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Transfer of learning between the arms during bimanual reaching.

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Abstract—**This study examined how movement of one arm affects the rate of motor adaptation of the other arm during bimanual reaching in a viscous force-field. Forty healthy adult subjects performed four reaching tasks: (1) by dominant arm, (2) by nondominant arm, (3) by both arms with only dominant arm experiencing force-field and (4) by both arms with only nondominant arm experiencing the force-field. For dominant arm rate of motor adaptation was greater during the bimanual task than the unimanual task. For nondominant arm reaching errors were higher during the bimanual than unimanual task. These results suggest that during bimanual reaching, transfer of learning between arms occur in both directions and movement information transferred depends on arm dominance.**

I. Introduction

Transfer of learning is a process through which practicing a motor task in one condition improves performance in another condition. It has been shown that: (1) when one arm has learned a novel motor task, the other nontrained arm may demonstrate improved performance in the same task [1],[2], (2) practicing a unimanual task may lead to improved performance of a similar bimanual task [3] and (3) practicing a bimanual motor task may lead to improved performance of a similar unimanual task [4]-[5].

Several models of transfer of learning have been proposed based on unimanual reaching studies. These models include Callosal model [6], Proficiency model [7], Cross-activation model [8] and Dynamic dominance hypothesis [9]. The latter suggests that the dominant arm is more proficient in coordinating dynamical intersegmental interactions than the nondominant arm and therefore should be better in controlling trajectory direction of the arm endpoint. At the same time, the nondominant arm is specialized in static stabilizing tasks and thus is more proficient in specifying the final arm endpoint position [9]-[11]. As a result, during adaptations of unimanual arm reaching movements to visuomotor perturbations, the final arm endpoint position information is transferred from the dominant to the nondominant arm, while trajectory information is transferred from the nondominant arm to the dominant arm [10]. The situation is even more complex during bimanual tasks when motor learning could either impede [12], enhance [13] or have no effect [5] on transfer of learning between the arms due to interactions of a different degree between the arm controllers and movement dependent feedback.

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

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Little is known about whether or how transfer of learning takes place when both arms learn different reaching tasks simultaneously. The purpose of this study was to determine how movement of one arm affects the rate of motor adaptation of the other arm during bimanual reaching. It was hypothesized that arm dominance and simultaneous movement of the other arm during bimanual reaching tasks would affect the rate of motor adaptation to a viscous force-field.

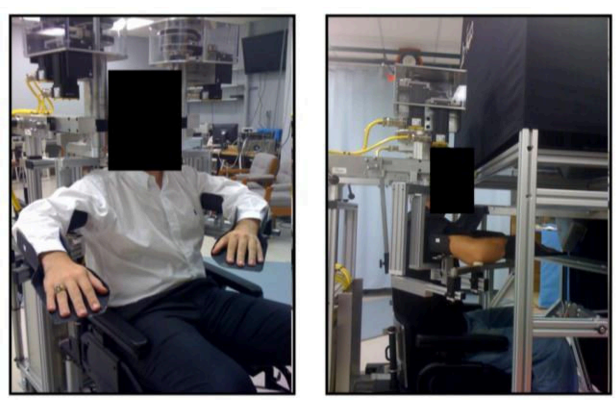
II. Methods

A. Subjects

Forty subjects (30 males and 10 females) were recruited for this study. The subjects had no known history of neuromuscular or neurologic disorders, and were right hand dominant in accordance with the Edinburg Inventory test [14]. 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

Subjects sat in a chair within the Kinarm bimanual robot (Fig. 1) [15] and were instructed to place two cursors indicating their index finger tips into the starting position displayed as two blue targets on a horizontal screen. The starting position for each arm was defined with a shoulder, elbow and wrist flexion angles of 30^0, 60^0 and 0^0 respectively. Subjects were asked to reach to eight randomly appearing targets or pairs of targets (1 cm diameter) arranged radially 10 cm away from the starting position as quickly and as accurately as possible. Consecutive reaching towards all eight targets defined a cycle. In order to start the task, the subject had to keep the index finger tip of each arm on the starting position target for 3 s before a green target or pair of targets appeared signaling the subject to initiate movement.



A. B.

Figure 1. The Kinarm robotic upper extremity assessment system. (a) Frontal view. (b) The visual display system on the right projects targets in the subjects field of view.

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The reaching time was defined as the time between the target(s) appearance and the reaching of the target(s) outer border. If the reaching time was less than 500 ms the green target turned yellow, between 500 and 1000 ms the target turned pink, and greater than 1000 ms the target turned red. Subjects were asked to perform reaching faster than 1000 ms.

The protocol consisted of 4 phases of reaching movements: (1) warm-up, (2) pre force-field exposure, (3) force-field exposure, and (4) catch trials. During the warm-up subjects performed 2 reaching cycles to ensure that the experimental setup was correct. Subjects then completed 20 cycles in the natural environment (zero force-field) during the pre-force-field exposure phase which allowed them the opportunity to become familiar with the task. The force-field exposure phase consisted of two blocks of reaching movements of 20 cycles of reaching in a velocity dependent force -field defined as,

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

where, the external force vector **F** applied to the hand was a function of the index finger tip 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 trial phase, subjects completed 10 cycles, in 3 of which the external velocity-dependent force was pseudo-randomly removed.

C. Experimental groups

Subjects were randomly divided into 4 groups (n=10 per group, Table 1); each group performed one of the following 4 reaching tasks: (1) by dominant arm (unimanual dominant group), (2) by nondominant arm (unimanual nondominant), (3) by both arms with only the dominant arm experiencing force-field during the force-field exposure phase (bimanual dominant) and (4) by both arms with only the nondominant arm experiencing force-field during the force-field exposure phase (bimanual nondominant). During unimanual tasks, subjects reached to targets with either the dominant or nondominant arm, while maintaining the index finger of the other arm within the starting position target. During bimanual reaching tasks, both arms performed out-of-phase reaching movements but only one arm experienced the force-field.

Table 1. Experimental groups

Subject Group	Exposure Arm	Force-field
Unimanual dominant	Right	CW
	Left	NA
Bimanual dominant	Right	CW
	Left	Null
Unimanual nondominant	Right	NA
	Left	CCW
Bimanual nondominant	Right	Null
	Left	CCW

CW = Clockwise, CCW = Counter Clockwise

D. Data analysis and statistics

The following measures of task performance were calculated from the fingertip trajectory data: (1) Perpendicular Displacement (PD), defined as the maximum perpendicular displacement of the finger trajectory from a straight line connecting the start and end targets. The PD was normalized to the perpendicular displacement in the first reach towards a target during the force-field exposure phase. (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 was calculated as the difference in the mean PD between the last four cycles of the exposure phase bout and the three catch trials (cm).

Movement Time (MT, ms) was defined as the time between movement onset and offset, which corresponded to time instances when the magnitude of the index finger tip velocity vector exceeded or became smaller than 5% of the velocity vector peak magnitude. A reaching movement was considered successful when: (1) movement time was less than 1000 ms and (2) the FPE was less than two standard deviation of the mean FPE for each individual.

The rate of motor adaptation [16] for each experimental condition was determined from the non-linear regression equation computed using the least squares difference method:

$$PD = e^{-bt} \quad (2)$$

where, PD is the normalized perpendicular displacement, *b* is the rate constant, i.e. the rate of motor adaptation, and *t* is the cycle number (0, 1, … k). Statistical differences between the regression equations obtained for the different experimental conditions were tested by the Rosenbrock and Quasi-Newton method. Two-way ANOVA's were conducted for all performance variables to test the effects of the unimanual vs. bimanual experimental conditions (two levels) and arm dominance (two levels: dominant and nondominant). The significance level for all statistical tests was set at 0.05.

III. Results

A. Endpoint trajectory

Initial exposure to the force-field in all four groups caused the index finger trajectory to deviate from a straight line. After 40 cycles of reaching in the force-field, the arm endpoint trajectory became straighter. During the catch trials, curvature of the endpoint trajectory changed direction compared to initial exposure trials and larger FPEs occurred compared to those during the later exposure to the force-field. The decrease in trajectory curvature with practice and large PDs in the opposite direction during the catch trials in each tested experimental group indicated that motor adaptation took place in all studied conditions [1],[10].

B. Rate of motor adaptation

The rate of motor adaptation (coefficient *b* in equation 2) of the arm exposed to viscous force-field was statistically larger than zero ($p<0.05$) for most of the experimental conditions and target directions, i.e. when averaged across

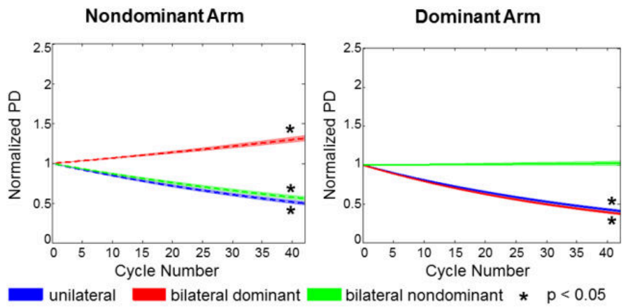

Figure 2. Normalized perpendicular displacement (mean±standard error) averaged across all targets for the left non-dominant and right dominant arm for the unimanual (blue line), bimanual dominant (red line) and the bimanual nondominant (green line) groups.

all subjects in each experiment group, PD decreased with practice confirming that motor adaptation took place.

When the rate of motor adaptation was calculated across all target directions for each experimental group, it was significantly larger than zero for the arms exposed to the force-field ($p<0.05$, Fig. 2) - for the dominant arm in the unimanual and bimanual dominant groups and for the nondominant arm in the unimanual and bimanual nondominant groups.

The rate of motor adaptation of the dominant arm was significantly higher in the bimanual dominant compared to the unimanual dominant groups ($p<0.05$, Fig. 2 right panel), indicating that motor adaptation of the dominant arm improved due to simultaneous unloaded reaching movements by the nondominant arm. On the contrary, the rate of motor adaptation of the nondominant arm was lower in the bimanual nondominant than in the unimanual nondominant group (Fig 1, left panel), suggesting an interference from reaching movements of the unloaded dominant arm.

The normalized PD of the dominant arm did not change during exposure of the nondominant arm during the bimanual nondominant task ($p>0.05$, Fig. 2, right panel, green line), whereas the PD of the nondominant arm increased significantly during the bimanual dominant task (Fig. 2, left panel, red line).

C. Aftereffects

The results of a two-way (experimental group x arm) ANOVA conducted on the aftereffects revealed that the unimanual groups had significantly larger aftereffects than the bimanual groups $F(1, 316) = 11.92$, $p < 0.05$ (Fig. 3). Also, the dominant arm had significantly larger aftereffects than the nondominant arm $F(1, 316) = 14.55$, $p<0.05$. The aftereffect of the dominant arm after the unimanual dominant task was greater than after the bimanual dominant condition ($p<0.05$); similarly the aftereffect of the nondominant arm was greater in the unimanual nondominant condition than in the bimanual nondominant task ($p<0.05$). These results imply that motor adaptation was more complete during the unimanual conditions than during the bimanual conditions.

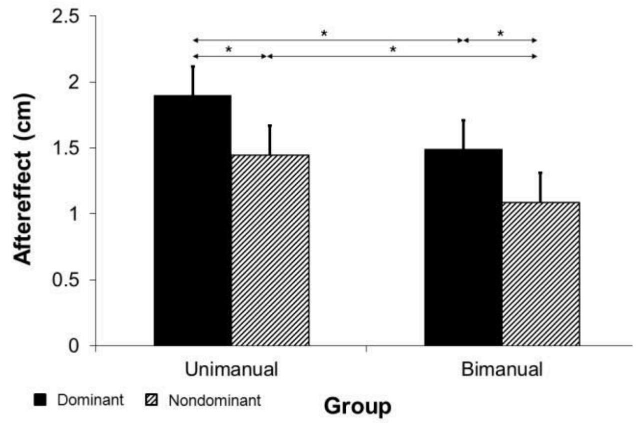

Figure 3. Aftereffects for the dominant arm (solid) and the nondominant arm (hashed) obtained during the unimanual and bimanual conditions when only one arm experiences the force-field. * denotes p<0.05.

D. Final position error during catch trials

The results of a two-way (experimental group x arm) ANOVA conducted on the FPE during the exposure phase revealed no significant effects ($p>0.05$) of the experimental condition on the arm's dominance. A similar analysis conducted on the FPE during the catch trial phase found an overall significant effect ($F(2,54) = 7.06$, $p<0.05$). Post-hoc analysis (Tukey HSD test) showed no difference in the dominant arm FPE between the unimanual and bimanual tasks ($F(2,27) = 1.75$, $p = 0.193$). However, the FPE of the nondominant arm was significantly greater in the bimanual nondominant group than in the unimanual nondominant and bimanual dominant groups ($F(2,27) = 6.84$, $p<0.05$; Fig. 4).

IV. Discussion

The purpose of this study was to determine whether transfer of learning between arms occurs during bimanual reaching. The results demonstrated that arm dominance and simultaneous movement of the arms during bimanual reaching affect the rate of motor adaptation. The rate of adaptation of the dominant arm was greater for the bimanual dominant group than for the unimanual dominant group (Fig. 2, right panel). This suggests that motion-dependent feedback from the nondominant arm during the bimanual dominant task enhanced the rate of motor adaptation of the dominant arm to the force-field. On the other hand, the FPE analysis suggests that feedback from the dominant arm in bimanual nondominant tasks interfered with the endpoint accuracy of the nondominant arm during the catch trials (Fig. 4). One possible explanation for these findings is that of the Dynamic dominance hypothesis [10],[11] that suggests that trajectory information (e.g. PD) is transferred from the nondominant to the dominant arm, whereas final endpoint position information (e.g. FPE) is transferred from the dominant to the nondominant arm.

There are a few limitations to this study that should be mentioned. First, this study considered whether transfer of learning would occur during bilateral reaching where the

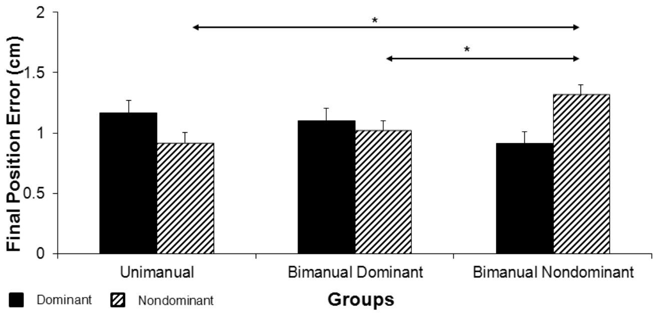

Figure 4. Final position error of the dominant arm (solid) and the nondominant arm (hashed) for the unimanual and bimanual groups during the catch trials. * denotes $p < 0.05$.

arms performed out-of-phase arm movements. Although out-of-phase movements are stable [17], it is believed that in-phase movements may be more stable which may yield different results [18]-[19]. A comparative study should be conducted to determine if there are any differences in transfer of learning during a bimanual task between in-phase and out-of-phase movements. It should also be noted that subjects' arms were continually supported throughout reaching movements by the Kinarm robot. This eliminated the involvement of anti-gravity muscles during the task. Most of the tasks that people perform do not happen in this type of environment. Lastly, subjects were not instructed to fixate on a specific arm or point during the performance of bimanual reaching and allowed to self-select their own strategy. Thus, the effect of divided attention on the obtained results could not be inferred in this study. Research has demonstrated that if a subject is instructed to focus attention on a single limb during a bimanual task, the unattended limb would make greater movement errors [20]. In the current study an attempt was made to examine the effect of divided attention by measuring reaction time between subjects, arms and tasks, but no significant differences were observed. Future studies may benefit from including eye tracking technology to evaluate whether there is any correlation between the amount of time spent focusing on a specific arm or target, reaching performance and motor adaptation.

The findings of this study may benefit occupational therapists when considering the design and purpose of bilateral versus unilateral goal oriented reaching in therapy. Depending on the objective of therapy, whether it is to improve arm trajectory or final endpoint accuracy, as well as which arm needs rehabilitation (dominant vs. nondominant), may alter the rehabilitation strategy.

V. Conclusion

The results from this study suggest that during bimanual reaching, transfer of learning between the arms occur in both directions and movement information transferred depends on arm dominance.

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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] H. Imamizu and S. Shimojo, "The locus of visual-motor learning at the task or manipulator level: implications from intermanual transfer," *Journal of Experimental Psychology*, vol. 21, no. 4, pp. 719 – 733, 1995.

[3] D. Nozaki and S. Scott, "Multi-compartment model can explain partial transfer of learning within the same limb between unimanual and bimanual reaching," *Exp Brain Res,* vol. 194, pp. 451 – 463, 2009.

[4] J. Hitchens and J. Patton, "Generalization of motor adaptation skills from bimanual-grasp to individual limbs," *Proceedings of the 28th EMBS Annual International Conference*, pp. 2706 – 2708, 2006.

[5] L. Tcheang, P.M. Bays, J.N. Ingram, and D.M. Wolpert, "Simultaneous bimanual dynamics are learned without interference," *Exp Brain Res*, vol. 183, no. 1, pp. 17 – 25, 2007.

[6] H. Tailor and K. Heilman, "Left-hemisphere motor dominance in right handers," *Cortex*, vol. 16, pp. 587 – 603, 1980.

[7] J. Laszlo, R. Baguley, and P. Bairstow, "Bilateral transfer in tapping skill in the absence of peripheral information," *Journal of Motor Behavior*, vol. 2, no. 4, pp. 261 – 271, 1970.

[8] S. Parlow and M. Kinsbourne, "Asymmetrical transfer of training between hands: implications for interhemispheric communication in normal brain." *Brain and Cognition*, vol. 11, pp. 98 – 113, 1989.

[9] R. Sainburg, "Evidence for a dynamic-dominance hypothesis of handedness." *Exp Brain Res*, vol. 142, pp. 241 – 258, 2002.

[10] 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.

[11] J. Wang and R. Sainburg, "The dominant and nondominant arms are specialized for stabilizing different features of task performance." *Exp Brain Res*, vol. 178, pp. 565 – 570, 2007.

[12] M. Casadio, V. Sanguineti, V. Squeri, L. Masia and P. Morasso, "Inter-limb interference during bimanual adaptation to dynamic environments," *Exp Brain Res*, vol. 202, no. 3, pp. 693 – 707, 2010.

[13] S. Vangheluwe, V Puttemans, N Wenderoth, M Van Baelen, and S.P. Swinnen, "Inter- and intralimb transfer of a bimanual task: generalizability of limb dissociation," *Behav Brain Res.,* vol. 154, no. 2, pp. 535 – 547, 2004.

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

[15] 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.

[16] 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.

[17] 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.

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

[19] 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.

[20] 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, 2002.