**35th Annual International Conference of the IEEE EMBS**
**Osaka, Japan, 3 - 7 July, 2013**

# The effect of the direction of force-fields on transfer of learning between the arms during bimanual reaching

Linda R. Harley, *Member, IEEE*, and Boris I. Prilutsky

*Abstract*—**This study examined the effects of force-field direction (extrinsic vs. intrinsic) on transfer of learning during bimanual reaching. Subjects performed bimanual reaching tasks in two force-fields: (1) intrinsic and (2) extrinsic. Motor adaptation of each arm was determined by measuring the deviation of the hand trajectory from a straight line. It was found that rate of motor adaptation of the dominant arm was the same in the two tasks. For the nondominant arm, the rate of motor adaptation was greater during reaching in the intrinsic force-field than in the extrinsic force-field. It is concluded that the load-related sensory feedback from the dominant arm interfered with motor adaptation of the nondominant arm.**

## I. INTRODUCTION

Have you ever attempted to rub your abdomen with one hand while tapping your head with the other? Separately these movements are easy to perform but their simultaneous executions require interlimb coordination that is learned over time. Motor adaptation is the process through which the Central Nervous System (CNS) improves upon performance. Transfer of learning is the process through which learning a motor task in one condition improves performance in another condition. Studies on motor adaptation have predominantly focused on movements of one arm [1]-[5]. Several studies have examined motor adaptations during bimanual tasks, i.e. when both arms were moving at the same time [6]-[15]. 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 [16]. Furthermore, they demonstrated that motor adaptation was greater when both arms experienced an intrinsic force-field compared to the case when only one arm experienced a force-field [17]. An intrinsic force-field refers to when the force-field applied to each arm is in the same direction in the joint space, i.e. the dominant arm experiences a clockwise (CW) force-field, while the nondominant experiences a counter clockwise (CCW) force-field. An extrinsic force field refers to when the force-field is applied in the Cartesian global coorindate space, thus both arms experience a CW force-field.

Studies have found that transfer of learning during reaching in a novel force-field depends on the direction of the force-field. Burgess et al. demonstrated that transfer of learning occurred during a unimanual reaching task after practicing in a bimanual reaching in the same extrinsic force-field environment [18]. Transfer of learning has also been shown to occur from the dominant to the nondominant arm during a unimanual reaching task when the same extrinsic force-field was applied to the arms [19]. Fine and Thoroughman, demonstrated that the direction but not the magnitude of the force-field affected motor behavior during a unimanual reaching [4]. Therefore, the direction of force-field applied to the arms seems to affect unimanual motor adaptation.

The current study examined whether the direction of the force-fields on both arms during bimanual reaching would influence the rate of motor adaptation. The purpose of this study was to determine the effects of extrinsic and intrinsic force-fields on transfer of learning during bimanual reaching. It was hypothesized that during bimanual reaching when each arm adapts to a force-field, transfer of learning should be greater for the extrinsic force-field than for the intrinsic force-field [18, 19].

## II. METHODS

### A. Subjects

Twenty subjects (14 males and 6 females) were recruited for this study. Subjects had no known history of neuromuscular or neurological disorders, and were right hand dominant in accordance with the Edinburg Inventory test [20]. 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 [16]. The Kinarm robot was used to record arm reaching movements and apply viscous force-fields [21]-[22]. Subjects were instructed to reach with both arms simultaneously toward two sets of 8 targets that were arranged radially 10 cm away from the starting position (Fig. 1). Consecutive reaching towards all 8 pairs of targets was defined as a cycle. Subjects started by placing each index fingertip in its own blue start target (S, Fig. 1) for 3 s before two green targets appeared, one for each arm. Subjects reached towards the two green targets simultaneously as accurately and quickly as possible. The targets changed color to yellow, pink or red if a reaching movement was performed faster than <500 ms, within 500 - 1000 ms or longer than >1000 ms, respectively. The subjects were instructed to try keeping the duration of reaching movements within 500 - 1000 ms. Subjects were able to see the location of the fingertips displayed on the screen at all times, however subjects' arms were covered in order to limit visual feedback of their arms position in space.

---

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

L. R. Harley is with the Georgia Tech Research Institute, Atlanta, GA 30332 USA (corresponding author: 770.561.1825; fax: 404.894.8051; email: linda.harley@gtri.gatech.edu)

B. I. Prilutsky is with the School of Applied Physiology and the Center for Human Movement Studies, Georgia Institute of Technology, Atlanta, GA 30332 USA (email: boris.prilutsky@ap.gatech.edu)

978-1-4577-0216-7/13/$26.00 ©2013 IEEE

Each experiment 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

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

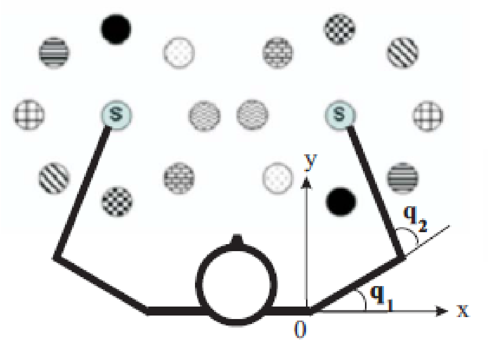

Figure 1. Schematic illustrating subject's arms and target positions during the experimental tasks. At the starting target location (symbol S), shoulder ($q_1$) and elbow ($q_2$) angles were $30^o$ and $60^o$, respectively. During bimanual tasks, the two arms were reaching simultaneously to 8 pairs of targets; each pair of targets appeared randomly and simultaneously in an out-of-phase pattern (shown by the same shading pattern of targets)

where, the external force vector **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 $\mathbf{B} = \begin{bmatrix} 0 & 10 \\ -10 & 0 \end{bmatrix} \left(\text{in N} \cdot \frac{\text{s}}{\text{m}}\right)$. For the bimanual intrinsic force-field condition, the force-field applied to each arm was in the same direction in the joint space, i.e. the dominant arm experienced a clockwise (CW) force-field of **B**, while the nondominant arm experienced a counter clockwise (CCW) force-field of **-B**. For the bimanual extrinsic force-field condition, the force-fields applied to the arms had the same direction in the Cartesian global coordinate space, thus both arms experienced a CW force-field of **B**. During the catch trials, subjects completed 10 cycles, in 3 of which the external velocity-dependent force-field was pseudo-randomly removed from both arms.

### C. *Experimental groups*

Subjects were randomly divided into 2 groups (n=10 per group, Tables 1 and 2); each group performed bimanual reaching tasks in one of the force-field: (1) intrinsic force-field (Bimanual Intrinsic), and (2) extrinsic force-field (Bimanual Extrinsic). The arms moved in an out-of-phase pattern during bimanual reaching (Fig. 1).

### D. *Data analysis and statistics*

Task performance was determined by calculating: (1) Perpendicular Displacement (PD), (2) Final Position Error (FPE), (3) The aftereffect, (4) Movement Time (MT) and (5) Rate of motor adaptation. PD was defined as the maximum perpendicular displacement of the fingertip trajectory from a straight line connecting the start and end targets. FPE was defined as the absolute difference in position between the end target and the index fingertip at movement offset. The aftereffect was defined as the difference in mean PD between the last four cycles of the exposure phase and the three catch trials. MT was defined as the time between movement onset and offset. Rate of motor adaptation (rate of decrease in PD) was defined by a non-linear exponential regression equation computed using the least square difference method [16],[23]. A reaching movement was considered successful when: (1) MT was less than 1000 ms and (2) FPE was less than 2 standard deviations of the mean FPE.

Table 1. Experimental groups

| Subject Group | Exposure Arm | Force-field |
|---|---|---|
| Bimanual Intrinsic | Right<br>Left | CW<br>CCW |
| Bimanual Extrinsic | Right<br>Left | CW<br>CW |

Table 2. Characteristics of subjects (mean±SD)

| Subject Group | Age (years) | Height (cm) | Mass (kg) |
|---|---|---|---|
| Bimanual Intrinsic | 33±11 | 177±12 | 89±20 |
| Bimanual Extrinsic | 40±12 | 180±9 | 93±24 |

To compare whether learning curves differed between experimental conditions, the regression lines were compared using the Rosenbrock and Quasi-Newton method with least squares. Two-way ANOVA analyses were conducted to test the effects of experimental conditions and arm dominance. The significance level was set at 0.05.

## III. RESULTS

### A. *Endpoint trajectory*

Initial exposure to the force-fields caused large fingertip movement deviations in both the arms for both groups. With practice the fingertip trajectories straightened. When the force-fields were pseudo-randomly removed from both the arms during the catch-trials, large trajectory deviations were observed in both arms in the opposite direction compared to the movement errors during initial force-field exposure. The regression analysis revealed that the rate of motor adaptation of the normalized PD was statistically different from zero for both arms and both groups. This result indicated that motor adaptation took place in all studied conditions [1],[24].

### *B. Rate of motor adaptation*

In both the Bimanual Intrinsic and Bimanual Extrinsic groups, the rate of change in PD with practice for both the dominant and nondominant arms was negative, indicating that both arms were able to adapt to the force-fields. For the dominant arm, there was no significant difference in the rate of motor adaptation between the Bimanual Intrinsic and Bimanual Extrinsic groups (Fig. 2, Fig. 3). For the nondominant arm, the rate of motor adaptation to the Bimanual Extrinsic task was significantly lower than to the Bimanual Intrinsic task. Therefore, it is plausible that the dominant arm interfered with the rate of motor adaptation of the nondominant arm during the Bimanual Extrinsic task. The rate of motor adaptation of the dominant arm was significantly greater than that of the nondominant arm for both groups.

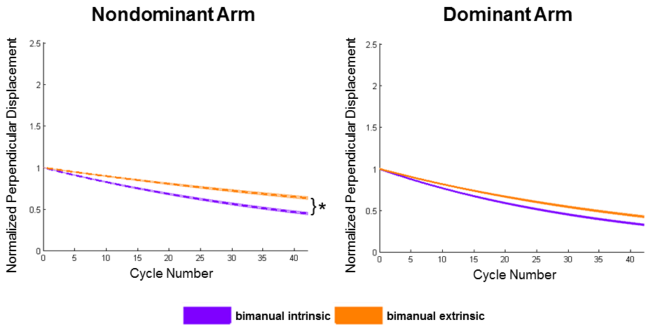

Figure 2. Normalized perpendicular displacement (mean±standard error) averaged across all targets for the left nondominant and right dominant arm during the Bimanual Intrinsic (purple line), and the Bimanual Extrinsic (orange line) tasks. * indicates significant difference between the groups ($p<0.05$).

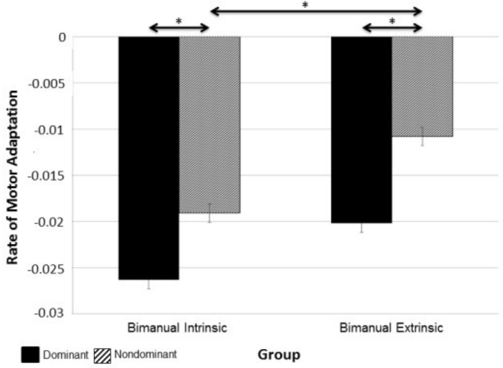

Figure 3. Rate of motor adapation (mean±standard error) averaged across all target for the nondominant and dominant arm. * denotes $p<0.05$

### *C. Aftereffects*

The results of a two-way (force-field x arm) ANOVA conducted on the aftereffects revealed a significant effect of arm dominance and that the aftereffects for the dominant arm were significantly greater than those of the nondominant arm F(1,316)=14.52, $p<0.01$ (Fig. 4). There was no significant difference of force-field on the aftereffects.

### *D. Final position error*

A two-way ANOVA (force-field x arm) conducted on FPE revealed no significant effects of the force-field direction or arm dominance on FPE.

### *E. Movement time*

A two-way ANOVA (force-field x arm) conducted on MT found no significant effects of the force-filed direction or arm dominance on MT.

## IV. DISCUSSION

The purpose of this study was to determine the effects of extrinsic and intrinsic force-field on transfer of learning between the arms during bimanual reaching. It was hypothesized that during bimanual reaching in viscous force-field, transfer of learning between the arms would be greater if the force-fields applied to the two arms had the same extrinsic direction. The results of this study demonstrated that the rate of motor adaptation of the nondominant arm during the Bimanual Intrinsic task was significantly faster than during the Bimanual Extrinsic task. This suggests that movement-dependent sensory feedback from the dominant arm interfered with the motor adaptation of the nondominant arm when extrinsic force-field was applied to both arms. Thus, the tested hypothesis was not supported. For the dominant arm, no difference in the rate of motor adaptation was found between the Bimanual Intrinsic and Bimanual Extrinsic experimental groups. Therefore, the nondominant arm neither interfered with nor aided the motor adaptation of the dominant arm when both arms experienced different force-fields. These results demonstrate that the direction of force-fields applied to the arms affect the motor adaptation of the nondominant arm but not the dominant arm.

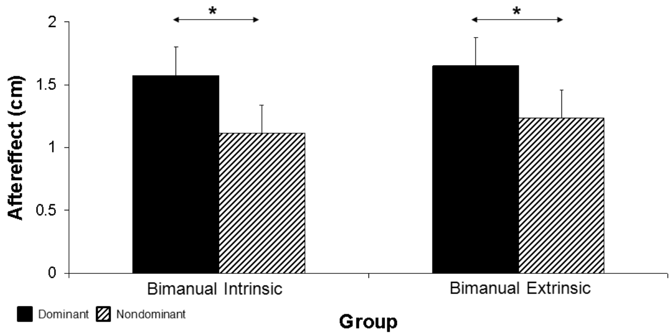

Figure 4. Aftereffects for the dominant arm (solid) and the nondominant arm (hashed) obtained during the bimanual intrinsic and bimanual extrinsic conditions. * denotes $p<0.05$.

There are several limitations to this study. First, it must be noted that the only difference between the Bimanual Intrinsic and Bimanual Extrinsic tasks was that the direction of the force-field on the nondominant arm was varied. Future studies, should examine effects of different force-fields applied to the dominant arm on the rate of motor adaptation. Secondly, only out-of-phase reaching movements were investigated in this study. Given differences in bimanual coordination between out-of-phase and in-phase movements [14], [25]-[28], future studies should investigate transfer of learning between the arms during in-phase bimanual tasks. Lastly, the results obtained in this study may be influenced by divided attention, i.e. the subject had to perform reaching movements to 2 different targets simultaneously. Research has demonstrated that if a subject is instructed to focus attention on a single limb during a bimanual task, that the unattended limb would make greater movement errors [29]. In this study, there was no significant difference in Movement Time between the tasks and the arms. This funding suggests that divided attention was not likely to affect the observation that the dominant arm interfered with motor learning of the nondominant arm. Future studies may benefit from using an eye tracking system to monitor gaze fixation points during bimanual reaching experiments.

## V. CONCLUSION

The rate of motor adaptation by the nondominant arm was faster during the Bimanual Intrinsic reaching task than during the Bimanual Extrinsic task. The rate of motor adaptation for the dominant arm did not differ between experimental tasks. Thus, the external load-related sensory feedback from the dominant arm interfered with the motor adaptation of the nondominant arm during the Bimanual Extrinsic task. Therefore, the direction of the force-field affects the motor adaptation of the nondominant arm but not the dominant arm.

## ACKNOWLEDGMENT

The authors wish to thank Brad Farrel, Ricky Mehta, Gregory Phillips and Gary Schwaiger for their assistance and the Center for Human Movement Studies at Georgia Tech for partial support of this study.

## REFERENCES

[1] P. DiZio and J.R. Lackner, “Motor adaptation to coriolis force perturbations and reaching movements; endpoint but not trajectory adaptation transfers to the non-exposed arm,” *Journal of Neurophysiology*, vol. 74, no. 4, pp. 1787 – 1792, 1995.

[2] N. Dounskaia, S. Swinnen, C. Walter, A. Spaepen, and S. Schueren, "Hierarchical control of different elbow-wrist coordination patterns," *Exp Brain Res*, vol. 121, pp. 239 - 254, 1998.

[3] A. Feldman, "Superposition of motor programs: Rapid forearm flexion in man," *Neuroscience*, vol. 5, pp. 91 - 95, 2006.

[4] M. Fine, and K. Thoroughman, "Motor adaptation to single force pulses: sensitive to direction but insensitive to within-movement pulse placement and magnitude," *Journal of Neuropysiology*, vol. 96, pp. 710 - 720, 2006.

[5] R. Shadmehr, and F. Mussa-Ivaldi, "Adaptive representation of dynamics during learning of a motor task," *Journal of Neuroscience*, vol. 14, no. 5, pp. 3208 - 3224, 1994.

[6] N. Albert, M. Weigelt, E. Hazeltine, and R. Ivry, "Target selection during bimanual reaching to direct cues is unaffected by the perceptual similarity of targets," *Journal of Experimental Psychology*, vol. 33, no. 5, pp. 1107 - 1116, 2007.

[7] J. Diedrichsen, R. Ivry, E. Hazeltine, S. Kennerly, and A. Cohen, "Bimanual interference associated with the selection of target locations," *Journal of Experimental Psychology*, vol. 29, no. 1, pp. 64 - 77, 2003.

[8] J. Diedrichsen, "Optimal task-dependent changes of bimanual feedback control and adaptation," *Current Biology*, vol. 17, pp. 1675 - 1679, 2007.

[9] C. Gerloff, and FG Andres, "Bimanual coordination and interhemispheric interaction," *Acta Psychologica*, vol. 110, pp. 161 - 186, 2002.

[10] S. Grafton, E. Hazeltine, and R. Ivry, "Motor sequence learning with the nondominant left hand: A pet functional imaging study," *Exp Brain Res*, vol. 146, pp. 369 - 378, 2002.

[11] E. Hazeltine, J. Diedrichsen, S. Kennerly, and R. Ivry, "Bimanual cross-talk during reaching movements is primarily related to response selection, not the specification of motor parameters," *Psychological Research*, vol. 67, pp. 56 - 70 , 2003.

[12] H. Heuer, "Simultaneous specification of amplitudes and directions of bimanual reversal movements," *Journal of Motor Behavior,* vol. 38, no. 4, pp. 285 - 298, 2006.

[13] J. Kelso, D. Southard, and D. Goodman, "On the nature of human interlimb coordination," *Science*, vol. 203, pp. 1029 - 1031, 1979.

[14] J. Kelso, D. Southard, and D. Goodman, “On the coordination of two-handed movements,” *Journal of Experimental Psychology,* vol. 5, no. 2, pp. 229 – 238, 1979.

[15] R. Walsh, S. Small, E. Chen, and A. Solodkin, "Network activation during bimanual movements in humans," *NeuroImage*, vol. 43, pp. 540 - 553, 2008.

[16] L.R. Harley, and B.I. Prilutsky, "Transfer of learning between the arms during bimanual reaching," *Proceedings of the 34th EMBS Annual International Conference*, pp. 6785 - 6788, 2012.

[17] L.R. Harley, and B.I. Prilutsky, "The effect of force feedback on transfer of learning during bimanual reaching," *Under Review for 35th EMBS Annual International Conference*, 2013.

[18] J. Burgess, R. Bareither, and J. Patton, "Single limb performance following contralateral bimanual limb training," *IEEE Transaction on neural systems and rehabilitation engineering*, vol. 15, no. 3, pp. 347 - 355, 2007.

[19] S. Criscimagna-Hemminger, O. Donchin, M. Gazzaniga, and R. Shadmehr, "Learned dynamics of reaching movements generalize from dominant to nondominant arm," *Journal of Neurophysiology*, vol. 89, pp. 168 - 176, 2003.

[20] R. Oldfield, “The assessment and analysis of handedness: the Edinburgh inventory,” *Neuropsychologia,* vol. 9, no. 1, pp. 97 – 113, 1971.

[21] BKIN Technologies, Kingston, ON, Canada. Accessed at: www.bkintechnologies.com on March 27, 2012

[22] S.H. Scott, “Apparatus for measuring and perturbing shoulder and elbow joint positions and torques during reaching,” *J Neuroscience Methods*, vol. 89, no. 2, pp. 119 – 127, 1999.

[23] K.M. Newell, Y.T. Liu and G. Mayer-Kress, “Time scales in motor learning and development,” *Psychol Rev*, vol. 108, no. 1, pp. 57 – 82, 2001.

[24] R. Sainburg and J. Wang, “Interlimb transfer of visuomotor rotations: independence of direction and final position information,” *Exp Brian Res*, vol. 145, pp. 437 – 447, 2002.

[25] S. Swinnen, C. Walter, T. Leet and D. Serrien, “Acquiring bimanual skills: contrasting forms of information feedback for interlimb decoupling,” *Journal of Experimental Psychology*, vol. 19, no. 6: pp. 1328 – 1344, 1993.

[26] L. Cohen, “Synchronous bimanual movements performed by homologous and non-homologous muscles,” *Perceptual and Motor Skills*, vol. 32, pp. 639 – 644, 1971.

[27] S. Swinnen, K. Jardin and R. Meulenbroek, “Between-limb asynchronies during bimanual coordination: Effects of manual dominance and attentional cueing,” *Neuropsychologia*, vol. 34, no. 12, pp. 1203 – 1212, 1996.

[28] S. Swinnen, K. Jardin, S. Verschueren, R. Meulenbroek, L. Franz, N. Dounskaia, and C. Walter, “Exploring interlimb constraints during bimanual graphic performance: effects of muscle grouping and direction,” *Behavioral Brain Research*, vol. 90, pp. 79 – 87, 1998.

[29] D. Sherwood and A. Kaiser, “Using concurrent visual feedback to focus attention in bimanual aiming movements,” *Research Quaterly for Exercise and Sport*, vol. 73, no. 4, pp. 478 – 484.