INTERMANUAL TRANSFER OF LEARNING REVEALS REPRESENTATIONS IN SIMULTANEOUS EXTRINSIC AND INTRINSIC COORDINATE SYSTEMS

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Abstract— **Recent research on learning and recovery in rehabilitation has raised questions about the manner in which the nervous system stores and recalls memories of skills learned. This is functionally important when an individual is asked to generalize what was learned to a different movement direction, another part of the workspace, or with the opposite hand. Subjects underwent training in Cartesian force field (Saddle type field) in a training workspace. This experiment built upon other approaches by testing before and after training in a new workspace and with the opposite hand in the presence of both extrinsic (Cartesian-based) and intrinsic (joint-based) force fields. Results show that training led to clearly better performance improvements in the extrinsic coordinate system, and also suggest that subjects are influenced by a joint based force field when they are asked to transfer their knowledge their opposite arm. These results suggest that there are multiple simultaneous representations of the training experience in the nervous system that subjects can recall when asked to generalize. These results may be important to the design of future rehabilitation regimens that optimize the training coordinate systems for the best chances of restoration of function.**

I. INTRODUCTION

Generalization, or the ability to transfer learned skills to unpracticed domains, is a critical gauge of success in nearly all fields that study learning. Since robot-facilitated training in rehabilitation is heavily influenced by neuroplastic changes and motor "relearning," the investigation of the nature of such generalization should guide the development of efficient methods for suitable environments in which patients learn task more quickly and efficiently. On critical parameter is the coordinate system(s) in which the nervous system stores and recalls memories. Knowing which coordinate system is used by the nervous system would allow better programming of therapeutic interventions that can optimize training regimes to evenly span the space of coordinate systems or focus on a portion of the workspace that needs therapeutic attention.

While there have been several studies that have probed this question, but there is not an agreement on the manner in which coordinate systems are used to generalize and extrapolate what was learned. Over the past decade or more, research on how robotic training changes dynamics has been used to understand the underlying function of the neural controller, the manner in which it adapts, and the manner in which it can transfer or generalize that knowledge. Most work has shown that central nervous system(CNS), attempting to attain a desired trajectory, acquires an internal model of the limb's dynamics and external forces to produce torques to that can move the hand along this desired trajectory. When the system dynamics are changed, the internal model was gradually adapted to cancel dynamics and perform the desired trajectory [24]. When asked to extrapolate what was learned, subjects performed best when the force field was also extrapolated in a joint based coordinate system [9][12][23][24].

In contrast, recent studies on transfer of skills from one limb to another have made several arguments on the coordinates of transfer. Studies have been conducted to see whether learning a force field with one limb generalizes to other and in which coordinate system. Researchers concluded that the skills acquired at the dominant hand were transferred to the non-dominant hand but vice versa was not true [3][6]. Most importantly, however, was the pattern of generalization, which was concluded to be consistent with an endpoint/extrinsic system. More specifically, people switch hands and behave like they are expecting forces that are based in an extrinsic coordinate system. Work from our group, similarly evaluated the patterns of generalization after bimanual training followed by single limb performance, and also showed evidence consistent with an endpoint/extrinsic system [3]. It is important to note that although the results of these intermanual experiments contradict the observation of a joint-based coordinate system, intermanual transfer exhibits only mild transfer compared to transfer seen in the dominant hand. It is possible that endpoint/extrinsic systems are available when intermanual transfer is required, but that also there is a joint-based storage and recall of information that is also part of the nervous system's attempts to transfer skills. No study has yet required intermanual transfer *and* transfer to another workspace (extrapolation). Such an experiment should determine whether a joint-based coordinate system, an extrinsic coordinate system, or both might be used in these activities that require the motor system to transfer skills.

Here we present results of a new experiment that not only evaluates generalization of intermanual transfer and workspace extrapolation, but it also takes special care to evaluate ability in both pre- and post- training phases, in order to establish the *change in performance* as a

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consequence of training. Our results support the intriguing hypothesis that there are multiple, simultaneous representations of sensorimotor experience stored in motor memory that can be drawn upon when the system is asked to generalize to unpracticed conditions.

II. MATERIALS AND METHODS

A. *Experimental Set-up:*

All subjects used the lightweight, low friction, two degrees of freedom manipulandum robot with a six-axis force-torque transducer (Lord F/T sensor) mounted on its end-effectors (the handle)[3]. Two low inertia DC torque motors (PMI Corp., model JR16M4CH) provided the forces at the end of the link on the handle which was held by the subjects. Position and velocity measurements were made using two optical encoders (Teledyne Gurley) and tachometers (PMI), respectively, mounted on the axes of the mechanical joints [24]. Visual feedback was provided to the subjects during the trials by displaying the position of the robot's handle. Data was collected and recorded at 400Hz.

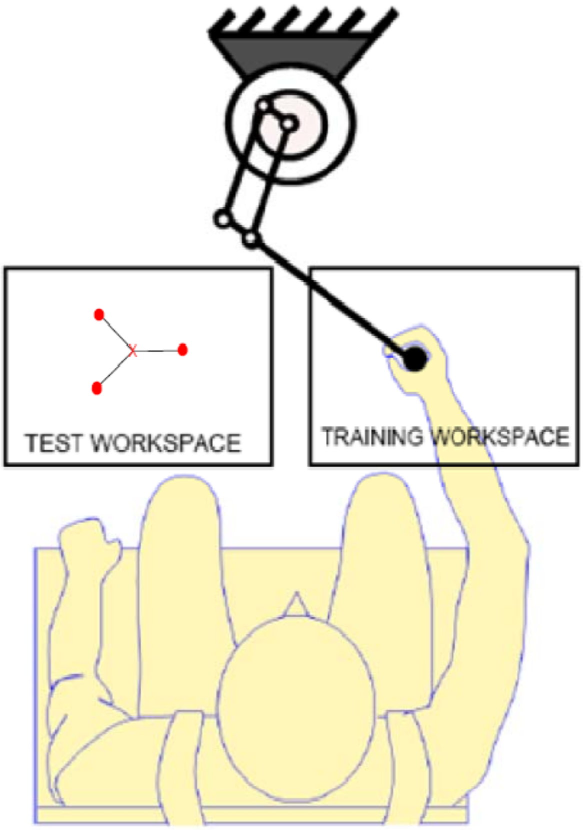

Figure 1: Subject seated in the chair in front of the manipulandum grasping the handle of the manipulandum. The arrangement of the workspaces and the targets are shown. (Figure not drawn to scale)

Each subject was seated facing the manipulandum so that the arm moved in a nearly horizontal motion (Fig 1). The center of the right experimental workspace was 25 cm from the full extent of forward reach, and anterior to the shoulder. Video was projected on a platform above the plane of movement.

B. *Subjects*

Nine right handed (2 male and 7 females) neurologically intact subjects aged 19-23 yrs (mean =21 yrs) participated in the experiment after signing the consent forms issued for the experiment in accordance with the Institutional Review Board. Each subject was tested on the experiment protocol listed in Fig.2.

C. *Experimental Protocol:*

Our goal was to evaluate and compare performance before and after movement training in the presence of a force field. Evaluations required subjects to extrapolate what they learned to an unpracticed workspace. Training was on the Cartesian force field,

$$f = B\,\dot{x} \quad (1)$$

where $\dot{x}$ is the Cartesian hand velocity vector and B is a viscosity matrix:

$$B = \begin{bmatrix} -10.1 & -11.2 \\ -11.2 & 11.1 \end{bmatrix} \text{N.sec/m}$$

This force field could also be expressed in a joint coordinate system.

$$\tau = W\dot{q} \quad (2)$$

This expression can also be formulated using either the angles of right or left arm, henceforth called “right joint” field or “left joint” field obtained from the Cartesian field using the Jacobian, $J_r^T = (\partial x_r / \partial q)$ (subscript r represents right hand and subscript l represents left hand), which transforms the forces into torques and hand velocity into joint velocity. The B matrix can be transformed to the W matrix using Jacobian as shown below:

$$W = J_o^T B J_o \quad (3)$$

So that relating joint motions to force is

$$f = (J(q^T))^{-1}\, W\dot{q} \quad (4)$$

Fields were constructed so that all three exert the same forces in the training workspace, but differed as subjects were asked to extrapolate.

Subjects were asked to move a cursor to 10 mm diameter target and stop, at which point a new target would appear. Targets appeared randomly in one of the three directions at a 10 cm distance. Audio and visual feedback was given at the end of each movement on their maximum movement speed in order to minimize any the trial-trial variation in speed.

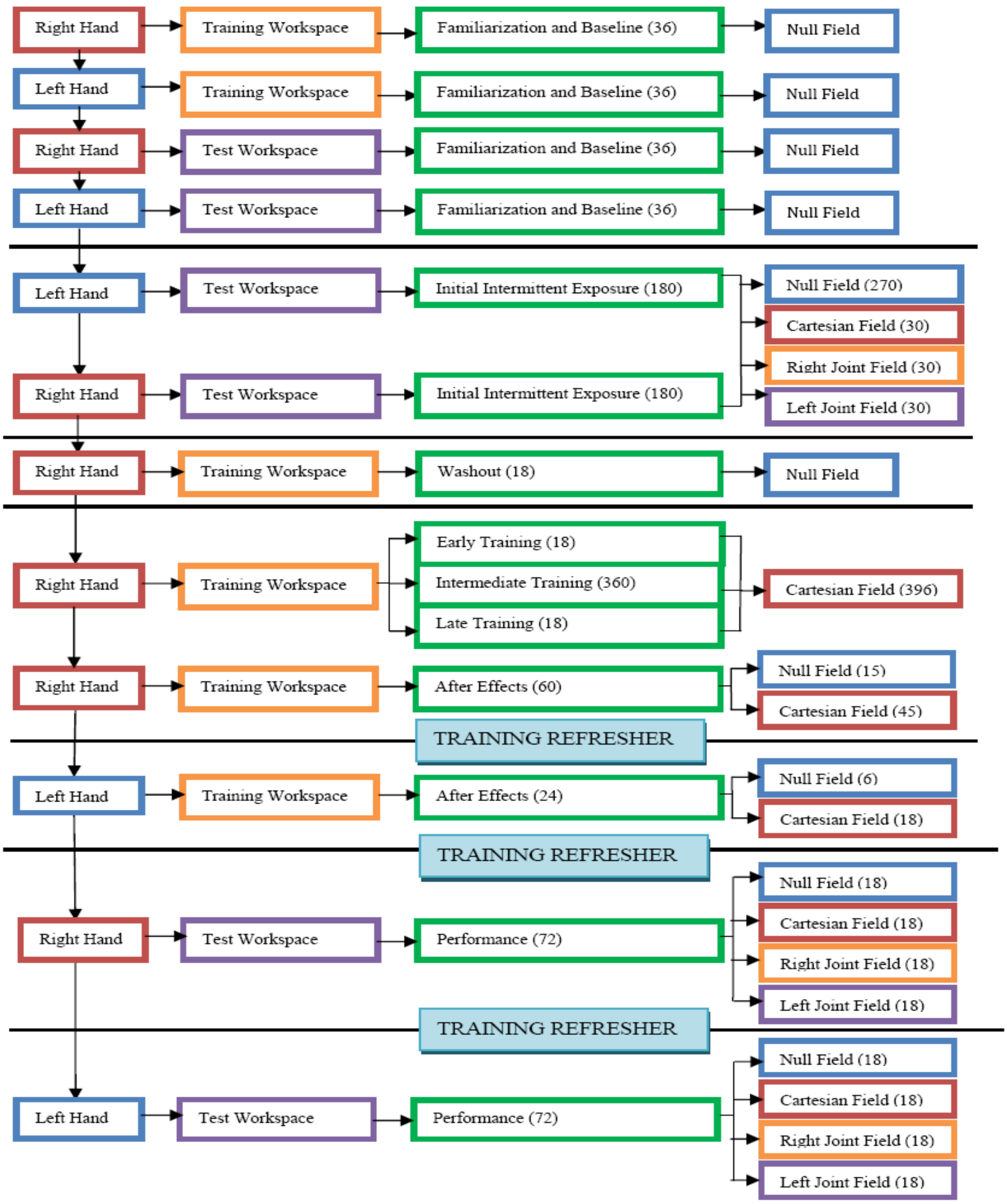

Figure 2: Outline of main procedure for the experiment: - The experiment begins with familiarization and baseline phase for both the hands in two different types of workspace (viz. right and left). It is followed by the initial intermittent exposure of the various fields on both the hands in the two different types of workspace. Subjects are then trained on their training hand (right hand) in the training (right workspace) in the Cartesian force field. After the training, subjects performed with the training hand (right hand) in the test workspace (left workspace) and later on with the test hand (left hand) in the test workspace.

The experiment consisted of *familiarization* phases to the two workspaces with both the hands, followed by a phase of 240 *baseline* movements with no forces in both the workspaces with the right and left hand. The subjects then experienced *intermittent exposure* to the various force fields in the test workspaces for both the right and left hand, followed by a *washout* phase to eliminate any carryover of skills. The training period followed with 396 trials, divided into 3 stages of early (18 trials), intermediate (360 trials) and late training (18 trials). Then, a phase of intermittent *catch trials* revealed the after-effects of adaptation [24]. There were training refreshers followed by a test of the non-training (left) hand in the training workspace, followed by evaluations both hands in the test workspace, where trials randomly had any of the four types of force field (null, Cartesian, right joint field and left joint field).

D. Data analysis

We assumed that subjects attempt to make straight line movements with a bell shaped velocity profiles, and measured maximum angular deviation from the straight line. A paired t- test ($\alpha=0.05$) was used to evaluate whether significant learning and adaptation occurred in the training phase for each subject and a paired t- test was performed to compute the changes in the group of subjects.

To compare the performance of subjects in four different types of force fields (Null {zero force}, Cartesian, Right joint field. Left joint field) with two different hands (right and left); we used a two way repeated measures analysis of variance (ANOVA).

III. RESULTS

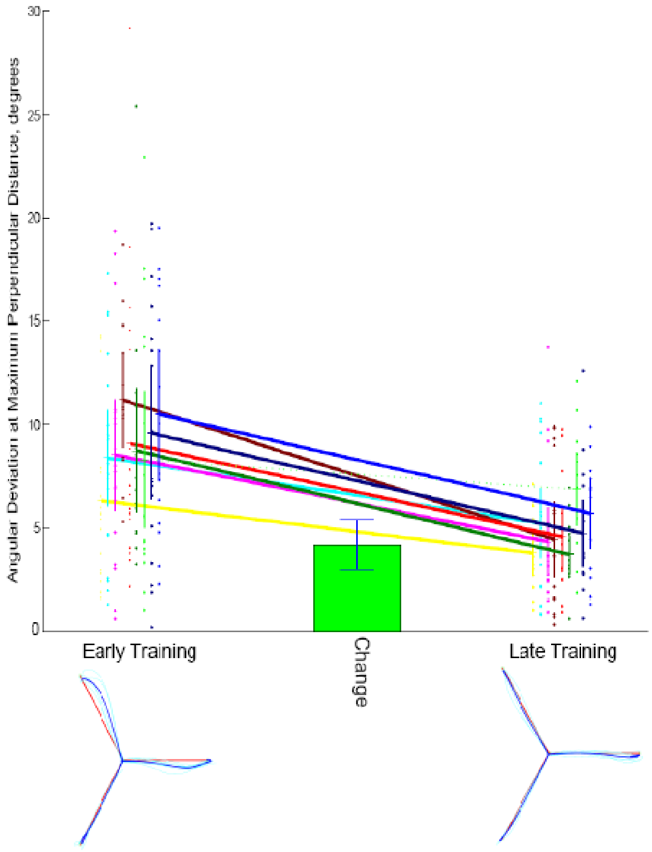

Figure 3: Evidence of Adaptation to Cartesian Field: Measures of angular deviation at maximum perpendicular distance are shown for 9 subjects in the training workspace at the beginning of the training phase and at the end of the training phase. Each dot represents the subject error measure for a specific trial. Each column of dots represents a particular subject with the early training phase on the left and late training phase on the right. The bar at the center of the plot represents the average change in error from the early training to late training, with the wings depicting the 95% confidence interval. The typical subject's trials for each corresponding phase are shown in the figure.

For showing the evidence of learning and adaptation of the Cartesian force field during the training phase, we compared the first 18 trials of early training with the last 18 trials of the late training phase. The effect of training was clear and significant evidence of learning and adaptation ($p<0.001$) (Fig.3).

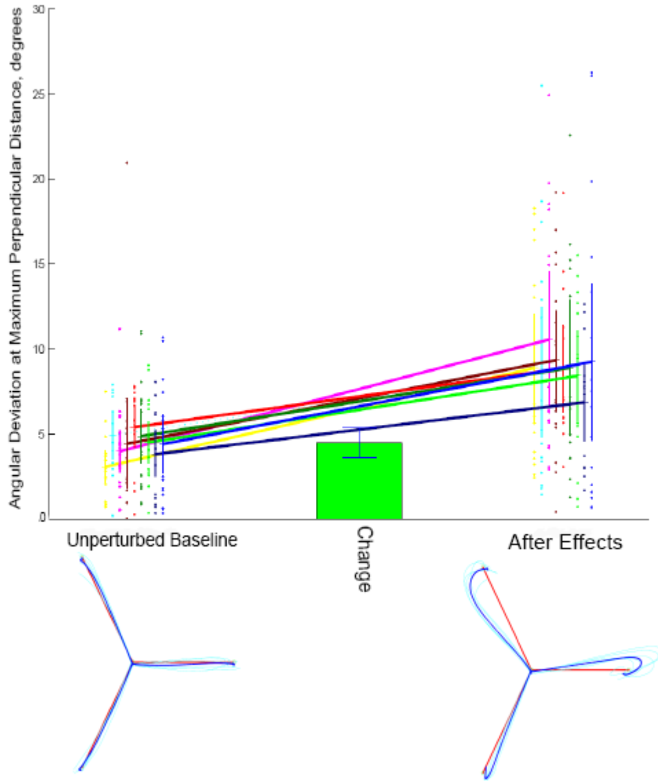

Figure 4: Evidence of learning: Measures of angular deviation at maximum perpendicular distance are shown for 9 subjects in the training workspace at the beginning of the experiment (baseline) and catch trials in the after effects stage. Each dot represents the subject error measure for a specific trial. Each column of dots represents a particular subject with the early training phase on the left and late training phase on the right. The vertical bold lines represent the significant learning curves for the subjects and dashed lines represent the vice versa. The bar at the center of the plot represents the average change in error from the early training to late training, with the wings depicting the 95% confidence interval. The typical subject's trials for each corresponding phase are shown in the figure.

We also compare the first 18 trials of unperturbed baseline with right hand in null field (no forces) to the 15 randomly presented catch trials (trials in which force was unexpectedly turned off) in the after-effects stage (Fig.4).

The path adopted by the subjects resembled a straight line from starting point to the end point target, and the velocity profile of the trials in the baseline had one peak, with approximately equal times spent to accelerate and decelerate the hand [7], [27]. As expected and seen in other studies, subjects moved straighter and thus reduced direction errors by the end of training (Fig. 3) and also showed significant after-effects following training ($p<0.0001$) (Fig. 4).

The most intriguing question is if and how subjects generalize. Our most critical method of evaluating this is to investigate if the subjects showed a significant ability for extrapolation and intermanual transfer, as indicated as a reduction in error (pre-to-post training) in some of the types of force field dual performance in the test workspace (Fig 5).

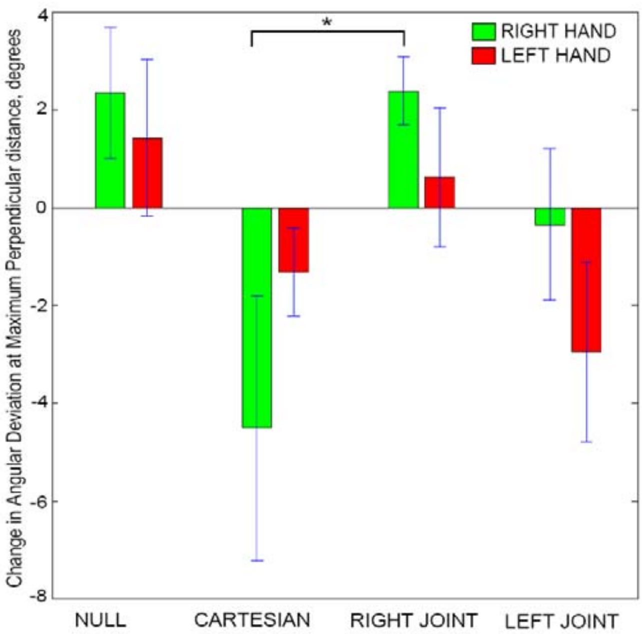

Figure 5: Change in Performance in Test Workspace Before Training and After Training: Figure shows Mean change in error for 9 subjects from initial intermittent exposure in test workspace before training to performance in the test workspace after training. Each pair of bars represents a force field. Each bar in a pair represents the left and right hand. The wings represent the 95% confidence interval. Figure shows that the subject gradually improved in their performance in the Cartesian force field after switching their workspaces.

The effects of training showed the striking ability to improve in the Cartesian field for both hands (right hand: $p=0.0055$, left hand: $p=0.0114$) (second set of green and red columns in Fig. 5), suggesting a Cartesian representation in the nervous system. Surprisingly, the right joint coordinate system, showed either degradation in skill or no change in skill (right hand: $p<0.0001$, left hand: $p<0.3544$). Most surprising was the influence on behavior of the opposite limb (left hand: $p=0.0067$), which showed a significant improvement in the force field that was formulated by creating a mirror image of the force field in the coordinate system of the contralateral arm (rightmost red bar). This result indicates that an intrinsic coordinate representation of the opposite limb that appears to be present at the same time as Cartesian representation.

IV. DISCUSSION

In the current study we have examined the coordinate systems that might be used when the subjects store and recall movement control information. Using extrapolation and intermanual transfer, we evaluated how subjects recall learned skills to generalize to a different workspace and a different limb. Our results indicate that an extrinsic coordinate representation is available to the nervous system along with an intrinsic coordinate representation, but in the coordinate system of the opposite limb.

The result is indeed intriguing that the opposite limb has available information that can facilitate motion when the subjects are asked to switch hands. This might be explained by fact that our nervous system often has this need to change hands and generalize learned skills on loads that depend on joint angles.

Because two different extrapolations showed a reduction in error due to training (Fig 5, Cartesian and left joint), our results support the hypothesis that there are multiple, simultaneous representations of sensorimotor experience stored in motor memory that can be drawn upon when the system is asked to generalize to unpracticed conditions.

The fact that subjects store the information in terms of end-point co-ordinates provides support to the hypothesis that knowledge about field dynamics is stored in extrinsic co-ordinate systems [6]. However this study contradicts a very similar approach [20] about generalization of dynamic environments and adaptation to force fields, which concluded that information about the workspaces and the details about the dynamic environment are stored in intrinsic co-ordinate systems i.e. the information is encoded in terms of different angular configurations of the upper limbs [9] , [12], [23] ,[24].

Another secondary but striking finding from the experiment was that subject's performance improves in the left joint field with the left hand in test workspace from before training and after training. This shows that the training in Cartesian field with the right hand in the training workspace improved the performance of the left hand in the left joint field. This implies that subjects were able to perform well in environment in which the system dynamics were flipped.

There are, however, some limitations to the experiment. The performance in the different fields were observed and assumed that the subjects didn't stiffen their hand while performing in these fields. Due to limitation of technology, we couldn't measure the EMG, which could help us confirm that the subjects didn't stiffen their hands and the various muscles acted accordingly to counteract the force fields.

This study's results contradict the results of another study which involves similar task of reaching movements in two different workspaces [24], but just involved a single dominant hand. The subject was trained in a similar manner in the same force fields and told to perform task in the new workspace with the same hand under force fields translated in joint co-ordinates and end-point co-ordinates. The result was that subject generalized in intrinsic (joint) co-ordinate system. The reason for this contradiction might be visual feedback. When subjects in the earlier study were told to perform in new workspace, there was no visual feedback provided, and subjects might have developed a model involving different geometrical constructs. It is possible that vision plays an important role in helping the CNS to store and generalize the dynamic environment and in transfer the skills.

Another confounding limitation is that subjects may have been influenced by exposure to too many fields at a time.

Such a high frequency of switching hands, simultaneous exposure to too many different force fields, and switching of workspaces may have influenced subjects to generalize differently and adapt in extrinsic co-ordinate system for the training hand. This both confusing and exciting, because it means that the conditions of training can be used to influence the dominant coordinate reference frame in which motor memory is stored and recalled.

In conclusion, we can say that humans generalize and improve more in extrinsic co-ordinate system as well as in intrinsic co-ordinate system when they transfer the knowledge to the opposite arm. This study is a stepping stone for the design of rehabilitation devices and also help in learning of motor control task. The study provides further evidence that motor tasks learned by one hand might be used to restore the function of the other hand.

REFERENCES

[1] A. A. Ahmed, D. M. Wolpert, and J. R. Flanagan, "Flexible representations of dynamics are used in object manipulation," *Curr Biol,* vol. 18, pp. 763-8, May 20 2008.

[2] L. B. Bagesteiro and R. L. Sainburg, "Handedness: dominant arm advantages in control of limb dynamics," *J Neurophysiol,* vol. 88, pp. 2408-21, Nov 2002.

[3] J. K. Burgess, R. Bareither, and J. L. Patton, "Single limb performance following contralateral bimanual limb training," *IEEE Trans Neural Syst Rehabil Eng,* vol. 15, pp. 347-55, Sep 2007.

[4] M. A. Conditt, F. Gandolfo, and F. A. Mussa-Ivaldi, "The motor system does not learn the dynamics of the arm by rote memorization of past experience," *J Neurophysiol,* vol. 78, pp. 554-60, Jul 1997.

[5] M. A. Conditt and F. A. Mussa-Ivaldi, "Central representation of time during motor learning," *Proc Natl Acad Sci U S A,* vol. 96, pp. 11625-30, Sep 28 1999.

[6] S. E. Criscimagna-Hemminger, O. Donchin, M. S. Gazzaniga, and R. Shadmehr, "Learned dynamics of reaching movements generalize from dominant to nondominant arm," *J Neurophysiol,* vol. 89, pp. 168-76, Jan 2003.

[7] O. Donchin and R. Shadmehr, "Change of desired trajectory caused by training in a novel motor task," *Conf Proc IEEE Eng Med Biol Soc,* vol. 6, pp. 4495-8, 2004.

[8] J. Kluzik, J. Diedrichsen, R. Shadmehr, and A. J. Bastian, "Reach adaptation: what determines whether we learn an internal model of the tool or adapt the model of our arm?," *J Neurophysiol,* vol. 100, pp. 1455-64, Sep 2008.

[9] J. W. Krakauer, Z. M. Pine, M. F. Ghilardi, and C. Ghez, "Learning of visuomotor transformations for vectorial planning of reaching trajectories," *J Neurosci,* vol. 20, pp. 8916-24, Dec 1 2000.

[10] J. R. Lackner and P. Dizio, "Rapid adaptation to Coriolis force perturbations of arm trajectory," *J Neurophysiol,* vol. 72, pp. 299-313, Jul 1994.

[11] N. Malfait, P. L. Gribble, and D. J. Ostry, "Generalization of motor learning based on multiple field exposures and local adaptation," *J Neurophysiol,* vol. 93, pp. 3327-38, Jun 2005.

[12] N. Malfait and D. J. Ostry, "Is interlimb transfer of force-field adaptation a cognitive response to the sudden introduction of load?," *J Neurosci,* vol. 24, pp. 8084-9, Sep 15 2004.

[13] J. L. Patton and F. A. Mussa-Ivaldi, "Robot-assisted adaptive training: custom force fields for teaching movement patterns," *IEEE Trans Biomed Eng,* vol. 51, pp. 636-46, Apr 2004.

[14] R. L. Sainburg, "Evidence for a dynamic-dominance hypothesis of handedness," *Exp Brain Res,* vol. 142, pp. 241-58, Jan 2002.

[15] R. L. Sainburg, "Handedness: differential specializations for control of trajectory and position," *Exerc Sport Sci Rev,* vol. 33, pp. 206-13, Oct 2005.

[16] R. L. Sainburg and S. V. Duff, "Does motor lateralization have implications for stroke rehabilitation?," *J Rehabil Res Dev,* vol. 43, pp. 311-22, May-Jun 2006.

[17] R. L. Sainburg, C. Ghez, and D. Kalakanis, "Intersegmental dynamics are controlled by sequential anticipatory, error correction, and postural mechanisms," *J Neurophysiol,* vol. 81, pp. 1045-56, Mar 1999.

[18] R. L. Sainburg, M. F. Ghilardi, H. Poizner, and C. Ghez, "Control of limb dynamics in normal subjects and patients without proprioception," *J Neurophysiol,* vol. 73, pp. 820-35, Feb 1995.

[19] R. L. Sainburg and D. Kalakanis, "Differences in control of limb dynamics during dominant and nondominant arm reaching," *J Neurophysiol,* vol. 83, pp. 2661-75, May 2000.

[20] R. L. Sainburg, J. E. Lateiner, M. L. Latash, and L. B. Bagesteiro, "Effects of altering initial position on movement direction and extent," *J Neurophysiol,* vol. 89, pp. 401-15, Jan 2003.

[21] R. L. Sainburg and S. Y. Schaefer, "Interlimb differences in control of movement extent," *J Neurophysiol,* vol. 92, pp. 1374-83, Sep 2004.

[22] R. L. Sainburg and J. Wang, "Interlimb transfer of visuomotor rotations: independence of direction and final position information," *Exp Brain Res,* vol. 145, pp. 437-47, Aug 2002.

[23] R. Shadmehr and Z. M. Moussavi, "Spatial generalization from learning dynamics of reaching movements," *J Neurosci,* vol. 20, pp. 7807-15, Oct 15 2000.

[24] R. Shadmehr and F. A. Mussa-Ivaldi, "Adaptive representation of dynamics during learning of a motor task," *J Neurosci,* vol. 14, pp. 3208-24, May 1994.

[25] J. Wang and R. L. Sainburg, "Interlimb transfer of novel inertial dynamics is asymmetrical," *J Neurophysiol,* vol. 92, pp. 349-60, Jul 2004.

[26] J. Wong, E. T. Wilson, N. Malfait, and P. L. Gribble, "The influence of visual perturbations on the neural control of limb stiffness," *J Neurophysiol,* vol. 101, pp. 246-57, Jan 2009.

[27] T. Flash and N. Hogan, "The coordination of arm movements: an experimentally confirmed mathematical model," *J Neurosci,* vol. 5, pp. 1688-703, Jul 1985.