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The effect of force feedback on transfer of learning between the arms during bimanual reaching.

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Abstract—**This study examined the effects of simultaneous learning of a force-field by two arms on transfer of learning during bimanual reaching. Subjects performed three reaching tasks by both arms: (1) with only dominant arm experiencing the force-field, (2) with only the nondominant arm experiencing the force-field, and (3) with both arms experiencing the same (intrinsic) force-field as in tasks (1) and (2). The results indicated that the rate of motor adaptation was greater when both arms experienced the intrinsic force-field than when only one arm experienced the force-field. Transfer of learning occurred in both directions due to the intrinsic force-field applied to the other arm: from the dominant arm to the nondominant arm and from the nondominant arm to the dominant arm.**

I. INTRODUCTION

Transfer of learning is a process through which practicing a motor task in one condition improves performance in another condition. Studies have shown that practicing a unimanual task may improve performance of a bimanual task [1]-[2], and that practicing a bimanual task may improve performance of a unimanual task [3]-[5]. Harley and Prilutsky demonstrated that during bimanual reaching, transfer of learning between the arms may occur simultaneously in both directions and that the movement information that is transferred depends on arm dominance [6]. To investigate the effect of transfer of learning during bimanual reaching further, the current study examined whether the rate of motor adaptation of dominant and nondominant arm depends on position and force feedback from the other arm.

During motor learning the Central Nervous System (CNS) is thought to compare the sensory feedback from the moving limb against the predicted feedback [7]-[11] and updates the motor plan as needed in order to reduce movement error [12]-[15]. Muscle, joint and skin receptors provide proprioceptive feedback to the CNS. These receptors include the Golgi tendon organs, located at the muscle-tendon junction and sensitive to produced muscle force, and the muscle spindles embedded in the belly parallel to muscle fibers and sensitive to muscle fiber length and velocity of stretch [16]. Novel external force-fields are often used to perturb arm reaching movements in order to determine a time-course of motor adaptation and transfer of learning [17]-[18]. During bimanual reaching, external force-fields may be applied to one or both arms. One question is how motor adaptation to a force-field by one arm depends on presence or absence of the same force-field applied to the other arm. It may be expected that the presence of similar load-dependent sensory feedback from both arms will increase speed and quality of motor adaptation compared to the case when only one arm experience the force-field.

Little is known about transfer of learning between arms when both arms are learning different or similar reaching tasks. The purpose of this study was to determine the effects of simultaneous learning of a force-field by two arms on transfer of learning during bimanual reaching. It was hypothesized that motor adaptation of dominant or nondominant arm would be greater when both arms learned the same force-field compared to the case when only one arm was exposed to the force-field.

II. METHODS

A. Subjects

Thirty subjects (22 males and 8 females) were recruited for this study. Subjects had no known history of neuromuscular or neurologic disorders, and were right hand dominant in accordance with the Edinburg Inventory test [19]. Informed written consent was obtained prior to the experiment. The study was approved by the Institutional Review Board of the Georgia Institute of Technology.

B. Protocol

The experimental protocol was identical to that used by Harley and Prilutsky in a previous study [6]. Subjects performed bimanual target reaching tasks as quickly and accurately as possible with the Kinarm robot (Fig. 1)[6],[20]-[21]. Subjects were instructed to reach simultaneously with both arms to 8 randomly appearing pairs of targets, arranged radially 10 cm away from the starting position as shown in Fig. 2. A cycle of bimanual reaching tasks was defined as a sequence of consecutive reaching movements towards all eight targets. Subjects started the task by keeping each index fingertip in the starting position for 3 s. Two green targets, one for each arm, signaled the subject to initiate movement. Subjects' reaching time was evaluated as the time between the appearance of the green targets and the moment of reaching to the targets. If the reaching time was less than 500 ms, the green target turned yellow; if it was between 500 and 1000 ms, the target turned pink; and if reaching took longer than 1000 ms, the target turned red. Subjects' arms were covered during the experiment so that they did not have visual feedback on their arm positions. However subjects were able to see the location of the fingertip displayed on the screen.

This work was done as partial fulfillment of the corresponding author's doctorate degree.

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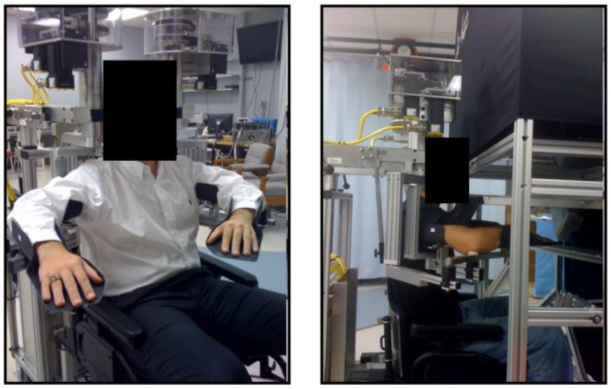
The experiments consisted of 4 phases of bimanual reaching tasks: (1) warm-up (2 cycles, no force field), (2) zero force-field exposure (20 cycles), (3) force-field exposure (40 cycles), and (4) catch trials. The force-field was defined as



A. B.

Figure 1. Subjects sat in the kinarm (a) with their arms supported in the horizontal plane, (b) in front of a back projected display system, that showed the targets in the subjects field of vision.

$$\mathbf{F} = \begin{bmatrix} F_x \\ F_y \end{bmatrix} = \mathbf{B} * \mathbf{V} \text{ (in N)}, \quad (1)$$

where, the external force vector $\mathbf{F}$ applied to the hand was a function of the index fingertip velocity vector $\boldsymbol{V} = \begin{bmatrix} V_x \\ V_y \end{bmatrix}$ (in m/s) and the viscosity matrix $\mathbf{B} = \begin{bmatrix} 0 & 10 \\ -10 & 0 \end{bmatrix} \left(\text{in N} \cdot \frac{\text{s}}{\text{m}}\right)$. During the catch trials, subjects completed 10 cycles, in 3 of which the force-field was pseudo-randomly removed.

C. Experimental groups

Subjects were randomly divided into 3 groups (n=10 per group, Table 1). Each group performed one of the following 3 reaching tasks: (1) by both arms with only the right dominant arm experiencing a clockwise (CW) force-field (Bimanual Dominant), (2) by both arms with only the left nondominant arm experiencing a counterclockwise (CCW) force-field (Bimanual Nondominant), and (3) by both arms with both arms experiencing the same intrinsic force-fields (CW for dominant arm, and CCW for nondominant arm; Bimanual Both). During bimanual reaching, both arms performed out-of-phase reaching movements (Fig. 2).

Table 1. Experimental Groups

Subject Group	Exposure Arm	Force-field
Bimanual Dominant	Right	CW
	Left	Null
Bimanual Nondominant	Right	Null
	Left	CCW
Bimanual Both	Right	CW
	Left	CCW

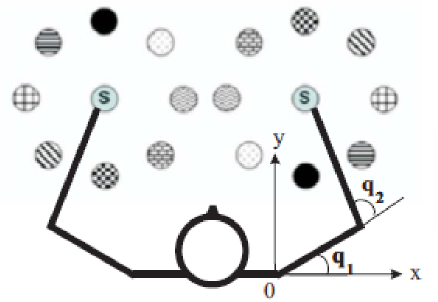


Figure 2. Schematic illustrating subject's arms and target positions during the experimental tasks. At the starting target location (symbol S), shoulder (q_1) and elbow (q_2) angles were 30° and 60°, respectively. During bimanual tasks, the two arms were reaching simultaneously to 8 pairs of targets; each pair of targets appeared randomly and simultaneously in an out-of-phase pattern (shown by the same shading pattern of targets

D. Data analysis and statistics

Task performance was determined from the fingertip trajectory data by calculating the following variables: (1) Perpendicular Displacement (PD), defined as the maximum perpendicular displacement of the finger trajectory from a straight line connecting the start and end targets. (2) Final Position Error (FPE, cm), defined as the absolute difference in position between the end target and the index fingertip at movement offset. (3) The aftereffect (cm), defined as the difference in the mean PD between the last four cycles of the force-field exposure phase and the catch trials. (4) Movement Time (MT, ms), defined as the time between movement onset and offset. (5) Rate of Motor Adaptation of PD was determined by a non-linear exponential regression equation computed using the least squares difference method [6],[22]. A reaching movement was considered successful when: (1) MT was less than 1000 ms and (2) FPE was less than 2 standard deviation of mean FPE for each individual.

Two-way ANOVA analyses were conducted on PD, FPE, Aftereffect and MT, to test the effects of the experimental groups (three levels: bimanual dominant, bimanual nondominant, bimanual both) and arm dominance (two levels: dominant, nondominant). Statistical differences between the regression equations were tested by the Rosenbrock and Quasi-Newton method. The significance level for all statistical tests was set at 0.05.

III. RESULTS

A. Endpoint trajectory

Initial exposure to the force-field caused the index fingertip trajectory to deviate from a straight line. After repeated performance of the task, the trajectory became straighter. During the catch trial, the endpoint trajectory changed direction compared to the initial force-field exposure, and the FPEs increased. These results indicate that motor adaptation took place for all the groups [23]-[24].

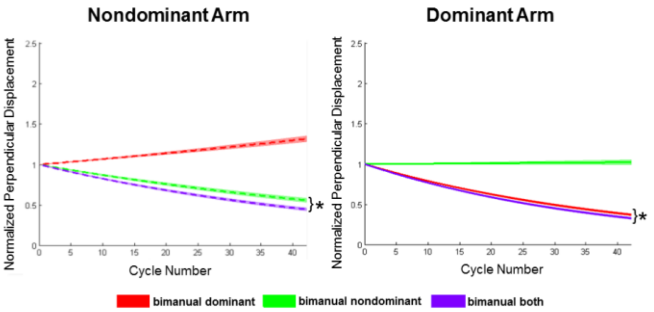


Figure 3. Normalized perpendicular displacement (mean±standard error) averaged across all targets for the nondominant and dominant arm for the Bimanual Dominant (red line), Bimanual Nondominant (green line) and the Bimanual Both (purple line) groups. * indicates significant difference between the groups (p<0.05).

B. *Rate of motor adaptation*

The rate of motor adaptation of the arm(s) exposed to the force-fields was statistically significant which indicates that motor adaptation occurred for those subjects. In addition averaging across all subjects in each experiment group, PD decreased with practice. This confirmed that motor adaptation took place for the arm(s) exposed to the force-field. Thus, motor adaptation of each arm took place in all group of subjects, including the Bilateral Both group.

The rate of motor adaptation of the dominant arm was significantly higher for the Bimanual Both group compared to the Bimanual Dominant group (p<0.05, Fig. 3 right panel, Fig. 4). Similarly, the rate of motor adaptation of the nondominant arm was significantly higher for the Bimanual Both group compared to the Bimanual Nondominant group (p<0.05, Fig. 3 left panel, Fig. 4). These results indicated that transfer of learning occurred in both directions - from the dominant to the nondominant arm and from the nondominant to the dominant arm - when force-dependent feedback was available from both arms. The rate of motor adaptation of the dominant arm was significantly greater than that of the nondominant arm for the Bimanual Both group (p<0.05). This indicated that the dominant arm benefitted more from the transfer of learning than the nondominant arm.

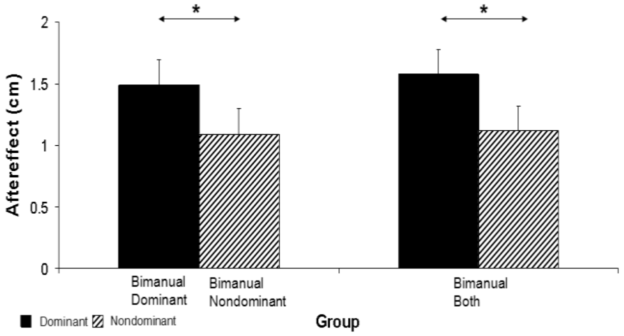


Figure 5. Aftereffects for the dominant arm (solid) and the nondominant arm (hashed). * denotes p<0.05.

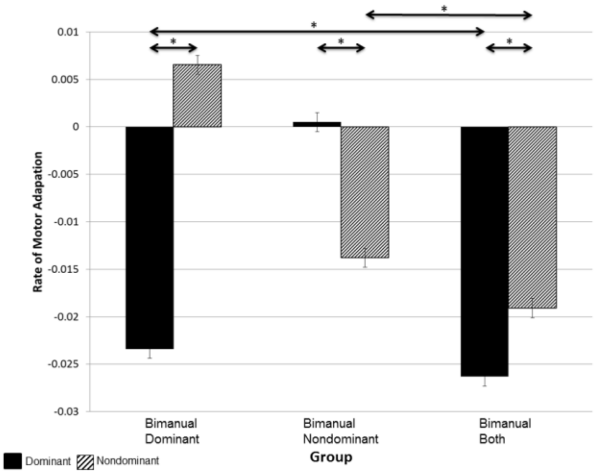


Figure 4. Rate of motor adaptation (mean±standard error) averaged across all targets for the nondominant and dominant arm. * denotes p<0.05.

C. *Aftereffects*

The two-way ANOVA (experimental group x arm) conducted on the aftereffects revealed that the dominant arm had a significantly greater aftereffect than the nondominant arm F(1,316) = 17.00, p<0.01 (Fig. 5). There was no significant group effect, nor interaction group-arm effects.

D. *Final position error*

The two-way ANOVA (experimental group x arm) conducted on the FPE revealed that during the force-field exposure phase there was no significant effects of the experimental condition or the arm dominance on the final position error. A similar analysis of the FPE during the catch trial phase revealed a significant interaction effect between experimental groups and the arms F(2,54) = 4.099, p<0.05. Post-hoc analysis (Tukey HSD) showed that the FPE of the nondominant arm was significantly smaller for the Bimanual Dominant group compared to the Bimanual Both group. This result suggests that there was interference between the arms during the catch trials and this interference could have resulted in no statistical differences in the aftereffects between groups.

E. *Movement time*

The two-way ANOVA (experimental group x arm) conducted on the Movement Time revealed a significant interaction effect between the groups and the arms F(2,54)=7.5, p<0.01. There was no difference in movement time of the dominant arm between the groups. However, the movement time of the nondominant arm was significantly shorter during the catch trials in the Bimanual Dominant group than in the other groups F(2,27)=10.93, p<0.01. This may result from the fact that the nondominant arm did not experience a force-field during the Bimanual Dominant task.

IV. DISCUSSION

The purpose of this study was to determine the effects of simultaneous learning of a force-field by two arms on transfer of learning during bimanual reaching. The hypothesis stated that motor adaptation would be greater when both arms learned the same intrinsic force-field compared to the case when only one arm was exposed to the force-field. The results of this study indicate that the rate of motor adaptation was significantly faster for both the nondominant and the dominant arms during the bimanual reaching tasks when both arms experienced the same intrinsic force field compared to bimanual reaching in which only the dominant or nondominant arm experiences the force-field. Therefore, the research hypothesis was supported.

The increase of rate of motor adaptation for the Bimanual Both group was likely due to transfer of learning between the two arms. It may be suggested that during bimanual reaching, load-related sensory information was transferred between the arms in both directions: from the dominant to the nondominant arm and from the nondominant to the dominant arm. Both the dominant and nondominant arms benefited from this transfer of learning. In this study the same intrinsic force-fields were applied to left and right arms. It may be expected that if the two arms experience opposite force-fields, the transfer of learning between the arms may be affected [5]. This study only considered out-of-phase movements [25], Fig. 2. It is likely that in-phase movements may be more stable and yield different results [26]-[29].

V. CONCLUSION

The results from this study suggest that during bimanual reaching in intrinsic force fields, transfer of learning occurred in both directions: from the dominant to the nondominant arm and from the nondominant to the dominant arm. This transfer of learning was likely mediated by load-dependent feedback from both arms.

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