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Learning to tie well with others: bimanual versus intermanual performance of a highly practised skill

Jamie C. Gorman & Michael J. Crites

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Learning to tie well with others: bimanual versus intermanual performance of a highly practised skill

Jamie C. Gorman* and Michael J. Crites

Department of Psychological Sciences, Texas Tech University, Lubbock, TX, USA

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Studies indicate that novices are faster in manual tasks when performing with a partner ('intermanual') than with their own two hands ('bimanual'). The generality of this 'mode effect' was examined using a highly practised bimanual task, shoe tying, at which participants were experts. Speed–variability correlations confirmed participants were bimanually skilled but not intermanually skilled. Contrary to results using novices, intermanual was slower, such that prior skill reverses the effect. Analyses incorporating the similarity of shoe-tying strategies across dyads implicated a perceptual rather than shared knowledge/representation basis for intermanual performance. Practice effects indicated that intermanual performance built upon prior bimanual skill, such that novel relative timings between dyads' hands must be acquired. Motor transfer effects provided support for this conclusion. During shoe tying, hands were tightly coupled in the intermanual mode due to the perceptual coupling constraints of intermanual performance. Increased coupling was correlated with slower performance. Implications for real-world tasks (e.g. surgical knot tying) are described.

Practitioner Summary: Novice participants perform manual tasks faster with a partner ('intermanual') than on their own ('bimanual'). The generality of this 'mode effect' was investigated using a highly practised bimanual task, shoe tying. The mode effect was reversed and mechanisms underlying intermanual skill acquisition were identified. Practical implications extend to tasks such as surgical knot tying.

Keywords: coordination; coupling; interpersonal; practice effects; motor transfer; recurrence

1. Introduction

People coordinate their hand movements individually (e.g. pouring a cup of coffee) and with each other (e.g. handing someone a cup of coffee) on a daily basis. Manipulating objects with the hands provides a channel of sensation and perception that specifies one's relationship with the objects and people around them. Interestingly, when people handle unfamiliar objects, their manual coordination patterns are more complex and varied than handling a familiar object (Gibson 1962). This study presents a twist on that observation. Instead of manipulating object familiarity, we sought to manipulate the novelty of manual coordination patterns with which a familiar object is handled. In this study, we asked participants to tie a shoe as they normally would with their own two hands (the 'bimanual' coordination mode) or with another person, each handling one shoelace (the 'intermanual' coordination mode). At the heart of this study lies the question, what is the nature of skill acquisition such that people may perform novel interpersonal coordination patterns (e.g. intermanual) for accomplishing a highly practised bimanual task?

Multiple experiments have revealed the practical implications of this issue by finding that intermanual is faster than bimanual performance for novice participants across a variety of domains (e.g. in teleoperation tasks; Glynn and Henning 2000; Gorman and Crites 2013; in team pursuit-rotor tasks; Reed et al. 2006; Wegner and Zeaman 1956; and in laparoscopic cutting tasks; Zheng, Swanström, and Mackenzie 2007; Zheng et al. 2005). However, because those studies used novice participants performing novel tasks, they avoid the question of whether such effects generalise to well-honed bimanual skills. Should we expect to see the same intermanual advantage, for example, in laparoscopy performed by bimanually trained surgeons? If not, then what skills need to be acquired to perform effectively in the intermanual mode? Shoe tying is ideal for addressing this issue because even novice participants are highly skilled in the bimanual mode, but little is known about how they will perform when required to tie with a partner.

This study uses shoe tying to investigate: bimanual versus intermanual differences in speed of task performance ('mode effects'), what practice effects and transfer look like in the unfamiliar intermanual mode and differences in how the hands are dynamically coupled in bimanual and intermanual modes.

*Corresponding author. Email: jamie.gorman@ttu.edu

1.1 Mode effects and 'same' versus 'mixed' intermanual strategies

What are mode effects and how do they come about? It has been shown that people type two-handed letter sequences faster than one-handed letter sequences (e.g. 'b-y' is faster than 'm-y'; Koeneke et al. 2004; Rosenbaum, Kenny, and Derr 1983), and skilled typists prefer typing two-handed, two-letter sequences over one-handed two-letter sequences, although they are unaware of it (Beilock and Holt 2007). Also (as cited before), two hands from different people (intermanual) are faster than two hands from the same person (bimanual) when performing novel tasks. In these instances, mode effects arise wherein bimanual performance is faster (and preferred) than unimanual, and intermanual is faster than bimanual.

It has been shown that bimanual versus unimanual mode effects, wherein unimanual is slower, are caused by differences in cortical processing demands, where unimanual is associated with heavier cortical processing demands (Koeneke et al. 2004). What about intermanual versus bimanual mode effects, wherein intermanual is faster? The cortical demand theory seems to suggest that intermanual should be slower than bimanual, because both people are contributing unimanually to overall performance. However, previous research has found the opposite. Because coordination is between people in the intermanual mode, the cortical demand theory may not fully apply. Therefore, researchers have looked beyond the cortical demand theory and towards interpersonal factors for potential explanations for intermanual mode effects.

Zheng et al. (2005) and Zheng, Swanström, and Mackenzie (2007) argued that dyads performing intermanually were able to gain a speed advantage over bimanual performance in their laparoscopic cutting task by anticipating each other's movements through the development of shared knowledge (e.g. a shared mental model; Cannon-Bowers, Salas, and Converse 1993), thereby circumventing biomechanical limitations of individual performance. Gorman and Crites (2013) replicated the effect in a teleoperations task and agreed that intermanual performance was likely faster due to anticipatory movements. However, we argued that shared knowledge is beyond the requirements of simple intermanual coordination tasks, which seem to be based more on real-time perceptual–motor interactions. Specifically, we argued that intermanual speed advantages were due to dyads' reliance on mutual perceptual information rather than on individual biomechanical constraints (see also, Mechsner et al. 2001).

This issue can be disentangled, to a degree, using the shoe-tying task. Because people learn different shoe-tying strategies from an early age (e.g. 'Bunny ears' vs. 'Loop-the-loop'; Murphy 2004), 'same' dyads (i.e. homogeneous strategies) have a higher degree of shared knowledge and movement representations than 'mixed' dyads (i.e. heterogeneous strategies). Because 'mixed' dyads have different shoe-tying strategies, they must rely on a more varied perceptual–motor array of shoe-tying patterns to coordinate intermanual performance. Hence, similarities and differences between participants' initial shoe-tying strategies introduce the question of whether intermanual performance is better when shared strategies and movement representations are in place (same) versus enhanced reliance on perceptual–motor interactions when they are not (mixed).

Because same dyads have access to shared strategies and movement representations, whereas mixed dyads must rely more heavily on real-time perceptual–motor interactions, the 'same' versus 'mixed' distinction also has a 'top-down' versus 'bottom-up' processing dimension. In previous research in another team domain, we found that shared top-down procedures interfere with novel task performance, whereas bottom-up organisation of new coordination links facilitates novel task performance (Gorman, Cooke, and Amazeen 2010), so we expected mixed dyads to outperform same dyads. But why should we expect this with novel intermanual shoe tying?

One challenge of tying in an intermanual mode is that experienced tiers have to suppress highly practised ('automatic') bimanual patterns to accommodate each other's unique movement timings. If bimanual automaticity interferes with intermanual performance in this way, then it explains why novices perform so well as dyads in past research because, for novices, automaticity has not yet set in.[1] In the shoe-tying task, because intermanual patterns are congruent with the bimanual strategies of same dyads, it should be more difficult for them to suppress automatic motor patterns during the intermanual task of coordinating novel movement timings. However, because intermanual patterns are incongruent with the bimanual strategies of mixed dyads, they should be in a better position to coordinate novel movement timings. In this way, we think that top-down processing of 'familiar' patterns by same dyads will result in poorer performance than bottom-up processing of 'unfamiliar' patterns by mixed dyads: because all intermanual shoe-tying patterns are, by their nature, novel and unfamiliar, the mixed dyad approach should be a better fit to the task at hand.

Finally, because performance should already be 'automatic' in the bimanual but not in the intermanual mode, we expected the previously reported intermanual speed advantage (using novices) to be absent in the shoe-tying task. We expected the opposite mode effect, such that bimanual should be faster than intermanual. This would not be surprising, of course, but it would demonstrate that mode effects are, in general, context- and task-specific (Jung et al. 2011). Assuming that intermanual is inferior to bimanual performance, what is the nature of intermanual skill acquisition such that dyads might tie effectively?

1.2 Practice effects and motor transfer in the intermanual mode

To establish that participants were already skilled in the bimanual but not in the intermanual mode, we examined speed–variability shoe-tying correlations in each mode. When movements are unskilled, subcomponents (i.e. the hands) are more variably related from trial to trial, such that the cooperative system is ‘loosely assembled’ (Thelen et al. 1993). However, when movements are highly skilled, we should see fast performance with little variability from trial to trial. From this perspective, we expected bimanual shoe tying to reflect a greater skill level through faster task performance correlated with lower variability; if intermanual really is a novel mode, then we should not see that same pattern of correlation for intermanual shoe tying. If that was the case, then we analysed practice effects to help identify the nature of skill acquisition in the novel intermanual mode.[2]

Practice effects generally entail that performance (here, trial times) of a novel task improves (trial times decrease) with the number of trials performed. We assumed we would see practice effects with intermanual but not with bimanual trial times, but the more specific question of *how* performance improves in the intermanual mode was our primary concern. The ‘how’ question is important because, if we know how people improve with practice, then it suggests what they need to learn to perform effectively. We specifically asked, what type of practice function best describes the relationship between practice and performance in the novel intermanual mode?

In specifying candidate practice functions, we looked towards the cognitive and motor learning literatures. Let y be the time taken to perform a task (e.g. tie a shoe), x be trial number, y_0 be the time to perform the task prior to practice and r be the rate of change in performance (i.e. decrease in trial time) as practice (number of trials) increases. These variables and parameters can be arranged in conventional ways to specify qualitatively different functions relating practice and performance (Equations (1)–(3); Anderson 2001; Heathcote, Brown, and Mewhort 2000; Newell, Liu, and Mayer-Kress 2001).

$$\text{linear}: \quad y = y_0 - rx, \tag{1}$$

$$\text{power law}: \quad y = y_0 x^{-r}, \tag{2}$$

$$\text{exponential}: \quad y = y_0\,\mathrm{e}^{-rx}. \tag{3}$$

In Equation (1) (linear), performance is arithmetically related to amount of practice, such that performance changes in the same way following each trial. This function, however, may be more typical of transfer effects (Gorman and Crites 2013) than practice effects. Both Equations (2) and (3) describe nonlinear practice effects, which are more typical of skill acquisition. In Equation (2) (power law), performance varies as a power of practice, such that performance changes exponentially as practice changes exponentially (i.e. a power law is linear on a log–log plot). The ‘power law of practice’ is found when the distribution of performance is the same over different scales of practice. Because of this ‘scale invariance’ property, a power law describes practice effects across learners with different performance characteristics (Newell, Liu, and Mayer-Kress 2001). In Equation (3) (exponential), the change in performance on each trial is proportional to number of trials performed, such that performance increases exponentially as practice increases arithmetically (i.e. an exponential function is linear on a log–linear plot). Exponential practice effects are found when the distribution of performance is bound to a specific scale of practice. Lacking the power law’s scale invariance property, exponential practice effects describe a unique trajectory towards a fixed-point of learning (Newell, Liu, and Mayer-Kress 2001). By seeing which function best fits intermanual trial times, we can draw out the nature of practice effects as simple transfer (linear), as the combining of different performance characteristics during skill acquisition (power law), or as the emergence of a unique performance trajectory (exponential) underlying intermanual skill acquisition.

Traditionally, a power law is thought to be the general law of practice (Newell and Rosenbloom 1981), which is due largely to seminal works in the fields of cognitive and motor learning that studied skill acquisition by combining data across different learners (e.g. Crossman 1959; Snoddy 1926). Whereas a power law is a better fit for practice effects combined across learners with different performance characteristics, an exponential function is a better fit for a practice effect on a unique performance trajectory (Newell, Liu, and Mayer-Kress 2001; Newell, Mayer-Kress, and Liu 2006; Joseph, King, and Newell 2013; Stratton et al. 2007). Based on these differences between power law and exponential practice effects, if dyads combine different, previously learned bimanual performance characteristics to generate intermanual patterns, then we expected to see power law practice effects. Alternatively, if dyads are developing a new skill with a unique performance trajectory, then we expected to see exponential practice effects. In other words, power law practice indicates that dyads build intermanual patterns on top of previously learned bimanual patterns by combining their intrinsically different performance characteristics (i.e. bimanual timing characteristics), whereas exponential practice indicates that dyads must acquire a new performance trajectory.

Another aspect of practice that is useful in identifying the nature of intermanual skill acquisition is motor transfer (Nozaki, Kurtzer, and Scott 2006). If dyads reorganise existing bimanual patterns and timings to perform in the intermanual mode (as would be suggested by power law practice effects), then it stands to reason that initially faster bimanual tiers should slow down and initially slower bimanual tiers should speed up to match each other during intermanual performance. In that case, we expected to observe motor transfer effects wherein initially slower tiers speed up and initially faster tiers slow down during bimanual performance subsequent to intermanual practice. Alternatively, if intermanual patterns and timings are specific to the intermanual mode (as would be indicated by exponential practice functions), then we should not observe motor transfer.

To look for the presence or absence of motor transfer, we examined differences between bimanual shoe-tying trial times before and after intermanual performance for significant speeding up or slowing down. If motor transfer is observed, then this would further indicate that intermanual performance requires the acquisition of novel intermanual timings across dyads' different bimanual performance characteristics, rather than the acquisition of an altogether different shoe-tying skill.

1.3 Dynamic coupling between the hands

We have described how we examine mode effects and practice effects in terms of trial times, but how do we examine mode differences in the shoe-tying process itself? We propose that the need for the hands to either move together (coupled) or work independently (uncoupled) during task performance varies according to coordination mode. To assess varying degrees of dynamic coupling between the hands, we analysed movement time series from the left and right hands during shoe tying using cross recurrence quantification (CRQ) analysis, which is a method for analysing coupling between any two dynamical systems (Shockley et al. 2002).

Coupling across a medium (e.g. a physical or mechanical connection) allows two dynamical systems to influence each other's behaviour. For example, the pendulums of two clocks hanging on the same wall are physically coupled through the wall and synchronise over time (Huygens 1673; Strogatz 2003). However, if the clocks are uncoupled, by hanging them on different walls, then they will not influence each other, and they will not synchronise. Measuring coupling using CRQ analysis allows us to assess the degree to which two systems (here, the hands) are able to influence each other through different coupling mediums.

CRQ analysis proceeds by constructing a cross recurrence plot (CRP). A CRP represents the times at which two dynamical systems that generate two observed time series are in a similar dynamical state by plotting a point whenever those systems inhabit the same location of a shared dynamical space (a 'phase space'; Figure 1b). The plotted points are called 'recurrent points', and the amount and relative spacing of recurrent points in a CRP are used to assess coupling between the two systems. Figure 1 shows an example shoe-tying CRP and illustrates the basic sequence of CRP steps as (a) collection of hand time series data, (b) reconstructing a shared phase space across the hands and (c) plotting recurrent points in the CRP whenever the hands share the same location in phase space. The specifics of how we perform these steps are provided in Section 2.

Following standard CRQ procedures, we quantified coupling in terms of percentage recurrence (%REC), which is the number of recurrent points divided by the possible number of recurrent points in a CRP (in Figure 1c, the amount of filled-in space divided by the total space) and MAXLINE, which is the longest diagonal sequence of recurrent points in a CRP (Shockley et al. 2007; Shockley, Santana, and Fowler 2003; in Figure 1c, the longest diagonal line segment of the filled-in space). In this study, %REC quantifies the degree to which the hands are coupled, and MAXLINE quantifies the stability of that coupling (Aks 2011; Shockley et al. 2002).

For coupling to occur during shoe tying, there must be a coupling medium linking the hands. In the bimanual case, this coupling can be through neuromuscular and perceptual channels. In the intermanual case, we are dealing with physically separate neuromuscular systems, so this coupling can only occur through perceptual (e.g. visual; haptic) channels (Richardson, Marsh, and Schmidt 2005). If coupling (%REC; MAXLINE) differs between bimanual and intermanual coordination modes, then it may be explained by differences in the coupling mediums associated with those modes.

1.4 This study

We asked dyads to tie a shoe-like apparatus during three blocks of trials. First, participants completed the task as they normally would, bimanually. Next, participants completed the task as a dyad, intermanually, with each participant handling one shoelace. Finally, each participant completed the task once more bimanually. The purpose of the first set of bimanual trials was to provide a baseline against which intermanual performance may be compared and to determine participants' shoe-tying strategies prior to intermanual performance. The purpose of the intermanual trials was to investigate mode effects and practice effects in this novel coordination mode. The purpose of the second set of bimanual trials following intermanual performance was to determine whether motor transfer occurred from the intermanual trials to subsequent bimanual performance.

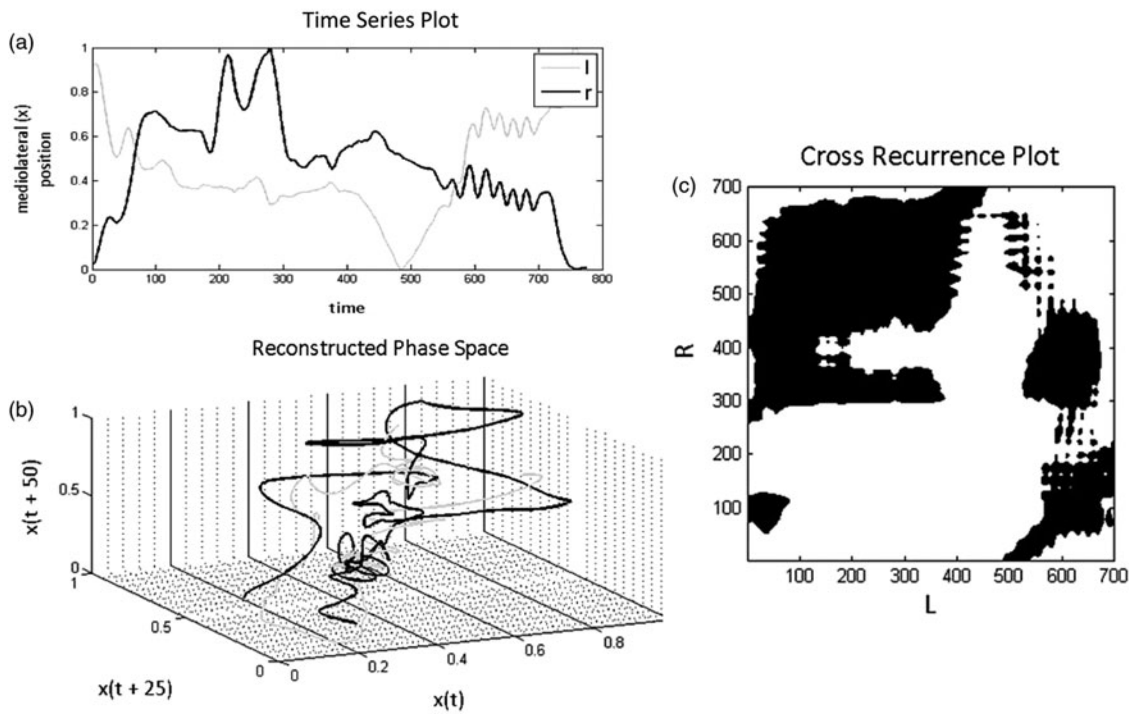

Figure 1. (a) Right (r [black]) and left (l [grey]) time series from a Bunny-ear trial, (b) PSR of that trial (only three-dimensions are shown for illustrative purposes) and (c) CRP for that trial. The large black cross-recurrent pattern in the top-left portion of (c) corresponds to left-handed (early in the trial) followed by right-handed (later in the trial) bunny-ear formation.

Dyads' shoe-tying data were analysed in several ways to address the following questions:

- Are mode effects present for intermanual compared with bimanual for this highly practised task, and does having a same versus mixed shoe-tying strategy differently impacts dyads' performance in the intermanual mode?
- Do speed–variability correlations confirm that participants are bimanually but not intermanually skilled, and, if so, then what do practice functions look like when people perform in the novel intermanual mode?
- Does motor transfer occur from intermanual to subsequent bimanual performance?
- What does coupling between the hands look like under the different coordination modes, and how is it related to task performance?

2. Methods

2.1 Participants

Seventy-two undergraduates (36 dyads) from a major university in the southern USA participated for partial course credit. Participants' mean age was $M = 18.60$ (SD $= 1.09$), and 75.3% were female. The preponderance of female participants was unplanned. Three dyads were all male, 21 were all female and 12 were mixed gender. Four dyads reported knowing each other (i.e. classmates) prior to participation. All participants were required to be right handed, which was verified using the Edinburgh Handedness Inventory (Oldfield 1971). All participants reported being familiar with shoe tying, and 85.1% reported tying a shoe at least daily or weekly.

2.2 Experimental design

Participants first used the bimanual coordination mode to complete 10 trials (B1). Next, participants used the intermanual mode to complete 20 trials as a dyad (Inter). Finally, participants completed another 10 trials using the bimanual coordination mode (B2). Members of dyads participated in the B1 and B2 conditions separately. A within-subjects variable, Coordination Mode, indexed the first, second and third blocks of trials. All dyads participated in the same coordination mode order: B1 → Inter → B2. The number of trials in each block was determined by the number of trials required to reach performance asymptote during pilot testing.

An experimenter observed participants through a video monitor during B1 to record their shoe-tying strategy (i.e. ‘Bunny ears’, ‘Loop-the-loop’ or ‘Other’). If dyad members used the same strategy during B1, then the dyad was assigned to the same level of a two-level between-dyads organismic variable, strategy. If dyad members used different strategies during B1, then the dyad was assigned to the mixed level of strategy (there were eight mixed-strategy dyads). Hence, the experiment was a 3 (Coordination Mode) × 2 (Strategy) mixed-subjects design.

Verbal communication (talking vs. non-talking) was also manipulated between-dyads. However, that manipulation had no bearing on the study’s outcomes and is not reported in this paper.

2.3 Apparatus

A black shoe-like apparatus (referred to hereafter as the ‘shoe’) was secured on top of a black cardboard box. We used this apparatus instead of a real shoe so as not to bias participants with a particular shoe type (e.g. men’s vs. women’s). A grey lace was used to tie the shoe, and small black pushpins were used to set the laces in their starting positions for each trial. Small white squares located on either side of the shoe served as home keys. The home keys marked participants’ required starting and ending positions for each trial. Figure 2 shows the shoe.

An eight-camera Vicon MX-T10 motion capture system captured participants’ movements (100 Hz) as they tied the shoe. Data were collected from reflective markers attached to rubber rings that participants wore on their index fingers. A 2.4 GHz wireless camera was focused on participants’ hands while they tied the shoe and transmitted real-time colour video to a 19 in. HD monitor located at an experimenter control station. This video feed was used to identify participants’ shoe-tying strategy during the B1 trials and was not recorded.

2.4 Measures

2.4.1 Shoe-tying speed

To measure shoe-tying speed, a predetermined volume (Figure 3) was used to start and stop motion capture analysis for each trial. The exact location of the start/stop volume was determined during pilot testing and was located 25 mm (approximately 1 in.) above the home keys. The start/stop volume was used to identify the onset and offset of movement

Figure 2. The shoe apparatus used in this study: (a) side-view of the shoe, (b) top-down view of the shoe with the markers on the home keys, (c) motion capture room and (d) a participant wearing a ring-marker at the starting/ending position on the right home key.

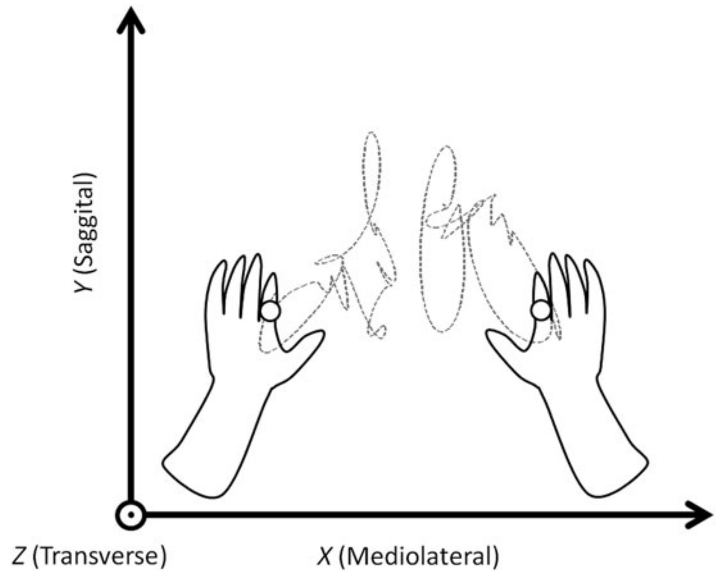

Figure 3. Orientation of the shoe coordinate system showing example movement data (dashed lines) from a ‘Loop-the-loop’ trial; the start/stop volume was fixed in the coordinate system, with its base 25 mm (approximately 1 in.) above the home keys in the positive transverse direction (the positive transverse axis points out of the paper).

duration for each trial, such that movement onset occurred when the first hand entered the volume, on its way to the shoe, and offset occurred when the last hand exited the volume, on its way back to its home key. For example, if a participant’s left hand crossed into the start/stop volume first, on its way to the shoe, then trial time started; if the participant’s right hand exited the start/stop volume last, on its way back to its home key, then trial time stopped. Trial time was measured as offset minus onset in seconds. Trial times in the bimanual coordination mode were averaged between participants for comparison with intermanual trials. Participants were never explicitly informed of bimanual performance differences within their dyad.

The start/stop volume was used also to truncate movement data for subsequent variability and dynamic coupling analysis by removing samples at the beginning and end of a trial when participants’ hands were not in the start/stop volume, which eliminated non-shoe-tying information from those analyses.

2.4.2 *Shoe-tying variability*

Shoe-tying variability was measured in millimetres in the mediolateral (X) dimension. The mediolateral dimension contained the most shoe-tying information: it had greater variance across trials ($M = 2435.36$; SD $= 1028.97$) than either the saggital (Y) ($M = 629.69$; SD $= 577.51$) or the transverse (Z) ($M = 241.61$; SD $= 1065.92$) dimensions. Generalised variance (GenVar; Wilks 1960) was used because it provides a single, scalar index of the multivariate scatter of measurements between the hands. GenVar was computed for each trial as the determinant of the covariance matrix between the left and right hands for that trial (Equation (4)). GenVar scores in the bimanual coordination mode were averaged between participants for comparison with intermanual trials. Participants were never explicitly informed of bimanual variability differences within their dyad.

$$\text{GenVar} = \begin{vmatrix} \text{Var(right)} & \text{Cov(right, left)} \\ \text{Cov(right, left)} & \text{Var(left)} \end{vmatrix} = \text{Var(right) Var (left)} - \text{Cov(right, left)}^2. \quad (4)$$

2.4.3 *Covariate measures*

These measures were taken to control for possible confounds on shoe-tying performance. We measured participant’s dexterity and their hand span for this purpose. We also collected responses on demographic and debriefing surveys for this purpose; however, those data had no bearing on the outcomes of any statistical analyses and are not reported in this paper.

To measure dexterity, the Grooved Pegboard test (Trites 1989) was administered using instructions provided by Lafayette Instruments (Instrument 2002). Participants fit grooved pegs into a pegboard as fast as possible twice for each hand. The average completion time across trials and across hands was taken as the overall dexterity score, where a lower score indicates better dexterity. Each participant's hand span was recorded as the distance between the tip of their thumb and the tip of their pinky finger, with those fingers outstretched. Hand span measures were recorded separately for each hand and averaged to obtain an overall score.

2.4.4 Dynamic coupling measures

Prior to CRQ analysis, we used a second-order Butterworth low-pass filter to smooth all mediolateral data. We chose a cut-off frequency of 85 Hz, such that the summed residuals of the filtered data were zero across 20 randomly selected trials (10 right hand and 10 left hand). We used forward–backward filtering to retain all phase information.

To perform CRQ analysis, we first performed phase space reconstruction (PSR) on each time series. Given that an observed univariate time series is generated by a higher dimensional dynamical system, PSR is a necessary first step to unpack the time series into an appropriate number of dynamical dimensions (the 'embedding dimension') to track the state of the dynamical system (Takens 1981). For CRQ, it is needed to determine when the two systems are 'close enough' within a threshold to say they are in the same dynamical state. Using the empirical PSR approach (Abarbanel 1996), we chose the first minimum of the average mutual information function as the time delay (τ), and we then used that τ to choose the number of time-delayed dimensions (d_E) at which the false nearest neighbour function reached zero. The integer dimension d_E specifies the number of independent dynamical dimensions (i.e. dynamical degrees of freedom; position, velocity and so forth) needed to unfold the time series into the proper embedding dimension for the dynamical system that generated it. Following recommendations for CRQ analysis, all movement data were normalised and rescaled using maximum-distance rescaling prior to PSR (Shockley 2005). For technical references on these analyses, we refer the reader to Aks (2011) and Shelhamer (2007; Chapters 8 and 9).

Based on performing PSR on 20 randomly selected trials, the dynamical space for shoe tying was highly consistent, with $\tau = 25$ and $d_E = 4$. With four dimensions, we accounted for four dynamical degrees of freedom (displacement, velocity, acceleration and jerk) with a time delay of 0.25 s for shoe tying. We specified a 25% maximum distance radius for detecting recurrent points (Shockley 2005), which resulted in a 5–7% recurrence across the randomly selected trials. Figure 1 shows an example shoe-tying CRP using the PSR parameter values $\tau = 25$ and $d_E = 4$ with radius = 25%, which we used in constructing all CRPs.

To construct a CRP for each shoe-tying trial, the left (l) and right (r) hand time series (Figure 1a) were unfolded into a shared dynamical space using the PSR parameter values and radius setting described above (Figure 1b). Recurrent points were plotted in the CRP whenever the trajectories L and R crossed within 25% maximum distance of the two most separate points in the PSR (Figure 1c). As shown in the example of Figure 1, the axes of the CRP correspond to time, such that a recurrent point plotted at [200, 100] indicates that R and L were in the same dynamical state at time 200 of the right-hand time series and at time 100 of the left-hand time series.

Once a CRP was constructed for each trial, we extracted %REC and MAXLINE from each plot. %REC quantifies coupling between the left and right hands and is computed as the total number of recurrent points divided by the total number of possible recurrent points, as a percentage (Equation (5); Shockley 2005). For example, the %REC of the CRP in Figure 1 is 37%. If the CRP were more filled in, then %REC would be higher.

$$\%\mathrm{REC} = \frac{\text{total number of recurrent points}}{\text{total number of possible recurrent points}} \times 100. \tag{5}$$

MAXLINE quantifies the stability of recurrent patterns and is computed as the longest continuous diagonal of recurrent points (Shockley 2005). MAXLINE is inversely related to the largest Lyapunov exponent, an index of dynamical stability (Aks 2011; Gorman et al. 2012). The MAXLINE of the example CRP in Figure 4 is 416 samples, which corresponds to left-handed followed by right-handed bunny-ear formation in a Bunny-ear trial. %REC and MAXLINE scores in the bimanual coordination mode were averaged between participants for comparison with intermanual trials.

2.5 Procedure

Informed consent was obtained prior to the start of each experimental session. Participants were then shown the shoe and were read a description of the coordination modes in which they would be tying the shoe. Participants were instructed to 'tie the shoe as quickly as possible' and to 'tie the shoe similar to the way you would normally tie a shoe'. Prior to each trial, participants were instructed to place the marker rings on their index fingers and to put their hands as flat as possible on the

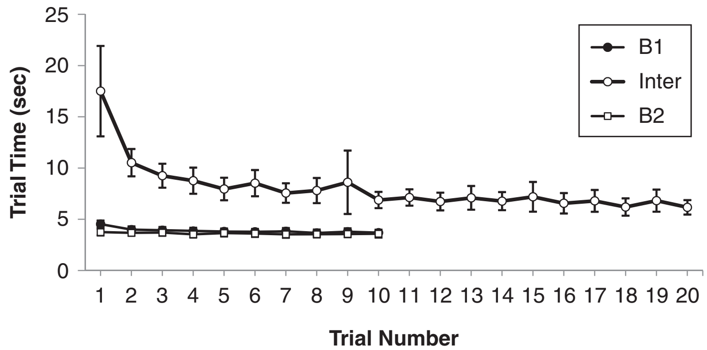

Figure 4. Mean trial times showing performance asymptote for the first set of bimanual trials (B1), the intermanual trials (Inter) and the second set of bimanual trials (B2). Error bars are 95% confidence intervals.

box with markers centred on the home keys. At the outset of each trial, the experimenter started motion capture and indicated that participants should start when ready by ringing an electronic bell. Participants indicated trial completion by saying 'Done' with their hands back in the flat position on the home keys. The experimenter then stopped motion capture and inspected the knot to ensure it was securely tied (one dyad was replaced due to their inability to securely tie the knot). To ensure that the starting position was identical for each trial, the initial fold-over tie was locked into place, and the laces were secured in their starting positions using pushpins. Participants were instructed not to retie the fold-over tie and to not double-knot the laces.

Participants were randomly assigned as either Participant 1 (P1) or Participant 2 (P2). P1 completed the B1 trials while P2 completed the Grooved Pegboard test, the Edinburgh Handedness Inventory and the demographics survey. Participants then switched roles. Individual instructions were given to each participant for their current task. The experimenter recorded each participant's shoe-tying strategy during their B1 trials. After the B1 trials, P1 and P2 completed the intermanual trials. For the Inter condition, P1 was instructed to sit on the right side of the shoe and to use their right hand, and P2 was instructed to sit on the left side of the shoe and to use their left hand (note that P1 was the faster bimanual tier in 16 dyads and P2 was the faster bimanual tier in 20 dyads). Participants were instructed to put their free hand either behind their back or underneath their leg, such that their free hand should not interfere with the task in any way. Upon completing the Inter condition, the dyad was again separated. P1 then completed the B2 trials while P2's hand span measurements were recorded. Participants then switched roles, and P2 completed the B2 trials while P1's hand span measurements and post-test survey were completed. P2 then completed the post-test survey. Both participants were then debriefed and thanked for their time. Experimental sessions lasted 75 min.

3. Results

3.1 Mode effects and 'same' versus 'mixed' intermanual strategies

Repeated contrasts on the instructed performance variable, Speed, were first analysed between each level of trial to determine whether dyads reached asymptotic levels of performance in each coordination mode. Trial 1 versus Trial 2 contrasts were significant for B1 ($p < 0.001$) and Inter ($p < 0.001$); none of the contrasts were significant for B2. As shown in Figure 4, trial times did not continue to significantly decrease beyond Trial 2 in a linear sense. However, the visible numeric decreases in trial times are analysed below to examine nonlinear practice effects.

Because performance asymptote occurred prior to the last trial in all conditions, and because participants were instructed to 'tie the shoe as quickly as possible for every trial', the minimum trial time (MinTime) was obtained for each dyad across all trials at each level of Coordination Mode for analysing mode effects. MinTime measures the highest level of performance achieved at each level of Coordination Mode.

MinTime was analysed using a 3 (Coordination Mode) × 2 (Strategy) mixed ANCOVA. Dexterity was used as a covariate because it was significantly correlated with MinTime at each level of Coordination Mode (all $r > 0.35$ and $p < 0.05$). As would be expected, MinTime increased as Dexterity decreased. The covariate was significant in the ANCOVA, $t(33) = 2.95$, $p < 0.01$, $\eta^2 = 0.21$. Standard homogeneity of regression and independence of treatment and covariate assumptions were upheld. We note the statistical conclusions were the same whether the covariate was used or not.

The main effect of Coordination Mode was significant, $F(2, 33) = 30.81$, $p < 0.01$, $\eta^2 = 0.65$, indicating a mode effect (Figure 5a). We conducted planned follow-up main comparisons on Coordination Mode to analyse the mode effect. Inter MinTime ($M = 5.02$; SD = 1.66) was significantly slower than both B1 ($M = 3.39$, SD = 0.80), $F(1, 34) = 14.89$,

$p < 0.001$, $\eta^2 = 0.31$, and B2 ($M = 3.19$, SD $= 0.80$), $F\,(1, 34) = 25.36$, $p < 0.001$, $\eta^2 = 0.43$. B1 was not significantly different from B2 ($p > 0.09$).

The Coordination Mode × Strategy interaction was significant, $F\,(2, 33) = 4.48$, $p < 0.02$, $\eta^2 = 0.21$. A planned follow-up simple effects analysis was conducted on Strategy at each level of Coordination Mode to determine whether same versus mixed shoe-tying strategies differently impacted speed in the intermanual mode. The simple effects analysis revealed that the effect of Strategy was significant at the Inter level of Coordination Mode, $F\,(1, 33) = 4.22$, $p < 0.05$, $\eta^2 = 0.11$, but not at either B1 or B2 ($p > 0.12$). As shown in Figure 5b, mixed strategy dyads ($M = 3.98$, SD $= 1.30$) exhibited significantly faster MinTime than same strategy dyads ($M = 5.31$, SD $= 1.65$), $F\,(1, 33) = 4.22$, $p < 0.05$, $\eta^2 = 0.11$.

3.2 Speed–variability correlation

GenVar was computed for each trial at which MinTime was observed. In this way, GenVar was yoked to MinTime in terms of the highest level of performance achieved at each level of Coordination Mode. MinTime and GenVar were uncorrelated across all of these trials, $r\,(106) = 0.02$; however, to determine whether the speed–variability relationship reflected skill level, we analysed these correlations separately for each Coordination Mode. Table 1 shows the relevant correlations in bold.

MinTime was positively correlated with GenVar within and between the B1 and B2 conditions; however, they were uncorrelated in the Inter condition. These significant positive correlations in the bimanual conditions confirm that participants were highly skilled in that coordination mode.

3.3 Practice effects and motor transfer

To examine practice effects and the nature of intermanual skill acquisition, we fit linear, exponential and power law functions to trial times with trial number as the independent variable. We also fit these function to the bimanual trial times to provide points of reference against which practice effects in the novel intermanual mode could be compared. Because participants were instructed to tie the shoe as quickly as possible, and given no indication that they would be evaluated on the basis of variability, we analysed practice effects for trial times only. We did not average across dyads' trials in each

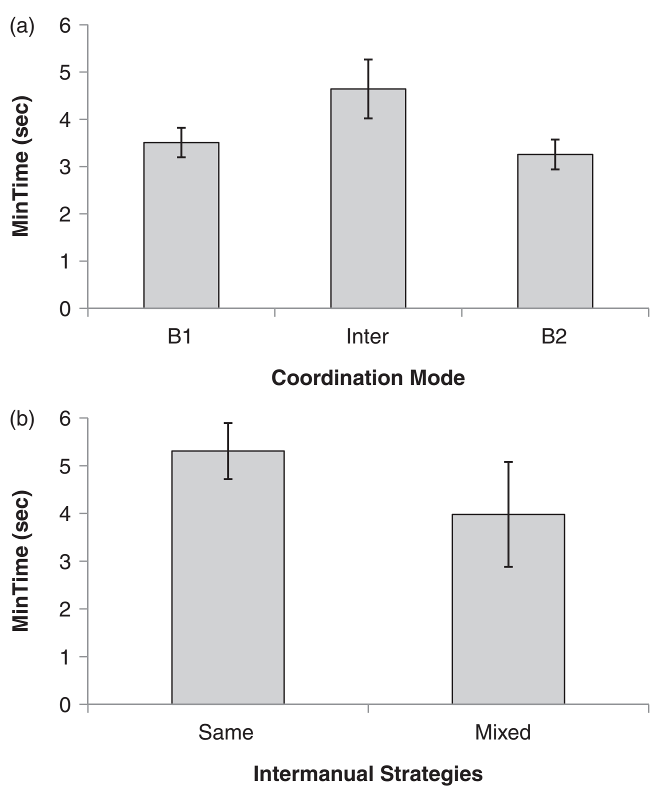

Figure 5. (a) Mean MinTime for the first set of bimanual trials (B1), the intermanual trials (Inter) and the second set of bimanual trials (B2) and (b) mean MinTime for dyads with a same versus mixed shoe-tying strategy in the intermanual condition. Error bars indicate 95% confidence intervals.

Table 1. Intercorrelations between MinTime and GenVar at each level of Coordination Mode.

	1	2	3	4	5	6
1. B1 MinTime	1.00					
2. Inter MinTime	0.29	1.00				
3. B2 MinTime	0.94**	0.42*	1.00			
4. B1 GenVar	**0.52****	**− 0.00**	**0.37***	1.00		
5. Inter GenVar	**−0.07**	**0.15**	**0.05**	− 0.04	1.00	
6. B2 GenVar	**0.61****	**0.04**	**0.49****	0.96**	0.09	1.00

Notes: $N = 36$; *$p < 0.05$; **$p < 0.01$. B1, first set of bimanual trials; Inter, intermanual trials; B2, second set of bimanual trials. Speed–variability correlations are in bold.

coordination mode prior to fitting the functions, as recommended for identifying the time scaling characteristics of skill acquisition (Newell, Liu, and Mayer-Kress 2001; Newell, Mayer-Kress, and Liu 2006; Stratton et al. 2007). However, the data were averaged across participants within each dyad in the bimanual (B1 and B2) conditions. The amount of variance explained (R^2) was calculated for linear, exponential and power law fits for each dyad at each level of Coordination Mode (Figure 6).

The individual R^2 values were analysed using a 3 (Coordination Mode) × 2 (Strategy) × 3 (Practice Function) mixed ANOVA. The main effect of Practice Function was significant, F (2, 68) 22.49, $p < 0.001$, $\eta^2 = 0.40$. Over all experimental conditions, a power law was a better fit to the trial series ($M = 0.32$; SD $= 0.13$) than either linear ($M = 0.24$; SD $= 0.12$) or exponential ($M = 0.26$; SD $= 0.11$) functions. The Coordination Mode × Practice Function interaction was significant, F (4, 136) $= 10.29$, $p < 0.001$, $\eta^2 = 0.23$. A post hoc simple effects analysis ($\alpha_{\text{Bon}} = 0.05/3 = 0.0167$) of Practice Function at each level of Coordination Mode revealed a simple effect of Practice Function for Inter, F (1.30, 44.24; Greenhouse–Geisser correction used) $= 20.49$, $p < 0.001$, $\eta^2 = 0.38$, but not for B1 ($p > 0.02$) or B2 ($p > 0.75$). As shown in Figure 6, the Inter data were better fit by a power law ($M = 0.46$; SD $= 0.25$) than by either a linear ($M = 0.27$; SD $= 0.15$) or an exponential function ($M = 0.33$; SD $= 0.18$). There were no significant Strategy effects.

Table 2 shows mean R^2 model fit values over individual trial series (i.e. the fit values analysed here) and R^2 values for the group-averaged trial series (e.g. the classic approach used in studies by Crossman (1959) and Snoddy (1926)). The R^2 values for the group-averaged data were characteristically larger than the R^2 values for the averaged individual data, which is in line with prior results (e.g. Joseph, King, and Newell 2013; Stratton et al. 2007).

The results in Table 1 suggest positive motor transfer from intermanual to subsequent bimanual performance. As shown by the pattern of correlations between B1–MinTime, Inter–MinTime and B2–MinTime in Table 1, speed in the first set of bimanual trials was uncorrelated with speed in the intermanual trials, r (34) $= 0.29$, $p > 0.09$. However, dyads that tied faster in the intermanual trials tended to tie faster in second set of bimanual trials, r (34) $= 0.42$, $p = 0.01$. As shown in Table 1, we did not observe that same pattern for variability.

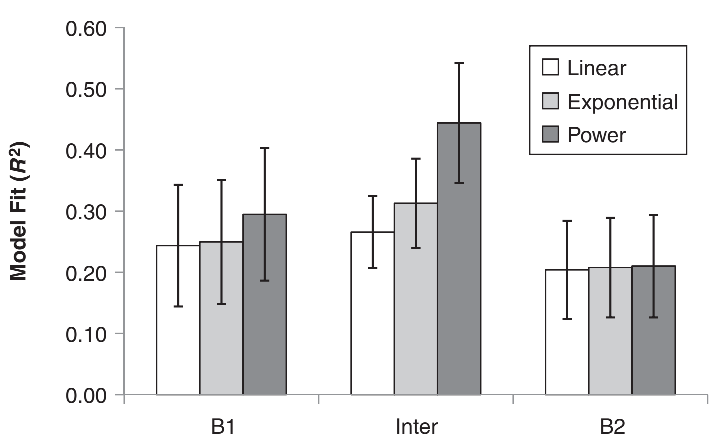

Figure 6. Average model fit (R^2) for linear, exponential and power law functions for individual data as a function of coordination mode (B1, first set of bimanual trials; Inter, intermanual trials; B2, second set of bimanual trials). Error bars indicate 95% confidence intervals.

Table 2. Model fit values (R^2) at each level of Coordination Mode for linear, exponential and power law fits across individual and group-averaged speed data.

	Linear	Exponential	Power
Means of individual fits			
B1	0.30	0.30	0.37
Inter	0.27	0.33	0.46
B2	0.16	0.16	0.16
Fits of group-averaged data			
B1	0.61	0.62	0.86
Inter	0.49	0.55	0.86
B2	0.54	0.54	0.65

Note: B1, first set of bimanual trials; Inter, intermanual trials; B2, second set of bimanual trials.

To determine whether tying with a partner compelled either slower partners to speed up or faster partners to slow down during the second set of bimanual trials, we performed analyses comparing shoe-tying speed (MinTime) at B1 versus B2 separately for slower and faster members of dyads. Two post hoc paired-samples t-tests ($\alpha_{\mathrm{Bon}} = 0.05/2 = 0.025$) revealed that initially slower partners significantly sped up from B1 ($M = 3.80$; SD = 1.07) to B2 ($M = 3.47$; SD = 1.11), t (35) = 4.85, $p < 0.001$, $d = 0.81$. However, speed of initially faster partners was not altered from B1 ($M = 2.97$; SD = 0.64) to B2 ($M = 2.90$; SD = 0.65), t (35) = 1.18, $p = 0.246$, $d = 0.20$. A separate follow-up analysis indicated that this effect was not moderated by Strategy.

We also examined speed differences between individual bimanual times (i.e. before averaging) to examine performance differences before and after intermanual tying. Post hoc independent-samples t-tests ($\alpha_{\mathrm{Bon}} = 0.05/2 = 0.025$) indicated that faster tiers were significantly faster than their slower partners during both B1, t (34) = 3.98, $p < 0.001$, $d = 0.66$, and B2, t (34) = 2.65, $p = 0.01$, $d = 0.44$. However, dyads shaved 0.16 s off this initial difference from B1 (mean difference = 0.83 s) to B2 (mean difference = 0.67 s); paired-samples t (35) = 1.96, one-tailed $p < 0.03$, $d = 0.32$. Intermanual performance was uncorrelated with the size of the within-dyad, bimanual performance difference (i.e. absolute value of faster minus slower time) for both B1, r (34) = 0.14, $p = 0.43$, and B2, r (34) = 0.04, $p = 0.83$. Intermanual performance was also uncorrelated with both slower, r (34) = 0.26, $p = 0.13$, and faster, r (34) = 0.28, $p = 0.10$, participants' B1 times, but was positively correlated with both slower, r (34) = 0.34, $p = 0.041$, and faster, r (34) = 0.45, $p = 0.006$, participants' B2 times. Separate follow-up analyses indicated that none of these effects were moderated by Strategy.

3.4 Dynamic coupling between the hands

Because participants were instructed to tie the shoe as quickly as possible, we analysed %REC and MAXLINE for the trials at which MinTime was recorded. No covariates were significant in this analysis.

%REC was analysed using a 3 (Coordination Mode) × 2 (Strategy) mixed ANOVA. The main effect of Coordination Mode was significant, F (2, 33) = 7.10, $p < 0.01$, $\eta^2 = 0.30$ (Figure 7a); no other omnibus effects were significant. Post hoc main comparisons on Coordination Mode ($\alpha_{\mathrm{Bon}} = 0.05/3 = 0.0167$) revealed that Inter resulted in significantly higher %REC ($M = 10.24$; SD = 7.96) than either B1 ($M = 3.62$; SD = 4.66), F (1, 34) = 11.29, $p < 0.01$, $\eta^2 = 0.25$, or B2 ($M = 3.13$; SD = 4.29), F (1, 34) = 13.59, $p < 0.01$, $\eta^2 = 0.29$. B1 and B2 were not significantly different.

MAXLINE was similarly analysed using a 3 (Coordination Mode) × 2 (Strategy) mixed ANOVA. The main effect of Coordination Mode was significant, F (2, 33) = 17.09, $p < 0.001$, $\eta^2 = 0.51$ (Figure 7b); no other omnibus effects were significant. Post hoc main comparisons on Coordination Mode ($\alpha_{\mathrm{Bon}} = 0.05/3 = 0.0167$) revealed that Inter resulted in significantly greater MAXLINE ($M = 118.44$; SD = 74.47) than either B1 ($M = 34.97$; SD = 35.34), F (1, 34) = 21.25, $p < 0.001$, $\eta^2 = 0.39$, or B2 ($M = 29.60$; SD = 32.35), F (1, 34) = 26.84, $p < 0.001$, $\eta^2 = 0.44$. B1 and B2 were not significantly different.

Correlations between coupling measures and MinTime were analysed as a function of Coordination Mode to examine how changes in the shoe-tying process were related to performance changes. As shown in Table 3, decreases in %REC and MAXLINE were correlated with decreases in MinTime at each level of Coordination Mode. Simply put, faster performance was associated with increased decoupling between the hands in both coordination modes.

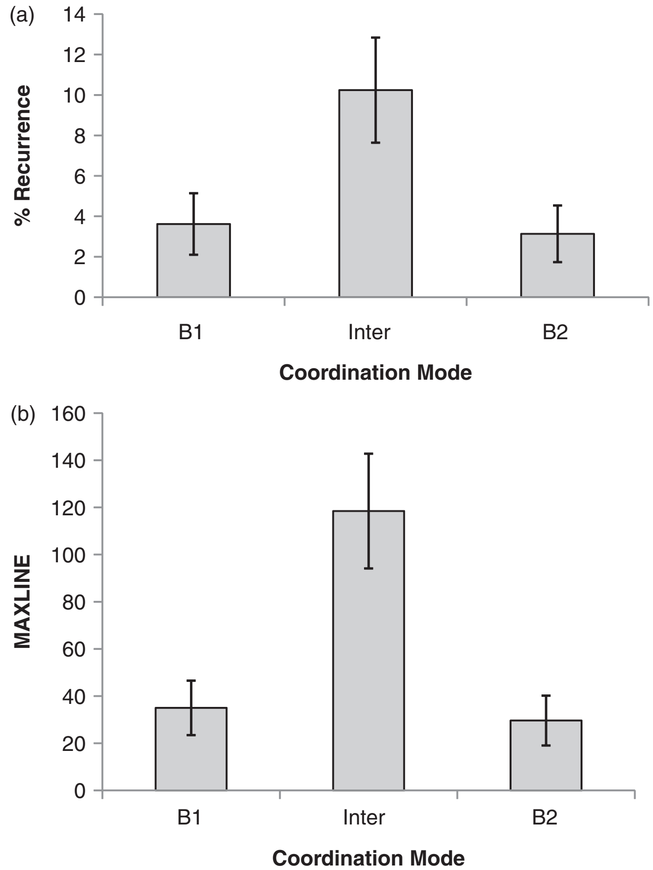

Figure 7. (a) Mean %REC computed over the minimum-time trials for the first set of bimanual trials (B1), the intermanual trials (Inter) and the second set of bimanual trials (B2) and (b) mean MAXLINE computed at MinTime for B1, Inter and B2. Error bars indicate 95% confidence intervals.

4. Discussion

4.1 Mode effects and 'same' versus 'mixed' intermanual strategies

One purpose in using the shoe-tying task was to determine whether previously reported intermanual mode effects, wherein intermanual is faster than bimanual, generalise to well-honed bimanual skills. Unlike earlier studies that found intermanual speed advantages using novices (e.g. Gorman and Crites 2013; Reed et al. 2006; Zheng et al. 2005; Zheng, Swanström, and Mackenzie 2007), we found that intermanual performance was significantly slower than bimanual performance. This mode effect, wherein intermanual is slower, is not surprising and is obviously due to participants' high level of experience with bimanual shoe tying. This finding demonstrates that mode effects are more dependent on task context and prior experience than described in past research.

It is important to note that the amount of intermanual practice in our study was dwarfed by the years of bimanual practice participants brought with them. Thus, it remains unclear whether dyads' intermanual shoe-tying performance could eventually equal bimanual performance with similar amounts of practice (e.g. over years). We have found that novice mode

Table 3. Correlations between the MinTime and the %REC and MAXLINE (ML) dynamic coupling measures for each level of Coordination Mode.

	B1		Inter		B2	
	%REC	ML	%REC	ML	%REC	ML
MinTime	0.73**	0.85**	0.42*	0.75**	0.66**	0.85**

Notes: $N = 36$; $*p < 0.05$; $**p < 0.01$. B1, first set of bimanual trials; Inter, intermanual trials; B2, second set of bimanual trials.

effects can even out and disappear with practice (Gorman and Crites 2013), so it may be possible for dyads to eventually equal bimanual shoe-tying performance. However, the time needed for testing that hypothesis (maybe years) is prohibitive, so we are cautious in making any specific predictions. As an alternative, a multi-session, warm-up versus retention study, similar to the design of the Joseph, King, and Newell's (2013) experiment, could help clarify the timescale needed to capture persistent intermanual learning.

Based on the finding that intermanual mode effects present unique performance challenges, what is the basis of intermanual performance? To begin to address this, we asked how dyads with 'mixed' strategies perform compared with dyads with 'same' strategies, and found that mixed dyads outperformed same dyads on the instructed performance variable, speed. Hence, the basis of intermanual performance is such that shared strategies interfere with novel task performance, and there is an advantage to having mixed strategies. We think that shared strategies (or shared movement representations) invoke highly automated bimanual patterns in a novel situation where they may not fit (i.e. intermanual tying) more so than mixed strategies (or incongruent representations), which compel dyads to more directly depend on perceiving and reacting to each other's movements in real time, which is critical to novel task performance.

These interpretations are in line with prior findings that found performance advantages for interaction-based ('bottom-up') compared with shared knowledge-based ('top-down') organisation of team performance under novel task conditions (Gorman, Cooke, and Amazeen 2010). That research found that under novel conditions, it may not be best to share a prefigured team solution, or procedural strategy, because performance arises from real-time interactions as the novel situation unfolds. For intermanual performance, it may be better to direct attention towards a partner's movements and unique timing characteristics rather than emphasise shared, top-down strategies during skill acquisition.

4.2 Practice effects and motor transfer

Speed and variability were correlated in the bimanual mode but not in the intermanual mode. This finding is consistent with the hypothesis that more highly skilled performances are also less variable (Thelen et al. 1993). Given the observed intermanual mode effect and that dyads were unskilled in this novel mode, intermanual practice effects provide a window into the requirements of intermanual skill acquisition.

An exponential practice effect is the naturally occurring *individual-level* practice effect, and a power law practice effect typically arises when skill acquisition is combined across people with different performance characteristics (Anderson 2001; Newell, Liu, and Mayer-Kress 2001). We found power law practice effects for dyadic, intermanual shoe tying, and, unsurprisingly, no clear practice effects in the bimanual conditions (i.e. participants were already skilled in that mode). If a power law implies people of different inherent performance characteristics combining against a backdrop of skill acquisition, then the intermanual practice curves reflect a combining of related slow and fast shoe-tying processes (as reflected in the scale invariance property). From this perspective, we think the predominance of power law practice resulted from dyads organising intermanual patterns on top of their intrinsically different bimanual performance characteristics (i.e. speed of bimanual task performance). From a practical standpoint, intermanual skill seems to require acquisition of novel relative timings between one's own and someone else's hand.

The R^2 fit values were characteristically lower in the individual functions than the group-averaged functions (Table 2; Joseph, King, and Newell 2013), and the power law fit had significantly higher individual R^2 and higher group-averaged R^2 values for the intermanual condition only. Power laws are typically found with group-averaged data, and exponential functions appear when group-averaged data are broken down and analysed individually (Newell, Liu, and Mayer-Kress 2001). That power law practice held across both group-averaged and 'individual' intermanual data indicates that intermanual skill acquisition occurred by combining different performance characteristics even on a dyadic basis.

Power-law practice functions support the hypothesis that dyads build novel intermanual patterns on top of previously acquired bimanual skill. In this light, we further hypothesised that initially faster and slower tiers would adjust their performance characteristics to accommodate each other during intermanual performance. We expected to observe these adjustments through motor transfer effects from intermanual practice to subsequent bimanual performance (Nozaki, Kurtzer, and Scott 2006), which we did observe.

Having tied for 20 trials with a faster partner, initially slower partners significantly sped up during the second set of bimanual trials, but initially faster partners were unaffected. Partners were never explicitly informed of bimanual performance differences within the dyad; however, slower partners implicitly adapted to the performance level of their faster partners. One can infer from this pattern of motor transfer that the acquisition of novel timing during intermanual performance is asymmetric, with the slower partner's timing being more significantly affected. This is consistent with Reed et al.'s (2006) finding that slower partners sped up to match faster partners. We think that dyads produce intermanual patterns appropriate to their unique combination of strategies and interpersonal timing constraints; in general, the faster tier provides a 'speed limit' on intermanual performance, but both members of the dyad may influence the upper bound of performance. If the basis of intermanual performance is perceptual, and skill acquisition proceeds with the integration of novel, dyad-level relative timings, then skill acquisition occurs as the slower and faster partners combine their timing characteristics across perceptual channels to reach optimal performance.

Within-dyad comparisons indicated that individual bimanual times (i.e. before averaging) were significantly different both before and after intermanual performance. However, those differences were uncorrelated with intermanual performance and did not influence the results of the intermanual trials. Initial performance differences were significantly reduced (by 0.16 s) following internmanual performance, which, as just described, was primarily due to the slower partner speeding up. By the end of the study, however, bimanual performances of both partners were positively correlated with intermanual trial times. This result suggests that intermanual ('team') performance exerts an influence on individual ('team member') performance even after dyads are separated.

4.3 Dynamic coupling between the hands

Bimanual tying exhibited significantly lower between-hand coupling than intermanual tying, independent of the intermanual strategy effect. Because coupling must take place across perceptual channels during intermanual performance, we take these results to indicate the presence of added perceptual coupling constraints not present during bimanual tying: whether strategies were shared or mixed, all dyads had to visually detect and perceive each other's movements to perform intermanually. That dyads' hands had to be perceptually coupled during intermanual performance may explain why mixed dyads outperformed same dyads.

If the basis of intermanual performance is perceptual, then mixed dyads performed better because they were compelled to attend to this source of information more so than same dyads who came in with the same strategy. In retrospect, we think it may be incorrect to think that shared strategies or knowledge facilitates intermanual performance (cf. Zheng, Swanström, and Mackenzie 2007), because top-down expectancies may actually get in the way when the primary task is bottom-up perception and timing of each other's movements in real time.

During bimanual shoe tying, the hands displayed relatively weak coupling – they moved relatively independently – and lower coupling was consistently correlated with better performance in the bimanual mode. Thus, a highly skilled shoe-tying pattern is fast and occurs across independently assembled hand movements. So is this what skilled tying looks like? Although performance was significantly slower and the hands were more tightly coupled, we observed the same correlation between coupling and performance in the intermanual mode. Uncoupled does not mean disorganised. In an unrhythmic task such as shoe tying, movements are more 'complementary' than 'synchronised', with each subsequent step building on the previous one, where 'sync' (Strogatz 2003) may actually hurt human performance. The resulting picture one gets of skilled tying is of uncoupled, but temporally organised, hand movements, where the big difference between skilled bimanual and novel intermanual is that intermanual performance comes with added perceptual (i.e. visual; haptic) coupling constraints.

Presumably, people learn to decouple their hand movements and automate performance in the bimanual mode at an early age by becoming less dependent on the perceptual aspects of shoe tying. Wouldn't becoming skilled in an intermanual mode, then, require dyads to somehow become less dependent on perceptual coupling? Supposing that the distinguishing characteristic of intermanual performance is its bottom-up, perceptual organisation, one might accomplish this by 'perturbing' the perceptual information (e.g. by randomly occluding some aspects of partners' movements) to make this coupling more flexible. The goal of such 'perturbation training' would be to allow dyads to develop novel solutions to the bottom-up timing requirements of intermanual performance, which has been shown to result in the development of flexible team coordination processes in other domains (Gorman, Cooke, and Amazeen 2010). Furthermore, supposing that acquisition of novel relative timings across perceptual channels presents the immediate challenge of intermanual performance, the more complementary the timing characteristics of potential tiers, the less that must be coordinated though perceptual modalities. From a design perspective, matching partners according to their timing characteristics may also help relax perceptual coupling requirements.

5. Conclusion

The shape of intermanual practice functions and the pattern of subsequent motor transfer suggest that what participants acquire during intermanual performance are new combinations of relative timings between the hands for tying with a partner. When participants tie together, they are not performing an entirely new skill. They build upon their bimanual skill, such that dyads must coordinate each other's differently timed hand movements (as previously acquired through bimanual performance) to perform intermanually. The asymmetric pattern of motor transfer that we observed further suggests that slower partners adjust their performance characteristics to those of their faster partner during intermanual skill acquisition, an adaptation that may be fundamental to intermanual skill (Reed et al. 2006). That decoupling of the hands was associated with high performance in both coordination modes implicates ‘complementarity’ rather than synchronisation as the essential timing mechanism to be acquired.

In coordinating intermanual performance, does the left hand need to ‘know’ what the right hand is doing? Although participants brought knowledge and well-honed bimanual strategies to the shoe-tying task, our data suggest that *not* sharing the same strategy leads to superior intermanual performance, at least during the initial stages of intermanual skill acquisition. Because people bring different intrinsic timings to the intermanual task, relying on shared top-down strategies may interfere with picking up the primary source of information for performing such tasks; namely, bottom-up timing of each other’s hand movements.

We started this paper by asking a practical question, do intermanual mode effects found using novice participants generalise to highly practised bimanual skills? Based on our data, such generalisations should be made with caution. It may be dangerous, for example, to generalise such effects to a surgical context, wherein surgeons trained in classic bimanual suturing and knot-tying techniques (Murphy 2001) may be required to perform intermanually with mechanical (Bermas et al. 2004) or robotic (Guru et al. 2012) assistants or if asked to tie with a human partner (Zheng, Swanström, and Mackenzie 2007; Zheng et al. 2005). Based on our results, extensive practice with different relative timings between the effectors (either mechanical, robotic or human) may be required before performance in a novel intermanual mode equals performance in a highly practised bimanual mode.

Knowing what skills need to be acquired means knowing what needs to be trained. Intermanual skill acquisition may benefit from training aimed at either varying the relative timings and perceptual couplings between the hands or by simply instructing dyads on what type of perceptual information they should attend to. Such approaches may benefit intermanual skill acquisition in industrial and surgical settings or even when one loses the use of a hand (e.g. due to paralysis, amputation or after stroke) and must learn to perform bimanual tasks with the help of assistive personnel and/or technologies. For instance, assistive technologies could be designed to change and adapt to patients’ intrinsic timing characteristics, and assistive personnel could be trained to focus on bottom-up, perceptual aspects of intermanual task performance during rehabilitation.

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Disclosure statement

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Notes

1. We thank an anonymous reviewer for pointing out these connections between bimanual automaticity and the challenges of intermanual shoe tying.
2. We are hesitant to say ‘learning’ because demonstration of learning conventionally requires evidence of retention, so we say ‘practice effect’ instead to reflect the task-relevant acquisition of a new or modified skill when the coordination requirements for performing a familiar skill change.

References

Abarbanel, H. 1996. *Analysis of Observed Chaotic Data*. New York, NY: Springer.

Aks, D. J. 2011. “Analysis of Recurrence: Overview and Application to Eye-Movement Behavior.” In *Nonlinear Dynamical Systems Analysis for the Behavioral Sciences Using Real Data*, edited by S. J. Guastello and R. A. M. Gregson, 231–250. Boca Raton, FL: CRC Press.

Anderson, R. B. 2001. “The Power Law as an Emergent Property.” *Memory & Cognition* 29: 1061–1068.

Beilock, S. L. and L. E. Holt. 2007. “Embodied Preference Judgments: Can Likeability be Driven by the Motor System?” *Psychological Science* 18: 51–57.

Bermas, H., M. Fenoglio, W. Haun, and J. T. Moore. 2004. “Laparoscopic Suturing and Knot Tying: A Comparison of Standard Techniques to a Mechanical Assist Device.” *Journal of the Society of Laparoendoscopic Surgeons* 8: 187–189.

Cannon-Bowers, J. A., E. Salas, and S. Converse. 1993. “Shared Mental Models in Expert Team Decision Making.” In *Current Issues in Individual and Group Decision Making*, edited by N. J. Castellan Jr., 221–246. Hillsdale, NJ: Erlbaum.

Crites, M. J., and J. C. Gorman. 2013. “Learning to Tie Well with Others: Bimanual vs. Intermanual Coordination During Shoe-Tying.” In *Proceedings of the Human Factors and Ergonomics Society 57th Annual Meeting*, 1377–1381. Santa Monica, CA: Human Factors and Ergonomics Society.

Crossman, E. 1959. “A Theory of the Acquisition of Speed-Skill.” *Ergonomics* 2: 153–166.

Gibson, J. J. 1962. “Observations on Active Touch.” *Psychological Review* 69: 477–491.

Glynn, S. J., and R. A. Henning. 2000. “Can Teams Outperform Individuals in a Simulated Dynamic Control Task?” In *Proceedings of the Human Factors and Ergonomics Society 44th Annual Meeting*, 141–144. Santa Monica, CA: Human Factors and Ergonomics Society.

Gorman, J. C., N. J. Cooke, and P. G. Amazeen. 2010. “Training Adaptive Teams.” *Human Factors* 52: 295–307.

Gorman, J. C., and M. J. Crites. 2013. “Are Two Hands (From Different People) Better Than One? Mode Effects and Differential Transfer Between Manual Coordination Modes.” *Human Factors* 55: 815–829.

Gorman, J. C., E. E. Hessler, P. G. Amazeen, N. J. Cooke, and S. M. Shope. 2012. “Dynamical Analysis in Real Time: Detecting Perturbations to Team Communication.” *Ergonomics* 55: 825–839.

Guru, K. A., M. R. Sheikh, S. J. Raza, A. P. Stegemann, and J. Nyquist. 2012. “Novel Knot Tying Technique for Robot-Assisted Surgery.” *The Canadian Journal of Urology* 19: 6401–6403.

Heathcote, A., S. Brown, and D. J. K. Mewhort. 2000. “The Power Law Repealed: The Case for an Exponential Law of Practice.” *Psychonomic Bulletin and Review* 7: 185–207.

Huygens, C. 1673. *Horologium Oscillatorium, 1673*. London: Dawsons.

Instrument, L. 2002. *Grooved Pegboard Test User Instructions*. Lafayette, IN: Lafayette Instrument.

Joseph, M. E., A. C. King, and K. M. Newell. 2013. “Task Difficulty and the Time Scales of Warm-Up and Motor Learning.” *Journal of Motor Behavior* 45: 231–238.

Jung, C., A. Hollander, K. Muller, and W. Prinz. 2011. “Sharing a Bimanual Task Between Two: Evidence of Temporal Alignment in Interpersonal Coordination.” *Experimental Brain Research* 211: 471–482.

Koeneke, S., K. Lutz, T. Wustenberg, and L. Jancke. 2004. “Bimanual Versus Unimanual: What Makes the Difference?” *NeuroImage* 7: 1336–1350.

Mechsner, F., D. Kerzel, G. Knoblich, and W. Prinz. 2001. “Perceptual Basis of Bimanual Coordination.” *Nature* 414: 69–73.

Murphy, D. L. 2001. “Endoscopic Suturing and Knot Tying: Theory into Practice.” *Annals of Surgery* 234: 607–612.

Murphy, J. 2004. *Learn to Tie Your Shoes*. Floral Park, NY: CB Publishing.

Newell, K. M., Y.-T. Liu, and G. Mayer-Kress. 2001. “Time Scales in Motor Learning and Development.” *Psychological Review* 108: 57–82.

Newell, K. M., G. Mayer-Kress, and Y. -T. Liu. 2006. “Human Learning: Power Laws or Multiple Characteristic Time Scales.” *Tutorials in Quantitative Methods for Psychology* 2: 66–76.

Newell, A., and P. S. Rosenbloom. 1981. “Mechanisms of Skill Acquisition and the Law of Practice.” In *Cognitive Skills and Their Acquisition*, edited by J. R. Anderson, 1–55. Hillsdale, NJ: Erlbaum.

Nozaki, D., I. Kurtzer, and S. H. Scott. 2006. “Limited Transfer of Learning Between Unimanual and Bimanual Skills Within the Same Limb.” *Nature Neuroscience* 9: 1364–1366.

Oldfield, R. C. 1971. “The Assessment and Analysis of Handedness: The Edinburgh Inventory.” *Neuropsychologia* 9: 97–113.

Reed, K., M. Peshkin, M. J. Hartmann, M. Grabowecky, J. Patton, and P. M. Vishton. 2006. “Haptically Linked Dyads: Are Two Motor-Control Systems Better Than One?” *Psychological Science* 17: 365–366.

Richardson, M. J., K. L. Marsh, and R. C. Schmidt. 2005. “Effects of Visual and Verbal Interaction on Unintentional Interpersonal Coordination.” *Journal of Experimental Psychology: Human Perception and Performance* 31: 62–79.

Rosenbaum, D. A., S. B. Kenny, and M. A. Derr. 1983. “Hierarchical Control of Rapid Movement Sequences.” *Journal of Experimental Psychology: Human Perception and Performance* 9: 86–102.

Shelhamer, M. 2007. *Nonlinear Dynamics in Physiology: A State-Space Approach*. Singapore: World Scientific Publishing.

Shockley, K. 2005. “Cross Recurrence Quantification of Interpersonal Postural Activity.” In *Tutorials in Contemporary Nonlinear Methods for the Behavioral Sciences*, edited by M. A. Riley and G. C. Van Orden, 142–177. Retrieved June 1, 2012, from http://www.nsf.gov/sbe/bcs/pac/nmbs/nmbs.jsp

Shockley, K., A. A. Baker, M. J. Richardson, and C. A. Fowler. 2007. “Articularoty Constraints on Interpersonal Postural Coordination.” *Journal of Experimental Psychology: Human Perception and Performance* 33: 201–208.

Shockley, K., M. Butwill, J. P. Zbilut, and C. L. Webber. 2002. “Cross Recurrence Quantification of Coupled Oscillators.” *Physics Letters A* 305: 59–69.

Shockley, K., M.-V. Santana, and C. A. Fowler. 2003. “Mutual Interpersonal Postural Constraints are Involved in Cooperative Conversation.” *Journal of Experimental Psychology: Human Perception and Performance* 29: 326–332.

Snoddy, G. S. 1926. “Learning and Stability: A Psychophysiological Analysis of a Case of Motor Learning with Clinical Applications.” *Journal of Applied Psychology* 10: 1–36.

Stratton, S. M., Y. T. Liu, S. L. Hong, G. Mayer-Kress, and K. M. Newell. 2007. “Snoddy (1926) Revisited: Time Scales of Motor Learning.” *Journal of Motor Behavior* 39: 503–515.

Strogatz, S. 2003. *Sync: The Emerging Science of Spontaneous Order*. New York: Hyperion.

Takens, F. 1981. “Detecting Strange Attractors in Turbulence.” *Lecture Notes in Mathematics* 898: 366–381.

Thelen, E., D. Corbetta, K. Kamm, J. P. Spencer, K. Schneider, and R. F. Zernicke. 1993. “The Transition to Reaching: Mapping Intention and Intrinsic Dynamics.” *Child Development* 64: 1058–1098.

Trites, R. 1989. *Grooved Pegboard Test*. Lafayette, IN: Lafayette Instrument.

Wegner, N., and D. Zeaman. 1956. “Team and Individual Performances on a Motor Learning Task.” *Journal of General Psychology* 55: 127–142.

Wilks, S. 1960. “Multidimensional Statistical Scatter.” In *Contributions to Probability and Statistics: Essays in Honor of Harold Hotelling*, edited by I. Olkin, S. G. Ghury, W. G. Hoeffding, W. G. Madow, and H. B. Mann, 486–503. Stanford, CA: Stanford University Press.

Zheng, B., L. Swanström, and C. L. Mackenzie. 2007. “A Laboratory Study on Anticipatory Movement in Laparoscopic Surgery: A Behavioral Indicator for Team Collaboration.” *Surgical Endoscopy* 21: 935–940.

Zheng, B., F. Verjee, A. Lomax, and C. MacKenzie. 2005. “Video Analysis of Endoscopic Cutting Task Performed by One Versus Two Operators.” *Surgical Endoscopy and Other Interventional Techniques* 19: 1388–1395.