2010

INJURY-INDUCED HAND DOMINANCE TRANSFER

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ABSTRACT OF DISSERTATION

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The Graduate School
University of Kentucky
2010

INJURY-INDUCED HAND DOMINANCE TRANSFER

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A dissertation submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Rehabilitation Sciences
in the College of Health Sciences
at the University of Kentucky

By

Kathleen E. Yancosek

Lexington, Kentucky

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ABSTRACT OF DISSERTATION

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Hand dominance is the preferential use of one hand over the other for motor tasks. 90% of people are right-hand dominant, and the majority of injuries (acute and cumulative trauma) occur to the dominant limb, creating a *double-impact* injury whereby a person is left in a functional state of single-handedness and must rely on the less-dexterous, non-dominant hand. When loss of dominant hand function is permanent, a forced shift of dominance is termed injury-induced hand dominance transfer (I-IHDT).

Military service members injured in combat operation may face I-IHDT following mutilating injuries (crush, avulsion, burn and blast wounds) that result in dominant limb amputation or limb salvage. Military occupational therapy practitioners utilize an intervention called *Handwriting For Heroes* to facilitate hand dominance transfer. This intervention trains the injured military member how to write again using the previously non-dominant hand. Efficacy and clinical effectiveness studies were needed to validate the use of this intervention.

This dissertation contains three studies related to I-IHDT. One study measured handwriting performance in adults who previously (greater than 2 years ago) lost function of their dominant hands. Results verified that handwriting performance, when measured on two separate occasions (six-weeks apart) was similar (stable). A second study examined the efficacy of *Handwriting For Heroes* in non-impaired participants. Results demonstrated a positive effect on the variables that measured the written product: legibility, writing speed (letters-per-minute); as well as a positive effect on the variables that measured the writing process: kinematic and kinetic parameters. The final study examined the clinical effectiveness of *Handwriting For Heroes* in an injured military population. Results did not show as positive results as the efficacy study, despite similar compliance with the intervention. Specifically, non-impaired participants started with faster writing speeds in their non-dominant hands (higher letters-per-minute) and made more gains (wider ranges). The non-impaired participants also started with faster dexterity (betters scores on the Grooved Pegboard) but they made fewer gains than the injured service members (smaller ranges). Nevertheless, injured participants clearly made gains in all dependent variables thereby demonstrating clinical effectiveness of the intervention.

KEYWORDS: Hand Dominance, Handwriting, Limb-Salvage, Dexterity, Amputation

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DEDICATION

This dissertation is dedicated to military service members who were wounded while executing their duties in fulfillment of the mission entrusted to them.

ACKNOWLEDGEMENTS

I extend my gratitude to the following members of my committee:

Dr. Dana Howell, my advisor and committee chair: thank you for your diligence in setting an exceptionally high standard and your patience with me as I struggled to reach that standard! I have grown so much under your wing!

Dr. Anne Harrison, my committee co-chair: thank you for your wisdom and encouragement. I enjoy your student-centered teaching style!

Dr. Colleen Schneck who was my advisor in 2001 at Eastern Kentucky University where I completed my Master's degree, thank you for your authentic (and on-going) concern for my educational and professional development. You have a contagious passion for occupational therapy education, and I hope to work for you one day!

Dr. Teresa Brininger, my Army mentor: thank you for your soldier-centered perspective on research. Thanks for encouraging me to make a difference in military occupational therapy! I am following in your boot tracks, Ma'am!

Dr. Patrick Kitzman, my Neuroplasticity professor: thank you for teaching me about the marvelous complexity of the human nervous system. Thank you for teaching me that a scholar is always in pursuit of the next question!

Dr. William Calderhead, my single-subject research design expert: thank you for the countless hours you spent teaching me the intricacies of research and manuscript writing. I appreciate your availability and guidance!

I also extend my gratitude to these people:

I would like to thank my husband, Barry, and our amazing sons, Joshua and William, who supported me with unconditional love!

Thank you to my friends and neighbors, Lindsay, Becky, and Kathryn, who helped me in practical ways to juggle personal and professional responsibilities.

I am grateful to Kristi Say, OTR/L and Michelle Hunter, OTD, OTR/L for collecting data at Walter Reed Army Medical Center. I appreciate the support of the entire staff at Walter Reed. They were willing to help me in many ways.

Lastly, I acknowledge that the equipment and supplies used in the experiments of this dissertation were funded through a seed grant through the University of Kentucky's Center for Clinical and Translation Science. I am extremely thankful for that support.

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Injury-Induced Hand Dominance Transfer

Extremity injuries occur in 60-75% of reported injuries in military personnel (Ficke & Pollack, 2007). When extremity injuries are severe, military surgeons must decide to amputate or salvage the limb. Limb salvage is a general term defining the surgical, often multiple and staged, procedures done to spare a limb at risk of amputation. Conditions encountered in the military that necessitate salvage versus amputation decisions include multi-tissue injuries caused from low and high-energy trauma such as blast explosions, rifle projectiles, and motor vehicle accidents (Kumar, Grewal, Chung, & Bradley, 2009).

Advances in military aerovacuation out of the theatre of operation; early, forward medical capabilities; and microvascular and plastic reconstructive surgery at military medical centers all contribute to an increase in the saving of injured extremities. However, despite advances in limb salvage, there remains a high associated morbidity, both immediate and long-term (McCready, 1988). This morbidity is a central concern for military occupational therapy practitioners who provide ongoing and extensive rehabilitation for service members with limb salvage.

A service member with a salvaged limb is a complex patient. This complexity is confounded by the limited number of evidence-based practice strategies upon which to build clinical practice guidelines for this patient population. A salvaged limb generally involves all components of neuromuscular-skeletal systems. This translates into multiple surgeries, increased risk of infection, prolonged use of pain medication, various healing rates of involved bone and soft-tissue structures, extended periods of immobilization, frequent medical and rehabilitation visits, and numerous off-duty work days, or medical discharge from the military. Not surprising is that oftentimes, despite valiant efforts to save a limb, early-delayed amputation is recommended if a limb is painful, stiff, and non-functional six months after salvage (Burdette et al., 2009).

An adult who undergoes upper limb salvage is similar to an adult who sustains upper limb amputation in that both groups (1) most likely sustained trauma and subsequently have concomitant injuries, (2) are left in a functional state of single

handedness, (3) are at risk of repetitive stress/overuse disorders of the single functioning limb (4) require extensive medical and rehabilitation services, and (5) are at risk for lasting disability that affects participation in employment, educational, and leisure pursuits.

The issue of upper limb dominance as it relates to salvaged or amputated limbs is of unique concern to occupational therapy practitioners. This concern exists largely because of established understanding that the dominant limb has more strength, endurance, speed, and dexterity, and when lost translates into increased disability. Lost dominant hand function requires a transfer of dominance skills for participation in fine motor, dexterity activities that cannot be replaced by a prosthesis following amputation nor are generally recovered after extensive, multi-tissue injury (Smurr, Gulick, Yancosek, & Ganz, 2008). Because handwriting is the activity most often associated with hand dominance (Doyen & Carlier, 2002), it is a focus area of a hand dominance transfer program. Handwriting is viewed as a necessary skill for an injured service member who leaves the military and enrolls in college or seeks civilian employment that requires handwriting skills (Smurr et al., 2008).

Handwriting For Heroes is a rehabilitation workbook specifically designed for all military service members who face injury-induced hand dominance transfer (I-IHDT) following mutilating hand injuries to a dominant upper extremity, and subsequently undergo limb salvage or amputation.

Statement of the Problem

Military service members injured while conducting operations in Iraq and Afghanistan, who sustain blast injuries that result in amputation or upper limb salvage of a dominant limb, potentially face the need for I-IHDT. Currently, there is limited research from which to build a clinical practice guideline for facilitating a hand dominance transfer in adults.

overview of the problem.

When a military service member permanently loses function of his dominant hand, s/he faces a double-impact injury: (1) he is left in a functional state of single-handedness and (2) he is at a neuromotor disadvantage because of losing the stronger,

faster, more dexterous limb. This double-impact injury affects his ability to perform activities of daily living, return to military duty, seek employment in the civilian sector, enroll and meet the demands of attending college, and engage in previously enjoyed sports and leisure activities. Service members with upper limb amputation or mutilating hand injuries, including burns, crush injuries, and multi-tissue injury that result in limb salvage, largely make up this unique slice of an injured military cohort.

Occupational therapy practitioners are challenged with clinical decisions related to the distribution of time and effort between the following treatment approaches: (1) direct rehabilitation to the injured side or teaching the replacement of function with a prosthesis, (2) augment the functional loss with adaptive equipment/teach one-handed performance of motor skills, (3) train the remaining (previously non-dominant) limb to assume dominant hand functions (speed, dexterity, strength, endurance), or (4) a hybrid of any of these approaches.

Permanent Loss of Dominant Hand Function

Understanding the constructs of dexterity and hand dominance is foundational to appreciating hand dominance transfer following a permanent loss of dominant hand function. In the context of rehabilitation sciences, dexterity and hand dominance are connected through the occupation of handwriting. Hand dominance is most often defined by the functional dexterity task of handwriting (Granville, Ehrman, & Perelle, 1980).

Monitoring dexterity changes in the previously non-dominant hand, through handwriting performance improvements, becomes a strategy for tracking motor control changes that represent the necessary learning process of hand dominance transfer. This is possible through digital technologies that afford advanced methods of handwriting analysis. Overall, changes in handwriting performance become traceable artifacts of motor learning. These changes in performance capture the plasticity of an adult neuromotor system, which contributes to rehabilitation scientists' understanding of behavioral changes following illness and injury.

Comprehension of hand dominance transfer may be expanded by systematically studying the efficacy and clinical effectiveness of *Handwriting For Heroes (Yancosek & Gulick, 2008)*, a therapy intervention designed to facilitate hand dominance transfer.

Efficacy relates to whether an intervention works under ideal conditions; whereas effectiveness relates to whether the intervention works under routine clinical conditions (Pittler & White, 1999). Patients with multiple clinical issues often receive many interventions simultaneously and these co-interventions may overlap and influence the one intervention being scientifically evaluated (Pittler & White, 1999), so it is often easier to conduct efficacy research prior to intervention studies.

Moreover, many medical and behavioral health scientists suggest establishing efficacy prior to effectiveness trials because of limited resources, constraints on busy rehabilitation professionals, and if an intervention does not work under ideal conditions it likely will not work under "real-world" conditions (Pittler & White, 1999). The importance of efficacy and effectiveness research is fundamental to rehabilitation because the most necessary question asked is "Does this intervention work?"

The efficacy of *Handwriting For Heroes* was evaluated with five healthy adults. The clinical effectiveness of the intervention was then evaluated with injured military personnel. To strengthen comprehension of hand dominance transfer, a theory and clinical practice model were evaluated as critical underpinnings. Dynamical Systems Theory (DST) and the Task-Oriented Approach (TOA) was examined in detail in relation to this line of inquiry. Additionally, in Chapter 5, DST and TOA were used to elucidate the results and discussion of the three contributing studies of this dissertation.

Definition of Terms

Dexterity

Workbook dexterity is defined as "fine, voluntary movements used to manipulate small objects during a specific task" (Backman, Cork, Gibson, & Parsons, 1992). Dexterity develops as hand strength and sensation mature and work together in a complementary relationship to facilitate hand function. Hand function, in turn, allows interaction with objects in the environment, and when combined with executive cognitive skills, creates a platform for independence in activities of daily living (ADL). Of all physiological capabilities (force, speed, endurance, and dexterity), dexterity has the strongest influence on versatile human functions needed for self-care, vocational, and avocational pursuits (Latash & Latash, 1994). Loss of dexterity, whether the result of

insult to the central or peripheral nervous systems, impairs a person's performance of basic and advanced ADL.

When dexterity is compromised in both upper limbs, a person is left in a functional state of dependence. When dexterity is compromised in one upper limb, a person is left in a functional state of single-handedness. Unilateral dexterity loss may be temporary, such as when recovering from tendon laceration/repair, fracture/fixation, or neuropraxia/splinting.

Conversely, dexterity loss may be permanent, such as is common in partial or complete amputation of the upper limb; brachial plexus avulsion; chronic, unilateral lymphodema; hemiparesis following stroke; focal hand dystonia; and limb salvage following mutilating hand injury (crush, avulsion, burns); or the result of "neglect-like-syndrome" following minor trauma or surgery of the upper extremity, such as complex regional pain syndrome (CRPS) (Frettloh, Hoppe, & Maier, 2006).

There are innate differences in dexterity influenced by hand dominance (Bryden & Roy, 2005; Klein, 2007). Although most activities are accomplished bimanually, the dominant hand acts as the more dexterous, main executor while the non-dominant hand acts as supporter (Eggers & Mennen, 1997). In the context of rehabilitation, permanent loss of dexterity in the dominant hand is more devastating because dexterity skill previously endowed to the dominant hand must be transferred to the non-dominant hand (Walsh, Belding, Taylor, & Nunley, 1993).

This forced shift of hand dominance is termed injury-induced hand dominance transfer (I-IHDT). It conceptually defines the necessary transfer of lateralized skill proficiency to the non-dominant hand imposed on a person by insult to the central or peripheral nervous systems or musculoskeletal systems. Persons with unilateral dexterity loss of the dominant limb have two challenges: first, they are forced to complete two-handed tasks with one hand. Second, the remaining limb, which primarily functioned as the supporting limb, must assume dexterity responsibilities of the dominant limb. Hand dominance is therefore a critical factor related to rehabilitation addressing dexterity of persons with upper limb injuries.

Hand Dominance

Hand dominance may be established in the prenatal period, (Dehaene-Lambertz, Dehaene, & Hertz-Pannier, 2002; Holowka & Petitto, 2002) and is a documented factor implicated in prevalence, incidence, and morbidity of upper extremity injury. Cumulative trauma disorders are more prevalent in dominant extremities (Shiri, Varonen, Helivaara, & Viikari-Juntura, 2007). Also, several studies report higher incidence of trauma to the dominant hand (Clark, Scott, & Anderson, 1985; Hazani, Buntic, & Brooks, 2009; Hill, Riaz, Mozzam, & Brennen, 1998; Master, Piorkowski, Zani, & Babigian, 2008). In the traditional anatomical models of disability ratings, medical impairments are rated higher if the dominant upper extremity is involved (American Medical Association, 1993; Kessler, 1970). Self-reported disability following distal radius fracture is significantly higher when a dominant hand is involved (Beaule et al., 2000). A study investigating performance of basic activities of daily living found a significant positive correlation between injury of a dominant hand and disability (Rajan, Premkumar, Rajkumar, & Richard, 2005).

A discussion on dexterity and hand dominance generally involves the topic of handwriting because hand dominance is often *solely* defined by the hand used for writing (Granville et al., 1980). Also, despite handwriting being a basic skill learned early in life, it is purported to be the highest form of unilateral hand dexterity skill attained by the general population. Two compelling characteristics of handwriting capture the essence of both dexterity and hand dominance. First, dexterity generally implies an interaction with a tool or object needed to accomplish a goal, and handwriting captures the hand's interface with a commonly encountered tool and accomplishes a goal. And, secondly, handwriting captures the hand's unique link to the brain for planning and executing purposeful movements (Bonney, 1992; Chu, 1997), and in so doing, handwriting provides a link between the peripheral manifestation of dexterity and the origin of dominance in the brain.

Handwriting

In the 17th Century, Italian physician, Camillo Baldi, described handwriting as a type of expressive movement (Baldi, 1622). Four centuries later, researchers still

describe handwriting as a record of movement, motor control, and psychosocial status (Burr, 2002). Scientists continue to analyze handwriting to explore personality (Lewison & Zubin, 1942), movement, and motor control.

Handwriting is a complex form of language expression that is mastered early and used throughout life (Feder & Majnemer, 2007; Graham & Harris, 2005). The full range and extent of handwriting activities of Americans have never been investigated, so findings from studies in other countries are cautiously extrapolated. In a cross-sectional survey of 523 healthy adults (ages 18-54) living in Australia, 1.3% reported handwriting to be "not important at all"; 21% reported handwriting to be "extremely important"; and 38% reported a preference for handwriting over other technologies (McMahon, McCluskey, & Lannin, 2008). College students, white-collar workers, and those over 25 years of age were most likely to engage in handwriting activities. The top three most frequent handwriting activities were signing documents, writing notes/reminders, and writing "to-do" lists.

As part of a Canadian study (Dixon, Kurzman, & Friesen, 1993), participants were asked about handwriting activities. Results showed that younger people write more than older people, and women write more than men. There was also an interaction effect between gender and age, meaning that younger females write more. Respondents of young and old age reportedly spent 69% of "writing time" in handwriting activities compared with typing; however, it should be noted that this study was done in 1993 before the widespread use of computers and proliferation of hand-held personal digital assistants (PDA). Historians, however, suggest that new technology related to written expression does not entirely eliminate its predecessor, but rather imposes a new type of work-demand (Martin, 1994).

Handwriting is considered a graphomotor skill that is multidimensional and highly dependent upon sensory, motor, and cognitive processes. Handwriting is a form of expressive language universal to established cultures. Handwriting is considered a necessary skill for participation in many facets of life, such as school and work. As a skill learned early in life, handwriting is often overlooked as important until illness or injury limits ability to engage in tasks that require handwriting. The link between

handwriting and hand dominance, begins with a review of literature related to cerebral lateralization.

Cerebral Lateralization

If handwriting, as the manifestation of expressive language, is the defining neuromotor skill of human lateralization (Doyen & Carlier, 2002; Granville et al., 1980; Roszkowski, Snelbecker, & Sacks, 1981), and hand dominance is the peripheral, or functional, manifestation of cerebral lateralization, then the link between hand dominance and handwriting might be language. Despite the fact that it is a well-accepted finding in cognitive neuroscience that language is lateralized to the left-hemisphere (Josse & Tzourio-Mazoyer, 2004; Wada, Clarke, & Hamm, 1975), the probable link between right-handedness and language lateralization has not yet been fully elucidated (Auer et al., 2009).

Some scientists consider left-handedness an atypical motor lateralization (McManus, Bryden, & Johnson, 1993), noting that less than 10% of the world population is left-handed (McManus, 2002). "Atypical" (right or bilateral) language lateralization is uncommon, except in cases with a positive history of neurological disorder (Miller, Dodrill, Born, & Ojemann, 2003; Satz, Orsini, Saslow, & Henry, 1985). Theories of "pathological left handedness"(Coren & Halpern, 1991; Satz et al., 1985) purport that a subset of left-handers would have been right-handers but sustained early brain lesions to the frontotemporal and frontopareital cortex thereby forcing a shift in lateralization for language and related skilled-motor functions. Further support for the connection between "atypical" language lateralization and left-handedness is the elevated prevalence of left-handedness in neuromotor disorders, such as developmental disorders(Goez & Zelnick, 2008), learning disorders (Ferrari, 2007), mental retardation (Pipe & Coren, 1990), epilepsy (Sveller et al., 2006), autism (Escalante-Mead, Minshew, & Sweeney, 2003), schizophrenia and psychopathologies (Mayer & Kosson, 2000).

A literature review of lateralization of hand dominance reveals divergent theories (Chieh, Wenbin, & Nuttall, 2003). One theory purports that hand dominance is caused by a single gene called the "right-shift factor" which produces a right-sided preference (Annett, 1985). Another theory suggests a strong influence of in-uterine exposure to

testosterone thereby explaining the high prevalence of left-handedness in males (Coren, 1994). Handedness is commonly thought to not be fully discernable until a child is older than three years old; however one study correlates hand preference during prenatal thumb sucking with post-natal handedness (Hepper, Wells, & Lynch, 2005).

A recent study (Auer et al., 2009) evaluated language lateralization via functional magnetic resonance imaging (fMRI) in 15 participants with obstetrical brachial plexus injuries who subsequently had full (typical) use of only one upper extremity. Results showed a leftward shift of hand dominance and a rightward shift, albeit incomplete, of language lateralization in subjects who, through other assessments, were deemed to be "natural" right-handers. These findings support the link between language and hand use and mirror those mentioned above related to pathological left-handedness but without implications of central nervous system (CNS) involvement; rather, findings suggest that PNS injury, and resulting prolonged use of one hand, can also impose shifts in language and skilled-motor laterality.

Another fMRI study (Kloppel, Vongerichten, Van Eimeren, Frackowiak, & Siebner, 2007) investigated handedness in "converted left-handers" (adults who, as children, were forced to make a rightward shift of hand dominance for handwriting). Results showed two separate areas in the sensorimotor cortex that correlated with handedness. One area reflected long-term hand use, the other area did not. The researchers conclude that an innate left-handedness exists and is paradoxically strengthened by long-term use of the contralateral hand. Another study using positron emission tomography (PET) scanning to assess regional cerebral blood flow supported findings of cerebral resistance to a handedness shift in "converted lefthanders", despite years of right-hand writing (Siebner et al., 2002). These studies suggest that "conversion" (transfer) of handedness is possible, but that the central nervous system maintains an immutable feature of lateralization. A limitation in the literature is that no studies investigate the more probable leftward conversion following PNS injuries in adults. Replicating these neuroimaging studies to investigate leftward conversion may provide valuable information to compare the rightward versus the more probably leftward conversion following I-IHDT.

Evaluation

Evaluation of Dexterity

Due to structural and functional complexity of the human hand, dexterity has been an elusive construct for scientists to define (Bicchi, 2000). The complexity is magnified by the embedded cognitive (problem solving, planning, and attending) and sensory (vision, tactile, and proprioception) components of dexterity. In rehabilitation fields, dexterity is most frequently measured by the time it takes a person to move small objects, generally pegs of various sizes, from one space to another. A recent review provides an overview of fourteen commercially available dexterity assessments (Yancosek & Howell, 2009).

Pegboard dexterity assessments inadvertently offer information about a person's hand range of motion, sensation, and strength of intrinsic muscles needed for precision grip and coordinated, controlled movements. However, time-based dexterity assessments provide a limited description of dexterity. They provide minimal information on the quality, function, and sustainability (endurance) of hand movement. Furthermore, the only notable dexterity difference based on hand dominance is to discover that the dominant hand generally performs faster. This limits understanding of dexterity and hand dominance in terms of both evaluation and treatment planning used in rehabilitation.

A recent systematic review on evaluation tools used in hand therapy (Schoneveld, Wittink, & Takken, 2009) concluded that there is a need for more performance assessments that measure activity and participation. This is a reflection of a trend to move away from impairment-focused models in rehabilitative practice. This move is being driven by influential organizations such as the World Health Organization (WHO) and funding sources such as the National Institutes on Health (NIH) which seek research and clinical practice to translate into improved health and quality of life of citizens (National Advisory Mental Health Council, 2000; Tunis, Stryer, & Clancy, 2008). In practical terms, the current climate in health care emphasizes functional tasks as they relate to facilitating participation in life.

The trend of moving measurement tools toward assessing function and participation may be addressed through technology. Technology needs to be leveraged to provide advanced methods of measuring hand dexterity. The process of leveraging technology may be accelerated through research that focuses on measuring performance at the activity and participation levels, which in turn may generate product development. Specifically, technology may facilitate changes in dexterity assessments and relegate pegboard assessments that were developed in the early twentieth century to the museum shelves.

Occupational and physical therapists who are credentialed and work as Certified Hand Therapists (CHT) address "participation in life situations for individuals with upper quarter disease and injury" (Muenzen et al., 2002). With that over-arching clinical mindset, CHTs must diligently pursue methods to measure functional dexterity that relates to the construct of participation. One way to measure dexterity that is more functional than pegboard assessments and answers the call for more participation-based measurement tools is to measure handwriting using available digital technologies. These technologies are sensitive enough to detect performance changes and therefore have practical application in evaluating efficacy and effectiveness of treatment interventions used in the transfer of dexterity skills throughout rehabilitation of adults facing I-IHDT.

Evaluation of Handwriting

If handwriting is to be the portal to understand the rich construct of dexterity, it is necessary to examine the current methods used to evaluate handwriting performance of adults. Currently, handwriting is included in many self-report questionnaires on hand function. For example, handwriting is a specific item listed on the Disabilities of the Arm Shoulder, and Hand questionnaire (DASH) (MacDermid & Tottenham, 2004) and relates to the category of activities and participation in the International Classification of Functioning, Disability, and Health (ICF) (Drummond, Sampaio, Mancini, Kirkwood, & Stamm, 2007). Signing one's name is included in the physical domain portion of the Burn Specific Health Scale (Blades, Mellis, & Munster, 1982). Writing is one of seven functional tasks on the Jebsen-Taylor Test of Hand Function (Jebsen, Taylor, Trieschmann, Trotter, & Howard, 1969). Also, the Upper Limb Function Index includes

an item asking “I have difficulty writing or using a keyboard and/or mouse” (Stratford, Binkley, & Stratford, 2001).

Beyond self-rated scales, there is a need to better quantify hand function and provide more global assessments of dexterity needed for skillful, fine motor movements, such as handwriting (Adersen Hammond, Shay, & Szturm, 2009). The Handwriting Assessment Battery (HAB) was developed in response to this need; as such, it is the only handwriting assessment available for adults. It evaluates pen control and manipulation, writing speed, and writing legibility (Faddy, McCluskey, & Lannin, 2008) through a combination of eight subtests taken from three different assessments: Motor Assessment Scale (MAS) (Carr, Shepherd, Nordholm, & Lynne, 1985), Jebsen-Taylor Test of Hand Function (Jebsen et al., 1969), and the Evaluation Tool of Children’s Handwriting (ETCH) (Amundson, 1995). Thus far, the HAB has only been pilot tested on ten adults with brain injury; therefore, further validation and population studies are warranted.

The use of digital technology is highly reliable thus providing more precision in measurement (Mullineaux, 1999). In contrast, the traditional “paper-and-pencil” assessments used with children have ceiling effects that limit usefulness in adult populations. The research field of handwriting analysis (graphonomics) has led to advancements that quantify handwriting performance via digital collection and analysis of kinematic data from written output. For example, handwriting analysis through computer interfacing has been successfully used to capture disturbed motor control in patients with chronic undiagnosed wrist pain (Smeulders, Kreulen, & Bos, 2001). In a study using Dutch elementary school students with developmental coordination disorder, a digitizer was used to collect kinematic data to explore dynamic movement strategies used in handwriting processes (Smits-Engelsman & van Galen, 1997). Similarly, digital handwriting analysis captured by tablet computers and custom software packages has been used with children to sensitively discriminate developmental coordination disorders (Rosenblum, Goldstand, & Parush, 2006). Another study by Rosenblum and Werner (2006) examined kinematic characteristics of the handwriting process of 53 healthy persons from 60-94 years old by using a digitizing tablet and data collection and analysis software to collect and sort data into spatial, temporal, and pressure (on pen) components.

Establishing validity of assessment tools is necessary to ensure that the construct under evaluation is accurately and truly captured. Using a highly accurate apparatus decreases error distribution within the measurement tool and increases practitioners' confidence in detecting true performance variance. Chapter 2 describes the study done to establish reliability and validity of the handwriting evaluation apparatus used in the efficacy and effectiveness trials described in Chapters 3 and 4. A more descriptive explanation of the field of graphonomics helps elucidate the breadth and depth of the topic of handwriting, and helps set the stage for components of writing that should be evaluated during assessment and addressed through intervention.

Graphonomics

Graphonomics is a field of scientific study that is interested in generating knowledge of the process and product of handwritten output (Van Gemmert & Teulings, 2006). Graphomotor skills are handwriting, in the form of copying, transposing, or composing, as well as the skills of drawing, coloring, and tracing. Each one has unique neuromotor demands, for example composing is more demanding than copying because of the cognitive requirements of planning and expressing ideas in written form (Connelly, Gee, & Walsh, 2007). Besides different types of graphomotor skills, there are also various styles of handwriting, such as cursive, manuscript (print), and a hybrid (mixed). Two studies (Sovik, Arntzen, & Karlsdottir, 1993; Suen, 1983) showed cursive script to be faster than manuscript and a later study(Graham, Weintraub, & Berninger, 1998) that included a hybrid style as a category found the hybrid to be faster.

Graphomotor performance is dependent upon sensory perception, motor, and cognitive processes (Christensen, 2005). The interdependence of perception, cognition, and action systems capture the complexity of goal-directed movements (Creem-Regehr, 2009). Sensory-perceptual components include tactile sensation, proprioceptive-kinesthetic finger awareness (Schneck, 1991), and visual perception (Tomcheck & Schneck, 2006) (spatial discernment, left-right orientation, form recognition, and visual closure). Motor components include postural control, in-hand manipulation (Tomcheck & Schneck, 2006), ulnar-sided hand stabilization with radial-sided hand mobility reliant upon intrinsic muscle strength and coordination.

Cognitive components include attention, praxis (movement planning), memory, orthographic coding (using a code to represent a word in part or whole), (Berninger et al., 1992) and linguistic coding (translating auditory input to a cognitive representation of an object or idea). Both types of cognitive coding needed for written expression involve first knowing the language orally (Gentner, 1982). These cognitive skills become increasingly relevant during composition and transcription tasks.

Visual motor integration has received a lot of attention in the literature related to early handwriting skill acquisition (Weintraub & Graham, 2000). Visual motor integration may have a less important role for a skilled writer who has achieved automaticity, meaning that he or she is writing faster than the time required for visual feedback to influence writing performance (van Galen, 1991). Studies do however, consistently demonstrate that visual motor integration is necessary for the quality of handwriting early-on in the development of writing skills (Cornhill & Case-Smith, 1996).

Typically, three dimensions are used to measure handwriting performance: (1) legibility, (2) speed, and (3) ergonomic factors. A fourth dimension of fluency (or automaticity) has recently been suggested as critical to functional handwriting (Tucha, Tucha, & Lange, 2008). Legibility is sometimes referred to as readability and is influenced by consistency in legibility components of size, spacing (alignment), shape, and slant of letters. Size, specifically vertical stroke size, was found to be the most invariant property of handwriting (Teulings & Schomaker, 1993).

Writing speed is necessary to accomplish functional writing tasks (Amundson, 1995), and is inversely proportional to task complexity (Graham, Berninger, Weintraub, & Schafer, 1998). Peverly (2006) investigated the quantity and quality of essay writing and note-taking for adult learners and concluded that speed is important to reduce the cognitive load so that the mind can efficiently process information without thinking of basic letter formation. Fluency is the combined speed and smoothness (consistency) of writing that is believed to emerge from skill automaticity. Handwriting that is measured as a *product* may focus more on components of legibility; whereas fluency is a component linked to the writing *process*. Handwriting automaticity is coherent with the perspective that writing is a metacogntive act (Flower & Hayes, 1980). This view places

the emphasis of writing on the cognitive skills of planning (goal setting, generating and organizing ideas), translating ideas into text, and revising and editing text. Handwriting automaticity is important so learners are free for metacognitive tasks such as planning, problem solving, thinking, and memorizing. Writers must be cognitively free to engage in such tasks without thinking about motor planning and control of the writing instrument, spelling, vocabulary, or word selection.

Ergonomic factors include a proper and “mature” prehension of the writing instrument and body and paper positioning (Parush, Levanon-Erez, & Weintraub, 1998). Another ergonomic factor is the correct (efficient) amount of pressure to leave pencil or pen markings on the writing surface, without an over-pressure that fatigues the hand. Pressure has been shown as the least stable parameter of writing (Teulings & Schomaker, 1993).

Being able to define the parameters of handwriting enables more accurate evaluation of handwriting performance. Accurate evaluation, in turn, contributes to better development of appropriate intervention methods. In the context of this dissertation, evaluation and intervention are specifically related to dexterity (as captured by handwriting performance) and are directed at a population of adults who face I-IHDT.

Hand Dominance Transfer Intervention

Although a variety of trauma may lead to permanent loss of dominant hand function, a limited body of literature exists related to rehabilitative management of patients facing I-IHDT, leaving therapists with clinical questions of how and when to best facilitate hand dominance transfer. This gap in the literature likely reflects a research and clinical focus of resources on restoring function and improving outcomes for the impaired side, whereby hand dominance transfer is left to occur naturally (passively) over time. Chan and LaStayo (2003), in their description of management of mutilating hand injuries, recommend early instruction in activities of daily living, specifically if a dominant hand is injured; however, no methods are described.

One relevant study investigated effects of upper extremity trauma on hand dominance. Researchers used patient surveys and chart reviews at two regional hand

centers (Walsh et al., 1993), and discovered that sustained precision dexterity tasks of writing, drawing, and cutting with scissors were most frequently transferred to the non-dominant (unimpaired) hand. Researchers concluded that diagnosis, anatomical level of injury, and task complexity should be part of a therapist's decision to address hand dominance transfer. Eggers, Mennen, and Mendunsa (1997) discuss the phenomenon of hand dominance transfer as a product of functional adaptation to accomplish activities of daily living when motion and sensation are traumatically lost in the "main executor" arm and hand following brachial plexopathies. They conjecture that skilled actions beyond those of an 8-year old child require extensive deliberate practice to facilitate dominance transfer because of necessary proficiency, speed and agility. Before proceeding to a discussion of an intervention directed at hand-dominance transfer, a review of neuroplasticity research helps answer the question, "Is it possible for an adult facing I-IHDT to re-establish engrained neuromotor patterns in a non-dominant hand? "

Neuroplasticity

Injury-induced neuroplasticity is conceptualized as a *negative* disruption in equilibrium; whereas, activity-induced neuroplasticity is conceptualized as a *positive* disruption in equilibrium (Nudo, Milliken, Jenkins, & Merzenich, 1996). Both injury-induced and activity-induced plasticity are implicated in I-IHDT. Injury-induced reorganization is understood through ablation studies, and activity-induced reorganization is understood through environmental enrichment and training manipulation studies (Kaas, 1991). Both types of neuroplasticity initiate cortical reorganization through expansion of representations in sensory and motor areas, sprouting of axons, growth of dendritic arbors, increase in synaptic vessels, genesis of new synapses and cortical neurons, and, changes in gene expression (Mark, Taub, & Morris, 2006; Nudo, Wise, SiFuentes, & Milliken, 1996). Literature in neuroplasticity fosters appreciation of the possibility of I-IHDT in a mature neuromotor system because evidence from deafferentation (ablation) studies with animals show that motor cortex does reorganize after amputation (Donoghue, Suner, & Sanes, 1990; Sanes, Suner, & Donoghue, 1990). In fact, in a study of squirrel and prosimian galagos monkeys with long-standing forelimb amputations, motor cortex had no vacant areas, but rather

expansion of surrounding cortex from proximal forelimb areas (Wu & Kaas, 1999). Overall, the adult brain, once viewed as a static, information-processing machine, is now more accurately viewed as a dynamic "super-organ" that responds sensitively and immediately to disruptions in equilibrium (Jenkins, Merzenich, Ochs, Allard, & Guic Robles, 1990; Jenkins, Merzenich, & Recanzone, 1990).

Knowledge of activity-induced neuroplasticity (also called use/experience-dependent plasticity) is critical in designing rehabilitation strategies specific to skills acquisition training (Cohen & Mano, 2006). Cortical changes in primary motor areas with skill acquisition have been revealed through neuroimaging studies (Karni et al., 1995); therefore, skill acquisition is considered one manifestation of activity-dependent plasticity. Kleim and Jones (Kleim & Jones, 2008) discuss ten principles of activity-dependent plasticity. One principle, specificity, means that plasticity is enhanced when new learning is specific to a given skilled behavior rather than repetitious, unskilled movements (Elbert & Rockstroh, 2004). Intuitively, this means that skill acquisition is best facilitated by direct experiences with the task of a given desired activity.

Early animal studies also demonstrate key principles of activity-dependent plasticity (Jenkins, Merzenich, Ochs et al., 1990; Jenkins, Merzenich, & Recanzone, 1990; Merzenich, Recanzone, Jenkins, & Grajski, 1990; Nudo, Jenkins, & Merzenich, 1990; Nudo & Milliken, 1996; Nudo, Milliken et al., 1996) and provide information about meaningful modulators of structural, biological, and behavioral change. Modulators include attention, temporal synchrony, enriched environments, and repetitive activity. Xerri (Xerri, 2008) reviews experiments that frame neuroplasticity as a substrate of learning and emphasize an "idiosyncratic imprint" caused by the influence of experience and the environment.

Reorganization of cortical motor circuits continues at variable rates across one's lifespan based on cumulative activity and experience (Gemba & Sasaki, 1984; Sasaki & Gemba, 1987). Activity-dependent neuroplasticity is considered adaptive and longer lasting compared to the immediate or reactive representational plasticity typically seen within hours of injury (Elbert & Rockstroh, 2004). Adaptive neuroplasticity is believed to "consolidate" over the course of weeks, months, and even years based on the severity of injury. This long-term adaptive plasticity is confirmed in longitudinal studies that

show continued refinement of topographical maps of neural circuits over time (Xerri, 2008).

Intervention for Military-Specific Population

Combat operations produce high numbers of orthopedic injuries among U.S. military service members. Amputation or significant, multi-tissue trauma to upper limbs results in permanent loss of hand function. Because injuries that permanently impair hand function necessitate sophisticated rehabilitation programs, service members with upper limb salvage or amputation participate in extensive rehabilitation programs at military medical centers.

Amputee rehabilitation focuses primarily on integration of a prosthesis into movement repertoires to return service member to independence. Current prostheses lack sophistication to enable proficiency in fine motor tasks such as handwriting; therefore therapists facilitate hand dominance transfer for handwriting skills. Employability and vocational/educational training have been essential in rehabilitation of young military service members facing I-IHDT after sustaining mutilating hand injuries and/or amputation in combat operations in the global war on terror (GWOT) (Smurr et al., 2008). In response to employment and education needs, military occupational therapists specifically train military members facing I-IHDT how to transfer handwriting skills through a six-week intervention called, *Handwriting For Heroes (Yancosek & Gulick, 2008).*

Description of Intervention: Handwriting For Heroes

Handwriting For Heroes is one of two published and commercially available workbooks that address handwriting skills with adults. In contrast to *Callirobics: Handwriting Skills for Adults* (Laufer, 1995) which was developed for adults with central nervous system (CNS) dysfunction such as, stroke, Alzheimer's or Parkinsons Disease, brain injury, or developmental disability, *Handwriting For Heroes* was developed for adults with peripheral nervous system (PNS) dysfunction that result in permanent loss of hand function. More specifically, *Handwriting for Heroes* was developed for combat-wounded, military service members who face I-IHDT following

mutilating hand injuries to a dominant upper extremity, and undergo limb salvage or amputation. Use of the workbook is standard of care at major military medical centers.

Handwriting For Heroes is a six-week program with four main sections: (1) *Daily Exercises*, (2) *Homework*, (3) *Therapist's Tips*, and (4) *Website Companion*. Table 1.1 shows a breakdown of the handwriting activities by type, section location, and percentage of contribution to the workbook.

daily exercises section.

Twelve daily exercises make up a "daily dozen", named after the military's historic exercise/callisthenic training regimen. Seventy-two exercises are separated by week, so each week has 12 pages of exercises. Every page in the *Daily Exercises* section contains lines, shapes, or boxes for the handwriting activities for each day of the week. "Day 1" of each week presents a new handwriting exercise. "Day 2" through "Day 7", the learner repeats the exercise, aiming for gradual improvement based on feedback of visually inspecting the previous day's work. Ultimately, "Day 7" is compared to "Day 1" to mark improvement over the week. Figure 1.1 depicts the exercises, categorized by the 12 exercise types.

therapists' tips section.

Therapists' Tips accompany Weeks 1-5. Lessons in this section cover many topics of handwriting, and specifically answer the following questions: (1) "What should you use to learn to write with?"[p.1-14], (2) "Do special grips help?"[p.1-14], (3) "When to practice?"[p.2-15], (4) "To slant or not to slant?"[p.2-17], (5) "Why cursive? And Why not printing?"[p.5-15], and (6) "Does writing have to be legible?"[p.5-15] See Table 1.2 for a list of topics in the *Therapists' Tips* section.

homework section.

Homework is another section of the workbook. The workbook states that homework exercises are not suggested activities, but need to be completed as part of the full learning experience. There are 42 different homework assignments within five categories. The following are the categories, and the number of each type of activity and the percentage of homework assignments of that type are in brackets: (1) Basic dexterity

[5, 11.9%], (2) Functional writing [13, 31.0%], (3) Personal reflective writing [12, 28.6%], (4) Coloring pages [6, 14.3%], and (5) Dot-to-dot activities [6, 14.3%]. Table 1.3 depicts activities in the *Homework* section in the basic dexterity, functional writing, and personal reflective writing categories. Handwriting, as an act of self-expression, has been used in therapeutic writing, which is effective as a psychotherapeutic intervention to reduce anxiety and improve well-being (Kerner & Fitzpatrick, 2007; Pennebaker, 1993). There is a continual thread of positive-expectancy and motivation within the content of the workbook. For example, the learner repeatedly copies affirmations and quotes such as, "I can do anything I put my mind to" and "Today I feel better than yesterday. I can't wait until tomorrow." Also, there are multiple personal reflection activities in the *Homework* section to facilitate personal insight and written expressions of the self. website companion section.

An interactive website, http://www.handwritingforheroes.com, serves as the *Website companion* section which complements the workbook. Included are 6 "Extra Credit" bonus pages, examples of successfully completed pages, resources for amputees, stroke survivors, and adults with traumatic brain injury, as well as handwriting product information. Another resource is a self-perception questionnaire on handwriting ability that asks learners to rate their writing performance on a scale of 0-10 in comparison to their writing performance in the dominant hand. The website allows a learner to contact one of the authors for guidance or feedback. Figure 1.3 illustrates the extra credit activities provided in the *Website Companion* section.

instructional style.

The workbook instructs on cursive handwriting style, suggesting it causes less hand strain and diminishes the challenge of even spacing between printed letters. Legibility components are addressed throughout the workbook. The *Therapists' Tips* section in Week 2 (p. 2-17) states that slant should be consistent because it contributes to legibility, but choosing to slant (or not) is a personal style. The following exercises (and corresponding week) specifically instruct the learner to pay attention to slant consistency: Exercise 2 (Week 4), Exercise 4 (Weeks 1 and 4), Exercise 5 (Week 1), Exercise 6 (Week 6), Exercise 9 (Weeks 1-6), Exercise 10 (Week 1-6), and Exercise 11

(Weeks 1 and 3). For Exercise 3 (Range control), the first 2 weeks do not have a slant in the curved line to be traced; whereas weeks 3-6 introduce a rightward slant.

Size and shape of letters are addressed in Exercise 1 (Weeks 2-6) by presenting boxes of varying sizes and asking the learner to write different things (first name, last name, alphabet) in the box and adjust the script size to fit the box. Size and shape are also covered in the *Homework* section (Week 2-3) by prompting the learner to write appointments in a calendar grid, write names in a family tree boxes, write numbers in a checkbook ledger, and write their signature large and small. Global legibility, or readability, is covered every week in Exercise 5 where the learner is instructed to slow down and focus on neatness. Readability is discussed in the *Therapists' Tip* section for Week 5 (p 5-17) with three practical examples of how illegible script causes serious harm, for example, pharmacists' inability to read medicine prescriptions.

Both speed and legibility contribute to automaticity of handwriting. Studies support the inverse relationship between these two components of writing, meaning that legibility decreases when speed increases (Henderson, Sen, & Brown, 1989; Weintraub & Graham, 1998; Ziviani & Watson-Will, 1998). Daily Exercise 6 in *Handwriting For Heroes* emphasizes speed over legibility as a way to separately address each component; however, the ultimate goal is automaticity that requires competence in both speed and legibility.

Pressure is addressed once in the *Therapists' Tip* section Week 5 (p 5-15) with instruction to try two practical writing experiments: (1) write with cardboard as a backdrop surface behind the paper without puncturing the cardboard, and (2) write on tissue paper or aluminum foil, again without puncturing the material. Related to pressure regulation, proprioception and kinesthetic awareness are addressed by having the learner use a pencil (which provides more feedback) for Exercise 4 (Weeks 2-3), Exercise 7 (Weeks 4-5) and Exercise 8 (Week 1).

intervention training schedule and style.

Instructions of *Handwriting For Heroes* are provided at the start of each exercise. The instructions for *Daily Exercises* section are provided in Table 1.4. Instructions vary

across and between the prescribed exercises. The instructions are written directly to the learner.

The workbook instructs learners to work every day for 6 continuous weeks for an uninterrupted period of accumulated practice. This represents a blocked-practice training schedule. The authors of the workbook caution that learners will only have mastered the basic skills of cursive upon completion of the workbook. The authors also encourage therapists to attempt to learn how to write with their non-dominant hand so they too can experience the effort involved in the transfer.

Within each day's practice, there is a written and pictorial prompt at Exercise 6 to remind the learner to stop, rest, and stretch break. Also the first lesson in the *Therapists' Tips* section reminds the learner to take frequent breaks, look up, and stretch. This lesson also prompts the learner to do the workbook when he/she feels relaxed and focused.

A descriptive discussion of a clinical intervention is enriched by input from the field of motor control and motor learning. This allows exposure of effective treatment strategies and concepts that traverse many interventions.

Motor Control and Motor Learning

Instructional methods in *Handwriting For Heroes* reflect an assumption that adults who lose dominant hand function possess knowledge about how to write; specifically, they have awareness of basic letter formation, spelling, grammatical rules for expressing thoughts and ideas in writing. It is, however, assumed that learners do not possess motor control necessary for the execution of fluent handwriting performance using the non-dominant hand. Motor control is the regulation of movement for accuracy and relies on integrating neuromotor inputs (Creem-Regehr, 2009). The subsequent essential process of reorganization, adaptation and the creation of muscle synergies to gain skill proficiency can be termed motor learning (Donoghue et al., 1990). Motor learning and motor control are internal, and therefore, unobservable processes and must be studied by observing performance and measuring performance components. A wide variety of performance-based studies have been conducted across many fields and many tasks to examine how the specifics of practice such as timing, frequency, intensity and

repetitions affect achievement of skill mastery. Findings from these and other studies are reviewed.

The earliest and most intuitive findings of studies in skill acquisition point to practice, or repeated exposure to a task, as critical to learning (Schmidt & Wrisberg, 2000). Furthermore, the practice should be quality and deliberately executed because improper movement can be learned just as easily as proper movement (Schmidt & Wrisberg, 2000). In a study using transcranial magnetic stimulation (TMS), learning was evaluated in three groups trained to perform a skilled-motor action with the hands. The physical practice group showed reduction in movement errors and an increase in corresponding motor map size as compared to a control group (Cohen & Mano, 2006). Research by Teixeira and Okazaki (2007) suggests that lateralized practice leads to a long-lasting preference for the trained limb, regardless of established hand dominance. These findings support the notion that repetitive motor experience influences learning. In a lateralized practice study asking non-injured adults to repeatedly write a single sentence each day for 28 consecutive days with their non-dominant hand, participants showed improvements in speed and legibility suggesting that handwriting skills are transferable (Walker & Henneberg, 2007).

Differences between performance effects and learning have been suggested with learning leaving a "longer-lasting" imprint as compared to shorter lasting performance gains. Findings of several studies suggest that contextual interference (interruptions or alterations of the context) help facilitate this "longer-lasting" learning. Shea and Zimney(Shea & Zimny, 1983) theorize that the frequent switching between tasks places increased demands for focus and memory on the learner and the resulting deliberate attention to details of differences between tasks helps engrain and encode movement memories. In a series of three experiments (Ste-Marie, Clark, Findlay, & Latimer, 2004) conducted with young school children, high levels of contextual interference showed a greater retention and performance of handwriting skills, thus further supporting a random versus blocked practice schedule. Handwriting For Heroes uses an overall blocked practice schedule in that the learner is writing each day for forty-two consecutive days; however, the exercises vary within each day's writing tasks, thereby offering a form of contextual interference.

A final type of instructional method linked to motor learning is a cognitive-based style called verbal self-guidance wherein the learner uses "self-talk" to set a goal, plan an action, complete the task, and then assess performance (Missiuna, Mandich, Polatajko, & Malloy-Miller, 2001). This type of learning involves self-discovery and has also been applied and shown beneficial to handwriting skill instruction with children (Bernie & Rodger, 2004).

Dynamical Systems Theory

This section describes the theoretical underpinnings of the research described in this dissertation. Additionally, theory is combined with a practice model to better discuss the two primary aims of evaluating the efficacy and effectiveness of *Handwriting For Heroes*. Dynamical Systems Theory (DST) is the selected theory to explain changes in motor behavior related to a permanent loss of dominant hand function. The Task-Oriented Approach (TOA) is the practice model that provides information about how interventions are designed to improve motor behavior (Jongmans, Linthorst-Bakker, Westenberg, & Smits-Engelsman, 2003). Each is herein described.

Dynamical systems theory has been called "chaos theory" or "complexity theory" (Alligood, Sauer, & Yorke, 1997; Cambel, 1993; Waldrop, 1992; Zellermayer & Margolin, 2005) and has been used in sciences such as non-linear mathematics, physics, biology, chemistry, and human movement sciences (Davids, Button, & Bennett, 2008). Five of the main tenets of DST that provide foundational knowledge about why change is possible (and probable) given the complex, dynamical and emergent nature of the client are described below. **Error! Reference source not found.Error! Reference source not found.** provides examples of how the tenets enhance one's understanding of hand dominance transfer.

Sensitivity to initial conditions explains how a slight difference in the beginning state of the system can influence the final outcome (Hilborn, 2004). A system is represented by an adult client. In clinical terms, the initial characteristics and competencies of the client, and the initial task features, influence the client's outcome.

Systems that possess redundancy in degrees of freedom (DOF) are inherently able to adapt under changing circumstances (Mark et al., 2006). There is a high degree of

variability in sensorimotor performance, meaning that a system can accomplish a task in a variety of ways based on the many possible approaches that multiple DOF allow (Davids, Glazier, Araujo, & Bartlett, 2003). For example, it is possible to write with a pen held in either hand, or held in a foot or mouth. The redundancy of the system permits adaptation, flexibility, and variability of movement that ultimately impacts the outcome of the task. Redundancy in DOF helps explain how a client can solve a novel motor or behavioral challenge in real-time (Rose, 1997).

The emergence of self-organization and self-similarity characteristics of the system describes the eventual equilibrium and "patterning"(also called "fixing") that is achieved in a dynamical system (Mason, 2008). This tenet captures the idiosyncrasy of the individual as a self-organizing system controlled by non-linear dynamical systems (Kelso & Fuchs, 1995). Think of repeatable motor behaviors that people develop, such as signing their name. Over time, signatures become a written communication pattern that are efficient (lowest energy demands), effective (reach performance goals), predictable (consistent), and stable (minimal performance variability).

The idea of constraints is based upon the construct of redundancy of DOF. This tenet speaks to the interconnectedness of many subsystems within the larger system, each with embedded DOF. Davids, Button, Araujo, Renshaw, and Hristovski (2006) explain that constraints shape (limit and enable) movement and can be categorized into person, task, and environment components. Importantly, it is the interplay between constraints that drives a system's (re)organization. This captures the idea that behavior emerges out of the interaction between client's competencies, the task demands, and environmental affordances.

The final tenet is the principle of effector states and attractor conditions and describes how behavior is directed toward a goal (effector state) based on inputs (attractor conditions) that converge and create a performance trajectory (Livneh & Parker, 2005). Ikiugu(2005) wrote about the occupational-life-trajectory and posited that meaningfulness is the central attractor of human life. This tenet suggests that behaviors are not merely neural events, but rather they are goal-directed, purposeful, and the manifestation of what was available to meet task demands.

The Task-Oriented Approach

Dynamical systems theory has been foundational in the development of practice models that embrace the non-linear nature of human performance (Baum & Christiansen, 2005; Canadian Association of Occupational Therapists, 1991; Dunn, Brown, & McGuigan, 1994; Gielo-Perczak & Karwowski, 2003; Kielhofner, 1995; Law et al., 1996; Townsend & Polatajko, 2007). The TOA is also a model of practice based on DST. The TOA resonates with the philosophy of the founders of the occupational therapy profession who believed occupation to be a powerful therapeutic agent of change and catalyst for improved health (Dunton, 1915), and a bridge toward physical and mental health (Reilly, 1962; Trombly, 1995). The TOA is marked by four primary characteristics, which are described below.

In using the TOA, the intervention should be client-centered, meaningful, and occupation-based. The clinician addresses questions such as "*How* should the therapy sessions be structured?" "*How* do activity demands drive performance?" and "*How* should the environment be set up to facilitate optimal performance?" The clinician appreciates that competence in handwriting is linked to participation in many tasks, such as signing one's name, paying bills, writing letters or lists, completing paper-and-pencil based leisure tasks, and completion of work or education demands. In a study done with children, the TOA demonstrated effectiveness in improving the quality, not speed, of handwriting (Jongmans et al., 2003). Rather than approaching a hand dominance transfer training program through repetitive hand and digit strengthening exercises, fine-motor manipulation exercises such as grasp, move, and release of various small objects, and copying the same letter in repetition, the task-oriented approach is marked by features of direct engagement in functional tasks.

As a strategy of service delivery, the practitioner drives performance toward the effector state of handwriting skill mastery by manipulating constraints (person, environment, and task) to exploit attractors. One possible attractor is memory of past because the client was most likely highly proficient in handwriting prior to loss of hand function, and he will likely remember his engrained handwriting style (highly personalized, predictable in shape, slant, style, size, and a clear representation of a

personalized motor behavior). This example of an attractor highlights individualization of both process and outcome of services.

Constraints further imprint a mark of idiosyncratic nature to each writer and potentially each writing experience. Some task constraints include writing with different instruments on various papers or surfaces, and characteristic demands of the task, such as length of writing required (signing one's name, filling out a form, or composing a thought in a journal). Environmental constraints are less varied as handwriting is a closed-task; however, temperature, noise, and lighting could pose considerable influence over occupational performance. Additionally, when writing for emotional expression, the environment may facilitate or inhibit creativity. Personal constraints include age, gender, visual perceptual skills, psychological factors such as insight into functional loss, past occupational experiences and future occupational goals, values and beliefs in the need for and meaning of written expression, and motivation for change that may impact willingness to learn to write with the other hand.

See **Table 1.5** for a complete list of possible constraints.

From the perspective of the TOA, the client is at the core of assessment and intervention. This requires a clinician to work closely with the client to determine goals, interests, and other information specific to that individual in order to customize the clinical interaction. Clients are encouraged to be active participants, through facilitated problem solving, self-evaluation, and even task analysis (Bass-Haugen, Mathiowetz, & Flinn, 2007). The TOA focuses on the client and his or her meaningful roles and occupations to elicit changes in motor behavior. For example, an adult client with a hand injury may be asked to select a meaningful task to perform during intervention, and also asked to rate their anticipated performance before beginning the task.

Meaningful, purposeful, goal-directed tasks are used as the basis for assessment and intervention. The clinician observes the client engaging in the selected occupation, and identifies what movements are necessary, optimal, or superfluous (Schmidt & Wrisberg, 2008). Motor behaviors are also analyzed to determine if the movements are stable or in transition (Bass-Haugen et al., 2007), a concept which is based on the DST premise of effector and attractor states. A client with a recent injury to the dominant hand is likely to have movements that are in transition; in other words, each time the

client engages in a task, the movements are unpredictable. Using a self-selected, meaningful occupation as the task may help to stabilize the movement, due to the re-emergence of preferred movement patterns as well as the importance of goal-directed movement.

The TOA emphasizes that the environment should be natural (or a realistic simulation) and the objects in the environment should be authentic in order to encourage optimal motor behavior (Bass-Haugen et al., 2007). The clinician must identify aspects of the environment that may assist or hinder occupational performance, as well as understand that occupational performance varies depending on constraints or changes in the environment. It is necessary for the clinician to be aware of environmental aspects as well as personal factors related to the client, such as spasticity, weakness, or limited range of motion, that may influence motor behavior, and to address all of these issues in treatment. For instance, the therapist may have to address a client's limited active finger flexion in order to maximize engagement in an occupation such as handwriting. This might be accomplished through stretching exercises, or environmental modification by adapting the seating position, desk design, or writing surface (Shen, Kang, & Wu, 2003).

Finally, the TOA capitalizes on motor learning research that emphasizes whole versus part learning, practice schedules, and providing appropriate feedback. Clinicians must make decisions about whether to teach a skill as a part or a whole, and whether to teach a skill using blocked practice (practicing the same skill repeatedly), or random practice (varying the practice) (Guadagnoli & Lee, 2004). Often the most effective practice schedule begins with blocked practice, and move toward random practice. Additionally, the clinician should initially provide the client with extrinsic feedback about performance, but move toward self-evaluation, independent problem-solving, and intrinsic feedback (Guadagnoli & Lee, 2004). In the client with a dominant hand injury working on transferring hand dominance for writing, the clinician must determine if breaking writing down into its parts by copying letters, or working on the whole by asking the client to write a letter to a friend, will be the best approach. The clinician must also engage the client by varying the practice, and asking the client to identify problems or successes during the intervention.

In summary, there is a dynamic interplay between person, task, and environment, in such a way that no two clients have the same recovery experience (Pierce, 2003). Furthermore, by working collaboratively with the client, based on an appreciation for the uniqueness of the individual, the involvement of the environment, and the demands of the occupational task at hand, occupational therapy services are customized and contextualized.

Summary

This line of research is related to dexterity, hand dominance, and handwriting within a rehabilitation context for adults facing I-IHDT. Handwriting is considered the lateralized motor skill of hand dominance and the portal to examine a functional neuromotor skill that epitomizes the complex construct of dexterity. This line of research begins with establishment of reliability and validity of a digital apparatus to measure handwriting and progresses into a rehabilitation framework evaluating efficacy and effectiveness trials of *Handwriting For Heroes*, an intervention used in Military medical centers to facilitate hand dominance transfer. Frequently in rehabilitation and behavioral health settings, interventions are developed anecdotally based on cumulative knowledge and "expert opinion" of experienced clinicians (Graham & Harrison, 2005). Interventions are often implemented expeditiously to meet practical real-world demands for efficiency and standardization, albeit at the expense of antecedent scientific testing. Therefore, investigating the efficacy and clinical effectiveness of interventions is relevant to advance both the science and practice of rehabilitation.

Chapters 3 and 4 describe intervention studies designed to provide preliminary information. Chapter 3 describes the results of an efficacy trial with five healthy adults; whereas chapter 4 describes the results of a clinical effectiveness study with five impaired adults. Both studies use the apparatus pilot tested in the study described in Chapter 2, and both are an attempt to examine a hand dominance transfer protocol used in military treatment centers as standard of care.

Information about the outcome and the process of hand dominance transfer will add value to both evaluation and intervention strategies of rehabilitation professionals

addressing dexterity transfer to a previously non-dominant hand. The contribution and significance of this work is in both its novelty and translation into clinical practice.

Research Goals

The overarching goal of this research was to examine the efficacy and effectiveness of *Handwriting For Heroes* in facilitating hand dominance transfer of motor control as it pertains to handwriting.

Study #1: Specific Aims

Specific Aim 1: Develop data collection apparatus to analyze handwriting.

Specific Aim 2: Assess consistency (reliability) of graphomotor performance in a sample of adults who previously lost hand function

Study #2: Specific Aims

Specific Aim 1: Examine the efficacy of *Handwriting For Heroes* in non-impaired subjects.

Specific Aim 2: Establish data collection and analysis methods for monitoring graphomotor performance changes across time.

Study #3: Specific Aims

Specific Aim 1: Examine the clinical effectiveness of *Handwriting For Heroes* in an injured military population.

Specific Aim 2: Use a dynamical systems framework to describe motor learning based on the changes in fine motor control used to write with a non-dominant hand.

Specific Aim 3: Examine the influence of personal factors as modulators to transfer dominance in handwriting skill development.

Table 1.1 Number, section location, and percentage of all graphomotor activities in Handwriting For Heroes

Graphomotor Activity	Number of Activities	Section	Percentage of contribution to the workbook
Copying			
Letters	9	*Daily Exercises*	7.8%
Strings of letters	9	*Daily Exercises*	7.8%
Words	12	*Daily Exercises* *Homework* *Website Companion*	10.3%
Sentences	28	*Daily Exercises* *Homework*	24.1%
Symbols	1	*Daily Exercises*	0.0%
Numbers	3	*Daily Exercises* *Homework*	2.6%
Drawing			
Shapes	3	*Daily Exercises* *Homework*	2.6%
Dot-to-dot	6	*Homework*	5.2%
Tracing			
Letter forms	8	*Daily Exercises*	6.9%
Curvy lines	6	*Daily Exercises*	5.2%
Shading			
Shapes	2	*Daily Exercises*	1.7%
Composing	23	*Homework* *Website Companion*	19.8%
Transcribing	0		
Coloring	6	*Homework*	5.2%

Table 1.2 Topics per week in Therapists' Tips section of Handwriting For Heroes

Week	Educational Topic	Illustration Included
1	• Selecting a writing instrument • Using special grippers	Yes
2	• Paper position/orientation • Activities that develop fine motor dexterity • Furniture: chair, desk, and inclined writing surfaces	Yes
3	• Left-handed writing • Exercises to develop separation between sides of the hands, distal digital control, upper body strength development	No
4	• Posture • Stretches (neck, wrist, and finger) • Lighting	Yes
5	• Pressure • Managing hand pain	No

Table 1.3 Handwriting activities in the Homework section of Handwriting For Heroes

*Provided in workbook

Basic Dexterity Homework • Practice flipping a pen from end to end in your hand. If that's too easy, get a pen with a cap on it and put it on and take it off each end (repeatedly) without dropping the pen or the cap. (Week 1) • Place coins or marbles or buttons in Silly Putty® or TheraPutty® and work your fingers to pull the objects out. (Week 1) • Roll coins in coin wrappers. This is an excellent fine motor coordination task and one that works on the control of your thumb, index, and middle finger. (Week 1) • Place 10 small items (coins, buttons, marbles, paperclips) on a surface in front of you. Then, pick them up one at a time and keep them in your hand (don't drop any as you pick up the next item). Reverse the drill and place the items back on the surface, one at a time, without dropping any of those still in your hand. (Week 2) • Fidget with a pen and its cap. Place the cap on and off the pen and rotate the pen end to end to place the cap on the both ends of the pen without dropping the pen or the cap. This assignment you should do while watching television so that you learn to do it without watching your hand move. (Week 4)
Functional Homework • Practice printing a few things that you will likely always print, like your email address and your home address. (Week 1) • Write a list of grocery shopping and errands. Number each item to practice writing numbers, too. (Week 2) • Write the names of your family on the family tree graph* Write neatly in cursive. (Week 2) • Complete the calendar grid.* This exercise will help you write smaller letters/words in cursive. (Week 3) • Write the names and phone numbers of 10 of your closest friends and families. You could also try writing it on an index card for handy reference. (Week 3) • Write information on the news, weather, and sports.* (Week 3) • Use the checkbook ledger* to solve a practical math problem.* (Week 3) • Write yourself a "To-Do" list. Write it on paper that you can place where you can see it and check off tasks as you complete them. (Week 4) • Complete the budget worksheet on the corresponding page in this week's homework section. (Week 4) • Write a letter to a friend or family member. Tell them all about yourself and what you've been busy with lately. (Week 4) • Go to the movie listings of your local newspaper. Copy the names of the films currently playing and the show times. (Week 5) • Write every word you can think of that starts with the letter "S." See if you can come up with at least 100. (Week 6) • Write a paragraph that you've chosen from a magazine, book, or newspaper. (Week 6)

Personal Reflective Homework

- Practice writing your signature by writing it as many times as you can. Use the signature page.* Write it in the margins and in many directions. (Week 1)
- Write the days of the week and the months of the year. List the holidays and birthdays of family and friends during each month. * (Week 2)
- Find a quote from a book or magazine that you would like to memorize. Copy it seven times on the sheet provided. (Week 2)
- Complete your personal data sheet.* (Week 3)
- Practice your signature. Use the space provided in the homework section.* Write it both small and large. (Week 4)
- Fill in the personal journal entry on the corresponding page in this week's homework section.* (Week 5)
- People often doodle while taking on the phone. If you only have one functioning hand, you may think this isn't possible. So here's your homework for today: Call a friend, put the phone on speaker, then doodle as you converse. You can draw anything, write what they say, scribble back and forth…just doodle!! HAVE FUN!!! Tell them what you're up to so they will visit for a while, and you'll get your doodle time in! (Week 5)
- Use the guided sentences* to help you create a story of your childhood. (Week 5)
- Use recall to answer these questions* about your life and current living environment. (Week 5)
- Write a story about something from your childhood. Mail it to your parents or to an influential teacher. (Week 6)
- Write the words to your favorite song. You may have to visit the Internet to all the lyrics. (Week 6)
- Write (or print) the words that best express your thoughts to complete each statement.* (Week 6)

Table 1.4 Instructions for writing activities in the Daily Exercises section of Handwriting For Heroes

<u>Exercise 1:Warm-Up:</u> (Week 1) Make X's in the boxes as demonstrated in the first box. (Week 2) Write your first name in each box. Fill up the box. The variety of box sizes will force your brain to direct your hand to adjust its movements. (Week 3) Draw six circles, then make clocks out of them. Select a time for each clock, and write below the clock what that time of day represents. (Week 4) Write numbers 0-10 in each of the boxes below. (Week 5) Write your last name in each of the boxes, adjust the size to completely fill them. The variation in the box sizes will force your brain to tell your hand to adjust its movements. (Week 6) Write the alphabet or "half-a-bet" (i.e. only half of the alphabet) in each of the following boxes. Adjust the size of your script to make all the letters of the alphabet or half-a-bet fit.
<u>Exercise 2: Train-In-The-Rain:</u> (Week 1) Write two lines of this example. (Week 2) Copy both lines. Are you aware that all five letters have loops above the lines? (Week 3) Copy both lines of letters. (Week 4) Copy each line of the cursive letters "n, y and m, v". Keep your pen on the paper. Lift it only to move to the next line. Are you being consistent with your slant? (Week 5) Copy the lines of letters with lower "raindrop" loops. (Week 6) Copy the line of r's twice.
<u>Exercise 3:</u> <u>Range Control:</u> (Week 1-5) This exercise is about stretching and growing. Trace the following curvy line pattern, keeping your wrist stationary and stretch your fingers (thumb, index, and middle only). (Week 6) Trace the following curvy line pattern:
<u>Exercise 4:</u> <u>Stretches:</u> (Week 1) Write the following line of continuous letters twice. Be consistent with your slant. Do not lift your pen or pencil until you need to start a second line. (Week 2) Fill in each shape. If you have been using a pen, please switch to using a pencil for this exercise. (Week 3) Using a pencil, fill in the stars. (Week 4) Write the months of the year. How consistent are your loops and the slants? (Week 5) Copy the lines of two letter combinations. (Week 6) Copy the following two lines:

<u>Exercise 5:</u> <u>Spit Shine:</u> (Week 1-3) Repetition and attention to detail put the polishing touches on anything. In the military, that's what makes a good spit shine. In the following exercises, copy the following two lines, keeping a consistent slant. (Week 4) Repetition and attention to detail put the polishing touches on anything. In the military, that's what makes a good spit shine. Write the following two lines each day. (Week 5) Repetition and attention to detail put the polishing touches on anything. In the military, that's what makes a good spit shine. Write two lines of the continuous x, z, and q combinations. (Week 6) Repetition and attention to detail put the polishing touches on anything. In the military, that's what makes a good spit shine Copy the two lines each day.
<u>Exercise 6:</u> <u>Speed Drills:</u> (Week 1) Write the series of letters seven times on each day's two lines, moving as quickly as you can. As you write each letter, your pen or pencil will start from the right and move to the left before beginning the next letter. Speed is more important than neatness in this exercise. (Week 2) Your brain is familiar with common letter sequences that are repeated in many English language words. Copy the following two lines of letter sequences. (Week 3) Write two lines of the following sets of letters (w, u, r, s, o). Please move as quickly as you can. In this exercise, speed is more important than neatness. Are you aware that each letter involves moving from right to left? (Week 4) Write the letters e, o, m, n, v and y in the combined words *ney* and *move,* as show below. Did you notice that all the letters start with an upward motion? (Week 5) In this exercise, speed is more important than neatness. Write two lines of the letter combination e, z, e, q, u, e. Move as quickly as you can. (Week 6) Much of our writing involves commonly used words. Copy the following two lines of four small words. Work as fast as you can while maintaining the proper slant.
<u>Exercise 7: Boot Lacing:</u> (Week 1) These two words include frequently written letters that require you to lift your pen from the paper. As you resume writing, remember to maintain your slant. Copy these two lines. (Week 2) This exercise features two words that use the letters we are focusing on this week, which require lifting your pen from the paper between words. Please remember to resume your slant once you resume writing. Copy the following two lines: (Week 3) Make X's in the boxes as shown in the example. (Week 4) Using a pencil, trace inside the bubble letters of the words in the following sentence. (Week 5) Using a pencil, trace inside the bubble letters of the words. (Week 6) Keeping your pen on the paper, trace the letters in the sentence repeated below.
<u>Exercise 8:</u> <u>In Cadence:</u> Write by moving the pencil lead inside the outlined words. Please use a pencil for this exercise. (Week 2) Keep your pen on the paper as you trace the letters in each word of the sentence. (Week 3) Trace the letters in the sentence repeated below and on the following page. (Week 4) Keep your pen on the paper as you trace the letters in each word of the sentence. (Week 5) Keeping your pen on the paper, trace the letters of each word in the sentences to repeat each day. (Week 6) Keeping your pen on the paper, trace the letters in the sentence repeated below.

Exercise 9: Carbon Copy:
(Week 1-6) The following sentence contains every letter of the alphabet….really! You won't even know you've written the alphabet. It's the "medicine-in-the-applesauce" method of writing your ABCs. Write the sentence twice. How's your slant, by the way?

Exercise 10: Steady at the Ready:
(Week 1) Each day during this exercise you will combine "straight line" and "loop" letters. When you transition between line and loop, please pay careful attention to keeping your proper slant. Copy the following sentence once each day.
(Week 2) This exercise helps you combine straight line and loop letters. When you move between line and loop, pay careful attention not to lose your proper slant. Copy this sentence two times.
(Week 3,4): During this exercise, you will be combining straight line and loop letters. When you move between line and loop, be careful not to lose your proper slant. Copy the sentence two times.
(Week 5) Common words or strings of letters are used in much of our writing. Copy the following two lines. Work as fast as you can while maintaining a consistent slant.
(Week 6) This exercise gives you daily practice combining straight line and loop letters. When you move between line and loop, strive to keep a consistent slant. Write the following sentence two times.

Exercise 11: Endurance Training:
(Week 1) Now, neatness counts! Each week the "endurance drill" sentence will get longer. Copy the sentence(s). Are you keeping correct hand position and the same slant? Copy the sentence below.
(Week 2) NOW, neatness counts! Next week's "endurance drill" sentence will be longer. Are you keeping correct hand position and the same slant? Copy the one sentence below.
(Week 3) Copy the one sentence below. NOW, neatness counts! The sentence will be longer for next week's "endurance drill". Be careful not to lose your slant or the correct hand posture.
(Week 4) Striving for neatness, copy the sentence below.
(Week 5) Copy the sentence below. NOW, neatness counts!
(Week 6) You should be very good at this by now! Keep your lines of writing even across the page as you trace the following script.

Exercise 12: Esprit de Corps:
(Week 1) Copy these sentences on each of the day's two lines.
(Week 3-6) Copy the following sentence.

Table 1.5 Tenants of dynamical systems theory as it relates to hand dominance transfer

Five Main Tenets of Dynamical Systems Theory	**Considerations of A Hand Dominance Transfer**
Sensitivity to Initial Conditions	• Initial conditions such as age, gender, occupation, previous experiences, motivation, and laterality (strength of preference for dominant hand) affect the final outcome of hand dominance transfer.
Redundancy in Degrees of Freedom	• Loss of function in the dominant hand causes a drastic reduction in DOF within the body system. • Other injuries or limitations (such as brain or ocular injury) further reduce DOF, and impact the client's ability to transfer hand dominance.
Emergence and Patterning	• The client reorganizes and invents behavior strategies using the intact hand to accomplish basic movements. • The client is capable of learning new movement strategies over time, including maladaptive strategies, such as "learned non-use" (Taub et al., 1993) of the residual or "flail" limb. • Each client devises unique movement strategies that vary *within* and *between* task performances. • Over time, the client's sensorimotor performance emerges towards a state of equilibrium and the previously non-dominant hand emerges as the "new-dominant" hand. • Initial movements will be unsteady, uncoordinated, and generally unstable, but will (with time and experience) emerge as effective, efficient, predictable, and stable.
Constraints	• A combination of task demands, environmental pressures, and personal factors affects movement strategies. • Constraints can be manipulated to direct skills acquisition through repetitious exposure to task and environmental demands.

Effector States and Attractor Conditions	• Effector states dictate new movement strategies, such as one-handed approaches, adaptive equipment, desire for and use of a prosthesis, the use of the mouth, feet, and other body parts to complete tasks. • Attractor conditions influence what the client has to draw upon in order to accomplish any given task.

Table 1.6 Personal, task, and environmental constraints on handwriting performance

Personal	Task	Environmental
Age, gender, handedness	Properties of the writing instrument	Lighting
Co-morbidities (examples: eye or brain injury)	Properties of object being written on (digitizer, white or chalkboard, paper, fabrics)	Temperature
Occupational history and goals (is writing a hobby or related to a work/school role)	Time demands of writing	Noise/distractions
Neuromusculoskeletal functions: joint mobility, stability, muscle power, tone, endurance	Intensity/duration of task	Angle of writing surface
Mental functions: attention, memory, perception, energy	Purpose of writing	Height of writing surface
Vision and perception	Size of the space to write in	
Values and beliefs (Meaningfulness of writing)	Expectation of font (manuscript versus cursive)	

Exercise 1: Warm-ups

1.

2. Write your first name in each box. Fill up the box. The variety of box sizes will force your brain to direct your hand to adjust its movements.

3. Draw six circles, then make clocks out of them. Select a time for each clock, and write below the clock what that time of day represents.

4. Write numbers 0-10 in each of the boxes below.

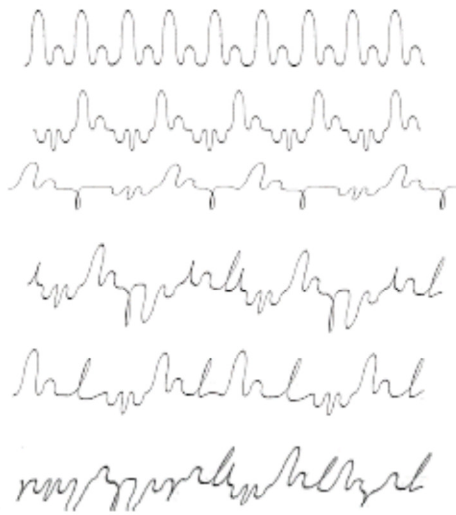
5. Write your last name in each of the boxes, adjust the size to completely fill them. The variation in the box sizes will force your brain to tell your hand to adjust its movements.

6.Write the alphabet or "half-a-bet" (i.e. only half of the alphabet) in each of the following boxes. Adjust the size of your script to make all the letters of the alphabet or half-a-bet fit.

Exercise 2: Train in the rain

1. cccccccccccccccccccccccccccccccccccccc
2. eeeeeeeeffffffffffeefffffeeeeeeeeeeeeeeee
eeeeeeeeeeeeeeeehhhhhhhhhhhhhhhhbbbbbbbbbbbb
3. iiiiiiiiiiiiitttttttttttttttttuuuuuuuuuuuuuuuu
ppppppppppppssssssssssssssoooooooooooooooo
4. nnnnnnnnnnnnnyyyyyyyyyyyynnnnnnn
mmmmmmmmmvvvvvvvvvvvvvvvvmmmmmm
5. gggggggggggggggggggggggggggggggggggg
qqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqq
6. uuuuuuuuuuuuuuuuuuuuuuuuuuuuuuuuuuuuuuu

Exercise 3:Range control



Exercise 4: Stretches

1. cccccccaaaaaaadddddddgggggggooooooo

2.

3.

4. January February March April May June July August September October November December

5. xoxoxoxoxoxoxoxoxoxoxoxoxoxoxoxoxoxoxo
ququququququququququququququququququququq

6. %%%%%%%%%%%%%%%%%%%%%%%%%%%
&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&

Exercise 5: Spit shine

1. ogogogogogogogogogogogogogogogogogoggo
cacacacacacacacacacacacacacacacacacaca
2. ehhehhehhehhehhehhehhehhehhehhehhehh
flefleflefleflefleflefleflefleflefleflefleflefflfle
3. sitsitsitsitsitsitsitsitsitsitsitsitsitsitsisitsit
pourpourpourpourpourpourpourpourpourpourpou
4. yyyyyyyyyyyyyyyyyyyyyyyyyyyyyy
mmmmmmmmmmmmmmmmmmmmmmmmmm
5. ggxggxggxggxggxggxggxggxggxggxggxggxggx
ggxggxggxggxgggxggxggxggxggxggxggxggxgg
6. ppppppppppppppppppppppppppppppp
dddddddddddddddddddddddddddddddddddd

Exercise 6: Speed drills

1. caodgg caodgg caodgg caodgg caodgg caodgg

2. age ag age age age edg edge edge edge edge edge
back back back back able able able able able able

3. wurso wurso wurso wurso wurso wurso wurso

4. ney ney ney ney ney ney ney ney ney ney
move move move move move move move move

5. egeque egeque egeque egeque egeque egeque egeque

6. the the the the the the the of of of of of of of of
on on on on on on on are are are are are are are

Exercise 7: Boot lacing	Exercise 8: In cadence	Exercise 9: Carbon copy
1. exit exit exit exit exit exit exit exit exit exceptional exceptional exceptional 2. like like like like like like like like like half half half half half half half half half 3.  4. Handwriting is fun for me! 5. Things are looking up for me! 6. I have finished lots of writing exercises!	1. I take one day at a time! 2. "Nothing of value comes without sacrifice."-John C. Maxwell 3. Today I feel better than yesterday. I can't wait until tomorrow. 4. Learning a skill takes time and energy. There are many things I would like to learn. 5. Each time I do this exercise, I get better and better. I will stick with it! 6. I feel great about achieving my handwriting goals. I did it!	1. The quick brown fox jumped over the lazy dog. 2. Once upon a time, a zealous boy named Jack Frost gave his extra quarters away. 3. When the crazy viper sneaked by, a big fox quickly jumped out of hiding. 4. The zookeeper fed the busy aardvark while Megan quickly fixed the jaguar's cage. 5. Queen Victoria always looked on the clearance rack for wide-bottom jeans with extra zippers. 6. Don't question my mother named Zada K. Bigley who is exceptionally virtuous, fashionable, and joyful.
Exercise 10: Steady at the ready	**Exercise 11: Endurance training**	**Exercise 12: Esprit de Corps**
1. I must overlook a lot of my mistakes in my writing early on. 2. I seek freedom from the thoughts of negativity. 3. I can do anything I put my mind to. 4. Focus on being positive and having a great day. 5. ful ful ful ful ful ful ful be be be be be be be ance ance ance ance ere ere ere ere ere ere ere ere 6. Never be too busy to meet someone new.	1. When I focus my energy and attention on learning to write these words, I can succeed. 2. To become successful at anything in life, remember that what you do today matters. 3. I will learn to write with my non-dominant hand; I will call it my "new-dominant" hand. 4. "Success is not measured by what a man accomplishes but by the opposition he has encountered." -Charles Lindbergh 5. Francis Bacon said, "By far, the best proof is experience." 6. The days ahead are bright.	1. I am motivated. I am working toward improving my writing skills and that takes time. 2. Do the following things this week: 1. Call a friend. 2. Read a book. 3. Take a nap. 3. Today I will focus on myself and not try to regulate anybody else except me. 4. Abraham Lincoln said, "Most people are about as happy as they make up their minds to be." 5. Spend time thinking about pleasant memories. There are many happy things I should remember. 6. Exercise every day and maintain a positive attitude.

Figure 1.1 Handwriting activities within Daily Exercises section of Handwriting For Heroes, sorted according to exercise type

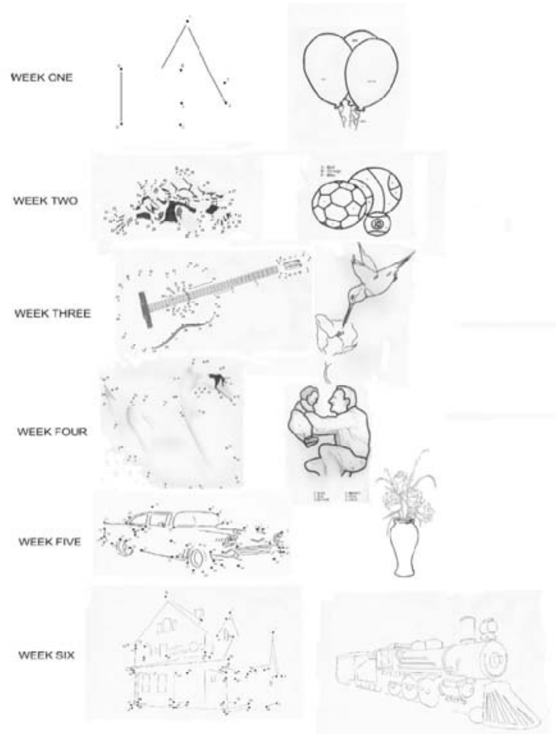


Figure 1.2 Thumbnail sketches of dot-to-dot and coloring activity from homework section of Handwriting for Heroes

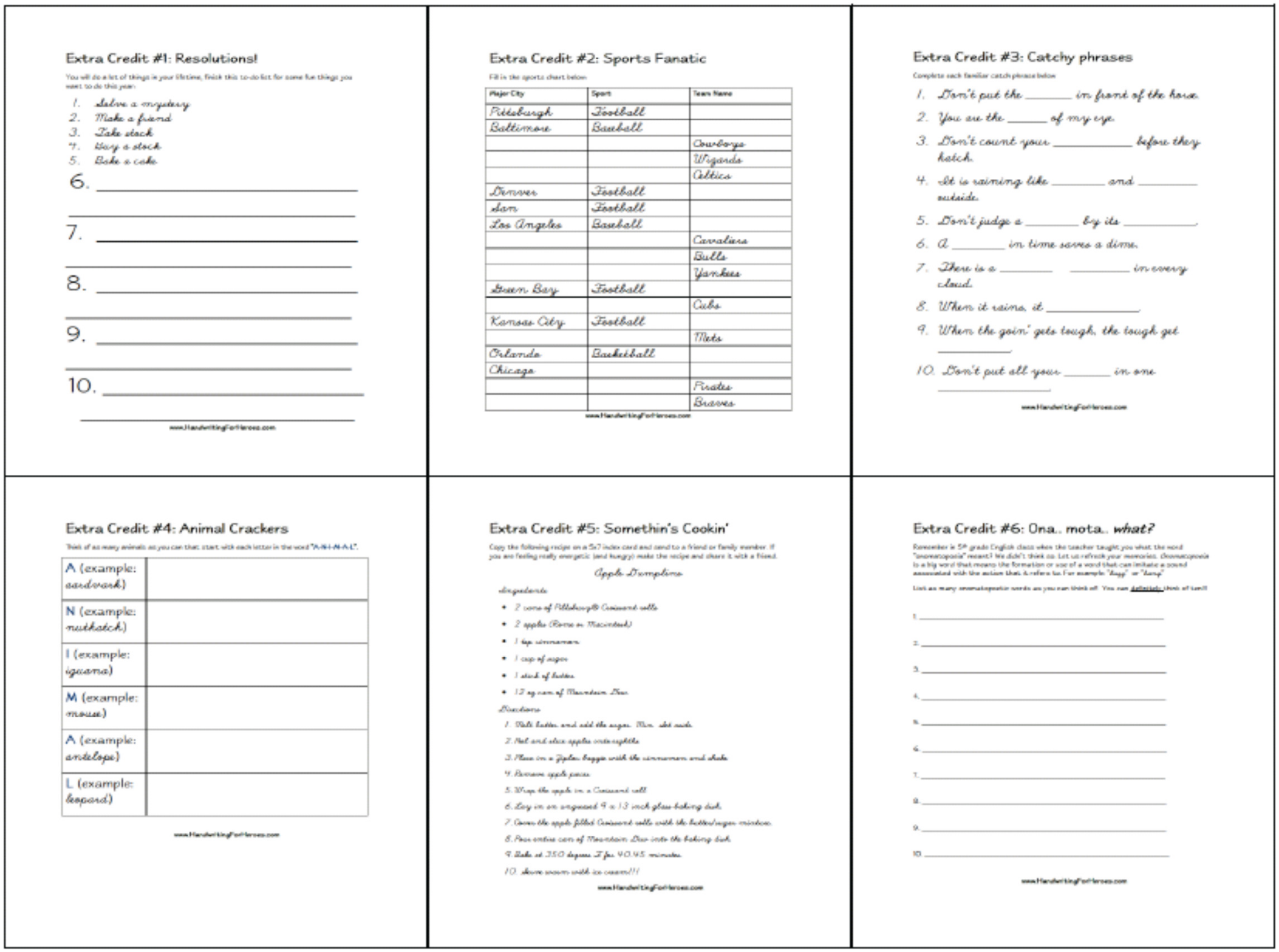


Figure 1.3 Extra credit activities provided in the Website Companion section of Handwriting for Heroes.

Chapter 2

Stability of Handwriting Performance Following Injury-Induced Hand Dominance Transfer in Adults

Most activities of daily living (ADL) are accomplished bimanually with the dominant hand as main executor and the non-dominant hand as supporter (Eggers & Mennen, 1997). When normal bilateral hand function is disrupted (Kimmerle, Mainwaring, & Borenstein, 2003), patients must complete two-handed tasks with one hand. A functional state of “single-handedness” may be temporary, such as is common in recovery from tendon laceration/repair, fracture/fixation, or neuropraxia/splinting; however, when prognosis for functional return is poor, a permanent state of single-handedness ensues. This one-handed situation is more difficult with dominant hand impairment because complex, fine motor coordination and skill must be transferred to the non-dominant hand (Walsh et al., 1993).

A forced shift of dominance is termed injury-induced hand dominance transfer (I-IHDT). It conceptually defines the imposed transfer of lateralized skill proficiency to the previously non-dominant hand. Besides amputation of a dominant upper extremity, other diagnoses potentially result in single-handedness and I-IHDT, such as brachial plexus avulsion; chronic, unilateral lymphodema; hemiparesis following stroke; focal hand dystonia; limb salvage following mutilating hand injury (crush, avulsion, burns), and complex regional pain syndrome (CRPS) following minor trauma or surgery (Frettloh et al., 2006).

Hand dominance is closely associated with, and often defined by, the functional neuromotor task of handwriting (Granville et al., 1980). Handwriting, as a form of functional dexterity, captures the hand’s interface with a commonly encountered tool. Handwriting also captures the hand’s intricate link to the brain for planning and executing purposeful movements, in this case, written expression (Bonney, 1992; Chu, 1997). Because handwriting is purported to be the highest form of unilateral hand dexterity skill attained by the general population (Plaskins-Thornton, 1996), it is an important component of I-IHDT.

Handwriting is a distinct, neuromotor skill of interest to occupational therapy practitioners. The Handwriting Assessment Battery (HAB) for adults evaluates pen control and manipulation, writing speed, and writing legibility (Faddy et al., 2008). Writing is one of seven functional tasks on the Jebsen-Taylor Test of Hand Function (Jebsen et al., 1969) Handwriting is included in many self-report questionnaires on hand function, for example handwriting is a specific item listed on the Disabilities of the Arm Shoulder, and Hand questionnaire (DASH) (MacDermid & Tottenham, 2004), signing one's name is included in the physical domain portion of the Burn Specific Health Scale (Blades et al., 1982), and the Upper Limb Function Index includes an item asking "I have difficulty writing or using a key board and/or mouse (Stratford et al., 2001).

Beyond self-rated scales, there is a need to better quantify fine motor control needed for handwriting (Adersen Hammond et al., 2009). The field of graphonomics provides technology to quantify handwriting (graphomotor) performance. This type of digital analysis was used to capture disturbed motor control in patients with chronic undiagnosed wrist pain (Smeulders et al., 2001). Leveraging digital technologies and using graphonomics as the portal to evaluate dexterity performance has clinical implications for evaluating the process and outcome of I-IHDT.

Literature Review

Many diagnoses may lead to I-IHDT; however, a limited body of literature exists. Chan and LaStayo (2003), in their description of management of mutilating hand injuries, recommend early instruction in ADL, specifically if a dominant hand is injured. Research on neuroplasticity, motor learning and inter-manual transfer informs clinical practice; however, these studies are generally limited by use of simple, non-functional motor tasks and/or recruitment of only non-impaired participants. One study evaluated ten, young, non-impaired adults who learned to write one character of a foreign alphabet with both hands (Andree & Maitra, 2002). They concluded that occupational therapy practitioners should select tasks that are meaningful and previously known to the person to best facilitate the transfer. Another study (Walker & Henneberg, 2007) on cross-dominance training required twenty-one non-impaired adults to repeatedly copy the same sentence daily for twenty-eight consecutive days. Results demonstrated that

participants, 20-56 years old, gained proficiency in non-dominant handwriting with no decrement from increasing age. They did not test for generalization of handwriting skill by assessing performance on novel handwriting tasks.

A cohort-controlled neuroimaging study examined sixteen adults who self-reported being "innately left-handed" but forced at the onset of school to convert to right-handedness. The study showed two cortical areas that correlated with handedness, and one area was more invariant than the other, regardless of sensorimotor training (Kloppel et al., 2007). The researchers concluded that despite learning to write with the right hand, these sixteen research subjects maintained a right-hemisphere dominance in the inferior parietal cortex and the rostrolateral premotor cortex. An additional neuroimaging study in humans found small, distinct writing centers in the brain but they were specific and highly individualized for each of fourteen subjects (Lubrano, Roux, & Demonet, 2004). Taken together, these behavioral and imaging studies demonstrate training effects, perhaps despite central nervous system fixation of hemisphere dominance, thereby suggesting that neuromotor plasticity in relation to handwriting is more of a peripheral phenomenon.

Purpose

The primary aim of this investigation was to assess graphomotor performance consistency of adults who lost hand function through amputation or permanent, multi-tissue damage to dominant upper limb greater than 2 years ago. The hypothesis was that after 2 years post injury, participants would have achieved a general level of single-hand function, and subsequent dominance transfer.

Methods

This pilot study was approved by the local Institutional Review Board. Participants were primarily recruited via letters mailed through local hand therapy and prosthetic centers. A secondary recruitment strategy was to make announcements about the study through a local amputee support group.

A one-group test-retest design was used, where participants provided two handwriting samples, six weeks apart. No intervention was provided in this study. Six

weeks was the time interval between assessments to accommodate future data comparison from planned clinical trials involving a six-week handwriting skill transfer intervention.

Twelve adults volunteered and provided written informed consent. Three participants were excluded from analysis for the following reasons: 84 years old with notable tremor during writing tasks; female with bilateral upper limb amputations who wrote with a prosthesis, and male who had undergone ray resection of the two most ulnar digits of his non-dominant hand. Data of nine participants (3 males, 6 females; aged 27-70- years, mean = 53.6 years) were analyzed. No participant withdrew from the study. All participants lost function of the right, dominant hand with an average time since loss of function of 15.0 years (range: 3-46 years). Eight participants were amputees and one participant had an attached but deformed and non-functional upper limb. See Figure 2.1 for select examples of participants.

Mechanism of injury was trauma for seven participants, multi-organ system failure for one participant, and localized blood clots with subsequent tissue necrosis/amputation in one participant. Six participants were retired, and three worked full-time. Eight participants reported daily engagement in handwriting tasks (average of 24.0 minutes per day). Participants who wore glasses for reading used them during the experiment. To increase study recruitment and enrollment, participants who did not drive were accommodated by having an investigator meet them at a convenient location. Participants performed all graphomotor activities from a seated position. They were free to angle the writing apparatus according to preference; however, regardless of stylistic preference, they were asked to complete the handwriting activities in cursive, not manuscript, form. The decision to have participants write in cursive was another decision made to accommodate future data comparison from planned clinical trials using the available handwriting intervention that instructs in cursive.

After three practice trials for familiarization, each participant completed the following six handwriting tasks: (1) *Compose a Sentence*, (2) *Copy Alphabet*, (3) *Copy Date*, (4) *Copy Sentence 1*, (5) *Copy Sentence 2*, and (6) *Draw Circles*. The *Copy Alphabet* and *Draw Circles* tasks were the same at test and re-test sessions; however, *Compose a Sentence*, *Copy Sentence 1*, and *Copy Sentence 2* were purposefully varied

between sessions to diminish effects from memory/learning of experimental tasks. Each writing task was presented visually on a 2-inch card mounted on blue cardstock paper placed in front of them. The card contained the instructions (which were also read to them) and an example of the completed writing activity in cursive.

To collect graphomotor output during each of the six tasks, a 3.5 X 7.0 inch piece of white, lined paper was taped to a digitizer tablet (WACOM Intuos 3, model PTZ-630) controlled by a Lenova Thinkpad notebook computer. MovAlyzR® software by NeuroScript™ was used to set-up, run the experiment, and capture the pen tip kinematic (left to right, and top to bottom, paper position; i.e. X and Y directions) and kinetic (pen tip on paper force) data at a sampling rate of 200 Hz. The IntuiS3 inking-pen was used as the wireless writing instrument. This apparatus offered a pen-on-paper feel with benefits of direct digital recording of the pen tip position and force. Customized code written with MATLAB® software was used to calculate further kinematic variables and calibrate the kinetic parameters of each handwriting activity. The following parameters were collected: force (g), average displacement in X and Y (cm), average velocity of the pen tip in X and Y (cm/s), and on-paper time (seconds).

In addition to kinematic and kinetic variables, stylistic stability of handwriting samples served as another metric of performance consistency. After data were collected, handwriting samples were trimmed to remove participants' identification codes and mounted to cardstock. The identification codes were re-written on the back of the cardstock. The principal investigator met separately with two objective evaluators who were uninvolved in the research study. One evaluator was a high-school administrator and one was a homemaker who previously worked as a behavioral health professional. Neither was experienced in handwriting assessment nor knowledgeable about the study objectives.

The investigator sequentially presented writing samples for all participants from six writing tasks by making two columns of the writing samples in random order. One column contained test samples for all participants and the second column contained re-test samples. The evaluators were instructed to visually inspect and correctly pair the handwriting samples thought to be written by the same participant (one from the test

column and one from the re-test column). After each evaluator made nine pairs, their results were calculated and recorded as the number of correct responses out of nine.

Kinematic and kinetic data in MATLAB were trimmed to 90% to cater for extreme pen movements (e.g. when dotting an i). In SPSS (v16, SPSS Inc., Chicago, IL, USA) data were then tested for normality (Shapiro-Wilks>0.05), and outliers removed. The test and re-test data were evaluated for analyzed using the intra-class coefficient of correlation (ICC).

To score and equate each participant's handwriting fluency to a grade school level, the total task time for writing the following sentence (*Copy Sentence 1*) was converted to a written-letters-per-minute score: "*Don't question my mother, Zada K. Bigley, who is exceptionally virtuous, fashionable, and joyful*." This sentence was rated at an adult level (13.4 grade level) according to the Flesch-Kincaid scale, a widely used tool to assess reading and writing complexity (Doak, Doak, & Root, 1996). The number of letters in the sentence (77) was multiplied by 60 seconds and then divided by the number of seconds each participant took to complete the task. This score was then compared to the handwriting fluency numbers of a large sample (N=900) provided by Graham, Berninger, Weintraub, and Schafer (1998) of school-aged children from 1st to 9th grade.

The Jebsen-Taylor Test of Hand Function (JTHF) (Jebsen et al., 1969) is a well-known hand function assessment with seven sub-tests. One sub-test measures the time it takes the adult to copy a sentence with 24 characters. *Copy Alphabet* task in this pilot study required participants to copy (in cursive without spaces between letters) the 26-characters of the alphabet. Because this handwriting activity closely matched the writing subtest of JTHF, task completion time was examined for each participant and compared to normative data of the non-dominant and dominant hands provided by original data from JTHF test.

Results

The various kinematic and kinetic data showed different stability over the 6-week period.

Table 2.1 shows means and standard deviations for all six writing tasks at test and re-test sessions. Calculating the differences between test and re-test measurements revealed relatively small group mean differences which demonstrate a trend of within-subject performance stability; however, between-subject variability is noted by the large standard deviations around the group means. The mean velocity (in the X direction) was the most stable parameter and force the least stable between testing sessions across all six tasks. *Draw Circles, Copy Date,* and *Copy Alphabet* were the most consistently performed task across participants; whereas *Compose a Sentence, Copy Sentence 1, and Copy Sentence 2* showed more variability across participants for all parameters. Velocity in X and Y directions was higher at re-test for all tasks despite longer on-paper time for *Copy Alphabet*, *Copy Sentence 1*, and *Copy Sentence 2*. Force was consistently greater at the re-test session for all tasks.Table 2.2 shows reliability analysis of data by quantification methods using ICC for graphomotor performance from test to re-test. The following kinematic parameters across the six tasks showed excellent correlation (0.80-1.00): mean velocity in X direction for *Copy Date*; mean velocity in Y direction for *Draw Circles*; On-paper time for *Copy Alphabet*. The kinematic parameters with the highest correlation between test and re-test sessions across all tasks were mean velocity in X direction and on-paper time; however, no single writing task had good to excellent correlation across all kinematic and kinetic parameters.

Performance stability was noted by objective evaluators who visually discerned handwriting features (size, shape, slant, and style) and matched handwriting samples from test and re-test sessions. The evaluators' ability to correctly match handwriting samples showed 100% success for three tasks: C*opy Alphabet, Copy Sentence 1,* and *Copy Sentence 2*. One evaluator correctly matched all 9 pairs for *Compose a Sentence* and *Copy Date* tasks; whereas, the second evaluator correctly matched 8 out of 9 pairs for both tasks. Both evaluators matched 8 out of 9 pairs for the *Draw Circles* task. Figure 2.2 shows different handwriting samples of three participants from the sentence copying tasks taken from the test and re-test sessions.

Using the written-letters-per-minute as a marker of fluency of writing and extrapolating fluency as a marker of writing competency, three participants performed between a 1st and 3rd grade fluency level with a range of 17-48 letters per minute; while

the remaining six participants scored between an 8th and 9th grade level with a range of 93-168 letters per minute. Table 2.3 shows a grade level equivalent for writing performance for each participant. Table 2.3 also shows each participant's on-paper time for *Copy Alphabet* task with comparisons to reference normative values for the writing subtest from the JTHF. Three participants met writing performance standards according to normative data from the dominant hand; three participants met writing performance standards according to data from the non-dominant hand; and three participants did not meet performance standards for dominant or non-dominant hand.

Discussion

Results of this pilot study captured writing performance stability within subjects as noted by minimal differences between re-test and test of group means for kinetic and kinematic parameters. The large standard deviations around group means reveal between-subject performance variability. The negative ICC values and the 95% CI that include a 0 value generally imply no correlation between test and re-test sessions; however given the minimal differences between test and re-test group means, the negative ICC values likely express large standard deviations captured statistically in the ICC values and CI.

As task complexity increased so did variability between test and re-test sessions; for example, *Composing a Sentence* showed more variability between testing session than did *Draw Circles* or *Copy Date* tasks. Likewise, performance of the three tasks that varied between sessions (*Compose a Sentence*, *Copy Sentence 1*, and *Copy Sentence 2*) was less consistent than performance on tasks that remained the same (*Draw Circles, Copy Date, Copy Alphabet*). In this way, perhaps kinematic analysis is too sensitive a measure of performance on complex handwriting tasks and tasks that vary (even slightly) between testing sessions.

The increased mean velocity in X and Y directions and greater force for all tasks at re-test suggest more effort on task performance at re-test. The longer on-paper time for *Copy Alphabet*, *Copy Sentence 1*, and *Copy Sentence 2* imply the same conclusion: a testing effect referred to as the "Hawthorne effect" which describes a change in performance caused by awareness of being tested (Steele-Johnson, 2000).

Visual analysis of handwriting samples is common among certified forensic document examiners, as well as occupational therapy practitioners administering traditional paper-and-pencil assessments in school settings. Visual analysis methods were applied in this pilot study as two independent evaluators matched test to re-test handwriting samples based on consistency in letter size, shape, slant, and overall style. So, while kinematic analysis was used to assess stability in the handwriting *process*, visual analysis assessed stability in the handwriting *product*.

Results of kinematic and visual analysis support the following conclusions: (1) despite instability of select kinematic and kinetic performance parameters, participants' written output was consistent (recognizably similar and therefore presumed stable) between test and re-test sessions, (2) results of both analyses show between-subject variability, and (3) between-subject variability expressed itself in unique writing styles which suggests an idiosyncratic nature of handwriting.

Adult-level writing demands mastery of fine motor coordination for basic writing fluency in order to liberate the brain to attend to higher order cognitive tasks (Connelly, Dockrell, & Barnett, 2005). Looking at grade level equivalence for each participant's writing speed aroused concern for three participants who wrote at speeds comparable to 1^{st}, 2^{nd}, and 3^{rd} graders, despite a significant amount of elapsed time since loss of dominant hand function.

A recent adult survey found 92 million Americans with literacy levels less than an 8^{th} grade level (Kutner, Greenberg, & Baer, 2005) ,and since the Flesh-Kincaid assessment rated the *Copy Sentence 2* task at a 13.4 grade level, it was possible that slow performance speed reflects difficulty with adult-level literacy tasks rather than limited fine motor control needed for writing. To search for an explanation, the on-paper time for the simple *Copy Alphabet* task, was compared to adult reference normative values of the similar JTHF writing subtest. This comparison showed that the three participants with low-grade-level writing speeds also did not meet performance standards for dominant *or* non-dominant hand, confirming a motor, rather than cognitive, performance constraint.

A closer look at these participants substantiates the conclusion of a motor control rather than literacy skill constraint. All three participants reported at least a 6^{th} grade

education and therefore assumed capable of writing the alphabet in the *Copy Alphabet* task. One participant reportedly wrote for less than 5 minutes per day since his amputation three years prior and another participant reported had not written since his amputation seven years prior. The third participant reportedly wrote each day since her amputation six years prior, and although she had slow performance (2^{nd} grade equivalent), she wrote faster than the other two participants.

These findings support other research that suggests handwriting is not an auto-emergent skill, but rather one that needs to be purposefully addressed (Graham, 1992; Jones & Christensen, 1999). For example, Eggers, Mennen, and Mendunsa (1997) discuss the phenomenon of hand dominance transfer as a product of functional adaptation to accomplish ADL when motion and sensation are traumatically lost in the "main executor" arm and hand and conjecture that skilled actions beyond those of an 8-year old child require extensive deliberate practice to facilitate transfer because of necessary proficiency, speed, and agility. In this study, all participants were independent in basic ADL; however, they had not all transferred handwriting skill at an adult proficiency level.

Implications for Practice and Research

Results showed 8 out of 9 participants engaged in handwriting tasks daily which suggest the notion that handwriting remains a meaningful, daily task and should be addressed in rehabilitation care plans. Results provide clinical value by establishing and describing a method for measuring functional handwriting skill. These methods may be replicated and extended to measure handwriting in other populations of interest. Study results also inform clinicians about overall graphomotor performance consistency across tasks and kinematic parameters. The sample is too small to establish normative data, but information can be used clinically, for example a therapist working with a patient who lost dominant hand function may repeat the tasks and measure the variables that showed excellent reliability to monitor a change over time to evaluate therapeutic progress.

Results of this pilot study guided two subsequent studies related to a six-week transfer intervention that uses handwriting as the defining motor task of hand dominance. Results have influenced these intervention studies in three primary ways.

First, single-subject research design was chosen to examine the clinical effectiveness of the intervention. This is a result of the large standard deviations around the group mean differences, the heterogeneity of the participants, and the difficulty in obtaining a large sample size. Single-subject research avoids group analysis by using a rigorous experimental approach where each participant is his or her own control. Secondly, much closer attention is being paid to personal factors that may influence performance such as neuromusculoskeletal functions in the sole, functioning limb (joint mobility, stability, power, tone, and endurance); cognitive functions of attention, memory, visual perception; and psychosocial factors such as insight into functional loss, past occupational experiences and future occupational goals, and motivation for transferring handwriting skill. Lastly, kinematic analysis proved valuable for simpler writing tasks, but traditional paper-and-pencil metrics are being used to measure letters-per-minute and legibility in complex, adult-level handwriting tasks.

Limitations

Gaining access to a population of community-dwelling adults with permanent loss of dominant hand function was difficult, resulting in a small and heterogeneous sample. A small sample prohibited statistical methods of regression analysis to discern variables, such as time-since-functional-loss, that may contribute to fine motor control necessary to establish stable movement patterns for handwriting. Because this was not a clinical study, we did not have access to the participants' medical records and other health information that may have influenced motor performance. Similarly we did not perform clinical evaluations that may have been useful to this study, such as cognitive, sensory, motor, or strength assessments. Finally, our concession to meet participants at convenient locations resulted in limited control over environmental constraints such as, time of day, lighting, noise/distractions, and room temperature. This may have contributed to between-subject variability.

Conclusion

This study examined graphomotor performance as a marker of hand dominance in a distinct sample of adults who lost dominant hand function and discovered what

kinematic and kinetic parameters were stable across time and across various functional writing tasks. This information has been useful in designing on-going clinical trials related to an intervention designed to facilitate hand dominance transfer. Research in this line of inquiry needs to be extended to advance initiatives in rehabilitation to minimize the severity of disability following dominant-hand injuries (Trybus, Lorkowski, Leszek, & Hladki, 2006). When hand-injured patients face I-IHDT, they deserve evidence-based interventions to accelerate necessary hand dominance transfer so they may be restored to full participation in activities of daily living, work, and leisure pursuits.

Table 2.1 Handwriting kinematics and kinetics as test and re-test means (standard deviation) for 6 writing tasks completed using the left hand in 9 participants with permanent loss of function in the previously, right-dominant hand.

Task	Mean velocity X direction (cm/s)	Mean velocity Y direction (cm/s)	X displacement (cm)	Y displacement (cm)	Force (g)	On-paper time (s)
Compose a sentence	0.83(0.50)	1.01(0.50)	6.18(0.80)	1.41(0.68)	68.14(41.46)	49.95(28.13)
Compose a sentence	0.76(0.53)	0.97(0.49)	7.10(1.64)	1.27(0.39)	110.78(63.32)	45.96(21.97)
Copy alphabet	0.55(0.29)	0.76(0.43)	8.02(2.96)	0.58(0.46)	113.29(32.52)	44.55(36.89)
Copy alphabet	0.53(0.30)	0.66(0.32)	8.43(2.48)	0.44(0.11)	122.66(63.18)	47.56(42.33)
Copy Date	0.81(0.45)	0.93(0.43)	4.71(2.29)	0.41(0.14)	74.28(40.49)	16.51(13.49)
Copy Date	0.77(0.37)	0.88(0.33)	5.13(1.21)	0.40(0.09)	107.89(55.49)	14.90(7.05)
Copy Sentence 1	0.72(0.42)	0.93(0.48)	7.09(1.53)	1.57(0.63)	62.59(27.82)	85.88(82.43)
Copy Sentence 1	0.64(0.38)	0.79(0.37)	7.43(1.51)	1.66(0.57)	103.65(59.55)	99.12(74.97)
Copy Sentence 2	0.70(0.37)	0.93(0.47)	7.22(1.35)	1.99(0.91)	68.03(29.37)	93.87(83.36)
Copy Sentence 2	0.67(0.39)	0.82(0.41)	7.51(1.42)	1.65(0.68)	95.99(55.98)	94.93(66.81)
Draw 4 circles	1.55(1.17)	1.19(0.68)	5.57(1.09)	1.18(0.27)	107.91(42.72)	10.33(5.59)
Draw 4 circles	1.27(0.74)	1.05(0.48)	5.53(1.59)	1.24(0.30)	128.82(34.12)	10.35(3.76)

Note. Gray area denotes re-test values; X: left to right paper direction; Y: top to bottom paper direction.

Table 2.2 Data are ICC* [lower and upper bound of 95% CI] of test-retest mean scores of handwriting kinematics and kinetics for 6 writing tasks completed using the left hand in 9 participants with permanent loss of function in the previously, right-dominant hand.**

Task	Mean Velocity		Displacement		Time	Force
	X direction	Y direction	X direction	Y direction	On-paper	
Compose a Sentence	.74 [.24-.93]	*.18 [-.48-.73]*	*-.27[-.76-.43]*	*-.04 [-.63-.60]*	*.34 [-.34-.80]*	*.59 [-.03-.89]*
Copy Alphabet	.70 [.16-.92]	*.00 [-.61-.63]*	.79 [.35-.95]	*.06 [-.57-.66]*	.81 [.40-.95]	.64 [.05-.90]
Copy Date	.81 [.41-.95]	*.38 [-.29-.81]*	.63 [.03-.90]	.71 [.17-.92]	.73 [.22-.93]	*.47 [-.19-.85]*
Copy Sentence 1	.67 [.11-.91]	*.19 [-.47-.73]*	.62 [.03-.90]	*.39 [-.29-.82]*	.88 [.60-.98]	*.43 [-.24-.83]*
Copy Sentence 2	.63 [.04-.92]	*-.01[-.61-.63]*	.71 [.17-.92]	*-.33 [-.78-.37]*	.78 [.33-.95]	*.61 [-.02-.89]*
Draw Circles	.77 [.31-.94]	.81 [.41-.95]	.39 [-.29-.82]	*.34 [-.34-.80]*	.69 [.15-.92]	.62 [.02-.90]

**ICC=intraclass correlation coefficient, **=Confidence Interval*
Note: X direction: left to right on paper; Y direction: top to bottom on paper.
Italicized numbers indicate a negative ICC or a CI that includes 0.
ICC Interpretation: Poor = <.19; Fair= .20-.39; Moderate = .40-.59;
Good = .60-.79; Excellent= .80-1.0

Table 2.3 Descriptive analysis of all participants

Gender	Age	Time Since Amputation	Highest Education Level	Writing Performance Grade Level Equivalent	On-Paper Time for *Copy Alphabet* Task
F	62	7	HS	8th	*28.54
F	59	16	HS	9th	10.39
F	65	46	AS	>9th	14.06
F	70	6	BS	9th	*37.08
M	58	7	HS	1st	**122.57
M	27	3	BS	3rd	**77.05
F	29	4	MS	>9th	* 23.77
M	61	40	HS	>9th	22.53
M	52	6	6th grade	2nd	**64.94

Note. HS=High School, AS=Associate's degree, BS=Bachelor's degree, MS=Master's degree

**Greater than 2 standard deviations above Jebsen Taylor Test of Hand Function (JTHF) writing subtest reference values for dominant hand*
***Greater than 2 standard deviations above JTHF reference values for non-dominant hand*

Figure 2.1 ***Example of participants.***

Top left: female participant with mutilating hand injury. Top right: male participant with high transradial amputation; Bottom left: male participant with transhumeral amputation; Bottom right: female participant with elbow disarticulation.

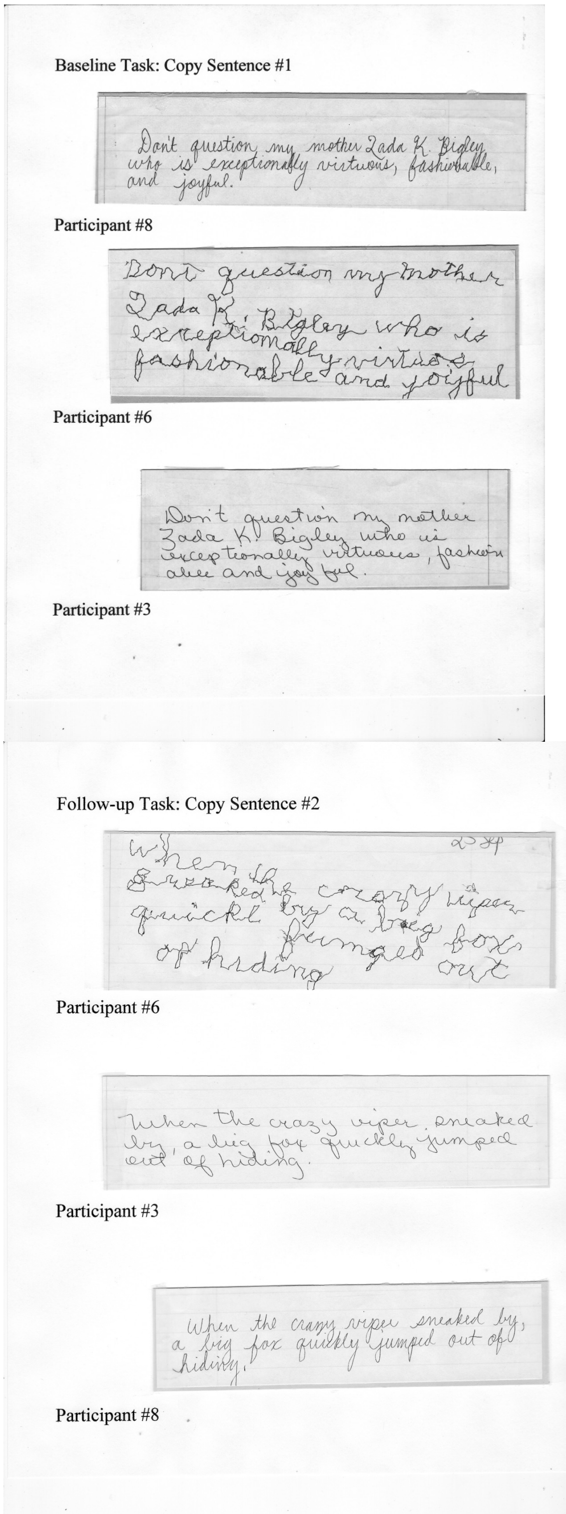


Figure 2.2 Copy Sentence tasks at baseline and follow-up.

Chapter 3

Efficacy of a Hand Dominance Transfer Intervention in Non-Impaired Adults

Handwriting For Heroes (Yancosek & Gulick, 2008) is one of two published rehabilitation programs commercially available to facilitate handwriting skill development with adults. In contrast to *Callirobics: Handwriting Skills for Adults* (Laufer, 1995) which was developed for adults with central nervous system (CNS) dysfunction such as: stroke, Alzheimer's or Parkinsons Disease, brain injury, or developmental disability, *Handwriting For Heroes* was developed for adults with peripheral nervous system (PNS) dysfunction that results in permanent loss of hand function. *Handwriting for Heroes* was specifically developed for combat-wounded, military service members who face injury-induced hand dominance transfer (I-IHDT) following mutilating hand injuries to a dominant upper extremity, and subsequently undergo limb salvage or amputation.

Extremity injuries, including limb amputations, occur in 60-75% of injuries in military personnel (Ficke & Pollack, 2007). Amputation of a dominant hand drastically impairs function and necessitates a comprehensive rehabilitation program. One component of the rehabilitation program is facilitating hand dominance transfer for participation in fine motor, dexterity activities that cannot be replaced by a prosthesis, such as handwriting (Smurr et al., 2008).

Handwriting is the activity most often associated with hand dominance (Doyen & Carlier, 2002) and is therefore the focus of a hand dominance transfer program. Handwriting captures the essence of dexterity and hand dominance in two primary ways. First, dexterity generally implies an interaction with a tool or object needed to accomplish a goal, and handwriting captures the hand's interface with a commonly encountered tool and accomplishes the goal of written communication. And, secondly, handwriting captures the hand's unique link to the brain for planning and executing purposeful movements, (Bonney, 1992; Chu, 1997) and in so doing, handwriting provides a link between the peripheral manifestation of dexterity and the origin of dominance in the brain.

Handwriting is a graphomotor skill that is multidimensional and highly dependent upon sensory, motor, and cognitive processes (Connelly et al., 2005;

Woodward & Swinth, 2002). Also, despite handwriting being a basic skill learned early in life, it is purported to be the highest form of unilateral hand dexterity skill attained by the general population (Plaskins-Thornton, 1996). Handwriting is viewed as a necessary skill for an injured service member who leaves the military and enrolls in college or seeks employment that requires handwriting skills (Smurr et al., 2008).

Although many diagnoses potentially lead to permanent loss of dominant hand function, a limited body of literature exists related to rehabilitative management of patients facing I-IHDT. For example, Chan and LaStayo, (2003) in their description of management of mutilating hand injuries, recommend early instruction in activities of daily living (ADL), specifically if a dominant hand is injured; however, no intervention methods are described. This gap in the literature likely reflects a research and rehabilitation focus on restoring or augmenting function and improving outcomes for the amputated or impaired side, whereby hand dominance transfer is left to emerge naturally over time through daily use of the remaining limb for ADL.

One relevant study investigated effects of upper extremity trauma on hand dominance. Researchers used patient surveys and chart reviews at two regional hand centers (Walsh et al., 1993) and discovered that sustained precision dexterity tasks of writing, drawing, and cutting with scissors were most frequently transferred to the non-dominant (unimpaired) hand. Researchers concluded that diagnosis, anatomical level of injury, and task complexity should be considered in therapies aimed to address a hand dominance transfer. Eggers, Mennen, and Mendunsa (1997) discuss the phenomenon of hand dominance transfer as a product of functional adaptation to accomplish activities of daily living when motion and sensation are traumatically lost in the "main executor" arm and hand following brachial plexopathies. They conjecture that skilled actions beyond those of an 8-year old child require extensive deliberate practice to facilitate dominance transfer because of necessary proficiency, speed, and agility. However, again, no rehabilitation methods are described. The lack of clearly defined practice guidelines leaves rehabilitation professionals with clinical questions of *how* and *when* to best facilitate hand dominance transfer in adults facing I-IHDT.

In rehabilitation and behavioral health settings, intervention protocols are occasionally developed anecdotally based on cumulative knowledge and expert opinion

of experienced clinicians (Graham & Harrison, 2005). Interventions may be implemented expeditiously to meet practical demands for efficiency and standardization, albeit at the expense of antecedent scientific testing. This, in turn, creates a shortage of clinically-tested protocols available to create an evidence-based practice for occupational therapy practitioners treating adults facing I-IHDT.

The purpose of this study was to evaluate the efficacy of *Handwriting For Heroes* with non-impaired participants. The distinction between an efficacy versus an effectiveness trial is relevant. Efficacy relates to whether or not an intervention works under ideal conditions, and often involves stricter inclusion criteria; whereas effectiveness relates to whether or not the intervention works under routine clinical conditions where patients likely have multiple issues and co-interventions are often necessary and may overlap and influence the intervention being scientifically evaluated (Pittler & White, 1999).

Many medical and behavioral health scientists suggest establishing efficacy prior to effectiveness trials because of limited resources available to researchers and the known constraints on busy rehabilitation professionals, with the most obvious reasoning being that if an intervention does not work under ideal conditions it likely will not work under "real-world" conditions.

Methods

Study Design

This study used a single-subject research design (SSRD) with non-concurrent replication across five non-impaired participants. Multiple probes were taken across baseline, intervention, and maintenance phases. The intervention was *Handwriting For Heroes*.

Description of Intervention

Handwriting For Heroes is a six-week program with four main sections: (1) *Daily Exercises*, (2) *Homework*, (3) *Therapist's Tips*, and (4) *Website Companion*. See Table 3.1 for a description of each section. The workbook instructs learners to work every day for six continuous weeks for an uninterrupted period of accumulated practice.

The workbook instructs on cursive handwriting style, suggesting it causes less hand strain and diminishes the challenge of even spacing between printed letters. Legibility components are addressed throughout the workbook. *Handwriting For Heroes* utilizes concepts of motor control and motor learning, such as: progressing from simple to complex; a massed practice schedule; using a page-layout that facilitates reflection on results to influence the learner's meta-cognitive strategy to improve performance; and contextual interference with frequent task changes.

Participants and Setting

Participants were recruited through two local universities. All participants signed informed consent approved by the local institutional review board. No compensation was provided for volunteering for this study. Five (4 males, 1 female) healthy, right-hand dominant adults (mean age 33 years) completed the study and simulated a leftward transfer of hand writing skills. No participants withdrew. See Table 3.2 for demographic information.

Beyond demographic information, the following personal factors were explored for influence in learning: cognition, laterality (strength of hand dominance), and visual-motor integration. A brief explanation for each personal factor, and the evaluation tool used, is provided in Table 3.3. The visual-motor integration assessment was administered at the first and final probe.

The location in which handwriting samples were collected varied between participants. Additionally, to accommodate one participant, the investigator met him at two locations (school and home); however the tables were the same height (29") at both locations. The other four participants were consistently seen at the same location (in their homes) for all probes. Table heights varied between 29" and 30" for all participants. Time of day for each probe was recorded, but because of the frequency of the probes and participants' schedules, it was not well controlled and ranged from 8:30am to 8:30pm.

Outcome Measures/Dependent Variables

1. A graphomotor performance assessment (handwriting sample) was performed at each meeting. The following parameters were measured:

   a. Displacement: trajectory length (displacement in centimeters) covered by the pen across the x and y axes. Measured in cm.
   b. Velocity: average of absolute velocity of the pen tip. Measured in mm/s.
   c. On-paper time. Measured in seconds.
   d. Pressure of pen on digitizer. Measured in Newton/mm.
   e. Letters-per-minute were counted by dividing the total letters written in a five-minute time period by five.
   f. Legibility was measured by counting the number of *readable* words written during an endurance task and dividing by the total number of *written* words and then multiplied by 100. This calculated a legibility percentage score as originally suggested by Alston (1983).
2. Dexterity was measured by the Grooved Pegboard, a standardized, time-based pegboard test with established reliability and validity (Yancosek & Howell, 2009). Each of the twenty-five pegs of the Grooved Pegboard has a ridge on one side and must be oriented correctly to fit into the twenty-five grooved peg holes. This ridge-effect necessitates visual attention to task and small movements of the thumb and index finger to orient the pegs correctly.
3. Compliance with the intervention was considered an outcome, as well as a contributing factor to the outcome since handwriting does not improve without direct practice (Dunsmuir & Blatchford, 2004; Graham, 1992; Jones & Christensen, 1999; Smits-Engelsman & van Galen, 1997). A compliance score was calculated by examining the participant's workbook each week during the Intervention phase. A score of one point for each completed daily exercise, and a score of zero for partially or not completed exercises was given. There were twelve exercises and one homework assignment for each day of the week, so a score between 0 and 91 [(13 exercises x 7 days/91)x100] was recorded for weekly compliance percentage. An overall compliance percentage score for the entire intervention was also calculated.

Procedures

Handwriting samples were written on a 3.4 x 6.8 inch piece of white, lined paper taped to a digitizer tablet (Wacom Intuis 3.0) controlled by a Lenovo Thinkpad notebook computer (Lenovo, Morrisville, NC). Participants were free to angle the digitizer according to preference and completed the handwriting activities in cursive form.

During each probe, participants completed the following handwriting tasks onto the digitizer: (1) *Copy Date*: the dates were random dates to allow variation of numbers to be copied, (2) *Copy Alphabet:* the 26-letter alphabet copied in cursive form without spaces between letters, (3) *Copy Sentence:* copy a 24-letter sentence, and (4) *Draw Circles:* participant drew four circles within boundaries provided by double-lined circles pre-printed onto the paper. *Draw Circles* and *Copy Alphabet* remained the same at each probe; whereas *Copy Sentence* and *Copy Date* were purposefully varied at each probe to diminish effects from memorization. Each activity was presented visually on a 4.5 x 2.0 inch card mounted on blue cardstock placed in front of them. The card contained the instructions (which also were read to them) and an example of the completed activity in cursive (generated by the same handwriting font, School Script, used in the *Handwriting For Heroes* workbook).

MovAlyzeR (Neuroscript, Tempe, AZ) was used to set-up, run the experiment, and capture the output of x, y, and z coordinates at a sampling rate of 200 Hz. The IntuiS3 inking-pen was used as the wireless writing instrument. This apparatus design offered a pen-on-paper feel with benefits of direct digital input to a Wacom tablet interactive screen (Wacom Technology Corporation, Vancouver, WA). Customized code written with Matlab (Mathworks, Natick, MA) software calculated the following kinematic and kinetic properties: (1) pen pressure (Newtons), (2) velocity in the x axis (mm/s), (3) velocity in the y axis (mm/s), (4) on-paper time (s), and (5) displacement in the x axis (cm), and (6) displacement in the y axis (cm).

To obtain the handwriting sample used to collect the letters-per-minute and the legibility variables, the following endurance handwriting activity was done (not performed onto the digitizer): participants opened the book *The History and Power of Writing* (Martin, 1994) to any page and copied text onto a standard lined piece of paper.

The pre-set option on the ULTRAK dual-timer clock system signaled an auditory cue to stop writing when five minutes elapsed. The number of readable words was counted and divided by the total number of written words and then multiplied by 100. This provided a legiblity percentage score as originally suggested by Alston (Alston, 1983).

To measure legibility, the first author met with two graduate students (raters) who read each word of all handwriting samples obtained at each probe for all participants. The instructions for scoring legibility were standardized and read to each rater prior to reading the writing samples. To prevent learning, no performance feedback was given regarding accuracy of reading the words. The results of rater 1 were concealed from rater 2.

Each word was presented individually, moving backwards across the text, using an adjustable view-window tool created out of cardstock for the purpose of shielding the reader from the other words on the page. This controlled the evaluators' ability to decipher the writing based on context clues traditionally available to a reader. Additionally, the samples of all participants were mixed together and presented randomly so the individual writing style of each participant did not become predictable to the raters.

The raw number of readable words per rater were entered into SPSS (v.16, SPSS Inc., Chicago, IL, USA) and a Pearson *r* statistic was performed to determine inter-rater reliability (consistency between the two raters). Inter-rater reliability ranged from 0.91 to 0.99 across participants ($p<.01$). See Table 3.4.

Data Collection

Five baseline probes occurred over a ten-day period. All measurements were taken in the same order at each probe by one evaluator. Time of day was recorded at each visit.

Based on scheduling availability of each participant, one to two probes occurred weekly throughout the six-week long intervention phase. The maintenance phase

examined skill retention following completion of the intervention. It began two weeks after the intervention ended and consisted of four additional probes. At the final maintenance probe, each participant completed all graphomotor activities and the pegboard dexterity assessment with their dominant hand.

Procedural Fidelity

One investigator collected all handwriting samples, administered all standardized assessments, and analyzed all the data in the same way across all five participants. The changes of time and settings within and between subjects were all recorded.

Procedural fidelity for the intervention was established by having each participant complete *Handwriting for Heroes* independently, in the same fashion that rehabilitation professionals might have a client complete the intervention as a home program. To measure the weekly and total overall "dose" of the intervention received by participants, compliance was systematically measured and recorded (described earlier).

Analysis

Visual analysis of graphed data is the accepted method to analyze single-subject results (Wolery & Harris, 1982). Data were sorted by phase and presented graphically, and analyzed visually for trend, variability, and level. These graphical depictions were created by plotting data for (1) letters-per-minute, (2) legibility percentage scores, and (3) scores on the Grooved Pegboard dexterity test.

The letters-per-minute score was recorded and equated to a grade-level. The grade-level equivalence was based on research published on writing competencies of 900 school-aged students, first through ninth grade (Graham, Berninger et al., 1998). This grade-level score was compared to the participants' dominant and non-dominant hand writing speed.

Visual analysis can be augmented by performing statistical analysis of individual performance change over time. To contrast the effect of behavior change for letters-per-minute, legibility, and dexterity (as per Grooved Pegboard) between the three phases of this experiment, a magnitude of effect was calculated. This statistical method is

described for single-subject research as the improvement rate difference (IRD) (Parker, Vannest, & Brown, 2009). The IRD is done by dividing the total number of improved data points from one phase by the total number of data points for the entire phase and then comparing as differences in the in-phase ratios: IRD= [(# of improved points in Phase x/#of total points in Phase x) – ([(# of improved points in Phase y/#of total points in Phase y)] x 100. (Phase x and Phase y represent generic terms for any of the three phases of this experiment.) An IRD equal to or under 50% is considered to reflect chance-only improvement between phases, and a negative IRD reflects a possible between-phase performance deterioration (Parker et al., 2009). When the data collected during one phase is markedly different from another phase, as would be expected when a treatment is effective, the IRD will be high.

Kinematic and kinetic data in Matlab (Mathworks, Natick, MA) were trimmed to 90% to cater for extreme pen movements (e.g. when dotting an i). In SPSS (v16, SPSS Inc., Chicago, IL) data were analyzed with a one-way Analysis of Variance, ANOVA, to analyze changes in kinematic and kinetic variables across phase (sorted by task) for each participant. After inspecting the source table, if the overall *p* value was significant for a variable, all possible pair-wise comparisons of means was made through the Least Square Difference, LSD, post-hoc analysis. This analysis facilitated understanding of how each variable changed for each writing task as they differed across phases.

To assess task difficulty of the endurance writing task, each sample was scored on Flesh-Kincaid scale, a widely used tool to assess reading and writing complexity (Doak et al., 1996). The samples were rated and revealed a range of reading difficulty levels, as would be expected in every day exposure to a variety of texts.

Results

According to the laterality quotients generated from the Edinburgh Handedness Inventory, all participants were strongly right-handed. Participants showed normal cognition as per the Short Blessed Test. All participants completed the study, accomplishing, to different degrees, a leftward transfer of handwriting skill. Compliance with the intervention varied across participants, ranging from 28% (Bart) to 100%

(Sabirah and Steve). Pre and post scores on the visual motor integration test were stable across all participants except one (Steve), who improved 26 points in scaled score.

Examination of the mean values per phase, percentage of non-overlapping data, and effect sizes show varying levels of positive results for all participants. (See Table 3.5). The IRD scores showed that, during the intervention phase, letters-per-minute and legibility showed increases in performance; whereas, scores on the Grooved Pegboard did not show improvement across any phase, except for Sabirah (Table 3.5).

Letters-per-minute changes demonstrated a grade-level improvement for all five participants. One participant (Ed) showed his improvement between the intervention and maintenance phases, another participant (Sabirah) improved a grade level between each phase, and all other participants improved between baseline and intervention phases only. See Figure 3.1 - Figure 3.5.

Legibility improvements were noted by large IRD for four of the five participants. The participant (Steve) who did not improve during the intervention wrote legibly during the baseline phase that affected calculation of IRD; in other words, his writing was quite legibly at baseline thereby leaving minimal room for improvement. Only one participant (Ed) continued to improve in writing speed (letters-per-minute) and legibility after the withdrawal/completion of the intervention. Legibility percentages for all participants across the three experimental phases are depicted in Figure 3.6.

For all participants, except Bart, there were correlations of varying strengths between outcome measures (legibility and letters-per-minute) and environmental and task factors (time of day and text difficulty). Sabirah and Ed showed a decrease in legibility when text difficulty increased. Three participants (Andrew, Steve, and Ed) showed correlation with an increase in letters-per-minute and an increased score for legibility. Steve also showed a positive correlation between text difficulty and letters-per-minute. Only one participant (Ed) showed a correlation between time of day and letters-per-minute. See Table 3.6 for direction, strength of correlations, corresponding *p* values, and interpretations.

Examining mean scores across each phase of the experiment for all kinematic variables demonstrated the following results: (1) *Copy Date* task showed the least change in kinetic and kinematic properties, (2) *Copy Alphabet* task showed the most

change, (3) Mean X and Y displacement were the most stable parameters across all tasks for all participants, (4) pressure was the most variable kinetic property across all tasks for all participants, (5) most significant changes were found in the pair wise comparison between the baseline and intervention phases, and (6) Ed had the least amount of change in graphomotor performance (2 variables changed within 3 tasks) whereas Sabirah had the most amount of change in performance (6 variables changed within 2 tasks). A final, notable result emerged from looking at kinematic variation across the four handwriting tasks performed onto the digitizer, all participants used the least amount of pressure when writing the numbers in *Copy Date* task than any other task, and conversely used the most pressure in *Trace Circles* task.

Comparison between non-dominant and dominant hand performance showed no participant achieving performance levels that met or exceeded dominant hand function. See Table 3.7. When comparing letters-per-minute from the highest score obtained during the intervention phase to the letters-per-minute of their dominant hand, the following were calculated as percentages of dominant hand performance: Andrew: 71%, Bart: 63%, Ed: 52%, Sabirah: 80%, and Steve: 63%. Comparing kinematic and kinetic variables between the dominant and non-dominant handwriting showed smaller values for X and Y displacement, meaning all writing samples with the non-dominant hand were consistently larger in height and width.

Discussion

This study described the efficacy testing of *Handwriting For Heroes,* an intervention created to facilitate handwriting skill development in clients who face I-IHDT. Results demonstrate the efficacy of an intervention based upon motor control and motor learning principles directed to facilitate handwriting skill development in the non-dominant hand. These results are directed to the foundation of establishing evidence-based practice for rehabilitation professionals working with adults who face I-IHDT. Investigating the efficacy of specific interventions helps advance the science and practice of rehabilitation.

Results of this trial with non-impaired participants show a strong relationship between the intervention and the outcome of improved handwriting skill. The large

effect sizes, high percentage of non-overlapping data, differences in means per phases, and large IRD for legibility and for letters-per-minute variables suggest that the intervention contributed to the change in handwriting performance. Furthermore, except for Ed, the end of the intervention marked performance stabilization. Looking closer at Ed's data reveal a plausible explanation for the difference in his results as compared to the other four participants. He began the intervention on May 12th and, because of scheduling difficulty, his fifth and final probe in the Intervention phase was June 9th which was the completion of the 3rd week of the intervention. Because he had an overall compliance rate of 81%, Ed's improved performance in the maintenance phase is likely a reflection of the gains he made during the last three weeks of the intervention that went undetected because no handwriting samples were collected during those weeks.

The legibility percentages of the participants show more variability in the Baseline phase as compared to both the Intervention and Maintenance phases. Legibility is foundationally important in writing because, combined with writing speed, contributes to writing automaticity. Writing automaticity, in turn, contributes to text-generation needed in compositional tasks and in converting auditory language into text as done in transcription (Peverly, 2006).

Writing automaticity was seen in the dominant handwriting samples obtained at the final probe. Each participant had a 100% legibility score and high-level speeds (letters-per-minute) for their dominant hand. No participant met the writing performance level of their dominant hand. This was expected because the intervention is only six-weeks long and because the dominance transfer was merely a simulation, no participant used their non-dominant hand for handwriting tasks outside the confines of the experiment (to do the intervention or complete the probes). It is interesting however, that the participants sustained their writing level performance with minimal decline into the maintenance phase.

The positive correlations that Andrew, Sabirah, and Steve showed between letters-per-minute and legibility were counter-intuitive and not in line with previous research that shows a negative correlation between legibility and (writing speed) letters-per-minute (faster writing is less legible). A possible explanation for this finding is that participants were developing handwriting skills for speed and neatness simultaneously,

thereby revealing a positive correlation between these sub-components (legibility and speed) of writing.

Ed and Sabirah showed strong, negative correlations between text difficulties and letters-per-minute (writing speed slowed as text difficulty increased). This finding is supported in the literature related to handwriting development in children (Graham, Berninger, Abbott, Abbott, & Whitaker, 1997); however care is taken in linking the findings because Sabirah was not a native English speaker which could account for her increased difficulty in copying the text, and Ed has too few data points in the Intervention phase. The final reason that caution is taken in drawing conclusions from this correlation is that while collecting the data during the experiment, the first author noted that participants were copying the text letter by letter, as opposed to a more mature cognitive strategy which is to read several words, hold them in one's working memory, and then write several words at a time.

The procedures used in this study offer sensitive ways to measure graphomotor performance change over time. The notion of measuring handwriting as a specific, functional dexterity task rather than using traditional dexterity assessments is supported by the overall lack of change in dexterity as measured by the Grooved Pegboard test. In other words, participants improved in a functionally dexterous task of handwriting that was not consistently detected by changes in their ability to move pegs in a pegboard: only Sabirah had an IRD above 50% (chance level) for Grooved Pegboard scores between Baseline and Intervention phases. This finding can be interpreted as support for a clear effect of the intervention rather than just exposure to the testing procedures of the probes.

Support for the efficacy of the intervention is also generated in light of the stability of scores for four participants on the visual motor integration assessment. Looking closely at the visual motor integration assessment of the one participant (Steve) who improved at the re-test revealed that he had skipped a page on the baseline assessment, which could account for a 15 point difference in scaled scores. These results could be interpreted to mean that the change in handwriting performance was from motor learning rather than from a change in visual motor integration ability.

The analysis of kinematic and kinetic variables also offered important findings about the change of the process of learning to write with the non-dominant hand. The X and Y displacement values showed minimal change in level, demonstrating stability in performance for writing size (space used to perform writing task). This was expected as each page was lined thereby providing spatial boundaries for the writing text, and offers confidence in interpreting the variation in the other kinematic variables. The majority of change detected for kinematic variables (for all tasks) occurred between the baseline and intervention phase, suggesting that the intervention, rather than just the passing of time or additional probes, influenced the change. Pressure was the least stable variable, a finding that is consistent with earlier research by scientists who measured writing parameters over time (Teulings & Schomaker, 1993). The participants who had the highest intervention compliance scores (Sabirah and Steve) had the greatest change in kinematic and kinetic variables across the four tasks, even in spite of Sabirah's obstacle of not beign a native English speaker or writer.

Limitations

This study was limited by convenience sampling, a non-concurrent baseline, and a narrow demographic (all participants were educated, right-handed professionals). Another weakness is the fact that scheduling difficulties for Ed limited the number of data points in his Intervention Phase.

One limitation in the experimental procedures is notable. The researcher who collected the data is the co-author of the *Handwriting For Heroes,* and that may have influenced the participants to comply with the intervention and to enroll in the study. Offsetting this possible source of bias, however, were the researcher's methods of ensuring procedural fidelity, academic oversight/accountability, and data sharing with the second author of this manuscript diminish potential bias.

Implications for Rehabilitation

The findings of this study have several implications for rehabilitation professionals. Results support the initiative to use technology and advance methods to measure functional performance (handwriting) rather than only measuring a component of a motor skill (dexterity). This study described methods to measure functional

performance that were more sensitive in detecting dexterity change that would be possible using only a traditional pegboard test.

Results support the use of SSRD to track change across time before, during, and after introduction of an intervention. This is relevant to busy practitioner-scientists who face obstacles to conducting large-scale clinical trials, such as resource constraints on time and funding (Satake, Jagaroo, & Maxwell, 2008). Also, SSRD is considered process research that is useful for practitioners who generally want to measure a client's response to treatment over time (Wolery & Harris, 1982). Overall, findings from this study tentatively affirm the use of *Handwriting For Heroes* as a useful rehabilitation intervention.

Conclusion

The importance of efficacy and effectiveness research is fundamental because the most necessary question asked is "Does this intervention work?" Efficacy research is valuable insomuch as it influences improvements of service provision through data-driven decision making in clinical practice. Data-driven decision-making is of increasing necessity because the current climate of health care reform requires demonstration of clinical and cost-effectiveness. This study was a starting point toward building an evidence-based practice for rehabilitation professionals working with adults facing I-IHDT. Handwriting is a functional task that was shown to be transferable to the non-dominant limb using a commercially available, 6-week intervention. Positive results, replicated across five non-impaired participants during this efficacy study, warrant a clinical effectiveness study.

Table 3.1 Description of the four sections of Handwriting For Heroes.

SECTION	DETAILED DESCRIPTION
Daily Exercises	Twelve daily exercises make up a "daily dozen", named after the military's historic exercise/callisthenic training regimen. Seventy-two exercises are separated by week, so each week has 12 pages of exercises. Every page in the *Daily Exercises* section contains lines, shapes, or boxes for the handwriting activities for each day of the week. "Day 1" of each week presents a new handwriting exercise. "Day 2" through "Day 7", the learner repeats the exercise, aiming for gradual improvement based on feedback of visually inspecting the previous day's work. Ultimately, "Day 7" is compared to "Day 1" to mark improvement over the week.
Homework	There are 42 different homework assignments within five categories. The following are the categories, and the number of each type of activity and the percentage of homework assignments of that type are in brackets: (1) Basic dexterity [5, 11.9%], (2) Functional writing [13, 31.0%], (3) Personal reflective writing [12, 28.6%], (4) Coloring pages [6, 14.3%], and (5) Dot-to-dot activities [6, 14.3%]. Handwriting, as an act of self-expression, has been used in therapeutic writing, which is effective as a psychotherapeutic intervention to reduce anxiety and improve well-being (Kerner & Fitzpatrick, 2007; Pennebaker, 1993).
Therapists' Tips	*Therapists' Tips* accompany Weeks 1-5. Lessons in this section cover many topics of handwriting, and specifically answer the following questions: (1) "What should you use to learn to write with?"[p.1-14], (2) "Do special grips help?"[p.1-14], (3) "When to practice?"[p.2-15], (4) "To slant or not to slant?"[p.2-17], (5) "Why cursive? And Why not printing?"[p.5-15], and (6) "Does writing have to be legible?"[p.5-15]
Website Companion	An interactive website, http://www.handwritingforheroes.com, serves as the *Website companion* section which complements the workbook. Included are 6 "Extra Credit" bonus pages, examples of successfully completed pages, resources for amputees, stroke survivors, and adults with traumatic brain injury, as well as handwriting product information. Another resource is a self-perception questionnaire on handwriting ability that asks learners to rate their writing performance on a scale of 0-10 in comparison to their writing performance in the dominant hand. The website allows a learner to contact one of the authors for guidance or feedback.

Table 3.2 Demographic information of participants

Participant	Age	Highest Education Level	Edinburgh Handedness Inventory[&]	Preferred Writing Style	Standard Score on Visual Motor Integration Test^	Score on Short Blessed Cognitive Test**
Bart	29	Associates degree	70	Cursive	(1)83 (2)83	0
Andrew	26	Masters in Public Health	70	Mixed	(1)87 (2)83	2
Sabirah†	35	Doctor of Philosophy	95	Manuscript	(1)92 (2)92	0
Steve	39	Bachelor of Art	65	Mixed	(1)72 (2)98*	0
Edward	35	Master of Science	100	Mixed	(1)87 (2)87	0

Note. Names have been changed to protect the identity of the participants.
†English was a second language
[&] *Below -40 = left-handed, between -40 and +40 = ambidextrous, and above +40 = right-handed*
^*(1) Baseline phase measurement and (2) Maintenance phase measurement*
**Steve skipped a page on the initial Beery Visual Motor Integration Assessment which could account for 15 of the 26 point discrepancy between test and re-test*
***0-4: Normal cognition, 5-9: Questionable impairment, and 10 or more: Impairment consistent with dementia*

Table 3.3 Personal factors, standard assessment to evaluate the factor as well as an explanation for why they are implicated in handwriting performance.

PERSONAL FACTOR VARIABLE	EXPLANATION	STANDARD ASSESSMENT
Visual-motor integration	Visual-motor integration is well-accepted as a unique and significant contribution to success in handwriting skill performance(Weintraub & Graham, 2000).	Beery-Bruktenica Visual Motor Integration (Beery^{TM} VMI) is a reliable and valid measure of visual-motor integration that has been standardized on 1,021 adults age 19-100 (Beery, 2008).
Cognition	Handwriting is a complex language processing skill that requires synchronization of multiple cognitive and sensorimotor processes. Handwriting involves focus, attention, planning, sequencing, working memory for spelling, content generation, and meaning-making (Berninger, 1994; Cornhill & Case-Smith, 1996; Fontana, Dagnino, Cocito, & Balestrino, 2008).	The Short Blessed Test is a valid and reliable cognitive screening tool that evaluates orientation, memory, central processing speed, and attention (Ball, Bisher, & Birge, 1999).
Laterality	Laterality, or handedness, inventories allows for a gradation of hand-dominance from right-handed to left-handed to ambidextrous based on the overall score.	The Edinburgh Handedness Inventory is a ten-item questionnaire that rates one's preference for hand use given ten different tasks (Oldfield, 1971). Of these ten tasks, five represent fine-motor dexterity while the remaining five represent more workbook dexterity tasks.

Table 3.4 Improvement Rate Differences (as percentage) for three dependent variables for intervention and maintenance Phases and Inter-rater reliability

Participant	Compliance	Phase	Grooved Pegboard	LPM*	Legibility	Inter-rater reliability
Bart	28%	Intervention	-90%	100%	100%	*r*=.91**
		Maintenance	0%	44%	0%	
Andrew	73%	Intervention	0%	100%	100%	*r*=.96**
		Maintenance	-58%	0%	0%	
Sabirah	100%	Intervention	92%	100%	100%	*r*=.91**
		Maintenance	52%	-8%	0%	
Steve	100%	Intervention	30%	43%	10%	*r*=.93**
		Maintenance	50%	0%	0%	
Ed	81%	Intervention	0%	-20%	60%	*r*=.99**
		Maintenance	15%	80%	70%	

Note.
**LPM for Letters-per-minute*
*** Inter-rater reliability for scoring legibility of writing endurance task, significant at p<.01*

Table 3.5 Mean values, percentage of non-overlapping data, and effect sizes for Grooved Pegboard and letters-per-minute outcomes

	Mean Values			% PND			Effect Size		
Andrew	Pegboard	B	88.4	Pegboard	B-I	25	Pegboard	B-I	-0.57
		I	87.1		I-M	0		I-M	-0.63
		M	84						
	LPM	B	40.2	LPM	B-I	100	LPM	B-I	3.91
		I	59.2		I-M	0		I-M	-0.25
		M	59						
Bart	Pegboard	B	85.8	Pegboard	B-I	9.1	Pegboard	B-I	0.1
		I	86.2		I-M	25		I-M	-1.01
		M	82.3						
	LPM	B	27	LPM	B-I	100	LPM	B-I	5.75
		I	39		I-M	75		I-M	1.29
		M	45						
Ed	Pegboard	B	91.2	Pegboard	B-I	40	Pegboard	B-I	-1.19
		I	87.4		I-M	25		I-M	-0.38
		M	86						
	LPM	B	47	LPM	B-I	20	LPM	B-I	-2.21
		I	43.4		I-M	75		I-M	1.49
		M	51.2						
Sabirah	Pegboard	B	108.8	Pegboard	B-I	91.7	Pegboard	B-I	-2.46
		I	91.8		I-M	60		I-M	-1.52
		M	79.2						
	LPM	B	32.4	LPM	B-I	100	LPM	B-I	2.84
		I	42.9		I-M	0		I-M	1.28
		M	49.4						
Steve	Pegboard	B	92.6	Pegboard	B-I	0	Pegboard	B-I	-0.99
		I	86.6		I-M	0		I-M	-1.21
		M	83.5						
	LPM	B	47.1	LPM	B-I	83.3	LPM	B-I	3.04
		I	59.8		I-M	0		I-M	0.46
		M	62.6						

Note. LPM=letters-per-minute; B=Baseline; I=Intervention; M=Maintenance; PND=percentage of non-overlapping data

Table 3.6 Correlation table for outcome measures, environment, and task factors

Participant	Correlation	Pearson r	Significance	Interpretation
Andrew	LPM and legibility	.793	.000**	Strong positive correlation
Bart	No significant correlations			
Ed	LPM and time of day	.660	.010*	Moderate-strong positive correlation
Ed	Legibility and text difficulty	-.715	.004**	Strong negative correlation
Sabirah	LPM and legibility	.633	.002**	Moderate-strong positive correlation
Sabirah	Legibility and text difficulty	-.747	.000**	Strong negative correlation
Steve	LPM and legibility	.653	.001**	Moderate positive correlation
Steve	LPM and text difficulty	.450	.041*	Weak-moderate positive correlation

Note. LPM=letters-per-minute
**Correlation is significant at .05 level (2-tailed)*
***Correlation is significant at .01 level (2-tailed)*

Table 3.7 Participants' letters-per-minute (LPM) and grade level equivalence for dominant and non-dominant hands

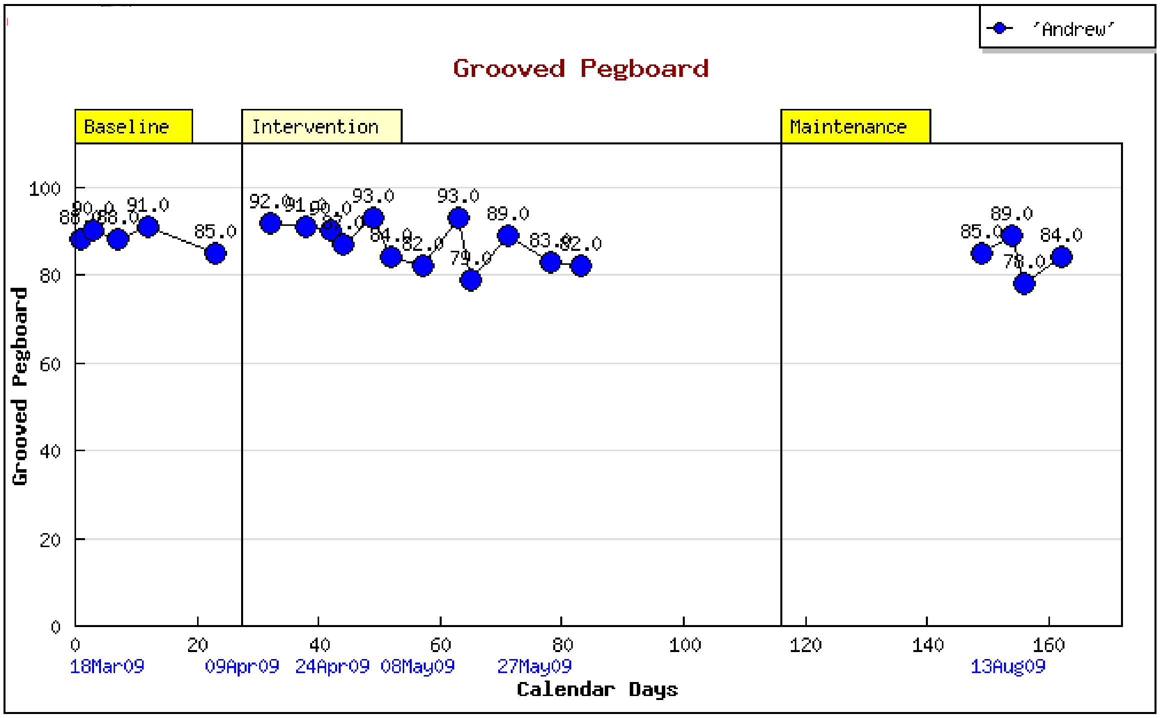
Participant	Dominant Hand LPM	Grade-level equivalent*	Non-Dominant Hand LPM	Grade-level equivalent*
Bart	71.4	5th	44.4	3rd
Andrew	94.6	7th	67.4	5th
Sabirah	67.6	5th	54.4	4th
Steve	106.4	8th	67.4	5th
Edward	99.6	7th	51.6	4th

*Note: *Grade level equivalence based on research by Graham et al. (1998)*

Table 3.8 Pair wise comparisons between phases and p-values for kinematic and kinetic variables per task for each participant.

Participant	Phase Comparison	Mean X velocity	Mean Y velocity	Mean X displacement	Mean Y displacement	Pressure	On-paper time
Bart	B-I	.000 (a)	.000(a) .000 (s)	.395(s)		.000(s)	.001(a) .000(s)
	I-M	.872(a)	.425(a) .102(s)	.009(s)		.109(s)	.027(a) .153(s)
Andrew	B-I	.547(a) .361(c)	.007(a) .156(c)		.950 (d)	.007(a) .299(d) .330(s)	
	I-M	.004(a) .007(c)	.008(a) .002(c)		.002(d)	.002(a) .002(d) .001(s)	
Sabirah	B-I	.038(a)	.044(a) .336(s)	.001(s)	.000(a)	.012(a)	.000(a) .003(s)
	I-M	.009(a)	.014(a) .008(s)	.796(s)	.253(a)	.277(a)	.070(a) .034(s)
Steve	B-I	.000(a) .001(s) .002(c)	.000(a)			.000(a) .000(s) .005(c)	.000(a) .000(s) .001(c)
	I-M	.847(a) .493(s) .558(c)	.696(a)			.000(a) .000(s) .001(c)	.552(a) .114(s) .959(c)
Edward	B-I	.005(s)				.005(d) .014(s) .107(c)	
	I-M	.004(s)				.005(d) .005(s) .001(c)	

Note. Only the pairs that demonstrated significance in the primary analysis are presented. Baseline Phase (B), Intervention Phase (I), Maintenance Phase (M), Copy Alphabet (a), Copy Date (d), Copy Sentence (s), Draw Circles (c)



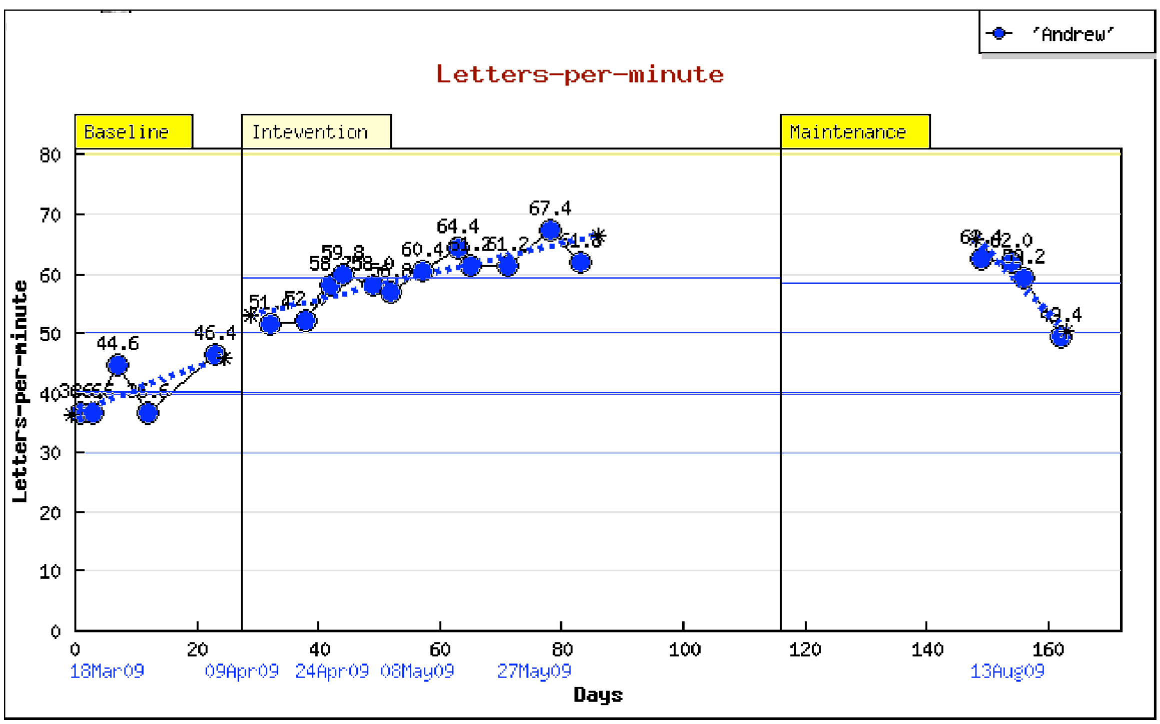
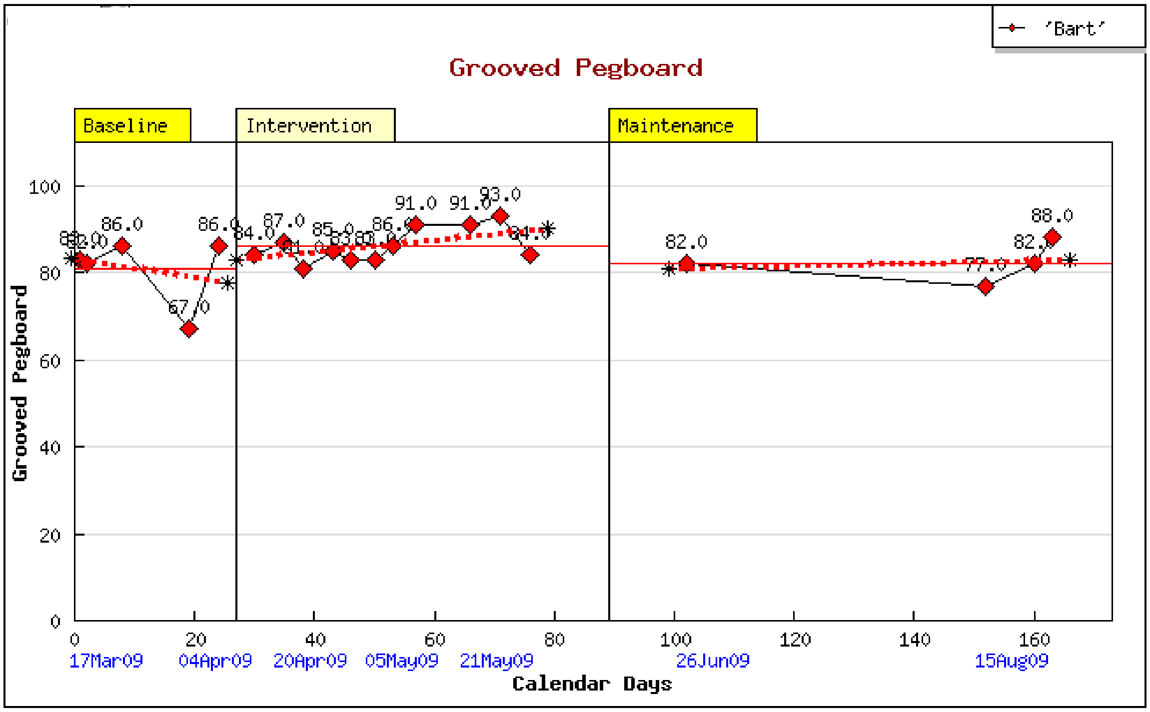


Figure 3.1 Grooved Pegboard and Letters-per-minute for Andrew

Table 3.9 Description of raw data for Andrew

ANDREW	BASELINE PROBES					INTERVENTION PROBES												MAINTENANCE PROBES			
	1	2	3	4	5	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4
Time of Day	1510	1415	1000	1000	1830	1200	1700	1500	1900	1400	1300	1300	1000	1300	1000	1300	1200	1030	1030	1300	1300
Legibility	86	76	85	93	89	95	96	97	96	100	100	96	99	97	98	98	99	100	98	99	99
Text. Diff.	15	14	10	22	11	11	8.4	13	15	9.5	14	17	13	11	12	13	9.5	11	17	13	13
LPM	37	37	45	37	46	51	52	58	60	58	57	60	64	61	61	67	62	62	62	59	49
Compliance						91		86		37		91		35		63					
	Days in Baseline Phase 23					**Days in Intervention Phase 52**												**Days in Maintenance Phase 14**			



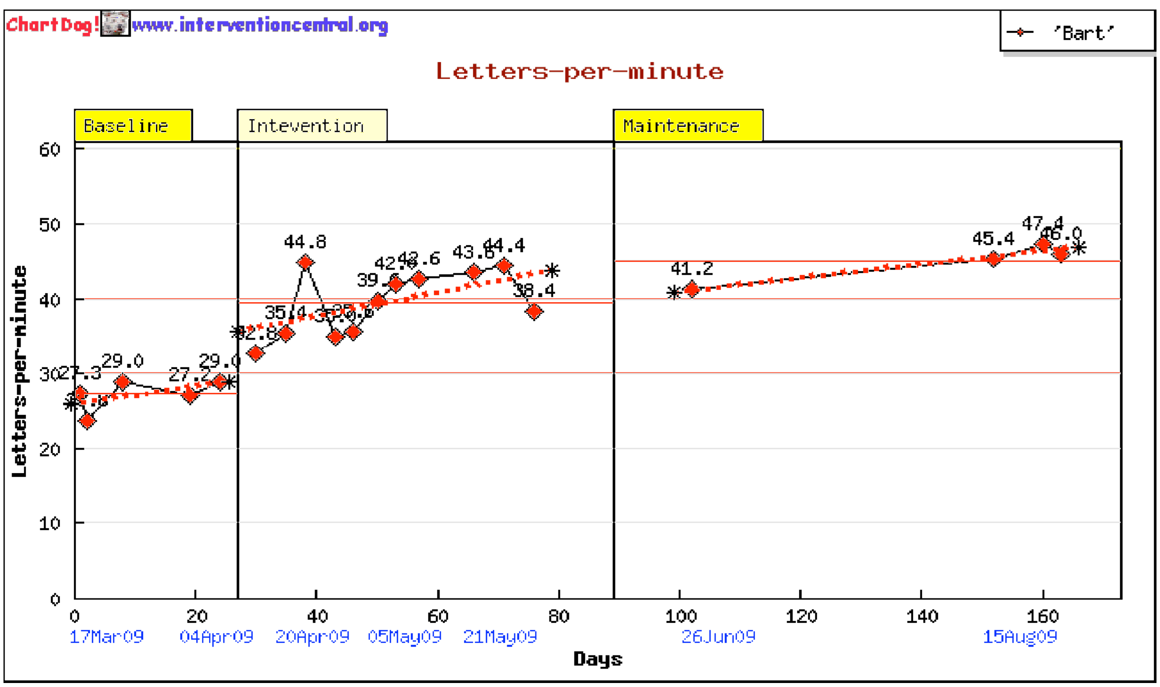
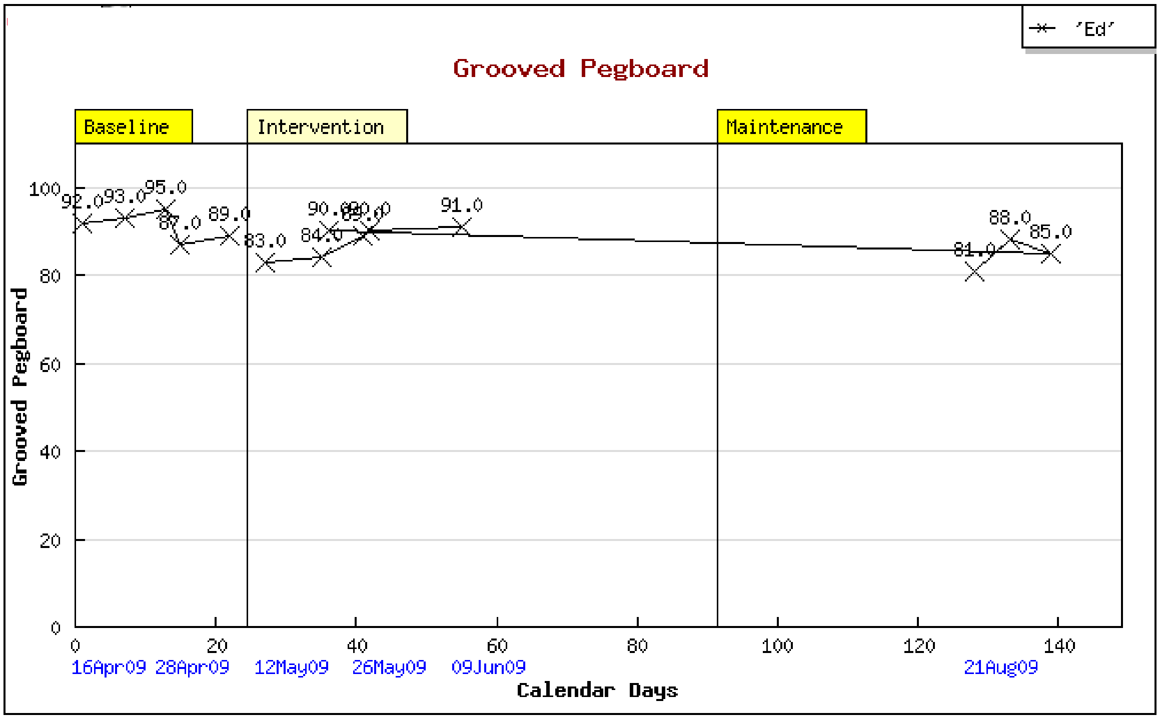


Figure 3.2 Grooved Pegboard and Letters-per-minute for Bart

Table 3.10 Description of raw data for Bart

BART	BASELINE PROBES					INTERVENTION PROBES												MAINTENANCE PROBES			
	1	2	3	4	5	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4
Time of Day	930	1800	1500	1300	1200	1900	1600	1900	1900	1400	1900	1200	1900	1200	1900	1600	-	1930	1030	1400	2030
Legibility	-	89	84	85	90	97	92	95	91	95	97	97	100	100	97	99	-	97	93	95	96
Text. Diff.	-	9.2	8.2	18	11	15	9.5	9.9	8.5	14	21	19	3.7	11	17	20	-	14	6.4	29	14
LPM	-	24	29	27	29	33	35	45	35	36	40	42	43	44	44	38	-	41	45	47	46
Compliance						91		32		12		12		9		0					
	Days in Baseline Phase 24					**Days in Intervention Phase 42**												**Days in Maintenance Phase 62**			



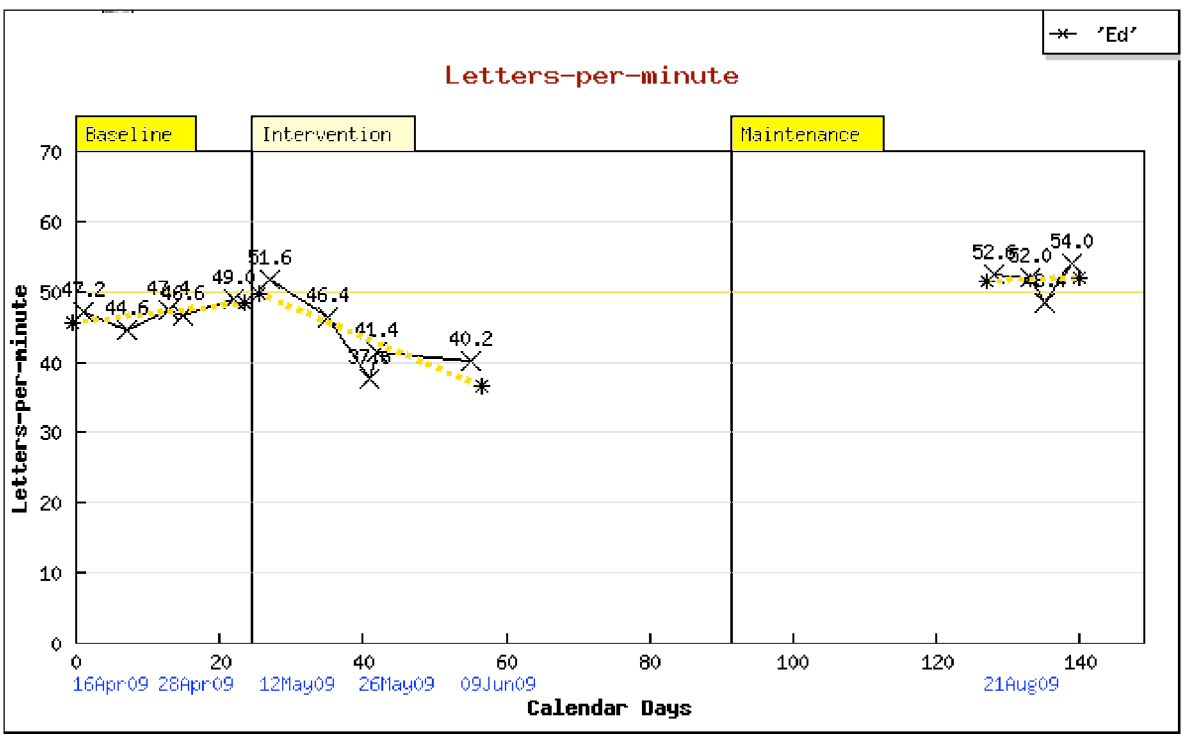
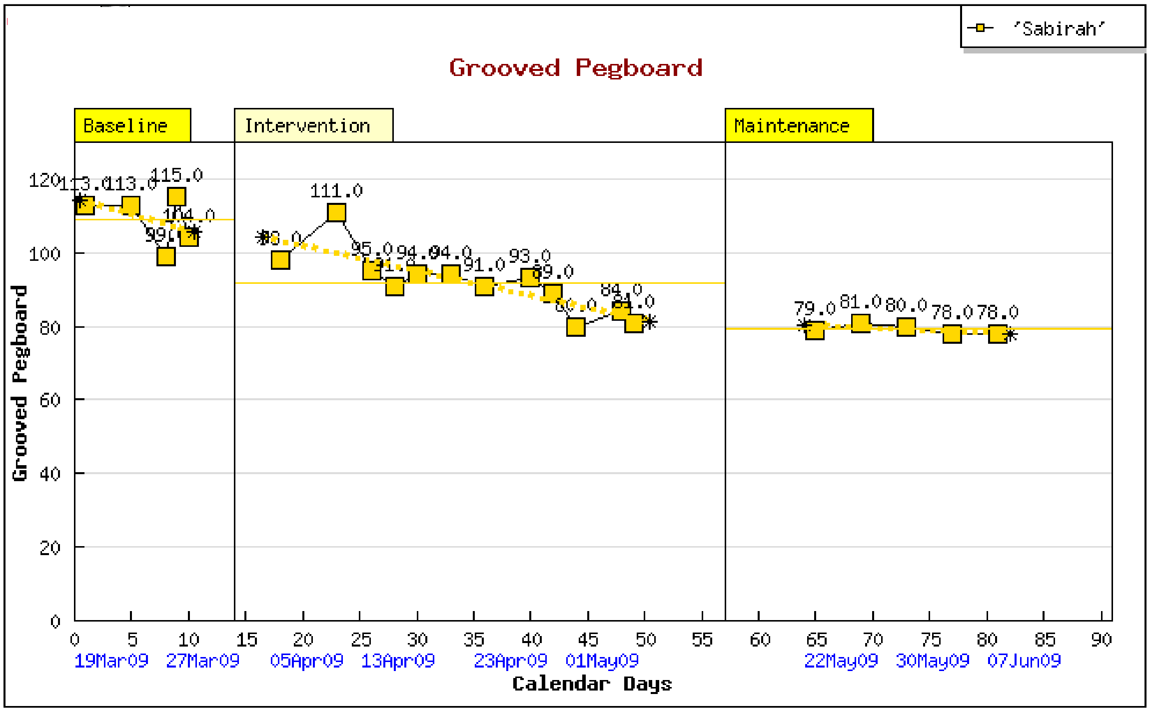


Figure 3.3 Grooved Pegboard and Letters-per-minute for Ed

Table 3.11 Description of raw data for Ed

ED	BASELINE PROBES					INTERVENTION PROBES												MAINTENANCE PROBES			
	1	2	3	4	5	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4
Time of Day	1100	1430	1100	1200	1700	1200	1300	900	1300	1000	-	-	-	-	-	-	-	1430	1830	1830	1730
Legibility	84	87	86	86	93	93	98	100	100	100	-	-	-	-	-	-	-	100	100	100	100
Text. Diff.	23	12	21	13	16	17	11	9.8	12	4.8	-	-	-	-	-	-	-	10	13	8.7	13
LPM	47	45	47	47	49	52	46	38	41	40	-	-	-	-	-	-	-	53	52	48	54
Compliance						91		84													
	Days in Baseline Phase 22					**Days in Intervention Phase 42**												**Days in Maintenance Phase 12**			



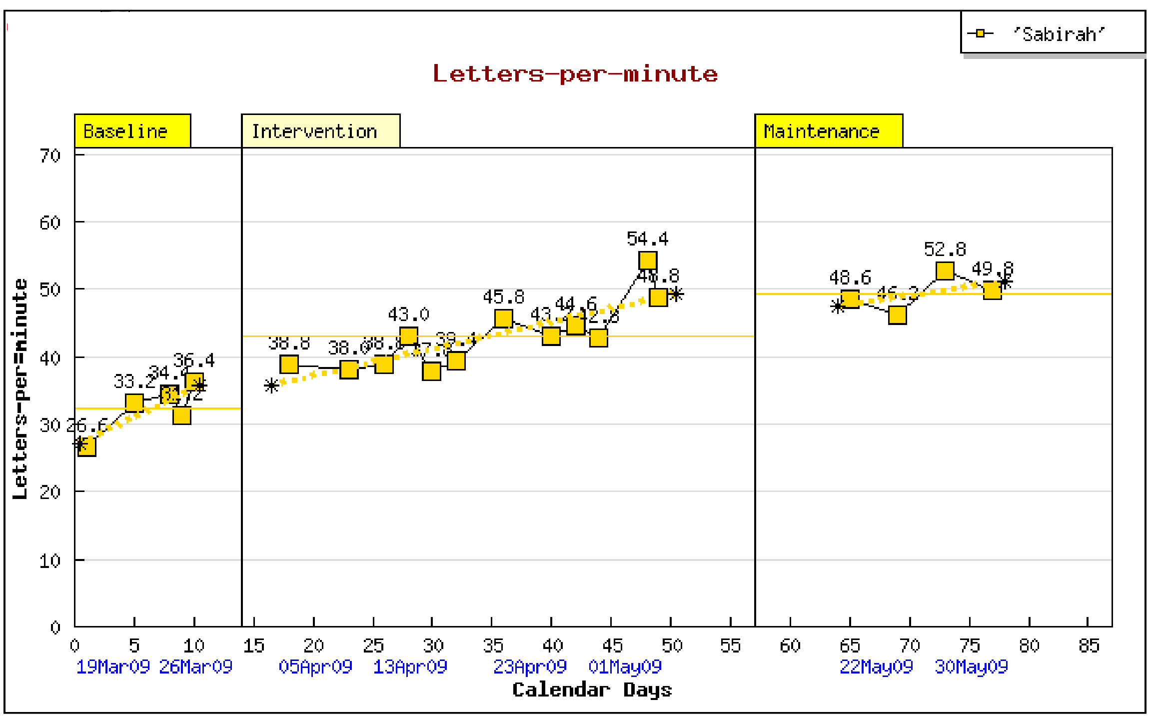
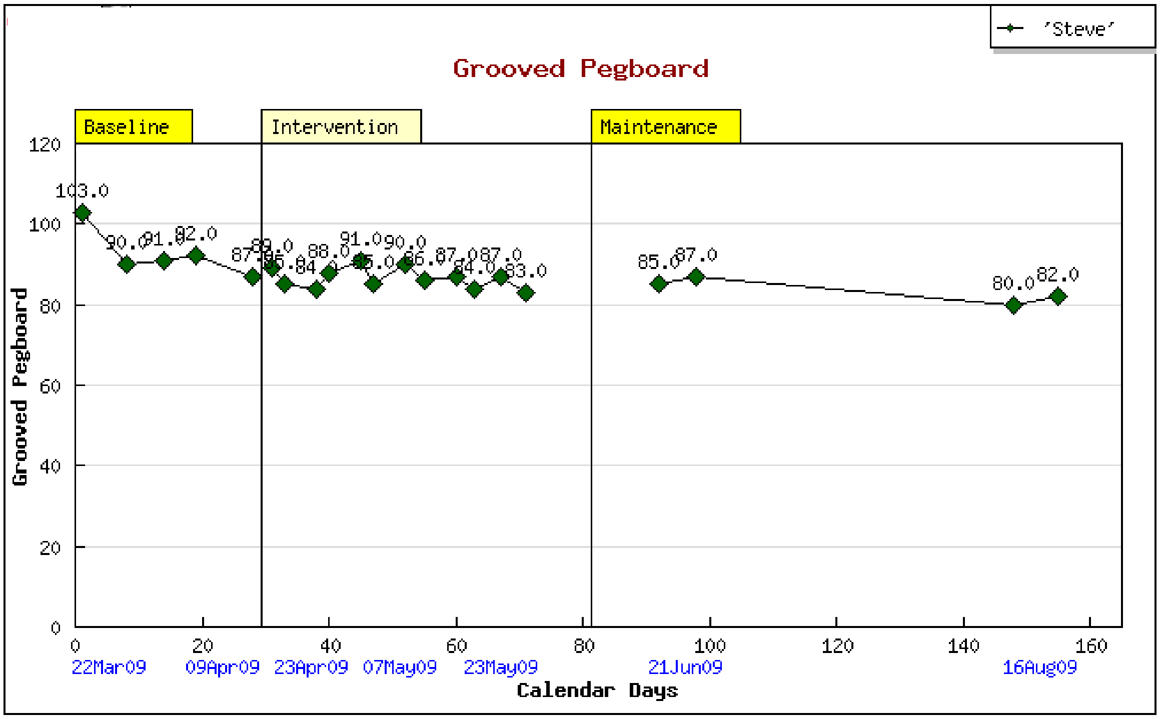


Figure 3.4 Grooved Pegboard and Letters-per-minute for Sabirah

Table 3.12 Description of raw data for Sabirah

SABIRAH	BASELINE PROBES					INTERVENTION PROBES												MAINTENANCE PROBES			
	1	2	3	4	5	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4
Time of Day	1730	815	1900	1600	1300	1300	1700	1400	1000	1900	1900	1900	930	1030	1200	1300	1330	1300	1300	1930	1330
Legibility	89	79	84	91	85	99	97	96	97	100	100	98	98	98	99	97	99	100	100	99	97
Text. Diff.	14	18	25	18	21	15	9.7	11	11	11	11	19	14	13	11	13	13	10	9.7	11	18
LPM	27	33	34	31	36	39	38	39	43	38	39	46	43	45	43	54	49	49	46	53	50
Compliance						100		100		100		100		100		100					
	Days in Baseline Phase 10					**Days in Intervention Phase 42**												**Days in Maintenance Phase 17**			



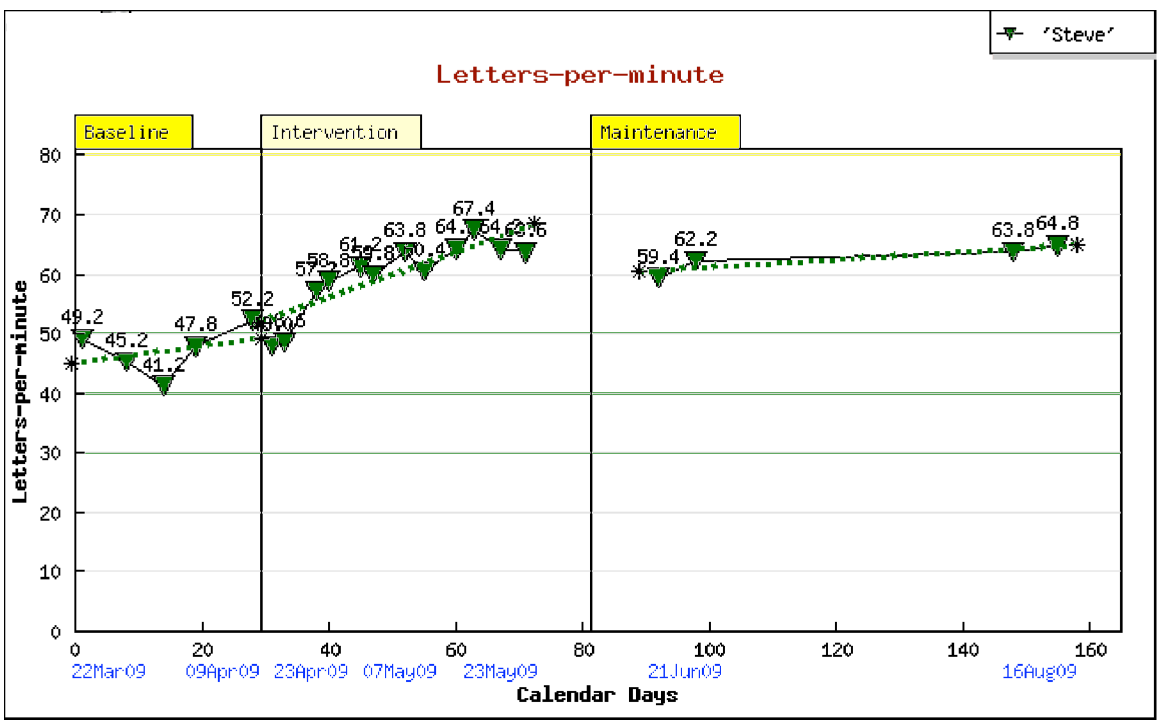


Figure 3.5 Grooved Pegboard and Letters-per-minute for Steve

Table 3.13 Description of raw data for Steve

STEVE	BASELINE PROBES					INTERVENTION PROBES												MAINTENANCE PROBES			
	1	2	3	4	5	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4
Time of Day	1500	1200	1000	1930	930	2000	2030	2030	2030	2030	2030	2030	2030	2030	1500	2030	2030	2000	2000	1200	1200
Legibility	87	93	94	97	97	97	96	98	96	97	97	100	100	100	98	98	100	100	100	98	99
Text. Diff.	14	7.1	12	10	11	13	10	14	13	15	12	16	29	12	27	13	11	20	16	13	12
LPM	49	45	41	48	52	48	49	57	59	61	60	64	60	64	67	64	64	59	62	64	65
Compliance						100		100		100		100		100		100					
	Days in Baseline Phase 28					**Days in Intervention Phase 42**												**Days in Maintenance Phase 64**			

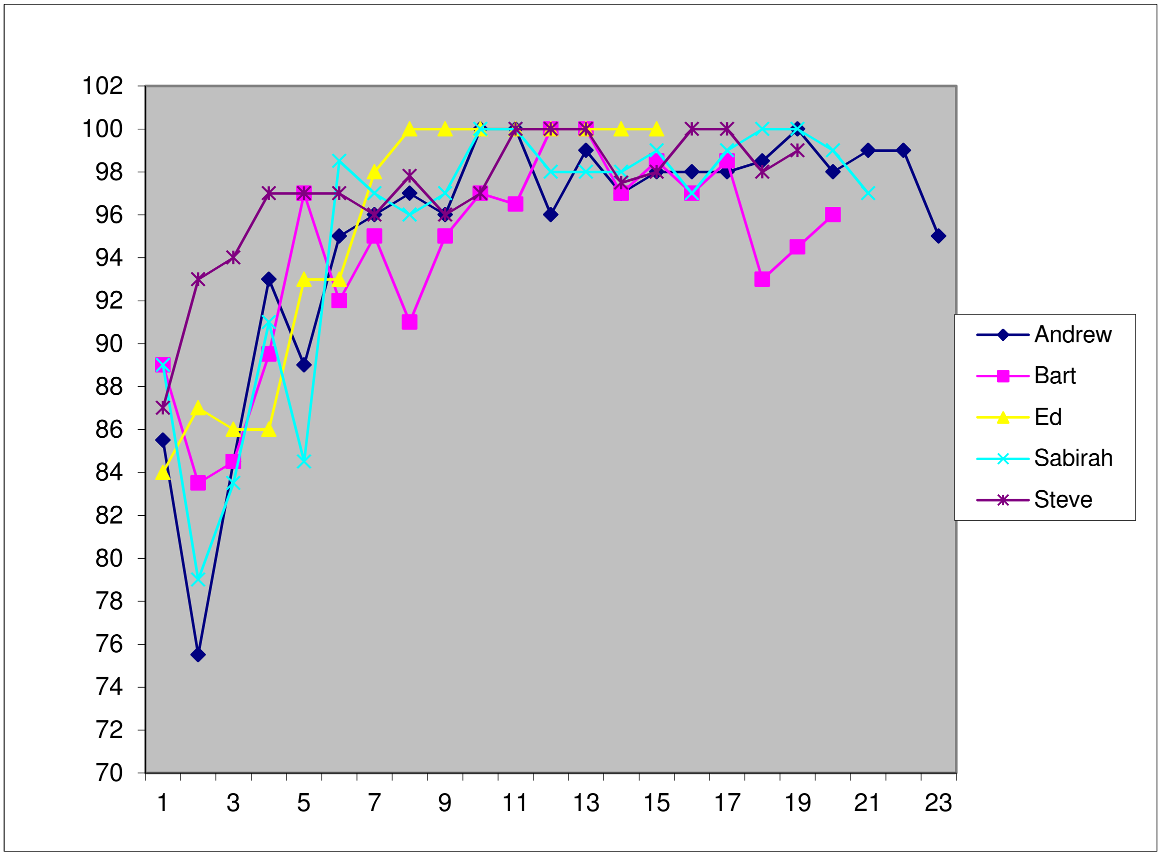


Figure 3.6 Legibility percentages for all participants across all three experimental phases

Chapter 4

Clinical Effectiveness of a Hand Dominance Transfer Intervention in Injured Military Members

Extremity injuries occur in 60-75% of reported injuries in military personnel (Ficke & Pollack, 2007). When extremity injuries are severe, military surgeons must decide to amputate or salvage the limb. Limb salvage is a general term defining the surgical, often multiple and staged, procedures done to spare a limb at risk of amputation. Conditions encountered in the military that necessitate salvage versus amputation decisions include multi-tissue injuries caused from low and high-energy trauma such as blast explosions, rifle projectiles, and motor vehicle accidents (Kumar et al., 2009).

Advances in military aerovacuation out of the theatre of operation; early, forward medical capabilities; and microvascular and plastic reconstructive surgery at military medical centers all contribute to an increase in the saving of injured extremities. However, despite advances in limb salvage, there remains a high associated morbidity, both immediate and long-term (McCready, 1988). This morbidity is a central concern for military occupational therapy practitioners who provide ongoing and extensive rehabilitation for service members with limb salvage.

A service member with a salvaged limb is a complex patient. This complexity is confounded by the limited number of evidence-based practice strategies upon which to build clinical practice guidelines for this patient population. A salvaged limb generally involves all components of neuromuscular-skeletal systems. This translates into multiple surgeries, increased risk of infection, prolonged use of pain medication, various healing rates of involved bone and soft-tissue structures, extended periods of immobilization, frequent medical and rehabilitation visits, and numerous off-duty work days. Surprisingly, oftentimes despite valiant efforts to save a limb, early-delayed amputation is recommended if a limb is painful, stiff, and non-functional six months after salvage (Burdette et al., 2009).

The issue of upper limb dominance as it relates to salvaged or amputated limbs is of unique concern. This concern exists largely because of established understanding that

the dominant limb has more strength, endurance, speed, and dexterity, and when lost translates into increased disability. Lost dominant hand function requires a transfer of dominance skills for participation in fine motor, dexterity activities that cannot be replaced by a prosthesis following amputation nor generally recovered after extensive, multi-tissue injury (Smurr et al., 2008). Because handwriting is the activity most often associated with hand dominance (Doyen & Carlier, 2002), it is a focus area of a hand dominance transfer program. Handwriting is viewed as a necessary skill for an injured service member who leaves the military and enrolls in college or seeks civilian employment that requires handwriting skills (Smurr et al., 2008).

Handwriting For Heroes is a rehabilitation workbook specifically designed for all military service members who face injury-induced hand dominance transfer (I-IHDT) following mutilating hand injuries to a dominant upper extremity, and subsequently undergo limb salvage or amputation (Yancosek & Gulick, 2008). *Handwriting For Heroes* has undergone an efficacy trial examining hand dominance transfer in unimpaired adults with positive findings; however the clinical effectiveness of the intervention remains untested.

Purpose

The purpose of this study was to evaluate the clinical effectiveness of *Handwriting For Heroes* in a military medical center where the intervention is standard of care for military service members who have undergone limb salvage or amputation of the dominant upper extremity.

Description of Intervention

Handwriting For Heroes (Yancosek & Gulick, 2008) is a six-week long hand dominance transfer intervention using a task-oriented approach with a distinct focus on handwriting skill development. The workbook includes twelve daily exercises that progress from simple to complex. The task-oriented approach to learning guides the service member through sentence writing, checkbook balancing tasks, journaling, dot-to-dot, and drawing activities that are staged over time to increase in complexity. The workbook also includes instructions for rote exercises such as working with TheraPutty® for finger strengthening, cyclic copying drills of common letter sequences,

repetitively flipping and catching a coin, and manipulating small objects with tweezers. These exercises are meant to improve dexterity in the non-dominant hand. The workbook instructs on cursive handwriting style because it causes less hand strain and diminishes the challenge of even spacing between printed letters. See **Error! Reference source not found.** for a description of the workbook's four main sections: (1) *Daily Exercises*, (2) *Homework*, (3) *Therapist's Tips*, and (4) *Website Companion*.

Methods

Study Design

This study used a single-subject research design (SSRD) with non-concurrent, replication across four participants. Multiple probes were taken in baseline, intervention, and maintenance phases.

Participants

Five injured, male service members (mean age 25 years) with a physician consult to occupational therapy for care of salvaged dominant upper limbs participated in this study. All participants signed informed consent approved by the military hospital's clinical research review board, and none received compensation for volunteering. One participant withdrew because of transfer to medical care facilities nearer to his hometown. See Table 4.1 for descriptive information of participants.

Measures

subjective and descriptive measures.

1. The Edinburgh Handedness Inventory is a ten-item questionnaire that rates participant's hand preference (prior to loss of dominant hand function) for ten different tasks (Oldfield, 1971). Of these tasks, five represent fine-motor dexterity and five represent more workbook dexterity tasks. This handedness inventory allows for a gradation of hand-dominance from right-handed to left-handed to ambidextrous based on the overall score.

2. The Short Blessed Test is a valid and reliable cognitive screening tool that evaluates orientation, memory, central processing speed, and attention (Ball et al.,

1999). Handwriting is a complex language processing skill that requires synchronization of multiple cognitive and sensorimotor processes. Handwriting involves focus, attention, planning, sequencing, working memory for spelling, content generation, and meaning-making (Berninger, 1994; Cornhill & Case-Smith, 1996; Fontana et al., 2008). This screening supported the assumption of adequate cognition needed to complete the *Handwriting For Heroes* intervention.

3 and 4. Self-reported pain and self-reported fatigue were measured using a Visual Analogue Scale (VAS) from 0-10. Pain is widely accepted to affect performance (Strong, Unruh, Wright, Baxter, & Wall, 2002), and this experiment took place in an acute and sub-acute care setting where pain levels fluctuate, particularly in this population that is often returning to the operating room for additional surgical procedures. Fatigue has been found to adversely affects handwriting performance (Parush, Pindak, Hanh-Markowitz, & Mazor-Karsenty, 1998), and was therefore also measured by a 0-10 VAS. Fatigue may fluctuate relative to time of day and medication use, and therefore those variables were also recorded.

outcome measures.

1. A graphomotor performance assessment (handwriting sample) was performed at each meeting. The following parameters were measured:

a. Displacement: trajectory length (displacement in centimeters) covered by the pen across the x and y axes. Measured in cm.
a. Velocity: average of absolute velocity of the pen tip. Measured in mm/s.
b. On-paper time. Measured in seconds.
c. Pressure of pen on digitizer. Measured in Newton/mm.
d. Letters-per-minute were counted by dividing the total letters written in a five-minute time period by five. The score was equated to a grade-level score based on research published on writing competencies of school-aged students, first to ninth graders (Graham, Berninger et al., 1998).
e. Legibility was measured by counting the number of *readable* words written during an endurance task and dividing by the total number of *written* words. When multiplied by 100, this provided a legibility

percentage score as originally suggested by Alston (1983).

2. Canadian Occupational Performance Measure (COPM) is an interview-based, valid and reliable measure used to detect change in perspective of performance and satisfaction with performance (Bosch, 1995; Bowman & Llewellyn, 2002; Chan & Lee, 1997). The COPM was modified by specifically asking interview questions to identify performance problems, issues, and concerns as they relate to handwriting tasks. The difference between scores before and after the intervention provided a score of clinical change, not statistical difference.

3. Dexterity was measured by the Grooved Pegboard, a standardized, time-based pegboard test with established reliability and validity (Yancosek & Howell, 2009). Each of the twenty-five pegs of the Grooved Pegboard has a ridge on one side and must be oriented correctly to fit into the twenty-five grooved peg holes. This ridge-effect necessitates visual attention to task and small movements of the thumb and index finger to orient the pegs correctly.

4. Self-perception of handwriting ability was measured by a questionnaire developed and pilot tested for the purpose of this study. Five questions asked the participants about readability (legibility), speed, and appearance (shape, size, slant, style), confidence in writing, and perceived level of importance of writing.

5. Compliance with the *Handwriting For Heroes* intervention was considered an outcome, as well as a contributing factor to the outcome since handwriting does not improve without direct practice (Dunsmuir & Blatchford, 2004; Graham, 1992; Jones & Christensen, 1999; Smits-Engelsman & van Galen, 1997). A compliance score was calculated by examining the participant's workbook each week during the Intervention phase. A score of one point for each completed daily exercise, and a score of zero for partially or not completed exercises was given. There were twelve exercises and one take home assignment for each day of the week, so a score between 0 and 91 (13 exercises x 7 days) was recorded for weekly compliance. An overall compliance score was also calculated. No minimum compliance was required.

6. Beery-Buktenica Visual Motor Integration (Beery™ VMI) is a reliable and valid measure of visual-motor integration that has been standardized on 1,021 adults age 19-100 (Beery, 2008). Participants copy 24 geometric shapes that progressively become

more difficult. Visual-motor integration is well-accepted as a significant contribution to success in handwriting performance (Weintraub & Graham, 2000).

Procedures

Each participant underwent five baseline probes. A baseline phase probe consisted of four measurements: (1) Grooved Pegboard (2) graphomotor performance assessment, (3) self-report pain measure, and (4) self-report hand fatigue measure. At the final baseline probe, the participant was given the *Handwriting For Heroes* workbook, instructed on the first lesson, enrolled in the weekly handwriting group, and told to work independently on the workbook on all other days.

Throughout the intervention phase, participants underwent bi-weekly probes. An intervention phase probe consists of six measurements: (1) Grooved Pegboard, (2) graphomotor performance assessment, (3) self-report pain measure, (4) self-report hand fatigue measure, (5) questionnaire on self perception of handwriting ability, and (6) compliance measurement.

Two weeks following the completion of the 6-week intervention period, the maintenance phase began. The maintenance phase examined skill retention and consisted of the following measurements: (1) Grooved Pegboard, (2) graphomotor performance assessment, (3) self-report pain measure, and (4) self-report hand fatigue measure.

To collect each handwriting sample during the graphomotor performance assessment, a 3.4 x 6.8 inch piece of white, lined paper was taped to a digitizer tablet (WACOM Intuis 3) controlled by a Lenovo Thinkpad notebook computer. MovAlyzR (Neuroscript, Tempe, AZ) was used to set-up, run the experiment, and capture/output x, y, and z coordinates at a sampling rate of 200 Hz. The IntuiS3 inking-pen was the wireless writing instrument. This set-up offered a pen-on-paper feel with direct digital input to Wacom tablet interactive screen. Customized program written with Matlab (MATLAB, Math Works Inc, MA) calculated kinematic and kinetic data of each handwriting sample.

During each probe, participants completed the following handwriting tasks onto the digitizer: (1) *Copy Date*: the dates were random dates to allow variation of numbers

to be copied, (2) *Copy Alphabet:* the 26-letter alphabet copied in cursive form without spaces between letters, (3) *Copy Sentence:* copy a 24-letter sentence, and (4) *Draw Circles:* participant drew four circles within boundaries provided by double-lined circles pre-printed onto the paper.

Draw Circles and *Copy Alphabet* remained the same at each probe; whereas *Copy Sentence* and *Copy Date* were purposefully varied at each probe to diminish effects from memorization. Participants angled the digitizer according to preference and completed the handwriting activities in cursive form. Each activity was presented on a 4.5 x 2.0 inch card mounted on blue cardstock placed in front of them. The card contained the instructions (which also were read to them) and an example of the completed activity in cursive (generated by the same handwriting font, School Script, used in *Handwriting For Heroes*).

A five-minute writing task was performed onto regular lined paper not attached to the digitizer. Participants opened a college textbook to any page and copied text. The pre-set option on the ULTRAK dual-timer clock system signaled an auditory cue to stop writing when five minutes elapsed. Total letters written were counted and divided by five to calculate a letters-per-minute variable. The samples from this task were also used to measure legibility. The first author met with two occupational therapists (raters) who read each word of all handwriting samples obtained at each probe. Words were individually presented to each rater through an adjustable view-window tool created out of cardstock for the purpose of shielding the reader from the other words on the page. To limit the evaluators' ability to decipher the writing based on context clues traditionally available to a reader, words were shown in the reverse-order than they were written. Additionally, the samples of all participants were mixed together and randomly presented to limit the rater's chance of improved deciphering based on familiarity with participants' writing styles.

Reliability

The following were intended to ensure procedural fidelity: 1) A standard operating procedure workbook was used to guide the execution of the experiment, 2) Each probe across the three phases was done in the same private treatment area by the

same occupational therapist, (3) All measurements of each probe were collected in one session, (4) Time of day was standardized as best as possible by scheduling treatment appointments for the same time each day, (5) The occupational therapist who collected the data was not involved in data analysis, (6) 20% of dexterity measurements (Grooved Pegboard) were timed by another occupational therapist and these data were measured for inter-rater reliability, (7) The instructions for rating the legibility of the writing samples were standardized and read to each rater prior to legibility testing, (8) To prevent learning, no performance feedback was given to the legibility raters regarding their accuracy of reading the words. Also, the results of rater 1 were concealed from rater 2, and (9) legibility was measured for all samples and the Pearson *r* statistic was performed as an inter-rater reliability score to determine consistency among the two raters. Reliability is reported in Table 4.3.

Data analysis

Data was described in detail for each participant and presented in a table format. Data included were age, preferred handwriting style, laterality score from Edinburgh Handedness Inventory, highest education level, scores on the COPM, and Beery™ VMI. Tables were made for each participant to describe outcome data: participants' compliance with the intervention, Grooved Pegboard scores, letters-per-minute, legibility; personal factors: self-perception of handwriting ability, self-report of pain and fatigue; environmental factor: time of day; and task factor: task difficulty. The task difficulty was measured for each endurance handwriting sample using the Flesh-Kincaid scale, a widely used tool to assess grade-level complexity of written text (Doak et al., 1996).

Data for outcome measures was graphically depicted and analyzed by visual analysis, the accepted method to analyze single-subject results (Wolery & Harris, 1982). These graphical depictions essentially represent "learning curves" for letters-per-minute and Grooved Pegboard Scores. Decreasing scores for the Grooved Pegboard and increasing scores for letters-per-minute show improved performance. These data show trend, variability, and level of data per phase.

To complement visual analysis of data, statistical analyses were done. To contrast the effect of behavior change between the three phases of this experiment, the data were described by phase means, percentage of non-overlapping data, and effect sizes. The effect size is calculated by subtracting the mean of the Baseline phase from the mean of the Intervention phase and then dividing the difference by the standard deviation of the Baseline phase values. Values can be positive or negative, and the stronger the effect of the intervention, the higher the absolute value of the effect score will be. Effect sizes are meaningful when compared across participants, or to other data sets which used similar experimental procedures.

To examine the correlation between outcome measures (legibility and letters-per-minute) and environmental and task factors (time of day and text difficulty), two-tailed Pearson r correlations were done in SPSS (SPSS version17, Chicago, IL). Because no participant reported any pain or hand fatigue, these personal factors were not analyzed. Numbers from weekly compliance scores could not be run because of limited statistical power given that each participant only had 6 compliance scores.

Kinematic and kinetic data in Matlab (Mathworks, Natick, MA) were trimmed to 90% to cater for extreme pen movements (e.g. when dotting an i). In SPSS data were analyzed with a one-way Analysis of Variance, ANOVA, to analyze changes in kinematic and kinetic variables across phase (sorted by task) for each participant. After inspecting the source table, if the overall p value was significant for a variable, all possible pair-wise comparisons of means was made through the Least Square Difference, LSD, post-hoc analysis. This analysis facilitated understanding of how each variable changed for each writing task as they differed across phases.

Data from an efficacy study done to evaluate the impact of *Handwriting For Heroes* with non-impaired adults was compared to results from this experiment. Because the efficacy study and the effectiveness study were both planned by the same researchers, the experimental methods were identical, thereby facilitating comparison of results.

Results

Four Infantrymen who sustained blast injuries while serving in military Operation Iraqi Freedom (OIF) and Operation Enduring Freedom (OEF) participated in the study. Three service members underwent limb salvage to their right, dominant upper limbs and one underwent limb salvage to his left, dominant upper limb. Two participants were greater than one year out from their initial injury. No participant had comorbidities; however, all had multiple concomitant injuries with frequent surgeries. Table 4.3 describes each participant's injury. Compliance was different across the participants with Rande stopping at Week 5 with no obvious change in handwriting performance. Also, two participants completed the intervention according to the suggested massed practice style of working on it each day for 42 consecutive days, while the other two participants had a start-stop-start work pattern (related to medical set-backs and holiday leave). All service members were high school graduates, and one had his Bachelor's of Art degree.

Graphed data of letters-per-minute and Grooved Pegboard scores show the direction of change (trend lines), variability, and levels (means) per phase. See **Figure 4.1 - Figure 4.4**. for each participant's performance curves**.**

Table 4.4 shows the values for means by phase for each participant for the Grooved Pegboard and for letters per minute, as well as the percentage of non-overlapping data, and the effect sizes. Kevin and Dave showed strong intervention affects with the percentage of non-overlapping data points higher than 50% for letters-per-minute, with corresponding effect sizes of 4.86 and 1.98, respectively.

Table 4.5 - Table 4.8 shows each participant's scores for outcome measures, environmental, task, and personal factors. No participant reported hand fatigue or pain. Text difficulty varied randomly across the probes. Time of day varied based on scheduling conflicts with other medical care providers, as well as the participant's personal schedules.

Grade level equivalence for each participant, based on the median values for all baseline probes, and the median value of the final five intervention probes, showed all participants advanced one grade level, with three participants writing at the 2nd grade level. (See Table 4.9).

kinematic variables.

Examining mean scores across each phase of the experiment for all kinematic variables demonstrated the following results: (1) *Copy Date* task showed the least change in kinetic and kinematic properties, (2) *Copy Alphabet* task showed the most change, (3) Mean X displacement was the most stable parameters across all tasks for all participants, (4) pressure was the most variable kinetic property across all tasks for all participants, (5) most significant changes were found in the pair wise comparison between the baseline and intervention phases, and (6) Kevin had the least amount of change in graphomotor performance (4 variables changed within 3 tasks) whereas Mike had the most amount of change in performance (6 variables changed within 3 tasks). A final, notable result emerged from looking at kinematic variation across the four handwriting tasks performed onto the digitizer, all participants used the least amount of pressure when writing the numbers in *Copy Date* task than any other task, and conversely used the most pressure in *Trace Circles* task. See Table 4.10 for p values for pair wise comparisons between Baseline, Intervention, and Maintenance phases.

COPM scores reflect clinical changes and show changes in each participant's perspective of his performance and satisfaction. When COPM results were organized according to handwriting tasks, rather than according to participants, results revealed that more complex tasks such as filling out college applications and writing letters had the least amount of change from pre to post-intervention. See Table 4.11. Also, changes on the self-perception of handwriting ability questionnaire showed perceived improvement across all participants. See Table 4.12.

legibility.

Legibility improvements were noted across participants. See Figure 4.5 for visualization of legibility changes for all participants. See Figure 4.6 - Figure 4.9 for visualization of participants' pre and post-intervention handwriting samples. Changes in letter sizes, shapes, and slant are noticeable. Mike continually crowded the left side of the writing paper during the endurance handwriting task, while leaving a wide right-side margin. This right-side neglect was also noted in his Beery™ VMI test booklet.

visual motor integration.

Scores of the VMI were stable for three participants. See Table 4.1. Dave made improvements on his VMI score, but it is notable that he had a foreign body lodged in his eye and bilateral corneal burns that likely affected his Baseline phase performance. See Figure 4.10 for pre- and post-intervention examples of each participant's attempt at copying the final (hardest) geometric figure (Figure #30) from the Beery™ VMI. Mike had the lowest score that remained unchanged following the intervention. For all participants, except Rande, there is notably less ballistic patterning to the lines on the post-intervention drawing. Although not a timed test, Kevin took greater than 2 hours to initially complete the VMI compared to 12 minutes to completion at the re-test (post-intervention).

outcome, tasks, and environmental factors.

Results of the correlations between outcome, task, and environmental factors revealed that time of day had the strongest correlation with writing outcomes (letters-per-minute and legibility) across two participants, meaning that later probe times correlated with poorer handwriting speed and legibility. Time of day fluctuated because of medical and personal situations and competing appointments with other healthcare services. Rande showed no correlation between factors and outcomes. See Table 4.13 for correlations, significance levels and interpretations.

Discussion

Two participants had undergone limb salvage with their primary injuries to their elbows and forearms with little direct trauma to the hand. Subsequently, they did not actively work on handwriting or hand dominance transfer until participation in this study which was one to two years after their initial injuries. These two participants showed less of an intervention effect than the two participants who enrolled in the study (and began the intervention) within weeks of their injury. The timeframe of when a patient with upper limb salvage accepts the prognosis of permanent loss of hand function and willingly engage in an intervention to transfer hand dominance has not been studied.

To varying degrees, all participants made improvements in outcome measures that captured the written *product* (letters-per-minute and legibility) and the writing

process (kinematic variables). Also, participants made improvements in basic dexterity (Grooved Pegboard). Improvements in letters-per-minute equated functionally to an improvement of one grade level (from 1st to 2nd) for three participants.

Because the military member participants all sustained blast injuries, and two participants had moderate and one had mild traumatic brain injuries, cognitive limitations may have been a contributing factor. For Mike and Dave, visual motor integration deficits may have been a possible contribution. In accordance with established research, deficits in VMI would also account for low legibility scores and slow handwriting speeds, particularly when copying text that requires visualization of the letters, spatial recognition of the letters' shapes and then manipulation of the pen or pencil to produce that shape on paper (Cornhill & Case-Smith, 1996; Weintraub & Graham, 2000). This finding is further validated by the fact that Mike made the most improvements in his handwriting process, as per kinematic changes of higher velocity in X and Y axes, and less on-paper time for three writing tasks. Despite gains in the writing *process* however, Mike had difficulty with improved handwriting *products*: speed and legibility. Deficits in VMI may well account for his low legibility scores given that legible writing requires mastery of spatial relationships in order to produce consistent slant, on-the-line, and evenly spaced connected letters to form a readable script (Cornhill & Case-Smith, 1996).

Other than a weak, positive correlation between text difficulty and letters-per-minute for Dave, the results of the correlation analysis between outcome measures (legibility and letters-per-minute) and environmental and task factors (time of day and text difficulty) were different than the patterns found in the efficacy trial with non-impaired participants. Specifically, time of day appeared to affect legibility and letters-per-minute showing moderate to moderate-strong correlation for Kevin and Mike. Although participants reported no hand fatigue at any of the probes, this correlation may be meaningful given that their only functioning hand could have performance decrements secondary to fatigue, which would validate findings in the children's literature showing a performance decline with fatigue (Parush, Pindak et al., 1998). The other possible explanation is related to effects of medication.

The possible explanation of the influence of medication and the general overall impact of sustaining trauma, and the general sequela that follows, should be considered. This is particularly valuable for military occupational therapy practitioners to bear in mind because an injured service member may wish to leave the military and attempt to meet the rigorous academic demands of college. If college is a goal, then participants will need to be able to write at speeds greater than those of second-grade equivalence, and *Handwriting For Heroes* will not be enough of an intervention strategy to help them achieve that goal.

The absence of a negative correlation between text difficulty and handwriting speed or legibility supports the following notion developed from results of the efficacy trial: participants copied the text letter for letter (an immature strategy) rather than reading several words, storing them in the working memory, and transposing them onto the paper (a mature cognitive strategy). The similarities in copying strategies between non-impaired and injured participants suggests that they shared a similar constraint on performance which was related primarily to motor control and motor planning rather than cognitive limitations.

Task difficulty did however seem to affect scores on the COPM; for example, the simpler the task the more favorable the change in performance and satisfaction on the COPM. The tasks that the participants reported less change in perceived performance ability and correspondingly less satisfaction with performance were more difficult handwriting tasks, and also were tasks that were not covered extensively in the intervention workbook. This again is explained by the relatively short duration of the intervention. As with any complex motor task, six-weeks of training in handwriting is expected to yield beginner-level skills. This was demonstrated by the participants' reporting that they were (or would be) able to sign their name, write dates on calendars, make "to-do" lists, complete word/number puzzles, and fill out medical forms with less ability to write letters or take notes/exams in college.

Limitations

This study was limited by the non-concurrent baseline, the short "inert" time between Intervention and Maintenance phases, and the expanded timelines due to

surgeries and recovery times of two participants. The single-subject design inherently has strong internal validity but is balanced by limitations of generalizing findings to other populations. However, this design was well suited for the effectiveness study in a clinical environment primarily because the design can be replicated by occupational therapy practitioners who wish to test this intervention with clients. A final limitation is that Kevin has missing data (no maintenance phase data points) because of scheduling conflicts.

Implications for Occupational Therapy

The findings of this study have several implications for occupational therapy.

Therapists should address VMI deficits through evaluation and treatment, particularly with cognitive limitations (TBI). Additionally, this investigation may generate interest into other patient populations who sustain peripheral neuromusculoskeletal injuries not caused from combat exposure, such as brachial plexus injuries, crush injuries, Chronic Regional Pain Syndrome (CRPS), or focal hand dystonias. The participants were compliant with the intervention. The two participants who began the intervention shortly after their injuries showed larger gains which support the argument for early initiation of the intervention. Given the contents of the modified COPM interview, and the results in perceived satisfaction and performance, occupational therapy practitioners may wish to augment the intervention with transcription and composition activities until the workbook undergoes revisions to incorporate more of these types of tasks.

Conclusions

Handwriting For Heroes is an intervention that injured service members willingly complied with the intervention and made performance improvements in outcomes that measured basic dexterity, handwriting products, and the process of writing. Outcomes were clinically significant as noted by the participants' improved perception of performance and satisfaction of that performance. *Handwriting For Heroes* is an effective treatment intervention for injured military service members who face I-IHDT. Occupational therapy practitioners should establish realistic goals for completing the intervention in the recommended massed-practice format of 42

consecutive days and should start the intervention early in the service member's rehabilitation plan.

Table 4.1 Demographic information of participants

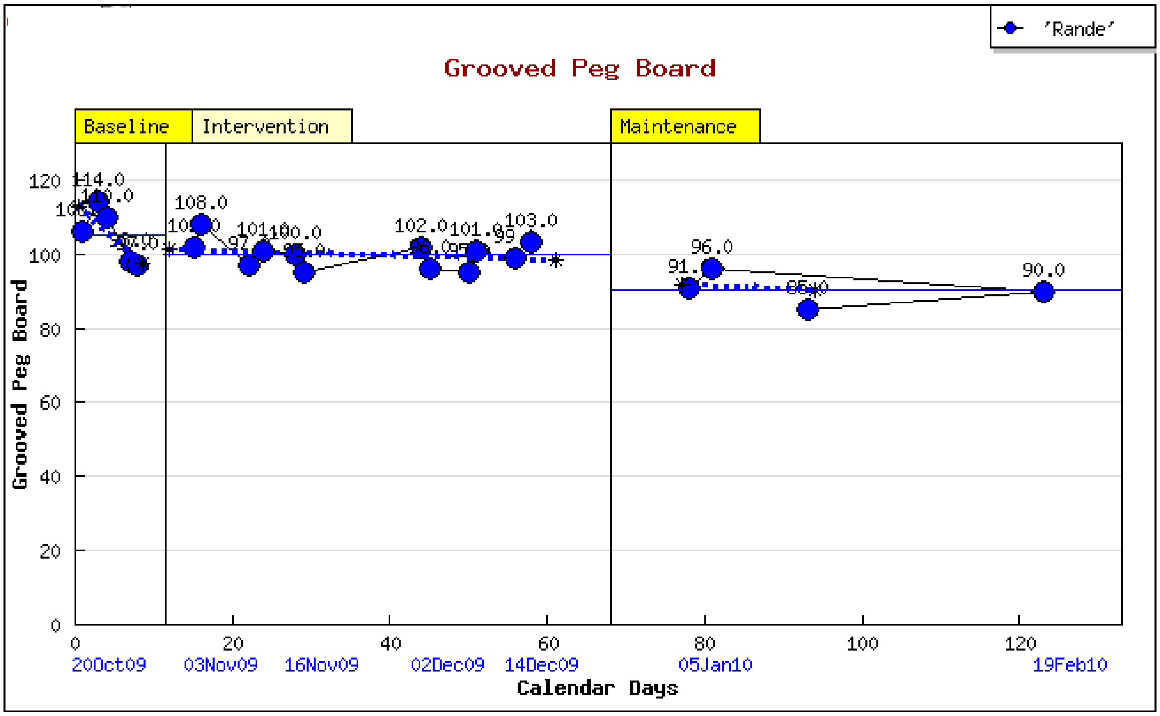
Participant (age)	Highest Education Level	Edinburgh Handedness Inventory[&]	Preferred Writing Style	Short Blessed Cognitive Test*	Relation to intervention	VMI	COPM: Performance	COPM: Satisfaction
Rande (28)	HS	-100, LHD	Mixed	0	Pre	92	3	3
					Post	92	6.6	7.4
Dave (23)	HS	60, RHD	Print	0	Pre	66	2.2	2.2
					Post	87	6.8	5.8
Kevin (27)	BA	50, RHD	Mixed	0	Pre	103	1	1
					Post	98	9.4	9.4
Mike (22)	HS	90, RHD	Print	1	Pre	66	3	1
					Post	66	7.6	7.8

Note. Names have been changed to protect the identity of the participants.

[&] *Below -40 = left-handed, between -40 and +40 = ambidextrous, and above +40 = right-handed.*

LHD= left hand dominant, RHD=right hand dominant

**0-4: Normal cognition, 5-9: Questionable impairment, and 10 or more: Impairment*



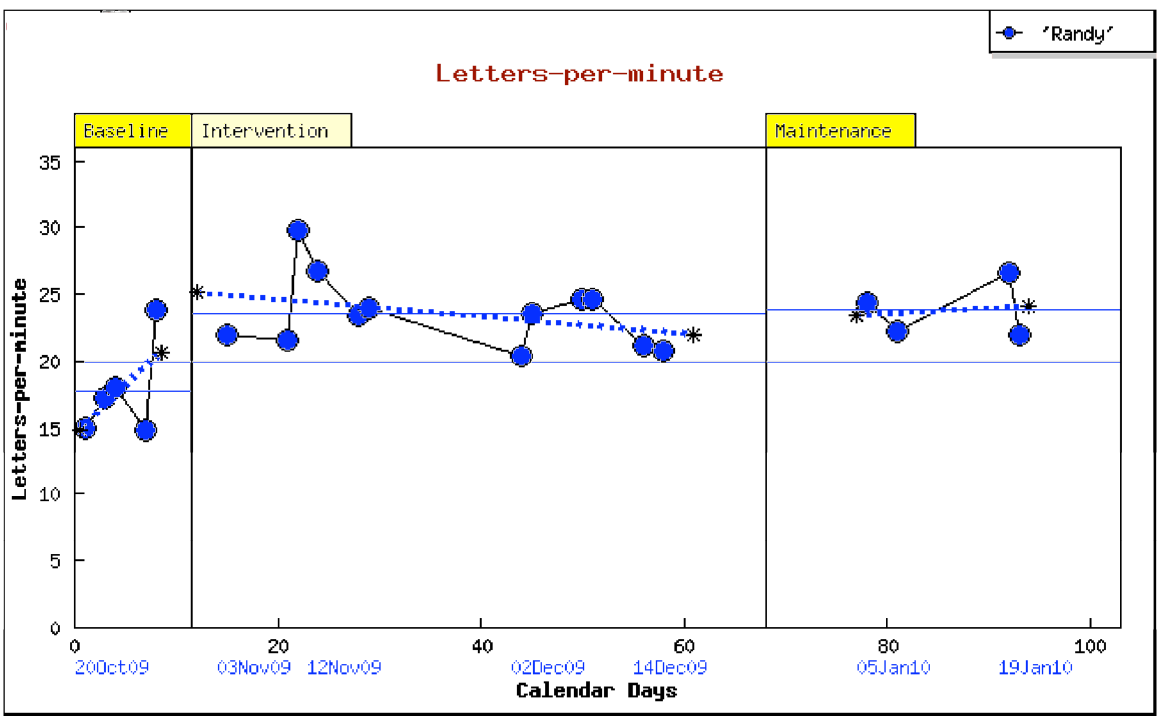
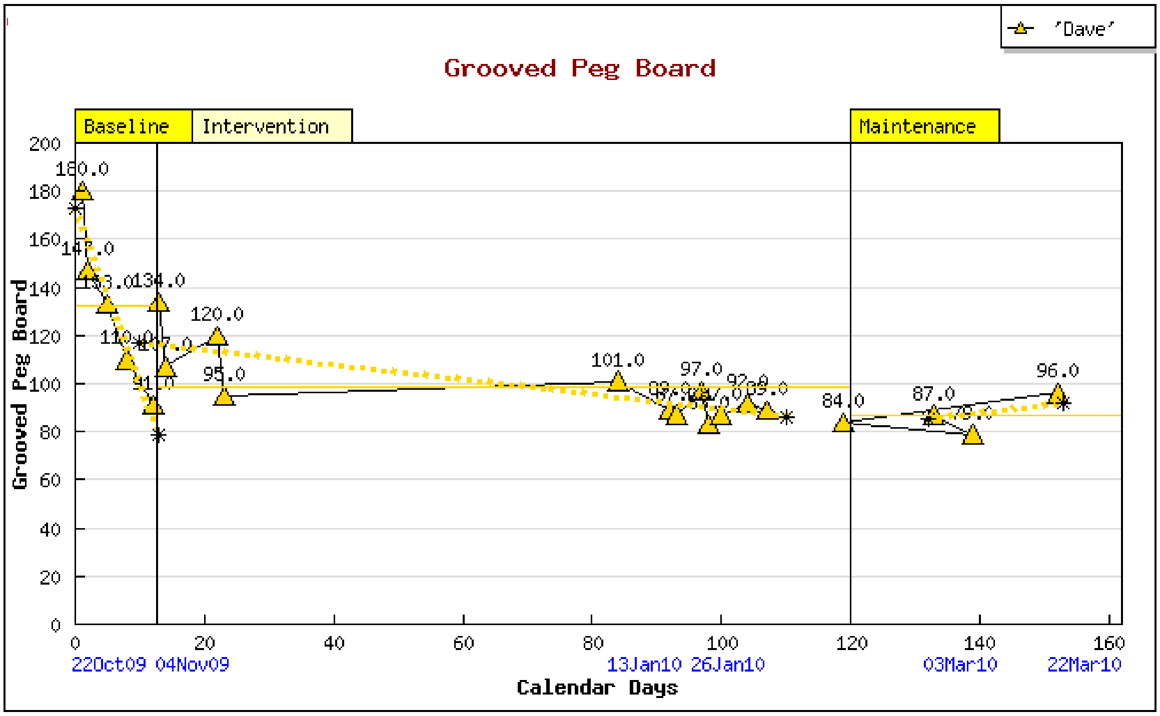


Figure 4.1 Letters Per Minute and Grooved Pegboard for Rande



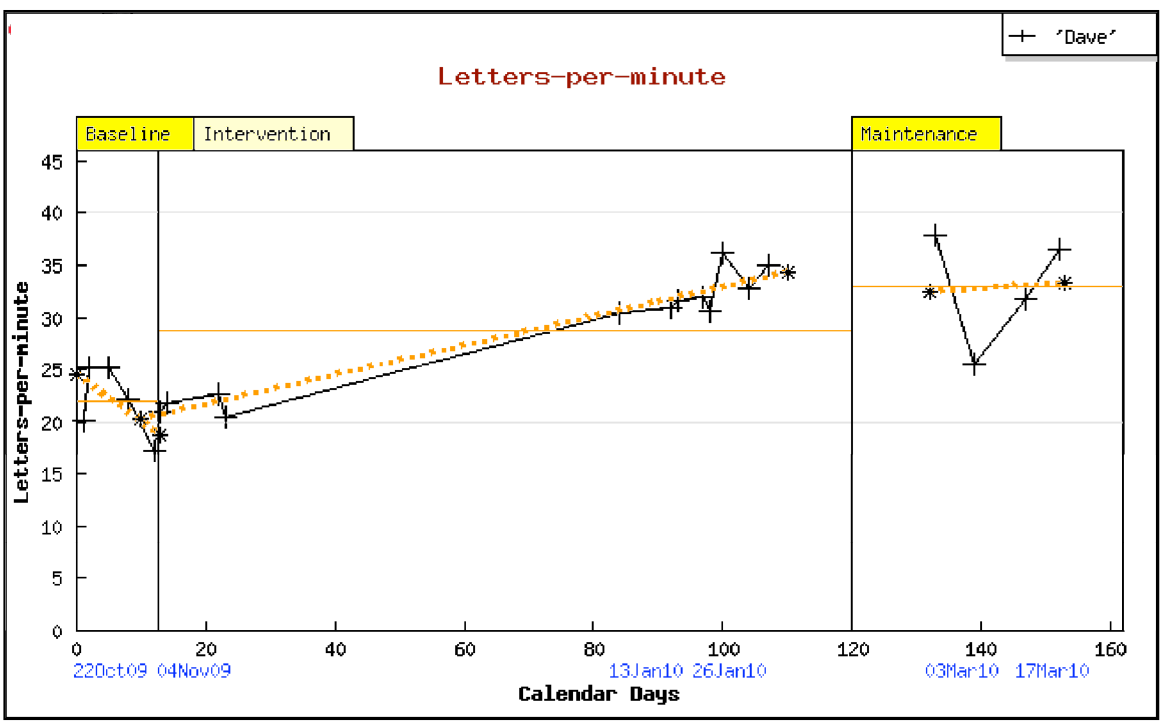
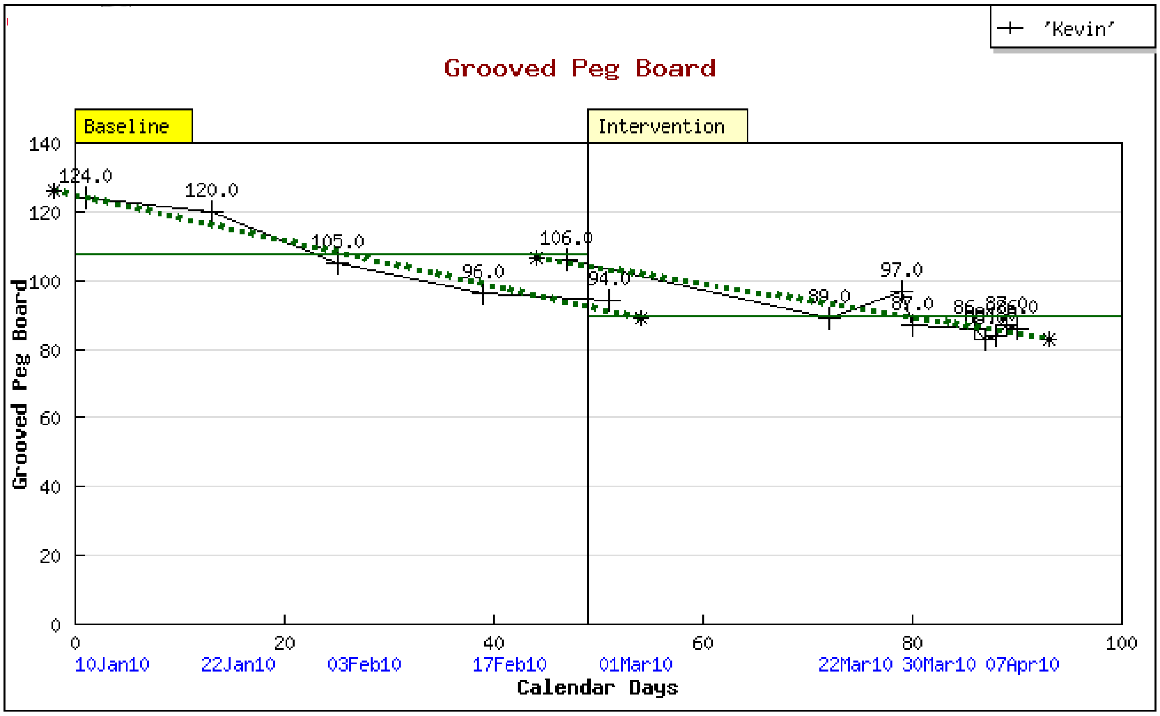


Figure 4.2 Letters Per Minute and Grooved Pegboard for Dave



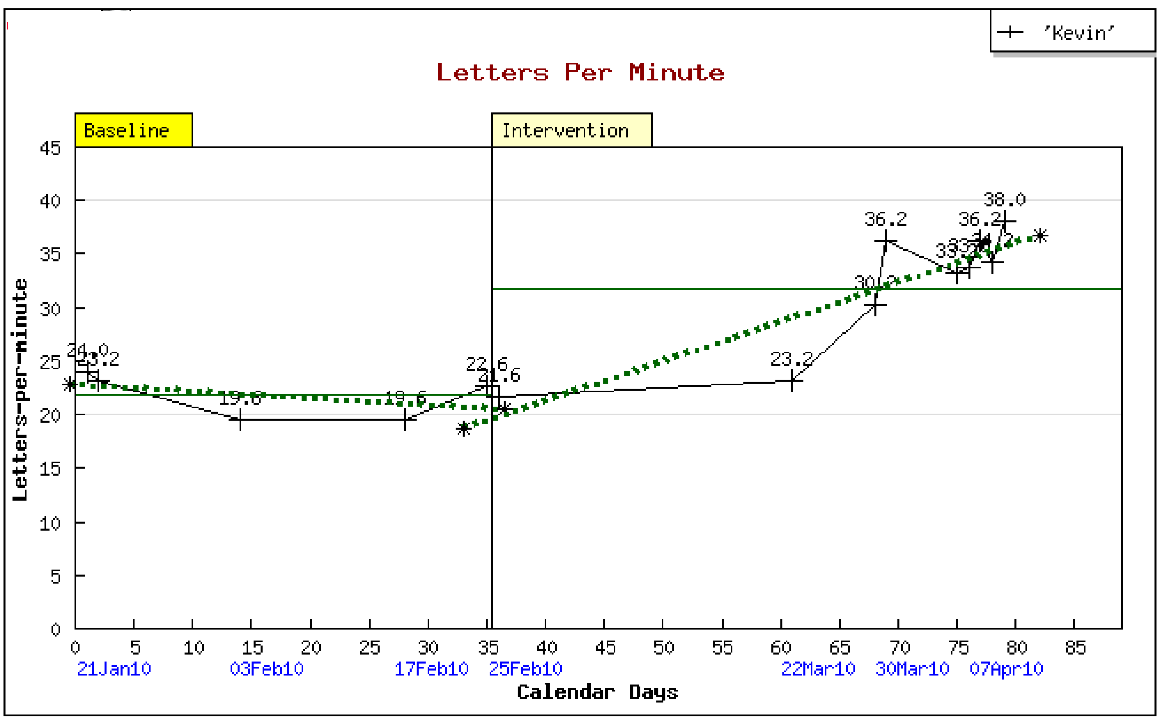
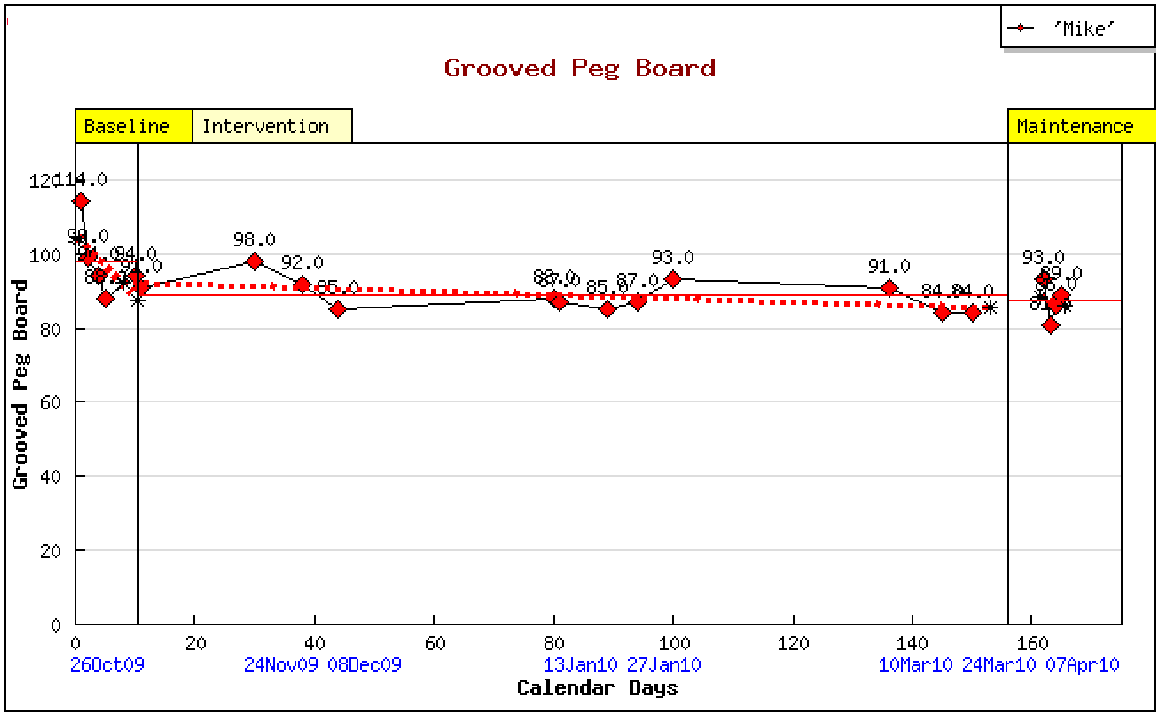


Figure 4.3 Letters Per Minute and Grooved Pegboard for Kevin



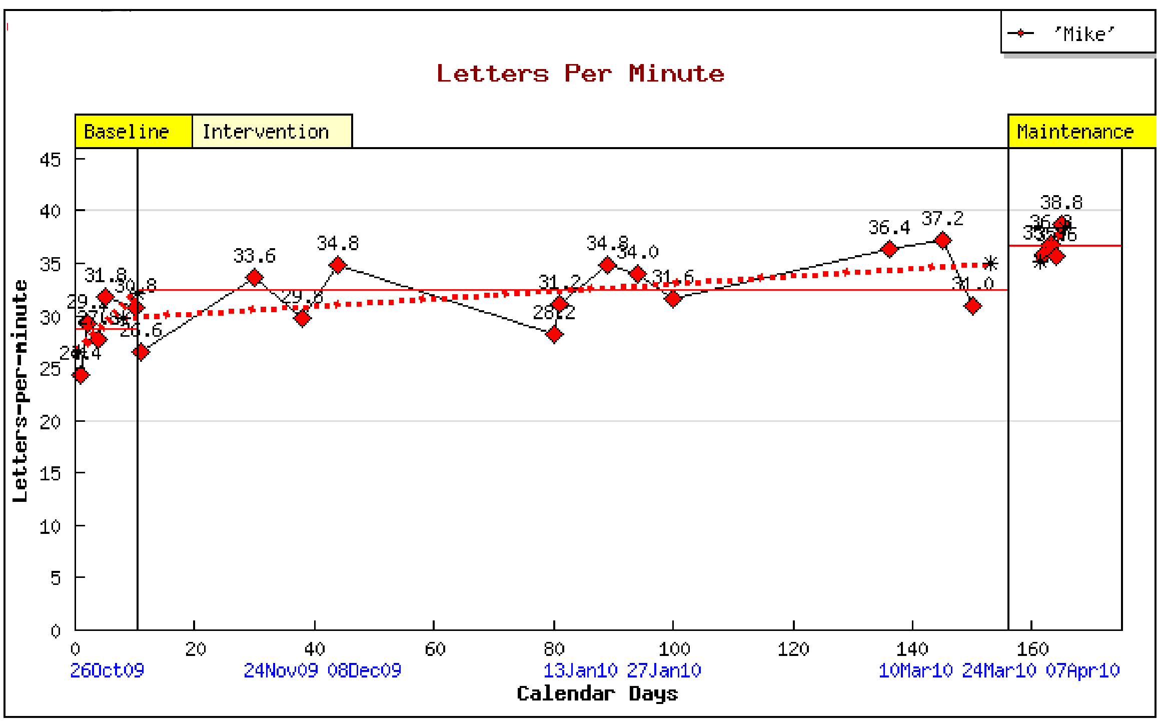


Figure 4.4 Letters Per Minute and Grooved Pegboard for Mike

Table 4.2 Medical information of participants

Participant	Rande	Dave	Kevin	Mike
Medication	None	Oxycodone, Elavil, Percocet, Dilaudid, Neurotin, amitryptiline, Lovenox, colace	Oxycodone, Neurontin	Lyrica, Klonopin, Oxycodone, Cymbalta, Vitamin C, Percocel, Seroquel
Date of injury	11 NOV 2007	31 AUG 2009	5 DEC 2009	20 SEP 2008
Mechanism of injury	Blast	Blast	Blast	Blast
Description of injury	Open, comminuted fracture of L radius, and ulna, Median, ulnar, and radial nerve injuries	R UE large soft tissue defect (elbow to axilla) with STSG, R ulnar styloid avulsion fraction, ulnar nerve injury, 2nd MC open fracture	R thumb amputation through proximal phalanx, R CMC fracture dislocation, R index finger base and tuft fracture, R middle finger proximal phalanx fracture and tip amputation	R elbow staged reconstruction with bone, tendon, nerve, and muscle involvement
Concomitant injuries	Previous osteomyelitis of L UE	Moderate TBI, bilateral corneal burns with intra-ocular foreign body, AC separation, bilateral maxillary sinus fractures, left tympanic 70% perforation, pneumothorax	Mild TBI, proximal phalanx fracture L thumb fracture, tinnitus, burns to chest and abdomen	Moderate TBI, PTSD, tinnitus
Number of Surgeries	56	7	12	58

Note. TBI=Traumatic brain injury, AC=acromion clavicular, MC=metacarpal, UE=upper extremity, PTSD=post-traumatic stress disorder, R=right, L=left, FTSG=full thickness skin graft, STSG= split thickness skin graft, CMC=carpometacarpal

Table 4.3 Inter-rater reliability for Grooved Pegboard and Legibility

Participant	Pegboard inter-rater reliability	Legibility inter-rater reliability
Rande	r = 1.00, p<.01	r = 1.00, p<.01
Dave	r = 1.00, p<.01	r = 0.993, p<.01
Kevin	r = 1.00, p<.01	r = 0.997, p<.01
Mike	r = 0.999, p<.01	r = 0.97, p<.01

Table 4.4 Mean values, percentage of non-overlapping data, and effect sizes for Grooved Pegboard and letters-per-minute outcomes

	Mean Values			% PND			Effect Size		
Rande	Pegboard	B	105	Pegboard	B-I	25	Pegboard	B-I	-0.69
		I	99.9		I-M	75		I-M	-2.48
		M	90.5						
	LPM	B	17.8	LPM	B-I	41.7	LPM	B-I	1.59
		I	23.6		I-M	0		I-M	0.09
		M	23.8						
Dave	Pegboard	B	107.2	Pegboard	B-I	41.7	Pegboard	B-I	-0.99
		I	73.4		I-M	25		I-M	-0.78
		M	61.5						
	LPM	B	22	LPM	B-I	66.7	LPM	B-I	1.98
		I	28.8		I-M	50		I-M	0.73
		M	33						
Kevin	Pegboard	B	107.8	Pegboard	B-I	77.8	Pegboard	B-I	-1.34
		I	89.4		I-M	-		I-M	-
		M	-						
	LPM	B	21.8	LPM	B-I	77.8	LPM	B-I	4.86
		I	31.8		I-M	-		I-M	-
		M	-						
Mike	Pegboard	B	97.8	Pegboard	B-I	50	Pegboard	B-I	-0.92
		I	88.8		I-M	25		I-M	-0.35
		M	87.3						
	LPM	B	28.8	LPM	B-I	50	LPM	B-I	1.26
		I	32.4		I-M	25		I-M	1.33
		M	36.8						

Note. LPM=letters-per-minute; B=Baseline; I=Intervention; M=Maintenance; PND=percentage of non-overlapping data

Table 4.5 Descriptive raw data for Rande.

RANDE	BASELINE PROBES					INTERVENTION PROBES												MAINTENANCE PROBES			
	1	2	3	4	5	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4
Time of Day	1400	1400	1000	1345	1410	1524	1445	1520	1536	1135	1425	1400	935	1406	1350	1150	930	1035	905	1100	1230
Pain	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hand Fatigue	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Legibility	100	100	100	100	92	96	100	100	97	100	100	100	95	100	100	94	100	100	100	100	100
Text. Diff.	6.7	11	19	8	13	11	26	13	12	16	12	8.6	15	13	7.5	21	15	6.7	6.7	25	15
LPM	15	17	18	15	24	22	22	30	27	23	24	20	24	25	25	21	21	24	22	27	22
Absence																					
Compliance						83.5		96.7		56		82.4		94.4		0.1					
Self-Perception						6.6		7		6.6		6.8		7.4		7.6					
	Days in Baseline Phase 8					Days in Intervention Phase 42												Days in Maintenance Phase 16			

Table 4.6 Descriptive raw data for Dave.

DAVE	BASELINE PROBES					INTERVENTION PROBES												MAINTENANCE PROBES			
	1	2	3	4	5	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4
Time of Day	1445	1100	1045	900	955	1425	2400	2215	910	850	1400	935	1305	920	1015	1025	915	915	845	1315	1345
Pain	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hand Fatigue	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Legibility	91	68	88	83	90	98	94	96	97	100	100	100	100	100	100	100	100	100	100	100	100
Text. Diff.	5	9	5	10	5.2	9.7	13	9.9	17	6.7	13	18	25	15	19	10	12	21	7.5	21	8.3
LPM	20	25	25	22	17	21	22	23	20	30	31	32	32	31	36	33	35	38	26	32	37
Absence							*		**		***		****			*****					
Compliance						99		99		99		100		86		99					
Self-Perception						4.8		6		6.6		7.6		8.44		8.44					
	Days in Baseline Phase 12					**Days in Intervention Phase 95**												**Days in Maintenance Phase 20**			

* 7 NOV eye and facial surgery
** 21 NOV-5 DEC Convalescent Leave
*** 8 DEC Foreign body excision from right neck
**** 18 DEC Ear surgery
***** 18 FEB Eye surgery

Table 4.7 Descriptive raw data for Kevin

KEVIN	BASELINE PROBES					INTERVENTION PROBES												MAINTENANCE PROBES			
	1	2	3	4	5	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4
Time of Day	1510	1515	1515	1430	1500	1115	830	915	830	930	1030	900	900	1430							
Pain	0	0	0	0	0	0	0	0	0	0	0	0	0	0							
Hand Fatigue	0	0	0	0	0	0	0	0	0	0	0	0	0	0							
Legibility	96	95	98	95	100	98	100	100	100	100	100	100	99	100							
Text. Diff.	13	14	2.3	8.8	13	11	25	25	16	11	19	6	12	6.7							
LPM	24	23	20	20	23	22	23	30	36	33	34	36	34	38							
Absence								*	**												
Compliance						100		98		73		73		74		58					
Self-Perception						3.8		X		5.8		6.2		6		6.4					
	Days in Baseline Phase 35					**Days in Intervention Phase 42**												**Days in Maintenance Phase**			

* 19 FEB Limb salvage surgery, no convalescent leave
**26 FEB Limb salvage surgery, no convalescent leave

Table 4.8 Descriptive raw data for Mike

MIKE	BASELINE PROBES					INTERVENTION PROBES												MAINTENANCE PROBES			
	1	2	3	4	5	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4
Time of Day	1455	1435	1115	905	1525	1545	1145	1020	1350	1350	1115	1000	945	1305	935	800	845	800	900	900	900
Pain	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hand Fatigue	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Legibility	91	73	92	79	75	91	91	94	99	87	87	94	100	88	90	96	95	97	93	93	86
Text. Diff.	9.9	13	15	9.9	19	12	19	12	13	20	16	25	12	9.5	20	12	12	10	7.9	13	18
LPM	24	29	28	32	31	27	34	30	35	28	31	35	34	32	36	37	31	36	37	36	39
Absence							*		**				***								
Compliance																					
Self-Perception						5.6		6.4		7.8		7.8		8.2		9					
	Days in Baseline Phase 10					**Days in Intervention Phase 140**												**Days in Maintenance Phase 4**			

* Limb salvage surgery 15 NOV, Convalescent Leave, - 24 NOV
** Holiday Leave 8 DEC - 13 JAN
*** Limb salvage surgery 2 FEB, Convalescent Leave, - 10 MAR

Table 4.9 Median values of letters-per-minute for Baseline and Intervention phases and corresponding grade-level equivalents

Participant	Baseline LPM	Grade-level equivalent	Intervention LPM	Grade-level equivalent
Rande	17.2	1	24	1-2
Dave	22.2	1	34	2
Kevin	22.6	1	34	2
Mike	29.2	2	34	2

Note. LPM=letters-per-minute

Table 4.10 Pair wise comparisons between phases and p-values for kinematic and kinetic variables per task for each participant.

Participant	Phase Comparison	Mean X velocity	Mean Y velocity	Mean X displacement	Mean Y displacement	Pressure	On-paper time
Dave	B-I	.003(c)	.003(c) .023(d)	.001(d)	.015(c) .008(s)		.000(c)
	I-M	.028(c)	.018(c) .299(d)	.855(d)	.682(c) .214(s)		.061(c)
Kevin	B-I	.012(c)	.025(a) .009(c)		.019(s)		.010(c)
	I-M						
Mike	B-I	.000(a) .000(c) .002(s)	.000(a) .000(c) .002(s)	.239(s)	.000(c) .007(s)	.011(a) .008(s)	.001(a) .000(c) .000(s)
	I-M	.023(a) .516(c) .201(s)	.087(a) .225(c) .198(s)	.006(s)	.795(c) .267(s)	.057(a) .796(s)	.255(a) .802(c) .459(s)
Rande	B-I	.002(a) .000(c)	.000(a) .000(c)		.025(c) .021(s)		.001(a) .000(c) .002(s)
	I-M	.881(a) .147(c)	.987(a) .117(c)		.396(c) .419(s)		.325(a) .164(c) .201(s)

Note. Only the pairs that demonstrated significance in the primary analysis are presented.
Baseline Phase (B), Intervention Phase (I), Maintenance Phase (M), Copy Alphabet (a), Copy Date (d), Copy Sentence (s), Draw Circles (c)

Table 4.11 Canadian Occupational Performance Measure (COPM) by task and by participant

Writing Task	Performance (pre, post)	Average Performance Improvement	Satisfaction (pre, post)	Average Satisfaction Improvement
Paying bills	(K:1,8)	7	(K:1,8)	7
Number/word puzzles	(K:1,9)	8	(K:1,9)	8
Signing name	(K:1,10) (R:3,10) (M:3,10) (D:5,10)	7	(K:1,10) (R:3,10) (M:1,10) (D:5,10)	7.5
Keeping a calendar	(K:1,10)	9	(K:1,10)	9
Writing a to-do" list	(K:1,10) (D:3,9)	7.5	(K:1,10) (D:3,9)	7.5
Drawing	(M:3,10)	7	(M:1,10)	9
Taking notes and exams in college	(M:3,6) (R:3,6) (D:1,5)	3.3	(M:1,6) (R:3,6) (D:1,2)	3
Completing medical forms	(M:3,10) (R:3,7)	5.5	(M:1,10) (R:3,10)	8
Filling out college applications	(M:3,6) (D:1,4) (R:3,4)	2.3	(M:1,8) (D:1,2) (R:4,6)	3.3
Writing letters	(D:1,6) (R:3,6)	4	(D:1,6) (R:3,5)	3.5

Note. Each participant's pre- and post-intervention score is represented in parentheses, R=Rande, D=Dave, K=Kevin, M=Mike

Table 4.12 Scores from self-perception questionnaire on handwriting ability

Writing parameter	Rande	Dave	Kevin	Mike
Readability	5 5 5 5 7 7	6 7 5 8 8 8	3 - 4 3 4 4	5 6 7 6 7 8
Speed	7 8 7 5 7 6	3 4 4 6 7 8	0 - 3 4 3 5	5 6 7 8 8 9
Appearance	5 6 6 7 7 7	2 4 7 7 8 8	2 - 3 7 4 4	4 5 7 8 8 9
Confidence	6 5 5 7 6 8	3 5 7 7 9 8	4 - 9 7 9 9	4 5 8 7 8 9
Importance	10 10 10 10 10 10	10 10 10 10 10 10	10 --- 10 10 10 10	10 10 10 10 10 10

Note. Numbers presented are weekly scores (progression from Week 1 to Week 6 is from left to right). ---Kevin has missing data for Week 2.

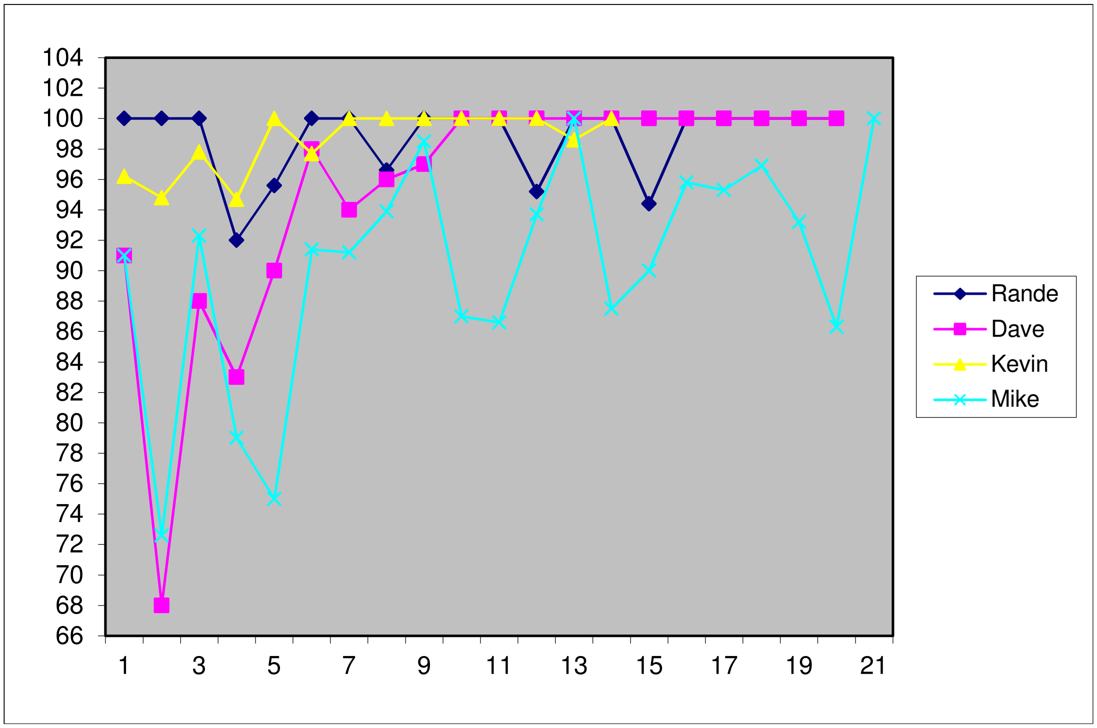


Figure 4.5 Legibility percentages for each participant across all phases of the experiment

Table 4.13 Correlation table for outcome measures, environment, and task factors

Participant	Correlation	Pearson r	Significance	Interpretation
Rande	No significant correlations			
Dave	LPM and text difficulty	.504	.020*	Weak, positive correlation
Kevin	Legibility and time of day	-.621	.018*	Moderate negative correlation
Kevin	LPM and time of day	-.558	.038*	Moderate negative correlation
Mike	Legibility and time of day	-.447	.042*	Moderate negative correlation
Mike	LPM and time of day	-.701	.000**	Moderate-strong negative correlation

Note. LPM=letters-per-minute
**Correlation is significant at .05 level (2-tailed)*
***Correlation is significant at .01 level (2-tailed)*

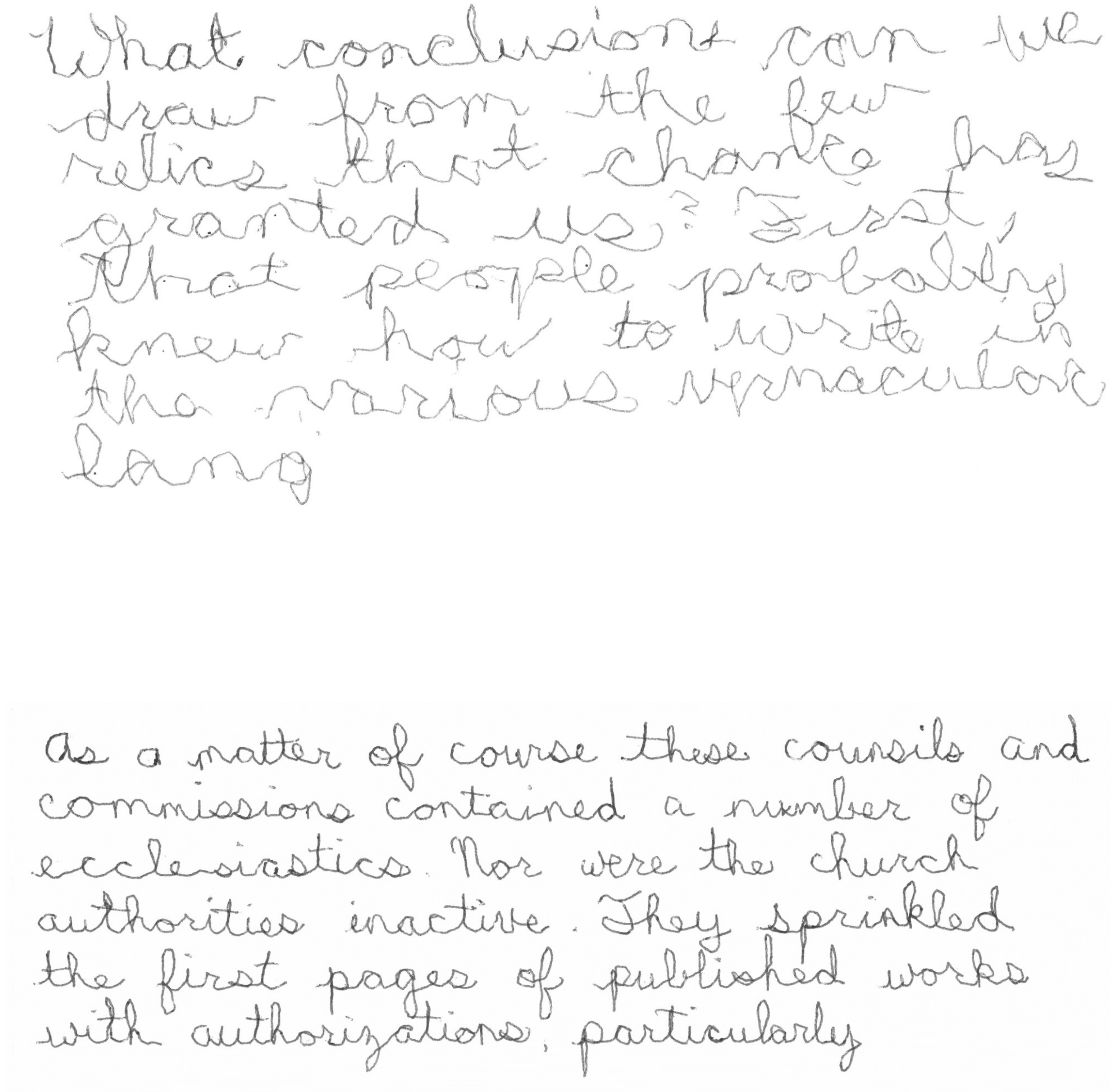
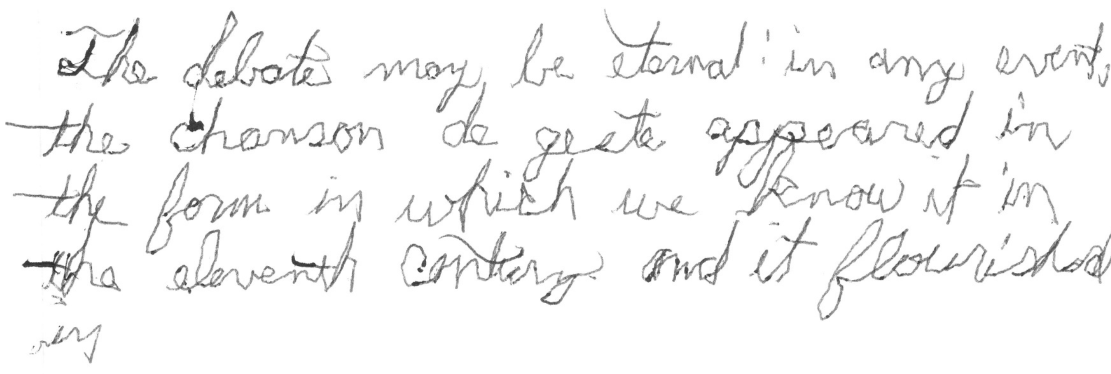


Figure 4.6 Baseline (Probe 1 – top) and Intervention (Probe 12 – bottom) handwriting samples from 5-minute endurance task for Dave



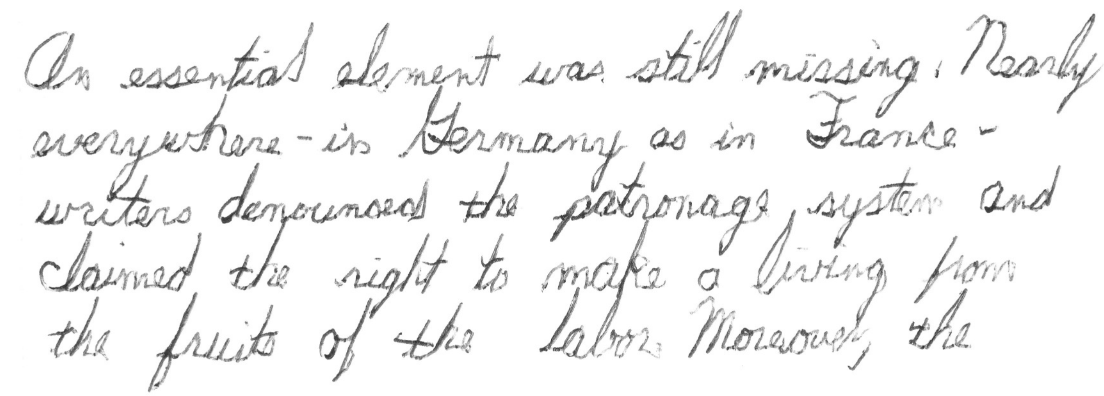


Figure 4.7 Baseline (Probe 1 – top) and Intervention (Probe 12 – bottom) handwriting samples from 5-minute endurance task for Kevin

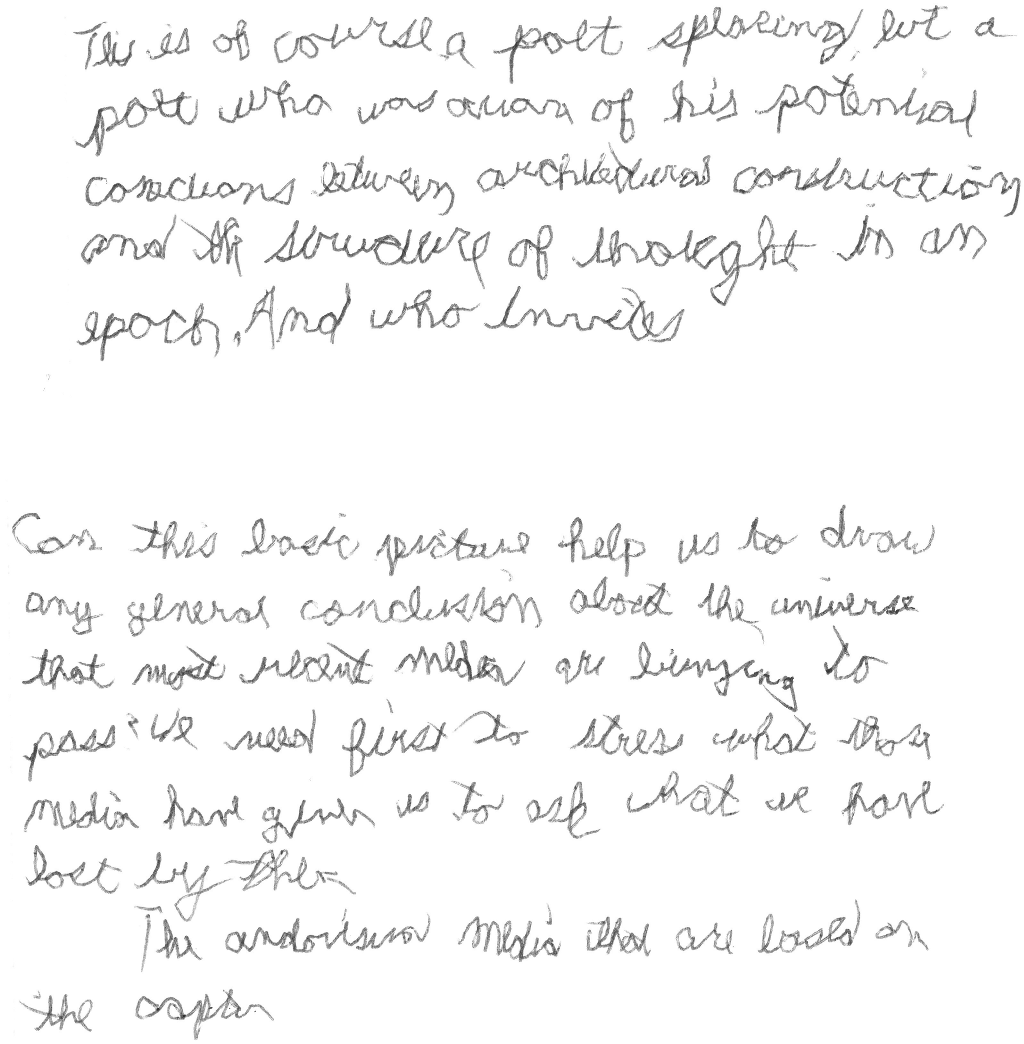
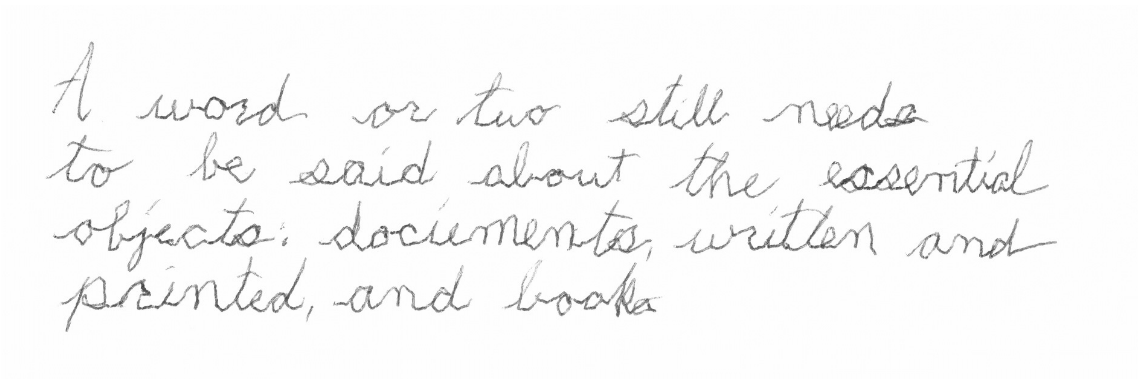


Figure 4.8 Baseline (Probe 1 – top) and Intervention (Probe 12 – bottom) handwriting samples from 5-minute endurance task for Mike



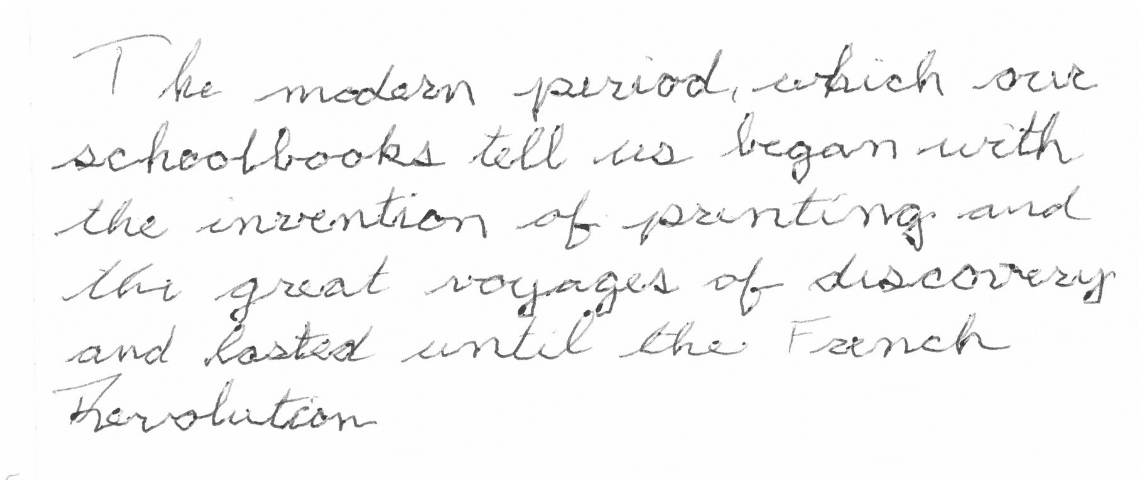


Figure 4.9 Baseline (Probe 1 – top) and Intervention (Probe 12 – bottom) handwriting samples from 5-minute endurance task for Rande

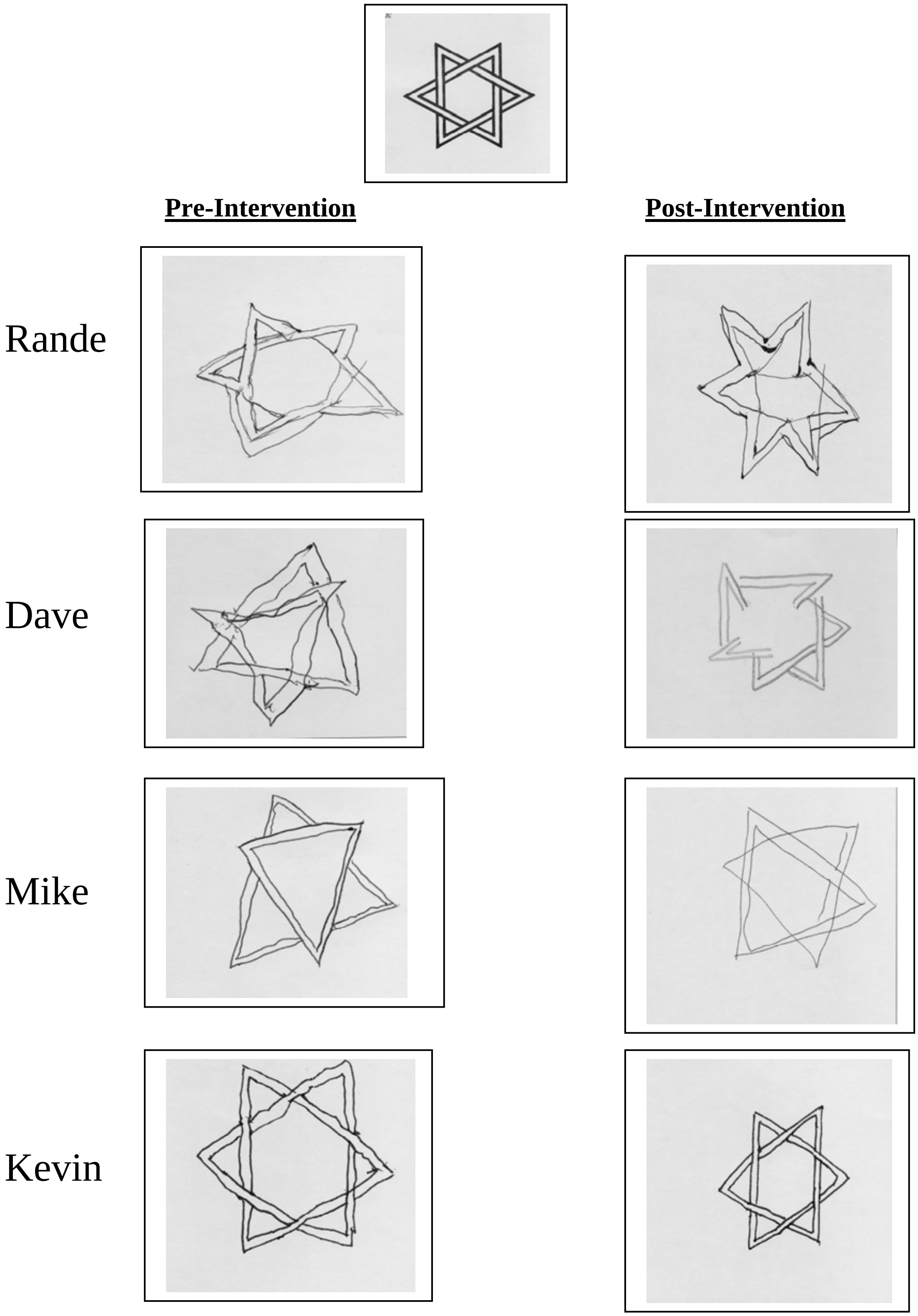


Figure 4.10 Performance on Figure #30 from VMI pre and post-intervention.

Chapter 5
Implications for Theory, Practice, and Research

Review of the Problem

Adults who undergo upper limb salvage or amputation present interesting rehabilitation challenges for occupational therapy practitioners. One challenge that has received minimal attention by researchers relates to adults who undergo amputation or limb salvage to the *dominant* extremity and subsequently face injury-induced hand dominance transfer (I-IHDT). Beyond being left in a functional state of single-handedness, they are at a neuromotor disadvantage caused by losing the stronger, faster, more dexterous upper limb. Currently, there is limited evidence based practice research from which to build clinical practice guidelines to address hand dominance transfer in patients who face I-IHDT. This dissertation was a series of three-studies with a focus on a specific intervention called *Handwriting For Heroes* (Yancosek & Gulick, 2008) that is used in military medical centers to facilitate hand dominance transfer in adults who undergo upper limb salvage or amputation.

Review of Specific Aims

The overarching goal of this research was to examine the efficacy and effectiveness of *Handwriting For Heroes* in facilitating hand dominance transfer of motor control as it pertains to handwriting. The following were the specific aims for each study:

Study #1: Specific Aims

Specific Aim 1: Develop data collection apparatus to analyze handwriting.

Specific Aim 2: Assess consistency (reliability) of graphomotor performance in a sample of adults who previously lost hand function

Study #2: Specific Aims

Specific Aim 1: Examine the efficacy of *Handwriting For Heroes* in non-impaired subjects.

Specific Aim 2: Establish data collection and analysis methods for monitoring graphomotor performance changes across time.

Study #3: Specific Aims

Specific Aim 1: Examine the clinical effectiveness of *Handwriting For Heroes* in an injured military population.

Specific Aim 2: Use a dynamical systems framework to describe motor learning based on the changes in fine motor control used to write with a non-dominant hand.

Specific Aim 3: Examine the influence of personal factors as modulators to transfer dominance in handwriting skill development.

Summary of Studies

Study #1

Study #1 served as a foundational experiment to establish a method to digitally measure handwriting performance in adults who previously (greater than 2 years ago) lost function of their dominant hands. This was a necessary first step to verify that handwriting performance, when measured on two separate occasions (six-weeks apart) was similar (stable). This study provided a foundation for subsequent studies to measure the effects of an intervention on handwriting performance and validate that changes detected would be accurately interpreted.

Study #2

Study #2 served two main purposes: (1) to establish data collection and analysis methods for monitoring handwriting performance changes across time, and (2) to examine the efficacy of *Handwriting For Heroes* in non-impaired subjects.

Study #3

Study #3 examined the clinical effectiveness of *Handwriting For Heroes* in an injured military population. A number of personal factors (pain, hand fatigue, compliance, and performance satisfaction) for each participant were measured as possible modulators to the hand dominance transfer process. Time of day was assessed as an environmental factor, and text-difficulty was assessed as a task factor that may influence the outcomes.

Review of Major Findings

Results of the pilot study described in Chapter 2 captured handwriting performance stability. Stability was found in some aspects of the writing *process*, as measured by kinematic and kinetic variables detected with a digitizer; stability was also found in the writing *product* as measured by visual analysis of the writing samples. Handwriting tasks and kinematic variables that showed the highest reliability were useful as measures in the subsequent studies to evaluate therapeutic progress during an intervention related to handwriting skill development. Both specific aims of this study were met.

Results from the efficacy study described in Chapter 3 demonstrated a positive effect on the dependent variables: legibility, writing speed (letters-per-minute), and kinematic variables from the independent variable, the *Handwriting For Heroes* intervention. Knowing how the intervention worked under ideal conditions was useful when comparing results to the clinical effectiveness study done with military service members who sustained devastating upper limb injuries and faced I-IHDT. The specific aims of this study were met.

Results of the clinical effectiveness study in Chapter 4 did not show as positive results as the efficacy study, despite similar compliance with the intervention. Specifically, non-impaired participants started with faster writing speeds in their non-dominant hands (higher letters-per-minute) and made more gains (wider ranges). The non-impaired participants also started with faster dexterity (betters scores on the Grooved Pegboard) but they made fewer gains than the injured service members (smaller ranges). Nevertheless, injured participants did improve in all dependent variables to advance their writing speeds by one grade level. Additionally, they perceived improvement as per the changes detected on the COPM and the perception of handwriting ability questionnaire. The specific aims of this study were met.

Findings Related to the Literature

The study described in Chapter 2 was the first of its kind to measure handwriting performance of the (previously) non-dominant hand in adults who lost dominant hand function and were forced to switch hand dominance. The following results supported

findings from other studies (1) pressure was the least stable kinetic parameter of handwriting performance (Teulings & Schomaker, 1993), (2) to meet adult-level writing demands, one must master demands for fine motor coordination so the brain can attend to higher order cognitive tasks (Connelly et al., 2005), (3) handwriting was an activity that participants engaged in daily (Dixon et al., 1993; McMahon et al., 2008), and (4) adult nervous systems are adaptive and responsive to change caused by injury to the peripheral nervous system (Kleim et al., 2002).

The positive effect of the intervention on letters-per-minute and legibility, with less notable effects on the Grooved Pegboard scores in the non-impaired participants during the efficacy study led to an examination of the components of *Handwriting For Heroes* that may have contributed to these results. Basic dexterity exercises make up a very small percentage of the total exercises and activities in *Handwriting For Heroes*. This suggests a specificity to training, meaning that a neuromotor system will demonstrate improved performance over time on tasks that are *specifically* practiced. Specificity of training as a key component to motor learning has been documented by other researchers (Kleim & Jones, 2008).

Another characteristic of *Handwriting For Heroes* that is in concert with principles of effective strategies of motor learning is the built-in frequency of contextual interference by having the learner switch between twelve types of handwriting tasks during one day's session. Also, *Handwriting For Heroes* embodies a task-oriented approach that has the learner do functional writing tasks such as addressing envelopes, writing grocery lists, completing calendar grids, and filling out checkbook ledger. The task-oriented approach is client-centered, and the *Handwriting For Heroes* intervention demonstrates client-centeredness by having the learner complete functional homework that is personalized as well as completing personal reflective homework such as finding and copying a quote from a magazine or book that resonates with them.

Findings from all three studies support research that suggests handwriting is a skill that needs to be purposefully addressed (Graham, 1992; Jones & Christensen, 1999). Eggers, Mennen, and Mendunsa (1997) suggest that skilled actions beyond those of an 8-year old child require extensive deliberate practice to facilitate dominance transfer because of necessary proficiency, speed, and agility. Their reasoning was supported in

the first study by evidence of limited skill proficiency in participants who had not deliberately worked at handwriting despite years of time since amputation. Their reasoning was also supported in the third study with the two military service members who had not worked on handwriting since their initial injuries in 2008.

Findings Related to Theories

Results of the research contained in this dissertation were juxtaposed with dynamical systems theory (DST) to describe changes in fine motor control used to write with a non-dominant hand in non-impaired and injured adults. DST reflects the belief shared with the profession of occupational therapy that behavior is shaped by the interaction between the person, task, and environment.

Table 1.5 describes the personal, task, and environmental constraints on handwriting performance. This theoretical perspective is useful when searching for explanation for the differences found when comparing the outcome measures between the five non-impaired participants and the four injured service members. The non-impaired participants started with better basic dexterity speeds (Grooved Pegboard scores) and handwriting speeds (more letters-per-minute) in the non-dominant hand than any of the four injured service members, including the two who had been functioning for greater than one year with only the use of the non-dominant hands. The idea that the task conditions were held constant throughout the execution of both experiments leads to analysis of personal and environmental constraints. The personal constraints of the injured participants, such as concomitant eye and brain injuries and the on-going use of narcotic medication, may well account for the differences in performance. The idea of personal competencies is related to the DST's position that a dynamical system is sensitive to initial conditions. This theoretical tenet is supported by the results that show how the injured military service members did not achieve as great a final outcome as did the non-impaired participants. Again, initial conditions of the injured participants included deficits from concomitant injuries that the non-impaired participants did not have to negotiate.

DST views an individual as a complex system capable of adaptation based on existing attributes, coordinated by available redundancy of Degrees Of Freedom (DOF), ultimately drawing upon personal competencies (and environmental affordances) to

produce goal-directed behavior. Results of studies in this dissertation demonstrate that adult neuromotor behavior is not fixed, but is driven by task demands or changes in the neuromotor systems as a result of injury (Davids et al., 2006). In other words, the uninjured adult participants who simulated a hand dominance transfer and the injured adult participants who were receiving *Handwriting For Heroes* as part of the standard of care were all capable of improving in the writing process and product.

Findings Related to Clinical Practice

This research contributes to evidence-based research needed to establish clinical practice guidelines for adults who face I-IHDT. Based on the combined findings of the efficacy and effectiveness studies in this dissertation, *Handwriting For Heroes* is a six-week intervention that participants complied with and occupational therapy practitioners can use the workbook with positive expectancy for improvement in handwriting speed, legibility, self-perception of handwriting ability, and improvement of perception and satisfaction with writing tasks, specifically simple writing tasks. The intervention should be completed in the recommended format of daily work for 42 days of massed practice, and should be started soon after traumatic injury to the dominant limb.

Treatment Considerations

In an effort to improve the precision of rehabilitation services for adults who face I-IHDT, evidence-based research is combined with clinical expertise to create the following general treatment guidelines for military occupational therapy practitioners: (1) thoroughly evaluate the neuromotor status of the "sound" (uninjured) limb and then educate the service member about risk for over-use injuries in that limb; (2) teach one-handed skills for accomplishment of activities of daily living (ADL). Videos are posted on *Handwriting For Heroes* Website Companion that shows one-handed shoe-tying, hair tying and jewelry application, and necktie tying; (3) issue adaptive equipment to aid in one-handed living. A full list of one-handed equipment is available on *Handwriting For Heroes* Website Companion; (4) facilitate the integration of the salvaged or residual limb (or prosthesis) back into functional movements; (5) address issues related to return to military duty, transition to civilian employment or college, and pursuit of previous or new

leisure activities, and (6) to begin handwriting skill transfer, encourage early initiation of using the *Handwriting For Heroes* workbook.

While further evidence-based practice research is necessary to elucidate ideal rehabilitation algorithms to facilitate I-IHDT, ideas gained from knowledge discovered in the literature review for this dissertation are applied here to provide occupational therapy practitioners with additional activities to aid in assisting injured service members to increase movement economy and efficiency. Research related to dexterity, handwriting, and hand dominance was translated into additional treatment activities to complement the methods *Handwriting For Heroes.* These activities are recommended to facilitate hand dominance transfer, and are organized into the categories of language, art, electronic media, motor control, and strength and precision. See Table 5.1. These methods are in accordance with the small body of literature related to traumatic loss of dominant hand function (Chan & LaStayo, 2003; Eggers & Mennen, 2001; Walsh et al., 1993).

Changes to *Handwriting For Heroes*

Looking closely at the intervention in relation to the efficacy and effectiveness studies suggest that a weakness of the workbook may be that it requires manuscript-style writing (printing) for only a few select tasks (writing street and email addresses), and cursive writing was not previously the stylistic preference for participants, which may slow skill transfer. Another weakness discovered in the workbook was inconsistencies, lack of clarity, and erroneous descriptions of tasks in the presentation of instructions, for the *Daily Exercises* section. See Table 5.2 for planned improvements to the manual. Major changes are categorized as follows: (A) Monitoring progress/outcome assessment, (B) Content, and (C) Editorial changes.

Future Research

Future research is needed to advance the efforts toward developing a clinical practice guideline related to I-IHDT. Two future survey studies are planned for immediate action. One will survey adults who undergo upper limb salvage. This study will explore stages of recovery and coping with loss of hand function. See Appendix B. The other survey will ask members of the American Society for Hand Therapists about treatment strategies and clinical decision making related to I-IHDT. See Appendix C.

Future effectiveness trials with larger, more diverse groups of adults may employ multivariate statistical analyses to better explore the possible modulators and mediators to hand dominance transfer, such as laterality, education level, gender, age, type of injury, length of time since loss of hand function, and motivation for change.

In the efficacy trial, it was noted that learners were intently focused on motor control and motor planning that they did not register the topic of the handwriting text they were copying. Thus, studies could incorporate comprehension testing along with handwriting performance measures to explore how cognitive components of handwriting change over time during the handwriting skill transfer. This research may be exceptionally useful given the likelihood of concomitant cognitive deficits in an injured military population.

Extensions of this dissertation into the field of neuroscience could employ neuroimaging techniques, such as using fMRI, PET, or the Wada test (intra-carotid injection of sodium amobarbitol) to assess cerebral lateralization of language and motor skills. These findings would inform rehabilitation professionals of the adaptive neuroplasticity which subserves all rehabilitation interventions and may specifically uncover answers on the connection between hand dominance, language lateralization, and change in an adult neuromotor system. Related research to I-IHDT should include longitudinal studies to assess long-term adaptations to functional loss of dominant hand function.

A study that explores the handwriting requirements needed for various types of employment would have been useful in establishing the value in transferring handwriting skills to the non-dominant hand. A study such as this could help justify occupational therapy practitioners' focus on handwriting during treatment sessions, as well as provide information for service members about the standards related to different types of employment.

Conclusions

When injured military service members face I-IHDT, they deserve evidence-based interventions to accelerate necessary hand dominance transfer so they may be restored to full participation in ADL, military duty or civilian employment, college, and

leisure pursuits. The studies in this dissertation provide initial support for *Handwriting For Heroes* as a useful workbook to address handwriting skill transfer to the previously non-dominant hand. Research related to I-IHDT needs to be extended to advance initiatives in rehabilitation to minimize the severity of disability following dominant-hand injuries (Trybus et al., 2006).

Table 5.1 Activities to facilitate hand dominance transfer following permanent loss of function

Language based	Art	Electronic devices	Motor control	Strength and precision
Compose text by writing letters, journal entries, or stories Transcribe text by listening to a talk radio show or a television program and take notes on key points	Draw Color Trace Paint	Text Type on various sized keyboards Use a mouse	Cut with scissors Pour variable amounts of water into containers of variable size: ex. Pour water from a large (heavy) jug into ice cube trays	Hammer: hammer golf tees into foam board Throw/catch

Table 5.2 Planned improvements for Handwriting For Heroes workbook

Category of Improvement	Specific Modification or Enhancement
Monitoring Progress/Outcome Assessment	Add a self-appraisal so the learner evaluates his/her work and identifies (circles or stars) the best writing sample per day and per week Add a weekly endurance writing task: write for 5 minutes, count characters and calculate the letters-per-minute Timing the length of each session. Add a start and stop time box at the bottom of each page Monitor pain, general fatigue, and hand fatigue Provide space for learners to write a goal to enhance cognitive learning strategies whereby they monitor achievement of the goal Add a weekly self-check for compliance. Have learners award one point for each completed exercise and homework activity for a total of 91 weekly points
Content	Add more composition assignments to *Homework* section Re-vamp endurance training exercises so the exercise increase in demand over time Add supplemental materials to the *Website companion* to assist learners who need easier or more difficult challenges Add information on other forms of written communication, such as keyboarding and voice recognition software Add transcription (note-taking) activities to *Homework* section Add a Therapists' Tip to Week 6
Editorial	Make instructions uniform Add a table of contents/subject index for Therapists' Tips Encourage the learner to self-regulate when he/she needs to take a break Place the exercises in the order as they appear in the weekly lessons (p. xi) Add Extra Credit activities to the manual to assist learners who are working without the *Website Companion* section

Appendix A

Self-Perception Questionnaire on Handwriting Ability
Instructions: Using a 0-10 Scale, please answer the following questions about your handwriting ability.

1. How does your handwriting ability *today* compare to your handwriting ability *before* your limb injury in terms of readability?
Readability means that someone who doesn't know you can read what you wrote.

0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
not at all alike										exactly alike

2. How does your handwriting ability *today* compare to your handwriting ability *before* your limb salvage in terms of speed?
Speed means the pace at which you are writing.

0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
not at all alike										exactly alike

3. How does your handwriting ability *today* compare to your handwriting *before* your limb salvage in terms of appearance.
Appearance means the shape, size, slant, and style of your writing.

0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
not at all alike										exactly alike

4. How confident are you in your writing ability?
Confidence means that you are sure of your ability to write.

0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
not confident at all										exactly alike

5. How important is learning to write again?
Important means that you value spending your time learning to write again.

0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
not important										extremely important

Appendix B

Instructions: We are interested in knowing how you feel *about* and respond *to* the current condition of your injured upper limb.

By *upper limb*, we mean any part of your arm (shoulder, elbow, wrist, or hand).

Please read each statement and circle the number that represents how you *most* feel about the statement. You may have agreed with all of these statements at one point in your recovery, but please answer based on how you feel ***today***.

1	2	3	4
Strongly Disagree	**Disagree**	**Agree**	**Strongly Agree**

1. I expect to get more range of motion in my upper limb.	1 2 3 4
2. The event(s) that caused my upper limb dysfunction was/were not fair.	1 2 3 4
3. I am frustrated with the lack of function in my upper limb.	1 2 3 4
4. The incident that injured my upper limb could have been avoided.	1 2 3 4
5. I feel helpless about changing the current condition of my upper limb.	1 2 3 4
6. I am comfortable asking for help from others when my upper limb cannot accomplish something I need done.	1 2 3 4

7. I allow others to help me now because I will eventually be fully independent again.	1 2 3 4
8. I feel self-conscious about the condition of my upper limb.	1 2 3 4
9. I frequently wish I could turn back time and avoid the incident that injured my upper limb.	1 2 3 4
10. I avoid social interactions because of the condition of my upper limb.	1 2 3 4
11. Since I injured my upper limb, I argue with others more frequently.	1 2 3 4
12. I openly share information about the cause and condition of my upper limb with people other than medical/rehabilitative professionals.	1 2 3 4
13. I expect the pain in my upper limb to go away.	1 2 3 4
14. I am angry about the condition of my upper limb.	1 2 3 4
15. Had I chosen differently, I would not have injured my upper limb.	1 2 3 4
16. I have figured out how to do everything I need to do despite the condition of my upper limb.	1 2 3 4
17. I expect to be able to do more with my upper limb in the future.	1 2 3 4

18. I feel resentful about what happened to my upper limb.	1 2 3 4
19. I believe there is little that can change the condition of my upper limb.	1 2 3 4
20. I feel overwhelmed by the thought of living with my upper limb this way forever.	1 2 3 4
21. I frequently rehearse how I could have done something different to change the events that led to the injury of my upper limb.	1 2 3 4
22. Eventually my upper limb will be like it was before I was injured.	1 2 3 4
23. I accept that my upper limb is going to be in this condition forever.	1 2 3 4
24. I am frequently in a depressed mood because of the condition of my upper limb.	1 2 3 4
25. I get upset when others ask me about what happened to my upper limb.	1 2 3 4

We also would like to know:

Age:_______

Gender: _____M_____F

Date of injury:____/_____/_________

Is your injured limb your dominant limb?_______Y______N

Are you considering having an elective amputation?_______Y______N

Did you experience other injuries (or medical problems) related to the incident that caused your upper limb injury?______Y_______N

(If you wish, you may use the space below to describe.)

Is there anything else you think we should know?

Appendix C

SURVEY FOR MEMBERS OF AMERICAN SOCIETY FOR HAND THERAPISTS

I am interested in knowing about you, your clinical practice, the ways in which you deal with clients who lose function of a dominant hand, and what you think should be the focus of research related to hand dominance transfer intervention programs.

This survey has three sections: (1) demographics, (2) clinical strategies used with clients who have dominant hand injuries, and (3) a research agenda for hand dominance transfer protocols.

Your time is valuable! I appreciate your commitment to rehabilitation science by participating in this survey-research project. I am committed to disseminating the results of this survey through the American Society of Hand Therapists. Please return the survey in the envelope provided, and thank you again for your involvement.

PART I: DEMOGRAPHICS

1. What are your credentials? (example: OTR/L, CHT, OTD, DPT, PhD)

____

2. How long have you been practicing?

☐ Less than 5 years
☐ Between 5-10 years
☐ Between 11-20 years
☐ Greater than 20 years

3. Check the box that best describes your current work setting:

☐ Out-patient clinic
☐ Acute Hospital
☐ Sub-acute rehabilitation center
☐ Community based practice setting
☐ Private, free-standing clinic
☐ School-based
☐ Other (please describe)

____

4. What is your role at your work setting?

- ☐ Supervisor
- ☐ Staff therapist
- ☐ Director of services
- ☐ other (please describe)

____

5. On average, about how many patients do you see per day?

- ☐ less than 5
- ☐ between 6-8
- ☐ between 9-15
- ☐ greater than 16

6. What is your work schedule?

- ☐ Part time
- ☐ Full time
- ☐ Per diem
- ☐ other (please describe)

____

7. How often do you treat clients with upper extremity injuries?

- ☐ less than 25% of the time
- ☐ between 26%-50% of the time
- ☐ between 51-75% of the time
- ☐ between 76-100% of the time

8. In your clinical practice, what is the primary <u>category</u> of injury?

- ☐ Neurological
- ☐ Neuromusculoskeletal (orthopedic)
- ☐ Systemic (autoimmune)

9. In your clinical practice, what is the primary <u>cause</u> of injury?

- ☐ Metabolic (example: gout, trigger finger, diabetes, Duputrens Disease)
- ☐ Autoimmune (example: rheumatoid arthritis)
- ☐ Trauma (example: Motor vehicle accidents, gun shot wounds)
- ☐ Sports/activity injury
- ☐ Cumulative Trauma/Repetitive Stress injury (example: carpal tunnel syndrome, deQuervain's disease, cubital tunnel syndrome)
- ☐ Congenital (example: syndactyly/polydactyly, limb defects)
- ☐ Infection

10. In your best estimation, what is the percentage of clients you treat with injuries to the <u>dominant</u> upper extremity?

- ☐ less than 25%
- ☐ between 26%-50%
- ☐ between 51-75%
- ☐ between 76-100%

<u>PART II: CLINICAL STRATEGIES AND DECISION MAKING</u>

11. How do you evaluate manual dexterity?

- ☐ Grip strength test (example: dynamometer)
- ☐ Peg-board test (example: Grooved pegboard, 9 hole pegboard, Minnesota Rate of Manipulation Test)
- ☐ Functional hand test (example: Jebsen Taylor Test of Hand Function)
- ☐ I rarely evaluate manual dexterity
- ☐ other (please explain)

____

12. How do you evaluate hand dominance?

- ☐ Ask client to report his/her dominant hand
- ☐ Compare right to left scores on a standardized strength or motor assessment
- ☐ Laterality quotient instrument (example: Edinburgh Handedness Inventory)
- ☐ Observation of movement (example: what side they wear their watch, hold their keys, operate their cellular phone)
- ☐ other (please explain)

____

13. When you are working with a client who has a unilateral injury, do you provide or recommend the following adaptive equipment?

Elastic shoelaces	☐Yes	☐No	☐Unfamiliar with product
One-handed cutting boards	☐Yes	☐No	☐Unfamiliar with product
Rocker knife	☐Yes	☐No	☐Unfamiliar with product
Knork®	☐Yes	☐No	☐Unfamiliar with product
One-handed (sling) backpack	☐Yes	☐No	☐Unfamiliar with product
Zip-Ties	☐Yes	☐No	☐Unfamiliar with product
One-handed nail clippers	☐Yes	☐No	☐Unfamiliar with product
One-handed dental flossers	☐Yes	☐No	☐Unfamiliar with product
Hands-Free can-opener	☐Yes	☐No	☐Unfamiliar with product
Pump bottle dispensers	☐Yes	☐No	☐Unfamiliar with product
Button hook	☐Yes	☐No	☐Unfamiliar with product
One-handed computer keyboard	☐Yes	☐No	☐Unfamiliar with product

Other adaptive equipment (please describe)

____

____

____

14. If you checked "yes" in any of the above boxes for question 13, how long does a client have to be unilaterally impaired for you to recommend the adaptive equipment?

☐ I recommend adaptive equipment immediately

☐ I wait several days to see how much hand function will return before I recommend adaptive equipment

☐ I wait several weeks to see how much hand function will return before I recommend adaptive equipment

☐ I did not check "yes" in any boxes for question 13.

15. When you are working with a client who has a unilateral injury, do you provide clients with education about injury risks to the non-injured (intact/sound) limb?

☐ Yes, I directly provide education about injury risks to the non-injured limb

☐ No, I do not directly provide education about injury risks to the non-injured limb

☐ Sometimes. It depends on how long the client will rely solely on one hand for all functions.

16. When you are working with a client who has a dominant hand injury, do you <u>directly</u> initiate a hand dominance transfer intervention?

☐ Yes, I directly initiate a hand dominance transfer intervention (proceed to question 18)

☐ No, I have never initiated a hand dominance transfer intervention

17. What is the primary reason you do not initiate a hand dominance transfer intervention with clients who lose dominant hand function?

- ☐ I assume the client has been slowly transferring hand dominance throughout his/her recovery time frame
- ☐ Most of my clients will regain full function in the dominant hand
- ☐ Most of my clients do not injure the dominant hand
- ☐ There is limited third-party reimbursement for this type of intervention
- ☐ I have limited time with my clients and choose to focus that time on recovery of the injured hand, *not* function of the non-injured hand
- ☐ There is no standard protocol to follow related to hand dominance transfer
- ☐ other (please explain)

____

18. When initiating a hand dominance transfer program, what influences your decision as to the *best time* to begin the program?

Injury severity	☐Yes	☐No
Poor prognosis for recovery	☐Yes	☐No
Age of client	☐Yes	☐No
Occupation of client	☐Yes	☐No
Client's request	☐Yes	☐No
Functional level of client	☐Yes	☐No

Other, please specify

____

____

19. When working with a client with a dominant hand injury, do you directly address the following fine motor, functional dexterity tasks in your hand dominance transfer program?

Shoe tying	☐Yes	☐No	☐Depends on the client
Handwriting	☐Yes	☐No	☐Depends on the client
Oral hygiene	☐Yes	☐No	☐Depends on the client
Clothing fasteners	☐Yes	☐No	☐Depends on the client
Work tasks	☐Yes	☐No	☐Depends on the client
Cooking	☐Yes	☐No	☐Depends on the client
Eating	☐Yes	☐No	☐Depends on the client
Typing	☐Yes	☐No	☐Depends on the client
Child care	☐Yes	☐No	☐Depends on the client
Playing a musical instrument	☐Yes	☐No	☐Depends on the client
Sports	☐Yes	☐No	☐Depends on the client
Hobbies	☐Yes	☐No	☐Depends on the client

Other (please specify)

____

____

____

20. In your experience, what factors improve a client's ability to transfer hand dominance?

Visual perceptual ability	☐Yes	☐No	☐Unsure
Visual motor integration	☐Yes	☐No	☐Unsure
Education level	☐Yes	☐No	☐Unsure
Intellect	☐Yes	☐No	☐Unsure
Motivation	☐Yes	☐No	☐Unsure
Work demands	☐Yes	☐No	☐Unsure
Intact cognition	☐Yes	☐No	☐Unsure
Ambidexterity	☐Yes	☐No	☐Unsure
Athleticism	☐Yes	☐No	☐Unsure
Youth	☐Yes	☐No	☐Unsure
Gender	☐Yes	☐No	☐Unsure
Race	☐Yes	☐No	☐Unsure
Culture	☐Yes	☐No	☐Unsure
Social status	☐Yes	☐No	☐Unsure
Economic status	☐Yes	☐No	☐Unsure

PART III: RESEARCH AGENDA FOR HAND DOMINANCE INTERVENTION PROGRAMS

Please rate how strongly you agree or disagree with the following statements by checking one response.

21. Rehabilitation scientists should investigate the factors that help facilitate a successful hand dominance transfer.

☐ Strongly agree ☐ Agree ☐ Neither agree nor disagree ☐ Disagree ☐ Strongly Disagree

22. Rehabilitation scientists should develop clinical care pathways (protocols) to assist therapists in facilitating hand dominance transfer in injured adult clients.

☐ Strongly agree ☐ Agree ☐ Neither agree nor disagree ☐ Disagree ☐ Strongly Disagree

23. Learning to write with the non-dominant hand is the best way to ensure a successful transfer of hand dominance for all other functional dexterity tasks.

☐ Strongly agree ☐ Agree ☐ Neither agree nor disagree ☐ Disagree ☐ Strongly Disagree

24. Adults with traumatic amputation of all or part of the dominant hand must undergo hand dominance transfer because most prosthetics lack sophistication in dexterity.

☐ Strongly agree ☐ Agree ☐ Neither agree nor disagree ☐ Disagree ☐ Strongly Disagree

25. Adults with traumatic amputation of all or part of the dominant hand will experience a hand dominance transfer <u>differently</u> than clients with a physically intact, but non- functional limb, such as those with a brachial plexus avulsion injury.

☐ Strongly agree ☐ Agree ☐ Neither agree nor disagree ☐ Disagree ☐ Strongly Disagree

26. Rehabilitation scientists should investigate the return to work rates of those who lose dominant hand function.

☐ Strongly agree ☐ Agree ☐ Neither agree nor disagree ☐ Disagree ☐ Strongly Disagree

27. Rehabilitation scientists should investigate virtual reality interventions to assist clients with hand dominance transfer.

- ☐ Strongly agree
- ☐ Agree
- ☐ Neither agree nor disagree
- ☐ Disagree
- ☐ Strongly Disagree

28. Rehabilitation scientists should use neuroimaging techniques to examine the change in the brain following peripheral injuries that permanent impair dominant hand function.

- ☐ Strongly agree
- ☐ Agree
- ☐ Neither agree nor disagree
- ☐ Disagree
- ☐ Strongly Disagree

29. Research funding and resources should be provided to more fully investigate hand dominance transfer in injured adults.

- ☐ Strongly agree
- ☐ Agree
- ☐ Neither agree nor disagree
- ☐ Disagree
- ☐ Strongly Disagree

30. If contacted later, would you be interested in participating in a research study related to hand dominance transfer intervention programs?

- ☐ Yes
- ☐ No
- ☐ Undecided

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