2015

THE APPLICATION OF HAND SWITCH COSTS TOWARDS UNDERSTANDING BIMANUAL MOVEMENTS: AN INVESTIGATION THROUGHOUT THE LIFESPAN

Gordon Young
Wilfrid Laurier University, youn2990@mylaurier.ca

Recommended Citation
Young, Gordon, "THE APPLICATION OF HAND SWITCH COSTS TOWARDS UNDERSTANDING BIMANUAL MOVEMENTS: AN INVESTIGATION THROUGHOUT THE LIFESPAN" (2015). *Theses and Dissertations (Comprehensive)*. 1766.
http://scholars.wlu.ca/etd/1766

THE APPLICATION OF HAND SWITCH COSTS TOWARDS UNDERSTANDING BIMANUAL MOVEMENTS: AN INVESTIGATION THROUGHOUT THE LIFESPAN

By

Gordon M. Young

BSc. Honours Kinesiology, McMaster University, 2013

THESIS

Submitted to the Faculty of Graduate & Postdoctoral Studies

In partial fulfillment of the requirements for

Master of Science in Kinesiology

Wilfrid Laurier University

Abstract

The objective of the present study was to examine the different kind of switch costs among a varied population using a modified bimanual serial reaction time task. Alternating between responses produce a cost of increased response time, which is termed a switch cost. However, not all switch costs are equal, and its effect on response time is dependent on what previous hand and digit combination was utilized. A detachable touchscreen tablet PC running a custom built JavaScript based software prompted participants to press down with their digits (2nd-5th) to corresponding buttons which would light up in a serial fashion. Response times for inter- to intra- hand, homologous to non-homologous digits, 'left-to-right' and right-to-left' switches were then recorded once the button was pressed. An example of a homologous switch would be the response time of the 3rd digit on the left hand if it followed the 3rd digit on the right hand. Left-handed (n=18) and right-handed (n=91) individuals, aged 5-58 years, M = 21.65 years, SD = 11.97 years, 65 females participated. Past research on bimanual digit movement within and between hands has not been congruous, suggesting either faster response times when a following digit movement is made on the same versus opposite hand, and vice versa. This incongruity is furthered by response time differences in homologous and non-homologous movement of the digits. This inconsistency exists because of differing objectives in past work, which are not focused on isolating response times when alternating between hands or digits. In this study, stimulus-response effects were minimized by using a personalized hand and digit orientation, with buttons customized to the width of the hands for each participant, and visual responses directly under the digits, still visible in a seated position. The effects of gender and handedness were insignificant. Quantitative results determined that age had the most significant effect on all types of response time, with the youngest ages (5-13 years) being the slowest, adolescents to middle adults (14-25 years) being the fastest, and a slight decline in middle to older adults' (26-58 years) response times. Additionally, errors played a significant role

explaining these differences in response time. Differences in errors for the same and opposite hand reflected the same trend found in response time for age. Furthermore, a greater number of errors were encountered progressing from the 2nd to 5th digit. Overall, this study highlights the impact of age on bimanual response time, and the lesser impact of gender and handedness, which should still be controlled for. Moreover, there may be implications for research on bimanual movements by considering the impact of errors, which may be a means to further the understanding of bimanual movement and coordination in the future.

Acknowledgements

The past two years have been an absolute pleasure and it begins with the people involved who could not have made the experience any more memorable. This begins with my supervisor, Pam, who gave me the metaphorical keys to unlock a successful post-graduate experience at Wilfrid Laurier University. Her drive and attitude is an inspiration for everyone around her, and I am fortunate to have been part of it. She is the boss, but also your awesome friend.

I would like to extend my gratitude to the thesis committee – Dr. Mike Cinelli, Dr. Jayne Kalmar, and Dr. Niechwiej-Szwedo. Thank you, not only for accepting the commitment of your valuable time to be part of this process, but for contributing your critical judgement and knowledgeable feedback to challenge me.

I am very thankful for all of the participants and friends who made this entire undertaking viable. I especially would like to recognize my friend Andy Kanmacher, and Mrs. Mary Perrett, who made my participant recruitment possible at Waterloo-Oxford D.S.S., and St. John's-Kilmarnock. I would also like to give my appreciation to Omas, the most helpful programmer, whom I wish all the success in the future.

A special place in my heart belongs to all of my labmates in the Lifespan for Psychomotor Behaviour Lab, for braving the windowless trenches with such poise and equanimity, a feat only a select few will truly understand. The world of research is truly not complete without a support group. My thanks extend to all of the master's students, staff, and faculty in Kinesiology for providing such a warm and hospitable environment.

Last but foremost, Mom and Dad. Your sacrifice to put me through school (which always seems to lead to more school) and unwavering support keeps me above all of life's hurdles. Thank you for being the caring and motivating individuals you are today.

Table of Contents

List of Figures

List of Appendices

Chapter 1: Introduction

1.1 Switching Sides of the Body: The motive for investigation

Many of the fine movements that our digits perfect are often overlooked, particularly the coordination of these extremities in their voluntary or involuntary nature. By choosing the most efficient muscle activity, a synergy between our limbs and appendages coexists from signals in the brain. This synergy is outwardly expressed and observed through bimanual movements. For example, a bimanual task such as driving a manual transmission with the left hand on the wheel and the right hand on the stick shift requires coordinating the upper limbs' muscle activation. When slowing down before a turn, the right limb is activated to change gears, followed by muscle activity in the left limb to rotate the wheel. If these movements were completely separate, the transition when activating limbs on opposite sides of the body would not be seamless, since a slight delay in hand and digit movement exists when coordinating a switch from the right limb to the left, analogous to flipping the on- and off- switch from one side of the body to the other. If we could observe and quantify this type of bimanual behaviour in an isolated fashion, what significance would this delay in switching sides of the body hold? Do differences in switches extend to the finer motor patterns in homologous digits? An exploratory investigation may help us measure this hemispheric proficiency (or inefficiency) if differences do exist. Therefore, the purpose of the current study intended to quantify bimanual switches using a bimanual serial reaction time task between limbs and identify any differences throughout the lifespan, handedness, and gender.

1.2 Switch Costs: What are they and why should we study them?

'Switch cost' is a loosely defined term that can be used to characterize and quantify the particular increase in reaction time. Effectively, 'cost' describes the increase in response time that is given up during a switch of muscle activity. Therefore, the response time (RT) switching between hands would be defined as inter- hand switch costs, and switching within the same hand as intra- hand switch costs (Trapp et al., 2012). Using a bimanual serial reaction time task to record for different types of RT switches, one could compare between various independent factors. To elaborate on the switch costs mentioned in the purpose above, the types of RT examined were: inter- and intra- hand, homologous and non-homologous, and left-to-right and right-to-left digit switches.

Research in bimanual movement has predominantly utilized stimulus-response mappings, context driven movements (i.e. reaching or grasping), or the synchrony of coupled movements. All of these require executive processes of the brain with attention and temporal organizations of behaviour (Swinnen & Wenderoth, 2004). Bimanual coordination is now seen as a dynamic entity which can change as a function of task complexity (spatiotemporal interlimb relationships), difficulty (motor performance), and experience (Franz et al., 2000). In contrast, a switch cost is unique because of its reflexive nature, providing a neurological insight into interhemispheric synchronization and desynchronization. It remains unclear how individual differences in interhemispheric interactions relate to motor performance (Fling & Seidler, 2012). Moving forward, a more complete understanding of the behavioural, physiological, and neurological mechanisms involved is necessary to encompass a true understanding of bimanual movements, and the potential role that hand switch costs may play.

To do so, this review will begin with the corpus callosum and how its growth relates to changes in bimanual ability throughout the lifespan, followed by hemispheric differences that may affect handedness and laterality. The anatomy and physiology of digit flexion will then provide details on what exact movement occurs in the study, and finally, research from Trapp et al.'s study (2012) will provide a structure for measuring bimanual switch costs, and a methodology akin to the one in the current study. This will provide the framework to understand the dynamic evolution of bimanual activity from young children to older adulthood, and any associated clinical implications**.**

1.3 Differences Throughout the Lifespan: Corpus callosum maturation and the link to bimanual movements

In bimanual coordination the corpus callosum (CC) coordinates the exchange of information between the two cerebral hemispheres and limb motions at different stages of planning and organization (Marteniuk et al., 1984). Until the mid-1900s, the CC was thought to exist as merely a crutch holding the two hemispheres apart from collapsing (Bogen, 1979). Since then, researchers have been curious about what relationship exists between the structure and function of the CC, particularly hemispheric specialization and interaction (Mooshagian, 2008). Interestingly, changes in bimanual performance mirror the maturational progression of the corpus callosum (Thompson et al., 2000). Work in neuroimaging has discovered that the microstructural properties of the CC and bimanual performance are strongly correlated (Swinnen & Wenderoth, 2004). The CC is accessible to non-invasive quantification by magnetic resonance imaging (MRI) techniques (Basser & Pierpaoli, 1998) and neurophysiological measurements such as transcranial magnetic stimulation (TMS) and diffusion tensor imaging (DTI) (Garvey & Mall, 2008). These measurements can identify the brain’s interconnections by manipulating magnetic fields to induce electric currents affecting the brain with little discomfort, and allows for a novel understanding of the brain that may diagnose functional connectivity and microstructure in healthy to abnormal patients. There is inconclusive evidence about the size and shape of the CC that covary with age, gender, and handedness. Generally, children and adolescents are believed to show an anterior to posterior progression of CC growth (Chung et al., 2001; Giorgio et al., 2010) with the anterior regions showing microstructural changes through young adulthood.

Fractional anisotropy (FA) values, obtained from DTI, are indicative of an increased density or compactness of fibre bundles or an increased myelination of white matter in the brain (Beaulieu, 2002). Paediatric studies have identified linear increases in white matter across ages 4 to 20 (Giedd et al., 2000). Callosal connections prove that FA values increase with age in childhood and adolescence, apexes in young adulthood, and decreases slightly in older ages. In children, bimanual coordination skills improve as a function of age for a large range of movements. Tasks such as bimanual hand clapping, circle drawing, reaction time tasks, and finger tapping all have been reported to improve as age increases (Barral et al., 2006**;** Marion et al., 2003**;** Wolff et al., 1998). Many studies in young adults have shown correlations between bimanual performance and individual characteristics of the CC. A high correlation between FA values and bimanual movement scores in a task of producing asynchronous finger-thumb opposition movements paced by a metronome of different frequencies were found in individuals with higher FA values of the midbody of the CC (Johansen-Berg et al., 2007). Older adults generally display slight changes in macrostructure from callosal shrinkage, but the results are modest (Sullivan et al., 2010). Decreased FA values in older adults are presumed to be due to a breakdown of myelin, and an anterior to posterior degradation (Inano et al., 2011). In participants 20 to 81 years old, a correlation was found between FA values in the posterior brain and speed of bimanual alternating finger taps. Older individuals with lower FA displayed slower tapping speeds (Sullivan et al., 2001). In a more recent study, older participants (average of 70 years old) with lower FA values demonstrated poorer performance on a bilateral precision/object manipulation task (Serbruyns et al., 2014). Bimanual skill performance generally deteriorates with advanced age, potentially due to regression of the CC (Bangert et al., 2010). Movements become slower, have greater variability, and reduced synchronization, particularly with higher levels of complexity (Summers et al., 2010; Marneweck et al., 2011). What we would expect for hand and digit switching should emulate the patterns of both behavioural strategies and CC size.

For this reason, groupings for age will be as follows: young children to adolescence (5-13 years), young to middle adults (14-25 years), and middle to older adults (26-58 years). The division between young children to adolescence and young to middle adults intends to separate differences in bimanual performance and reflect the change in CC size (Giorgio et al., 2010). Additionally, data collection differences varied based on the availability of the middle and high schools in the area. The participating middle school allowed for collection up to the age of 13, while data collection in the available high school ages resumed at age 17. The vast university aged participants were under 25 and rounded out the young to middle adult age group, and was included since the majority of CC size research made similar age divisions in the low 20s (Giedd et al., 2000; Jeeves & Moes, 1996). After the young to middle adult age group, slight differences in variability bimanual movements are often reported (Fling & Siedler, 2012). The age range is capped at 60 because of the large variability in motor skills and inconsistent past studies of corpus callosal size at that age (Jeeves & Moes, 1996). Based on bimanual performance and FA values across the ages, young children may display the greatest switch costs, the lowest switch costs would be found in young adulthood and increase in older adulthood.

1.4 Handedness and Laterality: Brain to hand movement

Understanding the regions of the brain involved in bimanual movements provide basic background knowledge, particularly for the following regarding handedness and differences in laterality. One of the various ways this understanding is approached has been the use of functional magnetic resonance imaging (fMRI), which measures brain activity by detecting changes in cerebral blood flow. It is worth noting that most fMRI studies often use right-handed participants exclusively, because of the expected consistency in motor and language dominance in right handers compared to left-handed individuals (Grafton et al., 2002), making research on left-handers quite scarce. Findings in fMRI research have indicated that movement in the right hand stimulates contralateral activation in the left hemisphere of the brain (Meng, Lu & Li, 2008; Babiloni et al., 2003; Gut et al., 2007). Recent fMRI measurements of dominant and non-dominant hand movement by Grabowska et al. (2012) reported that simple extension and contraction of the right 2nd digit elicited large contralateral activation (greater than the non-dominant hand) and relatively small ipsilateral activation. On the other side, the non-dominant hand revealed a more equal activation of both hemispheres (lesser right-hemispheric activation). The implication is that the dominant hand is strongly manipulated by the contralateral hemisphere, and the non-dominant hand is controlled evenly by both hemispheres, an effect consistently observed in right- and left-handers (Grabowska et al., 2012; Gut et al., 2007; Hanna-Pladdy et al., 2002).

Bimanual control is also likely influenced by deactivation, which would be described as decreased cerebral blood flow in an fMRI. Recent fMRI research by Tzourio-Mazoyer et al. (2015) recognized ipsilateral deactivation as a potential association with hand lateralization, which would coincide with the small ipsilateral activation found in the previously mentioned study by Grabowska et al. (2012). Across a sample of 284, inter-individual differences in manual skill between hands demonstrated large differences in ipsilateral deactivation. Looking at the primary motor cortex (M1), both handers exhibited ipsilateral deactivation of the M1 for both hands, but left-handers had a more balanced level of deactivation when moving the dominant hand compared to the non-dominant hand, reflecting a bilateral cortical specialization. FMRI research would hence imply that in a right-hander, movement of the dominant hand utilizes both contralateral activation and ipsilateral deactivation, while movement of the non-dominant hand uses a balanced contralateral activation and ipsilateral deactivation. Left-handers have the same implications, except differences between their dominant and non-dominant hand in regards to deactivation would be more balanced compared to right-handers. How this bilateral cortical specialization affects switch costs are unknown, but perhaps in the case of a balanced deactivation, one might expect a more balanced effect of laterality, suggesting smaller differences for left-to-right and right-to-left switches for left-handers compared to right-handers. It would be more difficult to comment on inter- and intra- switches, and homologous and non-homologous switches with handedness since it is not well studied.

1.5 Influences on the Task at Hand: The muscles of the hand involved in digit flexion

The bimanual serial reaction time task required participants to flex their 2nd to 5th digits; hence the relevant anatomy of the hand was considered since its performance reflected the outward performance of the brain. The biomechanics of the flexor system is often crucial for evaluation and treatment of disorders of the upper extremity. In application, knowledge of the anatomy and biomechanics is used by operating surgeons for correcting acute flexor injuries or secondary reconstruction (Idler, 1985). The morphology can explain the function, and vice versa (Goodman & Choueka, 2005). The muscles that control the digits can be divided into two groups: extrinsic (originating from outside of the hand) and intrinsic (originating from within the hand). As an oversimplification, extrinsic muscles are located in the anterior and posterior compartments of the forearm (outside of the hand), controlling crude movements and a forceful grip. The intrinsic muscles (located within the hand) are responsible for fine motor movements, particularly to the digits.

The flexor digitorum superficialis (FDS) is the most superficial of the extrinsic digit flexors. Innervated by the median nerve, four compartments of the FDS travel through the carpal tunnel and insert onto the middle phalanges of the 2nd to 5th digits (see Figure 1). The FDS flexes the proximal interphalangeal (PIP) and metacarpophalangeal (MCP) joint of each finger. Deeper to the FDS lies the flexor digitorum profundus (FDP). The FDP also passes through the carpal tunnel and insert onto the distal phalanges of the 2nd to 5th digits. Like the FDS, the FDP flexes the PIP and MCP, but is the sole flexor of the distal interphalangeal (DIP) joints. The median nerve innervates the lateral aspect (2nd and 3rd digit flexion), while the ulnar nerve innervates the medial aspect (4th and 5th digit flexion). The intrinsic muscles of the hand can be divided into four groups: thenar, hypothenar, interossei, and lumbrical muscles. Thenar muscles provide movement of the 1st digit. On the ulnar border of the palm, opposite of the thenar muscles is the hypothenar eminence. The three muscles of the hypothenar eminence (abductor digiti minimi, flexor digiti minimi brevis, and the opponens digiti minimi) act together to flex the 5th digit, innervated by the ulnar nerve, but also perform their own actions independently. There are four dorsal interossei muscles running between the metacarpals, centered around the 3rd digit such that two are on the lateral side, and two are on the medial side of the hand. There are three palmar interossei muscles located on the palmar portion of the 2nd, 4th, and 5th metacarpals that contribute to flexion of the MCP joints. They are all innervated by the deep branch of the ulnar nerve. The interossei assist the four lumbricals (same digits as the FDP) in flexion of the MCP joints, with the 2nd and 3rd digits innervated by the median nerve, and the 4th and 5th digit innervated by the ulnar nerve.

Some very minute discrepancies would suggest a variation in function. The different innervations between the median and ulnar nerve in flexion of the lumbricals suggest the 2nd and 3rd digits are separate from the 4th and 5th digits. The 5th digit is also mostly flexed by the hypothenar muscles, particularly the flexor digiti minimi brevis, flexor digiti minimi longus, and the opponens digiti minimi, which isolate it slightly from the other digits. While these differences may be minimal, forms of everyday practice could perpetuate them. Keyboard typing, as an example, would suggest overuse and preference of the 2nd and 3rd digit, rather than the lesser used 4th and 5th digits. While proper form for typing promotes use of the 2nd to 5th digit, many tend to neglect the 4th and 5th digits. It could be argued that the formation of the standard QWERTY keyboard is to blame, due to its poor staggering. To demonstrate, ask yourself which finger one would use to press the “z” and “x” finger. Most would say their 5th and 4th digit respectively, however that would suggest the two leftward digits would need to curl inwards (whereas the right hand's 4th and 5th digits move comfortably outwards to press '.' and '/'), an awkward enough movement for most to ignore proper typing and regress to usage of the 2nd and 3rd digits (see Figure 2 and 3). Besides keyboards, most buttons (elevator, crosswalk, kitchen appliances, etc.) are pushed with either the 2nd digit, or the entire palm. Similar to keyboard typing, muscles activated by the ulnar nerve may be lesser used. This could suggest that the 4th and 5th digits may be less effective in their movements, whether it be RT or errors made, in contrast to the 2nd and 3rd digits.

1.6 Research by Trapp and Colleagues: A framework for the current study on hand switch costs and response times

To address the question, "How does one measure hemispheric proficiency?" the application of hand switch costs can be applied to bimanual movement. Trapp and colleagues (2012) conducted the most recent study in the area of hand switch costs. They focused on learning-related changes in unilateral motor skill learning for sequential button presses of homologous index and middle fingers by using a bimanual serial reaction time task (SRTT) over a course of two weeks. As fast as possible, participants completed button presses for 15 letter sequences with a device 90 cm away from a computer screen. A sequence would include four between hand transitions [two switches for the right and left index fingers(2nd digit), and two switches for the right and left middle fingers (3rd digit)], and five within hand transitions (three switches from the left 3rd to 2nd digit, and two switches from right 2nd to 3rd digit; see Figure 4 for a visual). Feedback regarding average RTs was given after the end of each sequence. After 30 sequences, the first and last sequences indicated a significant decrease in hand switch RT for all participants. To measure global learning effects, the protocol was repeated two weeks later to examine the retention of switch costs over time. In the first few trials, average hand switch RTs in the second session were similar to the reduced hand switch RTs at the end of the first session.

Clearly, the effects of practice and training in hand switches were malleable and maintained lasting effects for at least two weeks. No significant differences were found between the sessions, but within a session, RT decreased significantly. During the first session, switch costs were found to reduce drastically after five trials and plateaued after ten trials. Since switch costs plateaued quickly within a session, it would be plausible to suggest that one extensive session would be sufficient to tease out the various components involved in the learning process.

Trapp and colleagues' (2012) results also confirmed past behavioural observations (Miller, 1982**;** Reeve & Proctor, 1984; Cooper & Mari-Beffa, 2008), with RT increasing significantly when switching between hands compared to within hands. Reaction times are representative of the neural activity behind managing shifts between different activities. Miller (1982) first laid out the plans to analyze the manner of transmission of movements from stimulus to response and determined that cuing the response of homologous digits (2nd to 2nd digit) was faster than non-homologous fingers (2nd to 3rd digit) of separate hands. The cuing of separate hands also showed larger reaction times, illustrating greater inter-hand than intra-hand reaction times (Reeve & Proctor, 1984). In the past, research looking at inter-hand switches had been more concerned about advanced preparation responses (Miller, 1982**;** Reeve & Proctor, 1984) or effects of task switching (Cooper & Mari-Beffa, 2008), rather than the RTs acquired from inter- and intra- hand switches. Since then, findings concerning within and between hand RTs have been inconsistent, with some suggesting keystrokes on different hands responding faster (Salthouse, 1986; Larochelle, 1984). Research by Miller and Ulrich (1998) discerned that hand activation occurred before the finger, since action of the motor cortex was observed before the activation of any signal in the finger, indicating that the motor response is hierarchical. Findings are congruent with the work of Cooper & Mari-Beffa (2008), suggesting the intra-hand advantage. Trap and colleagues (2012) allude to Rosenbaum and Kornblum's (1982) view of response preparation characteristics, where similar movement features (two digits of the same hand are more similar to digits from different hands) dictate the quickest response as a potential explanation. However, this has not been proven and remains hypothetical.

Serial reaction time tasks have become increasingly widespread in the past decade (Robertson, 2007). A SRTT can involve a temporal organization of behaviour, motor behaviour, high-order associations, and elements of prediction (Keele et al., 2004; Chafee & Ashe, 2007). In a SRTT, a visual cue appears on the screen, and the participant must react accordingly by selecting the correct response as quickly as they can. The cue then disappears, and after a fixed delay, the next visual cue appears, a process which repeats until the sequence is completed. The use of a SRTT in the current study was to effectively test the RT for the four digits of both hands through simple movements of digit flexion, utilizing components of implicit, skill, and motor learning (Robertson, 2007). Throughout a trial there is a potential risk of implicit learning from greater exposure, but the effects are often mollified by fatigue. This should be considered since the overall effects of learning may have been confounded, but could not be controlled for. Hence, it was important that the testing protocol was standardized for all participants.

Two methodological issues Trapp highlights were that: switches between hands were solely homologous (i.e. 2nd to 2nd digit); and that only two digits were analyzed. Stimuli were shown on screen as the letters ‘m’,’i', ‘M’, or ‘I’ indicating the middle or index digit. Uppercase letters indicated use of the left hand and lowercase letters for the right hand. Since there were only two choices (per hand), a somewhat ‘dichotomous choice reaction time’ was found in Trapp and colleagues’ work. In response, the current study removed letters (which may have increased RT through association with letters or symbols) and elements of typing, by using a touch screen tablet with columns that light up. Furthermore, the addition of two more digits (i.e. 4th and 5th), and switches between non-homologous fingers gave a clearer picture on the similarities and differences of finger activation to be mapped. Greater details of these improvements are provided in the methods section.

1.7 Hypothesis

Hand switch costs can be examined by looking at the RT differences in a bimanual serial reaction time task. Research in the area of corpus callosum maturation and task switch costs throughout the lifespan would suggest these differences follow the growth of the corpus callosum. Overall, young children should display the greatest switch costs, decreasing until young adulthood, and rising gradually into older adulthood.

Based on findings in laterality, left-handers would have the smallest differences between left- to right- hand switches and vice versa. Analysis of intra-hand switch costs with more than just the middle and index digits would likely follow Rosenbaum and Kornblum's (1982) view of similar responses, that same hand switches are faster than different hand switches. Lastly, inter-hand would be greater than intra-hand switch costs.

Chapter 2: Methods

2.1 Participants

A total of 109 neurologically healthy participants (age range = 5-58 years, M = 21.65 years, SD = 11.97 years, 65 females, 17 left-handers) completed the current study, grouped into young (5-13 years), adolescents to middle adults (14-25), and middle to older adults (26-60). Participants were asked to provide written informed consent (see Appendix C & D) in order to participate. Full approval for the study was granted by the Research Ethics Board of the University of Wilfrid Laurier. Participants were recruited from the local area of Waterloo, Ontario through posters and outreach websites (Kijiji, Craigslist). School aged participants were recruited from Waterloo-Oxford District Secondary School (Baden, Ontario), and St. John’s-Kilmarnock School (Breslau, Ontario). Adults were recruited from Wilfrid Laurier University (Waterloo, Ontario) and an office of the Bank of Montreal (Toronto, Ontario). There was no compensation for participation; however, participants had the opportunity to view their individual results and summarized reaction times after completion.

2.2 Questionnaires

Participant Information Questionnaire. All participants were screened for vision, nerve damage, head injuries, and neurological or psychiatric illnesses (see Appendix A) to ensure that they could comfortably use a tablet. Participants were asked if they had any past upper limb training such as music or sport, and the number of years that they participated in these activities. All information was recorded online using ‘Google Sheets’ and responses could only be accessed by the principal investigator.

Waterloo Handedness Questionnaire. The hand preference of participants as assessed using the Waterloo Handedness Questionnaire (WHQ) (see Appendix B), which is a self-report measure. Here participants were asked to indicate their preferred hand use for 36-unimanual tasks. Available responses included: left or right always (95% or more of the time), right or left usually (75% or more of the time), or equally (no hand preference), explained in the instructions and debriefing. Scores were given by the following: ‘left always’ = -2, ‘left usually’ = -1, ‘equally’ = 0, ‘right usually’ = +1, ‘right always’ = +2. Responses were then summed and ranged from -72 (strong left-hand preference) to +72 (strong right-hand preference) (Steenhuis, Bryden, Schwartz & Lawson, 1990).

2.3 Study Design

The study utilized a modified bimanual serial reaction time task (SRTT). The SRTT required the participant to press a digit down on the associated button when it lit up on the computer tablet. All button presses were conducted on the Acer Aspire Switch 10 Detachable Tablet PC running a custom built JavaScript based software (see Figure 5). With a 60Hz capable touch, an event is generated every 16.67 ms (1/60s). If a press is made just after a previous scan, this would cause a delay of two entire scans, meaning at most a maximum 34ms to the latency. Participants were seated at a desk upright with their left and right hand comfortably placed on the tablet, and elbows bent at approximately 90 degrees. The tablet was placed a distance approximately the participant's forearm length from the edge of the table. Hands were placed such that the four digits (2nd, 3rd, 4th, and 5th) of each hand hovered comfortably over the middle of the screen, so that the rectangular shaped buttons could be seen over the both the metacarpal and interphalangeal joints of the digits (see Figure 5). Regardless of the environment, the amount of noise in the background and available distractions were kept at a minimum for consistency of the participant's attention. Once the program was initiated, the participant was asked to touch down with each of their digits, one at a time, to set the buttons associated with each digit in a comfortable position, creating a customized stimulus-response mapping. In the ready position, hands were positioned above rectangular buttons on the screen. After the buttons were set, a five second countdown gave notice to the participant for the appearance of the first stimuli. Participants were asked to respond as quickly and accurately as possible by pressing the button which lit up (resembling a blue rectangle) with the corresponding digit.

In each trial, stimuli appeared one after another in a serial fashion when the correct button was pressed, with interval times randomized between 500-1000 milliseconds (ms). Response time was recorded from when the stimulus appeared to when the correct button was pressed. Correct responses were followed by a ‘beep’ sound, and the blue rectangle would then disappear. In the case of an incorrect button press, the blue rectangle would not disappear, and the program would record which hand the error was made on, including which digit was meant to be selected. The next correct button would not be visible until the correct button was pressed. Participants were given sequences of 20 presses where there were eight inter-hand switches and 11 intra-hand switches within the trial (see Figure 6). With eight possible button combinations the patterns of these sequences were randomized, but still fulfilled the prescribed requirements for inter- and intra-hand switches. There were a total of 20 trials, with an inter-trial ‘break’ of 5000ms to avoid muscle fatigue, and an extended break at the half-way point (10 trials). Participants were explicitly told how many trials were involved beforehand, and the current number of trials could always be monitored on the screen. Stimulus and response data were directly collected by the JavaScript program and compiled into an excel file for further analysis on IBM SPSS Statistics version 22.

2.4 Measurements and Data Preparation

Response time was recorded when the stimulus appeared to when the correct button was pressed. Correct responses were followed by a ‘beep’ sound, and the blue rectangle would then disappear, and the next stimuli would appear after a randomized interval time between 500-1000 milliseconds (ms).

Inter- and Intra- Hand RTs. Average RTs for both inter- and intra- hand was calculated by averaging all of the correct switches from the 20 trials for each participant. RTs were then compared as a function of age group, sex, and handedness.

The Homologous versus Non-Homologous Responses Within inter-hand switches, the difference between homologous and non-homologous fingers was calculated. The separation of all homologous switches (2^{nd} to 2^{nd} digit, 3^{rd} to 3^{rd} digit, etc.) from all non-homologous switches (2^{nd} to 3^{rd} digit, 4^{th} to 5^{th} digit, etc.) were analyzed separately for inter- hand switches. RTs were then compared as a function of age group, sex, and handedness.

Direction and Laterality within Hands. To reveal any potential asymmetry in limb performance, inter-hand switch times from the left to right hand and vice versa were analyzed separately. Particular focus on the RT of a participant's dominant versus non-dominant hand was examined based on their hand preference. Of the eight inter-hand trials, four were left to right, and conversely, the other four were right to left, for equivalence. Any significant differences between the two would suggest a preferred hemispheric-switch which is advantageous for one side over the other. RTs were then compared as a function of age group, sex, and handedness.

The Impact of Errors on RT. Errors were recorded for incorrect presses when one button was intended to be pressed, but replaced by another. Each trial recorded errors by determining if the wrong press was committed by the same hand (e.g. 3rd digit of the left hand instead of intending to press the 2nd digit on the left hand) or the opposite hand (4th digit of the left hand instead of intending to press the 3rd digit on the right hand). Additionally, the number of errors was recorded for each digit (the digit that was intended to be pressed). The next correct button on the tablet would not be visible until the correct button was pressed. Number of errors on the same or opposite hand, and errors for each digit was then compared as a function of age group, sex, and handedness.

Chapter 3: Results

3.1 Inter- and Intra- Hand RTs

A 3 x 2 x 2 x 2 mixed model analysis of variance (age x gender x handedness x type of switch) was conducted to assess the impact of age group, gender, and handedness, on the response times of inter- and intra- hand switches. Within-subjects effects showed no differences within type of switch (F(1,97) = 1.58, p = .211), with overall means of inter- (717.65 ms, SD = 193.85 ms) and intra- (729.05 ms, SD = 197.77 ms) hand switches. There was no significant interaction between inter- and intra- hand switches with age group (F(2,97) = .521, p = .595), with gender (F(1,97) = .482, p = .489), or with handedness (F(1,97) = .56, p = .457). Between-subjects effects indicated a significant main effect of age group, (F(2,97) = 24.72, p < 0.001) (see Figure 7). Bonferroni corrected post hoc tests showed that the middle age group had significantly faster times than both the youngest (p < 0.001) and oldest (p < 0.001) groups, but the youngest and oldest did not differ significantly from each other (p = .102), with the oldest group being non-significantly faster. Estimated marginal means collapsed across inter-,intra- hand switches for age groups reported times for young (861.25 ms, SD = 204.26 ms), middle (570.19 ms, SD = 68.59 ms), and old (738.61 ms, SD = 165.14) (see Figure 7). No significant main effect was found for gender (F(1,97) = 1.63, p = .205) or handedness (F(1,97) = .21, p = .645)

3.2 The Homologous versus Non-Homologous Responses

A 3 x 2 x 2 x 2 mixed model analysis of variance (age x gender x handedness x type of switch) was conducted to assess the impact of age group, gender, and handedness on the response times of homologous and non-homologous switches. Within-subjects effects showed no significant differences within type of switch (F(1,97) = .860, p = .356), with overall means of homologous (714.59 ms, SD = 192.94 ms) and non-homologous (725.03 ms, SD =208.04 ms) switches. There was no significant interaction between homologous and non-homologous switches with age group (F(2,97) = 2.017, $p = .139$), with gender (F(1,97) = .093, $p = .762$), or with handedness (F(1,97) = 1.067, $p = .304$). Between-subjects effects indicated a significant main effect of age group, (F(2,97) = 24.271, $p < 0.001$) (see Figure 8). Bonferroni corrected post hoc tests showed that the middle age group reported significantly faster times than the youngest ($p < 0.05$) and oldest ($p = .026$) groups, but the youngest and oldest did not differ significantly from each other ($p = .119$), with the oldest group once again being non-significantly faster. Estimated marginal means collapsed across homologous and non-homologous switches for age groups reported times for young (857.37 ms, SD =205.74 ms), middle (568.96 ms, SD =68.60 ms), and old (733.10 ms, SD =180.77 ms). No significant main effect was found for gender (F(1,97) = 1.380, $p = .243$), where estimated marginal means for gender or handedness (F(1,97) = .303, $p = .583$).

3.3 Direction and Laterality within Hands

A 3 x 2 x 2 x 2 mixed model analysis of variance (age x gender x handedness x type of switch) was conducted to assess the impact of age group, gender, and handedness on the response times of left-to-right and right-to-left hand switches. Within-subjects effects showed no significant differences between directionality in hand switches (F(1,97) = 1.399, $p = .240$), with overall means of ‘left-to-right’ (728.56 ms, SD = 208.32 ms) and ‘right-to-left’ (710.94 ms, SD =197.14 ms) switches. There was no significant interaction between direction of hand switches and age group (F(2,97) = 1.731, $p = .182$), with gender (F(1,97) = .553, $p = .459$), or with handedness (F(1,97) = .084, $p = .773$). However, overall analysis revealed a significant main effect of age group, (F(2,97) = 22.327, $p < 0.001$) (see Figure 9). Significant differences were again exhibited in age group, where the middle age group was significantly faster than the youngest ($p < 0.05$) and oldest ($p = .026$), with the oldest group being slightly faster (p =

.118) than the youngest group once again. Collapsed across left and right switches, no significant main effect was found for gender (F(1,97) = 1.376, p = .244) or handedness (F(1,97) = .300, p = .585).

Another point of interest was the effect of directionality and handedness, which was insignificant (F(1,97) = .084, p = .773), as collapsed means showed left-handers switched to their left hand (700.73 ms, SD = 193.85 ms) faster than to their right (714.04 ms, SD = 193.85 ms), which was the same pattern displayed by right-handers, who switched to their left hand (721.14 ms, SD = 193.85 ms) faster than to their right (743.08 ms, SD = 193.85 ms) (see Figure 12).

3.4 The Impact of Errors on RT

A 3 x 2 x 4 mixed model analysis of variance (age x gender x digit type) was conducted to assess the impact of age group and gender on errors made when a particular digit was meant to be pressed (e.g. the 3rd digit is meant to be pressed, but the 5th digit makes a press instead, recording an error for the 3rd digit) for each hand. Within-subjects effects showed significant differences between digits (F(7,91) = 3.830, p < .001), as overall mean errors increased from the 2nd to 5th digit in the left hand (see Figure 10). Generally, errors were significant at the p <.05 level if a digit was more than one digit away from another. More specifically for the left hand, pairwise comparisons showed that the 2nd digit had significantly fewer errors than the 4th (p < .01) and 5th (p < .01) digit, but not the 3rd (p = 1.000), the 3rd digit had significantly fewer errors than the 5th (p= .047) but not the 4th (p = 1.000) or 2nd (p= 1.000). In simpler terms, this illustrated the trend that error differences were significant between any particular digit and a digit more than one away (e.g. 2nd and 4th are significantly different, 4th and 5th are not). Errors also increased from the 2nd to 5th digit in the right hand (see Figure 10). Figure 10 may appear non-parametric, however with a skew value of 1.36 and 109 participants (satisfying the central limit theorem), the data is normal.Pairwise comparisons depicted the same trend found in the left hand, suggesting significant differences if more than a digit away.

Between-subjects effects indicated a significant main effect of age group, (F(2,97) = 3.299, p =.041). Estimated marginal means of errors for age groups reported times for young (1.96, SD = 1.19), middle (0.91, SD = 1.26), and old (1.50, SD = 1.56). Post hoc tests showed that the middle age group had significantly fewer errors than the youngest (p = .035), but not the oldest (p = 1.000) age group, while the youngest and oldest age groups were not significantly different (p = .965).

A 3 x 2 x 2 mixed model analysis of variance (age x gender x hand type) was conducted to assess the impact of age group and gender on the errors that were made with the same or opposite hand if a certain press was to be made (e.g. the 4th digit on the left hand is meant to be pressed, but the participant presses with the 3rd digit on the right hand, recording an ‘opposite hand’ error). Within-subjects effects showed significant differences between errors (F(1,97) = 33.060, p < .001), with overall means of same hand errors (6.96, SD =6.71) greater than different hand errors (4.63, SD =4.46). Between-subjects effects indicated a significant main effect of age group, (F(2,97) = 3.306, p = .041) (see Figure 11). Post hoc tests for young (7.85, SD =4.7), middle (3.62, SD =5.05), and old (5.94, SD =6.25) ages showed that the middle age group had significantly less errors than the youngest (p = .035), but not the oldest (p = 1.000) age group, while the youngest and oldest age groups did not significantly differ from each other (p = .962).

Chapter 4: Discussion

The objective of the present study was to examine switch costs among a population using a modified bimanual serial reaction time task. The particular focus was on inter- and intra- hand, directional (right-to-left and vice versa), and homologous versus non-homologous switch costs, for different ages, handedness, and genders.

4.1 The Lifespan Approach

The trend in age groups demonstrated a similar pattern in previously mentioned bimanual skills (circle drawing, finger tapping, etc.). Findings indicated a significant effect for age for all dependent measures (inter- and intra, directional, homologous and non-homologous switches). The youngest ages (5 to13 years of age) demonstrated the slowest responses, adolescents and young adults (14 to -25 years of age) demonstrated the fastest responses, and the oldest group (26 to 60 years of age) displayed a slow response, although not as slow as the youngest group for all switches. Switch costs had not previously been looked at across the lifespan. The speed of the response between different age groups was clearly very distinct, which could have been due to a multitude of reasons, one explanation being the ability to activate and inhibit signals of bimanual movement. In the case of age-related evolutions, there have been age differences in rhythmic bimanual movements (Barral et al., 2009). Young children often show a decrease in spatial and temporal variability when transitioning between inhibition and activation as they get older. The decrease in spatial and temporal variability may be reflected by a decrease in errors for bimanual movements. In the task, both errors per digit, as well as errors on the same versus opposite hand were measured. The youngest versus middle group was significantly different for all types, and similar to RT differences across the age groups, the oldest group made more errors than the middle group, but not as many as the youngest group.

Another explanation for age differences in RT could be traced to corpus callosal area and callosal structure, although evidence is inconclusive. MRI research for adults has noted significant differences in the widths of the anterior, central, and posterior regions of the CC in ages 20-81 (Junle et al., 2008), as it generally follows an inverted U-shaped curve, with the volume growing from childhood through young adulthood, peaking in the second or third decade (Swinnen, 2014). Consistent differences (although non-significant) for all RTs recorded suggested that males and left-handers performed faster than their counterparts. In regards to gender, past DTI analysis of the CC agrees with this, where significantly larger total callosal area in males have been found compared to females. Our results were the opposite in regards to the trend in handedness, where larger total callosal areas are found for right-handers, compared to left-handed individuals (Westerhausen et al., 2004). The macro- and microstructure of the callosal pathways could have been contributors to the observed RTs in the present study. Research in the CC however is susceptible to influences by external factors like toxins including alcohol and other white matter disease like dementia, etc., but part of a growing interest is to investigate if corpus callosal area has related differences in atrophy, reference values in different ages and genders, and differences in normality (Junle et al., 2008). Since CC differences could be observed, a performance component, such as a serial reaction time task, could complement these differences with a behavioural and performance aspect.

4.2 Inter- and Intra- Hand RTs

The overall estimated inter-switch average was faster than the intra-switch, which was not expected nor predicted. However, the difference was non-significant and may have been marginally influenced by the total number of switches (eight inter- to 11 intra- switches per trial for 20 trials). As previously mentioned, researchers have found that RT increases significantly when switching between hands compared to within hands(Trapp et al., 2012; Miller, 1982; Reeve & Proctor, 1984; Cooper & Mari-Beffa, 2008). It would have been thought that the increase in complexity of the serial reaction time task (compared to Trapp and colleagues' study, four digits per hand instead of two), both inter- and intra- switches would have exhibited a clear difference (like in Trapp and colleagues' study). RTs did not, and instead, the opposite was demonstrated, albeit non-significant. Although this difference is minute, we would still assume that the motor response from the brain is hierarchal (Miller & Ulrich, 1998), but evidence to suggest an intra-hand advantage (Cooper & Mari-Beffa, 2008) in regards to activation would be difficult to reinforce without use of an fMRI.

Instead, a finding in the accuracy of the presses may explicate inter- versus intra- differences and the reason for the slower intra-hand response. Errors were recorded when the wrong press was made on the same or opposite hand, and the next press was not made available until the correct press was executed. This meant that errors produced on the tablet would also reflect a larger RT. Consequently, higher RTs recorded for intra-switches may have been a result of the speed-accuracy relationship in the study, since errors made on the same hand were significantly greater than those made on different hands. Ultimately, the additional errors represented time needed for the feedback and response of another movement to be initiated.

Contrary to Trapp and colleagues' study which only examined intra-switches between the 2nd and 3rd digit, the current study added the 4th and 5th digits. Interestingly, the average error rate gradually increased from the 2nd to 5th digit in both hands, meaning the 4th and 5th digits contributed far more errors than the 2nd and 3rd digits, which may have conceivably increased the intra-switch times. The addition of errors may have been more telling of the increased RT, and interpreted why inter- and intra-switch times reflected such little difference.

4.3 The Homologous versus Non – Homologous Response

Subsequent homologous fingers presses were found to be minimally faster than non-homologous ones. Results were non-significant, but the pattern was fairly consistent for gender and handedness, with homologous fingers faster than non-homologous ones. This reaffirmed Miller's (1982) study that analyzed the process of transmission of finger movements from stimulus to response, which determined that the response of homologous fingers (2nd to 2nd digit) was faster than non-homologous fingers (2nd to 3rd digit) of separate hands. More importantly, these findings also extend Trapp et al.'s (2012) results, which did not have any hand switches for non-homologous fingers.

It has been hypothesized that the tendency to co-activate homologous muscles (which would prepare muscles for faster homologous switches) originates from the transient coupling of motor programs during a delay. If there is a temporal overlap of motor program parameters (homologous muscles) during the reaction time interval, reaction times of successive responses should be affected depending on whether the muscles are homologous or not (Heuer, 1993). We utilized a randomized interval of 500-1000 ms to wash out these effects, and as expected, homologous reactions were still faster. This followed research of independent movements, which revealed that a prompted response in a non-homologous condition is slower than a homologous one when a participant is informed well in advance (Heuer, 1986). The same advantage for homologous muscles is noted in rhythmic bimanual movements, suggesting that homologous muscles for in-phase and anti-phase are the most preferred and stable methods of coordination (Swinnen, 2004).

4.4 Direction and Laterality within Hands

Performance between right- and left-handers (M = 739.82 ms versus 713.36 ms) was non-significant. Despite having 18 left-handers, this sample was still above the typical average of left-handers at 10% (Bryden & McManus, 1992). While left-handers exhibited faster RTs, an unexpected pattern was found when looking at directional switches and handedness. The RTs for right-handers suggested that they were faster switching to their left hand, and the RTs for left-handers suggested they were also faster switching to their left hand (see Figure 12), which indicated no ipsilateral or contralateral advantage of handed activation.

Firstly, we expected a smaller difference between switches for left-handers, since they are stereotypically less lateralized (Yahagi & Kasai, 1999). This difference was quite similar for both left- and right-handers. Secondly, we hypothesized that switching to one's dominant hand would have incurred a quicker response. The differences observed between left- and right- handers were not expected when looking at left versus right presses. Instead one would have expected similar left and right values for left-handers and a more pronounced difference in left and right values for right-handers. The small magnitude of the RT may have made it difficult to make a clearer assessment, and may suggest that the difference is too minute.

Faster switching to the left hand opposed the inaugural research in stimulus-response compatibility, which found ipsilateral stimulus-response pathways consistently faster (right visual stimulus with right finger) in a choice reaction time task, irrespective of whether one of both eyes were used (Bradshaw & Perriment, 1970). Since left and right presses were in close proximity but could have been in overlapping visual fields, the effects of vision may have conferred visual clout. Differences may have been due to stimuli location, for example, Trapp and colleagues' stimuli placed on a screen (see Figure 4), compared to a stimuli directly under the digits (see Figure 5). Being a visually-guided action, eye dominance should be considered for future work, since it has shown to impact visuomotor transformation speed, although it is not fully understood. Right- handers have shorter RTs in response to a lateralized visual target contralateral to their dominant eye, whereas left-handers only with a right dominant eye exhibit shorter RTs with the left hand (Chaumillon, Blouin, & Guillaume, 2014). As there were faster RTs with presses in the left visual field for right-handers, one might suggest that the majority of our participants were right eye dominant. Additionally, it reinforces some implications of bilateral cortical specialization from fMRI research via behavioural performance that in a right-hander, movement of the dominant hand uses both contralateral activation and ipsilateral deactivation, while movement of the non-dominant hand uses a balanced lateral activation and ipsilateral deactivation. For left-handers, the dominant hand also involves contralateral activation and ipsilateral deactivation, however in the non-dominant hand, deactivation is more laterally balanced, reflected in performance (Tzourio-Mazoyer et al., 2015). The task at hand may not have been complex enough to tease out performance differences between hands. In future studies, this difference between left and right switching may be smaller or larger depending on the required dichotomy of left and right usage in the proposed task and how ‘handed’ a participant responds, while controlling for eye dominance.

4.5 The Impact of Errors on RT

With respect to error, it was found that there were a greater number of intra- hand errors. A possible explanation is the synergistic effect of the upper extremities. It is extremely unlikely during isolated digit movements that one independent muscle is activated. Antagonistic muscles are often involuntarily activated during force development of an agonist muscle (Sanei & Keir, 2013). When producing isometric force with one, two, or three digits, the other digits of the hand also generate a force. The involuntary force production by digits not explicitly utilized in a task is known as enslaving. Enslaving effects of digits have found to be larger in neighbouring digits (the 2nd digit has been found be the most independent, and the 4th digit to be the least), and could produce forces achieving up to 67.5% of the maximal force in single digit flexion exertions (Zatsiorsky, Li, & Latash, 2000). Muscle compartments of the flexor digitorum profundus (FDP) and flexor digitorum superficialis (FDS) may contain motor units that influence all four digits (Schroeder, Botte, & Gellman, 1990). The contrast of independence in the 2nd to 4th digit, combined with factors of continual practice (typing preference, daily use, etc.) may explain the significant graduated differences in errors from the 2nd to 5th digits in both hands.

Chapter 5: Limitations and Future Direction

Based on the recorded RTs, limitations in the study were previously noted. Inter- and intra-switches may have been influenced by the greater number of intra-switches, further exacerbated by the use of the 4th and 5th digit. The additional analysis of accuracy (errors) also makes a vast impact on RT, since missing a press added to the speed-accuracy relationship. Unexpectedly, the increase in errors from the 2nd to 5th digits meant that more time is added compared to studies only using the 2nd and 3rd digit. Differences in directional switches also conflicted with past research, since both left- and right-handers switched to their left side faster. A low number of left-handers, and not controlling for eye dominance may have shown different results. While differences between age groups were significant, the non-significant differences between the various types of switches (inter- and intra-, directional, homologous and non-homologous) may have been due to the low complexity of the task, and hence a more challenging task should be used in the future that still follows the original premise of this one being convenient, non-invasive, etc. to fully explore the examined trends.

For future research, the measurement of response times in the hands and digits supplied convenient information that if paired with advancing technology, could only enhance our understanding of how bimanual movements form into the exhibited behaviour we observe a regular basis. Since current research on handedness since the early 1990s has used fMRI, it should continue to do so for mapping patterns of hemispheric activation. Assuming that cerebral blood flow and neuronal activation are tightly linked, it would be interesting to see if there are any changes in blood flow observing the coordination between hand and digit movements, and to further understand the extent of transcallosal activity in bimanual synchrony. A study of that capacity would not require the measurement of response time per se, but instead use hand and digit movements similar to the ones conduct in this study to observe the patterned changes in oxygenated blood flow. If similar intra-individual differences exist (greater observed blood flow in inter- versus intra- switches, left to right versus right to left switches) it could confirm neural activation that would likely lead to predictable patterns in response time of a bimanual serial reaction time task. A highly correlated fMRI to bimanual task could create an easy to administer, convenient, and fMRI-free bimanual serial reaction time task to diagnose or recognize potential hemispheric issues. Furthermore, the existence of hemispheric specialization and its selective pressure as an evolutionary advantage is still debated, and hence the associated cognitive abilities of handedness, manual preference, strength, and symmetry of manual skills are still considered to reflect brain lateralization for associations such as language, spatial ability, and working memory (Mellet et al., 2014; Powell, Kemp & Finana, 2012). Research in cognitive associations using fMRI has an expansive range of potential in tandem with handedness, and the development of other bimanual performance-based tasks would be helpful in growing that type of research.

In the current study, musical instrument playing and sport experience were recorded (see Appendix B), and could be used for future research, however based on time sensitive pressure, the focus of this paper was geared towards age, sex, and handedness. However, building upon confirmed patterned brain activity, the effects of practice would be interesting to see if less or more cerebral bloodflow (using fMRI) would be needed to achieve similar results over multiple sessions, since switch costs have proven to be retained for at least two weeks (Trapp et al., 2012).

Digit pressing, the choice of digit and hand action in this study, was used to measure response time. However, the most efficient way to measure a pure reaction time between digits is still up in debate. An alternative to a digit pressing protocol could be conducted by resting digits on a touchscreen, and lift them up (digit extension instead of flexion) when a stimuli is presented. To our knowledge, touchscreen tablets do not possess the ability to detect more than two touches at once, and can only recognize pinch to zoom movements, commonly used to expand or compound an image. Extension of the fingers also may be difficult due to enslaving effects, but it remains an alternative. While the current study used rectangular columns that were meant to be visible over the digits, wider and longer targets may help reduce error, provided they fit a carefully rested digit orientation. Since the targets were visual, there may have been the chance that eye dominance may have played a part, where participants may have had an advantage pressing on one side over another. Either changing the stimulus to one that is different from visual, or testing binocular versus monocular vision may be worth considering. While this study moves forward with a more ‘natural’ fitting stimulus response setup (digits laid out comfortably with the stimulus close to the response), this concept can certainly be developed further. An appropriate example of technology that could be used to enhance testing would be a LEAP gesture-control system (Leap Motion Inc.), which improves upon the touchscreen tablet technology. While a discernible lag between digit strokes on a tablet is evident, LEAP has imperceptible lag when registering digit movements, swipes, and mid-air taps with a low latency. Technology such as LEAP would increase the accuracy of measuring digit movements, which is crucial for measuring data that is refined in milliseconds, particularly during hand or digit switches that require little to no latency. This is only one side of the user-interface disconnect that we face with using technology to acquire precise results, improving upon how data is acquired. How the user interacts to react appropriately would depend on the stimulus and how it is delivered. For the interim, consistency can appropriate these differences (inter- versus intra-response times, etc.). The use of improved technology may be able to pinpoint accuracy to discriminate greater significant differences between the likes of handedness and gender when controlling for age, which the current tablet may not have been able to.

Chapter 6: Summary and Conclusion

The observed behaviour revealed that with a modified bimanual serial reaction time task, the tandem of response times with errors across the lifespan showed the youngest ages being the slowest, adolescent and young adult ages being the fastest, and the oldest age group nearly as slow as the youngest. Gender and handedness showed slightly faster times for males and left-handers, although the differences were insignificant. Right-to-left and homologous switches showed slightly faster but insignificant times than their counterparts (left-to-right and non-homologous switches respectively). Inter- and intra-switch times unexpectedly had little to no difference, but the recorded errors demonstrate effects of greater intra- versus inter- errors, and an increasing amount of errors from the 2nd to 5th digit, effectively marginalizing intra-switches to inter-switches. Whether or not other factors contributed to the observed bimanual behaviour and differences in switch costs is beyond the scope of the present study and has to be addressed in future experiments. Knowledge of predictable differences in switches could potentiate a cognitive hierarchy to comprehend a hemispheric understanding of bimanual movements. This type of study does have areas that could use enhancement. Future research in bimanual performance and dexterity should preferentially engage use of fMRI technology to document real-time hemispheric interaction. This would help determine the origin of the movement and the activation of the hemispheres, and aid in the affirmation of the proposed cognitive hierarchy. Consideration for participation control extends to gender, handedness, eye dominance, and age. Combined with a more precise response measurement device, the inclusion of errors, and a greater complex task that can more effectively tease out differences between common intra-individual differences, more research is needed.

References

Adam, J., Hommel, B., & Umilta , C. (2003). Preparing for perception and action: I. the role of grouping in the response-cueing paradigm. *Cognitive Psychology, 46,* 302-358.

Adkins-Muir, D., & Jones, T. (2003). Cortical electrical stimulation combined with rehabilitative training: enhanced functional recovery and dendritic plasticity following focal cortical ischemia in rats. *Neurological Research, 27,* 780-788.

Aimonetti, J., & Nielsen, J. (2002). Cortical excitability and motor task in man: An investigation of the wrist extensor motor area. *Experimental Brain Research, 143*, 431-439.

Alonzo, A., Brassil, J., Taylor, J., Martin, D., & Loo, C. (2012). Daily transcranial direct current stimulation (tdcs) leads to greater increases in cortical excitability than second daily tran-scranial direct current stimulation. *Brain Stimulation, 5,* 208-213.

Avanzino, L., Bove, M., Trompetto, C., Tacchino, A., Ogliastro, C., & Ogliastro, C. (2008). 1-hz repetitive tms over ipsilateral motor cortex influences the performance of sequential finger movements of different complexity. *European Journal of Neuroscience, 27,* 1285-1291.

Babiloni, C., Carducci, F., Del Gratta, C., Demartin, M., Romani, G.L., Babiloni, F., Rossini, P. M. (2003). Hemispherical asymmetry in human SMA during voluntary simple unilateral movements: An fMRI study. *Cortex, 39*, 293-305.

Bangert, A., Reuter-Lorenz, P., Walsh, C., Schachter, A., & Seidler, R. (2010). Bimanual coordination and aging: Neurobehavioral implications. *Neuropsychologia, 48*, 1165-1170.

Barral, J., Debu, B., & Rival, C. (2006). Developmental changes in unimanual and bimanual aiming movements. *Developmental Neuropsychology, 29,* 415-429.

Barral, J., De Pretto, M., Debu, B., & Hauert, C. (2010). Activation and inhibition of bimanual movements in school-aged children. *Human Physiology, 36*(1), 47-57.

Basser, P., & Pierpaoli, C. (1998). A simplified method to measure the diffusion tensor from seven mr images. *Magnetic Resonance in Medicine, 39*, 928-934.

Beaulieu, C. (2002). The basis of anisotropic water diffusion in the nervous system – a technical review. *NMR in Biomedicine, 15,* 435-455.

Bengtsson, S., Nagy, Z., Skare, S., Forsman, L., Forssberg, H., & Ullen, F. (2005). Extensive piano practicing has regionally specific effects on white matter development. *Nature Neuroscience, 8,* 1148-1150.

Berryhill, M., & Hughes, H. (2009). On the minimization of task switch costs following long-term training. *Attention, Perception, & Psychophysics, 71,* 503-514.

Bogen, J. (1979). *The callosal syndromes in clinical neuropsychology*. (pp. 308-359). New York: Oxford University Press.

Boisgontier, M., Wittenberg, G., Fujiyama, H., Levin, O., & Swinnen, S. (2014). Complexity of central processing in simple and choice multilimb reaction-time tasks. *PLos ONE, 9*(2): e90457. doi:10.1371/journal.pone.0090457

Bradshaw, J., & Perriment, A. (1970). Laterality effects and choice reaction time in a unimanual two-finger task. *Perception and Psychophysics, 7*(3), 185-188.

Brinkman, C. (1984). Supplementary motor area of the monke'ys cerebral cortex: short- and long- term deficits after unilateral ablation and the effects of subsequent callosall section. *Journal of Neuroscience, 4*, 918-929.

Brinkman, J., & Kuypers, H. (1972). Splitbrain monkeys: cerebral control of ipsilateral and contralateral arm, hand, and finger movements . *Science, 176*, 536-538.

Cattaert, D., Semjen, A., & Summers, J. (1999). Simulating a neural cross-talk model for between-hand interference during bimanual circle drawing. *Biological Cybernetics*, *81*, 343-358.

Cepeda, N., Kramer, A., Gonzalez, S., & Jessica, M. (2001). Changes in executive control across the life span: Examination of task-switching performance. *Developmental Psychology, 37,* 715-730.

Chafee, M., & Ashe, J. (2007). Intelligence in action. *Nature Neuroscience*, *10*, 142-143.

Chaumillon, R., Blouin, J., & Guillaume, A. (2014). Eye dominance influences triggering action: The poffenberger paradigm revisited. *Cortex*, *58*, 86-98.

Chung, M., Worsley, K., Paus, T., Cherif, C., Collins, D., Giedd, J., Rapoport, J., & Evanst, C. (2001). A unified statistical approach to deformation-based morphometry. *Neuroimage: Clinical*, *14,* 596-606.

Cooper, S., & Mari-Beffa, P. (2008). The role of response repetition in task switching. *Journal of Experimental Psychology: Human Perception and Performance*, *34*, 1198-1211.

Debaere, F., Swinnen, S., Beatse, E., Sunaert, S., Van Hecke, P., & Duysens, J. (2001). Brain areas involved in interlimb coordination: A distributed network. *Neuroimage: Clinical*, *14,* 947-958.

Duncan, J. (1995). Attention, intelligence, and the frontal lobes. *The cognitive neurosciences*, 721-733.

Eliassen, J., Baynes, K., & Gazzaniga, M. (2000). Anterior and posterior callosal contributions to simultaneous bimanual movements of the hands and fingers. *Brain, 123*, 2501-2511.

Ferbert, A., Priori, A., Rothwell, J., Day, B., Colebatch, J., & Marsden, C. (1992). Interhemispheric inhibition of the human motor cortex. *Journal of Physiology, 453*, 525-546.

Fling, B., & Seidler, R. (2012). Task-dependent effects of interhemispheric inhibition on motor control. *Behavioural Brain Research, 226,* 211-217.

Franz, E. (2004). On the perceptual control of bimanual performance. *Journal of Motor Behavior, 36,* 380-381.

Franz, E., Elliassen, J., Ivry, R., & Gazzaniga, M. (1996). Dissociation of spatial and temporal coupling in the bimanual movements of callosotomy patients. *Brain, 7,* 306-310.

Franz, E., Rowse, A., & Ballantine, B. (2002). Does handedness determine what hand leads in a bimanual task?. *Journal of Motor Behavior, 34,* 402-413.

Franz, E., Waldie, K., & Smith, M. (2000). The effect of callosotomy on novel versus familiar bimanual actions: A neural dissociation between controlled and automatic processes. *Psychological Science, 11,* 82-85.

Fregni, F., & Pascual-Leone, A. (2007). Technology insight: Non-invasive brain stimulation in neurology-perspectives on the therapeutic potential of rtms and tdcs. *Nature Clinical Practice: Neurology, 3,* 383-393.

Garvey , M., & Mall, V. (2008). Transcranial magnetic stimulation in children. *Clinical Neurophysiology, 119,* 973-984.

Goodman, H., & Choukea, J. (2005). Biomechanics of the flexor tendons. *Hand Clinics, 21,* 129-149.

Giorgio, A., Watkins, K., Chadwick, M., James, S., Winmill, L., Douaud, G., & De Stefano, N. (2010). Longitudinal changes in grey and white matter during adolescence. *Neuroimage, 49,* 94-103.

Gomes-Osman, J., & Field-Fote, E. (2013). Bihemispheric anodal corticomotor stimulation using transcranial direct current stimulation improves bimanual typing task performance. *Journal of Motor Behavior, 45,* 361-367.

Gooijers, J., & Swinnen, S. (2014). Interactions between brain structure and behavior: the corpus callosum and bimanual coordination. *Neuroscience and Biobehavioral REviews, 43,* 1-19.

Grabowska, A., Gut, M., Binder, M., Forsberg, L., Rymarczyk, K., & Urbanik, A. (2012). Switching handedness: fMRI study of hand motor control in right-handers, left-handers and converted left-handers. *Acta neurobiol exp, 72,* 439-451.

Grafton, S., Hazeltine, E., & Ivry, R. (2002). Motor sequence learning with the nondominant hand a pet functional imaging study. *Experimental Brain Research, 146,* 369-378.

Gut, M.; Urbanik, A.; Forsberg, L.; Binder, M.; Rymarczyk, K.; Sobiecka, B.; Kozub, J.; Grabowska, A. (2007). *Brain correlates of right-handedness. Acta Neurobiologiae Experimentalis,* 67 (1), 43-51.

Hanna-Pladdy, B., Mendoza, J., Apostolos, G., & Heilman, K. (2002). Lateralised motor control: Hemispheric damage and the loss of deftness. *Journal of Neurological Neurosurgery Psychiatry, 73*, 574-577.

Hartley, A., & Little, D. (1999). Age-related differences and similarities in dual-task interference. *Journal of Experimental Psychology*, *128*, 416-449.

Hazeltine, E., Grafton, S., & Ivry, R. (1997). Attention and stimulus characteristics determine the locus of motor-sequence encoding. *Brain*, *120*, 123-140.

Heuer, H. (1986). *Generation and modulaton of action patterns*. (pp. 87-101). Berlin: Springer.

Heuer, H. (1993). Structural constraints on bimanual movements. *Psychological Research*, *55*, 83-98.

Hughes, C., & Franz, E. (2007). Experience-dependent effects in unimanual and bimanual reaction time tasks in musicians. *Journal of Motor Behavior, 39*(1), 3-8.

Hummel, F., & Cohen, L. (2006). Non-invasive brain stimulation: A new strategy to improve neurorehabilitation after stroke?. *The Lancet Neurology*, *5*, 708-712.

Hyde, K., Lerch, J., Norton, A., Forgeard, M., Winner, E., Evans, A., & Schlaug, G. (2009). Musical training shapes structural brain development. *The Journal of Neuroscience*, *29*, 3019-3025.

Idler, R. (1985). Anatomy and biomechanics of the digital flexor tendons. *Hands Clinics*, *1*(1), 3-11.

Inano, S., Takao, H., Hayashi, N., Abe, O., & Ohtomo, K. (2011). Effects of age and gender on white matter integrity. *American Journal of Neuroradiology*, *32*, 2103-2109.

Ivry, R., Diedrichsen, J., Spencer, R., Hazeltine, E., & Semjen, A. (2004). A cognitive neuroscience perspective on bimanual coordination and interference. *Neuro-Behavioral Determinants of Interlimb Coordination*. Boston, MA: Springer US

Jeeves, M., & Moes, P. (1996). Interhemispheric transfer time differences related to aging and gender. *Neuropsychologia*, *34*(7), 627-636.

Jimura, K., & Braver, S. (2010). Age-related shifts in brain activity dynamics during task switching. *Cerebral Cortex*, *20*, 1420-1431.

Johansen-Berg, H., Della-Maggiore, V., Behrens, T., Smith, S., & Paus, T. (2007). Integrity of white matter in the corpus callosum correlates with bimanual co-ordination skills. *Neuroimage*, *36,* T16-T21.

Junle, Y., Youmin, G., Yanjun, G., Mingyue, M., Qiujuan, Z., & Min, X. (2008). A mri quantitative study of corpus callosum in normal adults . *Journal of Medical Colleges*, *23,* 346-351.

Keele, S., Ivry, R., Mayr , U., Hazeltine, E., & Heuer, (2004). the cognitive and neural architecture of sequence representation. *Psychology Review, 110,* 316-339.

Kermadi, L., Liu, Y., Tempini, A., & Rouiller, E. (1997). Effects of reversible inactivation of the supplementary motor area (SMA) on unimanual grasp and bimanual pull on grasp performance in monkeys. *Somatosensory Motor Research, 14,* 268-280.

Kertesz, A., Polk, M., Black, S., & Howell, J. (1992). Anatomical asymmetries and functional laterality. *Brain, 115,* 589-605.

Kimura , D. (1977). Acquisition of a motor skill after left-hemisphere damage. *Brain, 100,* 527-542.

Kleim, J., Vadenberg, P., MacDonald, E., Mulrooney, R., & Pocock, D. (2003). Motor cortex stimulation enhances motor recovery and reduces peri-infarct dysfunction following ischemic insult. *Neurological Research, 25,* 789-793.

Koerte, I., Heinen, F., Fuchs, T., Ruediger, L., Pomschar, A., Stahl, R.,… Ertl-Wagner, B. (2009). Anisotropy of callosal motor fibers in combination with transcranial magnetic stimulation in the course of motor development. *Investigative Radiology, 44,* 279-284.

Kolominsky-Rabas, P., Weber, M., Gefeller, O., Neundoerfer, B., & Heuschmann, P. (2001). Epidemiology of ischemic stroke subtypes according to toast criteria: incidence, recurrence, and long-term survival in ischemic stroke subtypes. *Stroke, 32,* 2735-2740.

Kray, J., Eber, J., & Lindenberger, U. (2004). Age differences in executive functioning across the lifespan: The role of verbalization in task preparation. *Acta Psychologica, 115*(2-3), 143-165.

Larochelle, S. (1984). Some aspects of movements in skilled typewriting. *Attention and performance,* 43-54.

Leap Motion Inc. (n.d.). *Leap motion*. Retrieved from https://www.leapmotion.com/

Lindenberg, R., Renga, R., Zhu, L., Nair, D., & Schlaug, G. (2010). Bihemispheric brain stimulation facilitates motor recovery in chronic stroke patients. *Neurology, 75,* 2176-2184.

Liuzzi, G., Hörniß, V., Zimerman, M., Gerloff, C., & Friedhelm, H. (2011). Coordination of uncoupled bimanual movements by strictly timed interhemispheric connectivity. *The Journal of Neuroscience, 31,* 9111-9117.

Marion, S., Kilian, S., Naramor, T., & Brown, W. (2003). Normal development of bimanual coordination: Visuomotor and interhemispheric contributions. *Developmental Neuropsychology, 23,* 399-421.

Marteniuk, R., Mackenzie, C., & Baba, D. (1984). Bimanual movement control: Information processing and interaction effects. *The Quarterly Journal of Experimental Psychology,* 36, 335-365.

Meng , L., Lu, C., & Li, Y. (2008). Hemispheric lateralization of event-related brain potentials in different processing phases during unimanual finger movements. *Department of Occupational Therapy and Institute of Clinical Behavioral Science*, *8*, 2900-2912.

Meuter, R., & Allport, A. (1999). Bilingual language switching in naming: Asymmetrical costs of language selection. *Journal of Memory and Language*, *40*, 25-40.

Meyer, B., Roricht, S., Grafin von Einsiedel, H., Kruggel, F., & Weindl, A. (2005). Inhibitory and excitatory interhemispheric transfers between motor cortical areas in normal humans and patients with abnormalities of the corpus callosum. *Brain*, *118*, 429-440.

Miller, J. (1982). Discrete versus continuous stage models of human information processing: In search of partial output. *The Quarterly Journal of Experimental Psychology*, *8*, 273-296.

Miller, J., & Franz, E. (2005). Dissociation of bimanual responses with the simon effect: On the nonunitization of bimanual responses. *Journal of Motor Behavior*, *37*, 146-156.

Miller, J., & Ulrich, R. (1998). Locus of the effect of the number of alternative responses: Evidence from the lateralized readiness potential. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 1215-1231.

Mooshagian, E. (2008). Anatomy of the corpus callosum reveals its function. *The Journal of Neuroscience*, *28*, 1535-1536.

Murase, N., Duque, J., Mazzocchio, R., & Cohen, L. (2004). Influence of interhemispheric interactions on motor function in chronic stroke. *Annals of Neurology*, *55*, 400-409.

Nordstrom, M., & Butler, S. (2002). Reduced intracortical inhibition and facilitation of corticospinal neurons in musicians. *Experimental Brain Research*, *144*, 336-342.

Ozturk, A., Tascioglu, B., Aktekin, M., Kurtoglu, Z., & Erden, I. (2002). Morphometric comparison of the human corpus callosum in professional musicians and non-musicians by using in vivo magnetic resonance imaging. *Journal of Neuroradiology*, *29*, 29-304.

Pascual-Leone, A. (2001). The brain that plays music and is changed by it. *Annals of the New York Academy of Sciences*, *930*, 315-329.

Paus, T., Zijdenbos, A., Worsley, K., Collins, D., Blumenthal, J., & Giedd, J. (1999). Structural maturation of neural pathways in children and adolescents: In vivo study. *Science*, *283*, 1908-1911.

Perez, M., & Cohen, L. (2009). Interhemispheric inhibition between primary motor cortices: what have we learned?. *Journal of Physiology*, *587*, 725-726.

Poffenberger, A. (1912). Reaction time to retinal stimulation with special reference to the time lost in conduction through nerve centers. *Archives of Psychology*, *23*, 1-73.

Porter, R., & Lemon, R. (1993). *Corticospinal function and voluntary movement*. Oxford: Oxford Science Publications.

Powell, J., Kemp, G., & Finana, M. (2012). Association between language and spatial laterality and cognitive ability: An fmri study. *Neuroimage*, *59*(2), 1818-1829. Reeve, T., & Proctor, R. (1984). On the advance preparation of discrete finger responses. *Journal of Experimental Psychology: Human Perception and Performance, 10*, 541-553.

Reeve, T., Proctor, R., Weeks, D., & Dornier, L. (1992). Salience of stimulus and response features in choice-reaction tasks. *Perception and Psychophysics*, *52*, 453-460.

Reimers, S., & Maylor, E. (2005). Task switching across the life span: Effects of age on general and specific switch costs. *Development Psychology*, *41*, 661-671.

Robertson, E. (2007). The serial reaction time task: Implicit motor skill learning?. *The Journal of Neuroscience*, *27*, 10073-10075.

Rosenbaum, D., & Kornblum, S. (1982). A priming method for investigating the selection of motor-responses. *Acta Psychologica*, *51*, 223-243.

Salthouse, T. (1986). Perceptual, cognitive, and motoric aspects of transcription typing. *Psychological Bulletin*, *99*, 303-319.

Schluter, N., Rushworth, M., & Passingham, R. (1998). Temporary interference in human lateral pmc suggests dominance for the selection of movements. A study using transcranial magnetic stimulation. *Brain*, *121*, 785-799.

Schoner, G., & Kelso, J. (1988). Dynamic pattern generation in behavioral and neural systems. *Science*, *239*, 1513-1520.

Schroeder, V. H., Botte, M., & Gellman, H. (1990). Anatomy of the juncturae tendinum of the hand. *Journal of Hand Surgery* , *15*, 595-602.

Schuenke, M., Schulte, E., Schumacher, U. (2003). *Thieme atlas of anatomy: general anatomy and musculoskeletal system*. (3rd ed.). New Jersey: Icon Learning System.

Serbruyns, L., Gooijers, J., Caeyenberghs, K., Meesen, R., Cuypers, K., Sisti, H.,… Swinnen, S. (2014). Bimanual motor deficits in older adults predicted by diffusion tensor imaging metrics of corpus callosum subregions. *Brain Structure and Function*. doi: 10.1007/s00429-013-0654-z

Shen, Y., & Franz, E. (2005). Hemispheric competition in left-handers on bimanual reaction time tasks. *Journal of Motor Behavior*, *37*, 3-9.

Shim, J., Kim, S., Oh, S., Kang, N., Zatsiorsky, V., & Latash, M. (2005). Plastic changes in interhemispheric inhibition with practice of a two-handed force production task: A transcranial magnetic stimulation study. *Neuroscience Letters*, *374*, 104-108.

Steenhuis, R., Bryden, P., Schwartz , M., & Lawson, S. (1990). Reliability of hand preference items and factors. *Journal of Clincal and Experimental Neuropsychology*, *12*(6), 921-930.

Sullivan, E., Rohlfing, T., & Pfefferbaum, A. (2010). Longitudinal study of callosal microstructure in the normal adult aging brain using quantitative dti fiber tracking. *Developmental Neuropsychology*, *35*, 233-256.

Swinnen, S., Walter, C., Young, D., & Serrien, S. (1991). Control of asymmetrical bimanual movements. *Experimental Brain Research*, *85*, 163-173.

Swinnen, S. (1998). Exploring interlimb constraints during bimanual graphic performance: effects of muscle grouping and direction. *Behavioral Brain Research*, *90*, 79-87.

Swinnen, S. (2002). Intermanual coordination: From behavioural principles to neural-network interactions. *Nature Reviews: Neuroscience*, 3, 350-362.

Swinnen, S., & Wenderoth, N. (2004). Two hands, one brain: Cognitive neuroscience of bimanual skill. *Trends in cognitive sciences*, *8,* 18-25.

Tanji, J., Okano, K., & Sato, K. (1988). Neuronal activity in cortical motor areas related to ipsilateral, contralateral, and bimanual digit movements of the monkey. *Journal of Neurophysiology, 60,* 325-343.

Theios, J. (1975). The components of response latency in simple human information processing tasks. . *Attention and performance*, *5,* 418-440.

Thompson, P., Giedd, J., Woods, R., MacDonald, D., Evans, A., & Toga, A. (2000). Growth patterns in the developing brain detected by using continuum mechanical tensor maps. *Nature, 404*, 190-193.

Tracy, J., Faro, S., Mohammed, F., Pinus, A., Madi, S., & Laskas, J. (2001). Cerebellar mediation of the complexity of bimanual compared to unimanual movements. *Neurology*, *57,* 1862-1869.

Trapp, S., Lepsien, J., Sehm, B., Villringer, A., & Ragert, P. (2012). Changes of hand switching costs during bimanual sequential learning. *PLoS ONE*, *7*(9):e45857. doi: 10.1371/journal.pone.0045857

Tzouri-Mazoyer, N., Petit, L., Zago, L., Crivello, F., Vinuesa, N., Joliot, M., Jobard , G., & Mellet, E. (2015). Between-hand difference in ipsilateral deactivation is associated with hand lateralization: fmri mapping of 284 volunteers balanced for handedness. *Frontiers in Human Neuroscience, 9*(5), 1-12.

Vines, B., Cerruti, C., & Schlaug, G. (2008). Dual-hemisphere tdcs facilitates greater improvements for healthy subjects' non-dominant hand compared to unihemisphere stimulation. *BMC Neuroscience*, *9*:103. doi:10.1186/1471-2202-9-103

Wahl, M., Lauterbach-Soon, B., Hattingen, E., Jung, P., Singer, O., & Volz, S. (2007). Human motor corpus callosum: Topography, somatotopy, and link between microstructure and function. *Journal of Neuroscience, 27*, 12132-12138.

Wannier , T., Bastiaanse, C., Colombo, G., & Dietzz, V. (2001). Arm to leg coordination in human during walking, creeping, and swimming. *Experimental Brain Research*, *14*, 375-379.

Westerhausen, R., Kreuder, F., Sequeira, S., Walter, C., Woerner, W., Wittling, R., Schweiger, E., & Wittling, W. (2004). Effects of handedness and gender on macro- and microstructure of the corpus callosum and its subregions: a combined high-resolution and diffusion-tensor mri study. *Cognitive Brain Research*, *21*, 418-426.

Wiesendanger, M., Rouiller, E., Kazennikov, O., & Perrig, S. (1996). Is the supplementary motor area a bilaterally organized system?. *Advanced Neurology*, *70*, 85-93.

Wiesendanger, M., & Serrien, D. (2001). Toward a physiological understanding of human dexterity. *News Physiology Science*, *16*, 228-233.

Wolff, P., Kotwica, K., & Obregon, M. (1998). The development of interlimb coordination during bimanual finger tapping. *International Journal of Neuroscience*, *93*, 7-27.

Wyke , M. (1971). The effects of brain lesions on the learning performance of a bimanual co-ordination task. *Cortex*, *7*, 59-72.

Wylie, G., & Allport, A. (2000). Task switching and the measurement of switch costs. *Psychological Research*, *63*, 212-233.

Yahagi, S., & Kasai, T. (1999). Motor Evoked potentials induced by motor imagery reveal a functional asymmetry of cortical motor control in left- and right- handed human subjects. *Neuroscience Letters*, 276, 184-188.

Zaidel, E. (1978). *Concepts of cerebral dominance in the split brain: Cerebral correlates of conscious experience*. Amsterdam: Elsevier Science.

Zaidel, E., & Lacoboni, M. (2003). *The parallel brain: The cognitive neuroscience of the corpus callosum*. Cambridge, MA: Massachusetts Institute of Technology.

Zaidel, E., Zaidel, D., & Bogen, J. (1999). *The split brain*. Amsterdam: Elsevier Science.

Zatsiorsky, V., Li, Z., & Latash, M. (2000). Enslaving effects in multi-force finger production. *Experimental Brain Research*, *131*, 187-195.

Figures

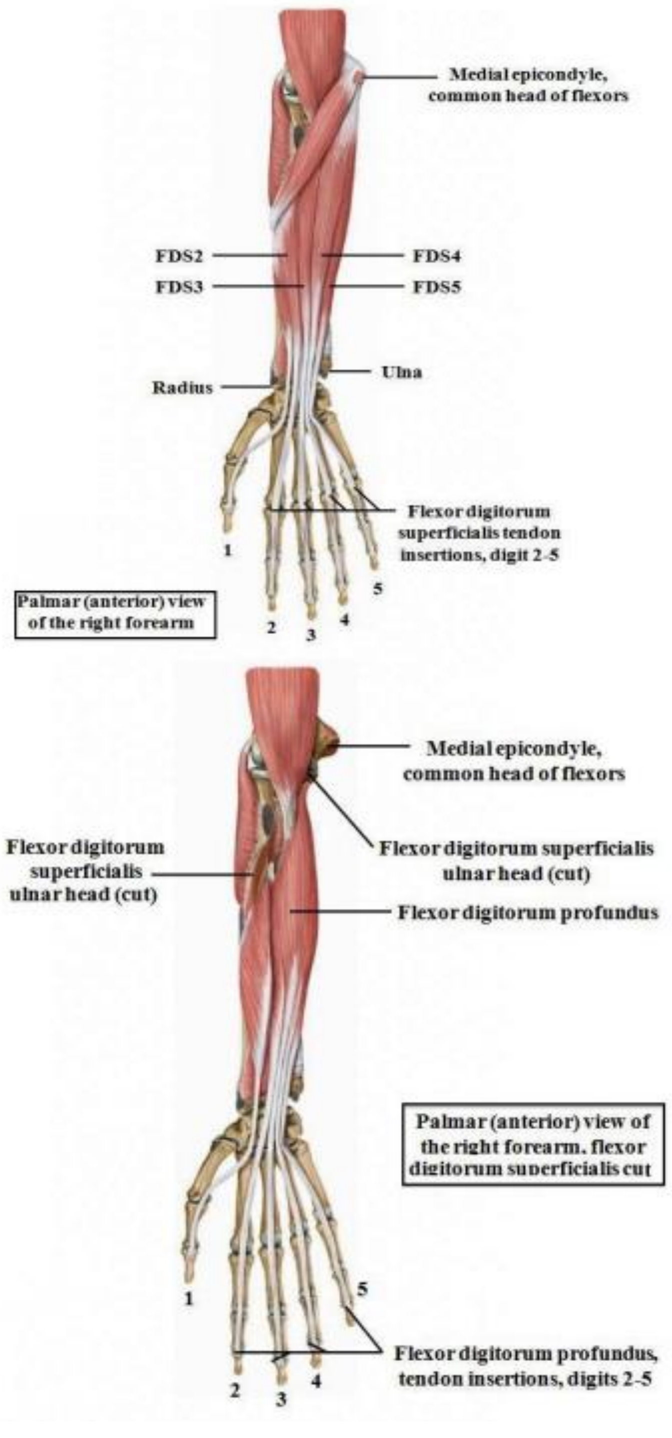

Figure 1: Palmar view of the forearm. Top: Origin and insertions of the four compartments of the FDS. Bottom: Origin and insertions of the FDP, with FDS cut (Schuenke et al., 2003)

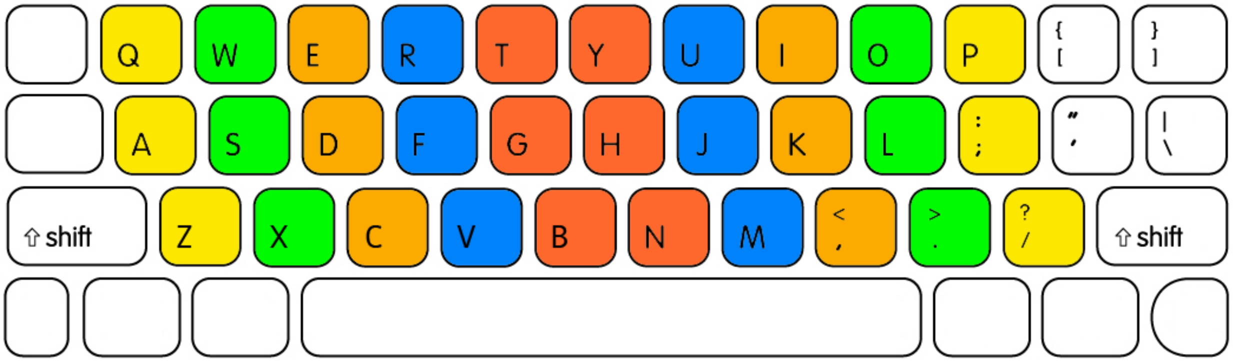

Figure 2: A typical digit selection on a QWERTY keyboard. A different colour corresponds to a different digit ("QWERTY finger placement," QWERTY finger placement).

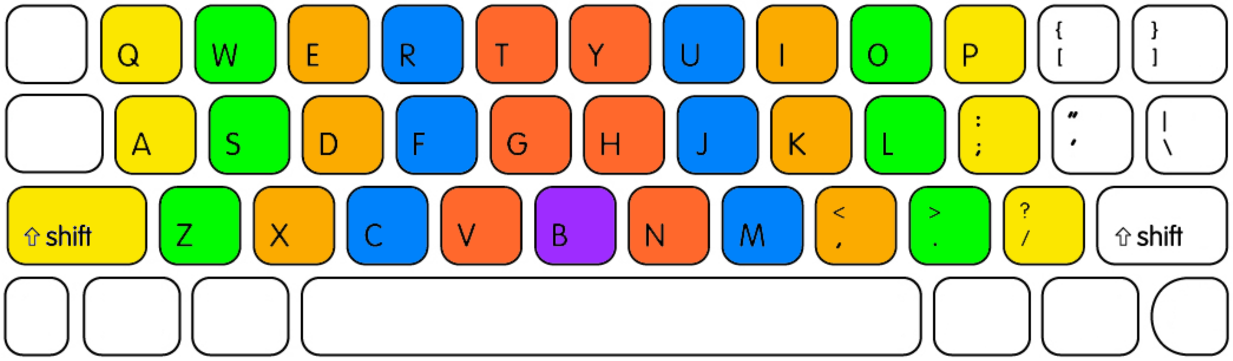

Figure 3: A more balanced QWERTY digit selection. A suggested method to type that is equal for both hands ("QWERTY suggested finger," QWERTY suggested finger placement).

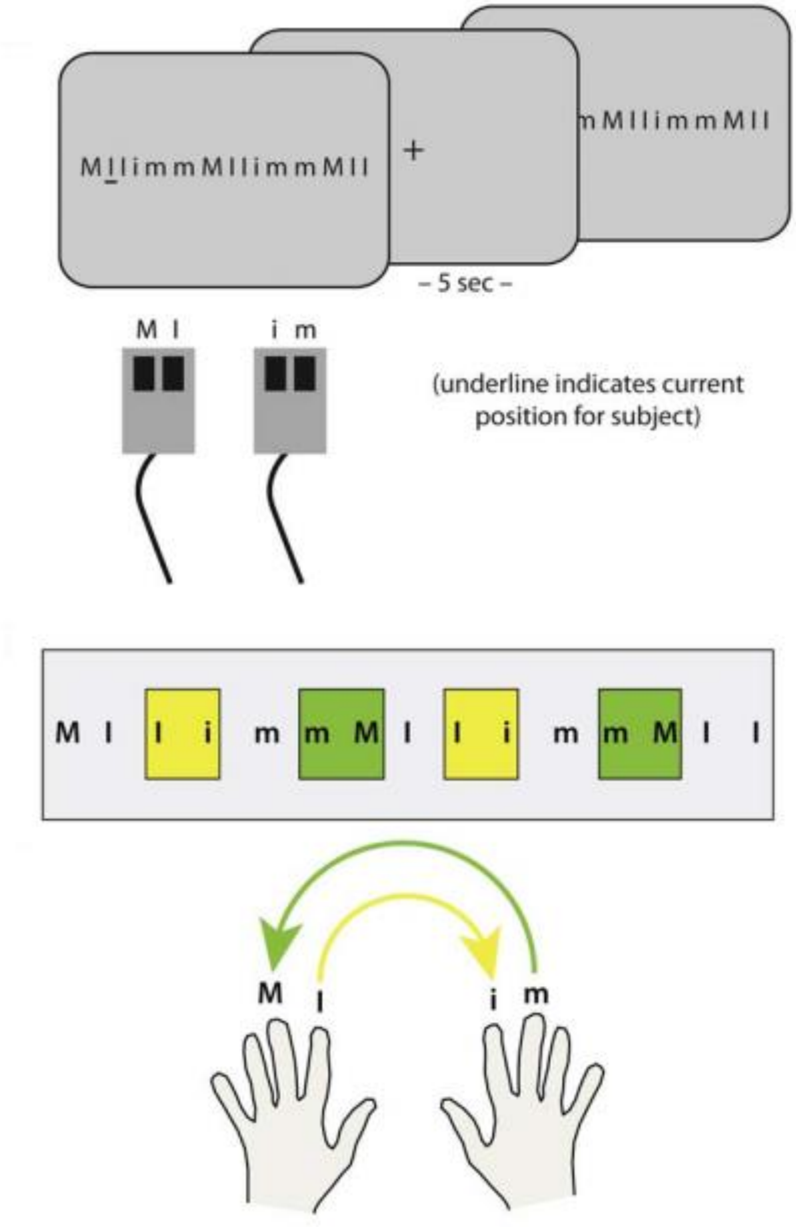

Figure 4: Visual of Trapp and colleagues' bimanual serial reaction time task. The letter 'm' suggests use of the 3rd digit, and 'i' for the 2nd digit, with uppercase letters suggesting use of the left hand and lowercase letters of the right. Green and yellow boxes indicate switches between the hands (Trapp et al., 2012).

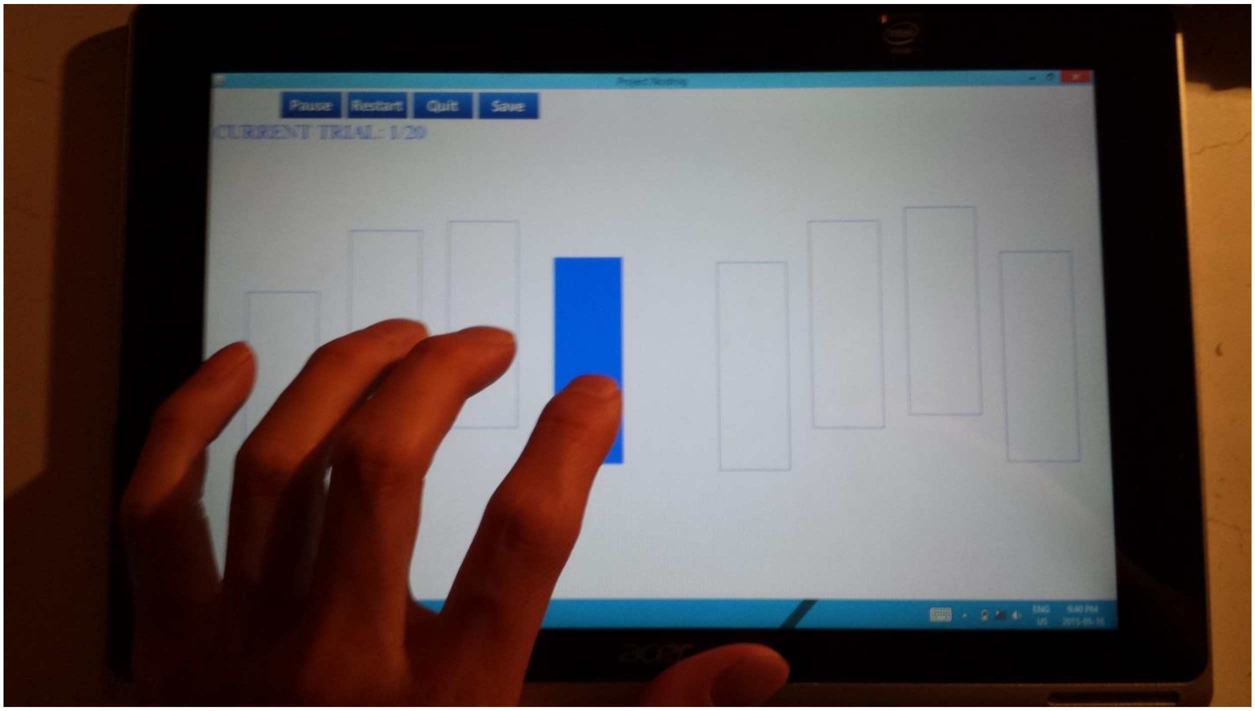

Figure 5: Exemplary left hand positioned on the tablet. A visual demonstration of a stimuli intended for the 2nd digit of the left hand.

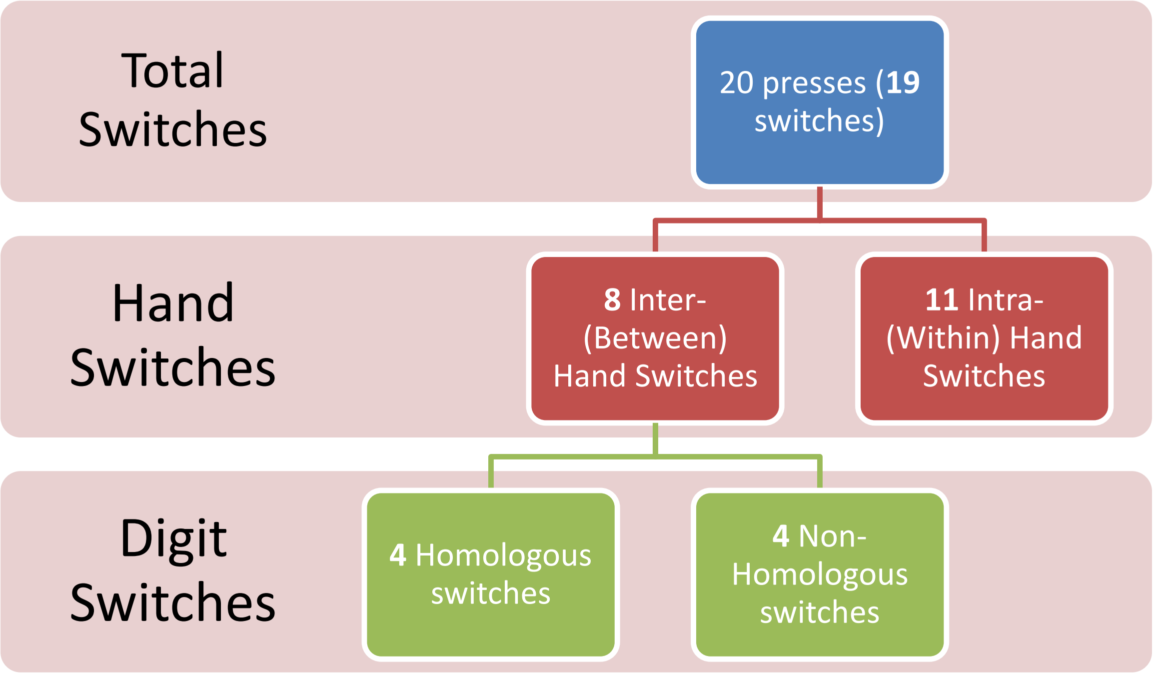

Figure 6: Breakdown of one trial. There were 20 trials per participant.

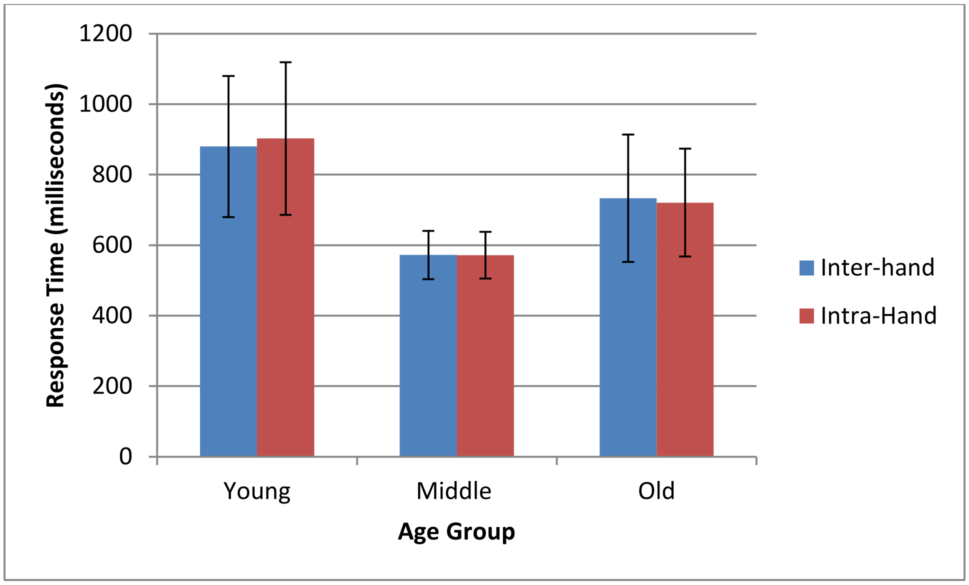

Figure 7: Graph of inter- and intra- hand switches across the three age groups. The significant interaction effect of inter-,intra- times, and age group (F(2,97) = .56, p < 0.001).

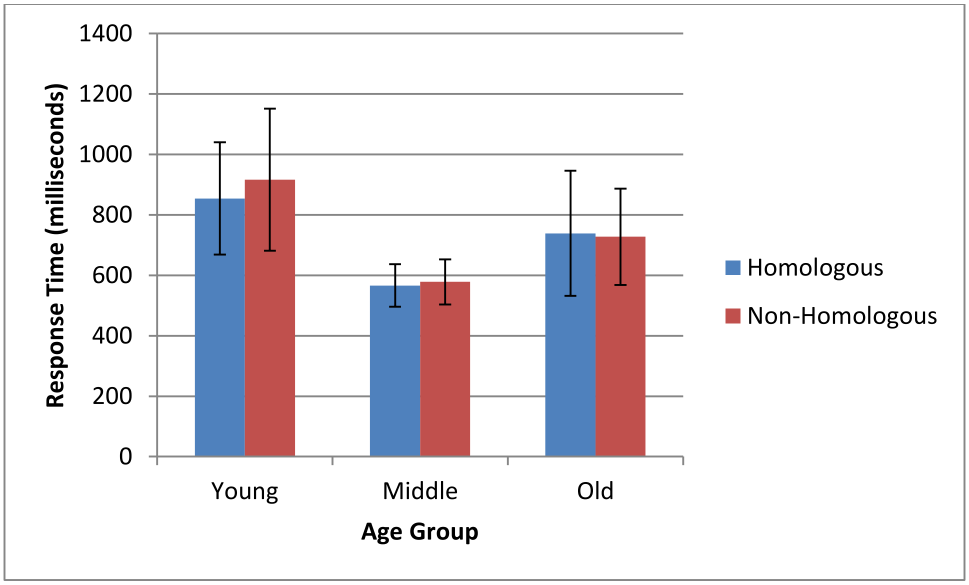

Figure 8: Graph of homologous and non-homologous switches across the three age groups. The significant interaction effect of homologous, non-homologous switches and age group (F(2,97) = 24.271, p < 0.001).

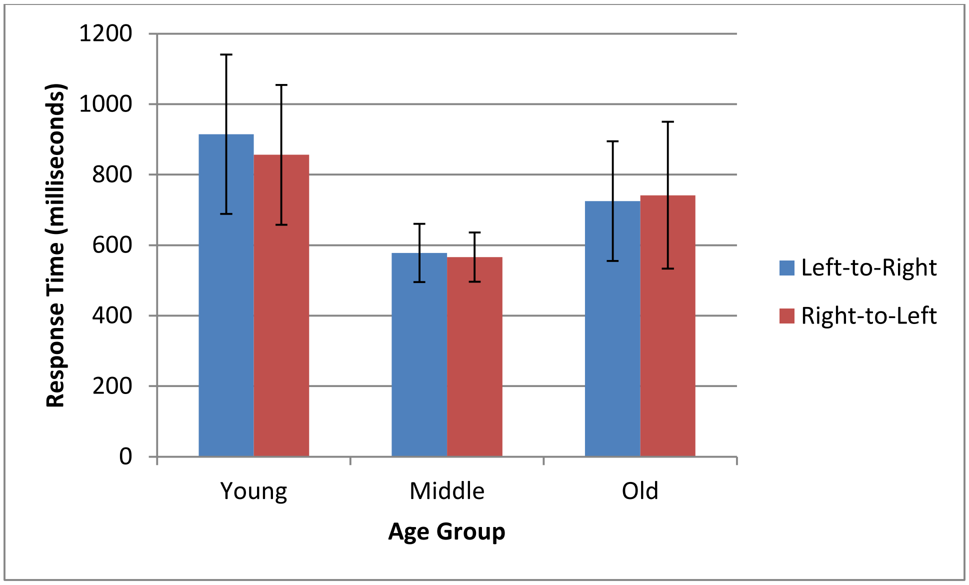

Figure 9: Graph of left-to-right and right-to-left switches across the three age groups. The significant interaction effect of left-to-right, right-to-left switches and age group (F(2,97) = 22.327, p < 0.001).

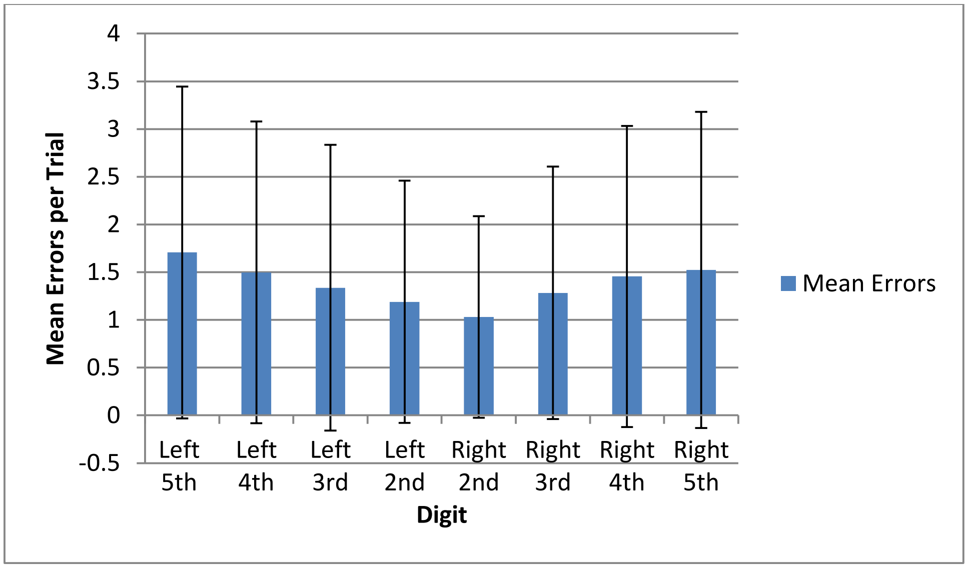

Figure 10: Graph of errors for the digits recorded. Within-subjects effects showed significant differences between digits (F(7,91) = 3.830, p < .001)

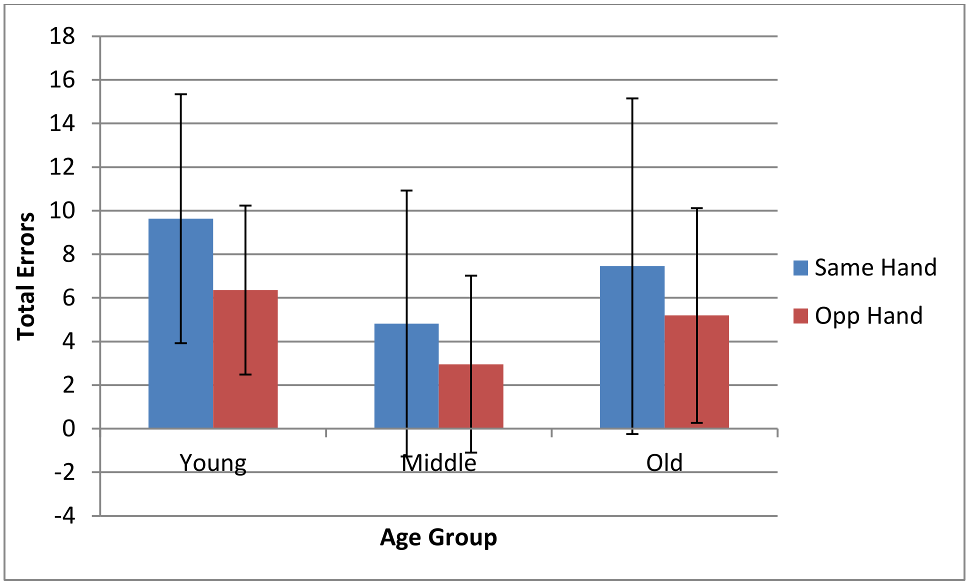

Figure 11: Graph of same and different hand errors across the three age groups. Within-subjects effects showed significant differences between errors (F(1,97) = 33.060, p < .001)

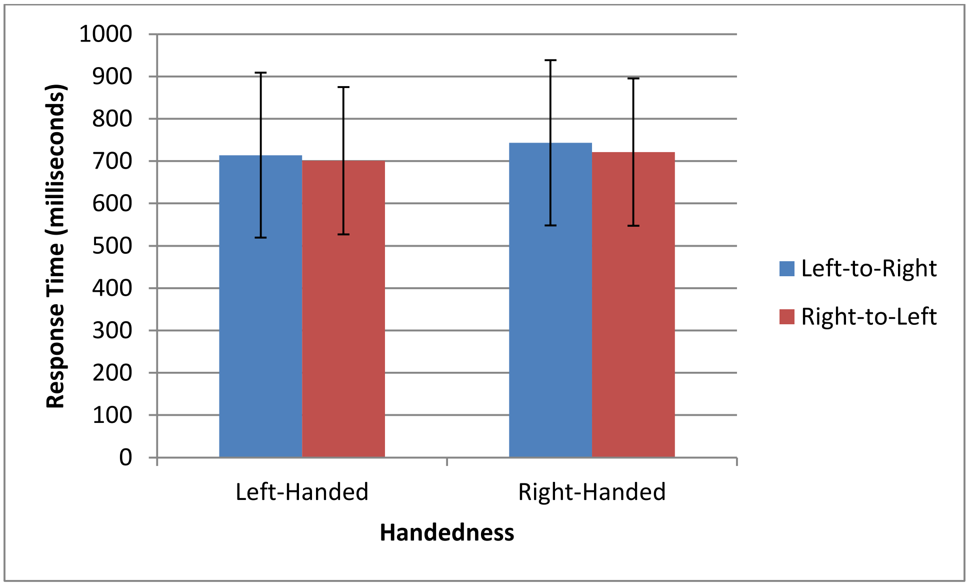

Figure 12: Graph of handedness and directional switches. No significant main effect was found for left to right switches and handedness (F(1,97) = .084, p = .773).

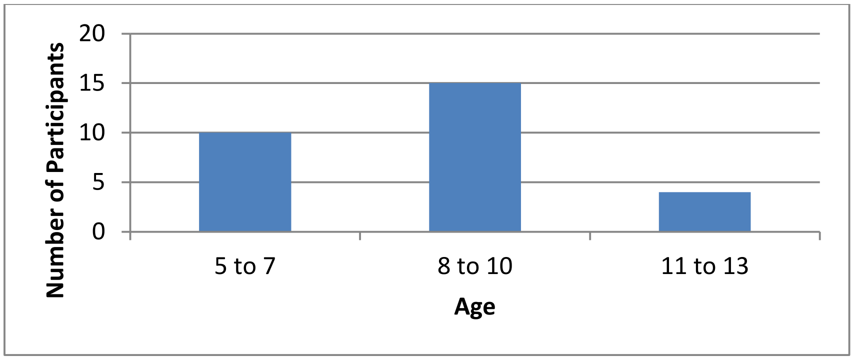

Figure 13: Graph of first age group distribution (5-13 years).

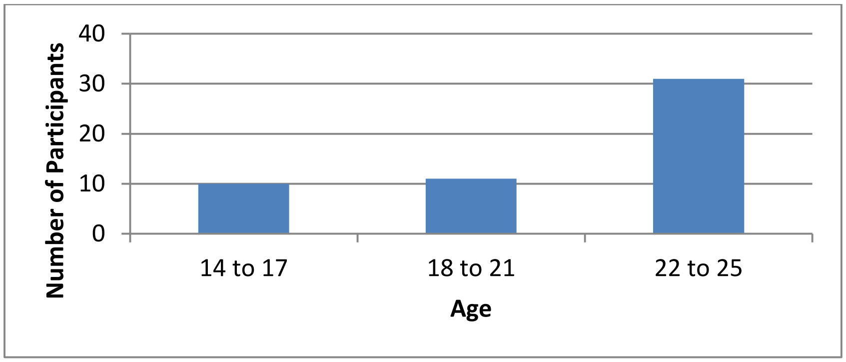

Figure 14: Graph of second age group distribution (14-25 years).

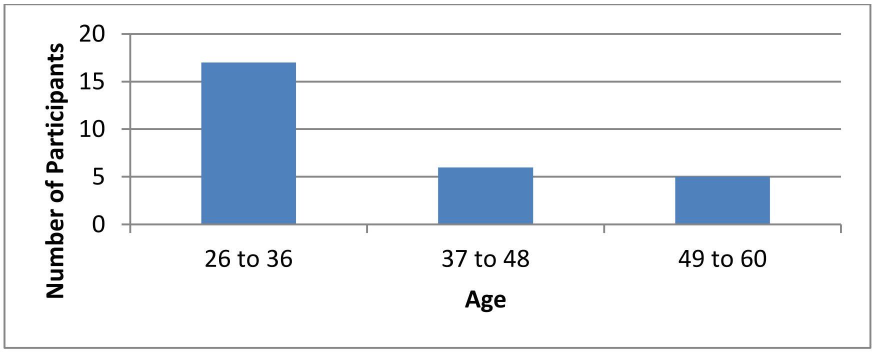

Figure 15: Graph of third age group distribution (26-60 years).

Appendix A: Waterloo Handedness Questionaire - Revised

(Steenhuis, Bryden, Schwartz & Lawson, 1990)

INSTRUCTIONS: Please indicate your hand preference for the following activities by circling the appropriate response. Think about each of the questions. You might try imagining yourself performing the task in question. There are five pages of questions, please do not skip any questions. Take your time.

- **If you use one hand 95% or more of the time to perform the described activity, then circle right always or left always as your response.**
- **If you use one hand about 75% of the time, then circle right usually or left usually.**
- **If you use both hands roughly the same amount of time, then circle equally.**

1. Which hand would you use to adjust the volume knob on a radio?

Left Always Left Usually Equally Right Usually Right Always

2. With which hand would you use a paintbrush to paint a wall?

Left Always Left Usually Equally Right Usually Right Always

3. With which hand would you use a spoon to eat soup?

Left Always Left Usually Equally Right Usually Right Always

4. Which hand would you use to point to something in the distance?

Left Always Left Usually Equally Right Usually Right Always

5. With which hand would use to throw a dart?

Left Always Left Usually Equally Right Usually Right Always

6. With which hand would you use the eraser on the end of a pencil?

Left Always Left Usually Equally Right Usually Right Always

7. In which hand would you hold a walking stick?

Left Always Left Usually Equally Right Usually Right Always

8. With which hand would you use an iron to iron a shirt?

Left Always Left Usually Equally Right Usually Right Always

9. Which hand would you use to draw a picture?

Left Always Left Usually Equally Right Usually Right Always

10. In which hand would you hold a mug full of coffee?

Left Always Left Usually Equally Right Usually Right Always

11. Which hand would you use to hammer a nail?

Left Always Left Usually Equally Right Usually Right Always

12. With which hand would you use the remote control for a TV?

Left Always Left Usually Equally Right Usually Right Always

13. With which hand would you use a knife to cut bread?

Left Always Left Usually Equally Right Usually Right Always

14. Which hand would you use to turn the pages of a book?

Left Always Left Usually Equally Right Usually Right Always

15. With which hand would you use a pair of scissors to cut paper?

Left Always Left Usually Equally Right Usually Right Always

16. Which hand would you use to erase a blackboard?

Left Always Left Usually Equally Right Usually Right Always

17. With which hand would you use a pair of tweezers?

Left Always Left Usually Equally Right Usually Right Always

18. Which hand would you use to pick up a book?

Left Always Left Usually Equally Right Usually Right Always

19. Which hand would you use to carry a suitcase?

Left Always Left Usually Equally Right Usually Right Always

20. Which hand would you use to pour a cup of coffee?

Left Always Left Usually Equally Right Usually Right Always

21. With which hand would you use a computer mouse?

Left Always Left Usually Equally Right Usually Right Always

22. Which hand would you use to insert a plug into an electrical outlet?

Left Always Left Usually Equally Right Usually Right Always

23. Which hand would you use to flip a coin?

Left Always Left Usually Equally Right Usually Right Always

24. With which hand would you use a toothbrush to brush your teeth?

Left Always Left Usually Equally Right Usually Right Always

25. Which hand would you use to throw a baseball?

Left Always Left Usually Equally Right Usually Right Always

26. Which hand would you use to turn a doorknob?

Left Always Left Usually Equally Right Usually Right Always

27. Which hand do use for writing?

Left Always Left Usually Equally Right Usually Right Always

28. Which hand would you use to pick up a piece of paper?

Left Always Left Usually Equally Right Usually Right Always

29. Which hand would you use to saw a piece of wood with a hand saw?

Left Always Left Usually Equally Right Usually Right Always

30. Which hand would you use to stir a liquid with a spoon?

Left Always Left Usually Equally Right Usually Right Always

31. In which hand would you hold an open umbrella?

Left Always Left Usually Equally Right Usually Right Always

32. In which hand would you hold a needle while sewing?

Left Always Left Usually Equally Right Usually Right Always

33. Which hand would you use to strike a match?

Left Always Left Usually Equally Right Usually Right Always

34. Which hand would you use to turn on a light switch?

Left Always Left Usually Equally Right Usually Right Always
35. Which hand would you use to open a drawer?
Left Always Left Usually Equally Right Usually Right Always
36. Which hand would you use to press the buttons on a calculator?
Left Always Left Usually Equally Right Usually Right Always

Is there any reason (e.g. injury why you have changed your hand preference for any of the above activities?
Yes No
Have you been given special training or encouragement to use a particular hand for certain activities?
Yes No
If you stated yes to either question, please explain:
____
____

Appendix B: Participant Information Questionnaire

Basic Information:

Identification (ID) Number: ________________
Full Name: ____
Gender (Circle one): Male Female
Age: _________ Birth date (day, month, year): _______________
Contact via phone (if any clarification on this form is needed): ________________________

Additional Information:

What do you consider yourself? (Circle one) LEFT HANDED RIGHT HANDED MIXED

Do you play a musical instrument? (Circle one) YES NO
If so, which one? ____________________
If so, how many years have you played? (Approximately) ___________________
Are you playing right now on a weekly basis? ___________________

Do you play any sports? (Circle one) YES NO
If so, which sports? (The major ones) ______________________________
If so, how many years have you been playing? (Approximately) ______________________
Which sport, if any, are you playing on a weekly basis? ___________________

Have you ever had any nerve damage in your hands? _______________________
Have you been diagnosed with any neurological or psychiatric illness? ___________________

Are you currently using any visual aids? (Glasses, contacts) (Circle one) YES NO
Do you have any additional vision issues? _________________________________

Have you ever had any major head injuries or concussions? (Circle one) YES NO
If so, how many, and approximately how long ago? ______________________________

Appendix C: Consent Form (Child)

WILFRID LAURIER UNIVERSITY
INFORMED CONSENT STATEMENT
Hand Switch Costs in Bimanual Movements: An Investigatory Examination throughout the Lifespan
Dr. Pam Bryden, Gordon Young

Your child is invited to participate in a research study. The purpose of this experiment is to examine reaction time in a bimanual serial reaction time task, to determine the differences in motor performance between varying age groups.

INFORMATION

Participants will be asked to complete a bimanual serial reaction time task, which is used to measure movement speed of the hands and fingers. This involves pressing buttons on a computer tablet as they appear on the screen. Participants will be completing multiple trials of this task.

The approximate time that this study will require is 15-20 minutes.

RISKS

There may be a slight chance of fatigue in the fingers from pressing the buttons on the tablet. To ensure that the study goes smoothly and quickly, there are strategic breaks placed within the program. In addition, we will ask participants throughout if a break is needed. Your child will be able to withdraw from the experiment at any time without repercussions.

BENEFITS

This research will provide further knowledge about the relationship between hand preference and motor performance in the area of kinesiology.

CONFIDENTIALITY

All of the data will be recorded using a participant ID number and not names. All identifying features that could eventually lead back to the participant's name will be deleted or removed. Only group means will be presented when possible, and if any individual data is presented, no identifying features will be used. Only the principal investigator and his supervisor of this study will have access to the data. All of the data will be kept locked.

CONTACT

If you have questions at any time about the study or the procedures (or if you experience adverse effects as a result of participating in this study) you may contact the primary researcher, Gordon Young, at youn2990@mylaurier.ca, or Dr. Pam Bryden, at pbryden@wlu.ca or (519) 884-0710 x4213. This project has been reviewed and approved by the University Research Ethics Board. If you feel that you had not been treated according to the descriptions in this form, or your rights as a participant in research had been violated during the course of this project, you may contact Dr. Robert Basso, Chair, University Research Ethics Board, Wilfrid Laurier University, (519) 884-1970, extension x4994 or rbasso@wlu.ca.

PARTICIPATION

Your child's participation in this study is voluntary; your child may decline to participate without penalty. If your child decides to participate, your child may withdraw from the study at any time without penalty and without loss of benefits to which your child is otherwise entitled. If your child withdraws from the study, every attempt will be made to remove your child's data from the study, and have it destroyed. Your child has the right to omit any question(s)/procedure(s) that your child chooses.

FEEDBACK AND PUBLICATION

If you have any questions, we will gladly answer them for you at any point. If you have any specific questions about the results of the study, they may be obtained by e-mailing Dr. Pam Bryden at pbryden@wlu.ca

CONSENT

I have read and understand the above information. I have received a copy of this form. I agree that my child will be allowed to participate in this study.

Participant's Name: ___________________________________ Date of Birth: ______________

Parent/Guardian's Signature: _____________________________ Date: _________________

Appendix D: Consent Form (Adult)

WILFRID LAURIER UNIVERSITY
INFORMED CONSENT STATEMENT
Hand Switch Costs in Bimanual Movements: An Investigatory Examination throughout the Lifespan
Dr. Pam Bryden, Gordon Young

You are invited to participate in a research study. The purpose of this experiment is to examine reaction time in a bimanual serial reaction time task, to determine the differences in motor performance between varying age groups.

INFORMATION

Participants will be asked to complete a bimanual serial reaction time task, which is used to measure movement speed of the hands and fingers. This consists of pressing buttons on the program as they light up to record reaction times. Participants will be completing multiple trials of this task.

The approximate time that this study will require is 15-20 minutes.

RISKS

There may be a slight chance of fatigue from pressing the buttons with your fingers. To ensure that the study goes smoothly and quickly, there are strategic breaks placed within the program. In addition, we will ask throughout if a break is required from the experiment. You will be able to withdraw from the experiment at any time without repercussions.

BENEFITS

This research will provide further knowledge about the relationship between hand preference and motor performance in the area of kinesiology.

CONFIDENTIALITY

All of the data will be recorded using a participant ID number and not names. All identifying features that could eventually lead back to the participant's name will be deleted or removed. Only group means will be presented when possible, and if any individual data is presented, no identifying features will be used. Only the principal investigator and his supervisor of this study will have access to the data. All of the data will be kept locked.

CONTACT

If you have questions at any time about the study or the procedures (or if you experience adverse effects as a result of participating in this study) you may contact the researcher, Gordon Young, at youn2990@mylaurier.ca, or Dr. Pam Bryden, at pbryden@wlu.ca or (519) 884-0710 x4213. This project has been reviewed and approved by the University Research Ethics Board. If you feel that you had not been treated according to the descriptions in this form, or your rights as a participant in research had been violated during the course of this project, you may contact Dr. Robert Basso, Chair, University Research Ethics Board, Wilfrid Laurier University, (519) 884-1970, extension x4994 or rbasso@wlu.ca.

PARTICIPATION

Your participation in this study is voluntary; you may decline to participate without penalty. If you decide to participate, you may withdraw from the study at any time without penalty and without loss of benefits to which you are otherwise entitled. If you withdraw from the study, every attempt will be made to remove your data from the study, and have it destroyed. You have the right to omit any question(s)/procedure(s) that you choose.

FEEDBACK AND PUBLICATION

If you have any questions, we will gladly answer them for you at any point. If you have any specific questions about the results of the study, they may be obtained by e-mailing Dr. Pam Bryden at pbryden@wlu.ca

CONSENT

I have read and understand the above information. I have received a copy of this form.

Participant's Name: ____________________________________ Date of Birth: _______________

Signature: _________________________________Date: __________________

Appendix E: Script Inviting Participants (Child & Adult)

Laterality Across the Lifespan:
The Application of Hand Switch Costs

SCRIPT INVITING PARTICIPANTS

Hello, my name is Gordon Young, and I am a second year Master's student at Wilfrid Laurier University. I would like to explain the basis behind this research in hopes that you and/or your child might be interested in participation. The purpose of my study is to investigate bimanual motor performance by measuring the reaction time between the left and right hand.

We will be looking at performance in both left and right hands for young children from the age of 5 to older adults at the age of 60. The study involves playing a game on a tablet that requires pressing buttons on a screen as they light up, as fast as you can. All information and data collected will remain confidential. Approximately 20 minutes of yours and/or your child's time will be required during a single session of testing. Participation is voluntary, and participants can withdraw from the study at any time they wish.

By participating in this research, you and/or your child will learn about scientific research and how it is conducted. Furthermore, one may learn about handedness (motor control) and the theory behind interhemispheric interactions in bimanual movement. By participating in this research you will help us to better understand bimanual ability throughout the lifespan.

This project has been reviewed and obtained ethical clearance through the Research Ethics Board at Wilfrid Laurier University

Please contact myself (519-884-0710 ext. 4775, youn2990@mylaurier.ca) or my supervisor, Dr. Pam Bryden (519-884-0710 ext. 4213, pbyrden@wlu.ca) at any time if you have questions about the study.

Appendix F: Recruitment Posters (Child & Adult)

Wilfrid Laurier University

Motor Control Study

We would like to invite you and/or your child to participate in a motor control study at Wilfrid Laurier University looking at bimanual reaction times in the left and right hand. The study involves a game on a tablet computer to press buttons on the screen when they light up. The game will take about twenty minutes of your time. If you are interested in being a part of the motor control study you will be asked to provide some basic information, along with contact information. We encourage participation, ***especially from left-handers***.

Please contact Gordon Young in the Department of Kinesiology and Physical Education at Wilfrid Laurier University, by emailing: youn2990@mylaurier.ca.

Participants: Ages 5-60

Estimated time to complete: 20 minutes

Location: Anywhere on WLU campus, we can come to you!

WLU Ethics approval number: #4196

Motor Control Study youn2990@mylaurier.ca Phone: (519) 884-1970 ext. **4775**	Motor Control Study youn2990@mylaurier.ca Phone: (519) 884-1970 ext. **4775**	Motor Control Study youn2990@mylaurier.ca Phone: (519) 884-1970 ext. **4775**	Motor Control Study youn2990@mylaurier.ca Phone: (519) 884-1970 ext. **4775**	Motor Control Study youn2990@mylaurier.ca Phone: (519) 884-1970 ext. **4775**	Motor Control Study youn2990@mylaurier.ca Phone: (519) 884-1970 ext. **4775**	Motor Control Study youn2990@mylaurier.ca Phone: (519) 884-1970 ext. **4775**	Motor Control Study youn2990@mylaurier.ca Phone: (519) 884-1970 ext. **4775**	Motor Control Study youn2990@mylaurier.ca Phone: (519) 884-1970 ext. **4775**	Motor Control Study youn2990@mylaurier.ca Phone: (519) 884-1970 ext. **4775**

Appendix G: Curriculum Vitae

GORDON YOUNG

140 Alvin Street • Waterloo, ON N2J 3J8 • (416)400-3192 • Youn2990@mylaurier.ca

Skills Summary

- Excellent writing and research skills developed as a research assistant and master's thesis student
- Refined presentation and interpersonal skills from numerous conference and thesis presentations
- Successful in team environments as an avid soccer player and
- Leadership experience working in Residence Life as a Senior Community Advisor
- Proficient in Microsoft Office (Word, Excel, PowerPoint)

Education

Wilfrid Laurier University, Waterloo, Ontario 2015 – Present

Master of Business Administration

- Enrolled in the accelerated full-time MBA program with Co-op stream

Wilfrid Laurier University, Waterloo, Ontario 2013 – 2015

MSc in Kinesiology

- Thesis-based program with a specialized focus on handedness and bimanual movements

McMaster University, Hamilton, Ontario 2008 – 2013

BSc in Honours Science Kinesiology

- Scientific background with lab experience in Exercise Testing, Chemistry, Biology and Physics
- Advanced courses in Health & Sport Psychology, Motor Behaviour, and Nutrition

Work Experience

Teaching Assistant at Wilfrid Laurier University, Waterloo, Ontario, September 2013 – April 2015

- Facilitated and assisted undergraduate students in laboratory work and supplementary lecturer
- Research Assistant for summer 2014 & 2015 at the Lifespan for Psychomotor Behaviour Lab

Coach at Power Soccer Academy, Toronto, Ontario, Summer 2013

- Developed and implemented organized soccer plans which fostered competitive team atmospheres

Senior Community Advisor at McMaster University, September 2010 - April 2013

- Mentor, role model, and team leader for 12 fellow community advisors in the most populated apartment- style residence at McMaster, a total of 506 students
- Increased community development and utilized university outreach programs for a residence floor of 80+ first year students in a safe and inclusive manner

Volunteer and Extra-Curricular Activities

President of the KPE Graduate Council, Waterloo, Ontario, September 2013 – August 2015
- Directed various operations from including health & wellness to campus & community
- Organized educational and social events for the entire MSc graduate student body

Player in the Grand River Soccer League and TMSL, Waterloo, Ontario, May 2014 – Present
- Ontario Soccer Association rep-level soccer player from 1999-2008, the last 5 years being at the provincial level in the CSL
- Captained the Bayview Seconday School's Varsity Soccer team in grade 11 and 12

Player in Wilfrid Laurier Intramurals, Waterloo, Ontario, 2013 – Present
- Participated in four indoor and outdoor soccer teams
- Participated in inner-tube water polo

Member of the Mental Health Task Force, Waterloo, Ontario, September 2014 - August 2015
- Worked alongside staff and faculty at WLU to encourage students to seek help for mental health behavioural issues

Conference Presenter for Kinesiology Research, Ontario, 2013-2015
- Presented at the Southern Ontario Motor Behaviour Symposium, Toronto, Ontario, May 2014
- Presented at the Canadian Society for Psychomotor Learning and Sports Psychology, London, Ontario, October 2014

Volunteer at Epilepsy Ontario-Waterloo-Wellington, Waterloo, Ontario, July 2014
- Assisted in event coordination of Raissa's Run, course preparation, and setup

MacServe Member at Habitat for Humanity, New Orleans, United States, February 2012
- Provided service with 'Habitat for Humanity' for New Orleans's upper and lower 9th ward, by aiding in the reconstruction of houses destroyed by Hurricane Katrina

Hobbies & Interests

- Participated and completed the United Way's CN Tower Climb (2011), Toronto Tough Mudder (2012), Toronto Islands Dragonboat Festival (2012), Goodlife Half-Marthon (2015)
- Backpacked throughout Europe in the summer of 2012
- Completed the Can Fit Personal Trainer Course
- High level competitive soccer player
- Fitness and health devotee
- Enthusiast for any outdoor activity such as biking or hiking