Relationship between Motor Generalization and Motor Transfer

by

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A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science

Approved March 2018 by the
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ARIZONA STATE UNIVERSITY

May 2018

ABSTRACT

Adapting to one novel condition of a motor task has been shown to generalize to other naïve conditions (i.e., motor generalization). In contrast, learning one task affects the proficiency of another task that is altogether different (i.e. motor transfer). Much more is known about motor generalization than about motor transfer, despite of decades of behavioral evidence. Moreover, motor generalization is studied as a probe to understanding how movements in any novel situations are affected by previous experiences. Thus, one could assume that mechanisms underlying transfer from trained to untrained tasks may be same as the ones known to be underlying motor generalization. However, the direct relationship between transfer and generalization has not yet been shown, thereby limiting the assumption that transfer and generalization rely on the same mechanisms. The purpose of this study was to test whether there is a relationship between motor generalization and motor transfer. To date, ten healthy young adult subjects were scored on their motor generalization ability and motor transfer ability on various upper extremity tasks. Although our current sample size is too small to clearly identify whether there is a relationship between generalization and transfer, Pearson product-moment correlation results and a priori power analysis suggest that a significant relationship will be observed with an increased sample size by 30%. If so, this would suggest that the mechanisms of transfer may be similar to those of motor generalization.

ACKNOWLEDGMENTS

I would like to thank my mentor – Dr. Sydney Schaefer for guiding me through each step during my thesis. She did not just prepare me for defending my thesis but taught me lessons which will help me as a professional in this field throughout my life. I will be forever thankful for her patience and time; as well as for being so approachable and closely involved with the project.

I would also like to thank the senior lab members – Boki Wang and Jennapher Lingo VanGilder for helping me with writing the thesis and helping me with my project. I would like to thank my friend - Saswata Haldar, for helping me make the figures for the thesis document. And lastly, I would like to acknowledge the support showed by my friends and family through the process.

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CHAPTER 1

INTRODUCTION

Motor skill learning or skill acquisition is necessary as humans encounter experiences which demand novel movement patterns. One important feature of such learning is *motor generalization*, in which adaptation to one novel condition of a learned motor task generalizes to other naïve conditions (Seidler & Noll, 2008; Poggio & Bizzi, 2004; McDougle, Bond & Taylor, 2017). For example, adapting movements to an unexpected visuomotor perturbation can help with adapting to other magnitudes of the perturbation. Another feature is *motor transfer*, in which learning one task affects proficiency of another task that is altogether different (Schaefer & Lang, 2012; Schmidt & Lee, 2014). In other words, motor generalization occurs between different conditions of the same task, whereas motor transfer occurs between different tasks.

We have evidence of motor transfer. Schaefer and Lang (2012) showed that training on a feeding task (which required spooning beans across cups) improved proficiency on a dressing task (which required sequential fastening of buttons). Motor transfer has also been demonstrated in clinical observations that show robust improvement on tests that systematically measure the ability to move arm and hand following training on tasks that differed substantially from items included in test (Beekhuizen & Field-Fote, 2005; Duncan et al., 2003; Hoffman & Field-Fote, 2010; Page, Sisto, Levine, & McGrath, 2004; Waddell, Birkenmeier, Moore, Hornby, & Lang, 2014; Wolf et al., 2006). The ability to transfer motor skills across tasks can be utilized in the field rehabilitation, such that training on certain tasks would surely transfer to other tasks. But to date, little is known about how motor transfer occurs. Cherry et. al. (2014) investigated if training on a stability platform balance task transferred to a single leg stance task, but there was no transfer observed, contradictory to findings of Schaefer and Lang (2012). This means the driving mechanism of motor transfer works across certain tasks but not with certain other tasks. For purposeful application of motor transfer in rehabilitation, there is a need to explore how and why transfer occurs.

Because there has been a substantial number of studies on motor generalization, they may help answer the questions regarding how and why motor transfer occurs. These studies are usually conducted on lab-based tasks such as a point-to-point reaching task under perturbations of movement directions (Sainburg, Ghez, & Kalakanis, 1999; Krakauer, Pine, Ghiraldi, & Ghez, 2000; Thoroughman and Shadmehr, 2000), amplitudes (Goodbody and Wolpert, 1998; Krakauer et al., 2000; Mattar and Ostry, 2010), speeds (Goodbody and Wolpert, 1998), and workspace locations (Malfait et al., 2005; Wang and Sainburg, 2005; Lei, Johnson, & Wang, 2013). Findings suggest generalization involves 'model-based learning' in which learning to adapt to a magnitude of perturbation does not restrict itself to that magnitude but is modelled across a large range of magnitudes (Donchin, Francis, & Shadmehr, 2003; Shadmehr & Mussa-Ivaldi, 1994; Thoroughman & Shadmehr, 2000). This entails that generalization to a second magnitude would be caused by the model formed during adaptation to first magnitude. Another mechanism involved is 'use-dependent learning', which relies on simple repetition of movements in desired direction and biases the next movement to become similar to the last movement execution. As subjects are adapting to a magnitude of perturbation, motor commands guiding movements to counter that magnitude become learned as a result of repetitive training. This use-dependent learning hinders generalization to a second magnitude because movement is biased to counter first magnitude (Classen, Liepert, Wise, Hallett, & Cohen, 1998; Diedrichsen, White, Newman, & Lally, 2010). Thus, ‘model-based learning’ and ‘use-dependent learning’ work independently and in opposing directions in motor generalization. An assumption accompanying these studies is that investigating generalization from one task condition to another is a probe to understating how movements in any novel situations are affected by previous experiences (Mattar & Ostry, 2007). For example, while describing motor generalization, Poggio & Bizzi (2004) stated “the ability to generalize: that is, to apply what has been learned from limited experience to new situations.” Likewise, Yin, Bi, Yu, & Wei (2016) stated “motor learning generalization examines how learning in one context influences the performance in untrained contexts.” Thus, the answers to what causes motor transfer to occur from a trained to untrained task may lie in what is known about process of motor generalization. **However, direct relationship between transfer and generalization has not yet been shown, thereby limiting the assumption that transfer and generalization rely on the same mechanisms.**

Through this study we aimed to test the relationship between transfer and generalization. A positive correlation between these two behavioral patterns would suggest that processes driving the two are similar. Based on our preliminary data, we hypothesized that a positive relationship exists between the amount of motor generalization and motor transfer in a group of healthy young adults.

In this study, motor generalization ability was quantified using a visuomotor rotation paradigm involving a point-to-point reaching task. Using this paradigm, motor generalization was calculated as change in performance on 30° perturbation as a result of adaptation to a 45° perturbation. Motor transfer was quantified as change in performance on a task requiring fastening of buttons as a result of training on a task in which they acquired and moved small objects from one container to another using a tool. As such, each subject had motor generalization score and a motor transfer score, and these scores were compared to find out if there is a relation between motor transfer and motor generalization.

CHAPTER 2

METHODS

2.1 Subjects

Ten neurologically-intact young adults (18-28 years old) participated in this study. Subjects were right-handed as indicated by a modified Edinburgh Handedness Inventory (Oldfield, 1971). Exclusion criteria included self-reported history of stroke, head injury or psychiatric conditions such as clinical depression or bipolar disorder. All subjects provided informed consent prior to enrollment. This study was approved by the Arizona State University Institutional Review Board.

Subjects completed a preliminary assessment simply to characterize dexterity, grip strength, tactile ability, and visuospatial judgement. Dexterity was measured by Grooved Pegboard Test (Grooved Pegboard Test, Lafayette Instrument Company, IN). Maximum grip strength of both hands was measured using a dynamometer (Andrews, Thomas, & Bohannon, 1996). Semmes-Weinstein monofilaments (Touch-Test, North Coast Medical, Inc, Gilroy, California) was applied to the palmar surface on the distal phalange of the index finger to measure cutaneous sensation. The Benton Judgement of Line Orientation (PAR Inc., Lutz, FL.; Benton, Sivan, Hamsher, Varney, & Spreen, 1994), measured the visuospatial judgement. These were done simply to verify intact function and were not analyzed further in this study.

2.2 Experimental Design:

This was a single session study aimed to test the relationship between motor transfer and motor generalization. Subjects performed two different modules in the session. Module 1 consisted of tasks that measured the motor generalization ability and Module 2 of tasks that measured the motor transfer ability. Upon enrollment, subjects were randomly assigned to one of two groups. Each group performed both the modules but in a different order. Group 1 performed Module 1 first and Group 2 performed Module 2 first such that the order effect was counterbalanced (Fig.1).

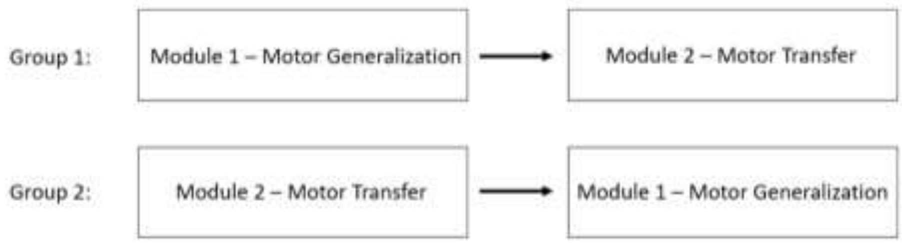

Figure 1. Experimental Design. Group 1 and Group 2 performed both the modules in opposite sequence to balance order effects. We collapsed across groups for data analysis.

Both modules were performed with subject's nondominant hand and are described in detail below in Sections 2.3 and 2.4. Importantly, performing this task with the nondominant hand was to ensure that the task was under-trained and not overlearned such that subjects had the potential to show training effects without confounds of floor or ceiling effects.

2.3 Module 1: Motor Generalization

Module 1 used a visuomotor adaptation paradigm in a point-to-point reaching task. A similar paradigm has been used previously to measure generalization (Krakauer et al., 2000, Pine et al. 1996, Sainburg et al., 1999; Seidler & Noll, 2008; Thoroughman and Shadmehr, 2000). The point-to-point reaching task in this study required subjects to reach to three targets projected in a three-dimensional virtual reality space with index finger of nondominant hand. The finger, hand and lower arm was visually blocked, but a visual feedback of the index finger was provided in form of a cursor during the entire module.

The visual feedback was manipulated to induce a directional error between the seen and actual path of hand movement. Subjects adapted to one magnitude of perturbation but were tested on another magnitude of perturbation, thereby measuring how adapting to one magnitude of perturbation changes the proficiency of adapting to another unexposed magnitude of perturbation.

For this module, subjects sat on a chair at a table (90 cm × 52 cm × 72cm) that was placed at their midline with its closest edge across their mid-thighs (Fig. 2A). Targets were projected one at a time on the table's surface and subjects slid their index finger on the table to reach targets (more detail below in Section 2.3.1.). The arm and hand were visually blocked by a half-silvered mirror placed horizontally at the chest level (Fig. 2B). Chair height was adjusted as per subject's comfort with respect to the visibility of the task in virtual reality space.

A three-dimensional immersive display was created using stereoscopy. Real-time image of task contents was projected top-down from an LCD projector (Cannon LV-WX300UST) mounted above a horizontally placed back-projection screen (Fig 2B). The image was then reflected in the mirror for subjects to view. The illusion of depth (third dimension) was created by wearing 3D glasses (CrystalEyes 4s, Engineering Systems Technologies GmbH & Co., Kaiserslautern, Germany). This depth was manipulated such that virtual objects could appear to be placed on the table's surface which was under the mirror.

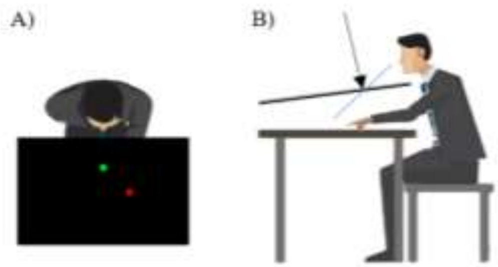

Figure 2. Experimental set-up: A) Visual feedback of index finger was represented by the cursor (green) while subject reaches displayed target (red); B) A mirror visually blocks the hand and arm. Black arrow represents projection of image onto mirror and blue line represents the line of sight.

Three-dimensional (3D) kinematic data were collected with an electromagnetic six degrees-of-freedom (6-DOF) movement recording system (Flock of Birds®, Ascension Technology Corp, Shelburne, VT). This system was integrated into Motion Monitor for Neuroscience and Rehabilitation software (Innovative Sports Training, Chicago, IL) for data collection and exporting. Two Flock of Birds sensors were used, with one placed on the dorsal portion of the distal phalanx of the nondominant index finger (secured to the fingernail, sensor Model 180) and the other one placed on the left temple of 3D glasses (sensor Model 800) during the entire task. The sensor on the 3D glasses was used for head-tracking which compensated for head movement such that visual feedback of task had its positive Y-axis in the direction subjects faced and X-axis to the right of subjects' midline.

2.3.1 Reaching Task.

The task was designed using Enhanced Biofeedback Module integrated into the Motion Monitor System. All the visual stimuli appeared to be placed on the table's surface in VR space. A sphere (white, 30mm radius) which served as the home location was placed at a semicircle of 18 cm radius, along the subject's midline (Fig. 3A). Three spherical targets (red, 30mm radius) were placed along the circumference of semicircle (18 cm radius) 40° apart from each other about the center of semicircle. The home location was proximal to subjects and three targets were distal. Real-time location of the index finger-tip was represented by a spherical cursor (green, 30mm radius).

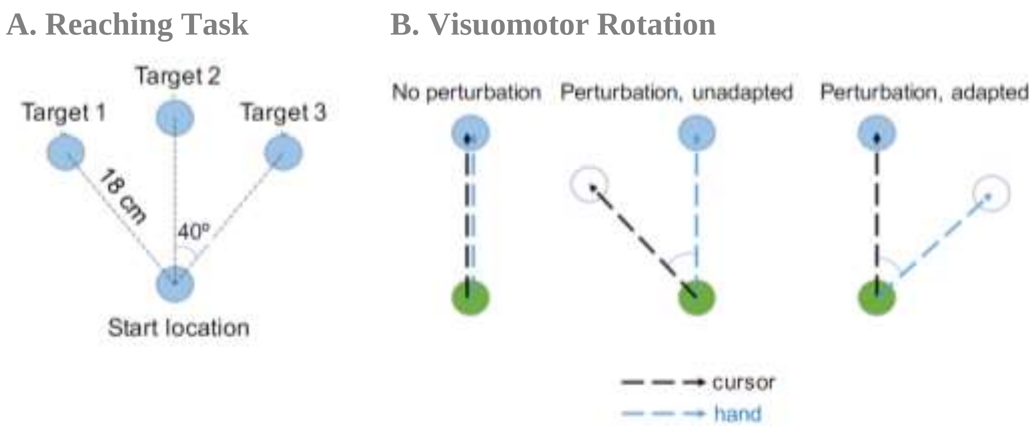

Figure 3. A) Displays the targets and start location which were displayed one by one to prompt subjects to reach them; B) Shows path followed by cursor with respect hand path (left to right) when no perturbation is imposed, when perturbation is imposed but subjects have not started adapting to it (i.e. when DE=-30° or -45°), and when subjects have complete adapted to imposed perturbation (i.e. when DE=0°).

Once subjects brought their index fingertip to the home location displayed in VR space, the home location disappeared and leftmost distal target appeared. This prompted the subjects to slide their finger to reach the displayed target. Once a successful reach was performed, target disappeared and the home location reappeared which prompted subjects to slide their finger back to home location. The same process occurred for the middle target and then the right-most target. The order of targets remained constant throughout the task. Each trial consisted of successful reaches to all three targets, starting and ending at the home location. Visual feedback of the index finger was provided during the entire task as a spherical cursor.

In this module, subjects adapted to a visuomotor rotation of magnitude 45° (counterclockwise) (Cunningham and Welch, 1994). That is, to successfully reach one of the distal targets, subjects had to aim 45° clockwise to the target (Fig. 3B). Before and after adaptation to 45° rotation, subjects were tested on how they performed on one trial of 30° counterclockwise rotation. There were washout sessions between 30° and 45° rotation trials to prevent any carry-over adaptation effect. We chose rotations of 30° and 45° because they are not wide apart and motor generalization is known to decrease as the angular distance from the trained to the untrained direction increases (Gandolfo et al., 1996; Krakauer et al., 2000). The measure of performance for the reaching task was calculated in terms of direction error (DE), which is the angle between the lines joining the start location with target and the start location with co-ordinates on index finger at peak velocity. DE of a trial was calculated as the average of DEs for all three targets in that trial. Since the DE was calculated at peak velocity, it was not contaminated by online error corrections (Krakauer, Pine, Ghilardi, & Ghez, 2000; Messier & Kalaska, 1999; Pine, Krakauer, Gordon, & Ghez, 1996). The module was carried out in a total of six sessions as mentioned in Table 1. Subjects were not informed in advance about the order of sessions, nor were they provided with any information about the applied rotations.

Table 1. At first, a baseline session without any perturbation was performed for training to subjects on the task followed by a pre-test session tested how subjects performed at 30° counterclockwise perturbation. Subjects then adapted to 45° counterclockwise perturbation in an adaptation session. Finally, a post-test session tested how subjects performed with 30° counterclockwise rotation. Washout sessions without were performed between two sessions of different magnitude of perturbations.

Session Order	Session Name	No. of Trials
1	Baseline (No perturbation)	16
2	Pre-test (30°)	1
3	Washout 1 (No perturbation)	16
4	Adaptation (45°)	24
5	Washout 2 (No perturbation)	16
6	Post-test (30°)	1

Difference between the DE at post-test and pre-test reflected how adaptation to 45° rotation *generalized* to 30° rotation. Motor Generalization Score was defined as the change in performance on 30° perturbation trial from pre-test to post-test:

$$Motor\ Generalization\ Score\ (MGS) = \frac{\text{DE of Pre} - \text{test} - \text{DE of Post} - \text{test}}{\text{DE of Pre} - \text{test}} \times 100$$

2.3.2 Data Processing.

Data analysis was performed offline with a custom MATLAB (Mathworks, Natick, MA) code. Kinematic data were collected at 100 Hz. Kinematic data were filtered using low-pass Butterworth filter (Winter, 1990) of 4^{th} order and 8 Hz cut-off frequency. The time frame of the outward reach from the home location to each target was calculated as the time for which each target was displayed using a custom MATLAB code. Movement onset was calculated as the time point when velocity exceeded 10% of the peak velocity of that reach (Hernandez, Ashton-Miller, & Alexander, 2012). Peak velocity during the outward movement was calculated as the first peak in the 3D resultant velocity profile. Some outward reach velocity profiles included more than one peaks, wherein a first peak represented feedforward adaptive corrections and following peaks represented the corrective movements (Krakauer, Pine, Ghilardi, & Ghez, 2000). As such, we extracted 3 values of peak velocity per trial, allowing us to analyze each target direction (left vs. middle vs. right) separately.

2.4 Module 2: Motor Transfer

This module measured how training one task affected the proficiency of another untrained task. Trained task was a simulated feeding task that required spooning beans from one cup to another. Untrained task was a simulated dressing task which required fastening buttons sequentially. These tasks have been previously used to measure motor transfer (Schaefer et al. 2012; Schaefer et al. 2013). The procedure and task set-up are described in detail below.

For this module, subjects sat in a chair at a table (152 cm × 76 cm × 71cm) that was placed at their midline with its closest edge across their mid-thighs. Chair height was adjusted to be as high as possible such that feet touched the floor and table did not contact the thighs.

2.4.1 Feeding Task.

The task apparatus consisted of four cups (9 cm diameter, 5.5 cm high) secured to a wooden board (Fig. 4A). Three cups were placed along an arc with an 18 cm radius. The fourth cup was the 'start cup'. The start was placed proximal to subjects, and the three cups placed along the arc were placed distally.

There were 30 raw kidney beans distributed evenly across the bottom of start cup. The task started when subjects picked up a plastic spoon with nondominant hand placed ipsilaterally besides start cup (weight = 1.8 grams). They then acquired two beans at a time from start cup and emptied it into one of the three distal cups and returned back to the start cup to acquire beans. Subjects moved beans from start cup to the ipsilateral cup first, then to the middle cup, followed by the contralateral cup, with respect to nondominant hand. This procedure was repeated five times in each trial until all beans from start cup were moved. Thus, each trial consisted of fifteen repetitions of spooning beans from one cup to another, with five repetitions for each distal cup. The measure of performance for the feeding task was the time taken for completing one trial.

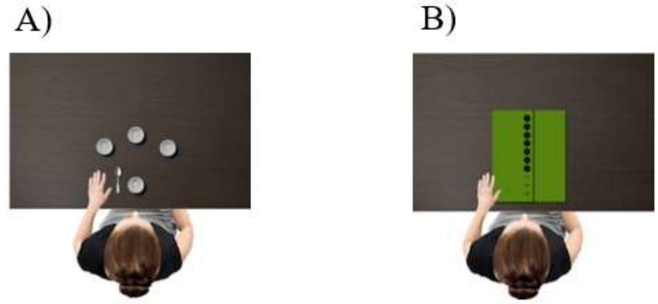

Figure 4. This figure displays the apparatus for feeding task (A) and dressing task (B).

2.4.2 Dressing Task.

The task apparatus consisted of 10 buttons (3 cm diameter) sewed 2 cm apart vertically to a piece of plain weave cotton fabric which was secured on a wooden board (Fig. 4B). The line of buttons was situated vertically at subject's midline. The button-side of the fabric was folded onto the board, while the button hole-side of the fabric was unfolded onto the table prior to each trial. Fabric weight (120 g/m^2) and thread count (78 per cm) were measured according to ASTM Test Methods D3776-96 and D3775-98, respectively (ASTM, 2001a, 2001b).

Task started with subjects folding the button-hole side fabric onto the wooden board. They then fastened buttons sequentially starting from the bottom-most button with their nondominant hand. A trial consisted of subjects successfully fastening all the buttons on the board. Subjects were instructed to move on to the next button only after previous button was completely fastened. The measure of performance for each trial of dressing task was the time taken to complete one trial. The two tasks were performed in the order mentioned in Table 2.

Table 2. Subjects performed the pre-test session which measured the baseline performance of both the tasks, followed with the training session in which subjects were trained on the feeding task (50 trials). Finally,

subjects performed post-test session that measured how the proficiency of both tasks has changed after training on the feeding task.

Order	Session	Task	Number of Trials
1	Pre-Test	Dressing	2
2	Training	Feeding	50
3	Post-Test	Dressing	2

Change in the measure of performance of dressing task from pre-test to post-test reflected how training on feeding task *transferred* to the dressing task. A Motor Transfer Score was defined as the change in performance on dressing task from pre-test to post-test:

$$Motor\ Transfer\ Score\ (MTS) = \frac{\text{Mean Dressing Pre} - \text{test Trial Time} - \text{Mean Dressing Post} - \text{test Trial Time}}{\text{Mean Dressing Pre} - \text{test Trial Time}} \times 100$$

2.5 Statistical Analysis

Minitab (Minitab Inc., State College, PA) and Microsoft Excel (Microsoft Office, Version 15) were used for all statistical analyses. To test if motor transfer and motor generalization had occurred, two separate paired t-tests were performed to compare: (i) each subjects' pre-test vs. post-test scores for Motor Transfer Scores and; (ii) each subjects' pre-test vs. post-test scores for Motor Generalization Score. Significance level (α) was chosen as 0.05, thus p-value of less than α indicated significant difference in means. Another repeated-measures, one-way ANOVA with session as a within-subject factor and mean DEs of last three trials of Baseline, Washout1 and Washout2 session as dependent variables, was performed to confirm whether the washout blocks restored performance to baseline levels in the motor generalization module. Assumption of normality was confirmed using Shapiro-Wilk test recommended for sample sizes smaller than 50 (Elliott & Woodward, 2006). The test was run at a significance level of 0.05 with p-value less than 0.05 suggesting violation of normality. If assumption of normality was disproved, either a non-parametric Wilcoxon/Kruskal-Wallis test (Kruskal & Wallis, 1952) were performed using JMP, Windows, Version 13 (SAS Institute Inc., Cary, NC) or a Box Cox Transformation (Box & Cox, 1964) was performed to transform data into a normally distributed dataset.

In order to investigate if Motor Transfer Scores were correlated with Motor Generalization Scores, a bivariate linear regression analysis (α=0.05) was performed to obtain a Pearson product-moment correlation coefficient. Assumptions of normality were also confirmed using Shapiro-Wilk test. A Pearson product-moment correlation coefficient of 0.59 was considered to be strong, between 0.30 and 0.59 was moderate, and below 0.30 was weak (Cohen 1988). A p-value of smaller than alpha (α) which is the significance level would suggest that the correlation observed is statistically significant with a confidence interval of 95%.

CHAPTER 3

RESULTS

3.1 Evidence of Motor Generalization and Motor Transfer

In Module 1, although subjects did not undergo enough trials by design to fully adapt to the 30° perturbation, their performance on the 30° perturbed trials improved from before to after adapting to the 45° perturbation (t=-5.73, p<0.0001) (Fig. 5, see trials in boxes). Thus, this improvement of performance was attributed to generalization of adaptation abilities gained from adapting to the 45° perturbation. The assumption of normality was confirmed using Shapiro-Wilk test (W=0.98, p=0.34). Verification of the success of washout blocks to restore performance to Baseline levels was done by comparing the subjects' mean of last three trials of baseline, Washout1 and Washout2 sessions. The assumption of normality was violated using Shapiro-Wilk test (W=0.96, p=0.0001). A non-parametric one-way comparison test showed there was no difference between these means, as indicated by absence of session effect (p=0.23), thus confirming the washout sessions' success.

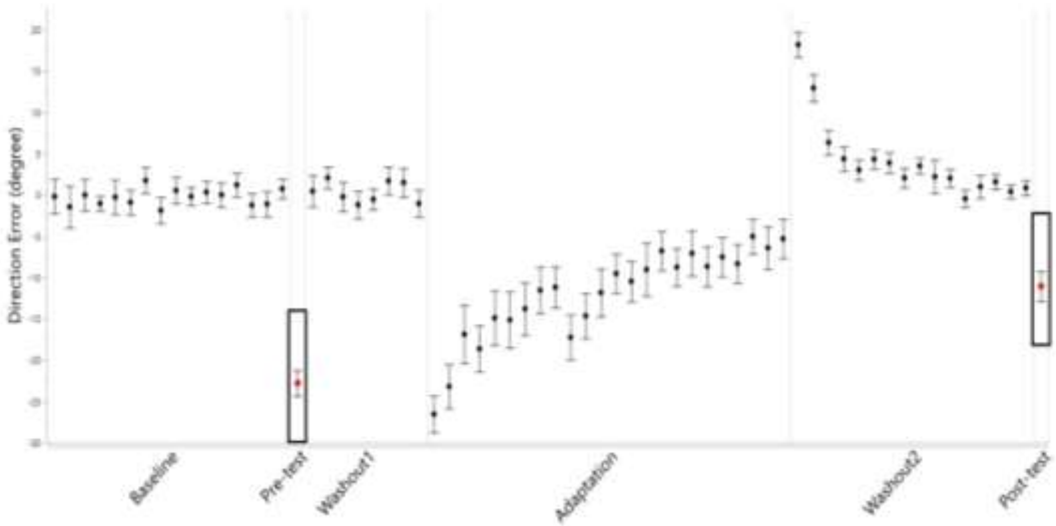

Figure 5. The figure displays mean Direction Error of all subjects for each trial and every session. The red circles represent trials with the 30° perturbation and black circles represent trials with the 45° perturbation. From the data points in boxes, we observe that there was decrease in error from pre-test to post-test (errors are in negative values). Error bars indicate SE. $*p<0.0001$.

Handpaths for all sessions of Module 1 are shown for a representative subject in Figure 6, in which there are several features of typical visuomotor adaptation. First, baseline reaches were directed straight toward the target, yielding a near-zero direction error (see also Fig. 5). Second, whenever a rotation perturbation was imposed (i.e., Pre-test, Adaptation, or Post-test), hook-like corrections were made late in the movement, indicating that subjects were in fact responsive to the perturbation. Third, during the Adaptation Session, the hook-like hand paths represent early adaptation trials and straighter paths represent late adaptation trials, indicating that adaptation did in fact occur. Fourth, compared to the Pre-test hand-paths, Post-test hand paths were straighter, as indicated by a direction error closer to zero (see Fig. 5). This suggests improvement in performance in terms of DE which can be attributed to motor generalization.

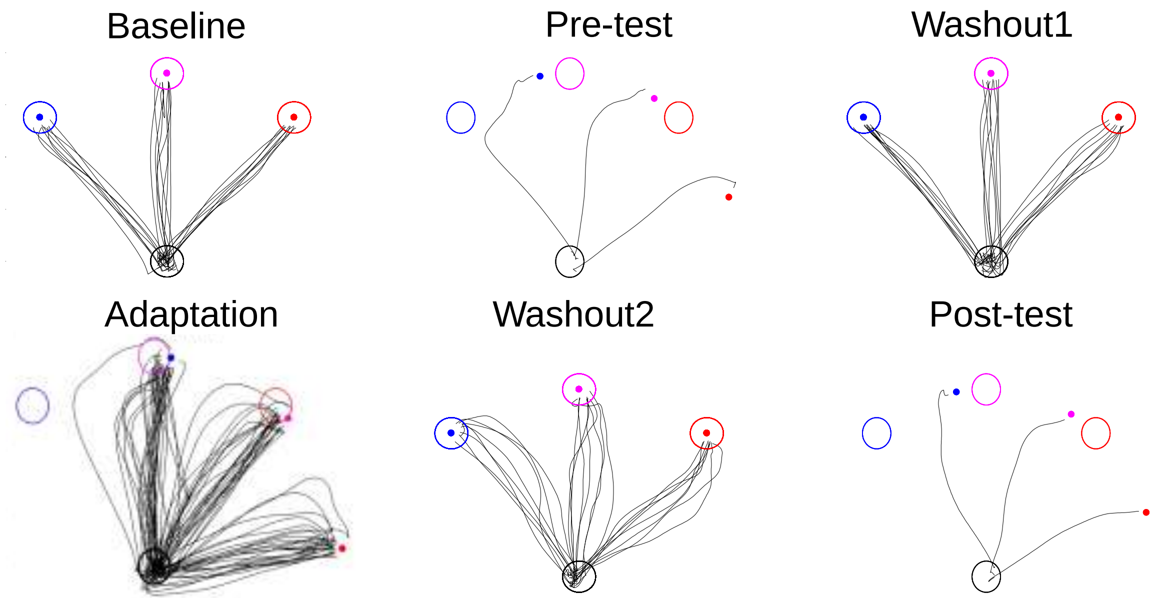

Figure 6. This figure shows hand paths (black paths) of subject on the XY plane for all trials in every session. The displayed target is represented by larger circles and small solid circles represent location at which index finger requires to reach for the cursor to reach the displayed target. Blue circles stand for Target 1, magenta for Target 2 and red for Target 3.

In Module 2, although subjects had no training on the dressing task, there was a statistically significant improvement in the dressing task's measure of performance from pre-test and post-test (t=-7.59, p<0.0001) (Fig. 7, see boxed values). Thus, this improvement was attributed to transfer of training from the trained feeding task to dressing task. The assumption of normality was disproved by the Shapiro-Wilk test (W=0.9243, p=0.001). A Box Cox Transformation was performed with lamda (λ) value of -0.5, the transformed data followed a normal distribution as confirmed by Shapiro-Wilk test (W=0.9760, p=0.5452).

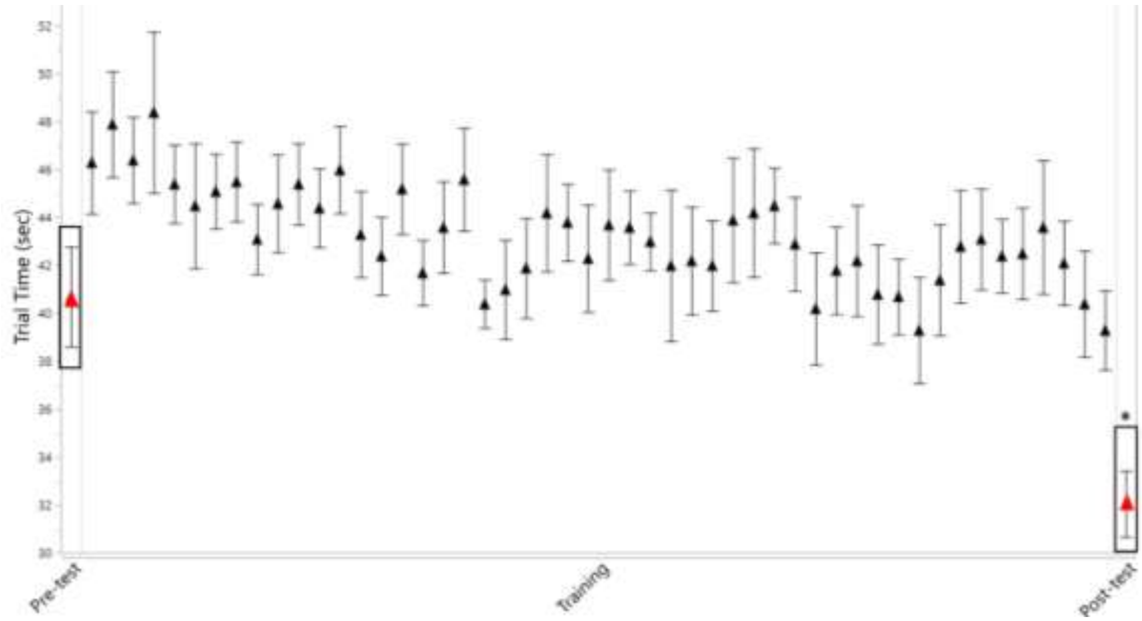

Figure 7. The figure displays mean Trial Time (sec) of all subjects for each trials and every sessions. Red triangles represent dressing trials and black triangles represent feeding trials. From the data points in boxes, we observe that there was decrease in error from pre-test to post-test. Error bars indicate SE. **p*<0.0001.

3.2 Relationship between Motor Generalization Scores and Motor Transfer Scores

Figure 8 shows a moderate correlation between the Motor Transfer Score and Motor Generalization Score of each subject across group (r=0.49) that, at this time, trended towards significance (p=0.15). Although this p-value suggests that the ability to transfer training between different tasks may not correlated with the ability to generalize adaptation across different magnitudes of a perturbation, a priori power analyses indicated that a sample size of 24 would be sufficient to detect a significant relationship with $\alpha = 0.05$ and $1-\beta = 0.8$. We therefore will collect at least five more subjects in this study following the thesis defense. The assumption of normality was confirmed by Shapiro-Wilk test (W=0.98, p=0.98 for Motor Generalization Scores; and W=0.97, p=0.11 for Motor Transfer Scores).

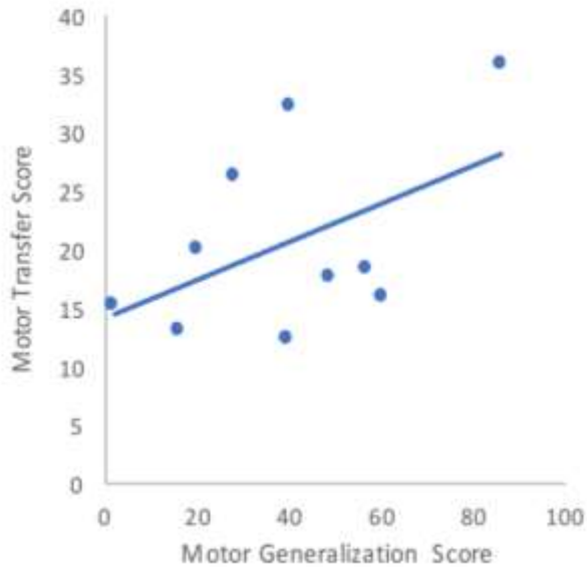

Figure 8. Motor Generalization Score of each subject is plotted against their Motor Transfer Score.

CHAPTER 4

DISCUSSION

In this study, we investigated whether motor transfer ability was related with motor generalization ability. To test this relationship, a Motor Generalization Score quantified generalization from one magnitude of perturbation to and a Motor Transfer Score quantified transfer from trained to untrained task. At this time, our sample size is too small to clearly identify whether there was or was not a correlation between the scores (see (Sullivan & Feinn, 2012; Lang, Rothman, & Cann, 1998), but based on our power analysis we expect there to be a significant relationship when we increase our sample size from 10 to 24. We will do so following the thesis defense and submission and, are encouraged by the preliminary findings from this study thus far.

After the study is equipped with enough statistical power, if a significant relationship between motor generalization and motor transfer is observed, it would suggest that both recruit similar mechanisms; and no relationship would suggest that they recruit unique mechanisms. A positive relationship would suggest that learning mechanisms identified to be involved in motor generalization are also recruited during motor transfer. Based on this finding, future studies can find ways to enhance motor transfer for applications in the field of rehabilitation. For example, if we find out that model-based learning is involved in motor transfer, future studies can investigate ways to utilize models learned during task training to enhance transfer; and if use-dependent learning is involved, then avoiding over-training on one task could help transfer to other tasks.

Although subjects had no extensive training on the 30° perturbation, their performance improved from pre-test to post-test, which shows that adaptation to the 45°

perturbation generalized to 30° perturbation. This suggests motor generalization did in fact occur, in accordance with previous findings (Krakauer et al., 2000, Pine et al. 1996, Sainburg et al., 1999; Seidler & Noll, 2008; Thoroughman and Shadmehr, 2000). Similarly, although subjects had no training on the dressing task, their performance improved from pre-test to post-test which shows that training on feeding task transferred to dressing task. This was also in accordance with previous findings (Schaefer et al. 2012; Schaefer et al. 2013). Again, we are encouraged by these preliminary findings, as they indicate that transfer and generalization can occur given our proposed protocol.

Although the sample size was small and likely contributed to the lack of significant correlation between transfer and generalization to date, we acknowledge that the types of tasks used in this study may also be important to consider. The Motor Transfer Score was calculated as improvement on the dressing task as a result of training on feeding task. The two tasks were spatiotemporally different (see Schaefer et al. 2013), requiring recruitment of different muscles and engaging different levels of fine motor skills (Schaefer 2015). Moreover, the point-to-point reaching task used to calculate Motor Generalization Score did not require fine motor control. This could mean that subjects' fine motor control ability had an influence on their Motor Transfer Score but not on the Motor Generalization Score. In other words, Motor Transfer Score represented the ability to transfer training from feeding to dressing as well as the fine motor control ability, but Motor Generalization Score did not account for the fine motor control ability. Thus, in the future, to address whether the biomechanics/task requirements matter, one could replace the dressing task with another task with similar muscle recruitment and spatiotemporal characteristics to the feeding and reaching tasks. In this way, one would be able to compare motor transfer and motor generalization without major differences in fine motor control ability.

Studies show that reaching movements are planned as a vector whose extent and direction are processed by the brain separately and independently. Extent of reach can be perturbed by changing gain of cursor with respect to movement of finger which is countered by learning a new scaling factor; whereas direction perturbed using visuomotor rotation is countered by learning a new reference axes (Krakauer, Pine, Ghilardi, & Ghez, 2000; Scheidt & Ghez, 2007). In this study, we found did not find a significant relationship between transfer and generalization when generalization was measured using visuomotor rotations. However, since gain perturbations are processed differently by the brain, perhaps processes involved in gain generalization are shared by motor transfer. Thus, in the future one could test the relationship of motor transfer with motor generalization calculated using gain perturbations instead.In this study, we focused on investigating if learning mechanisms of motor generalization and motor transfer are common or unique. Similarly, findings regarding the relationship between generalization and transfer can be used to investigate whether brain areas involved during generalization and transfer are common or unique. We would do this because brain areas involved in motor generalization have been identified but same is not true for motor transfer. Parietal, frontal and cerebellar regions have been identified to be active motor generalization (Burciu et al., 2014; Mutha, Sainburg, & Haaland, 2011b, 2011a; Seidler, 2010; Shadmehr & Holcomb, 1997; Thürer, Stockinger, Putze, Schultz, & Stein, 2017). A positive relationship between motor generalization and motor transfer is would suggest that both recruit common brain areas. This finding can be utilized for purposeful application of motor transfer in various ways.

For example, artificial stimulation brain areas involved in transfer during task training could enhance transfer to other tasks. Knowledge of brain areas involved in transfer can be used to draw rehabilitation plans for patients, for example, patients with lesions to brain areas involved in motor transfer would need to trained on all necessary tasks because motor transfer is not an option for them.

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