modes without the requirement for intermediary equipment. Additionally, constructing the task in this way allows for a comparison to previous research (e.g., Zheng et al., 2005) without the actual equipment to show that the results are a property of the motor system and cannot be attributed to the equipment.

Participants were asked to move a pipe to a particular area, place an object through the pipe, rest the object on a particular area on a box, simulate a cutting action at a particular place on the object, and then return the pipe/object to their original positions (Figure 3). Nearly all two-handed motions during this task were designed to exploit both temporal and spatial bimanual coupling.

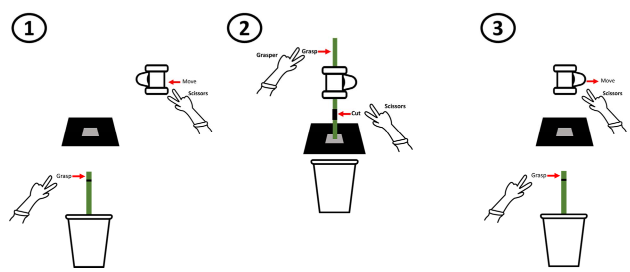

Figure 3. Participants were asked to move a pipe to a particular area, place an object through the pipe, and simulate a cutting action at a particular place on the object.

Procedure

At the beginning of the experimental session, informed consent was obtained. Participants were then shown the apparatus and were given a general overview of the two coordination modes in which they would be completing the task. Depending on the order of conditions, participants either completed the first set of trials bimanually or intermanually. At times when one participant was completing the task for the

Bi condition, the other participant was in a separate room completing questionnaires (e.g., demographics). Note that participants were not allowed to talk to each other before, during, or between trials.

Participants were instructed to “complete the task as quickly and accurately as possible,” which “means to complete the task as fast as possible and while still accurately completing the task.” Prior to each trial, participants were instructed to place the marker rings on their index fingers and to put their hands in the “ready position” with their fingers “as still and as flat as possible” on the home keys. Once participants indicated they were read to complete a trial, the experimenter started the motion-capture data collection and indicated that the subjects should begin upon hearing the “Go” signal from the experimenter. Upon completing each trial, participants indicated they were finished by saying “Done” when both hands were back in a flat position over the home keys; at this time, the experimenter stopped the motion-capture data for that trial. For the Inter condition, one participant was instructed to sit on the right side of the apparatus and to complete the task with his or her right-hand, and the other participant was instructed to sit on the left side of the apparatus and to complete the task with his or her left-hand. Prior to the start of Bi trials and Inter trials, participants performed a practice trial to indicate that they knew how to complete the task (i.e., they demonstrated that they knew how to accurately complete the task for each level of Mode). All assignments of Mode, Order, and role during the Inter condition were randomized.

RESULTS

Speed

The omnibus Mode × Order interaction was not significant, $F(1, 8) = .11$, $p = .752$, $\eta^2 = .01$. However, the main effect of Mode was significant, $F(1, 8) = 42.90$, $p < .001$, $\eta^2 = .84$. Overall, participants were significantly slower when using the Bi Mode ($M = 7.70$; $SD = 1.14$) compared to the Inter Mode ($M = 6.07$; $SD = .98$), which is shown in Figure 4. The main effect of Order was not significant, $F(1, 8) = .84$, $p = .386$, $\eta^2 = .10$.

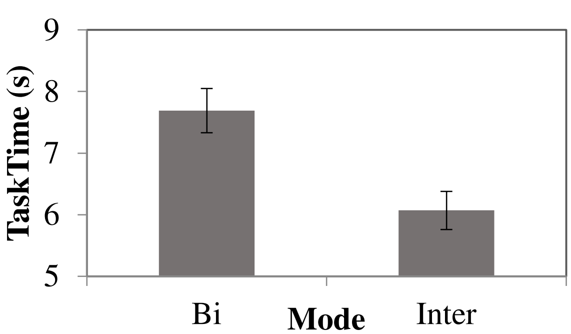

Figure 4. Mean TaskTime (speed) as a function of Mode (coordination mode). Error bars indicate standard error of the mean.

Coupling

The omnibus Mode × Order interaction was not significant, $F(1, 8) = .26$, $p = .655$, $\eta^2 = .026$. However, the main effect of Mode was significant, $F(1, 8) = 46.81$, $p < .001$, $\eta^2 = .85$. Overall, participants showed a higher degree of coupling when using the Bi Mode ($M = 22.02$; $SD = 3.82$) when compared to the Inter Mode ($M = 11.31$; $SD = 6.01$), which is shown in Figure 5. The main effect of Order was not significant, $F(1, 8) = 3.56$, $p = .096$, $\eta^2 = .31$.

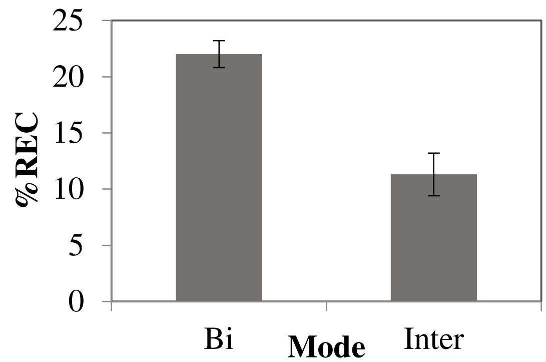

Figure 5. Mean %REC (coupling) as a function of Mode (coordination mode). Error bars indicate standard error of the mean.

Speed-Coupling Tradeoff

To analyze differences in coupling underlying the intermanual speed advantage, and because we instructed participants to complete the task as quickly as possible, the coupling measures were tested against the instructed performance variable, speed, to evaluate speed-coupling tradeoffs (Gorman & Crites, 2015).

Correlations between TaskTime and coupling measures were analyzed as a function of Mode. As shown in Table 1, decreases in %REC (coupling) were associated with decreases in TaskTime at each level of Mode. These results suggest that faster performance was associated with increased decoupling between the hands in both coordination Modes.

Table 1
Correlations between Task Time and %REC at Each Level of Mode (Bi = Bimanual Trials, Inter = Intermanual Trials).

	Bi	Inter
	%REC	%REC
TaskTime	0.37*	0.42*

Note. $N = 100$; *$p < .01$

DISCUSSION

This paper described an experiment that used a newly constructed task to investigate the intermanual speed advantage. In line with previous bimanual versus intermanual research for a previously unpracticed bimanual task, we observed an intermanual speed advantage. It was hypothesized that bimanual coupling is one of the contributing factors that underlies the intermanual speed advantage; specifically, there is less two-handed coupling when using the intermanual coordination mode for a previously unpracticed bimanual task. This hypothesis was supported. We observed less between-hand coupling when using the intermanual coordination mode when compared to the bimanual coordination mode. Additionally, it was hypothesized that coupling negatively impacts performance as measured by speed. We observed that speed and coupling measures were positively correlated, which showed that faster performance was associated with increased decoupling between the hands (regardless of coordination mode).

This finding of decoupled two-handed movements facilitating speed has also been observed when comparing these two coordination modes during a previously practiced bimanual task. Gorman and Crites (2015) investigated the intermanual speed advantage using a task in which participants already had extensive bimanual practice: shoe-tying. In this task, participants tied a shoe-like apparatus using both coordination modes. Contrary to the previously observed intermanual speed advantage using novices (e.g., teleoperation; Gorman & Crites, 2013), Gorman and Crites (2015) found that intermanual shoe-tying was slower than bimanual shoe-tying (i.e., a bimanual speed advantage) and these differences in performance were associated with lower between-hand coupling (i.e., bimanual was faster with less between-hand coupling, and intermanual was slower with more between-hand coupling). Gorman and Crites (2015) argued that the decoupling of the hands is what produced faster tying performance. As with the anticipatory movement effect described above (Zheng et al., 2005, 2007), participants must have learned to move each hand independently of the other when completing this bimanual task. However, because decoupling is important for effective performance in both coordination modes, it provides a more parsimonious explanation of skill development than the development of shared knowledge.

It may be that lack of bimanual coupling allows for potential anticipatory movements (i.e., people are able to make anticipatory movements because decoupled hands are free to move independently), which increases task performance as measured by speed. This effect may be relevant to human performance in settings ranging from medical to industrial, whenever coordinated hand movements are involved. Further research should address additional bimanual limitations contributing to the intermanual speed advantage, such as visuo-motor coupling, as well as the effect of previous bimanual practice observed during the Gorman and Crites (2015) study.

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