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NON-DOMINANT ARM TRAINING IMPROVES FUNCTIONAL PERFORMANCE AND MODIFIES SPONTANEOUS ARM SELECTION

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Abstract

The goal of this study is to investigate whether dexterity training of healthy subjects' non-dominant arm will lead to functional improvements in unilateral performance, and whether such improvements will lead to an increase in non-dominant arm selection during a reaching task. Before and after training, subjects used both arms to perform four functional tests, in addition to an arm selection task used to measure how frequently subjects chose their non-dominant arm to reach towards a large array of targets. Between these pre- and post-tests, we trained participants' non-dominant arm for four weeks in a paradigm that employed various exercises emphasizing object placement and manipulation, and speed and accuracy of arm movements. The dominant arm received no training. After training, the non-dominant arm was significantly improved on three of the four functional tests, while the dominant arm showed no significant changes. Additionally, the non-dominant arm was chosen significantly more after training during the post-test than during the pre-test. These results were consistent with our predictions and indicate that both functional and arm-selection changes are possible with general training of the non-dominant arm in right-handed individuals. The fact that non-dominant arm training can influence both performance and spontaneous arm selection has important implications for the rehabilitation of unilateral motor disorders, such as stroke or amputation.

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Chapter 1: Introduction

The purpose of this study is to investigate whether dexterity training of the non-dominant, left arm of healthy right-handed participants will generalize to improve that arm's functional performance, and whether training related improvements in dexterity might increase spontaneous selection of the non-dominant arm for reaching. Previous research has demonstrated that when the non-dominant arm performs better than the dominant arm, such as when reaching toward targets without visual feedback, individuals select that arm more often than they do under conditions in which the dominant arm performs more accurately (Przybyla, Coelho, Akpinar, Kirazci, & Sainburg, 2013; Coelho, Przybyla, Yadav, & Sainburg, 2013). The question of whether non-dominant arm training can affect both performance and spontaneous arm selection is relevant for rehabilitation of disorders that disrupt function of the dominant arm, such as amputation, peripheral neuropathies, and stroke. The efficacy of non-dominant arm training has previously been addressed in healthy participants and in clinical populations. For example, Yancosek and Calderhead (2012) examined training of writing ability in the left arm of right-handed participants, and currently incorporate this work with soldiers who have lost full or partial use of their dominant arm due to amputation. In healthy individuals, previous research has focused predominantly on task-specific training of the non-dominant arm. We have found no previous research that addresses whether dexterity training in the non-dominant arm can improve that arm's performance across a range of functional tasks, and whether this training affects the spontaneous selection of the non-dominant arm during reaching tasks. We now examine whether changes in non-dominant functional arm performance and selection in healthy participants occur with generalized training.

We propose that non-dominant arm training using a wide variety of dexterity exercises will generalize to improve functional performance and dexterity, as measured by standardized tests that were not trained. Krakauer (2009) defined motor adaptation as "a new mapping between well-learned movements and the spatial goal" (p. 405), while skill learning involves improvements in newly practiced tasks. We focus on training skill learning in the non-dominant arm of healthy adult participants. There is evidence that the learning of new motor behaviors and adaptation is still prevalent in stroke patients (refer to Kitago and Krakauer, 2013 for a review); stroke patients can benefit from learning generalizable skills that help them handle small objects, such as medications or buttons on a shirt.

The purpose of this study is to address whether or not a generalized training regimen, with a timeframe and frequency similar to that of a therapy regimen, will induce general improvement in the non-dominant limb of a healthy, young participant. Importantly, the training uses tasks that are substantially different from the tasks used in the tests. In our study, healthy right-handed individuals completed four weeks of dexterity training with only their non-dominant, left hands. They completed pre- and post-tests with both hands, in order to measure their baseline performance and degree of improvement, and to determine how frequently they chose each arm in a simple reaching task before and after training. After training, we found that participants had some significant improvement in their performance with their non-dominant arm on our measure of daily life function, the JTHFT; furthermore, participants chose their non-dominant arm significantly more in our target reaching task.

Dominant and Non-dominant Arm Performance and Selection

Each side of the spinal cord is innervated and largely receives direction from the contralateral brain hemisphere and direct descending signals from the contralateral cerebral hemisphere and brainstem, and sends sensory information to the contralateral brainstem, thalamus, and cerebral cortex (Kuypers, 1981). Handedness appears to reflect an asymmetry in the organization of sensorimotor control on the left and the right sides of the nervous system (Sainburg, 2014). This effect is visible in performance differences between the dominant and non-dominant limbs, as well as in which limb is selected for any particular task. Sainburg (2002) proposed the dynamic dominance hypothesis to explain these hemispheric differences in control, which purports that the hemisphere contralateral to the dominant arm is specialized for predictive control of limb dynamics that allow efficient coordination (Bagesteiro and Sainburg, 2002), while the non-dominant arm seems specialized for controlling impedance to insure robustness against unpredictable perturbations (Yadav and Sainburg, 2011; Yadav and Sainburg, 2014; Yadav and Sainburg, 2014).

In order to understand how to facilitate changes in non-dominant arm performance, it is important to understand how dominant and non-dominant hands are normally used. Performance differences between the dominant and non-dominant arm are quantifiable using tasks such as the Grooved Pegboard, grip strength, and finger-tapping test. The Grooved Pegboard task requires that participants place slim pins into corresponding slots; the orientation of the groove is different for each slot, requiring that participants rotate the pins. Bryden and Roy report an average of 52.2 ± 5.7 seconds for healthy, young (18-24 years old) right-handed individuals to complete the Grooved Pegboard task with their right hand and 60.5 ± 8 seconds for the left hand (2005). In healthy, right-handed adults, the dominant, right hand grip strength average has been reported as 40.33 kg, whereas the left hand averages 36.25 kg (Petersen, Petrick, Connor, & Conklin, 1989). The finger-tapping test is a measure commonly used to quantify distal speed and dexterity, by counting how many full taps a subject can complete in a certain amount of time. Peters (1980) found that right-handed males completed an average of 57.1 taps with their right hand within ten seconds, compared to an average of 50.8 with the left. The Jebsen Taylor Hand Function Test predicts performance on activities of daily living and correlates well with other measures of upper limb speed and dexterity (Beebe and Lang, 2009; Jebsen, Taylor, Trieschmann, Trotter, & Howard, 1969). It includes seven tasks, all of which are taken together for a total test time: writing, card turning, the movement of small objects, simulated feeding, checkers, large and light objects, and large and heavy objects (Jebsen et al., 1969). In the original work of Jebsen et al. (1969), the dominant arm of 20-59 year old men and women performs all tasks within 37.8 seconds, on average, and the non-dominant arm averages 60.2 seconds (as cited in Raad, 2014). Without the writing task, the remaining tasks total 25.85 for the dominant arm and 28.95 for the non-dominant (refer to Raad, 2014 for a list of means and standard errors by task.)

Arm dominance is not only measured by performance differences between each hand, but also by the arm selected for a task during a given activity. Self-report measures of handedness, such as the Edinburgh Inventory (Oldfield, 1971), measure handedness by aggregating responses to which arm the participant reports using for specific tasks (eg. writing or holding the scissors when cutting). Arm dominance also plays an important role when participants are given the opportunity to select their arm of choice when doing as simple a task as reaching for an item or range of targets. Right-handed participants typically choose their right arm to reach for targets to the right of their midline, and their left arm for targets to the left of their midline; however, the right arm is often chosen more frequently for targets in the midline (Mamolo, Roy, Rohr, & Bryden, 2006; Coelho et al., 2013; Przybyla et al., 2013).

Furthermore, arm selection can be affected by whether the right or the left arm experiences greater accuracy such as during perturbation or lack of vision (Przybyla, Good, & Sainburg, 2012), or efficiency for movements toward a particular target (Coelho et al., 2013), or even by the complexity of the task (Gabbard, Tapia, & Helbig, 2003). For example, in a planar reaching task toward a large array of targets, when vision is occluded, the left, non-dominant arm is more accurate for a significant range of the workspace, while under visual feedback conditions, the right arm tends to be more accurate (Przybyla et al., 2013). Under no-vision conditions, the left arm is selected more often than it is under visual feedback conditions, apparently influenced by its performance advantage (Przybyla et al., 2013). Similarly, arm selection has been shown to correspond with the advantages in mechanical costs between the arms (Coelho et al., 2013). These factors modulate, but do not seem to eliminate the strong influence of target proximity on hand selection. Helbig and Gabbard (2004) demonstrated that when faced with the option of choosing the hand closest to a target, or the hand on the same side of the body as the target, proximity to the object played the largest role in arm selection. Participants sat with crossed arms as they were presented with an a object (with the arm on top being alternated). Thus, participants were to choose between the convenience of reaching with the arm ipsilesional to the object or the with the hand that was closest to the object. They found that participants' arm selection was more influenced by the proximity of the item than by which side of the body the target was on. We now ask whether training of the non-dominant arm might improve performance and thereby influence arm selection.

Non-dominant Arm Training

Previous research on non-dominant arm training in healthy individuals has predominantly focused on training of discrete tasks, for example training the non-dominant hand in a writing task. Yancosek and Calderhead (2012) conducted a pilot study with five non-impaired, right-handed adults. After six weeks of writing training with the non-dominant arm, all participants demonstrated improvements in speed, and four out of five demonstrated improvements in legibility. Walker and Henneberg (2007) conducted a writing study with the non-dominant hand of a group of participants who were either left-handed or right-handed, and none of whom were ambidextrous, as confirmed by the Edinburgh Handedness Inventory. The twenty one participants were 20 to 56 years old (8 male, 13 female), and were divided into a young adult (20-22 years; mean 21) and older adult (30-56; mean 44) age group. For the writing training, participants wrote the same sentence with their non-preferred writing hand twice each day for 28 days. After the training period, participants' legibility was compared with the legibility of their preferred writing hand. Walker and Henneberg report a significant improvement in legibility, and furthermore report no significant difference in improvement by age group.

Walz et al. (2015) trained the left hand of right-handed participants in a variety of dexterity tasks, such as aiming, tapping, turning coins, and moving objects, for one hour every day for eleven days. The pre- and post-tests, done on both hands and using the same tasks as those trained, showed an overall improvement of roughly 30% in the left hand and roughly 19% in the right hand. While these findings suggested that the non-dominant arm showed training related improvements in more general aspects of dexterity, the generalizability of these findings is limited by the fact that training was done on the same tasks as testing. Pereira, Raja, & Gangavalli (2011) did a general training study with either the non-dominant or dominant arm of a mixed group of right- and left-handers. In that study, the Jebsen Taylor Hand Function Test, a general test of unilateral coordination and function, was used as a pre- and post-test. Training was completed over five days of twenty minutes of training, involving activities such as picking up and placing rice, and flipping coins. Their primary interest is whether any significant performance differences occur on the Jebsen Taylor Hand Function Test in the untrained, contralateral arm, which they did find. However, it is unclear what effect the training had on the trained, non-dominant arm.

Non-dominant Arm Training in a Clinical Setting

Therapy for clinical populations, such as the estimated 541,000 Americans living with upper limb amputation, may benefit from research investigating non-dominant limb training (Ziegler-Graham, MacKenzie, Ephraim, Travison, & Brookmeyer, 2008). The current standard of rehabilitation care for upper limb amputation tends to focus on pain management and training in prosthesis use (Management of Upper Extremity Amputation, 2014; Smurr, Gulick, Yancosek, & Ganz, 2008). The goals of physical rehabilitation with upper limb amputees (usually occupational therapy) tend to focus on increasing the patient's functionality by integrating prosthetic use into daily life, such as during personal hygiene (Gulick, 2007; Smurr et al., 2008). When a partial or complete amputation of the dominant arm occurs, the non-dominant arm must become the lead controller in most activities. This introduces the question of whether the previously non-dominant arm transitions into an efficient dominant controller over time. Philip & Frey (2014) reported the differences in non-dominant upper limb performance between individuals with partial or full amputation of the dominant arm and age-matched control participants. In this study, the mean time since amputation was 33 ± 12 years. Amputees performed a novel tracing task with their intact, non-dominant arm; the control participants performed the same task with each arm. These individuals had been using their non-dominant arm as the lead controller for decades. Participants with dominant arm amputations performed the task with similar speed and smoothness, measured as inflections in the tracing path, as the control subjects' dominant arms. This suggests a practice dependent improvement in non-dominant arm performance. However, task error rate (number of errors due to tracing outside the lines) remained significantly higher than age-matched participants' dominant arms, and similar to the non-dominant arm of the matched control participants. Thus, individuals with partial or full dominant arm amputations, forced to use the non-dominant arm as their lead controller during activities of daily living for many years following amputation, showed limited practice related improvements in this visual-motor task. These findings lead to the question of whether changes in motor lateralization are amenable to practice, and if so, whether focused non-dominant arm training might improve functional performance using the non-dominant arm.

Stroke patients with dominant arm paresis might also benefit from therapy targeting the non-dominant and less affected limb. Therapies such as constraint-induced movement therapy, in which the ipsilesional limb is gloved or splinted during intense therapy with the contralesional arm, is an effective and beneficial regimen for survivors of mild to high-moderate motor impairment (Miltner, Bauder, Sommer, Dettmers, & Taub, 1999). Another approach, bilateral training, encourages the use of both arms during therapy in order to improve bilateral coordination, as they are used together for daily life tasks (Waller & Whitall, 2008). However, for sufferers of more severe unilateral paresis these therapies may prove less successful, and use of the ipsilesional upper limb may present the best opportunity for independence and daily functionality. For this group, there may be benefit in exploring focused rehabilitation of the ipsilesional limb. If the ipsilesional arm is the previously dominant arm, it is likely natural for patients to continue to rely on this arm; however, if the ipsilesional arm is the previously non-dominant arm, it may be more difficult for patients to begin to use it in a dominant capacity, and more focused training may be beneficial (Rinehart, Singleton, Adair, Sadek, & Haaland, 2009). Further complicating this recovery, even a unilateral stroke from which the majority of motor deficits occur on the contralesional hemisphere will likely also cause a degree of functional loss in the ipsilesional hemisphere (Wetter, Poole, & Haaland, 2005; Kwon, Kim, & Jang, 2007; Schaefer, Haaland, & Sainburg, 2009). It is currently unknown to what extent training of the non-dominant, ipsilesional arm in stroke patients might lead to improvements in functional independence. Interestingly, little research has addressed whether training of the non-dominant arm in healthy individuals can improve that arm's functional performance.

Chapter 2: Materials and Methods

Participants

Ten young adults (four males and six females) between the ages of 19 and 23 were recruited from the college community. All were self-assessed as right-handed, which was confirmed by the Edinburgh Inventory. Participants signed an informed consent form approved by the institutional review board of the Pennsylvania State University Hershey.

Schedule

All participants took a battery of pre-tests; seven had four weeks of non-dominant arm training, while one subject had only three weeks of training due to unforeseen changes in availability. After training, the participants took the same battery of tests to measure any changes in performance. (Figure 1)

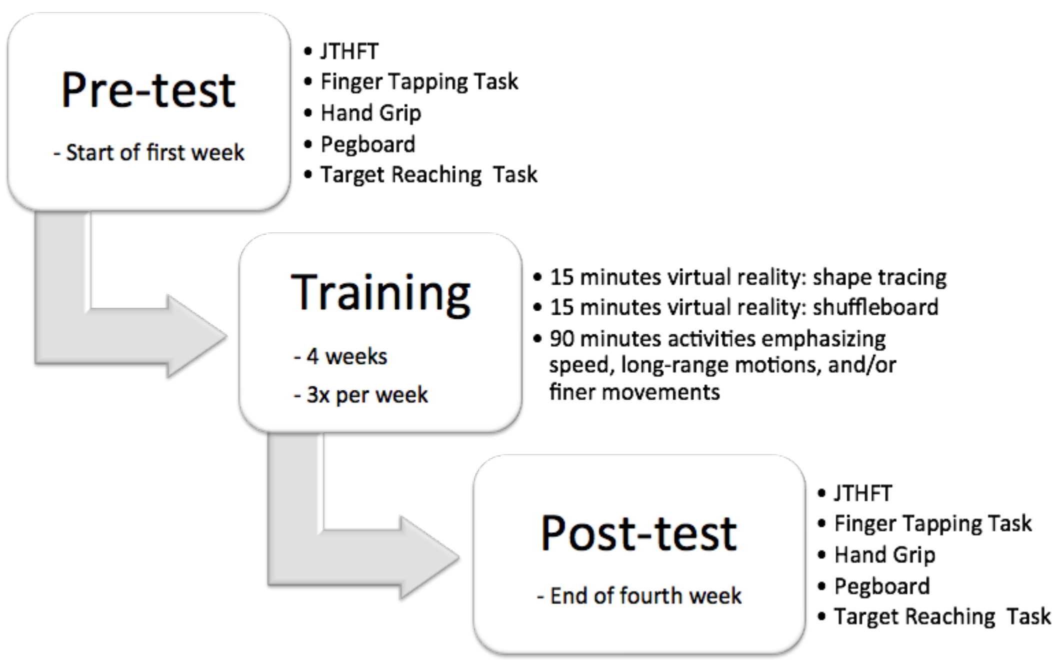


Figure 1. Participant testing and training schedule.

Pre- and Post-Test

In order to quantify baseline performance differences between the non-dominant and dominant arms, participants were given a battery of functional and arm selection tests before training. Each subject completed all tasks with both the non-dominant and dominant arm; the starting arm was alternated between participants, and then maintained for each subject throughout the experiment. Functionality was assessed through clinical tests, and arm selection was assessed with a target reaching task. **Due to technical problems, only eight of the ten participants completed the arm-selection task.** All participants completed the other four functional tasks.

Pre- and Post-Test: Performance Battery

The four tests of unilateral upper limb performance and dexterity included the Jebsen Taylor Hand Function Test (JTHFT), finger-tapping test, Grooved Pegboard test, and grip strength. The JTHFT is a well-characterized test that is predictive of performance in daily activities (Yancosek & Howell, 2009). Participants are timed completing a set of tasks, such as moving cans and writing, and their total time is recorded for each arm. In the finger-tapping test, participants are given ten seconds to perform as many finger taps as possible, and their average from five trials is recorded. Time taken to complete the test (in seconds) is recorded for the Grooved Pegboard test. For grip strength, hand grip maximum (kg) was measured with a dynamometer, and the average of three trials recorded (Mathiowetz, Weber, Volland, & Kashman, 1984).

Pre- and Post-Test: Target Reaching Test

Participants completed the target reaching task in the apparatus depicted below (Figure 2). In this setup, participants are seated in front of a mirror that is slightly below their chin, and onto which a TV is projecting targets and start circles (Przybyla et al., 2012). The mirror prevents participants from seeing their hands, and so they receive veridical feedback about their location from cursors representing the pointer finger of each arm.

Participants began with their left and right hands in one of the 2 cm start circles calibrated to each hand (Przybyla et al., 2013). These were placed with respect to an internal elbow joint angle of $\theta e = 75°$ and shoulder joint external angle of $\theta s = 25°$. Four rows of seven targets, each 3.5 cm, were presented in the horizontal workspace in front of participants, just below shoulder level. The targets were calibrated to each participant's arm lengths, such that each of the four rows appeared at 25%, 40%, 55%, and 70% of their arm length; three of the seven target columns were set at each quarter of the distance from the midline to the right and left arm start circles, respectively, as well as the final row directly in the midline.

For this test, participants were presented with one target at a time, and asked to reach towards the target with a punching motion, moving swiftly and stopping directly on the target. Participants were given both velocity and accuracy feedback, and were incentivized by receiving points for accurate and quick motions. Participants were instructed to reach with whichever arm they preferred towards the target, but were not given any indication that arm selection was of interest. We recorded the number of times each participant chose their non-dominant arm for each target.

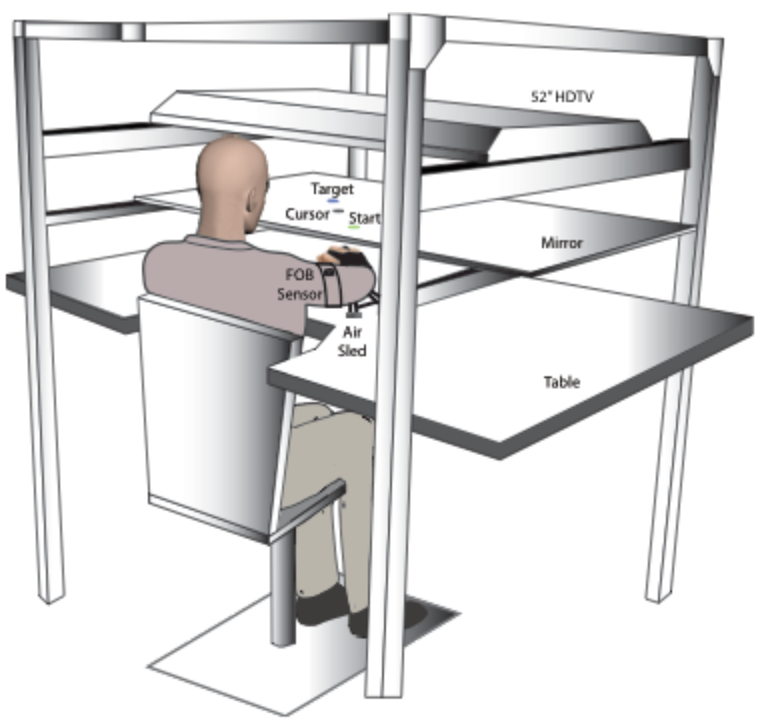


Figure 2. Target reaching and training apparatus.

Training Paradigm

After completing all pre-tests, participants began non-dominant arm training. Nine participants attended sessions for four weeks, three times per week, and two hours per session. The participants conducted all training with their non-dominant arm; their dominant arm received no training. Training activities were chosen that required rapid and accurate movements of the arm, manipulation of small and large objects, and slight resistive exercise of the arm and hands.

In each session, participants began with half an hour of virtual reality exercises using the apparatus described previously. These tasks were designed to require either rapid, predictive movements (such as during a shuffleboard task), or visual motor coordination (such as during a shape-tracing task). They completed fifteen minutes of a tracing task, in which they had a few seconds to trace shapes that ranged in difficulty from a circle to a complicated maple leaf; they subsequently completed fifteen minutes of a shuffleboard task. Both tasks required participants to hold their arm above the table in order to see their hand cursor and complete the movement.

For the remaining one and a half hours, participants completed a series of activities requiring rapid and accurate arm movements and object manipulation. Participants began by squeezing therapy putty and a resistance band, and then did the remaining activities in any order of their choosing. Some tasks required whole arm movements, for example picking up and placing objects, playing catch, pinning clothes pins to targets on a vertical yard stick and removing them, and tossing items into a bin. Other tasks emphasized finer movements, such as cutting out shapes, flipping coins, taking off lids to various items and putting them back on, and molding shapes out of putty.

Chapter 3: Results

In this short-term intervention study, we examined whether intensive dexterity training of the non-dominant arm in right-handers would lead to substantial improvements in standardized performance on tests of unilateral strength, dexterity, and functional performance, and whether such improvements are correlated with an increase in non-dominant arm selection during a reaching task (Przybyla et al, 2013). The study included a pre-test, a generalized training intervention, and a post-test. The pre- and post-tests included the target-reaching task and four components of a dexterity battery that included: the Jebsen Taylor Hand Function test (JTHFT), a neuropsychological test used to measure unilateral upper limb function in tasks that include simulated activities of daily living; the finger-tapping test and the Grooved Pegboard Task, standardized tests of upper limb speed and coordination; and hand grip, measured with a hand dynamometer. The pre- and post-tests were administered within a week before the beginning of training and the week following training. Between tests, the participants underwent three 2-hour long training sessions per week, over a four-week period. An ANOVA was used to determine whether there were any improvements in performances. We further explored any changes in left arm performance on the functional tasks using Tukey's Honest Significant Difference. We expected that only the non-dominant arm would demonstrate training related improvements in performance.

Non-dominant Arm Standardized Tests

The non-dominant arm results of the JTHFT are shown below (Figure 3a). The bars indicate the mean (±SE) completion time, in seconds, in both training conditions (pre, post). After the ANOVA analysis, a post-hoc Tukey HSD indicated significant differences in left hand performance before and after training. Training significantly decreased (improved) non-dominant arm time to complete the JTHFT, from on average 73.74 (± 4.48) to 61.27 (± 2.76) seconds (Tukey HSD, $p = .0003$). There are seven components of the JTHFT, which include writing, page turning, lifting small items, simulated feeding, stacking checkers, placing large and light objects (empty soup cans), and placing large and heavy objects (full soup cans). It should be noted that writing is one of the most important skills that participants seek to regain, after losing dominant arm function (Jordan, 2009).

The writing task requires participants to write a simple sentence, which calls on cognitive and language skills, in addition to dexterity. In order to determine whether improvements in dexterity occurred in the absence of the writing task, we quantified changes in the JTHFT on the six non-writing tasks. Post-hoc analysis revealed that training significantly decreased the time to complete the six item JTHFT, from on average 32.98 (± 2.00) to 28.20 (± .57) seconds (Tukey HSD, p = .0089). Figure 3b shows the six item JTHFT results. These results indicate a general effect of training on functional performance tasks without writing.

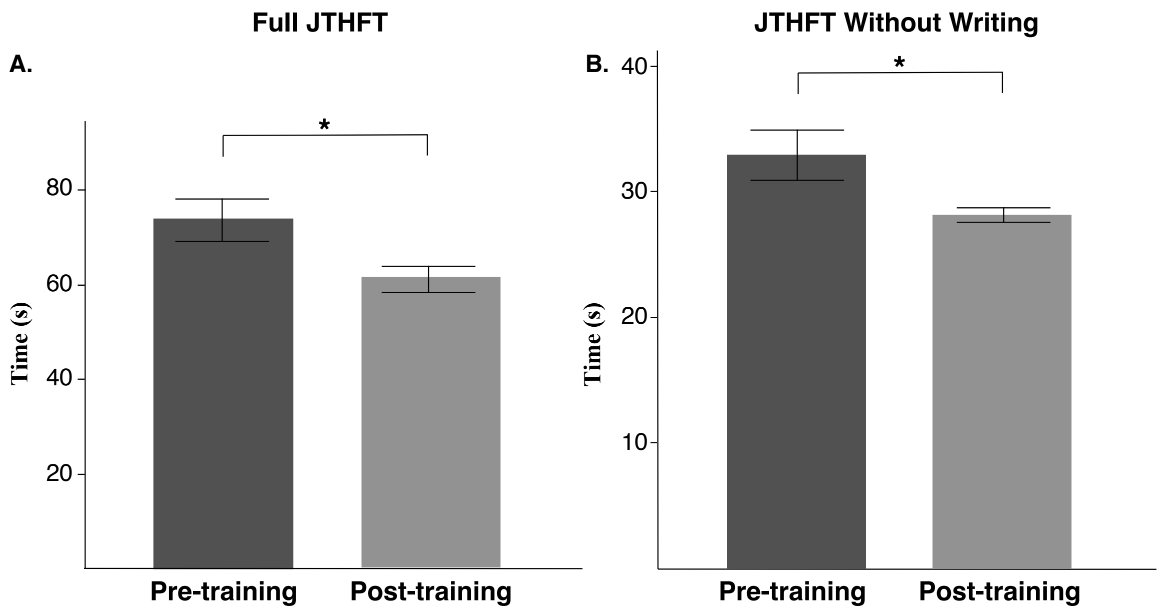


Figure 3. Time (s) for the non-dominant arm to complete JTHFT at pre- (dark grey bars) and post-training (light grey bars), averaged across participants. * indicates a significant difference between pre- and post-test. **a.** Full JTHFT: Time (s) **b.** JTHFT without the writing task: Time (s)

The finger-tapping test is a more specific standardized test of distal speed and dexterity (e.g. Heller et al., 1987; Jobbágy, Harcos, Karoly, & Fazekas, 2005). Figure 4a shows the mean number of taps in a ten second interval, across participants, for the non-dominant hand. Our ANOVA indicated a significant interaction between training and hand (p = .0056). Post-hoc analysis revealed that training significantly increased the number of taps completed by the left arm from an average of 41.19 (± 1.89) taps to an average of 44.44 (± 1.76) (Tukey HSD, p = .0354).

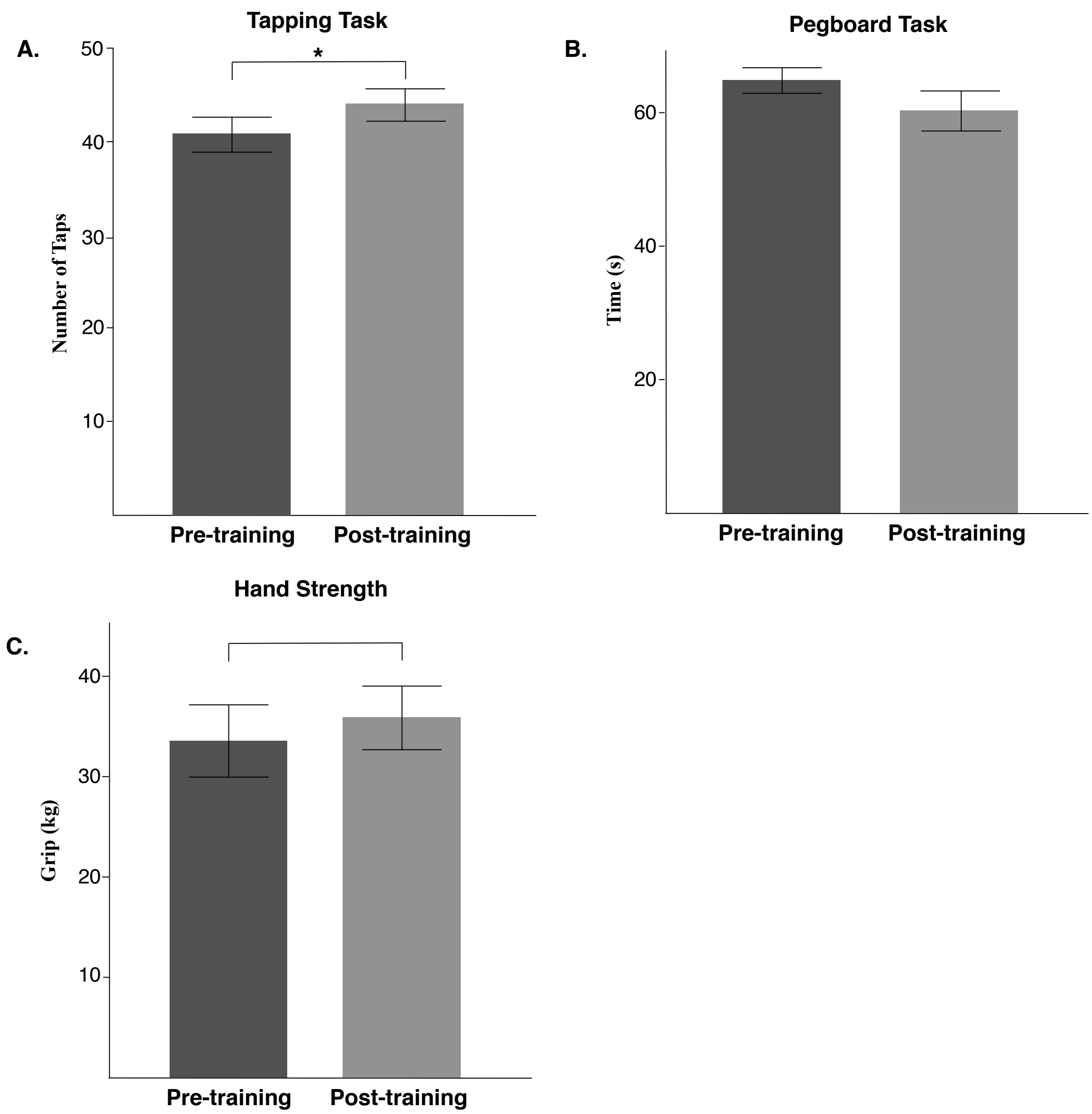


Figure 4. Non-dominant pre- (dark grey bars) and post-training (light grey bars) performance, mean averaged across participants. * indicates a significant difference between pre- and post-test. **a.** Finger-tapping test: Mean number of taps from each of the three ten second trials **b.** Grooved Pegboard: Time (s) **c.** Grip strength: Mean of three hand strength measures (kg)

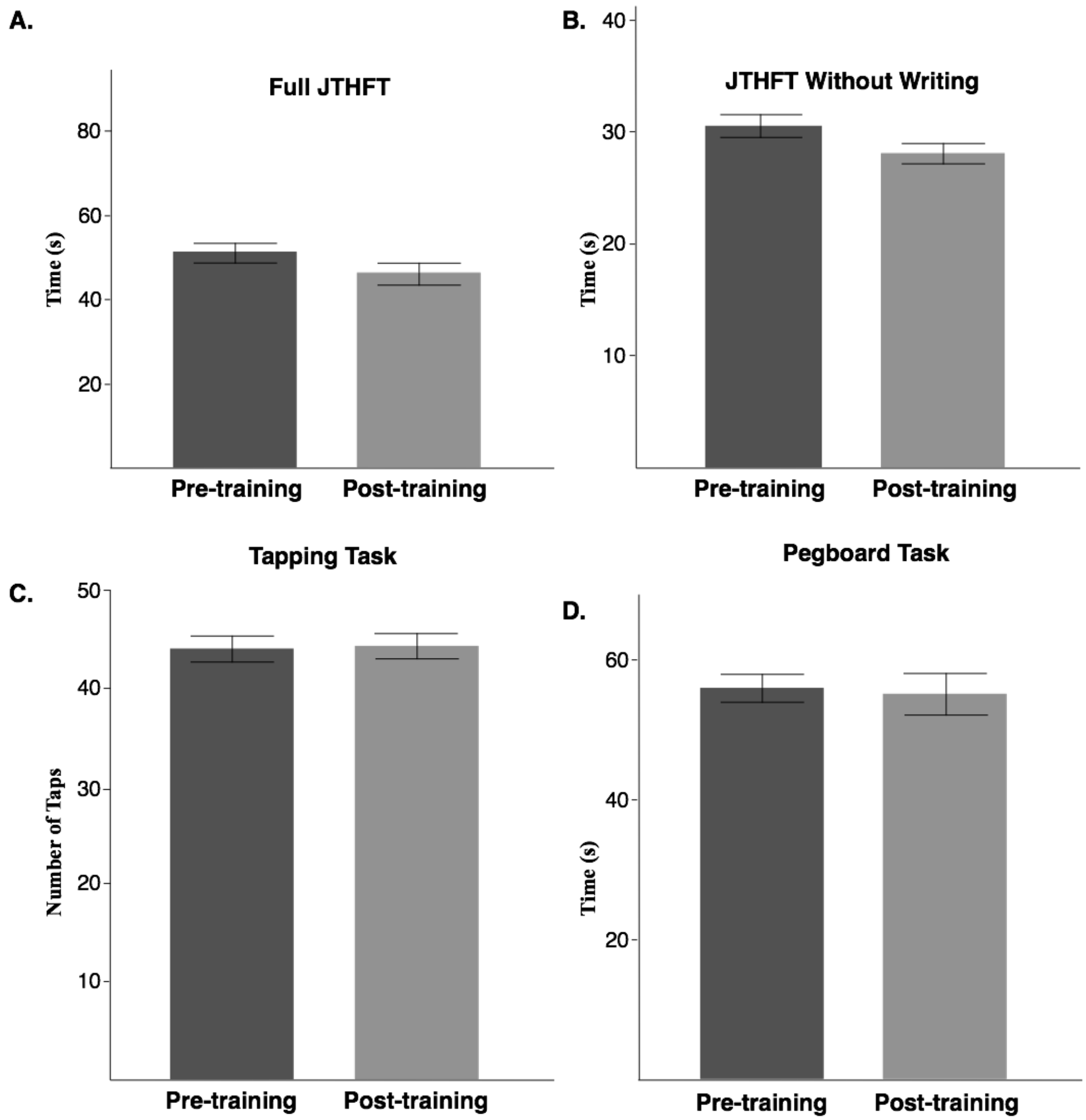
The Grooved Pegboard test (Figure 4b above), required that participants orient and place slender pins into corresponding slots, relying on motor planning processes requiring orientation and fine dexterity. No significant improvements in time to complete this task were made (Tukey HSD, $p = .321$). Additionally, there was no significant change in grip strength (Figure 4c above), with an initial average of 33.61 kg and a final average of 35.92 kg (Tukey HSD, $p = .181$). Taken together, these results indicate significant training dependent improvements in dexterity related functional performance tasks (JTHFT), as well as distal speed and dexterity (tapping). However, no improvements were seen in precision visual-motor performance as required by the Grooved Pegboard task, nor in hand grip strength. We next ask whether these improvements were limb, and training, specific.

	Jebsen Full (s)	Jebsen w/o writing (s)	Finger Tapping (number of taps)	Grooved Pegboard (s)	Grip Strength (kg)
Pre-test	73.74	32.98	41.19	67.17	33.61
Post-test	61.27*	28.21*	44.44*	62.44	35.92*

Table 1. Trained, non-dominant arm results before and after training. Asterisk indicates significant differences between the pre- and post-tests.

Arm Specificity of Training

It is plausible that the training related improvements shown above might be general effects that reflect motivation, general task organization, or cognitive engagement. In order to control for these factors, we tested the dominant, untrained arm on the same tests. The dominant arm showed no significant improvement on the JTHFT (7 item: Tukey HSD mean difference = 4.77; $p = .228$ | 6 item: Tukey HSD mean difference = 2.38; $p = .294$), nor on the finger-tapping test (Tukey HSD mean difference = 0.3; $p = .991$), the pegboard (Tukey HSD mean difference = .882; $p = .987$), or grip strength (Tukey HSD mean difference = 2.23; $p = .204$) (Figure 5). These results confirm that the effects of training on dexterity were limb-specific, and support the proposition that training related improvements in non-dominant arm performance did not result from more general effects, such as motivation, attention, or test familiarity. We next ask whether these changes in performance might influence arm selection during a reaching task.



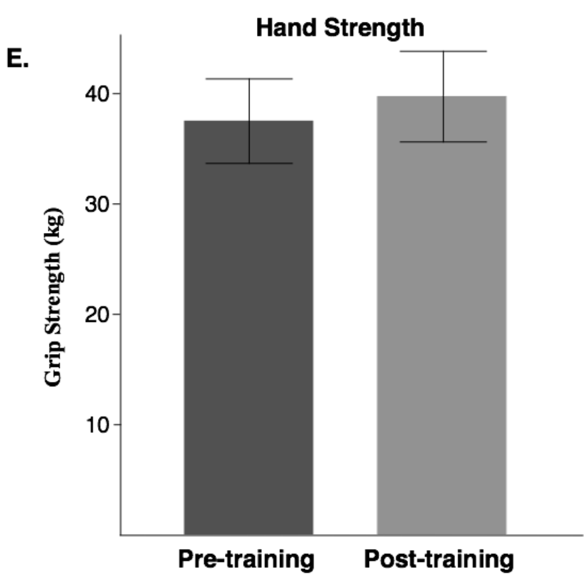


Figure 5. Dominant arm performance at pre- (dark grey bars) and post-training (light grey bars), averaged across participants. * indicates a significant difference between pre- and post-test. **a.** Full JTHFT, time (s) **b.** JTHFT without the writing task, time (s) **c.** Finger-tapping test: Number of taps **d.** Grooved Pegboard: Time (s) **e.** Grip strength: (kg)

	Jebsen Full (s)	Jebsen w/o writing (s)	Finger Tapping (number of taps)	Grooved Pegboard (s)	Grip Strength (kg)
Pre-test	49.11	29.51	45.58	57.90	37.57
Post-test	44.34	27.13	45.88	57.02	39.80

Table 2. Untrained, dominant arm results before and after training. There were no significant changes.

Arm Selection

Due to previous research on the relationship between arm performance and selection for a task, we investigated whether arm selection would be altered by the training. The pre- and post-tests included a target-reaching task in order to determine specifically whether the non-dominant arm might be chosen more for a simple reaching task after training. Participants were instructed to choose either arm to reach swiftly and stop on the center of each target. Figure 6 below shows the percentage of non-dominant and dominant arm selection for all reaches to each target, for both the pre-test before training and the post-test after training. Only the third and fourth columns demonstrated statistically significant changes. Due to the aforementioned work of Helbig and Gabbard (2004), our primary interest was whether the middle column, which is equidistant from both hands and therefore not affected by target proximity, would indicate any change in non-dominant arm selection after training. In this middle column, non-dominant arm selection increased from 15.39% to 32.99% (student $t = -5.64$, $p = .0001$). Figure 7 below shows the change in arm selection for the fourth column.

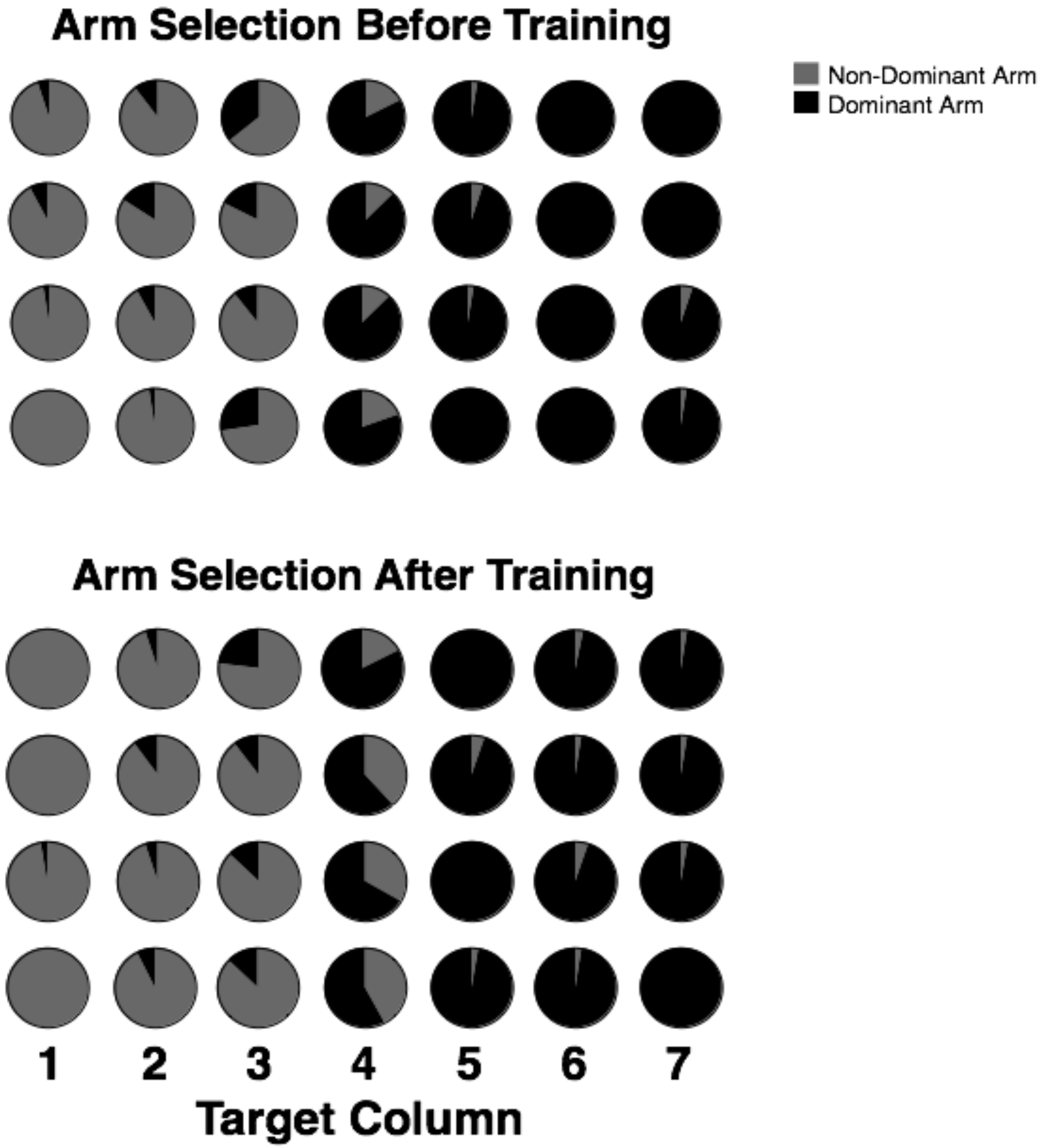


Figure 6. Percentage of dominant and non-dominant arm selection for each target, before and after training. Grey indicates non-dominant arm use, black indicates dominant arm use. The numbers 1-7 indicate the column, with 1 being farthest to the participant's left and 7 being farthest to their right. Only columns three and four showed significant changes between the pre- and post-tests. **a.** Arm selection before training **b.** Arm selection after training

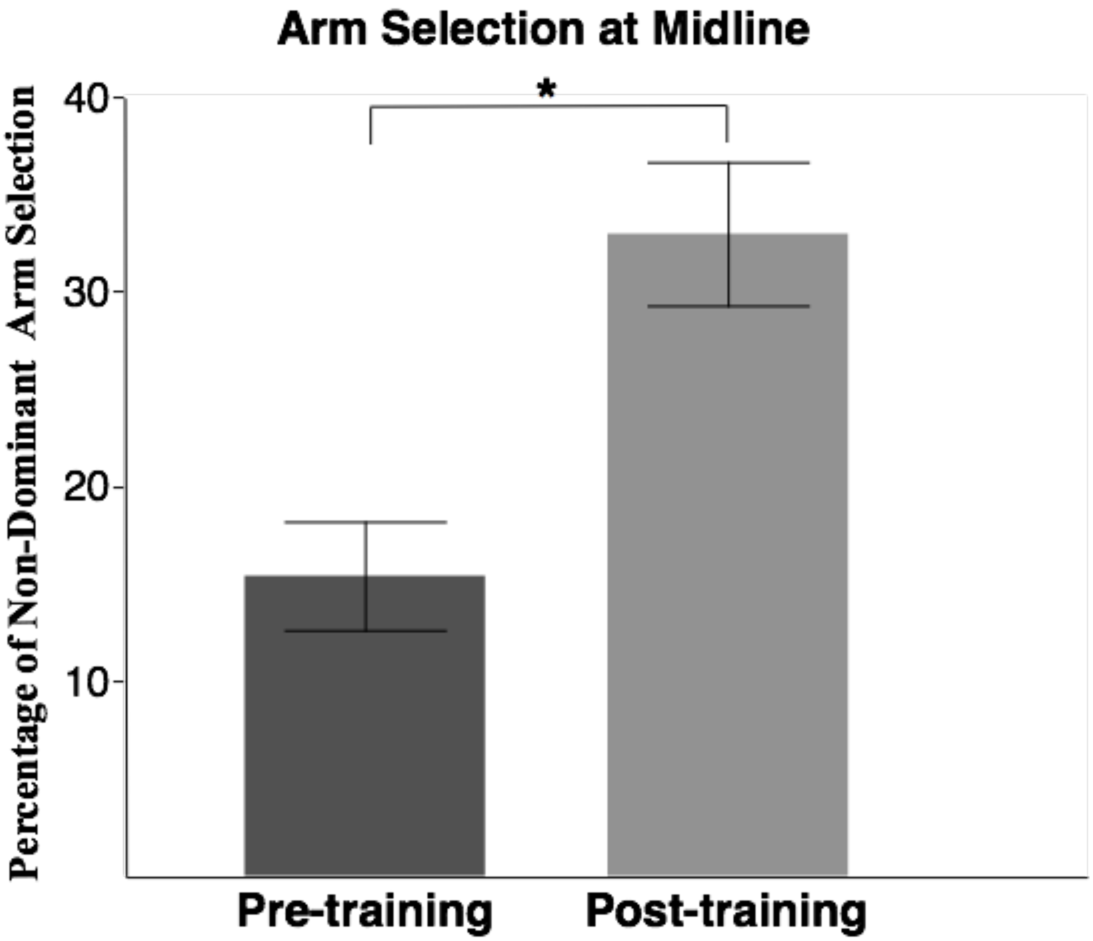


Figure 7. Proportion of non-dominant arm selection on the middle column of the target-reaching task, mean averaged across participants.

Chapter 4: Discussion

The purpose of this study is to investigate whether dexterity training of the non-dominant, left arm of healthy right-handed participants will generalize to improve that arm's functional performance, and whether training related improvements in dexterity will increase spontaneous selection of the left arm for reaching. Previous research has demonstrated that differences in performance characteristics between the arms can lead to predictable changes in arm selection during a reaching task (Przybyla et al., 2013; Coelho et al., 2013). The question of whether non-dominant arm training can affect both performance and spontaneous arm selection is critical for the rehabilitation of disorders that disrupt functionality and the use of the dominant arm. In our study, the non-dominant arm did show statistically significant improvements on two of the four functional measurements, the Jebsen Taylor Hand Function Test (JTHFT), both with and without the writing, and the finger-tapping test; there were no significant changes on the Grooved Pegboard Task nor the grip strength measurement. The dominant arm demonstrated no significant changes on any of these measurements; relevant to stroke rehabilitation, the dominant arm did not display any deleterious effects, statistically significant or otherwise. Furthermore, after training, the non-dominant arm was chosen significantly more in the arm selection target-reaching task than it was before training. These results were consistent with our predictions, and indicate there are some opportunities for changing both the functional performance of the non-dominant limb as well as spontaneous arm selection.

Amputation can result in the increased use of the non-dominant arm for dominant arm tasks and roles, yet there is little research examining how the resulting daily use affects the non-dominant arm's performance. Philip and Frey (2014) have examined the performance of the non-dominant arm during a tracing task. The individuals in the study, who had lived with partial or full amputation of the dominant arm for decades, showed improvements in speed and smoothness, but they did not show improvements in task completion for a visuomotor tracing task. This work examined the changes resulting from daily use, but did not examine changes in non-dominant arm functional performance in response to a focused training regime. Neither did it examine performance on a range of functionally related tasks. Our results support those reported by Philip and Frey (2014), as they corroborate the idea that non-dominate arm practice can improve non-dominate arm function, in addition to expanding on their results, by indicating that targeted practice can improve non-dominate arm function across a range of unilateral tasks and tests. The JTHFT and finger-tapping test emphasize speed as well as motor skills, however the motor skills required are predominantly gross - movements such as the entire arm being used to place a can or scoop a bean with a spoon. Dissimilarly, the Grooved Pegboard task requires the most fine motor skills of our four functional tasks by requiring participants to repeatedly rotate small objects with their fingers, and may prove to test the boundaries of fine motor skill enhancement. Additionally, the Grooved Pegboard task has the greatest visuomotor load of the four functional tasks, in that participants must be very specific in where they place the small pins throughout the duration of the task. This may add an additional difficulty for participants that is not present in the other functional tasks. Unlike the JTHFT, there are no other tasks in the Grooved Pegboard test that require more gross motor motions and less visuomotor skills, and during which participants can make up time. It is crucial to point out the difference between non-dominant arm training on a range of upper limb activities, as done here, and spontaneous practice such as might occur with partial or full amputation of the dominant arm (Philip and Frey, 2014). However, one other difference between these studies is the participant ages. In their study, the participants are older adults (mean 62 ± 7 years), whereas the participants in this study are young adults (21.1 ± 0.433). It is plausible that the differences in our findings may have less to do with the specific practice, and more to do with age-dependent differences in plasticity of the motor lateralization system.

Despite the statistically significant improvements in left arm performance on the majority of measures, the mechanisms underlying these changes remain speculative. There are two avenues for explaining such improvements. First, as discussed in the introduction, we expected general improvements in speed and coordination as a result of our motor training regimen. However, a second possible explanation might be cognitive and/or attentional. First, increased attention to the non-dominant arm or simply remembering to use it more often might result in selecting the non-dominant arm more during the post-test reaching-task. Concerns regarding these intentional changes in non-dominant arm selection are perhaps somewhat attenuated by the fact that the non-dominant arm was still not chosen more than the dominant in the post-test arm selection test, nor did non-dominant arm selection increase on the right half of the participants' space. Additionally, if intentional changes were made in the post test to exaggerate the improvements of the non-dominant arm, we might expect the dominant arm performance to be worse in the pre-test than in the post-test; this was not the case, and participants' dominant arms performed as well in the post-test as in the pre-test. This provides some evidence that participants were not attempting to out-perform their dominant arms with their non-dominant arms. Third, participants' confidence in their non-dominant arm's efficacy might have improved. All of these possible cognitive factors would benefit from exploration in future work with a larger sample and proper control group.

On average, the ten participants had slightly lower grip strength than the reported norms for this age group (Petersen et al., 1989). This may be due to the fact that all of our participants were college students, and therefore not representative of the larger college-aged population. Fain and Weatherford (2016) argue, in their recent study of grip and pinch strength, that the majority of functional norms used are outdated and do not apply to the current generation of college students. They suggest that this generation does not engage in as much physical labor as their counterparts from previous generations. Fain and Weatherford (2016) also reported data that combined grip strength findings from dominant and non-dominant hands, and reported a grip strength average of 36.55 kg for the right hand (whether dominant or non-dominant), and 35.45 kg for the left hand (whether dominant or non-dominant) for the 20-24 year old age group.

The transfer of learning between arms, often referred to as interlimb or bimanual transfer, is an important issue to consider in a unilateral arm training study. Many studies have demonstrated that it is possible for one arm to train on a novel task and the opposite arm to demonstrate improvements, or learning, despite not being trained; this result is apparent in a range of tasks, some of which, such as tapping and reaching, were used during the testing portion of this study (e.g. Teixeira, 2000; Sainburg and Wang, 2002). Contrary to this body of research, there were no transfer effects demonstrated on our tasks, as the right hand did not improve significantly. However, the conditions of this study were not the same as those in most transfer literature studies because the participants were not tested with both hands on the tasks they were trained on. Due to this difference, it is not expected that the right arm would show improvements; perhaps if participants had performed the trained tasks with their right arms at the end of left-arm training, improvements would have been evident. Furthermore, as summarized by Sainburg and Wang (2002), there are some contradictory findings regarding whether the non-dominant arm successfully transfers to the dominant, and this relationship is yet unclear (Parlow and Kinsbourne, 1989).

This study was viewed as a pilot study, and the sample was therefore limited in number of participants. This resulted in a small sample in which all participants completed the left arm training, resulting in no true control group. Instead, the right, untrained arm was used as a control. It was expected that if there were significant changes in the left arm's performance, but not in the right arm's, the training was both effective and specific to the trained arm. Furthermore, it was expected that any test-retest improvements would be visible in the performance of both arms. As there were no significant improvements in the right arm performance, it is presumed that the training's benefits are specific to the trained arm, and that there were no test-retest effects.

Additional limitations result from the sample used in this study. Participants were recruited from an undergraduate college population, and therefore may not be representative of the general healthy population. For instance, it is possible that individuals with more labor-intensive occupations may have already increased the functionality of their non-dominant arm through more regular use. If so, it may be less feasible to improve non-dominant arm function through our training paradigm. Furthermore, because this study was seen as a pilot exploration investigating whether any improvements were possible, participants were encouraged to use their left arm even outside the lab, in order to maximize their experiences with their left arm. However, this means that exactly how much practice they had with their left arm is not quantified and not held consistent across participants. Now that some improvements have been demonstrated as possible, future work would benefit from addressing this currently unaccounted for training time and quantifying what number of training hours yields the optimal results. This pilot study shows promising results for our small convenience sample and can serve as proof of concept for a larger, more representative assessment that would address such limitations.

It is not possible to speculate from this research alone whether any similar training effects would be seen in either of the clinical populations addressed in this paper. However, Maenza, Good, Winstein, & Sainburg (2015) conducted a study using a very similar training paradigm with a sample of four stroke patients with moderate to severe paresis. They report improvements on “measures of unilateral function, activities of daily living, and functional independence” as well as improvements on the JTHFT (Maenza et al., 2015). Their work indicates that there may be clinical application of this training paradigm for a stroke population, and furthermore that there may be not only statistical improvement for these populations, but functional improvements as well.

With these results in mind, the next steps for this research would be a larger-scale study incorporating a stroke population, a healthy population with a larger age range, and a proper control group in which participants come in for the pre- and post-tests along the same schedule, without any training intervention in between. Other appropriate follow-up studies would address the aforementioned topics of efficacy, attention, and effort, and try to parse out what effects these have on non-dominant arm use and performance. For example, one group might undergo the same test and training schedule, but forego the regular training for a very simple stimulus-response task in which they are rewarded for using their left arm. This would be done in order to encourage them to think of using their left arm, and the post-test would indicate if their left arm is chosen more after this focused attention. Given the three caveats (small sample, lack of control group, unaccounted for time in training paradigm) discussed previously, the results of this study should not be naively extrapolated to a larger population. However, this pilot, in conjunction with the previously discussed work from Maenza et al. (2015), demonstrate that a larger study holds promise for functional and selection gains with the non-dominant arm.

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