Movement Skill Generalization Relevant to Robotic Neuro-rehabilitation

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THESIS
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Contribution of Authors

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SUMMARY

Upper limb extremity rehabilitation practices are increasingly involving robotic interaction for repetitive practice, and there is growing skepticism whether such systems can provide the relevant practice that can be generalized (or transferred) to functional activities in the real world. Most importantly, will patients be able to generalize in three critical ways: (1) to unpracticed directions, (2) to unpracticed movement distances, and (3) to unpracticed weight-eliminated conditions? Rather than presuming that patients could generalize in three conditions, this study tested multiple hypotheses to see if there was any evidence of such generalization ability in healthy individuals. We found that there was some evidence in all conditions except for the ability of healthy subjects to generalize to large movements after practicing small. Such results suggest that larger robotic systems are advantageous for training functional motions that would not be possible with smaller systems [37].
I. BACKGROUND

A. Stroke and Brain Injury

Stroke is one of the most common ailments afflicting people in the United States. It is the third highest cause of death, after heart disease and cancer. Within the US alone, a stroke occurs somewhere about every 40 seconds and this year alone, people will spend approximately $74 billion to treat stroke and stroke-related disabilities [34].

Strokes can be categorized as being of one of two primary types – ischemic or hemorrhagic. According to the American Stroke Association, ischemic strokes account for 87% of all strokes while hemorrhagic strokes cover the balance. An ischemic stroke occurs when a blood clot forms and stops the flow of blood into the brain. Alternatively, a transient ischemic attack (TIA) occurs when a temporary blood clot forms causing a “mini-stroke.” With hemorrhagic strokes, a blood vessel ruptures causing leakage and an interruption to normal blood flow.

The impact of stroke on an individual – though variable – can be quite severe and affect all aspects of their lives. Physically, the patient may endure moments of extreme muscle fatigue or tightness and/or a loss of balance. Other post-stroke symptoms include aphasia or apraxia (language impairments), depression, spatial neglect, etc. Several technological advances have led to revolutionary changes in current healthcare treatment. New devices such as the bionic arm or the new series of transplantation surgeries are at the forefront of the evolution in medical care.
Fig. 1 – Anatomy of a stroke. [32]
But can this be taken a step further? Rather than just focus on what new and innovative devices can be developed to help provide a better quality of life, can clinical therapies be developed that can perhaps help stroke sufferers gain back some degree of independent motor control? It is important to note that while this particular study has been motivated by stroke and stroke-related research, it is by no means only singularly applicable. The scope of this research is applicable to other brain-injury related rehabilitation as well.

Finding new avenues for rehabilitating stroke and other brain-injury sufferers has been an area of research for numerous years. Scientists have been trying to understand how the nervous system and the muscles interact to allow us to perform our everyday activities. How we “learn” certain behaviors and translate them to other areas of our lives (i.e. “generalize”) is a key focus area.

B. **Learning and Generalization**

Imagine chasing a soccer ball through a field, weaving in between your opponents, left and right, front and back. The ability to perform such a complex set of movements is something that was learned over time, with repetitive practice (and numerous mistakes along the way). This skill acquisition ability is “learning” and one’s ability to adapt these skills elsewhere – in another instance or perhaps a complementary situation – is called “generalization.”
This interplay of learning and generalization is a key component of motor control learning and therefore rehabilitation. Can an individual learn a skill and retain it long enough to generalize it after having suffered some sort of neurological trauma? And more importantly – for this study – are healthy individuals able to do this? If not, is it fair to expect this skill acquisition and adaptation from those who are already injured?

C. **Robots and Rehabilitation**

Traditionally, brain-injury patients are sent to either physical or occupational therapists (sometimes both) where they are tested for ranges of motion (ROM), etc. in order to provide the most optimal rehabilitation possible to help them regain their ability to function autonomously in everyday activities. Tests such as the Fugl-Meyer help in this determination [31]. However, there are limitations to what can be done by therapists in a clinical setting.

Robotic devices – on the other hand –can implement novel forms of mechanical manipulation impossible for therapists to emulate because of limited speed, sensing, strength and repeatability of the therapist’s neuromuscular system [20].

D. **Study Objectives and Hypotheses**

The ability to perform a complex series of motor functions such as chasing a soccer ball or rapidly grasping an object is learned through extensive practice. An important utility of learning is that it can transfer to related situations, or be generalized. For example, robotic neurorehabilitation often uses small workspaces for practice, which
may not transfer to the larger three-dimensional motions of many everyday tasks. This is also especially true in upper limb extremity rehabilitation where repetitive practice cannot always fully represent all the task skills that the patient wishes to recover [3-4; 12-13]. Though prior research has shown that robotic therapy is better for long term rehabilitation than current conventional therapies, there is still skepticism whether robotic and virtual reality systems can provide the relevant practice environment needed to generalize to real function in daily activities. It remains to be seen whether the robotic devices currently available can provide relevant training or whether larger, more ambitious systems are required. Studies on healthy individuals can more easily determine whether there are any underlying neural resources for generalization. If the intact brain cannot generalize to various conditions, there is little hope in expecting any greater ability after brain injury. This is not to imply that this isn’t possible, but the likelihood is much smaller.

In this study, we focused on the ability to generalize learning in three ways that are critical to neurorehabilitation. First, we wanted to verify prior results that people trained in some movement directions can generalize to other directions [2, 3]. Second, we were interested in generalizing to different movement amplitudes since our everyday activities involve reaching towards objects at a variety of distances from our bodies. Gravity assistance has become an important part of rehabilitation techniques [8, 14, 15, 18, 19]. It is being used both for upper and lower extremities and has been found to be beneficial. Yet little is known about how well people might function after removing the assistance. Hence, our third question was whether learning that occurs with a gravity
assist device could be generalized to a non-assist environment (and vice versa) [11].
Subjects performed a reaching task towards targets presented in the visual field and had to learn how to move straight in the presence of a visual distortion, and were evaluated on their ability to generalize what they learned to various combinations of the three factors [6,7]. Movement extents were changed between 0.1 m (small) and 0.3 m (large) in amplitude. By examining this phenomenon in generalization, we anticipate being able to gain a better understanding of what size robots and workspaces would be most optimal for stroke and other brain-injury rehabilitation in the future.

The hypotheses we tested with this experiment are as follows:

- Subjects will be able to generalize from small to large movements.
- Subjects can generalize to unpracticed movement directions.
- Subjects will be able to generalize from gravity cancellation to a normal gravity environment.
- Subjects can generalize to combinations of the factors presented.
II. METHODS

A. **Apparatus**

The robotic system used for this study is located in the Robotics Lab of the Sensory Motor Performance Program (SMPP) of the Rehabilitation Institute of Chicago (RIC) which is affiliated with Northwestern University. The system includes the Virtual Reality And Robotics Optical Operations Machine (VRROOM), Personal Augmented Reality Immersive System (PARIS), and a Flock of Birds head tracking system. Additionally, we used the Wilmington Robotic Exoskeleton (WREX) for the gravity cancellation tests.

1. **Virtual Reality and Robotic Optical Operations Machine (VRROOM)**

   The Virtual Reality and Robotic Optical Operations Machine (VRROOM) is an integrated system combining virtual reality graphics environment, haptic force feedback and tracing of limb segments using a magnetic tracking system [2].

   The VRROOM uses the Personal Augmented Reality Immersive System (PARIS) to perform the reaching task movements along with a Flock of Birds head tracking system that allows researchers to track a subject’s movements [2,12]. The PARIS system employs a Christie Mirage “field sequential enabled” DLP projector and a double mirror-folded light path to illuminate the overhead high contrast black screen [2]. The PHANToM® 3.0 robot (developed by SensAble Technologies) is installed underneath the mirrors and its handle can move about in the designated workspace (Fig. 2). The PHANToM® 3.0 is a large
workspace, light-touch device with an extensive library for control and rendering of haptic objects [12]. This quality is especially useful when creating virtual reality environments that need to remain underneath the high contrast black screen – keeping it relatively undamaged by all the movements being made with its handle.
Fig. 2 – A representation of the experimental setup without the gravity assist device. The subject sat in front of the screen and manipulated the handle of the PhanTOM® 3.0 robot from underneath. The yellow cursor represents the subject’s hand location on the handle and the red circle is a sample target which moves within the allocated workspace.
2. **Wilmington Robotic Exoskeleton (WREX)**

The Wilmington Robotic Exoskeleton is an external orthotic device originally designed to assist young children with muscular dystrophy with everyday activities. It is now also being used to gain better understanding of the impact of gravity (or lack thereof) on one’s arm when moving about in a 3-dimensional space [25]. The WREX is a 2 link orthotic, with 4 total degrees of freedom (2 at the shoulder and 2 at the elbow). Once the orthotic is securely strapped to an individual, it provides a sense of flotation within 3D movement space. This flotation feeling minimizes the impact of gravity and makes arm movements easier. Since only a right-hand support is currently available, subjects were required to be right-hand dominant to participate.
Fig. 3 – Wilmington Robotic Exoskeleton (WREX). A) A diagrammatic representation of WREX. This particular version is attached to wheelchairs. B) An example of how the WREX is fitted to a young adult. Only a right hand version is available at the moment. [30]
B. **Subjects**

Twenty-eight healthy right-hand dominant subjects – 17 males and 11 females ranging in age from 21 to 35 years – with no known neurological or musculoskeletal disorders participated in this study. The research was conducted at the Robotics Lab of the Sensory Motor Performance Program (SMPP) in affiliation with the Rehabilitation Institute of Chicago (RIC) and Northwestern University. Informed consent was provided under IRB # 0784-012. Subjects were compensated for their time. IRB Approval was also received from the University of Illinois at Chicago under IRB # 2010-0087.

C. **Protocol Development**

1. **Crossover Design**

   This experiment is a 2x2 crossover design study, where both inter- and intra- comparisons occurring. In order to study how learning and generalization were influenced by three different factors, four groups (7 subjects in each, randomly assigned) trained on separate sequences of training and test conditions. The groups were first broken into a 2x2 factor format, where one of the factors was movement distance (large versus small) and the other was gravity assistance (on versus off). Additionally each subject was asked to generalize to unpracticed movement directions (60 degrees from the practiced directions). Groups 1 and 2 trained on small movements. Group 1 had gravity cancellation assist while Group 2 did not. Groups 3 and 4 performed on large movements, but Group 3 had the gravity assist device while Group 4 did not.
2. **Visual Distortion**

The purpose of the learning task was to gain the ability to perform in the presence of the visual distortion. This distortion was calculated by first generating an average “gaze” vector, which predicted how a subject would view the centroid of targets when seated in front of it. The gaze vector was determined to start approximately at the eye level of a subject and continue into the centroid of targets presented in the virtual environment. Hence, subjects were encouraged to sit in within the same space so that their eyes would be in approximately the same spot as others. A homogeneous transformation was performed that rotated all visual stimuli counter-clockwise (CCW) by 45° about the gaze vector (Fig. 4). The 45° measure for the distortion was chosen arbitrarily – we wanted to ensure that the distortion was strong enough to cause an adaptation to occur.
Fig. 4 – A representation of the visual field encountered by the subjects. The first figure shows both planes – the green is distorted by 45° CCW and the gray is the standard position. The second image shows how subjects will move within the standard, undistorted plane. The third image shows the same targets with the visual distortion turned on. The subject’s movements change to accommodate the distortion.
3. **Subject Task**

Subjects were asked to perform a series of randomized target reaching movements using the robotic handle attached to the PhanTOM® 3.0. The robot handle was represented as a yellow cursor in the virtual reality environment (Fig. 2). The subjects’ task was to place this cursor inside the spherical, semi-transparent targets presented within the workspace. They were instructed to make the most accurate and ergonomic movement possible to get to the targets shown. The subjects were not able to see where their arms were under the screen.

4. **Subject Visual Feedback**

Once a target was reached (i.e. the cursor entered the semitransparent sphere), it would change color based on whether the movement time and velocity was within specified range. For this experiment, since we were using healthy individuals, we allowed up to 5 seconds for reaching from 1 target to another, with a preferred time range of 1.4 -1.7 seconds, and a velocity threshold of 0.08 m/s. If the subject was able to enter the semi-transparent target within the preferred time allotted and within the velocity threshold, the sphere would turn green.

If just outside of that range, the target turned yellow. However, if it took a subject longer than 5 seconds to reach the target or he/she moved too slowly, the sphere would turn red. Only once a target was reached would a new target would appear in the workspace. The targets were presented in a random walk pattern throughout the workspace. This means that subjects did
not need to return to a starting point in order to continue on (an experimental design known as “center out”). Target locations were restricted to be in one of three evenly-spaced directions (each 120 degrees apart). Short rests were provided to prevent arm fatigue from occurring.

5. **Protocol Design**

For each protocol, subjects first made a series of 15 movements before exposure to the visual distortion for each of the factors (baseline phase). Subjects were also briefly exposed to the distortion pre- and post-training in each of the generalization conditions (pre-exposure and post-exposure phases, 15 trials in each condition) to determine initial error and improvement due to training. The training phase of the experiment consisted of 300 movements. At the end of training and in each generalization condition, a series of 15 catch trials were presented intermittently and randomly distributed. In these catch trials, the subjects were surprised by the sudden removal of the visual distortion to determine if there were any after-effects due to learning. A sample protocol is included in Appendix D.
III. ANALYSIS

A. **Maximum Perpendicular Distance**

The primary error measure chosen for analysis was maximum perpendicular distance, which was calculated by measuring the farthest perpendicular distance from a straight line to the target (Fig. 5). We normalized this by dividing by ideal movement distance. Other error measures were also considered, including elapsed time, initial direction error, and non-normalized maximum perpendicular distance.

Since we wanted to see if learning and generalization would occur, we compared the pre- and post-training error. Outliers were removed by identifying error that was beyond 3 standard deviations. These pre- and post-errors for each phase for each subject are shown in Fig. 6, where each subject is a different color. The values for the phase were averaged and run through a paired t-test to determine if there was improvement in performance and/or if the presence of after-effects could be seen.
Fig. 5 – An example of how the maximum perpendicular distance is calculated. The red lines shown indicate ideal trajectories from target to target. The blue lines are actual trajectories that are done without the presence of the visual distortion. The green line represents the actual trajectory in the presence of the visual distortion. Perpendicular distance, indicated by the black line segment, is the maximum of all perpendicular distances between the trajectory to the ideal straight line to the target.
IV. RESULTS AND DISCUSSION

A. **Direct Effect of Training**

As expected, all subjects were able to complete the movements easily and made relatively straight lines to the target before being disturbed by the visual distortion. We first restricted our focus to only the training phase and how subjects showed evidence of learning. Upon exposure to the visual distortion, subject made large errors that were greatly recovered by the end of training (Fig. 6A). Large after-effects were also present by the end of training (Fig. 6B, right columns of dots). The confounding effect of movements speeds did not change across training (Fig. 6C) but were higher in the catch trials (Fig. 6D).

We repeated this process of analysis on all the pre- and post-phases for all groups and generalization conditions in order to determine the ability to generalize. We found evidence of both learning and after-effects from the data sets. All the groups except Group 2 showed both significant reductions of maximum perpendicular distance and increase in after-effects in the training phase.

We frequently observed no significant improvement in performance, but still a significant presence of after-effects. For these trials we investigated these further to determine why there was no improvement although there were after-effects. Group 2’s failure to show significance (they trained on small movements without gravity assistance) was the floor effect, whereby the error level was already quite low to start with. The normalized error metric showed an average value of 0.25 from the start to end of the training phase. The peak speed profile showed that the average speed remained at
Fig. 6 – Pre- to post-training analysis for Group 1. Panels A and B show the primary error metric -- maximum perpendicular distance -- across training, Panels C and D show the peak speeds. Each color represents a subject with solid diagonal lines indicating significant change (pre to post training) within that subject ($\alpha=0.05$). Dotted diagonal lines indicate no significance. In Panel A, the error (max perpendicular distance) from pre- to post-training is decreased. Panel B shows an error increase when the visual distortion is turned off, showing a significant presence of after-effects. These results show that both learning and generalization have occurred across training. Although peak speed did not vary much during the learning phase, subjects sped up once the distortion was turned off.
Fig. 7 – Pre- to post-training analysis for Group 1 for a generalization test. Panels A and B show the error metric -- maximum perpendicular distance -- across training. Panels C and D show the peak speeds. Each color represents a subject with solid diagonal lines indicating significant change (pre to post training) within that subject ($\alpha=0.05$). Dotted diagonal lines indicate no significance. In Panel A, the error (max perpendicular distance) from pre- to post-training shows a slight decrease. Panel B shows an error increase when the visual distortion is turned off, showing a significant presence of after-effects. These results show that generalization has occurred, with some learning across training. Although peak speed did not vary much during the learning phase, subjects sped up once the distortion was turned off.
0.2 m/s. A look at the baseline phase showed that the error value was also at 0.25. Since the error was already low, and training did not yield a decrease in error, a floor effect was determined. Therefore, for this condition, we concluded there was sufficient evidence of learning.

B. **Generalization Tests**

1. **Single Factor**

   We used the same techniques to investigate the central question - how subjects were able to generalize what they learned to unpracticed conditions. Group 1, which practiced on small movements with gravity cancellation, did not show significant improvement (error reduction) but did show evidence of significant after-effects for all three factors: size, direction and gravity assistance. For better understanding of this paradoxical result, we inspected the peak speed for a possible explanation. For both direction and gravity generalization, we discovered a speed-accuracy tradeoff where speeds increased from pre- to post-training. Therefore, for these conditions, we concluded there was sufficient evidence of generalization.

   A slightly different situation took place for size generalization, where a peak speed change was not evident and hence could not explain the result. Furthermore, final error was not as low as Group 3, which practiced these conditions directly. Since the error never decreased to a low level, nor was there a
speed-accuracy tradeoff, we concluded their ability to generalize from small to large movements was wrong.

2. **2-Factor and 3-Factor**

   Next, we looked at how well subjects were able to generalize to 2 different conditions at the same time. The direction and size generalization showed significance ($\rho < 0.05$) in both performance and after-effects. For the direction and gravity generalization, we found only significant ($\rho < 0.05$) after-effects. The final combination – where all 3 factors were generalized concurrently – also indicated significant ($\rho < 0.05$) improvement in performance and after-effects.

   The analysis was repeated for the remaining training groups. Again, for several conditions we found only significant after-effects. However, from the peak speed profiles, we found evidence of a speed-accuracy trade-off to explain these, with the exception of the generalizations to unpracticed directions in Groups 3 and 4. For these two cases, we found a “floor” effect that could explain the lack of error reduction -- initial error was already low before training even began. Here we observed very fast learning that occurred in the early exposure trials.

3. **Non-Normalized Maximum Perpendicular Distance**

   All the analysis done on maximum perpendicular distance so far has been on data normalized to the ideal trajectory. To ensure that results are not confounded or biased by our normalization, we repeated the analysis. Appendix D shows the charts generated for
non-normalized maximum perpendicular distance. While all the test conditions show significant after-effects, similar to the normalized data. However, it also appears that there are fewer cases where performance is significant. Consequently, we conclude that the more revealing results come from data that has been normalized.
Table I – Retrospective power analysis. P-values for maximum perpendicular distance and associated speed profiles were found. Cohen’s “d” value was found and along with standard deviation, used to determine the power of the experiment. It is theorized that a type 1 error may be occurring where the null hypothesis is correct but is being rejected. In this case, the presence of after-effects implies that learning took place, but the lack of significant improvement in performance implies otherwise. The power values are calculated as percentages. In instances where the analysis didn’t indicate a specific error type (i.e. after-effects, improvement in performance, speed increase or the floor effect), secondary analysis was performed to understand the implications of the data.
C. **Power Analysis**

A retrospective power analysis was done on the error measure used – maximum perpendicular distance. The purpose of this analysis was to determine the strength of the conclusions drawn, i.e. could more data have changed the results found in cases where there was no significant effect? Using the *p*-values that were generated for all the generalization tests that compared pre- and post-training changes, the corresponding means and standard deviation values were used to generate Cohen’s “*d*” value [33]. Together, these values – mean, standard deviation, Cohen’s *d*, significance – were used in statistical software “R” to calculate a power value.

Table I shows the *p*-values for each of the generalization tests. The setup was the same as that for analyzing maximum perpendicular distance. The shading scheme used shows significant after-effects in blue and significant improvement in performance as green. Values for these conditions are placed in the cause found, i.e. for the training condition for Group 2, a floor effect was found. Using just the error measure, we found evidence of improvement in performance and evidence of after-effects. We hypothesized that one of the primary reasons for not always seeing an improvement in performance even with the presence of after-effects is the speed-accuracy tradeoff. As such, we also performed a retrospective power analysis on speed.

In general, a higher power value indicates that the results would not change substantially if more data had been collected and analyzed. The retrospective power analysis done for the groups thought to show a speed-accuracy tradeoff showed high power (greater than 60%), suggesting that when we failed to detect clear evidence of
generalization in the after effects, we were fairly certain that either the speed or the floor effect was the reason. The one exception was Group 1 size generalization, where subjects practiced on small movements and then were asked to transfer the skill to large motions. In that condition, subjects showed evidence of after effects but no performance improvement, and no change in speed. In this case, the data suggest that subject generalized incorrectly.

D. **Conclusions**

This study evaluated the healthy nervous system’s ability to generalize learned skills in three-dimensional reaching movements using a large workspace, three-dimensional haptic/graphic interface [1-4, 10, 12, 13]. We found encouraging ability for skills to be generalized across space and to different gravitational assistance, except for the ability to generalize to large movements after practicing small movements. While these results should be further tested in other movement environments and contexts, these preliminary results suggest that larger robotic systems are advantageous for training the functional motions that can include large actions.

When examining how subjects performed under 2 simultaneous generalization tests, we found that direction and size (combined) yielded significant learning and after-effects when trained on small movements, while individually these factors showed only a presence of after-effects without significant error reduction. A similar scenario takes place for combined size and gravity generalization. For the combined direction and gravity generalization, we found only significant after-effects under the same conditions. From the peak speed profiles, we once again found evidence of a speed-accuracy trade-off to explain this. This implied that accuracy might have decreased as subjects became
faster causing error to either stay the same or (counter intuitively) increase even though learning took place [9].

There may be an order-effect occurring which can be indicated by a lack of improvement in performance while still showing the presence of after-effects [16]. The phases within the protocols for the 4 training groups could not be completely randomized with the logistical constraints of the equipment, i.e. moving a subject in and out of the gravity assist device requires constant familiarization training, in addition to potentially cancelling out any learning affect that might be seen. Although this limits the conclusions that can be drawn from some of the later conclusions, learning and generalization are still evident and indicate that these parameters are having an impact on the nervous system.

The one area showing clear difficulty in generalization is where subjects make large movements after practicing on small movements. This was not true in the reverse case – subjects were able to generalize to small movements after practicing large movements. Movements that are larger tend to have velocities that are not found in movements with smaller extent. This result suggests that extrapolation of skills in small to large movements presents the greatest challenge.

In this experiment, we ask subjects to make large and small reaching movements within the workspace. Even when they are moving within the distorted plane, movement sizes remain consistent. However, what if instead of keeping movement sizes “honest,” subjects end up unknowingly making large movements when asked to make small movements. What this does is essentially amplify the degree of error. The primary implication of this mode of research is that perhaps larger robotic systems aren’t needed – if smaller robotic systems can be programmed to do this amplification, can similar or
better results be generated?

The skepticism of robots and virtual reality for functional practice, the results show that subjects were able to perform multiple combined generalizations. This suggests that these robotic systems may be practical for practice of everyday activities [4, 12, 13]. Overall, we conclude that training on robotic systems should not presume that training within a small workspace will lead to beneficial capabilities in the sweeping spaces of larger functional activities. However, larger robotic systems, which can more closely emulate real world actions, may provide the best tools for learning and generalization.

A potential application for this kind of research and data is in developing new training methods for astronauts planning on going into space. Exposure to a zero-gravity environment can cause some spatial disorientation and require both learning and generalization in a limited amount of time. While individuals training for space flight are trained underwater to simulate zero-gravity conditions, could using a virtual robotic environment be used as an alternative training tool? Research has been conducted to understand how spaceflight (and exposure to microgravity) has an impact on locomotion and spatial accuracy [36], but by providing further training involving visual distortions in a small workspace, the time it takes for individuals to actually fully learn and adapt in the new environment can be shortened.
CITED LITERATURE


APPENDIX A: MAXIMUM PERPENDICULAR DISTANCE PLOTS

Appendix A – Group 1 condition – where subjects trained on small movements with the WREX. These figures show maximum perpendicular distance analysis.
Appendix A – Group 2 condition – where subjects trained on small movements without the WREX. These figures show maximum perpendicular distance analysis.
Appendix A – Group 3 condition – where subjects trained on large movements with the WREX. These figures show maximum perpendicular distance analysis.
Appendix A – Group 4 condition – where subjects trained on large movements without the WREX. These figures show maximum perpendicular distance analysis.
Appendix B – An example of the protocol used for the study. This particular protocol shows training on small movements with the gravity assist (Group 1).
Appendix C – Group 1 condition – where subjects trained on small movements with the WREX. These figures show peak speed profiles.
APPENDIX C (continued)

Appendix C – Group 2 condition – where subjects trained on small movements without the WREX. These figures show peak speed profiles.
APPENDIX C (continued)

Appendix C – Group 3 condition – where subjects trained on large movements with the WREX. These figures show peak speed profiles.
Appendix C – Group 4 condition – where subjects trained on large movements without the WREX. These figures show peak speed profiles.
APPENDIX D: NON-NORMALIZED MAXIMUM PERPENDICULAR DISTANCE

Appendix D – Group 1 condition – where subjects trained on small movements with the WREX. These figures show maximum perpendicular distance analysis that is non-normalized.
Appendix D – Group 2 condition – where subjects trained on small movements without the WREX. These figures show maximum perpendicular distance analysis that is non-normalized.
Appendix D – Group 3 condition – where subjects trained on large movements with the WREX. These figures show maximum perpendicular distance analysis that is non-normalized.
Appendix D – Group 4 condition – where subjects trained on large movements without the WREX. These figures show maximum perpendicular distance analysis that is non-normalized.
APPENDIX E: CONSENT FORM

Rehabilitation Institute of Chicago  
Sensory Motor Performance Program (SMPP)  

CONSENT FORM FOR RESEARCH  

Title: Error-enhanced learning & recovery in 2 & 3 dimensions  

Principal Investigator: James L. Patton  
Funded by: National Institutes of Health  

You are being asked to take part in a research study. This document has important information about the reason for the study and what you will do if you choose to be in this research study.  

What is the reason for doing this study?  

This study is being done because we want to better understand learning and how it plays a role in the way people control their movements. You are asked to take part in this study because you are a healthy person who can help us understand how the nervous system learns to control its movements in new environments.  

What will you do if you choose to be in this study?  

As a subject in this study, you will be asked to come to the Robotics Laboratory at the Rehabilitation Institute of Chicago, in room 1385.  

Beyond any visits that you make just to view the apparatus, your part in this study involves 2 visits on 2 days in a row. The first visit will last approximately 1.5 hours, and the second visit will last approximately 40 minutes.  

As a subject in this study you will first be asked to answer some questions to confirm that you can take part in this study. The questions will concern your age, height and weight, your general state of health, and whether you have any additional injuries or disorders that may influence the movement of your arm.  

The experiment will involve using an apparatus (VRROOM) that displays images on a screen in front of you and also is attached to a robot that can push on your arm while you move. You will be asked to sit, put on virtual reality glasses and move the handle of the robot from one point in space to another in order to make a cursor move to a target displayed on the screen. The instructor will show you how to pace your movements. You will first get familiar with the apparatus, and once you feel comfortable you will be asked to make repeated movements for about 1 hour as the computer records the location of your arm. Sometimes you might feel the robot push and disturb your movement.  

After completing the session, you can let us know about the level of comfort and how your arm felt during these movements. You will return on the next day for a brief follow-up session using the
same apparatus to see what you remember from the day before. Afterwards, a summary print out of your results will be made available to you.

What are some of the risks and discomforts that may happen to people who are in this study?

Taking part in this study may involve the following risk to you – fatigue and muscle soreness the next day. To minimize the chance that this will happen, you can take rests anytime you want to, and you may ask to have the procedure stopped if you have any discomfort or other concerns.

What are some of the benefits that are likely to come from my being in this study?

There will be no direct benefit to you by your participation in this study. Taking part in this study may help scientists to better understand how the nervous system adapts and learns how to control movements.

Are there any financial costs to being in this study?

There will be no costs to you for being in this study. You will be paid $30 upon completion of each visit. If you do not complete the experiment, you will be paid according the percentage of the experiment that you complete. You are responsible for your own transportation and/or parking costs.

If I have questions or concerns about this research study, whom can I call?

You can call us with your questions or concerns. If you have any illness or injury during your time on this study, you should call us promptly. James Patton, Ph.D. is the person in charge of this research study. You can call him/her at telephone (312) 238-1277 Monday through Friday, from 9am to 6pm. For problems arising evenings or weekends, you may call Dr. Patton at (847) 334-1056.

What are my rights as a research subject?

If you choose to be in this study, you have the right to be treated with respect, including respect for your decision whether or not you wish to continue or stop being in the study. You are free to choose to stop being in the study at any time.

Choosing not to be in this study or to stop being in this study will not result in any penalty to you or loss of benefit to which you are entitled. Specifically, your choice not to be in this study will not negatively affect class standing if you are a student, or employment status at RIC or Northwestern University.

If you want to speak with someone who is not directly involved in this research, or have questions about your rights as a research subject, please contact the Office for the Protection of Research Subjects. You can call them at 312-503-9338.
What about my confidentiality?

Involvement in this research study may result in a loss of privacy, since persons other than us might view your study records. Unless required by law, only the following people can review your study records:

- Representatives of the National Institutes of Health
- Representatives of the Department of Health and Human Services
- The Northwestern University Institutional Review Board

They are required to keep your personal information confidential.

Results of this study may be used for teaching, research, publications, or presentations at scientific meetings. If your individual results are discussed, your identity will be protected.

Consent Summary:

I have read this consent form and the research study has been explained to me. I have been given time to ask questions, and have been told whom to contact if I have more questions. I agree to be in the research study described above.

A copy of this consent form will be provided to me after I sign it.

Subject’s Name (printed) and Signature ___________________________ Date __________

Name (printed) and Signature of Person Obtaining Consent ___________________________
APPENDIX F: CREDITS AND PERMISSIONS

VITA

NAME: Deivya Bansal

EDUCATION: B.S., Bioengineering, University of Illinois – Chicago, Chicago, Illinois, 2005

M.S., Bioengineering, University of Illinois – Chicago, Chicago, Illinois, 2014

TEACHING: Department of Chemistry, University of Illinois – Chicago; Chemistry Laboratory for Undergraduates, 2010

PROFESSIONAL: International Council on Systems Engineering

MEMBERSHIP