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The effects of task demands on bimanual skill acquisition

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Abstract

Bimanual coordination is essential for everyday activities. It is thought that different degrees of demands may affect learning of new bimanual patterns. One demand is at the level of performance and involves breaking the tendency to produce mirror-symmetric movements. A second is at a perceptual level and involves controlling each hand to separate (i.e., split) goals. A third demand involves switching between different task contexts (e.g., a different uni- or bimanual task), instead of continuously practicing one task repeatedly. Here, we studied the effect of these task demands on motor planning (reaction time) and execution (error) while subjects learned a novel bimanual isometric pinch force task. In Experiment 1, subjects continuously practiced in one of the two extremes of the following bimanual conditions: (1) symmetric force demands and a perceptually unified target for each hand or (2) asymmetric force demands and perceptually split targets. Subjects performing in the asymmetric condition showed some interference between hands, but all subjects, regardless of group, could learn the isometric pinch force task similarly. In Experiment 2, subjects practiced these and two other conditions, but in a paradigm where practice was briefly interrupted by the performance of either a unimanual or a different bimanual condition. Reaction times were longer and errors were larger well after the interruption when the main movement to be learned required asymmetric forces. There was no effect when the main movement required symmetric forces. These findings demonstrate two main points. First, people can learn bimanual tasks with very different demands on the same timescale if they are not interrupted. Second, interruption during learning can negatively impact both planning and execution and this depends on the demands of the bimanual task to be learned. This information will be important for training patient populations, who may be more susceptible to increased task demands.

Keywords

Bimanual; Skill learning; Motor control; Task demands

Introduction

One of the interesting problems in human movement is bimanual control. Understanding how our brain learns to coordinate our two hands is important for determining the organization of neural systems involved in this behavior, as well as the limitations in processing bilateral sensorimotor functions (Swinnen and Wenderoth 2004). In our daily

lives, we also routinely depend on bimanual coordination for many activities and grow increasingly reliant on these strategies as we age (Kilbreath and Heard 2005). Different bimanual tasks, however, can vary considerably in what each hand does. Some coordination patterns, for example, require that each hand performs the same activity such as carrying a tray of food. Other coordination patterns require each limb to produce different actions to accomplish a goal such as opening a jar. A high degree of flexibility is required for us to accomplish these possible types of coordination patterns (Mechsner 2004); White and Diedrichsen 2010).

Previous research has shown that specific demands can affect bimanual coordination. At a motor execution level, there is a tendency to produce mirror-symmetric movements. This means that it is more demanding to make asymmetric movements, and interference can occur when the hands have to produce different amplitudes, directions, frequencies, or forces (Kelso et al. 1979; Klapp 1979; Franz et al. 1991, 1996; Summers et al. 1993; Harabst et al. 2000). At a perceptual level, there are demands related to whether each hand is coordinated toward perceptual-unified or separate goals. For example, providing unifying perceptual representations for both hands can minimize interference between different limb movements. Mechsner et al. (2001) showed that individuals were successfully able to execute a challenging bimanual coordination task when the sensory representation for each hand was simplified to be perceptually unified. Other authors have also supported the importance of perceptual representation to aid with bimanual coordination (Zaal et al. 2000; Franz et al. 2001; Swinnen et al. 1997).

At a motor planning level, studies have demonstrated that reaction times can also be affected by these two demands. Some studies have demonstrated slower reaction times when individuals produce asymmetric movements (i.e., Spijkers et al. 1997), whereas others have shown that reaction time is strongly affected by the perceptual representation of the task and not movement symmetry (Hazeltine et al. 2003; Kunde and Weigelt 2005). A recent study by Franz and McCormick (2010) shows a complex relationship between these demands. They measured reaction times in a bimanual reaching task with varying degrees of motor-spatial demands. In symmetric trials where both hands reached the same distance, irrespective of the perceptual goal, subjects had decreased reaction times. For asymmetric reaches, they showed increased reaction times when they had to reach toward perceptually separate targets. Moreover, when subjects made these same asymmetrical reaches to targets that were now unified by a perceptual linkage bar, the reaction times matched those of the symmetrical reaches. This finding suggests that there is a functional hierarchical organization such that the representations that unify objects can overcome sensorimotor interference effects.

Together, these findings support the theory that bimanual interference can be observed in measures of motor planning and execution, and they may be different processes (Spijkers and Heuer 1995). However, these previous studies have focused on the analysis of familiar movements, such as reaching or finger-tapping, and motor networks may be engaged differently during bimanual skill acquisition compared to performing a familiar task (Gerloff and Andres 2002; Sun et al. 2007). Here, we were interested to explore how bimanual interference may manifest with respect to motor planning and execution during learning of a novel bimanual task. In previously described models of bimanual coordination, increasing task challenge may result in destabilization of bimanual performance or interference from limitations in neural resources (Swinnen and Wenderoth 2004). Our main hypothesis was that we could detect changes at the motor planning and execution levels by varying the demands of the bimanual skill to be learned. In order to do this, we created different combinations of bimanual configurations that represented different degrees of demands; for example, perceptually split targets requiring asymmetric forces having higher demands

compared to perceptually unified targets requiring symmetric forces. In an additional experiment, we also considered increasing the overall demands of the task by introducing task switching into the practice paradigm. Compared to practicing the same task repeatedly, task switching has been shown to increase task demands resulting in increased reaction times and increased errors (Monsell 2003).

We adapted a paradigm that has previously been used to study unimanual motor skill learning to a bimanual context (Reis et al. 2009; Schambra et al. 2011). This consisted of an isometric pinch force task (Fig. 1a) that required subjects to learn a complex mapping rule with both hands between force production and computer cursor movement distance through repeated practice. In Experiment 1, we asked how bimanual execution would differ while individuals learned a novel bimanual task with different demands. We hypothesized that individuals would produce larger errors and have longer reaction times while they learned to produce asymmetric forces to perceptually separate goals (higher demands task) (Swinnen et al. 1993; Summers 2002). In Experiment 2, we added task switching to either a unimanual or a different bimanual task to the practice schedule.

Methods

Participants

Fifty-six right-handed healthy individuals with no history of chronic neurological, psychiatric, or medical conditions (mean age 26.6 ± 6.1 years) participated in the study. Handedness was determined using the Edinburgh Handedness Inventory (Oldfield 1971), and test scores ranged between 75 and 100 (mean score 93.8 ± 7.2). Subjects were also assessed for their self-perceived average playing time and skill at video games on a 10-point scale. There was no difference between the groups (Time Played: $F(7, 48) = 0.83$, $p = 0.57$; Skill: $F(7, 47) = 0.81$, $p = 0.58$). All subjects signed informed consent approved by Johns Hopkins Institutional Review Board and in accordance with the Declaration of Helsinki.

Task

Figure 1a illustrates the experimental setup. Participants were seated in a chair approximately 60 cm away from a 19-inch LCD computer monitor. Subjects were instructed to control cursor(s) on the monitor toward directly cued goal target(s) using either one or two identical isometric force transducers (FUTEK Advanced Sensor Technology, Inc.) and were given a score based on their accuracy. This was a novel task that subjects had never performed previously. In each of their hands, they held the force transducers between their thumb and the lateral aspect of the middle phalanx of the index finger. Pinching the force transducer moved a cursor only in the vertical direction. Data from the force transducers were sampled using custom software written in Matlab (Mathworks Inc., Natick MA). This software also controlled the progress of the experiment and gave feedback to the subject via the computer monitor. Subjects were given 1-min rest breaks after every sixty trials.

Before the experiment, subjects were exposed to a brief practice tutorial so they understood how to control the cursors. During the experiment, a trial began with subjects resting both hands (force on transducers <0.5 N) before the presentation of the target(s). Target(s) appeared at a random time interval between 1 and 2.5 s after subjects were visually prompted to the start of a new trial. This prevented subjects from anticipating target presentation. Initiation of 0.5 N of force comprised the reaction time for each hand. Subjects were given 520 ms after target presentation to initiate cursor movement or their score was penalized. These prolonged trials occurred less than five percent of trials and were eliminated from post-testing analysis. Subjects were instructed to move their cursor(s) quickly to their targets and a trial was terminated when their rate of force generation

decreased to below 0.03 N/ms for both hands. In other words, corrections for overshooting were not allowed. This threshold was determined from pilot data and resulted in average total pinch durations of 400 ± 14 ms, and we eliminated trials that were longer than 830 ms.

In this visuo-motor task, subjects learned a mapping rule between their isometric force production and cursor movement on the screen (Fig. 1a). We chose a sigmoid-shaped mapping rule between the pinch force and cursor movement to increase the challenge and learning time of the task (Reis et al. 2009). In post-experiment questioning, subjects qualitatively rated the challenge of the experiment as moderate to very difficult. Most of the subjects were able to give general descriptions of the mapping rule, such as the targets in the middle were the most challenging, which is the steepest portion of force–distance mapping rule. They, however, had a difficult time giving an explicit description of the mapping rule for all targets. In that sense, subjects developed an implicit understanding of the underlying mapping rule since they were still able to improve their performance. Previous research has also shown that subjects are still able to develop an internal model of a nonlinear mapping rule when individuals are provided with online feedback and do not have an explicit awareness of the transformation (Rieger et al. 2008).

This same mapping rule was used for both hands and across all experimental conditions. To test for learning and generalization, we created two sets of five target positions along the mapping rule. Training blocks comprised of five different target locations and were the majority of blocks (Fig. 2a). Testing blocks comprised five new target locations and were practiced only during the first and last block of each experimental session (Fig. 2b). Within a block, the same target locations were used across all conditions and in both hands. The targets were pseudorandomly ordered where each of the five possible target positions was displayed four times. Every subject saw the same order of targets displayed. Individuals were unaware of the pattern of targets and thus perceived the target sequences as random on post-session questioning. Two-minute rest breaks were given after every third block to minimize fatigue. The maximum force for the mapping rule was between 25 and 40 % of maximum volitional contraction for most subjects (De Jong and Van Galen 1999).

After each trial, subjects received end-cursor positions and feedback of the absolute distance in millimeters between the user-controlled cursor and the target. To motivate them, this measurement was also presented to the subject as the value for their score on the trial. Trial scores were totaled over the course of each block. During the experiment, they were repeatedly encouraged to improve on the scores of each block. Signed distance in millimeters between the cursor and target were used for error analysis.

Measures

The two measures we used to measure motor planning and execution were reaction time and root mean squared error (RMSE), respectively. RMSE was calculated as the distance between the subject-controlled cursor and target in millimeters. We chose to use the RMSE as our measure of error because it is a combination of constant error and variable error, and our goal was to average errors across all targets that span across different components of the nonlinear mapping rule (Schmidt and Lee 2005).

Conditions

We created an experimental setup that allowed us to test the effects of four different combinations of perceptual and force task demands learning (Fig. 1b). Task demands were minimized in the bimanual perceptual-unified, force-symmetric condition (PUFS). Visually, subjects saw a “dumb-bell shaped” object (two circles with a bar between). Although the goal in this condition was to produce equal forces with both hands to reach the target, this

was not an absolute constraint as subjects were allowed to produce asymmetric forces (i.e., the dots would separate vertically and the bar would elongate). In comparison, task demands were maximized in the bimanual perceptual-separate, force-asymmetric condition (PSFA). Subjects in this condition controlled two separate cursors toward targets which required different forces from each hand. Equal numbers of target pairs within a block required subjects to either press harder with their right (RH) or left (LH) hand, but in a random sequence. Intermediate task demands were present in the other two conditions, perceptual-separate, force-symmetric (PSFS) and perceptual-unified, force-asymmetric (PUFA). In the PUFA condition, subjects controlled perceptually linked cursors toward a target that required different forces from each hand. Depending on the condition, we used language that was consistent with the cursor and target configurations at the beginning of each block (Franz and McCormick 2010). In the unimanual condition (UNI), subjects rested their left hand on their ipsilateral leg while they controlled a single cursor with their right hand.

Experiment 1

Subjects ($n = 16$) were randomly assigned to either extreme of the different task-demand conditions, perceptual-unified, force-symmetric (PUFS) or perceptual-separate, force-asymmetric (PSFA). The PUFS condition had linked cursors with symmetric force; the PSFA had separate cursors with asymmetric force. In both conditions, they performed 25 continuous blocks (500 total trials) of bimanual practice. Blocks 2 through 24 consisted of training blocks and Blocks 1 and 25 consisted of testing blocks with new targets to assess for generalization.

Experiment 2

In Experiment 2A, subjects ($n = 32$) were randomly assigned to four different bimanual task-demand conditions—perceptually separate or unified paired with symmetric or asymmetric forces (i.e., PUFS, PUFA, PSFS, and PSFA). In contrast to Experiment 1, subjects learned the bimanual task after a brief exposure to a unimanual context; subjects first practiced one baseline block in a bimanual condition, were interrupted by a single unimanual block, and then performed twenty-one blocks of bimanual practice (460 trials total, 440 bimanual trials, and 20 unimanual trials). We chose to use the unimanual context in the task switch because this paradigm has been shown to increase demands on the neural system (Serrien 2008). Blocks 3 through 21 consisted of training blocks and Blocks 1 and 22 consisted of testing blocks with new targets to assess for generalization.

In Experiment 2B, eight additional subjects practiced learning a bimanual task that was interrupted by a different bimanual condition (Serrien 2009). Specifically, subjects practiced the bimanual perceptually separate, forceasymmetric or PSFA condition and were interrupted by a block of perceptually unified, force-symmetric or PUFS (460 trials total, 440 PSFA, and 20 PUFS).

Analysis

We measured how quickly subjects learned to improve their reaction time (i.e., planning) and total error (i.e., motor execution). We show the data in blocks of trials (1 Block = 20 trials) since this is how subjects were tested, that is, 25 blocks with short breaks between. We used larger bin sizes for statistical analysis (1 Bin = 60 trials) over the first 300 trials—this reduced the number of repeated measures from 25 to 5 and captured the learning curve. We used separate repeated measures analyses of variance (ANOVA_{RM}) to assess total error and reaction time with factors: CONDITION (PUFS, PSFA, PSFA, and PSFS) and TIME. To compare the change in total error and reaction time, an interaction with CONDITION and TIME was used for the analysis. We used one-way ANOVA to assess RMSE and reaction time for single bin comparisons. When F tests were significant ($p < 0.05$), post hoc

contrasts were carried out using *Fisher's LSD* (least significant difference). All statistical analyses were completed using the STAT ISTICA (StatSoft, version 10) software package.

Results

Experiment 1

In Experiment 1, we first evaluated whether subjects had actually learned the nonlinear mapping rule. Figure 2a shows data from the last training block and Fig. 2b shows data from the testing block to assess for generalization. We found that we were able to fit the sigmoidal function to the performance of both hands in both bimanual conditions (condition PUFS, LH: $r^2 = 0.94$; RH: $r^2 = 0.97$; condition PSFA, LH: $r^2 = 0.90$; RH: $r^2 = 0.93$). We also modeled the data in the testing block using a polynomial function with higher-order terms. Specifically, we considered the regression equation, $Y = \beta_0 + \beta_1 * X + \beta_2 * X^2 + \beta_3 * X^3$. We centered the polynomial terms to minimize collinearity. We found that both the β_1 and β_3 coefficients were significant for the left and right hands in both bimanual conditions ($p < 0.001$). The significance of the β_3 coefficient suggests that the nonlinear mapping rule of both hands generalized to the new targets.

We were most interested in how quickly subjects learned to improve their performance. Our findings show that people learned these two tasks with different perceptual and isometric force demands, quite similarly. Figure 3a shows the data for the right and left hand in both conditions as they performed 25 continuous blocks (500 total trials) of bimanual practice. The TIME factor was the first 300 trials grouped into five bins of 60 trials (Fig. 3b). Based on our hypothesis, we expected that subjects in the PSFA group would show lower total errors over the course of skill learning. Surprisingly, the two extreme task demands that we tested were both learned without a significant group effect difference in error or in the learning rate (CONDITION $\times$ Time) in both hands (RMSE, LH: $F(1, 14) = 0.08$, $p = 0.78$; RH: $F(1, 14) = 0.14$, $p = 0.72$; learning rate, LH: $F(4, 56) = 0.78$, $p = 0.54$; RH: $F(4, 56) = 1.7$, $p = 0.16$). We were also surprised that there was not a significant difference in reaction time (Fig. 5a) in either condition for either hand (LH: $F(1, 14) = 0.03$, $p = 0.87$; RH: $F(1, 14) = 0.01$, $p = 0.92$).

We were initially puzzled by this result, as prior work would suggest that the difficulty level of these tasks is quite different. Therefore, we performed an internal check to see whether, on a target-by-target basis, performance on our task was similar to other reported bimanual experiments (Spijkers and Heuer 1995; Heuer et al. 1998). We first confirmed that subjects overshot low targets (i.e., 1 and 2) and undershot high targets (i.e., 4 and 5) (all $p < 0.001$). Then, we compared the asymmetric and symmetric force conditions and observed that individuals overshot the lowest target (1) in the asymmetric force condition more than the symmetric condition (LH: $p = 0.009$; RH: $p = 0.003$). For the second lowest target (2), the right hand in the asymmetric force condition overshot the target more than in the symmetric force condition (RH: $p < 0.001$). For the highest target (5), there was a stronger trend for the left hand in the asymmetric force condition to undershoot the target more than in the symmetric condition ($p = 0.09$). Thus, our asymmetric task produces motor overflow consistent with prior work (Hu and Newell 2011). In sum, we see expected biases for given targets, but the more global measure of RMSE error changed similarly in these two conditions during learning.

Last, in order to understand whether there were systematic differences in the reaction times in either hand, we compared these differences for both conditions on a trial-by-trial basis. We did not observe a significant difference in reaction times between the two bimanual conditions when we examined the targets separately. We also did not see a significant difference in reaction time between targets with different amplitudes. Overall, we found that

the RH had a faster reaction time than the LH for both the PUFS and PSFA conditions ($p < 0.001$). This finding is supportive of other bimanual studies which show that the dominant hand leads in right-handed individuals (Stucchi and Viviani 1993; Swinnen et al. 1996).

Experiment 2

In Experiment 2A, we observed that a single block of unimanual practice interferes markedly with motor planning and execution in the higher demand conditions. With respect to execution, there were increased errors in the bimanual conditions that require asymmetric force production. Figure 4a shows the data for the right and left hand in both conditions as they performed interrupted bimanual practice. The first 300 trials after unimanual practice were grouped into five bins of 60 trials since there was evidence of significant disruption after the unimanual block for certain conditions (Fig. 4b). We found a significant group effect difference in error for both hands in the different bimanual conditions (LH: $F(3, 28) = 4.32$, $p = 0.013$; RH: $F(3, 28) = 8.96$, $p < 0.001$). Post hoc analysis revealed that subjects had increased error in the conditions that required asymmetrical forces and did not depend on whether the cursors and targets were perceptually unified or not (LH: $p < 0.001$; RH: $p < 0.05$). The disrupted learning after the unimanual block resulted in different learning rates between the symmetric and asymmetric conditions (LH: $F(12, 112) = 1.9$, $p < 0.05$; RH: $F(12, 112) = 1.93$, $p < 0.05$). We also considered that decreased error during the unimanual block may be associated with greater interference in subsequent bimanual learning (Brashers-Krug et al. 1996; Goedert and Willingham 2002). We did not find a significant difference between errors on the unimanual block in the different bimanual conditions ($F(3) = 1.94$, $p = 0.15$).

With respect to reaction time (Fig. 5b, c), only the PSFA condition had significantly increased reaction times during early (Bin 1) bimanual practice after the unimanual block (LH: $p < 0.05$; RH: $p < 0.05$) but was not significantly different to the other conditions after late learning (Bin 5, LH: $p = 0.99$; RH: $p = 0.78$); Both symmetric conditions and the PUFA condition showed diminished reaction times. These reaction time results during early bimanual practice after the task switch are comparable to the prior study by Franz and McCormick (2010).

Experiment 2B shows that interrupting practice with another bimanual condition (compared with the unimanual condition) causes similar change in performance. We observed that the high demand PSFA condition is sensitive to interference from task switching with the lower demand PUFS condition. We compared reaction times and error in this experiment with the PSFA condition in Experiment 2A (Fig. 6). We observed no significant group effect in RMSE (LH: $F(1, 14) = 0.02$, $p = 0.90$; RH: $F(1, 14) = 0.1$, $p = 0.76$) or difference in learning rate (LH: $F(4, 56) = 0.79$, $p = 0.53$; RH: $F(4, 56) = 0.96$, $p = 0.44$). There was also not a significance difference in reaction times during early learning (LH: $F(1, 14) = 0.02$, $p = 0.89$; RH: $F(1, 14) = 1.34$, $p = 0.72$). Together, this suggests that there is also an associated cost with switching between different bimanual conditions with different task demands.

Asymmetric force conditions

We found in Experiments 2A and B that interrupted practice increased errors in the two conditions that required asymmetric forces, PSFA and PUFA. For each hand, we further examined the target pairs when either the LH had to press with lower force than the RH and vice versa. Figure 7 shows a summary of the results for both hands in the continuous and interrupted practice schedules. Five bins of thirty trials (150 total trials) were used for the analysis, since these target pairs separately represented half of the total trials in the asymmetric conditions. We then compared the total error results in all the asymmetric conditions during continuous and interrupted practice; PSFA condition in Experiment 1, two

PSFA conditions in Experiment 2, and the PUFA condition in Experiment 2. Figure 7a demonstrates the results when the LH had to press with lower force than the RH. The RH pressing with higher force produced similar RMSE ($F(3, 28) = 0.11, p = 0.95$) and had similar learning rates ($F(12, 112) = 1, p = 0.45$) in both the continuous and the task-switching experiments. In contrast, the LH pressing with lower force showed a reduced RMSE in the continuous practice experiment ($F(3, 28) = 3.46, p = 0.03$) compared with the task-switching experiments. Figure 7b shows the opposite force pair when the RH pressed with lower force than the LH. Similar findings were also seen in this pairing scenario. The LH pressing with higher force produced similar error ($F(3, 28) = 0.33, p = 0.81$) and had similar learning rates ($F(12, 112) = 0.98, p = 0.48$) in both the continuous and the task-switching experiments. The RH with lower force showed a trend toward reduced error in the continuous practice experiment ($F(3, 28) = 1.69, p = 0.19$) compared with the task-switching experiments. This observation suggests that in comparison with learning a bimanual task continuously, switching between conditions results in a trend toward greater errors on the hand producing lower forces in asymmetric force conditions.

Discussion

Here, we have shown people learning to perform a novel bimanual skill task, and importantly what kinds of bimanual conditions are easily interfered with during the learning process. We consider our task a form of skill acquisition since subjects reduced their errors by learning a complex mapping between force and cursor movement without previous experience performing a similar task. They were also able to generalize their performance through repeated practice to a novel set of targets without deterioration. This is in contrast to other forms of motor learning, such as adaptation, where individuals learn to regain performance of a familiar motor movement (i.e., reaching and walking) in the setting of a perturbation (Shadmehr and Mussa-Ivaldi 1994; Reisman et al. 2005). With that perspective, we considered how task demands may affect reaction time (motor planning) and error (motor execution).

Experiment 1

Healthy individuals were able to learn an isometric task that required asymmetric forces and separate goal representations similarly to symmetric forces and common goal representations as long as they practiced the same condition continuously. Specifically, they learned the symmetric and asymmetric conditions with similar errors and reaction times. This finding is in contrast with previous studies that found symmetric patterns of movement to be easier to produce than asymmetric patterns [i.e., (Franz et al. 1991; Harabst et al. 2000; Spijkers et al. 1997; Scott Kelso et al. 1983)].

At a very basic level, our task shared some characteristics observed prior work. We showed that the asymmetric condition biased subjects to overshoot the lowest targets and undershoot the highest targets more than symmetric condition. This suggests that there was some interference between the two hands. That being said, we still saw similar overall error patterns when we assessed the RMSE error over the five targets. We speculate that this may be explained by several factors.

Our unexpected finding may be due the fact that this is isometric task, as opposed to other bimanual tasks that have been studied such as reaching (Peper and Carson 1999). Our task may have had easier timing requirements. Bimanual limb movements such as arm reaching show tight temporal coupling, and movement amplitudes tend to be correlated with movement time. For example, when individuals produce asymmetric bimanual reaching movements with different amplitudes, the hand that reaches the shorter distance may overshoot because it is temporally constrained with the hand that reaches farther (Heuer et

al. 1998; Marteniuk et al. 1984). In comparison, force amplitude and timing have been demonstrated to be relatively independent (Peper and Carson 1999; Gordon and Ghez 1987) which may make it easier to produce asymmetric forces.

We also gave our subjects online feedback of their cursor position, which could have assisted in their ability to produce asymmetric forces. Previous studies in reaching tasks have shown that compared to internally guided movements, providing visual feedback may help to decouple the movement of both hands (Diedrichsen et al. 2004; Cardoso de Oliveira and Barthelemy 2005). Indeed, this is a more natural way of moving, which is one reason that feedback was given.

We may not have observed a difference in reaction time between the two conditions because of the manner in which targets were presented. Motor planning can be divided into stages which include response selection and response programming. Previous research suggests that reaction time costs when individuals produce asymmetric movements are largely due to response selection processing rather than later stages in the chain of sensorimotor processing (Diedrichsen et al. 2001, 2003b). Increased reaction times in those studies were associated with translation of symbolic cues into their associated movements, such as cuing the trajectories of bimanual arm reaches with letters or different colors. In our experiment, individuals received information regarding the relative amplitude specification for the two hands, in the asymmetric force conditions. Although there was a nonlinear mapping between force and cursor movement, response selection was likely facilitated by the manner in which the target locations were cued.

Experiment 2

Perhaps, more interestingly, in Experiment 2, we show a clear disruption in learning demanding bimanual conditions (i.e., asymmetric forces) when individuals briefly switch to another uni- or bimanual condition early in training. In other words, a single block of trials with different movement demands interferes dramatically early in learning process. With respect to motor planning, interference led to longer reaction times when the goal was split and the force requirement was asymmetric. However, when we made the force requirement symmetric, this reaction time deficit diminished. Reaction time was unaffected when the goal was unified, regardless of force requirement. This suggests that motor planning is sensitive to an interaction between perceptual goal and force. These findings also argue in favor of a hierarchical organization such that more abstract representations can override motor execution constraints (Franz and McCormick 2010; Riek and Woolley 2005). In contrast, error (i.e., motor execution) was greater only when the force requirement was asymmetric; the goal representation did not matter.

We attribute the main results in Experiment 2 to the increased demands from switching between different learning contexts. Task switching is associated with a reconfiguration of mental processes (Monsell 2003) that may influence motor performance, including inhibiting responses from the previous task, selection and activation of new goals and plans, and sequencing of operations (Gopher et al. 2000). Compared to performing the same task repeatedly, there is enhanced activation of multiple brain areas during task switching which is associated with increased neural costs (Dove et al. 2000; Braver et al. 2003). Previous research has shown that these increased costs result in increased reaction times and reduced accuracy (Allport et al. 1994; Mayr and Keele 2000; Schuch and Koch 2003). Another perspective is that bimanual interference resulted from competing cognitive processes on shared resources, akin to a dual-task process (Remy et al. 2010). In our experiment, both cognitive processes, task switching and early skill learning, require high attentional demands that are also important for bimanual skill learning (Peters 1985) and coordination (Franz 2004; Amazeen et al. 2005). Hence, the interaction between these two competing processes

on attentional resources may have resulted in enough demands on the neural system for us to detect differences with only a brief task switch.

Originally, in our experimental design, we considered more instances of task switching, but early pilot data suggested that only one block was sufficient to significantly disrupt the high demand conditions. This in contrast to many paradigms that use repeated task switches to assess for associated costs, such as comparing a mixed ABABAB task block with a single task block of AA or BBB (for review, see (Kiesel et al. 2010)). Interestingly, we observed that the associated costs at the motor execution and planning levels resolved over different time frames; performance error differences in the high demand conditions lasted nearly the entire experimental session, whereas reaction times converged much earlier.

We also observed that the interference effects from the task switching resolved more slowly than typically reported in the literature. There are several factors that could have contributed to the prolonged disruption we observed from task switching. First, task-switching experiments in the literature have primarily used simple motor movements familiar to individuals, such as keyboard presses, whereas our task was considered very challenging by most subjects and comprised a learning component (i.e., (Koch et al. 2004; Bernardin and Mason 2011)). Processing costs have been shown to be larger in switches between more complex tasks and when the participants switched to tasks that were relatively unfamiliar (Rubinstein et al. 2001). Second, task switching between unimanual and bimanual contexts may have resulted in a contextual interference effect (Wood and Ging 1991; Tsutsui et al. 1998) that was dependent on the motor command of the bimanual task. It is possible that, when the motor command for both hands was the same in the symmetric force conditions, the contextual interference with the unimanual context may have been lower. Yet, when the motor command for both hands was the different in the asymmetric force conditions, the contextual interference with the unimanual context was higher, resulting in disrupted performance in the asymmetric force conditions. Third, working memory has been suggested to be an important system that mediates task switch processing and bimanual interference (Wenderoth et al. 2004; Liefooghe et al. 2008) and working motor memory processes have been shown to last many minutes without loss (McVea et al. 2009). Last, the interruption block may have resulted in subjects adopting a different strategy in the asymmetric force conditions. It is hard to pinpoint the exact nature of such a strategy in this experiment, but we clearly observed increased errors in the low-force hand after the interruption block (Fig. 6).

Two sources of cross-talk

Together, these results suggest that processes that control motor planning and execution during bimanual skill learning are both susceptible to the effects of neural cross-talk, and that task demands may affect these neural processes differently (Fig. 8 shows a summary schematic). These findings are in support of the model of cross-talk originally described by Spijkers and Heuer (1995), which showed that that interference occurs both at the motor execution and planning levels, and that they are separate processes. In their original experiment, subjects produced different patterns of periodic bimanual reaching movements with small or large amplitudes at different tempos. On measures of motor execution, they found evidence of cross-talk when amplitudes in both hands became coupled in conditions that required both hands to produce asymmetric movements. On measures of motor planning, they also found that the preceding amplitude, which was associated with reprogramming, was also a source of cross-talk.

At a planning level, response initiation in the context of task switching represents a significant cost which may be mitigated by giving individuals enough time to program their upcoming movement (Rogers and Monsell 1995). In the previously mentioned model of

cross-talk, bimanual interference is also thought to occur ahead of movement during motor parameter specification. If individuals are given sufficient time to reach a steady state in the parameter specification processes during the planning process, it is easier for them to decouple their hands (Spijkers et al. 1997; Heuer et al. 1998; Steglich et al. 1999). We, however, constrained subjects to react quickly after target presentation. With this reasoning, task switching in Experiment 2 may have resulted in an increased cost for parameter specification in the highest demand condition (PSFA). With continued practice, the cost of parameter specification was diminished. Simplifying the command for both hands into a perceptually unified object, in the PUFA condition, appears to have facilitated the process of parameter specification for asymmetric force production. We did not observe an associated reaction time cost in this condition.

At a motor execution level, we found that task switching resulted in increased errors in the bimanual conditions that required each hand to produce asymmetric forces. In isometric force production, previous research has showed that compared to higher forces, there is less variability when individuals produce lower forces based on physiologic signal-dependent noise (Jones et al. 2002). Consistent with those findings, we observed that the low-force hand had decreased error in Experiment 1. In comparison, we observed in Experiment 2 that the low-force hand, irrespective of side, had a trend toward increased errors. We reason that this may be secondary to an enhanced interhemispheric interference phenomenon which gradually resolved over the experimental session. This is supported by the idea that interhemispheric connectivity assists task performance under challenging conditions (Belger and Banich 1998) and particularly during bimanual task learning (Sun et al. 2007; Serrien 2009; Gerloff and Andres 2002). Even in a learned asymmetric bimanual isometric task, effects of transcallosal interhemispheric cross-talk can be seen (Franz et al. 1996; Diedrichsen et al. 2003a); the hand that produces higher force causes interference on the hand that produced less force, likely through a mechanism of motor overflow (Hu and Newell 2011). Recently, Serrien (2009) used EEG functional coherence analysis to compare interhemispheric connectivity while individuals learned a challenging bimanual coordination pattern in either continuous or interrupted practice schedules. Results showed that compared with the continuous practice schedule, interhemispheric connectivity was enhanced when the practice schedule involved task switching. In our experiment, task switching during bimanual learning may have led to increased interhemispheric connectivity of motor areas. Together, this may have resulted in enhanced motor overflow from the hemisphere primarily controlling the high-force hand to cause increased interference on the hand that produced lower force.

Summary

In summary, we showed that certain bimanual conditions with increased demands are more susceptible to interference during skill acquisition. The most challenging bimanual learning environment would be one where each hand has different goals and the forces required are distinct. This is akin to many everyday situations, such as driving a stick-shift car where the hand that steers is responsible for direction and the hand that moves the gear shift is responsible for gear/speed. Using different demand conditions, we also observed that bimanual interference occurs at the motor planning and execution levels, and that they are likely separate processes. These findings in our isometric force task may help us understand how different demands affect patients with neurologic injuries, such as stroke, traumatic brain injury, and multiple sclerosis. Studies have demonstrated that individuals in those patient populations have tendencies to produce mirror-symmetric movements much more than controls and have more difficulty performing bimanual tasks (Larson et al. 2002; Kim et al. 2003; Caeyenberghs et al. 2011). These manifestations may be the result of reduced abilities in the nervous system to handle task demands. Using isometric force tasks in patient

populations may have limitations, however, because they do not manage inertial forces of the limbs or fingers, which are important factors for many daily bimanual movements (Harabst et al. 2000). Future studies should assess the effects of task demands in these clinical populations and using different bimanual tasks.

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References

- Allport, DA.; Styles, EA.; Hsieh, S. Shifting intentional set: exploring the dynamic control of tasks. In: Umiltà, C.; Moscovitch, M.; Umiltà, C.; Moscovitch, M., editors. *Attention and performance 15: conscious and nonconscious information processing*. Cambridge: The MIT Press; 1994. p. 421–452.
- Amazeen EL, Ringenbach SD, Amazeen PG. The effects of attention and handedness on coordination dynamics in a bimanual Fitts' law task. *Exp Brain Res*. 2005; 164:484–499. [PubMed: 15971067]
- Belger A, Banich MT. Costs and benefits of integrating information between the cerebral hemispheres: a computational perspective. *Neuropsychology*. 1998; 12:380–398. [PubMed: 9673995]
- Bernardin BJ, Mason AH. Bimanual coordination affects motor task switching. *Exp Brain Res*. 2011; 215:257–267. [PubMed: 21984054]
- Brashers-Krug T, Shadmehr R, Bizzi E. Consolidation in human motor memory. *Nature*. 1996; 382:252–255. [PubMed: 8717039]
- Braver TS, Reynolds JR, Donaldson DI. Neural mechanisms of transient and sustained cognitive control during task switching. *Neuron*. 2003; 39:713–726. [PubMed: 12925284]
- Caeyenberghs K, Leemans A, Coxon J, Leunissen I, Drijckoningen D, Geurts M, Gooijers J, Michiels K, Sunaert S, Swinnen SP. Bimanual coordination and corpus callosum microstructure in young adults with traumatic brain injury: a diffusion tensor imaging study. *J Neurotrauma*. 2011; 28:897–913. [PubMed: 21501046]
- Cardoso de Oliveira S, Barthelemy S. Visual feedback reduces bimanual coupling of movement amplitudes, but not of directions. *Exp Brain Res*. 2005; 162:78–88. [PubMed: 15772872]
- De Jong WP, Van Galen GP. Muscles act as low-pass filters on neuromotor noise. *Proceedings of the 9th biennial conference of the international graphonomics society*. 1999:25–29.
- Diedrichsen J, Hazeltine E, Kennerley S, Ivry RB. Moving to directly cued locations abolishes spatial interference during bimanual actions. *Psychol Sci*. 2001; 12:493–498. [PubMed: 11760137]
- Diedrichsen J, Hazeltine E, Nurss WK, Ivry RB. The role of the corpus callosum in the coupling of bimanual isometric force pulses. *J Neurophysiol*. 2003a; 90:2409–2418. [PubMed: 14534269]
- Diedrichsen J, Ivry RB, Hazeltine E, Kennerley S, Cohen A. Bimanual interference associated with the selection of target locations. *J Exp Psychol Hum Percept Perform*. 2003b; 29:64–77. [PubMed: 12669748]
- Diedrichsen J, Nabisan R, Kennerley SW, Ivry RB. Independent on-line control of the two hands during bimanual reaching. *Eur J Neurosci*. 2004; 19:1643–1652. [PubMed: 15066160]
- Dove A, Pollmann S, Schubert T, Wiggins CJ, von Cramon DY. Prefrontal cortex activation in task switching: an event-related fMRI study. *Brain Res Cogn Brain Res*. 2000; 9:103–109. [PubMed: 10666562]
- Franz EA. Attentional distribution of task parameters to the two hands during bimanual performance of right- and left-handers. *J Mot Behav*. 2004; 36:71–81. [PubMed: 14766490]
- Franz EA, McCormick R. Conceptual unifying constraints override sensorimotor interference during anticipatory control of bimanual actions. *Exp Brain Res*. 2010; 205:273–282. [PubMed: 20652230]
- Franz EA, Zelaznik HN, McCabe G. Spatial topological constraints in a bimanual task. *Acta Psychol (Amst)*. 1991; 77:137–151. [PubMed: 1759589]
- Franz EA, Eliassen JC, Ivry RB, Gazzaniga MS. Dissociation of spatial and temporal coupling in the bimanual movements of callosotomy patients. *Psychol Sci*. 1996; 7:306–310.

- Franz EA, Zelaznik HN, Swinnen SS, Walter C. Spatial conceptual influences on the coordination of bimanual actions: when a dual task becomes a single task. *J Mot Behav.* 2001; 33:103–112. [PubMed: 11265060]
- Gerloff C, Andres FG. Bimanual coordination and interhemispheric interaction. *Acta Psychol (Amst).* 2002; 110:161–186. [PubMed: 12102104]
- Goedert KM, Willingham DB. Patterns of interference in sequence learning and prism adaptation inconsistent with the consolidation hypothesis. *Learn Mem.* 2002; 9:279–292. [PubMed: 12359837]
- Gopher D, Armony L, Greenspan Y. Switching tasks and attention policies. *J Exp Psychol Gen.* 2000; 129:308–339. [PubMed: 11006903]
- Gordon J, Ghez C. Trajectory control in targeted force impulses. II. Pulse height control. *Exp Brain Res.* 1987; 67:241–252. [PubMed: 3622687]
- Harabst KB, Lazarus JA, Whittall J. Accuracy of dynamic isometric force production: the influence of age and bimanual activation patterns. *Motor Control.* 2000; 4:232–256. [PubMed: 11500577]
- Hazeltine E, Diedrichsen J, Kennerley SW, Ivry RB. Bimanual cross-talk during reaching movements is primarily related to response selection, not the specification of motor parameters. *Psychol Res.* 2003; 67:56–70. [PubMed: 12589450]
- Heuer H, Spijkers W, Kleinsorge T, van der Loo H, Steglich C. The time course of cross-talk during the simultaneous specification of bimanual movement amplitudes. *Exp Brain Res.* 1998; 118:381–392. [PubMed: 9497145]
- Hu X, Newell KM. Dependence of asymmetrical interference on task demands and hand dominance in bimanual isometric force tasks. *Exp Brain Res.* 2011; 208:533–541. [PubMed: 21132279]
- Jones KE, Hamilton AF, Wolpert DM. Sources of signal-dependent noise during isometric force production. *J Neurophysiol.* 2002; 88:1533–1544. [PubMed: 12205173]
- Kelso JA, Southard DL, Goodman D. On the nature of human interlimb coordination. *Science.* 1979; 203:1029–1031. [PubMed: 424729]
- Kiesel A, Steinhauser M, Wendt M, Falkenstein M, Jost K, Philipp AM, Koch I. Control and interference in task switching – a review. *Psychol Bull.* 2010; 136:849–874. [PubMed: 20804238]
- Kilbreath SL, Heard RC. Frequency of hand use in healthy older persons. *Aust J Physiother.* 2005; 51:119–122. [PubMed: 15924514]
- Kim YH, Jang SH, Chang Y, Byun WM, Son S, Ahn SH. Bilateral primary sensorimotor cortex activation of post-stroke mirror movements: an fMRI study. *NeuroReport.* 2003; 14:1329–1332. [PubMed: 12876467]
- Klapp ST. Doing two things at once: the role of temporal compatibility. *Mem Cognit.* 1979; 7:375–381.
- Koch I, Gade M, Philipp AM. Inhibition of response mode in task switching. *Exp Psychol.* 2004; 51:52–58. [PubMed: 14959506]
- Kunde W, Weigelt M. Goal congruency in bimanual object manipulation. *J Exp Psychol Hum Percept Perform.* 2005; 31:145–156. [PubMed: 15709869]
- Larson EB, Burnison DS, Brown WS. Callosal function in multiple sclerosis: bimanual motor coordination. *Cortex.* 2002; 38:201–214. [PubMed: 12056689]
- Liefvooghe B, Barrouillet P, Vandierendonck A, Camos V. Working memory costs of task switching. *J Exp Psychol Learn Mem Cogn.* 2008; 34:478–494. [PubMed: 18444750]
- Marteniuk RG, MacKenzie CL, Baba DM. Bimanual movement control: information processing and interaction effects. *Q J Exp Psychol A Hum Exp Psychol.* 1984; 36A:335–365.
- Mayr U, Keele SW. Changing internal constraints on action: the role of backward inhibition. *J Exp Psychol Gen.* 2000; 129:4–26. [PubMed: 10756484]
- McVea DA, Taylor AJ, Pearson KG. Long-lasting working memories of obstacles established by foreleg stepping in walking cats require area 5 of the posterior parietal cortex. *J Neurosci.* 2009; 29:9396–9404. [PubMed: 19625530]
- Mechner F. A psychological approach to human voluntary movement. *J Mot Behav.* 2004; 36:355–370. [PubMed: 15695214]

- Mechner F, Kerzel D, Knoblich G, Prinz W. Perceptual basis of bimanual coordination. *Nature*. 2001; 414:69–73. [PubMed: 11689944]
- Monsell S. Task switching. *Trends Cogn Sci*. 2003; 7:134–140. [PubMed: 12639695]
- Oldfield RC. The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia*. 1971; 9:97–113. [PubMed: 5146491]
- Peper CE, Carson RG. Bimanual coordination between isometric contractions and rhythmic movements: an asymmetric coupling. *Exp Brain Res*. 1999; 129:417–432. [PubMed: 10591913]
- Peters M. Constraints in the performance of bimanual tasks and their expression in unskilled and skilled subjects. *Q J Exp Psychol A Hum Exp Psychol*. 1985; 37:171–196.
- Reis J, Schambra HM, Cohen LG, Buch ER, Fritsch B, Zarahn E, Celnik PA, Krakauer JW. Noninvasive cortical stimulation enhances motor skill acquisition over multiple days through an effect on consolidation. *Proc Natl Acad Sci USA*. 2009; 106:1590–1595. [PubMed: 19164589]
- Reisman DS, Block HJ, Bastian AJ. Interlimb coordination during locomotion: what can be adapted and stored? *J Neurophysiol*. 2005; 94:2403–2415. [PubMed: 15958603]
- Remy F, Wenderoth N, Lipkens K, Swinnen SP. Dual-task interference during initial learning of a new motor task results from competition for the same brain areas. *Neuropsychologia*. 2010; 48:2517–2527. [PubMed: 20434467]
- Rieger M, Verwey WB, Massen C. The effect of continuous, nonlinearly transformed visual feedback on rapid aiming movements. *Exp Brain Res*. 2008; 191:1–12. [PubMed: 18704386]
- Riek S, Woolley D. Hierarchical organisation of neuro-anatomical constraints in interlimb coordination. *Hum Mov Sci*. 2005; 24:798–814. [PubMed: 16330121]
- Rogers RD, Monsell S. Costs of a predictable switch between simple cognitive tasks. *J Exp Psychol Gen*. 1995; 124:207–231.
- Rubinstein JS, Meyer DE, Evans JE. Executive control of cognitive processes in task switching. *J Exp Psychol Hum Percept Perform*. 2001; 27:763–797. [PubMed: 11518143]
- Schambra HM, Abe M, Luckenbaugh DA, Reis J, Krakauer JW, Cohen LG. Probing for hemispheric specialization for motor skill learning: a transcranial direct current stimulation study. *J Neurophysiol*. 2011; 106:652–661. [PubMed: 21613597]
- Schmidt, R.; Lee, T. Motor control and learning: a behavioral emphasis. 4th edn. Human Kinetics: Champaign; 2005.
- Schuch S, Koch I. The role of response selection for inhibition of task sets in task shifting. *J Exp Psychol Hum Percept Perform*. 2003; 29:92–105. [PubMed: 12669750]
- Scott Kelso JA, Putnam CA, Goodman D. On the space-time structure of human interlimb coordination. *Q J Exp Psychol A Hum Exp Psychol*. 1983; 35A:347–375.
- Serrien DJ. Coordination constraints during bimanual versus unimanual performance conditions. *Neuropsychologia*. 2008; 46:419–425. [PubMed: 17904169]
- Serrien DJ. Interactions between new and pre-existing dynamics in bimanual movement control. *Exp Brain Res*. 2009; 197:269–278. [PubMed: 19565226]
- Shadmehr R, Mussa-Ivaldi FA. Adaptive representation of dynamics during learning of a motor task. *J Neurosci*. 1994; 14:3208–3224. [PubMed: 8182467]
- Spijkers W, Heuer H. Structural constraints on the performance of symmetrical bimanual movements with different amplitudes. *Q J Exp Psychol A Hum Exp Psychol*. 1995; 48A:716–740.
- Spijkers W, Heuer H, Kleinsorge T, van der Loo H. Preparation of bimanual movements with same and different amplitudes: specification interference as revealed by reaction time. *Acta Psychol*. 1997; 96:207–227.
- Steglich C, Heuer H, Spijkers W, Kleinsorge T. Bimanual coupling during the specification of isometric forces. *Exp Brain Res*. 1999; 129:302–316. [PubMed: 10591904]
- Stucchi N, Viviani P. Cerebral dominance and asynchrony between bimanual two-dimensional movements. *J Exp Psychol Hum Percept Perform*. 1993; 19:1200–1220. [PubMed: 8294888]
- Summers J. Practice and training in bimanual coordination tasks: strategies and constraints. *Brain Cogn*. 2002; 48:166–178. [PubMed: 11812040]
- Summers JJ, Rosenbaum DA, Burns BD, Ford SK. Production of polyrhythms. *J Exp Psychol Hum Percept Perform*. 1993; 19:416–428. [PubMed: 8473848]

- Sun FT, Miller LM, Rao AA, D'Esposito M. Functional connectivity of cortical networks involved in bimanual motor sequence learning. *Cereb Cortex*. 2007; 17:1227–1234. [PubMed: 16855008]
- Swinnen SP, Wenderoth N. Two hands, one brain: cognitive neuroscience of bimanual skill. *Trends Cogn Sci*. 2004; 8:18–25. [PubMed: 14697399]
- Swinnen SP, Walter CB, Lee TD, Serrien DJ. Acquiring bimanual skills: contrasting forms of information feedback for interlimb decoupling. *J Exp Psychol Learn Mem Cogn*. 1993; 19:1328–1344. [PubMed: 8270889]
- Swinnen SP, Jardin K, Meulenbroek R. Between-limb asynchronies during bimanual coordination: effects of manual dominance and attentional cueing. *Neuropsychologia*. 1996; 34:1203–1213. [PubMed: 8951832]
- Swinnen SP, Lee TD, Verschueren S, Serrien DJ, Bogaerds H. Interlimb coordination: learning and transfer under different feedback conditions. *Hum Mov Sci*. 1997; 16:749–785.
- Tsutsui S, Lee TD, Hodges NJ. Contextual interference in learning new patterns of bimanual coordination. *J Mot Behav*. 1998; 30:151–157. [PubMed: 20037030]
- Wenderoth N, Debaere F, Sunaert S, van Hecke P, Swinnen SP. Parieto-premotor areas mediate directional interference during bimanual movements. *Cereb Cortex*. 2004; 14:1153–1163. [PubMed: 15142955]
- White O, Diedrichsen J. Responsibility assignment in redundant systems. *Curr Biol*. 2010; 20:1290–1295. [PubMed: 20598886]
- Wood CA, Ging CA. The role of interference and task similarity on the acquisition, retention, and transfer of simple motor skills. *Res Q Exerc Sport*. 1991; 62:18–26. [PubMed: 2028089]
- Zaal FT, Bingham GP, Schmidt RC. Visual perception of mean relative phase and phase variability. *J Exp Psychol Hum Percept Perform*. 2000; 26:1209–1220. [PubMed: 10884018]

Fig. 1.

Experimental setup and visual display of different conditions. **a** Subjects control cursors on the screen vertically to one of five possible targets by applying isometric forces to force transducers. A sigmoid function defines the mapping rule between force applied and movement of the cursor. **b** Unimanual (right hand) shown on the left side and different bimanual conditions on the right: perceptual unified, force-symmetric, perceptual-separate, force-asymmetric, perceptual-separate, force-symmetric, perceptual-unified, force-asymmetric. Icons in the bimanual condition indicate what the target cursor configuration looked like.

Fig. 2.

End-cursor positions for the LH and RH to targets along the force–cursor mapping rule for conditions PSFA and PUFS. **a** Average end-cursor positions in last training block. **b** Average end-cursor positions in testing block to assess generalization of learned force–cursor mapping rule to new targets.

Fig. 3. Cursor distance RMSE for the right and left hands as subjects continuously practiced 500 trials (25 blocks) in the PSFA and PUFS conditions. Subjects in both groups learned the conditions with similar variability. **b** The first 300 trials binned into five groups for the analysis.

Fig. 4.

Cursor distance RMSE for the right and left hands. Subjects practiced in an interrupted schedule where bimanual practice was briefly interrupted by a single block (20 trials) of unimanual (UNI) practice (right hand only) in different bimanual conditions (PSFA, PUFS, PSFS, PUFA). A brief block of unimanual practice interferes markedly increased errors in the bimanual tasks that require asymmetric force production. The first 300 trials after UNI practice binned into five groups for the analysis.

Fig. 5.

a Reaction time results during continued practice in the bimanual conditions, PUFS and PSFA. **b** Reaction time results during interrupted practice in the bimanual conditions. **c** Reaction time results from the first 300 trials after UNI interrupted practice in different bimanual conditions.

Fig. 6.

Bimanual practice in the PSFA condition was briefly interrupted by a single block (20 trials) of bimanual practice in the PUFS condition. **a** We compared cursor distance RMSE for the right and left hands in the PSFA condition interrupted by either the UNI or PUFS condition. Subjects in both groups learned with similar errors in both conditions. **b** The first 300 trials after UNI or PUFS practice binned into five groups for the analysis.

Fig. 7.

Comparison of cursor distance RMSE in asymmetric bimanual conditions with continuous (*solid line*) and interrupted practice (*broken line*). Irrespective of side, the hand that pressed with lower force was disrupted in the interrupted practice paradigm compared to continuous practice. **a** RMSE when the right hand pressed with higher force than the left hand. **b** RMSE when the left hand pressed with higher force than the right hand

Fig. 8.

Summary of bimanual interrupted learning in bimanual conditions with different levels of demands. **a** At the motor planning level, individuals had lower reaction times when they produced symmetric forces. When they produced asymmetric forces, reaction times were lower when the goal was perceptually unified compared with the separate goal representation. **b** At the motor execution level, individuals had increased error in the asymmetric force conditions irrespective of the goal representation.