TRANSFER OF MIRROR WRITING
IN LEFT AND RIGHT HANDERS

A Thesis in
Kinesiology
by
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ABSTRACT

This study investigated the relative effects of handedness, direction of writing, and visual feedback on transfer of learning using a mirror-writing task. Three main hypotheses are tested; transfer effects are best (regardless of handedness) when transfer conditions match practice conditions in external, “task space”. Transfer effects are also present when joint mechanics are matched, or mirrored, although not as strong. In addition, transfer is best when visual feedback is the same as the condition practiced and is congruent with writing direction.

Utilizing a mirror writing experimental paradigm, two sets of subjects (left-handers and right-handers), practiced one of four possible writing and feedback conditions. All subjects practiced and were tested on a digital tablet whereby they received real-time feedback of their writing in a separate display above the area in which they wrote. Testing occurred over a period of five days; days 1 and 2 were test/retest days, and days 2-4 were practice days. Writing and feedback occurred in either a normal or “mirrored” direction, and both practice and transfer tests occurred with both the right and left hands. In addition, participants were assessed in their ability to write an unpracticed word to evaluate the robustness of transfer effects. To determine the extent of improvement and transfer, two variables were measured: time to completion, and number of velocity minima.

The findings showed that there were significant within-subject learning and transfer effects from pre- to post-practice. All participants improved in mirror writing ability, regardless of visual feedback direction for both dependent variables, time to
completion and # of velocity minima. In addition, participants appeared to exhibit strong transfer effects as evidenced by their improved ability to write a non-practiced word, and improvements to the opposite arm, and different visual feedback conditions, in a scaled manner. Results suggested that left-handed mirror writing improved the most, implying that the left hand has a strong propensity to mirror write, however, the right hand also seemed to exhibit similar mirror writing ability, albeit not as strong.

The experimental findings show that both left and right-handers have the ability to exhibit, learn and transfer mirror writing. This is in opposition to past studies that have shown that only left-handers have an enhanced ability to mirror write, when compared to right-handers. Furthermore, the present investigation revealed that the practice of mirror writing by both right and left-handers changes and improves different writing conditions in joint and task space coordinates. In addition, results showed supported the hypothesis that transfer occurs best to visual feedback conditions that are previously practiced, and not necessarily to familiar presentations of feedback.

Overall, the results support the idea that the kind and extent of transfer of learning is task-dependent and not simply a manifestation of either inherent qualities of the learner or the environment alone.
TABLE OF CONTENTS

List of Tables ........................................................................................................vi
List of Figures .........................................................................................................vii
Acknowledgements ................................................................................................viii

Chapter 1. INTRODUCTION................................................................................1
Hypotheses ............................................................................................................13

Chapter 2. METHODS.........................................................................................15
Participants ...........................................................................................................15
Apparatus .............................................................................................................15
Task and Procedures .............................................................................................16
Data Analysis ..........................................................................................................21
Statistical Analysis ................................................................................................23

Chapter 3. RESULTS..........................................................................................24
Qualitative Assessment ..........................................................................................24
Time to Completion – Practice Word .................................................................24
Velocity Minima – Practice Word .......................................................................26
Time to Completion – Transfer Word .................................................................28
Velocity Minima – Transfer Word .......................................................................29

Chapter 4. DISCUSSION.....................................................................................32

Bibliography ..........................................................................................................42
LIST OF TABLES

Table 1. Time to Completion: Practice Word Results...........................................25
Table 2. Velocity Minima: Practice Word Results..................................................27
Table 3. Time to Completion: Transfer Word..........................................................28
Table 4. Velocity Minima: Transfer Word.................................................................30
LIST OF FIGURES

Figure 1. Graphic representation of WACOM Cintiq 21ux……………………………………16
Figure 2. Condition #7 (example)……………………………………………………………………..19
Figure 3. Time to completion for the practice word as a function of condition…………26
Figure 4. Time to completion for the transfer word as a function of condition………………..27
Figure 5. Velocity Minima for the practice word as a function of condition…………………..29
Figure 6. Velocity Minima for the transfer word as a function of condition…………………..30
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Chapter 1. INTRODUCTION

Two key features of motor learning that accompany practice are 1) improvement in performance; and 2) the enhanced adaptability of the organism for future performances. These adaptive possibilities afford the agent (acting within specific environmental and task conditions) the discovery of multiple solutions for a unique motor problem. In other words, with further exposure to a particular perceptual-motor problem, individuals become more adept in satisfactorily and consistently accomplishing the intended goal, in spite of greater mechanical and processing demands. For example, highly skilled athletes rely on utilizing coordinated movements more reliably (when compared with novices) in the face of greater challenges than was initially present in the beginning stages of learning. With learning it becomes possible to reproduce the desired outcome in novel and more demanding environmental settings and with a variety of joint/limb arrangements.

The concept of adaptation implies that learners become more flexible in their means of accomplishing the given task by exploiting unique and relatively unpracticed motor strategies. Turvey (1990) has labeled this phenomena as, “indefiniteness of action plans”. He goes on further to explain this concept; “It is possible to configure different degrees of freedom in the same way to achieve the same purpose and the same degrees of freedom in different ways to achieve different purposes.” In other words, effectors used to achieve a desired outcome may be rearranged in novel way so as to bring about the same outcome, and the same effectors may be exploited in like manner to bring about an entirely different result. This phenomenon may be observed when an individual attempts to write their name with different limbs. The same general outcome can be achieved and
preserved, with different limbs (e.g. non-dominant hand, mouth, foot), albeit variably expressed. In contrast, the same limb/hand can write an infinite number of words and phrases, both practiced and unpracticed. This characteristic and highly adaptive flexibility of the human motor system serves as the basis for understanding phenomenon classically defined in motor behavior literature as “transfer of learning”.

The enormous flexibility in the selection of action plans relieves the system of relying on a single solution to a given ‘motor problem’, thus making the agent more adaptive. Furthermore, this flexibility resulting from practice of specific skills offers the performer an opportunity for enhanced ability in successfully accomplishing seemingly unrelated and unpracticed skills. If this were not the case, the adaptive characteristics of such a system would not provide the organism with the means to survive in a demanding and infinitely complex world.

The ability for an individual to obtain the same outcome despite changes in either intra-effector or inter-effector strategy has been classically defined in the literature as motor equivalence (Bernstein, 1947, 1967; Lashley, 1930). One such example of this phenomenon has been demonstrated in a classic paper by Karl Lashley (1942), where subjects were asked to perform both normal and mirror writing with a pen during separate trials held by their right hand, left hand, and teeth. Despite the experimentally imposed requirements of writing with unpracticed effectors subjects were consistently able to reproduce the letters in a perceptually identifiable manner. In other words, the general qualitative features of the writing were preserved regardless of the effector employed.

In another seminal experiment referencing the notion of motor equivalence, subjects were asked to copy the following palindromic sentence: Able was I ere I saw
Elba, using their right hand, left hand, mouth, and right foot (Raibert, 1977). Not unlike Lashley’s findings, participants successfully reproduced the sentence regardless of the utilized effector. It is unlikely than any of the participants had previously attempted to write in cursive with their mouth or foot, making the findings all the more noteworthy. Despite the lack of overt practice with the mouth and other appendages, the general characteristics of the writing were preserved in a coherent and recognizable style. These examples provide empirical support for the robust flexibility that the motor system affords the learner.

In a more thorough examination of motor equivalence in handwriting, Terzuolo and Viviani (1979) asked subjects to write letters under various spatio-temporal conditions. In some cases, subjects were required to write the letter “a” within varying criterion times. Another condition required spatially scaling the size of the letter. After examining the velocity profiles of the individual pen-tip trajectories, Terzuolo and Viviani (1979) discovered that the letters, “…generally preserve their characteristic velocity profiles even when they are welded into words. Increasing the size of the letters does not affect the spatial invariance’s, just the absolute amount of time to complete them” (Terzuolo & Viviani, 1979). This non-trivial finding provides evidence that individuals are not constrained by the spatio-temporal specifics learned in the initial practice conditions. If this were not the case, while initially learning to handwrite on small lined paper would do little, if anything, to facilitate improvement in performance when one was asked to write on a large blackboard making learning a very tedious and arduous task. In a situation such as this, the level of performance would likely be similar to the initial performance such as when writing on lined paper. Conceptually, the
solution to a given task as obtained by practice may be $\textit{transferred}$ to another limb, or to other attempted skills and behaviors. This characteristic phenomenon of learning has been classically defined in the motor learning literature as $\textit{transfer of learning}$ (Thorndike, 1906; Thorndike, 1923; Thorndike & Woodworth, 1901).

During the early 20$^{th}$ century, Woodworth (1938) defined transfer of learning as, “…the carrying over of an act or way of acting from one performance to another.” He further distinguishes between $\textit{transfer}$ and $\textit{transfer effect}$, the latter being understood as, “The effect of this transferred act upon the execution or learning of the second performance.”, implying that the effect can be either positive or negative in nature. Stated simply, transfer effect may be considered by the more commonly accepted definition of transfer of learning; “…the influence of having previously practiced or performed a skill or skills on the learning of a new skill” (Magill, 2001). It is clear from the definition that the concept of transfer of learning does not preference either the facilitation of learning or the degradation of skill sets.

The influence of prior experiences may affect the immediate and subsequent performance(s) in a negative manner (i.e., $\textit{negative transfer}$), and is not limited to promoting positive changes in performance as might be assumed. More interestingly, in situations where $\textit{positive transfer}$ occurs, unpracticed effector(s) appear to take advantage of or exploit the practiced limb’s improvement in performance. It is as if the unpracticed effectors (when allowed to engage in the task) ‘get something for nothing’, simply due to previous practice with other effectors. This would suggest that there are universal patterns of learning that transcend the particularities of either the task or the individual’s biomechanical and physiological structure.
One particular type of learning associated with transfer is the phenomenon of *bilateral transfer*. Formally, bilateral transfer is defined as the transfer of learning that occurs between two appendages, or effectors (Ellis, 1965; Magill, 2001). Historically, bilateral transfer was rigorously examined during the 1930s, and into the 1950s. In particular, T.W. Cook’s findings revealed that bilateral transfer is a common and ubiquitous phenomenon among most individuals (Cook, 1936). More recently, in a study examining the incidence of bilateral transfer subjects learned how to mirror write with their dominant hand and were found to be able to successfully transfer the newly acquired skill to their non-dominant hand (Latash, 1999). Results revealed that bilateral transfer occurred for both left and right-handers, once again confirming this unique behavioral phenomenon in a more contemporary scientific study.

Despite the large and overwhelming body of evidence supporting the phenomenon of transfer of learning, and disparate findings and a variety of theories regarding the processes underlying transfer lack explanatory power and appear to be conceptually incongruent. Current theoretical perspectives regarding transfer are not unlike some of the original theories of transfer proposed at the turn of and early 20th century. For example, the Identical Elements Theory postulated that the degree of transfer is a function of the number of hypothetical *elements* identical to those that were present in the original learning conditions (Hergenhahn & Olson, 2005; Thorndike & Woodworth, 1901; Thorndike, 1913). In line with prevailing Behaviorism theories of the early 20th century, these hypothetical elements could be further discriminated as either *stimulus* or *response* elements. According to these theories, the greater degree of symmetry or similarity between practice elements and transfer elements (in terms of both
stimulus and response), the likelihood of transfer is enhanced (Holding, 1976; Osgood, 1949;). Furthermore, Thorndike acknowledged that not only could the similitude of stimulus elements facilitate transfer effects, but learning procedures (or “response” elements) could also be transferred. In other words, the degree of transfer between two contexts also depends on a procedural component, or strategy of behaving, and not simply the relationship between stimulus elements (Hergenhahn & Olson, 2005). More contemporarily, similar problems in regard to “procedural” learning and transfer are still being questioned. For example, when transferring to novel skill contexts, do individuals learn and transfer the “joint/internal/planning procedures or “task/external/perceptual” procedures, or perhaps both? Apparently, Thorndike never attempted to address such a distinction in regard to transferring procedural knowledge, but modern theories are not lacking in such differentiations, making the understanding of transfer seemingly more complex.

As a result of the aforementioned studies, two primary criticisms arise when evaluating the theoretical usefulness of the Identical Elements Theory. First, is the question of what constitutes a “stimulus element”, and relatedly, how to successfully evaluate and compare similarity between two different contexts (i.e., both stimuli and response, or environmental and kinematic/kinetic elements). The second criticism involves the number of elements that must be related in order to elicit the previously learned response or action. Most fundamentally, the Identical Elements Theory, other than providing a mere description of learning, offers no further insight into the processes involved in transfer of learning. Here, like most Behavioristic paradigms, the Identical Elements Theory succumbs to similar failures and a warranted criticisms, such as those
previously mentioned. In essence, it is too simplistic and vague to assume similarities in responses and stimuli across different contexts, and practically difficult to assure that the same number of elements are present in non-learning environments so as to elicit a desired degree of transfer.

More contemporarily, and elaborating further on these observations, it appears that two opposing theoretical viewpoints dominate the transfer literature. One camp suggests that the extent of transfer is dependent on the degree to which external or “task space variables” are previously learned, and that joint configurations are redundant, (necessarily relieving the system from consolidating complex internal dynamics). This theoretical camp places responsibility for transfer squarely on the shoulders of environmental regularities and invariance’s. The other camp claims that the critical behavioral information facilitating transfer is the learned internal or joint space variables, irrespective of task space requirements. This perspective places responsibility for transfer solely in the hands of the learner/organism. However, these two perspectives, force a theoretical dichotomy that may not be based on more robust empirical observations and tests. Perhaps transfer of learning involves both intrinsic and extrinsic factors that manifest only by degree, based on the constraints of the entire system (task, environment, and organism).

By way of example, and as was briefly mentioned earlier, Latash (1999) demonstrated that subjects were able to successfully transfer learned dominant hand mirror writing to the non-dominant hand. The conclusion was that subjects learned the particular coordination strategy by relying on external space variables rather than effector specific variables. In this particular experiment, it is important to point out that the
direction of writing remained consistent between transfer conditions. In consideration of this (in regard to direction of writing), the conclusion that external space variables (as opposed to internal/joint space variables) are exclusively learned and transferred should be acknowledged as a methodological limitation. For example, one essential critique of the study is that it failed to examine the extent of transfer under conditions whereby subjects were required to write and transfer in the opposing direction to that which was learned. If internal/joint space coordinates were also learned in addition to external coordinates, the extent to which they were transferred would only be manifest under such conditions whereby participants would be required to write in the opposite direction given that joint mechanics would be mirrored. Thus the findings of this particular study, although providing support for the consolidation and transfer of task-space coordinates, was unable to reveal (due to methodological limitations) the potential of subjects learning and transferring joint-space coordinates across different task/goal conditions.

Other studies have produced inconsistent and conflicting findings, some of which provide support for learning and transfer of external coordinates and others in favor of internal coordinate transference (Imamizu et al., 1995). For example, Imamizu at al. found in an aiming task with rotated visual feedback close to 100% transfer, supporting the notion of learned task-space transformation. In contrast, and in a later experiment Imamizu et al. (1998) provided evidence for transfer of intrinsic coordinates during pointing tasks with linear joint angle transformations.

Tankle and Heilman (1983) found that both right-handed and left-handed subjects performed best when using their left-hand to mirror write. This is a nontrivial finding, especially when considering that right-handers in this study were able to mirror write
better than normal writing with their left hand, after practice. This may suggest that right-handers rely on previously learned joint-space coordinates when transferring to left-hand mirror writing (due to the fact that the direction of writing is inverted and joint configurations are mirrored when compared with normal right-hand writing). If right-handed subjects exploit external space coordinates rather than internal coordinates, it would be expected that their performance in left-handed normal writing would exceed their unpracticed mirror writing ability. Yang (1997) discovered that when writing Chinese characters during transfer conditions right-handers performed better when asked to normal write with their left hand rather than when mirror writing. These findings, in light of the results of Tankle and Heilman (1983), are interesting, and appear to parallel one another in support. Given that Chinese characters are written inversely (within task space), to English characters, it would suggest that even right-hand dominant individuals do better at mirror writing when using the left hand. In this study, Chinese “normal-writing” would actually be English mirrored-writing, thereby giving support to the preferred ability for the left hand (regardless of hand dominance) to mirror-write.

Tucha, Aschenbrenner, and Lange (2000) using a mirror writing paradigm demonstrated that left handed subjects were more adept at mirror writing than right-handed subjects as evidenced by a decrease in the number of inversions within the velocity profile of the writing. In addition, when comparing performance between preferred and non-preferred hands left-handed subjects appeared to exhibit similar performance scores between left-handed mirror writing and right-handed (non-preferred) normal writing. A similar trend was observed in right-handed subjects when comparing right-handed mirror writing and left-handed normal writing. Specifically, right-handers
performance was similar between right-handed mirror writing and left-handed normal writing, lending further support to learned and transferable internal-coordinates given that the joint mechanics were mirrored in respect to one another.

Finally, a study examining bimanual transfer of a bilateral line-star drawing task to star-line drawing under different rotation direction requirements (clockwise, counterclockwise) produced findings consistent with the learning of both joint and task-space coordinates (Vangheluwe et al., 2004). Subjects initially practiced a bimanual drawing task whereby the left hand produced a vertical line co-temporally with the right-handed engaged in star drawing (produced in the clockwise direction). Results revealed that ideal transfer occurred for left-handed line drawing, counterclockwise right-handed star drawing, and more interestingly to left-handed star (counterclockwise), right-handed line drawing, suggesting a mirrored transfer effect thereby providing evidence for joint-space transfer. The initially improved transfer condition supports task-space learning, while the second supports joint-space learning due to its high degree of internal-space symmetry with the original practice condition. This would indicate that practice contexts do not favor one learning capacity exclusively. Rather, it would suggest that depending on task constraints, learning can manifest itself in either task-space or joint-space along a continuum of behavioral expression.

In spite of these equivocal and disparate findings, it is clear that the motor system is capable of exhibiting a significant number of stable behaviors and an enhanced resilience to perturbation when attempting to accomplish goals whether it be writing one’s signature or an arbitrary sentence. This stability is partially derived from the organism’s adaptive characteristics and capabilities, including the ability to solve a given
task or goal in a variety of ways. In the case of writing a signature with any of the possible effectors or combinations thereof it is apparent that the learned and transferred information cannot be expressed solely as a specific learned combination of joint and/or muscle orientations, but is also configured in task space. Alternatively, it is important not to ignore or downplay the extent to which a particular orientation of joint coordinates may become learned and may influence future experiences. A more reasonable position is to assert that task demands and learner characteristics may shift the extent to which learned joint or task-space variables manifest themselves in subsequent performances.

Therefore, to understand why transfer occurs and to explicate its subsequent mechanism(s), there must be a theoretical recognition of the various and potential causal influences contributing to the promotion of adaptability in the organism. Through an acknowledgement of factors that may plausibly contribute to transfer-like effects, such as the learned behavioral pattern(s) and the relevant perceptual components, it will aid in developing a more all-encompassing and comprehensive theory of motor learning transfer of learning in general and transfer of learning more specifically. Rather than relying on or presupposing internal models or abstract control mechanisms to transform coordinate spaces (external or internal) perhaps transfer of learning is better viewed as a behavioral artifact or manifestation of the confluence of external (i.e. environmental, task) and internal (i.e. biomechanical, perceptual) constraints. If this is the case, the degree of transfer could be determined by a similarity in the dynamic interplay between more or less stable constraints that vary according to different task demands along a continuum. As a result of previous experiences the individual is constantly being shaped, becoming differentially “tuned” to environmental invariants, and as a result of consistent
interactions with exogenous stabilities, the individual (i.e. perceptual, cognitive, and biomechanical nuances) shifts away from certain behavioral tendencies, and new behavioral tendencies become viable, creating new possibilities for increased performance and transfer within varying contexts.

Through a systematic investigation inquiring into how specific constraints (acting at all levels) interact and lead to positive transfer, an understanding of the process of this phenomenon can be realized (Kelso & Zanone, 2002; Zanone & Kelso, 1992, 1997). This type of approach is in line with more recent assertions as endorsed by Dynamical Systems Theory. Proponents state; “…the machine-conception interpretations in general leads to convenient and easily imagined models of process but it does not, necessarily, lead to an understanding of [actual] process” (Kugler et al., 1980). In line with this belief, the current study is committed to understanding and further elucidating the processes involved in transfer of learning, namely that of bilateral transfer in both task- and joint-space coordinates.

Given these past findings standing in opposition to more polemic explanations (i.e., extrinsic vs. intrinsic coordinate consolidation) of the mechanisms of transfer, it would appear reasonable to propose a more comprehensive model of transfer whereby a multi-faceted set of constraints (made up of effectual invariants) dictate the degree to which the learned and coupled task-space and joint-space coordinates are expressed and made manifest in novel skill attempts. In line with the claim that both intrinsic and extrinsic coordinates are learned during practice, Kakei et al. (1999, 2001) have provided neurological evidence that neurons in the ventral portion of the premotor cortex code in task space variables (effector independent), while the primary motor cortex (i.e., M1)
codes in both “coordinate systems”, although is predominantly represented by extrinsically tuned neurons. Although the current study does not explicitly examine brain behavior, these findings lend credence to the theoretical position that task demands dictate the degree to which behavior appear to reflect joint and/or task-space coordinates along a hypothetical continuum of learning and transfer.

**Hypotheses**

This study investigated transfer of mirror writing under various visual and writing conditions. The current focus was to examine transfer of mirror writing framed in the context of learning occurring within joint- and/or task-space coordinate systems.

1) It was hypothesized depending on subjects’ initial skill ability, and the condition practiced, both joint and task variables would be learned and transferred, although contingently and disproportionately, based on the particular transfer condition and the condition originally practiced. For example, left-handed subjects who practiced left-handed mirror writing (right-to-left) with congruent visual feedback (i.e., mirrored feedback) were hypothesized to transfer best to conditions with the right hand that involved writing from right-to-left (mirror writing), and secondarily, to right-handed “normal writing”. Transfer to those conditions would reflect transfer within “task-space” and “joint-space”, respectively. Presumably, transfer effects are preferred for joint-space symmetry given that left-handed mirror writing is an inverse mechanical manifestation for right-handed “normal” writing.

2) It was hypothesized that right-handers who practiced right-handed mirror would transfer best to left-handed mirror writing (right-to-left) and secondarily, left-
handed normal writing (left-to-right), once again reflecting transfer via “task-space” and “joint-space” variables. This hypothesis was made in light of the mixed experimental findings of the past and the evidence that coding happens in terms of both task- and joint-space.

3) It was hypothesized that practice with a particular direction of visual feedback (e.g. either right-to-left or left-to-right) would differentially affect the degree of transfer to the other arm and to different conditions of writing (normal vs. mirrored). It was expected that the degree of transfer will be better for conditions involving similar presentations of visual feedback, whereby practice conditions that matched transfer conditions (both right-to-left) would be more likely to elicit greater transfer effects. For example, for practice conditions whereby study participants write mirrored (right-to-left), it is expected that transfer tests with similar visual feedback (regardless of the arm used, or direction of writing) will present with better performance scores than those with non-practiced visual feedback (left-to-right).

4) Finally, it was hypothesized that left-handers would have a proclivity to produce an enhanced ability to mirror write. This is due to the overwhelming body of literature that suggests that left-handers are superior to right-handers in their ability to mirror write.
Chapter 2. METHODS

Participants

A group of volunteers (N=32; 14 female, 18 male) from the Pennsylvania State University with a mean age of 24.8 years (SD=3.5) were recruited for the study. Two groups of sixteen individuals were differentiated on the basis of hand dominance. One group consisted of 16 left-hand dominant volunteers and the other, 16 right-hand volunteers (left-handed group; 6 female, 10 male, right-handed group; 8 female, 8 male). Hand dominance was determined using the Edinburgh handedness inventory prior to the testing procedures (Oldfield, 1971). In addition, potential participants were screened before actual testing. Screening involved evaluation via an oral questionnaire whereby those with severe visual or physical limitations that may have confounded the experimental results were excluded from testing. All participants provided informed consent and all procedures were in accordance with regulations and guidelines approved by the IRB of Pennsylvania State University. Each subject received monetary compensation upon completion of the experiment.

Apparatus

The experiment was carried out using a WACOM Cintiq 21ux, LCD Graphics Tablet (see Figure 1). The screen size of the Cintiq 21ux is 21.3” diagonally, with an active working area of 17” x 12.75”. Display resolution of the tablet is 1600 x 1200 pixels and has a coordinate accuracy of ± 1 pixel. Participants used a small hand-held stylus similar in shape and size to a standard ballpoint pen and wrote directly on to the tablet surface. The output of the stylus was viewed in real-time directly on the surface of
the tablet. To prevent subjects from viewing their arm during writing, a visual blockade rested over the graphic tablet covering the area designated on the screen for the writing input. For each separate trial, $x$- (horizontal) and $y$- (vertical) position and velocity data were recorded to provide a basis on which to evaluate the kinematics of handwriting. Data were stored on a personal computer, which was connected to the tablet. Furthermore, data processing was carried out with a standard computational program (MATLAB; Mathworks, Sherborn, MA, USA) for the analysis of handwriting movements.

Figure 1. Graphic representation of WACOM Cintiq 21ux.

Task and Procedures

To examine the task relevant constraints underlying transfer of the skill of mirror writing, the experimental protocol involved learning to mirror write under various visual feedback conditions. Prior to testing volunteers’ handedness was assessed using an empirically validated handedness test (Oldfield, 1971). The test was employed to qualitatively categorize participants according to hand/arm dominance. Two groups of 16 participants were differentiated on the basis of hand dominance: Group R- Right hand
dominant, Group L- Left hand dominant. During testing all participants practiced the assigned task with their dominant hand.

Testing took place over a period of 5 consecutive days. The 5 days consisted of a pretest, followed by 3 days of practice, concluded by a posttest on the fifth day. On the first day of testing (pretest), subjects were evaluated in 8 randomly assigned testing conditions, as outlined below. The data obtained during the pretest was used as a baseline measure to compare against post-practice learning effects and to infer the extent of learning and transfer. Following the pretest, they were asked to practice mirror writing on three consecutive days in the laboratory according to a randomly assigned condition. On day 5 (posttest), participants were reassessed under the same testing conditions as initially performed during the pretest.

The testing conditions are outlined below. The orientation of the arrow indicates the direction of the pen-tip trajectory in space and direction of visual feedback in relation to the midline of the body, respectively (see Figure 2). Participants performed 6 trials of each condition during both pre- and post- test conditions, resulting in 48 total trials.

1. Left-hand – Mirrored writing (←) – mirrored visual feedback (←)
2. Left-hand - Mirrored writing (←) – normal visual feedback (→)
3. Left-hand - Normal writing (→) – mirrored visual feedback (←)
4. Left-hand - Normal writing (→) – normal visual feedback (→) *
5. Right-hand – Mirrored writing (←) – mirrored visual feedback (←)
6. Right-hand – Mirrored writing (←) – normal visual feedback (→)
7. Right-hand – Normal writing (→) – mirrored visual feedback (←)
8. Right-hand – Normal writing (→) – normal visual feedback (→) *

*Bold-faced rows represent control conditions, for left- and right-handed groups respectively.*
The practice conditions according to right- and left-handed subjects are outlined below. Eight participants were randomly assigned to each respective group, for a total of 4 groups.

**Left Hand Group(s):**

1. (L) – Mirror writing (←) – Normal visual feedback (→)
2. (L) – Mirror writing (←) – Mirrored visual feedback (↔)

**Right Hand Group(s):**

1. (R) - Mirror writing (↔) – Normal visual feedback (→)
2. (R) - Mirror writing (↔) – Mirrored visual feedback (↔)
During testing, participants were seated in front of a desk with the height of the seat adjusted such that the elbows rested comfortably on the surface of the desk. The graphic tablet sat directly in front of the subject in a horizontally oriented position. To maximize writing comfort and visual clarity, the tablet was angled up 10 to 15 degrees from the surface of the table. Following screening, subjects were offered a short period of time to familiarize themselves with the set-up before proceeding with the testing. Participants were instructed to write in the box at the bottom of the display screen and to direct their attention to the feedback (writing trajectory) in the box above the writing box (see Figure 2). They were asked to ensure that the pen-tip did not exceed the perimeter of
the writing box and to maintain contact with the surface of the tablet throughout the duration of each trial. The trial was terminated if either of the aforementioned restrictions was violated, whereby the trial was repeated under such circumstances. Before the experiment was initiated, mirror-reversed script was briefly explained and demonstrated.

Instructions were given to place the pen tip in the appropriate place within the writing box at the beginning of each trial and as defined by each condition. In addition, all trials were self-initiated. Trials began by resting the pen tip onto the surface of the tablet and pressing and holding down a small button at the distal portion of the stylus. Releasing the button terminated the trial. Throughout all pre-/post-tests and practice trials, subjects were asked to write a 7-letter word, “measure”, in their preferred cursive writing style. After completion of writing the word “measure”, under all 8 conditions, participants were then asked to repeat all 8 conditions writing the word “caramel”. The last set of 8 conditions (i.e. “caramel”) served as a transfer-test for assessing the degree to which subjects were successfully able to transfer the practiced skill of mirror writing to novel skill contexts. It was assumed that mirror writing, if adequately learned, would be adequately transferred to different words. Testing commenced after participants were adequately familiarized with the experimental protocol. As mentioned previously, 6 trials of each of the 8 conditions were performed. The first four conditions involved the use of the dominant arm and the last four involved the non-dominant arm. Testing ended upon completion of the 96 trials (“measure” = 48; “caramel” = 48).

Practice testing occurred over a period of 3 consecutive days subsequent to pretesting. Participants practiced within conditions that were assigned on the first day,
performing 50 practice trials of the respective condition on each of the three days. Only the word “measure” was written during practice trials. After the 3 practice days were completed, a post-test on day 5 consisted of the same testing protocol performed on the first day, including writing the transfer word “caramel”.

Data Analysis

To ensure that subjects were writing the prescribed word, “measure”, a systematic subjective evaluation was employed across trials. Similar to the method used by Longstaff and Heath (1997) and Braswell and Rosengren (2002) a subjective assessment using criteria such as general legibility, accuracy of letter formation and consistency of letter size provided the basis of perceptual judgment and comparison (Braswell & Rosengren, 2002; Rubin & Henderson, 1982; Schneck, 1991; Wann & Jones, 1986). Two independent judges ranked each trial using a qualitative rating scale. The procedure, not unlike Braswell and Rosengren (2002) relied upon a 4-point rating scale that assigned a single value representative of a predetermined criterion of the actual quality of writing. The value ‘1’ was assigned to words that were considered to be an entirely unrecognizable scribble or were missing letters altogether. Words that were undifferentiated and not recognizable as the target word and were misspelled were assigned a ‘2’. Trials assigned a ‘3’ were recognizable but were considered poorly constructed forms. Lastly, a ‘4’ was assigned to those samples that adhered most closely to the idealized word/letter form based on the individual subjects’ preferred writing style (e.g. right-handed normal writing for a right-hander). Only those trials that were assigned a 3 or 4 were included for further analysis.
In accordance with past findings, the performance measure, time to completion, has been demonstrated to be a reliable indicator of changes and improvement in performance associated with learning, particularly in handwriting (Latash, 1999; Wright, 1990). In line with these findings, the mean writing time of each trial was recorded and used to infer learning from pre- to post-practice and across all conditions. A statistically significant decrease in the time taken to write one trial indicated an improvement in performance and indicated potential evidence of transfer of learning to the non-dominant effector and/or condition.

Previous studies have supported the notion that the stroke is the fundamental unit of interest for the analysis of handwriting (Edelman & Flash, 1987; Hollerbach, 1981; Viviani & Cenzato, 1985). A stroke is defined by the distance between two sequential extreme scores of the respective coordinates (x, y) and corresponds to 0-points in velocity trajectories. A minimum number of strokes are suggestive of movement automation - an expected outcome of positive learning and transfer. Involved in the evaluation of kinematic data, the number of minima of the direction of the tangential velocity profiles for each trial was calculated. Mean scores of each condition were determined and used to compare learning effects from pre- to post-practice under the assigned transfer conditions (Wright, 1990).
**Statistical Analysis**

A repeated measures ANOVA was performed on each of the dependent variables (i.e. time to completion, # of velocity minima). Handedness (right- and left-handed participants) and Practice Group (LM-LR, RL; RM-LR, RL) were assessed as between factor comparisons, while Conditions (8) were assessed as a within factor analysis. When a significant effect of condition was observed, comparisons between the various factors were examined post hoc for handedness, groups, and conditions. The Greenhouse-Geisser epsilon was used to adjust for probabilities. An alpha value of .05 was used for all statistical tests.
Chapter 3. RESULTS

Qualitative Assessment

Each of the individual trials were qualitatively assessed to ensure that the to-be-produced words (i.e., “measure”, “caramel”) were actually replicated. Qualitative analysis based on overall/general legibility, accuracy of letter formation, and completed letter topology revealed that all individual samples matched the task words. All words were assigned either a 3 or 4, thereby including all writing trials for further quantitative analysis. As expected, a certain degree of inter-trial and between subject variability was observed, in a qualitative sense. Nevertheless, each sample remained consistent with the required task goals and did not warrant exclusion of any particular trial from further analysis. The inter-rater reliability on all of the data was determined to be approximately 95%. Any discrepancies between the raters’ individual judgments were resolved by meeting and rating collaboratively.

To examine the extent of transfer across arms and across conditions, the statistical analysis relied upon a 2 (dominant hand) x 4 (practice condition) x 16 (pre/post conditions) repeated-measures ANOVA conducted on both dependent variables: time to completion and the number of velocity inflections. Tukey’s HSD post hoc tests were used to determine significance where appropriate.

Time to Completion – Practice Word

Repeated-measures ANOVA tests revealed that no between-subject practice effects for present for either Dominant Hand $F (1, 28) = 1.85, p = .18$, and across Learning Conditions, $F (3, 28) = 1.83, p = 1.64$. Both of these findings suggest that
neither hand dominance nor the specific conditions of practice were sufficient enough to illicit significant changes during learning strong enough to bring about transfer effects. Furthermore, no interaction effects were noted either for between-subject or within-subject factors: Learning Condition * Pre/Post Conditions, $p = .24$.

However, within-subject practice effects were noted for pre/post conditions, $F = 22.518$, $p = .000$, with an eta-squared value of .446. Post hoc tests (Tukey’s HSD) revealed that all pre/post conditions were significant except for condition # 6 (R-RL), $p = .181$ (see Figure 4), suggesting that practicing mirror writing does not benefit the particular circumstance whereby one writes normally with their right hand and receives mirrored feedback. Table 1 below outlines the statistical details by each condition.

<table>
<thead>
<tr>
<th>Condition</th>
<th>$p$-value</th>
<th>Mean Difference</th>
<th>Std. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-LR</td>
<td>.011</td>
<td>908.6</td>
<td>334.7</td>
</tr>
<tr>
<td>L_RL</td>
<td>.033</td>
<td>1904.8</td>
<td>850.5</td>
</tr>
<tr>
<td>LM_LR</td>
<td>.000</td>
<td>6948.2</td>
<td>1642.7</td>
</tr>
<tr>
<td>LM_RL</td>
<td>.000</td>
<td>2934.7</td>
<td>504.2</td>
</tr>
<tr>
<td>R_LR</td>
<td>.005</td>
<td>1126.9</td>
<td>365.2</td>
</tr>
<tr>
<td>R_RL</td>
<td>.181</td>
<td>401.7</td>
<td>589.2</td>
</tr>
<tr>
<td>RM_LR</td>
<td>.000</td>
<td>7125.5</td>
<td>1339.2</td>
</tr>
<tr>
<td>RM_RL</td>
<td>.000</td>
<td>3129.0</td>
<td>657.7</td>
</tr>
</tbody>
</table>

Table 1.
Velocity Minima – Practice Word

Not unlike the results for the time to completion dependent variable, between-subject practice effects were not present. Neither Dominant Hand $F(1, 28) = .160, p = .692$, or Learning Condition, $F(3, 28) = 2.12, p = .140$, exhibited any statistically significant differences during pre/post testing. Also, no between-subject interaction effects were noted for Dominant Hand*Learning Condition. This was similar for within-subject interaction effects. ANOVAs revealed no interaction effects for Learning Condition * Pre/Post Conditions ($p = .129$).

The lack of between-subject findings was contrasted with the significant within-subject practice effects for pre/post conditions: $F = 24.57, p = .000$, with an eta-squared value of .467. As displayed in Figure 5, Tukey’s HSD post hoc tests demonstrated that
all pre/post conditions were statistically different other than for conditions 1 (L-LR), 2 (L-RL), 5 (R-LR), and 6 (R-RL). Table 2 outlines the specific values for each condition.

<table>
<thead>
<tr>
<th>Condition</th>
<th>p-value</th>
<th>Mean Difference</th>
<th>Std. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-LR</td>
<td>.725</td>
<td>-.26</td>
<td>.74</td>
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<tr>
<td>L_RL</td>
<td>.067</td>
<td>2.15</td>
<td>1.13</td>
</tr>
<tr>
<td>LM_LR</td>
<td>.000</td>
<td>9.49</td>
<td>1.85</td>
</tr>
<tr>
<td>LM_RL</td>
<td>.000</td>
<td>3.85</td>
<td>.83</td>
</tr>
<tr>
<td>R_LR</td>
<td>.114</td>
<td>1.12</td>
<td>.68</td>
</tr>
<tr>
<td>R_RL</td>
<td>.163</td>
<td>1.41</td>
<td>.99</td>
</tr>
<tr>
<td>RM_LR</td>
<td>.000</td>
<td>11.58</td>
<td>2.01</td>
</tr>
<tr>
<td>RM_RL</td>
<td>.000</td>
<td>5.32</td>
<td>1.07</td>
</tr>
</tbody>
</table>

Table 2.

Figure 4 - Velocity Minima for the practice word.
**Time to Completion – Transfer Word**

There were no between-subject practice effects for Dominant Hand, $F(1, 28) = 1.702, p = .203$, and for Practice condition, $F(3, 28) = 1.480, p = .245$. Furthermore, there were no interaction effects for Dominant Hand * Practice Condition. Within-subject analyses revealed no interaction effects for Conditions*Practice Conditions, $p = .115$, and no effects for Conditions*Dominant Hand. However, within-subject practice effects were noted for Pre/Post Conditions, $F = 22.055, p = .000$, with an eta-squared value of .441. Post hoc tests (Tukey HSD) revealed that all pre/post conditions were significant except for condition 6 (R-RL). See Figure 6 below for a graphical display of the data. See Table 3 below.

<table>
<thead>
<tr>
<th>Condition</th>
<th>$p$-value</th>
<th>Mean Difference</th>
<th>Std. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-LR</td>
<td>.002</td>
<td>891.5</td>
<td>259.8</td>
</tr>
<tr>
<td>L_RL</td>
<td>.038</td>
<td>1692.8</td>
<td>775.6</td>
</tr>
<tr>
<td>LM_LR</td>
<td>.000</td>
<td>4802.5</td>
<td>1215.9</td>
</tr>
<tr>
<td>LM_RL</td>
<td>.000</td>
<td>2144.6</td>
<td>485.9</td>
</tr>
<tr>
<td>R_LR</td>
<td>.016</td>
<td>507.9</td>
<td>198.8</td>
</tr>
<tr>
<td>R_RL</td>
<td>.066</td>
<td>1273.9</td>
<td>666.5</td>
</tr>
<tr>
<td>RM_LR</td>
<td>.000</td>
<td>3855.4</td>
<td>705.4</td>
</tr>
<tr>
<td>RM_RL</td>
<td>.000</td>
<td>1877.8</td>
<td>298.1</td>
</tr>
</tbody>
</table>

Table 3.
Velocity Minima – Transfer Word

There were no between-subject practice effects for Dominant Hand, F (1, 28) = .409, \( p = .527 \), and for Practice condition, F (3, 28) = 2.413, \( p = .108 \). Furthermore, there were no interaction effects for Dominant Hand * Practice Condition. Within-subject analyses revealed no interaction effects for Conditions*Practice Conditions, \( p = .195 \), and no effects for Conditions*Dominant Hand. However, within-subject practice effects were noted for Pre/Post Conditions, F = 17.086, \( p = .000 \), with an eta-squared value of .387.
Post hoc tests (Tukey HSD) revealed that all pre/post conditions were significant except for conditions 1 (L-LR), 2 (L-RL) and 6 (R-RL). See Figure 7 below for a graphical display of the data. See Table 4 below.

<table>
<thead>
<tr>
<th>Condition</th>
<th>p-value</th>
<th>Mean Difference</th>
<th>Std. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-LR</td>
<td>.304</td>
<td>.61</td>
<td>.58</td>
</tr>
<tr>
<td>L_RL</td>
<td>.294</td>
<td>.68</td>
<td>.63</td>
</tr>
<tr>
<td>LM_LR</td>
<td>.004</td>
<td>4.47</td>
<td>1.41</td>
</tr>
<tr>
<td>LM_RL</td>
<td>.004</td>
<td>2.15</td>
<td>1.69</td>
</tr>
<tr>
<td>R_LR</td>
<td>.024</td>
<td>.84</td>
<td>.35</td>
</tr>
<tr>
<td>R_RL</td>
<td>.859</td>
<td>.13</td>
<td>.73</td>
</tr>
<tr>
<td>RM_LR</td>
<td>.000</td>
<td>5.83</td>
<td>1.40</td>
</tr>
<tr>
<td>RM_RL</td>
<td>.001</td>
<td>2.82</td>
<td>.72</td>
</tr>
</tbody>
</table>

Table 4.
Figure 6 - Velocity Minima for the transfer word.
Chapter 4. DISCUSSION

As mentioned previously, Latash (1999), although providing evidence for learning and transfer within an extrinsic reference frame, was unable to empirically rule out the possibility of joint-space transfer due to the study’s methodological limitations. Similarly, Imamizu and Shimojo (1995) demonstrated that intermanual transfer of learning occurs at a “task level” for target aiming under rotated visual feedback, but were unable to exclude the possibility of transfer occurring at the “manipulator level” as they failed to assess transfer under conditions that were in mirror joint-symmetry with the originally learned effector’s kinematic orientation. This possibility, namely of transfer of mirror writing to joint-space coordinates, in addition to task-space coordinates, contributed to motivating the current study’s protocol for examining potential transfer to mirrored and normal writing tasks. This more comprehensive approach afforded the opportunity to examine the nature of the coordinate system(s) (i.e., intrinsic vs. extrinsic) involved in transfer of learning.

Overall, the results of the current study provide support for the phenomenon of intermanual transfer of learning, lending additional credence to its prevalence amongst motor skills. More specifically, and as has been suggested (Latash, 1999; Van Mier & Peterson, 2006) transfer is primarily facilitated when practice and transfer conditions are similar in regard to external space variables, as opposed to joint-space variables.

A number of other studies have provided evidence in favor of learning and transfer in extrinsic (i.e., task space) coordinate variables. In a study by Rogosky and Rosenbaum (2000), where subjects were asked to perform reaching movements to
distorted visual targets that varied with respect to hand displacements (extrinsic information) and joint displacements (intrinsic information, or joint configurations and muscle torques), provided further support for learning occurring within an extrinsic reference frame. In a more recent study, providing contradictory findings to those that claim that left-handers are somehow superior in performing mirror-like tasks, Van Mier and Peterson (2006) demonstrated that learning a sequential maze task by right- and left-handers did not find left-handers superior to right-handers in producing movements from right-to-left. In this particular case, no transfer to the mirror-reflected maze occurred for either group of subjects, once again making the case stronger for effector-independent coding exclusively. However, it may be argued in this study that culturally specific language characters were not used, and the constraint of producing acceptable written forms was not an issue. This could preclude the possibility of observing left-side dominant preferences for mirror writing, such as were seen in the current study.

In a more straightforward example of the aforementioned phenomenon, and in line with the notion of left-handed superiority for mirror writing, Tucha, Aschenbrenner, and Lange (2000) examined the pre-given behavioral layout of both right- and left-handers when asked to write both in a normal and mirrored fashion. They were able to demonstrate that left-handers appear to have a significant advantage and adeptness to mirror write when compared with right-handers. Nevertheless, no transfer tests were performed, unlike the current study which examined the extent of transfer of learning after learning to mirror write across limbs.

An alternative, and more likely explanation of the superiority of left-hand dominant mirror writing that relies and builds upon simple biomechanical descriptions,
suggests that perceptual constraints may play a role in the perceived ease of left-handers to exhibit mirror writing. For example, when writing normally (left-to-right) with the left-hand, it may be difficult to view the outcome of your writing because the hand blocks the view of the already written words. This may likely explain why many left-handers adopt a more “hooked” posture of their wrist and hand to accommodate for the blocked vision. Alternatively, writing from left-to-right with the right-hand would not pose the same problem and similarly, writing from right-to-left with the left-hand. This may help to explain why left-handers find mirror writing more comfortable, and perhaps explain their inherent adeptness with the task.

It is obvious that one such cultural convention of the English language (whereby words and sentences are written from left-to-right) would constrain the behavioral choice(s) a left-hander would make. On a regular basis it would be ineffective and non-functional to write in a mirrored-fashion because by convention, reading in the English language also occurs from left-to-right thus providing a cultural and cognitive constraint on behavioral manifestations for left-handed individuals. In the case of the current study, in contrast with normal writing conditions, there was a displacement of the presentation of the visual feedback. This may help to explain why left-handed subjects were able to successfully transfer the learned behavioral information to right-handed mirror writing. Due to the fact that the feedback box on the screen was located above the writing-box, the problem of the writing hand occluding the words on the page is a non-issue.

Although not examining directional hand preferences within writing tasks, Braswell and Rosengren (2002) looked at directional tendencies in a set of drawing tasks. In line with biomechanical explanations of writing direction preferences, they were able
to show that when right-handed subjects were asked to draw a cross-like figure with the left-hand they tended to draw the horizontal line of the cross from right-to-left. This runs counter to transfer mechanisms that place priority exclusively in the coding of extrinsic reference frames during learning, given that the left hand (while writing the horizontal line of the cross) move in an inverse and symmetrical direction as would normally occur with their right hand. Despite this empirical retort, the findings of Braswell and Rosengren (2002) can only explain directional preferences for drawing tasks. In the case of writing the English language, and the necessarily continuous nature of cursive writing, it would be impossible to perform right-to-left writing movements, suggesting that conventional, or cognitive constraints impose upon biomechanically preferred patterns that may be elicited in other less culturally constrained types of writing (e.g. writing block letters). The current study provides evidence for the relative importance of task constraints on exhibited behavior. The results of the current study may have been significantly different if subjects were asked to write using block letters or if a separate “feedback box” was not provided. It is possible (such as in writing block letters) that despite general production requirements of having to place adjacent letters in a reversed order, the actual production of letters may remain consistent across overall directional demands. For example, although the order of letter arrangement may remain consistent, the actual starting point of letter formation may vary, especially if writing block letter. Further experimentation would be required to determine if this is the case, and to detect the extent to which task demands (cursive vs. block letters) influence performance variables.
For Hollerbach (1981), handwriting occurs as a result of an underlying oscillatory process that is necessarily constrained by the biomechanical nuances of the individual effectors used to produce the writing. The attractiveness of this theoretical formulation is that the complexity of handwriting can be simplified due to the fact that there exists prototypical letter shapes based on the preferred oscillation patterns of the effectors based on mechanical preferences. In addition, these preferred oscillation patterns are biomechanically embedded and do not necessarily require learning but tend to be reproduced simply based on already present biomechanical constraints and tendencies, such as mass and length characteristics of appendages.

According to the findings of Hollerbach, to produce the same kinematic features (i.e., individual words or letters), a simple solution exists, such that a virtual effector point in external space (e.g. x- and y- oscillations) is required. Rather than having to control multiple “intrinsic” dimensions of a characteristic of a particular writing unit, the individual must merely learn to establish a functional coordination pattern between the two oscillatory components. This may serve to reduce the informational load of learning and afford transfer to different effectors that otherwise have never attempted the task. In the current study, this idea would help to partially explain the rapid adaptive changes that occurred across limbs without the prior engagement of the unpracticed effector.

Within this framework, transfer may consist (at least in the case of cursive writing) of perceptual learning of the kinematic variables defining the coupled oscillators in an extrinsic reference frame. When the unpracticed limb begins to engage in attempting to solve the previously solved “problem” (by the practiced effector), the task simply becomes one of learning to bring into functional alignment the mechanical
degrees of freedom of that limb and to match the limb’s already present preferred coordination tendencies, with the previously learned perceptual invariants of the words or letters. If this is the case, this would significantly enhance the adaptive ability of the organism due to the fact that all of the information necessary to reproduce the task with an alternative effector was previously learned. In other words, all of the information that is potentially “available” for the learner during the original training experience is superfluous, except for a finite set of functionally relevant perceptual invariants. The remainder of the solution that must be solved by the unpracticed limb becomes one of functionally aligning mechanical and perceptual invariants, requiring a dynamic exploration of the effector’s preferred tendencies that stabilize the perceptual invariants, thereby accomplishing the task goal. This is in line with Newell and McDonald’s (1992) notion that motor learning can be conceived as being “the perceptual-motor act of learning to coordinate the perceptual invariants with the action invariants.” In this case, the perceptual invariants would be the unique characteristics of the cursive letters and words, and the action invariants of the movements that produce the appropriate coupling between the two oscillators that constitute the “virtual effector” as proposed by Hollerbach. In the case of transfer of learning, regardless of the effector employed it is viable to reproduce consistent and previously learned oscillation patterns with more or less degrees of variability in letter reproduction.

An essential finding concerning the nature of transfer was that although transfer of learning between effectors is possible, there exists identifiable, characteristic, and systematic variability based on the biomechanical nuances of the effector employed (Wright, 1990). This not only suggests that the learned and transferred information is of
an abstract type, and the kinematic differences between specific instances of writing samples can be traced back to the biomechanical nuances of the effectors, rather than a unique and supposed “motor program” that is representative of each limb or posture. Clearly, it would be maladaptive, on both an ontogenetic and phylogenetic time scale, if learning only occurred within an intrinsic reference frame. The organism must rely on an ability to generalize across variable contexts if it is expected to survive. Learning and transfer within an extrinsic reference frame (perhaps along with intrinsic reference frames) would appear to be a highly favored advantage when considering large time scales. Along these lines, the current study’s results corroborate past findings (Zanone & Kelso, 2002) demonstrating that transfer occurs in a more abstract reference frame that can be exploited irrespective of the effector being utilized. Zanone and Kelso (2002) suggested that independent effector systems might share a similar coordination dynamic that may be modified as a result of practice with a particular effector, which may help to explain why even “normal” writing conditions improved slightly. Learning a new skill involves a phase transition (or a parameterization) in the overall, shared dynamics, ultimately leading to a new attractor state that different effectors may exploit.

As was suggested (Zanone & Kelso, 2002), the abstract nature of transfer represents the more functional aspects of learning whereby the learner (based on perception of the task) inculcates a task-level attractive state of the coordination dynamics. In the case of handwriting, it would be functionally preferred to learn the task-related characteristics (kinematics of the letters and words) for the sake of generalizability to novel writing situations.
Criscimagna-Hemminger et al. (2003) provided further evidence for effector-independent learning and transfer in a velocity-dependent force field. Their findings revealed that transfer only occurs from the dominant hand to the non-dominant hand, such that subjects who initially learned the task with the non-dominant hand showed no significant improvements in performance post-practice, for the dominant hand. The inference made by the authors (on a neurological level) was that when the dominant arm is being used (by right-handers), the right, non-dominant cerebral hemisphere is informationally served by the left-hemisphere. However, when the left arm is initially being employed to carry out the task, no transfer to the right arm is observed, and according to the authors is due to some sort of informational inhibition between right and left cerebral hemispheres such that the dominant left-hemisphere is unable to accept and exploit the new information coded in the non-dominant, right-hemisphere. In the current study, participants only practiced with their dominant hand, so future studies would have to evaluate transfer outcomes under conditions where participants practiced with their non-dominant hand. However, results of this study reveal that those who practiced with the dominant hand, also showed significant levels of transfer to both the non-dominant and the dominant hand. This would suggest (contrary to Criscimagna-Hemminger et al. (2003)) that the dominant cerebral hemisphere can receive novel information from the non-dominant, and help to provide a partial neurological explanation for transfer of learning. Obviously in both studies, brain activity was not directly measured, so it is difficult to rely on this postulation as an explanation.

However, is this the best explanation? Perhaps, but a more intuitive explanation may be at hand. Mutha, Haaland, and Sainburg (2012) were able to demonstrate and
clarify that the left brain hemisphere has a major and privileged role in the learning and adaptation of new motor skills. This may help to explain why right-handers in the current study were able to successfully and quickly learn mirror writing and exhibit notable improvements in the unpracticed non-dominant hand, thereby countering previous empirical claims that left-handers are more adept at learning mirror writing. There would appear to be a strong sense in which informational sharing is occurring between hemispheres and therefore facilitating transfer of learning to the unpracticed limb. Perhaps the two hemispheres may be considered to be two coupled subunits of a larger neural system (i.e., the brain) that have their own potentially independent inherent behavioral tendencies. Through experience (perhaps based on epigenetic mechanisms) a particular hemisphere becomes “dominant” in influence and the opposite hemisphere “serves” the other by becoming enslaved with it. This mechanism would be incredibly efficient, especially in light of the so-called “degrees of freedom problem”, such that a minimal number of cognitive resources as are represented neurally, can be consolidated into a singular organizational unit (i.e., the dominant hemisphere). Rather than assigning specific responsibilities to each hemisphere, thus increasing the complexity and informational load, the neural-degrees-of-freedom-problem (and therefore functional problems) could be solved more easily if one hemisphere entrains to the other. In this case, the dominant hemisphere constrains the non-dominant hemisphere to behave in a similar fashion. In the case of left-handed learning, it is not necessarily the case that there is limited informational transformation to the dominant-hemisphere but that the left-hemisphere’s (in the case of right-handers) behavioral stability is such that a small perturbation by the opposite hemisphere is insufficient to destabilize its behavioral
tendencies in a significant way, thus little to no transfer of learning in the dominant limb is expressed. In light of this, the asymmetric nature of transfer may be a result of an ongoing competition-cooperation dynamic between the two hemispheres. Within this theoretical framework, transfer of learning will depend on the degree to which the contralateral (to that of the dominant hand), or controlling hemisphere, affords the possibility of certain behavioral manifestations. If the dominant hemisphere constrains the behavior of the non-dominant hemisphere, then the non-dominant hemisphere may be able to rely on the opposite hemisphere to shape and influence the efferent commands and ultimately, the non-dominant limb’s behavior. This proposed neurological mechanism (within the Dynamic Systems paradigm of understanding) could significantly reduce the computational complexity of novel behaviors performed by unpracticed effectors, and offer an alternative explanation for the phenomenon of transfer of learning. For instance, this would stand in contrast to those more abstract theories that suggest that transfer is a result of forming novel motor programs and/or modifying the parameters of such programs based on changes in the environment. A more accurate and pragmatic understanding of transfer of learning requires a more robust and less static notion of information processing – one that gives credence to the dynamics of the nervous system, and the functional demands on the organism.
BIBLIOGRAPHY


