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# Are Two Hands (From Different People) Better Than One? Mode Effects and Differential Transfer Between Manual Coordination Modes

Jamie C. Gorman and Michael J. Crites, Texas Tech University, Lubbock

**Objective:** We report an experiment in which we investigated differential transfer between unimanual (one-handed), bimanual (two-handed), and intermanual (different peoples' hands) coordination modes.

**Background:** People perform some manual tasks faster than others ("mode effects"). However, little is known about transfer between coordination modes. To investigate differential transfer, we draw hypotheses from two perspectives—information based and constraint based—of bimanual and interpersonal coordination and skill acquisition.

**Method:** Participants drove a teleoperated rover around a circular path in sets of two 2-min trials using two of the different coordination modes. Speed and variability of the rover's path were measured. Order of coordination modes was manipulated to examine differential transfer and mode effects.

**Results:** Differential transfer analyses revealed patterns of positive transfer from simpler (localized spatiotemporal constraints) to more complex (distributed spatiotemporal constraints) coordination modes paired with negative transfer in the opposite direction. Mode effects indicated that intermanual performance was significantly faster than unimanual performance, and bimanual performance was intermediate. Importantly, all of these effects disappeared with practice.

**Conclusion:** The observed patterns of differential transfer between coordination modes may be better accounted for by a constraint-based explanation of differential transfer than by an information-based one. Mode effects may be attributable to anticipatory movements based on dyads' access to mutual visual information.

**Application:** Although people may be faster using more-complex coordination modes, when operators transition between modes, they may be more effective transitioning from simpler (e.g., bimanual) to more complex (e.g., intermanual) modes than vice versa. However, this difference may be critical only for novel or rarely practiced tasks.

**Keywords:** bimanual, intermanual, interpersonal, unimanual, team, teleoperations

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## **INTRODUCTION**

To successfully carry out manual coordination tasks, people must dynamically coordinate their hand movements using perceptual and physiological information. It is not surprising that some manual coordination tasks are easier to perform than others (e.g., Kelso, 1995; Koeneke, Lutz, Wüstenberg, & Jäncke, 2004; Peper, Beek, & van Wieringen, 1995; Robertson, 2001; Serrien, 2008; Treffner & Turvey, 1993). For example, people type two-handed letter sequences faster than one-handed letter sequences on a standard keyboard (e.g., *b-y* is faster than *m-y*; Koeneke et al., 2004; Rosenbaum, Kenny, & Derr, 1983), and skilled typists prefer two-handed two-letter sequences, compared with one-handed two-letter sequences, although they cannot say why (Beilock & Holt, 2007). Moreover, for some specialized tasks, two hands from different people are faster than two hands from the same person (e.g., laparoscopic cutting; Zheng, Swanström, & Mackenzie, 2007). Comparatively little is known, however, about the ease with which people transfer performance of one manual coordination task to another, and even less is known about transfer of manual skill when more than one person is involved (Richardson, Marsh, & Baron, 2007).

The ability to transition between *manual coordination modes*—including unimanual (one-handed), bimanual (two-handed), and intermanual (different peoples' hands)—has major ramifications in applied domains, such as medicine (e.g., surgical knot tying; Murphy, 2001; controlling a robotic arm; Piccigallo et al., 2010) and teleoperations (Shull & Gonzalez, 2006). Interestingly, expert operators (e.g., surgeons tying knots) learn to transition between manual coordination modes effortlessly. For example, tying knots using either two-handed or one-handed (either hand) instrument control may be required during endoscopic surgery (Cuschieri & Szabo, 1995; Murphy, 2001). One question that

naturally arises, then, is, What aspects of manual skill transfer across coordination modes?

We investigated this question in a teleoperated robot task environment in which a four-wheel-drive “rover” could be remotely operated with three different control schemes: unimanual, whereby one person drives the rover using a single joystick for steering and acceleration; bimanual, whereby one person drives the rover using one joystick to steer and a different joystick to accelerate; and intermanual, which is identical to bimanual, but the joysticks for steering and acceleration are operated by different people sitting next to each other. The order in which participants used these control schemes to drive the rover around a circular path was manipulated to investigate differential transfer between coordination modes in terms of driving speed and variability. In this way, the critical question for transfer is, Does participating in one coordination mode enhance (or harm) performance in a different coordination mode?

Though there are no previous studies directly examining transfer between these manual coordination modes, basic literature on bimanual coordination and motor skill acquisition provides a reasonable theoretical lens through which to view the problem of transfer between coordination modes. We briefly outline two theoretical perspectives. We do so not as a test of one perspective versus the other but to introduce complementary viewpoints that motivated our hypotheses and our interpretation of results in the current study.

### The Information-Based Perspective

Several studies have revealed that perceptual information facilitates performance of complex individual and interpersonal coordination tasks. Mechsner, Kerzel, Knoblich, and Prinz (2001) demonstrated continuous, stable performance of an inherently unstable (“practically impossible”) bimanual coordination pattern: four movements of the right hand for every three movements of the left hand, a 4:3 movement ratio. Mechsner et al. achieved this result by having participants rotate two flags, one for each hand, using mechanical cranks hidden under a table, such that participants’ flags were

visible but their hands were not. Using a gearing mechanism, a 4:3 hand movement ratio corresponded to a 1:1 flag movement ratio. By focusing on keeping the flags moving in a symmetric pattern, naive participants were able to stably perform the practically impossible 4:3 hand movement ratio. Thus, within an individual, complex motor patterns can be achieved by following a simple visual pattern.

Richardson, Marsh, Isenhower, Goodman, and Schmidt and colleagues (2007) demonstrated that performances of interpersonal movement patterns in dyads are also mediated by visual information. They found that participants who rocked next to each other in rocking chairs exhibited patterns of stability in unintentional in-phase and anti-phase rocking that are strikingly similar to those of an individual rhythmically oscillating their limbs. Importantly, the degree to which these patterns of stability were observed was mediated by participants’ access to visual information about their partner’s movements. Similarly, Oullier, de Guzman, Jantzen, Lagarde, and Kelso (2008) observed unintentional synchronization (i.e., in phase) during interpersonal finger tapping when two people visually attended each other’s taps. However, that synchronization dissolved rapidly when visual coupling was lost.

These studies suggest that bimanual and intermanual coordination may be more independent of physiological linkages within the human motor system than previously thought (Mechsner et al., 2001). In particular, studies such as these demonstrate how complex individual and interpersonal movement patterns may be organized through informational linkages (e.g., visual information). Taken together, studies such as these suggest that movement organization may be governed by one’s own movements and simple representations of others’ movement goals. This has motivated some scientists to theorize that a *common coding* between participants’ perceptions and actions (e.g., the mirror neuron system; Rizzolatti & Craighero, 2004) may provide a common physiological basis that facilitates transfer of coordination patterns from intrapersonal (e.g., bimanual) to interpersonal (e.g., intermanual) levels of analysis and vice versa (Knoblich & Sebanz, 2006; Sebanz & Knoblich, 2009).



Figure 1. Complex movements do not reduce to simple, component movements: The skilled batter on the right incorporates external forces into his swing (e.g., gravity; inertia; ball dynamics) that the unskilled batter does not.

### The Constraint-Based Perspective

Research on motor skill acquisition suggests that complex movements, such as those of the skilled batter in Figure 1, incorporate forces external to physiological linkages to support motor control (Bernstein, 1991/1996; Turvey, Fitch, & Tuller, 1982). During motor skill acquisition, parts of the body become *functionally* linked—physiologically distributed body parts are constrained to act as single, functional units, without the need for executive control (a “coordinative structure”; Kugler, Kelso, & Turvey, 1982)—such that physiological components dynamically interact with environmental and task constraints in the production of skilled movements (Davids, Button, & Bennett, 2008; Newell, 1986). For example, the skilled batter incorporates gravitational and inertial forces, as well as the speed and trajectory of the approaching ball, into his swing that the unskilled batter does not, such that the determinants of complex movements are not directly reducible to separate control of simple physiological motor units.

At a descriptive level, the implication for motor skill acquisition is that learning proceeds from simple, independently controlled physiological components, such as those of the unskilled batter, to complex, integrated movement patterns, such as those of the skilled batter, as external forces are incorporated in the form of new spatiotemporal constraints across

the body or across different people’s bodies, as the case may be. In the team domain, for example, team members function as independent agents prior to team skill acquisition, but they become constrained (or “compelled”) to act as a single, functional unit—to behave in ways beyond their own agency to accomplish a team-level goal—following team skill acquisition (Gorman & Cooke, 2011; Gorman, Cooke, & Amazeen, 2010).

Interestingly, once acquired, constraints may not be easily subtracted to yield the same level of performance. Take, for example, an experienced golfer who wants to isolate one component of his or her swing for correction. This can be difficult to achieve, and it may actually result in a temporary drop in performance. Because learning typically proceeds from simple physiological components to complex, integrated patterns (Knight, 2004), incorporating component changes that alter an existing swing pattern requires practice (Lee, Ishikura, Kegel, Gonzalez, & Passmore, 2008), such that the entire swing may be rebuilt, from the ground up, from simple components. In this way, a constraint-based perspective on motor skill acquisition leads us to expect positive transfer from simpler manual coordination patterns (those emphasizing localized spatiotemporal constraints; e.g., within an individual) to more complex ones (those emphasizing distributed spatiotemporal constraints; e.g., across individuals) and negative transfer in the opposite direction.

### The Current Study

It is well documented that people are faster in some manual coordination modes than in others (e.g., Koeneke et al., 2004; Serrien, 2008; Zheng et al., 2007). One aspect of the current study was to replicate those “mode effects.” Based on prior results, we expected bimanual control to be faster than unimanual control and intermanual control to be faster than bimanual control. However, our primary aim was to investigate differences in manual coordination modes in the context of differential transfer.

To investigate whether skill transfer between unimanual, bimanual, and intermanual rover control depends on the order of coordination modes, we manipulated coordination mode order

between participants to represent all possible patterns of transfer from one coordination mode (Task 1) to another (Task 2) using a differential transfer paradigm. In the differential transfer paradigm, participants perform two tasks, with some performing the tasks in one order (e.g., bimanual to intermanual) and others performing the tasks in a different order (e.g., intermanual to bimanual); a significant Order  $\times$  Task interaction shows differential transfer (Yaremko, Harari, Harrison, & Lynn, 1986). Hence, the primary goal of the current study was to examine Coordination Mode Order  $\times$  Task interactions on speed and variability of rover control.

In the intermanual condition (described later), participants are sitting next to each other, and they can clearly see each other's movements while controlling the rover. Therefore, from an information-based perspective, we hypothesized positive transfer (increasing speed; decreasing variability) from bimanual control to intermanual control, and vice versa, because of mutual access to the same visual information. If we do see that pattern of transfer, and it is attributable to common coding (e.g., mirror neurons), then we reasoned that we should not see that same pattern of positive transfer between unimanual and bimanual control, because the physiological (e.g., kinesthetic) information is so different (Koeneke et al., 2004).

From a constraint-based perspective, we hypothesized that we should see positive transfer from unimanual-to-bimanual, bimanual-to-intermanual, and unimanual-to-intermanual rover control, because all of those transitions are from simpler to more-complex control schemes that require constraints to be added, in the form of new coordinative links across the body, or across different people's bodies, when moving from one control scheme to the next. From the constraint-based perspective, those positive transfer results should be paired with negative transfer (decreasing speed; increasing variability) from bimanual-to-unimanual, intermanual-to-bimanual, and intermanual-to-unimanual control, because all of those transitions are from more-complex to simpler control schemes that require previously practiced coordinative links across the body, or across different people's bodies, to be subtracted.

Because it deals with motor learning, the constraint-based perspective may be more meaningfully linked with patterns of transfer during skill acquisition, whereas the information-based perspective may be more relevant to patterns of transfer across steady-state (intrinsically stable) task performances. Furthermore, as noted earlier, highly practiced operators, such as surgeons, seem to be able to transition between coordination modes effortlessly. Therefore, we had participants perform multiple trials in each manual coordination mode to explore whether mode effects and patterns of differential transfer depend on practice.

## METHOD

### Participants

A total of 72 undergraduates (36 dyads) from Texas Tech participated for partial course credit. Participants' mean age was 19.03 ( $SD = 2.08$ ), and 70.80% were female. Of the dyads, 4 were all male, 19 were all female, and 13 were mixed gender. The preponderance of female participants was unplanned; the participant pool during the time of the study was approximately 64% female. Of the dyads, four reported knowing each other (i.e., were classmates) prior to participation. Of the 72 participants, 70 (97%) self-reported being right-handed.

### Experimental Design

There were three manual coordination modes in the experiment corresponding to unimanual (Uni), bimanual (Bi), and intermanual (Inter) rover control. Dyads were randomly assigned to one of six levels of a between-subjects variable, coordination mode order: Uni $\rightarrow$ Bi, Uni $\rightarrow$ Inter, Bi $\rightarrow$ Uni, Bi $\rightarrow$ Inter, Inter $\rightarrow$ Uni, or Inter $\rightarrow$ Bi. Members of dyads participated in the Uni and Bi conditions separately, in a random order, so that their mean performance could be compared with dyad performance in the Inter condition. A within-subjects variable, task, indexed the first and second task performed in each of the between-subjects condition orders. For example, in the Uni $\rightarrow$ Bi condition, Task 1 indexes performance in the Uni condition and Task 2 indexes performance in the Bi condition. Practice was manipulated with a within-subjects variable trial, by having

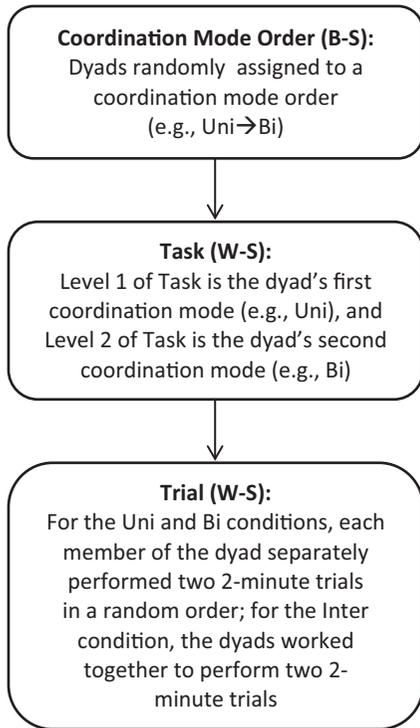


Figure 2. This flow diagram represents the sequence of factors manipulated in the experiment (B-S = between subjects; W-S = within subjects).

participants perform two 2-min trials at each level of task. Length of trial (2 min) was based on pilot testing: Shorter trials did not allow participants to reach and maintain a consistent driving pattern, and longer trials led to boredom. The sequence of factors used in the experiment and their relationships are summarized in Figure 2.

### Apparatus

Participants remotely operated a Lynxmotion A4WD1 Rover, which was located in a separate motion-capture room, using a HiTec Laser 6 FM transmitter. The transmitter had two joysticks, which were configured differently depending on coordination mode (Figure 3): In the Uni condition, the right joystick controlled both steering (left-right joystick movement) and acceleration (up-down joystick movement); in the Bi and Inter conditions, the left joystick controlled steering (left-right), and the right joystick controlled acceleration (up-down). These

task conditions were designed so that the same vehicle degrees of freedom had to be coordinated in each condition, but the effectors to be coordinated (i.e., participants' hands) were increasingly physiologically and informationally distributed from Uni to Bi to Inter (cf. Koeneke et al., 2004).

The rover was equipped with a front-mounted 2.4-GHz wireless camera that transmitted real-time color video to a 19-in. high-definition monitor in the participant room. An eight-camera Vicon MX-T10 motion-capture system captured movement data from the rover (100 Hz) as participants drove the rover around a circular path (diameter = 1,067 mm) traced on the floor of the motion-capture room (Figure 3). Data were collected from a reflective marker attached to the front center of the rover. Participants wore headphones that continuously emitted pink noise in all conditions, which was done to ensure that participants did not talk in the Inter condition and that participants had mutual access to only visual and physiological (i.e., kinesthetic) information in all conditions.

### Measures

Performance was measured as speed and variability of the rover around the circular path during each 2-min trial; these measures were computed from the movement data from each trial (e.g., Figure 4). Speed was measured as the revolutions per minute (RPMs) around the circular path. Variability was computed as the root mean square error (RMSE), in millimeters, of the  $\{x, y\}$  residuals between the observed rover path and the least-squares circle of best fit for each trial. For Uni and Bi trials, speed and variability were taken as average RPMs and RMSE, respectively, across both members of the dyad for comparing Uni, Bi, and Inter conditions.

### Procedure

After arriving for the experiment, each member of the dyad completed an informed-consent form. Dyads were then given a 2-min demonstration on how to control the rover using the transmitter; however, participants were not allowed to talk to each other for the duration of the experiment. Participants then completed two 2-min trials in their Task 1 coordination

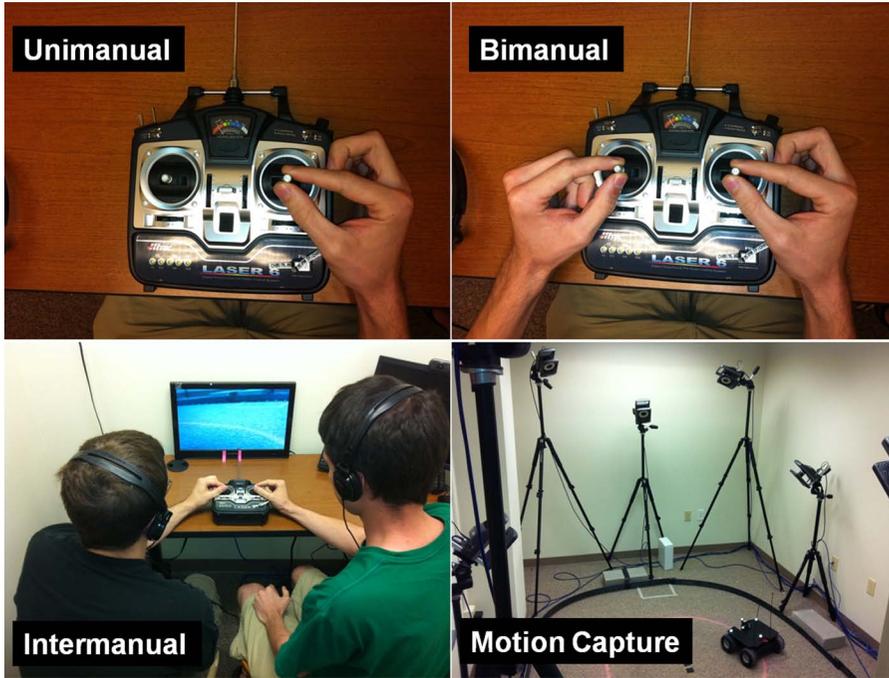


Figure 3. Manual coordination modes and experiment apparatus.

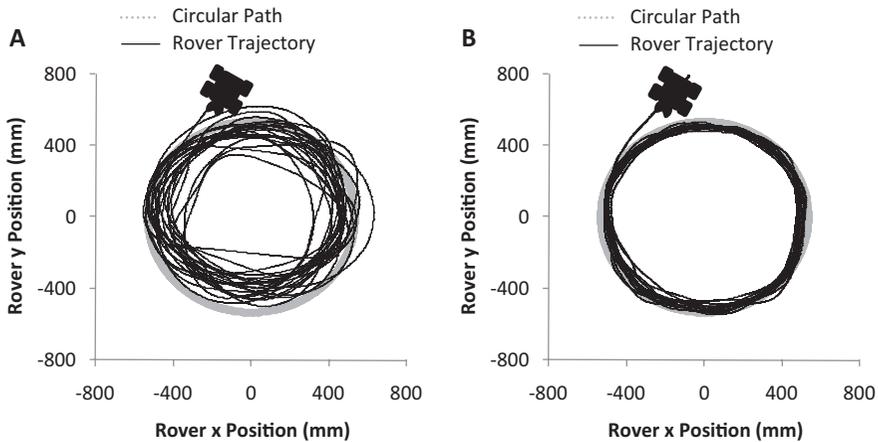


Figure 4. Top-down view of rover movement data, showing the rover and the prescribed circular path (the rover is not drawn to scale), taken from a reflective marker placed on the front center of the rover: Panel A shows a high-variability intermanual trial (revolutions per minute [RPMs] = 11; root mean square error [RMSE] = 72.64 mm); Panel B shows a low-variability intermanual trial (RPMs = 7; RMSE = 36.62 mm).

mode, followed by two 2-min trials in their Task 2 coordination mode. Prior to completing the trials for each task, participants were either separately (Uni and Bi) or together (Inter) given

instructions on transmitter controls specific to that coordination mode. Participants donned the pink noise-emitting headphones before completing each set of trials. For both the Uni and

Bi conditions, each member of the dyad completed his or her two trials separately, in a randomized order. During that time, the other member of the dyad sat in a separate participant room and completed demographics and teamwork surveys (the teamwork surveys are not analyzed here). Participants were randomly assigned to either steering or acceleration for the Inter condition. After completing all experimental trials, participants were debriefed. Participation lasted approximately 45 min.

## RESULTS

Dyads' speed and variability in completing the rover trials were analyzed in two ways to examine (a) differential transfer effects (e.g., Bi→Inter vs. Inter→Bi) and (b) mode effects (i.e., differences in difficulty between Uni, Bi, and Inter). We present these results in turn to address our differential transfer and mode effect hypotheses.

### Differential Transfer

To examine differential transfer, we partitioned the between-subjects variability using planned contrasts on coordination mode order according to increasing (Uni→Bi; Bi→Inter; Uni→Inter) versus decreasing (Bi→Uni; Inter→Bi; Inter→Uni) physiological and informational distribution of effectors (i.e., hands), which resulted in the following set of four non-orthogonal contrasts on coordination mode order:

1. Uni→Bi versus Bi→Uni
2. Bi→Uni versus Bi→Inter
3. Bi→Inter versus Inter→Bi
4. Uni→Inter versus Inter→Uni

Speed and variability were uncorrelated across all experimental trials,  $r(142) = -.003$ ,  $p = .974$ , and speed and variability were uncorrelated within each Coordination Mode  $\times$  Task  $\times$  Trial condition ( $n = 12$ ; all  $p > .10$ , two tailed). Therefore, we analyzed speed and variability separately using two 6 (coordination mode order)  $\times$  2 (task)  $\times$  2 (trial) mixed ANOVAs. For each dependent variable, we report the results of the planned contrasts on coordination mode order and their interactions

with task and trial, followed by the omnibus Coordination Mode Order  $\times$  Task  $\times$  Trial interaction, the Task  $\times$  Trial interaction, and the task and trial main effects. Those results are followed by a joint analysis of change in speed and variability from Task 1 to Task 2 to explore the contribution of speed–accuracy trade-off to differential transfer.

*Speed.* The first contrast, Uni→Bi versus Bi→Uni, revealed a significant Coordination Mode Order  $\times$  Task  $\times$  Trial interaction,  $F(1, 30) = 4.98$ ,  $p = .033$ ,  $\eta^2 = .14$ . The Coordination Mode Order  $\times$  Task interaction, Coordination Mode Order  $\times$  Trial interaction, and coordination mode order main effect were not significant. We conducted follow-up analyses to examine the three-way interaction. The simple Coordination Mode Order  $\times$  Trial interaction was significant at Trial 1,  $F(1, 30) = 5.20$ ,  $p = .030$ ,  $\eta^2 = .15$ , but not at Trial 2. As shown by the increasing versus decreasing pattern of means in Figure 5a, we observed a differential transfer effect with positive transfer (i.e., increasing speed) from Uni→Bi and negative transfer (i.e., decreasing speed) from Bi→Uni at Trial 1. However, that effect disappeared at Trial 2.

The second contrast, Bi→Uni versus Bi→Inter, also revealed a significant Coordination Mode Order  $\times$  Task  $\times$  Trial interaction,  $F(1, 30) = 15.12$ ,  $p = .001$ ,  $\eta^2 = .34$ . No other effects related to this contrast were significant. Follow-up analyses of the three-way interaction revealed that the simple Coordination Mode Order  $\times$  Task interaction was significant at Trial 1,  $F(1, 30) = 7.63$ ,  $p = .010$ ,  $\eta^2 = .20$ , but not at Trial 2. As shown in Figure 5b, we observed a differential transfer effect with positive transfer from Bi→Inter and negative transfer from Bi→Uni at Trial 1, but that effect disappeared at Trial 2.

The third contrast, Bi→Inter versus Inter→Bi, also revealed a significant Coordination Mode Order  $\times$  Task  $\times$  Trial interaction,  $F(1, 30) = 10.04$ ,  $p = .004$ ,  $\eta^2 = .25$ , and a significant Coordination Mode Order  $\times$  Task interaction,  $F(1, 30) = 4.22$ ,  $p = .049$ ,  $\eta^2 = .12$ . No other effects related to this contrast were significant. Follow-up analysis of the three-way interaction revealed that the simple Coordination Mode Order  $\times$  Task interaction was significant at Trial 1,  $F(1, 30) = 8.12$ ,  $p = .008$ ,  $\eta^2 = .21$ , but not at Trial 2. As shown in Figure 5c, we

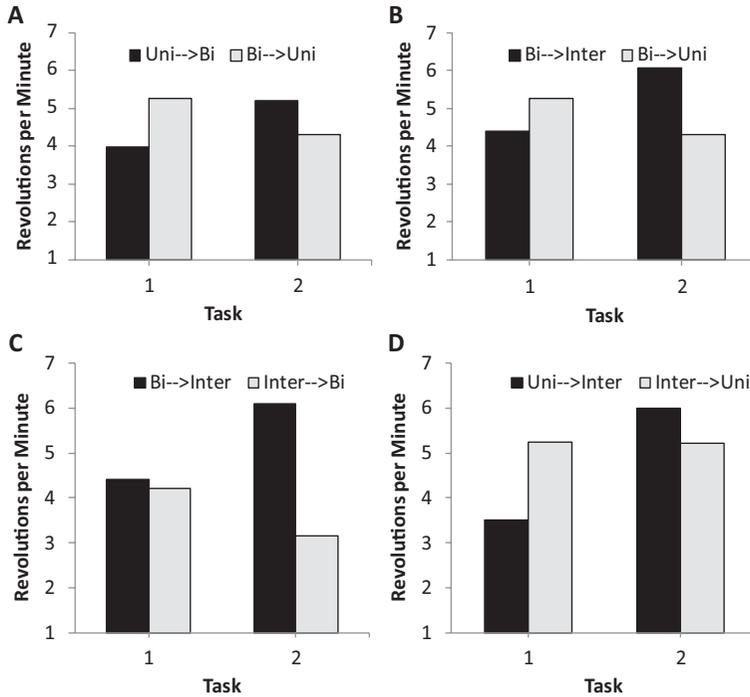


Figure 5. Patterns of differential transfer for speed between coordination modes at Trial 1.

observed a differential transfer effect with positive transfer from Bi→Inter and negative transfer from Inter→Bi at Trial 1. However, that effect disappeared at Trial 2.

The fourth contrast, Uni→Inter versus Inter→Uni, revealed a significant Coordination Mode Order × Task interaction,  $F(1, 30) = 5.36$ ,  $p = .028$ ,  $\eta^2 = .15$ . No other effects related to this contrast were significant. Figure 5d shows the interaction at Trial 1, but we observed the same result, positive transfer from Uni→Inter and zero transfer from Inter→Uni, across both trials.

The omnibus Coordination Mode Order × Task × Trial interaction was significant,  $F(5, 30) = 4.57$ ,  $p = .003$ ,  $\eta^2 = .43$ . The details of this interaction are provided by the planned contrasts. The omnibus Task × Trial interaction was also significant,  $F(1, 30) = 5.04$ ,  $p = .032$ ,  $\eta^2 = .14$ . Bonferroni paired  $t$  tests ( $\alpha_{\text{BON}} = .05/2 = .025$ ;  $SE = .20$ ) revealed that participants exhibited a numerically greater increase in RPMs from Trial 1 ( $M = 4.44$ ,  $SD = 1.96$ ) to Trial 2 ( $M = 5.31$ ,  $SD = 2.04$ ) for Task 1,  $t(30) = -4.35$ ,  $p < .001$ ,  $d = -1.74$ , than from Trial 1 ( $M = 5.00$ ,  $SD$

$= 2.39$ ) to Trial 2 ( $M = 5.49$ ,  $SD = 2.46$ ) for Task 2,  $t(30) = -2.45$ ,  $p < .001$ ,  $d = -.98$ , although both differences were significant. The main effect of trial was significant,  $F(1, 30) = 47.54$ ,  $p < .001$ ,  $\eta^2 = .61$ . Participants exhibited greater RPMs at Trial 2 ( $M = 5.40$ ,  $SD = 2.09$ ) than they did at Trial 1 ( $M = 4.72$ ,  $SD = 1.93$ ) across all conditions. The main effect of task was not significant.

*Variability.* The first contrast, Uni→Bi versus Bi→Uni, revealed a significant Coordination Mode Order × Trial interaction,  $F(1, 30) = 11.89$ ,  $p = .002$ ,  $\eta^2 = .28$ . No other effects were significant for this contrast; therefore, we conducted follow-up analyses on the two-way interaction. Bonferroni paired  $t$  tests ( $\alpha_{\text{BON}} = .05/2 = .025$ ;  $SE = 2.95$ ) revealed that RMSE decreased significantly from Trial 1 ( $M = 69.66$ ,  $SD = 14.15$ ) to Trial 2 ( $M = 59.09$ ,  $SD = 5.27$ ) for Bi→Uni,  $t(30) = -2.50$ ,  $p = .018$ ,  $d = -1.44$ , but RMSE did not change significantly from Trial 1 ( $M = 64.77$ ,  $SD = 15.80$ ) to Trial 2 ( $M = 68.56$ ,  $SD = 19.38$ ) for Uni→Bi,  $t(30) = -.89$ ,  $p = .38$ ,  $d = -.52$ . To facilitate visual comparisons

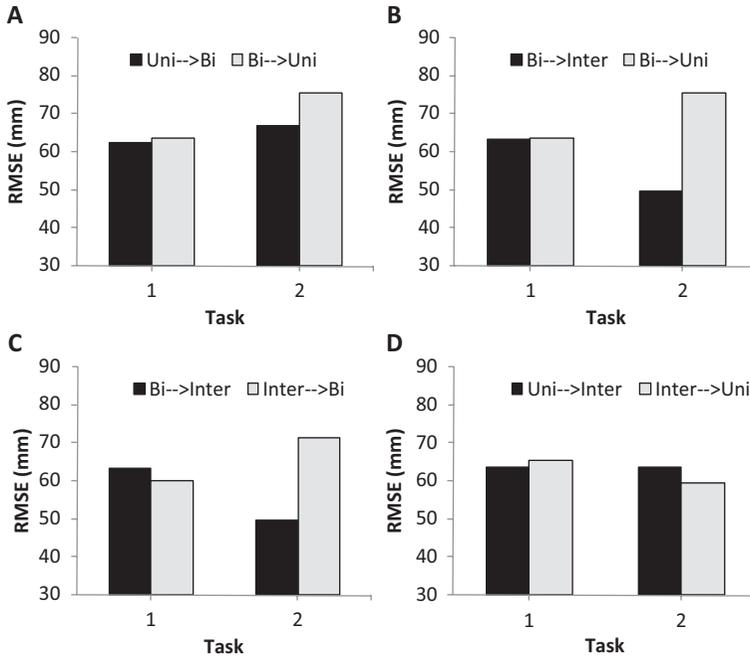


Figure 6. Patterns of differential transfer for variability between coordination modes at Trial 1.

with the RPM differential transfer effects in Figure 5, in Figure 6a, we show the observed pattern of RMSE transfer from Uni→Bi and from Bi→Uni as a function of task at Trial 1.

The second contrast, Bi→Uni versus Bi→Inter, revealed a significant Coordination Mode Order × Task × Trial interaction,  $F(1, 30) = 7.13, p = .012, \eta^2 = .19$ , and a significant Coordination Mode Order × Trial interaction,  $F(1, 30) = 6.03, p = .020, \eta^2 = .17$ . The coordination mode order main effect and the Coordination Mode Order × Task interaction were not significant. Like the speed analysis, follow-up analyses of the three-way interaction revealed that the simple Coordination Mode Order × Task interaction was significant at Trial 1,  $F(1, 30) = 9.70, p = .004, \eta^2 = .24$ , but not at Trial 2. As shown in Figure 6b, we observed a differential transfer effect with positive transfer (i.e., decreasing variability) from Bi→Inter and negative transfer (i.e., increasing variability) from Bi→Uni at Trial 1. However, that effect disappeared at Trial 2.

The third contrast, Bi→Inter versus Inter→Bi, revealed a significant Coordination Mode Order × Task × Trial interaction,  $F(1, 30)$

$= 8.56, p = .006, \eta^2 = .22$ . No other effects related to this contrast were significant. The simple Coordination Mode Order × Task interaction was significant at Trial 1,  $F(1, 30) = 9.32, p = .005, \eta^2 = .24$ , but not at Trial 2. As shown in Figure 6c, we observed a differential transfer effect with positive transfer from Bi→Inter and negative transfer from Inter→Bi at Trial 1. However, that effect disappeared at Trial 2.

The fourth contrast, Uni→Inter versus Inter→Uni, yielded no significant results. For comparison with previous graphs, however, we show the observed pattern of means as a function of task at Trial 1 in Figure 6d.

The omnibus Coordination Mode Order × Task × Trial interaction was significant,  $F(5, 30) = 2.81, p = .034, \eta^2 = .32$ . The details of this interaction are provided by the planned contrasts. The main effect of trial was also significant,  $F(1, 30) = 14.80, p = .001, \eta^2 = .33$ . Performance was significantly less variable at Trial 2 ( $M = 59.22, SD = 11.86$ ) than at Trial 1 ( $M = 63.84, SD = 12.38$ ). The main effect of task and the omnibus Task × Trial interaction were not significant.

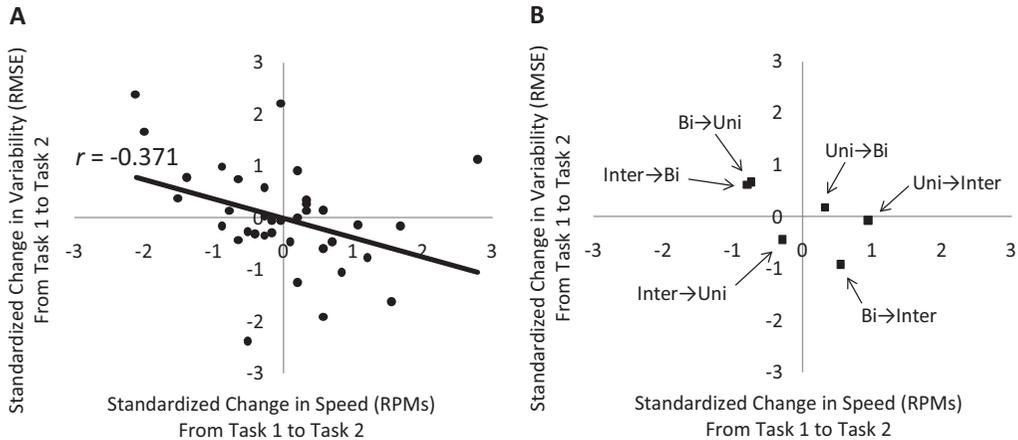


Figure 7. Standardized change in variability (from Task 1 to Task 2) as a function of standardized change in speed (from Task 1 to Task 2) at Trial 1: Panel A is the scatterplot for all dyads in the experiment; Panel B reproduces the scatterplot as a set of standardized bivariate means for the six levels of coordination mode order.

*Speed–accuracy trade-off.* For both speed and variability, significant patterns of differential transfer were detected at Trial 1 but not at Trial 2. How can we be confident that the positive Trial 1 Speed transfer effects in some conditions were not simply attributable to associated increases in variability—a speed–accuracy trade-off? We addressed this question in two ways, first by examining speed–accuracy trade-off across all dyads and second by exploring the potential contribution of speed–accuracy trade-off to patterns of transfer for the six levels of coordination mode order.

First, if dyads were trading accuracy for speed, then positive changes in speed from Task 1 to Task 2 should be associated with increasing variability between those tasks. To explore that possibility, we plotted the standardized speed and variability change scores (i.e.,  $z$  scores for Task 2 performance minus Task 1 performance, calculated across all dyads) at Trial 1 (Figure 7a). We plot standardized change scores because the original ratio-scaled variables were measured in different units. For both standardized change scores, positive values show an increase and negative values show a decrease in the measured variable from Task 1 to Task 2. Counter to speed–accuracy trade-off, dyads were most likely to either improve or diminish on speed

and variability simultaneously when moving from Task 1 to Task 2,  $r(34) = -.371$ ,  $p = .026$ . (The same analysis was not significant at Trial 2,  $r[34] = .178$ ,  $p = .298$ .)

Second, we plotted the Trial 1 bivariate group means of the standardized change scores by level of coordination mode order (Figure 7b). The purpose of this analysis was to determine the relative contribution of speed–accuracy trade-off to the observed pattern of transfer for each level of coordination mode order. That relative contribution can be inferred from the locations of the bivariate mean standardized change scores for the coordination mode orders in the two-dimensional “change-in-speed” versus “change-in-variability” space shown in Figure 7b. If positive speed transfer came at the cost of increased variability, then the coordination mode order would fall into the upper-right (first) quadrant of this space. As shown by the pattern of bivariate means in Figure 7b, Uni→Bi was the only viable candidate. However, a one-sample Hotelling’s  $T^2$  on the Uni→Bi standardized change scores indicated that the Uni→Bi bivariate mean change score was not significantly different from the origin,  $T^2 = 10.26$ ,  $F(2, 4) = 4.10$ ,  $p = .107$ ,  $D^2 = 1.71$ . (The same analysis at Trial 2 yielded no conditions in the first quadrant significantly different from the origin,

and the same results would have been obtained using raw change scores and their means.)

Together, these results establish that, at a correlational level, the differential transfer effects reported previously were not artifacts of speed–accuracy trade-off when transitioning between coordination modes. Differential transfer affected speed and variability similarly, such that performance tended to either increase or decrease on both variables when transitioning between coordination modes. On the basis of that finding, we concluded that speed–accuracy trade-off did not play a significant role in the observed differential transfer effects.

### Mode Effects

To examine whether some manual coordination modes were more difficult than others and, furthermore, to qualify patterns of differential transfer based on differences in the difficulty of coordination modes, we ran separate one-way ANOVAs on speed and variability at each level of trial with coordination mode (Uni, Bi, or Inter) as a within-subjects factor. Because dyads did not participate under all levels of coordination mode, the analysis had to be initially set up as a two-way ANOVA with coordination mode (the “treatment” effect) and dyad (the “subjects” effect) as between-subjects factors. In the model specification, however, only the main effects, and not the interaction (i.e., “Treatment  $\times$  Subjects”), were specified. Hence, the Coordination Mode  $\times$  Dyad interaction becomes the error term, which is the appropriate error term for analyzing the within-subjects coordination mode effect.

For speed, the effect of coordination mode was significant at Trial 1,  $F(2, 34) = 8.01$ ,  $p = .001$ ,  $\eta^2 = .32$ , but not at Trial 2. A Tukey HSD test ( $\alpha_{FW} = .05$ ) on mean Trial 1 speed revealed that participants were significantly faster in the Inter condition compared with the Uni condition (Figure 8). The effect of coordination mode on variability was not significant at either Trial 1 or Trial 2.

## DISCUSSION

In the current study, we found that participants differentially encountered difficulty or enhancement transitioning from one manual

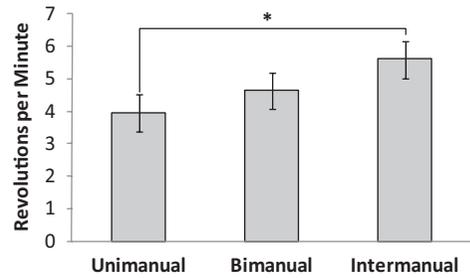


Figure 8. As shown by mean revolutions per minute by manual coordination mode (averaged across Task), intermanual control was significantly faster than unimanual control but not bimanual control at Trial 1 (error bars are 95% confidence intervals;  $*p < .05$  with  $\alpha_{FW} = .05$ ).

coordination mode to another, depending on the order of coordination modes. We also observed that intermanual performance was significantly faster than unimanual, which agrees with prior research (i.e., mode effects). In the following sections, we discuss these differential transfer and mode effects in turn, followed by a discussion of differential transfer in light of mode effects.

### Differential Transfer

We observed positive transfer from spatio-temporally simpler to more complex manual control (e.g., Bi  $\rightarrow$  Inter) paired with negative transfer in the opposite direction (e.g., Inter  $\rightarrow$  Bi) for both speed and variability. However, the speed analysis yielded more significant patterns of this type (i.e., positive Uni  $\rightarrow$  Bi vs. negative Bi  $\rightarrow$  Uni; positive Uni  $\rightarrow$  Inter). Overall, these results support a constraint-based explanation of manual skill transfer across intra- and interpersonal coordination modes, although a constraint-based approach has typically been applied to the acquisition of individual skill (e.g., Davids et al., 2008; Kugler et al., 1982; Newell, 1986).

From a constraint-based perspective, positive transfer occurs when an existing coordination pattern is functionally adapted to a new coordination mode, and negative transfer occurs when a novel mode competes with an existing pattern (Davids et al., 2008). According to this

view, early on in skill acquisition, bimanual performance, for example, may be functionally (but not physiologically) adapted to intermanual performance, whereas intermanual performance may significantly alter the characteristics of subsequent bimanual performance. In this way, we think the differential transfer results suggest that not only do more complex control schemes not immediately reduce to simple motor components in the individual (e.g., Bi→Uni), but team motor skills (i.e., in dyads) are not immediately transferable to individual skill (e.g., Inter→Bi). From a practical standpoint, this finding suggests that after intermanual skill acquisition, operators should practice the task on their own before attempting individual (e.g., bimanual) performance.

The significant main effect of trial indicates that learning occurred across all coordination modes. Indeed, except for the unimanual-intermanual effect on speed, constraint-based transfer disappeared with practice. A practical implication is that it may be easier for an operator to transition from a simpler manual control scheme to a more complex one than vice versa, but that difference may be critical only for novel or rarely practiced tasks as opposed to well-honed, persistent manual coordination skills. Newell, Mayer-Kress, and colleagues (Newell, Liu, & Mayer-Kress, 2001; Stratton, Liu, Hong, Mayer-Kress, & Newell, 2007) have argued for two characteristic time scales in motor learning: short-term learning effects, which reflect transient changes attributable to “warm-up,” against a backdrop of long-term, persistent motor skill acquisition. Importantly, short-term learning effects attributable to “warm-up decrement” disappear as the persistent level of skill increases (Newell et al., 2001). Recast in light of the current study, this theory predicts that differential transfer effects, like those at Trial 1, may briefly return as warm-up decrement following periods of nonuse but should continue to fade as persistent skill level increases. With sufficient practice, operators may learn to shift between qualitatively different, yet equally effective, coordination patterns depending on the manual coordination mode, without exhibiting differential transfer (cf. Knight, 2004).

Although we observed positive bimanual-to-intermanual transfer, it was not paired with

positive intermanual-to-bimanual transfer, which we predicted from an information-based perspective. However, we do not want to rule out the importance of an information-based perspective for understanding transfer of manual coordination skill. We did not explicitly instruct our participants to visually attend to each other's movements; they simply sat next to each other. In the future, a stronger manipulation, like explicitly coupling one participant's movements to the other's through the visual channel (e.g., Richardson, Marsh, Isenhower, Goodman, & Schmidt, 2007; Oullier et al., 2008), through the verbal channel (e.g., Shockley, Baker, Richardson, & Fowler, 2007), or through a combination of perceptual channels during task acquisition (Jacobs & Michaels, 2007), may demonstrate a stronger relationship between perceptual information and transfer between manual coordination modes.

### Mode Effects

Prior studies comparing manual coordination modes have shown that bimanual is faster than unimanual and that intermanual is faster than bimanual. We replicated those mode effects in the current study, to a degree (Figure 8). These types of mode effects have been attributed to differences in cortical processing demands in the unimanual versus bimanual case (e.g., unimanual is slower because it is associated with increased cortical demands; Koeneke et al., 2004), and in the bimanual-versus-intermanual case, intermanual is faster because of the development of anticipatory movements via shared expectations (e.g., a shared mental model [SMM]; Zheng et al., 2007). To what, then, do we owe the significant speed advantage of intermanual compared with unimanual control?

Like Zheng et al. (2007), we think dyads can circumvent the biomechanical limitations of intrapersonal manual coordination via anticipation. However, if dyads' advantage is attributable to an SMM, as Zheng et al. suggest, then it entails a high-level knowledge representation, likely beyond the requirements of the rover task, to explain dyads' advantage. Another potential explanation is that the speed advantage of intermanual control is attributable to dyads' enhanced reliance on mutual visual information

rather than individual kinesthetic feedback, a hypothesis that was not tested in the current study. This latter hypothesis, however, is consistent with findings such as Mechsner et al.'s (2001), that participants' coordination capabilities are enhanced when following simple visual patterns rather than relying entirely on their own (intrinsic) coordination dynamics. Whether dyads' speed advantage may be accounted for by informational organization of their coordination dynamics or by specifications of an SMM should be investigated in future research (cf. Newell, 1986).

### Combined Transfer and Mode Effects

As described earlier, participants were significantly faster in the intermanual coordination mode compared with the unimanual coordination mode. In the language of constraint-based transfer, participants were faster in the more spatiotemporally complex (intermanual) mode than in the simpler (unimanual) mode. If spatiotemporal distribution of coordination constraints predominates performance, then when transitioning between highly disparate coordination modes, such as between unimanual and intermanual, mode effects should play a principal role in determining performance differences, such that patterns of differential transfer may be induced by mode effects alone. In that case, we should see positive transfer from simpler to more complex modes, paired with negative transfer in the opposite direction, attributable entirely to differences in mode difficulty. That is, mode effects would confound transfer effects.

However, if that were the case, then we would not have observed differential transfer patterns, such as those between bimanual and intermanual in Figures 5c and 6c. We see in those graphs instances of relatively "pure" differential transfer, wherein performance is roughly equivalent at Task 1, and the performance difference is observed at Task 2. Furthermore, as shown in Figure 8, the simple bimanual-versus-intermanual mode effect was not significant. Taken together, these results suggest that patterns of differential transfer between coordination modes—in particular, between bimanual and

intermanual—are not attributable to mode effects alone. Indeed, for some coordination modes, transfer effects may combine with mode effects to produce findings such as those in the current study. In future research, careful examination of participant's eye and hand movements may shed light on the degree to which mode effects have an impact on differential transfer for some coordination modes. If differential transfer is primarily attributable to mode effects, then we expect movement differences to be encapsulated within coordination modes with little or no carryover of previously practiced movements to novel modes.

### CONCLUSION

On the surface, two hands, from different people (intermanual), are better than one (unimanual), at least in terms of speed. The intermediate differences, between unimanual and bimanual and between bimanual and intermanual, although not significant on their own, become important in the context of differential transfer. From a constraint-based perspective, interpersonal performance does not uniquely reduce to simple components of intrapersonal performance because interpersonal performance is spatiotemporally distributed among different people. Accordingly, we found that not only do people perform differently (faster) on interpersonal, compared with intrapersonal, versions of the same task, but they also differentially encounter difficulty or enhancement, at least initially, transitioning between interpersonal and intrapersonal coordination modes.

In the current study, we used a circular driving task and manual control mechanism that tapped perceptual and physiological but not cognitive (e.g., memory, decision making) resources. As noted earlier, expert operators (e.g., surgeons) learn to transition effortlessly between manual coordination modes in cognitively demanding task environments. In cognitively demanding task environments, alternative explanations for mode effects, such as SMMs, can directly affect performance. Therefore, in future work on mode switching, researchers should continue to examine mode effects and the question of what transfers across coordination modes in more cognitively demanding task environments.

## ACKNOWLEDGMENTS

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## KEY POINTS

- Differential transfer effects indicated positive transfer from spatiotemporally simpler control schemes to more complex ones (e.g., bimanual to intermanual) and negative transfer in the opposite direction (e.g., intermanual to bimanual), which supports a constraint-based explanation of manual skill transfer.
- As expected, we observed coordination mode effects, whereby intermanual control was significantly faster than unimanual control and speed of bimanual control was intermediate.
- Differential transfer and mode effects disappeared rapidly with practice, such that these types of effects may primarily affect novel or rarely practiced manual coordination tasks rather than well-honed, persistent manual coordination skills.
- The impact of coordination mode on task performance should be further explored to determine high-level cognitive requirements for mitigating differential transfer and mode effects in more cognitively demanding task environments.

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