VIRTUAL REALITY ASSESSMENT OF EXECUTIVE DECISION MAKING IN PAEDIATRICS: A LONGITUDINAL STUDY OF FEASIBILITY

by

Devon Abel

A thesis submitted to the graduate program of Rehabilitation Sciences

In conformity with the requirements for

the degree of Master’s of Science

Queen’s University

Kingston, Ontario, Canada

(March, 2015)

Copyright ©Devon Abel, 2015
Abstract

The identification of sports related paediatric concussive injuries has become an important general public health issue, as current neurocognitive computer based assessments are unable to measure baseline changes in executive decision making (EDM) in children that result following a concussion. This is because the brain areas associated with EDM vulnerable to pediatric concussion are also maturing and improving with time.

The feasibility of the Object Hit task to detect change in EDM attributes with respect to age was assessed. The Object Hit task was implemented on the virtual reality assessment platform of the KINARM exoskeleton robot. Twenty children aged five to eighteen years with typical health and development that completed the Object Hit task between three to five times over the past three years were included in the analysis. Five attributes of the Object Hit task were selected (targets hit, median error, mean hand speed, hand movement area, and hand selection overlap) for assessing distinctive components of EDM; processing time, reaction time, working memory, and action planning. Linear regression analysis was calculated for each of the five selected performance attributes with respect to age.

The results from this study indicate that overall measures of performance on the Object Hit task are responsive to longitudinal age related changes in EDM from five to eighteen years of age. The overall performance measures were able to identify age related improvements over the entire age range with 84% of the change in targets hit accounted for by age, and 72% of the change in median error accounted for by age. Performance attributes specific to working memory (hand movement area), reaction time (hand speed), and action planning (hand selection overlap), were not responsive to age.

The regression trend line with 95% confidence boundaries calculated for targets hit results has characteristics that allow it to establish a normative profile of change in EDM with age; however the
results would benefit from a study including greater participant numbers. Future research should be completed evaluating the sensitivity of task to detect declined EDM following a concussion.
Acknowledgements

All triumphs come with trials and tribulations. Completing my Master's in Rehabilitation Science has been a work in progress for some time, but I have gained so much experience and information about myself through the process. For the past three years, I have learned and overcome so many obstacles and challenges in the process of completing my thesis. And I have only been able to do so with the help of some very important people. First I would like to thank my supervisor, Dr. Lucie Pelland, for always being there to push me in the right direction and for being patient with me while I learned and grew both in my academic and personal life. I would like to thank Justin Peterson, from the Center of Neuroscience, for all of his assistance from training on the KINARM to extracting data. I would also like to thank Dr. Linda McLean from the School of Rehabilitation Science for all her support and guidance in completing my thesis. I would also like to thank Carla Henderson and Noreen Choe for their previous work on the KINARM making my project possible. I would like to thank all my fellow rehabilitation students who made the program a fun and enjoyable experience. Thanks to Abby, Heather, Grace and Carrie. I want to thank my family and friends for all their unconditional love and support over the years. And lastly I’d like to thank all the participants and their families for volunteering their time and energy to come in for the study multiple times over the past 5 years. Without amazing people like you, this research wouldn’t be possible.
# Table of Contents

Abstract .................................................................................................................................................. ii

Acknowledgements ................................................................................................................................. iv

List of Figures .......................................................................................................................................... vii

List of Tables ........................................................................................................................................... viii

List of Abbreviations .............................................................................................................................. ix

Chapter 1 Introduction ............................................................................................................................. 1

Chapter 2 Literature Review .................................................................................................................... 8
  2.1 Overview of sport-related concussion in paediatrics ........................................................................ 8
    2.1.1 Developmental vulnerability of the brain ...................................................................................... 8
    2.1.2 Methods for diagnosis of concussion effects in children and adolescents ............................... 11
  2.2 Current EDM assessment techniques ............................................................................................... 11
    2.2.1 Adult assessment ......................................................................................................................... 11
    2.2.2 Paediatric assessment ................................................................................................................. 13
  2.3 Object Hit task .................................................................................................................................. 14
    2.3.1 Object Hit task procedure ........................................................................................................... 15
    2.3.2 Working memory and hand movement area ................................................................................. 16
    2.3.3 Processing time and median error ............................................................................................... 17
    2.3.4 Action planning and hand selection overlap ............................................................................. 18
    2.3.5 EDM and targets hit .................................................................................................................... 19

Chapter 3 Methods ................................................................................................................................. 21
  3.1 Statement of ethics ............................................................................................................................. 21
  3.2 Recruitment strategy .......................................................................................................................... 21
  3.3 VR assessment of selected components of EDM .............................................................................. 23
  3.4 Experimental procedure ................................................................................................................. 26
  3.5 Measured attributes .......................................................................................................................... 28
    3.5.1 Targets hit .................................................................................................................................... 30
    3.5.2 Median error ............................................................................................................................... 30
    3.5.3 Mean hand speed ....................................................................................................................... 31
    3.5.4 Hand movement area ............................................................................................................... 31
    3.5.5 Hand selection overlap ............................................................................................................ 32
  3.6 Statistical analysis ............................................................................................................................. 33

Chapter 4 Results ................................................................................................................................... 35
4.1 Description of the study group.............................................................................................35
4.2 Assessment of normality .....................................................................................................35
4.3 Linear regression models of calculated performance attributes........................................36
4.4 Summary of results ...............................................................................................................40
Chapter 5 Discussion ....................................................................................................................42
  5.1 Object Hit task attributes results .......................................................................................42
  5.2 Clinical implications ...........................................................................................................46
Chapter 6 Conclusions and Limitations ....................................................................................48
References...................................................................................................................................50
Appendix A REB Approval .........................................................................................................58
Appendix B Consent Form ..........................................................................................................59
Appendix C Personal Information Form ....................................................................................60
Appendix D Participant Data .......................................................................................................66
Appendix E Additional Figures .................................................................................................70
List of Figures

Figure 1: KINARM Exoskeleton Robot ........................................................................................................... 24
Figure 2: Schematic Representation of Object Hit Task.................................................................................. 26
Figure 3: Hand Trajectory and Movement Area Calculation.............................................................................. 32
Figure 4: Depiction of Object Hit Task Results................................................................................................. 33
Figure 5: Linear Regression Analysis versus Age for
(Panel A) Targets Hit
(Panel B) Median Error
(Panel C) Hand Movement Area................................................................................................................... 37
Figure 6: Linear Regression Analysis versus Age for
(Panel A) Mean Hand Speed
(Panel B) Hand Selection Overlap .................................................................................................................. 38
Figure 7: Individual Hand Selection Overlap Trend Lines................................................................................ 40
List of Tables

Table 1: EDM Component Summary ........................................................................................................... 16
Table 2: Assessment Schedule Summary .................................................................................................... 22
Table 3: Measured Attributes Summary .................................................................................................... 29
Table 4: Assessment of Normality of Distribution for Calculated Performance Attributes .................. 36
Table 5: Summary of Results ...................................................................................................................... 41
## List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>dlPFC</td>
<td>dorsolateral prefrontal cortex</td>
</tr>
<tr>
<td>EDM</td>
<td>executive decision making</td>
</tr>
<tr>
<td>fMRI</td>
<td>functional Magnetic Resonance Imaging</td>
</tr>
<tr>
<td>ImPACT</td>
<td>immediate post-concussion assessment and cognitive testing</td>
</tr>
<tr>
<td>KINARM</td>
<td>kinesiological instrument for normal and altered reaching movement</td>
</tr>
<tr>
<td>NIH</td>
<td>National Institutes of Health</td>
</tr>
<tr>
<td>OFC</td>
<td>orbitofrontal cortex</td>
</tr>
<tr>
<td>PCSS</td>
<td>Post-Concussion Symptom Scale</td>
</tr>
<tr>
<td>PFC</td>
<td>prefrontal cortex</td>
</tr>
<tr>
<td>VR</td>
<td>virtual reality</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

Participation in recreational and competitive sport is an important component of healthy development of children and adolescents. Regular participation in physical activities and sports in children and adolescents has been associated with improved musculoskeletal and cardiovascular health, as well as positively influencing cognitive abilities, academic performance and the development of social skills (Guskiewicz & McLeod, 2011; Lambourne & Donnelly, 2011; Caine, Maffulli, & Caine, 2008; Powell, 2001). Organized sports programs offer a supportive environment for regular participation in physical activities where children can grow physically, mentally and socially, as well as providing opportunity for personal success and possible future employment (Powell, 2001). One negative aspect of youth organized sports is the increasing expectation of excellence from young athletes, with its associated emphasis on high levels of physical training and competition which increase the risk for sport-related injuries (Guskiewicz & McLeod, 2011; Caine, Maffulli, & Caine, 2008).

Concussions are the most commonly reported injury related to sports participation in paediatrics (Yeates, 2010; Marar et al., 2012; Emery & Meeuwise, 2006). A recent epidemiological survey of visits to emergency departments in Canada estimated the incidence of concussion in children and adolescents, 10 to 14 years of age, to be 207.9 per 100,000 participants in sport and recreational activities (Harris et al., 2012). This rate of concussion incidence is more than three times the rate reported in adults 20 to 24 years old. While the tendency for young athletes to engage in higher risk taking behaviours, combined with lesser sport-related experience, contributes to this higher than expected concussion incidence (Clacy, Sharman, & Lovell, 2013),
the specific vulnerability of paediatric athletes to concussions primarily results from the lowered threshold of the developing brain to injury (Halstead & Walter, 2010; Reeves et al., 2012).

A concussion results when a paediatric athlete receives a blow to the head or any part of the body that causes the head to accelerate. This sudden acceleration causes stretching and shearing of white matter tracts. These force-induced injuries do not occur uniformly throughout the brain, with unmyelinated and thinly myelinated axons having a high susceptibility to injury, even at low magnitudes of applied force (Reeves, Doperalski, & Phillips, 2014). In addition to being less resistant to applied forces, unmyelinated and thinly myelinated axons take longer to recover from injury, if they recover at all. This disrupts the structural and functional connectivity of the brain (Giza & Hovda, 2001). In child and youth development, myelination of the white matter tracts of the brain occurs over a protracted time line, with some areas of the brain undergoing myelination up to 21 years of age (Reeves et al., 2012). It is this prolonged window of myelination which increases the likelihood of children and adolescents to concussive injuries in contact sports and to recurrent concussions when compared to adults (Reeves, Doperalski, & Phillips, 2014; Reeves, Phillips, & Povlishock, 2005; Reeves et al., 2012; Guskiewicz & McLeod, 2011; Guskiewicz et al., 2007; Guskiewicz et al., 2005).

The effects of concussive injuries in paediatrics appear to be cumulative, in that the incidence of one injury is the highest predictor of subsequent concussions. As well, retrospective studies have described an association between a history of concussive injury sustained in childhood and adolescence to depression and neurodegenerative disease of the brain later in life (Segalowitz & Brown, 1991; Johnson, Stewart, & Smith, 2013). Therefore, the identification of concussion in paediatric athletes and effective monitoring of recovery from these injuries are essential components of the risk management for sport-related concussion in youth sports. The reality,
however, is that the resultant effects of these cumulative injuries cannot be predicted with any level of certainty using current clinical and neuroimaging assessments.

Currently, clinical diagnosis of concussion is principally based on the self-report of symptoms, which can vary in nature (i.e., physical, emotional, sleep disturbance, cognitive), frequency, duration and intensity; a complete list of the most frequent symptoms associated to concussions is provided by Halstead & Walter (2010). With significant variability in presenting symptomology, the clinical diagnosis of concussion, and the monitoring of recovery in brain function following injury, is highly ‘subjective’ and strongly influenced by the clinicians experience, knowledge, and even belief about concussions. Clinical diagnosis is even more difficult in paediatric populations due to the limited ability of children and adolescents to recognize symptoms and to effectively communicate how they feel to a health care professional (Halstead & Walter, 2010).

To address this limitation of a clinical diagnosis based on symptomology, a variety of standardized assessments have been developed (Eckner & Kutcher, 2010; Guskiewicz et al., 2004). Some of these assessments have been developed for acute (i.e. sideline) diagnosis, with the most commonly used of these assessments being the Standardized Assessment of Concussion (McCrea, Kelly & Randolph, 2000) and the Sport Concussion Assessment Tool (SCAT) – child version (McCrory et al., 2013). These sideline assessments are designed to be practical, combining self-report of symptoms with assessments of basic neurocognitive function (Eckner & Kutcher, 2010). Other assessments have been designed to provide a comprehensive evaluation of baseline neurocognitive function, including The HeadMinder Concussion Resolution Index (Kaushik, & Erlanger, 2006) and Cogsport (Collie et al., 2006). The most commonly used of these baseline neurocognitive assessments is the Immediate Post-concussion Assessment and Cognitive Testing (ImPACT) (Meehan et al., 2012; Iverson et al., 2002). These more ‘formal’
assessments are meant to provide a player-specific baseline reference of neurocognitive function that can subsequently be used over the season to quantify the extent of impairment in neurocognitive function following a potentially concussive event. In this way clinical diagnosis of concussion and recovery is based on the change in neurocognitive assessment scores.

Performance on specific custom tests of neurocognitive function, namely, working memory, processing time, and planning tasks, have been shown to correlate to self-report symptomology and to the extent of disruption in brain structure and function seen with functional Magnetic Resonance Imaging (fMRI) (Erlanger et al., 2003; Powell, 2001; Toledo et al., 2012, Schatz et al., 2006; Schatz et al., 2010). These specific attributes of neurocognitive function, namely working memory, processing time and action planning, which have the highest sensitivity for diagnosis and management of concussive injuries are all components of executive decision making (EDM) (Okonkwo, Tempel, & Maroon, 2014; Graham et al., 2014). EDM is a general term that describes the cognitive process of choosing and implementing a preferred course of action from a set of alternatives on the basis of given criteria or strategies (Blakemore & Robbins, 2012). The term EDM is used, rather than neurocognitive function, as it distinguishes that other cognitive functions of emotional, social or general intelligence are not being assessed (Schatz et al., 2006). The specific attributes of EDM assessed for concussion diagnosis are mediated by the prefrontal cortex, an area of the brain that is vulnerable to concussion-related injury in paediatrics. While having good specificity to identify EDM function in adults, neurocognitive assessments, such as the ImPACT, were designed for adults with the assumption that baseline neurocognitive function does not change over the course of a season. This assumption is not valid for children and adolescents for whom working memory, action planning, and processing time is expected to improve in continuous fashion as a function of brain development and learning (Register-Mihalik et al., 2012; Barlow et al., 2011; Newman et al., 2013; Lichtenstein, Moser,
Schatz, 2014; McCrory et al., 2004). Additionally, neurocognitive assessments designed for adults rely on language and reading skills as a basis for assessment and comprehension of the neurocognitive tasks. Children and adolescents do not have a reliable basis for understanding language or reading comprehension. These language based skills have a highly variable rate of maturation that is also based on brain development and learning with age (de Jong & van der Leij, 2002).

To address these limitations, firstly, assessment in children should be compared to a normative profile of development which accounts for typical development with age rather than an individualized baseline score (Schmidt et al., 2012). As with all paediatric assessments, the reliability of using an outcome cut-off score for clinical diagnosis is influenced by the change in the score as a result of normal child development. In order to establish a clinically relevant outcome cut-off score for EDM functioning, there needs to be an understanding of age dependent changes across the entire spectrum of maturation. For example, the diagnosis of delayed or disorder language development with phonetic and phonemic assessment is dependent on the understanding of the range of phonetic and phonemic outcomes that are typical at each stage of development that occur with age over the entire course of maturation (Dodd et al., 2003).

Secondly, the most appropriate way to assess EDM attributes in children and adolescents is using sensorimotor evaluation, as it eliminates the reliance on language and higher order brain functioning that are still in the process of development (Lovell & Fazio, 2008). Language comprehension and reading have a highly variable rate of development in children and adolescents (de Jong & van der Leij, 2002), while sensorimotor skills are sufficiently developed in young children to reliable assess EDM (Casey, Giedd, & Thomas, 2000). Attributes of sensorimotor coordination correlate with specific attributes of neurocognitive function, including
processing time, working memory, and action planning in children and adolescents (Rigoli et al., 2012; Siegel & Ryan, 1989; Pennequin, Sorel, & Fontaine, 2010). For example Rigoli et al. (2012) determined the catching and aiming composite score on the Movement Assessment Battery for Children (MABC-2) (Henderson, Sugden, & Barnett, 2007) correlates with working memory on the Wechsler Intelligence Scale for Children-IV (Wechsler, 2003) in children twelve to sixteen years of age. The use of virtual-reality (VR) assessment allows for the design of sensorimotor tasks that can combine the evaluation of components of interest into one cohesive task that is also engaging for children and adolescents. VR allows for the manipulation of sensorimotor tasks to measure specific variables of coordination and associated EDM components, while providing objective, quantitative, and precise outcome measures (Laufer & Weiss, 2011; Holden, 2005).

The Object Hit task used in this study was developed by Tyryshkin et al. (2013), it is a sensorimotor, VR-based assessment which can assess specific components of EDM known to be vulnerable to injury in paediatric concussions, namely working memory, processing time, and action planning. The Object Hit task is designed at the macro-level as a ‘game’ in which participants are asked to use virtual paddles to ‘hit’ objects distributed throughout a VR workspace. The task is implemented on the KINARM Exoskeleton Robot platform (Scott, 1999). A set of performance parameters are used to assess attributes of EDM, namely processing time, working memory, and planning of bimanual action.

The purpose of the current investigation was to characterize within-subject changes in the Object Hit task performance scores in children and adolescents five to eighteen years of age with repeated assessments at quasi-equal intervals scheduled every six to twelve months. Statistical analysis of the expected age-dependent scores would provide a basis for determining meaningful
cut-off scores for concussion identification in paediatrics, while repeated assessments in individuals would allow for the identification of the contribution of the underlying structure of individual trends to the overall measurement of age-related change in performance.
Chapter 2

Literature Review

2.1 Overview of sport-related concussion in paediatrics

Concussions are the most commonly reported specific injury in contact sports in childhood (Yeates, 2010), with football, soccer, basketball, lacrosse, wrestling, and ice hockey associated with the highest risk for concussion (Marar et al., 2012; Emery & Meeuwise, 2006). Pediatric athletes are at a significantly higher risk for concussive injuries which can occur at lower magnitudes of force application when compared to adults (Halstead & Walter, 2010). Children and adolescents also take longer to recover from concussions when compared to adults, and are at higher risk for lasting symptoms of concussions that can interfere with school, social and family relationships, sport participation and the development of overall child health (Emery & Meeuwise, 2006; Halstead & Walter, 2010). The specific vulnerability of pediatric athletes to concussions primarily results from the lowered threshold of the developing brain to injury (Halstead & Walter, 2010; Reeves et al., 2012).

2.1.1 Developmental vulnerability of the brain

During development, the brain undergoes a series of maturational processes to alter its structural and functional connectivity. The connectivity of the brain is a dynamic process shaped by experience, with repeated correlation between an input and output strengthening a given synaptic connection and leading to the pruning of unnecessary connections (Casey, Giedd, & Thomas, 2000; Casey et al., 2005). As synaptic connections are established with maturation, axons are
myelinated to further increase speed of information transfer, optimizing the communication within the brain (Casey, Giedd, & Thomas, 2000).

It is the ongoing myelination process that increases the vulnerability of child and adolescent athletes to concussive injuries. Myelination continues to occur in the brain into the early twenties which means that some areas of the brain are thinly myelinated or completely unmyelinated through childhood and adolescence (Casey, Giedd, & Thomas, 2000; Casey et al., 2005). The unmyelinated or thinly myelinated white fiber tracts are at high risk for shear injury, which can lower the magnitudes of force necessary to cause injury (Toledo et al., 2012; Segalowitz & Brown, 1991). Shearing of the vulnerable white matter tracts following a concussion leads to the unregulated release of neurotransmitters, which not only disrupts functional connectivity of the brain and the speed and ability to transfer information, but it also disrupts the established myelin and ongoing developmental process (Giza & Hovda, 2001). It is important to consider that the timeline of development of the brain, including levels of myelination, is non-linear, with different lobes of the brain typically developing at different ages and with different rates (Casey, Giedd, & Thomas, 2000; Gogtay et al., 2004). Consequently, the brain areas that have a protracted developmental period are more vulnerable to sport-related concussive injuries, this includes the areas of the brain involved in executive decision making (EDM), namely the parietal cortex and the prefrontal cortex (PFC) (Casey, Giedd, & Thomas, 2000; Casey et al., 2005).

The parietal cortex, situated between the frontal and occipital cortexes, undergoes a slightly prolonged developmental period, lasting up to ten years, from one to ten years of age (Casey et al., 2005; Thompson & Nelson, 2001). The parietal cortex is associated with EDM functions involved in working memory (Baddeley, 2003). It acts as a temporary information storage system that simultaneously processes incoming information and retrieves other required information in
order to plan and guide execution of a sensorimotor task based on prior knowledge and current sensory inputs (Bayliss et al., 2003; Baddeley, 2003; D’Esposito et al., 1995). Due to the prolonged development, the parietal cortex is more vulnerable to concussive injury, and thus issues with working memory are commonly reported following a concussion (Powell, 2001; Toledo et al., 2012).

The PFC has the most prolonged development period, lasting almost two decades as increases in myelination occur well into the early twenties (Casey et al., 2005; Thomspn & Nelson, 2001). The PFC is important for the EDM processes involved in forming a goal, preparing the necessary action, implementing the action, and verifying proper plan execution (Anderson, 2002). The prefrontal cortex can be subdivided into regions, namely the dorsolateral PFC (dIPFC) and the orbitofrontal cortex (OFC), that account for specific EDM functions in relation to the planning, preparation, and production of sensorimotor actions. The dIPFC is associated with control and response inhibition (Rubia et al., 2001; Konishi et al., 1999; Konishi et al., 1998; Kawashima et al., 1996; Casey et al., 1997). It encompasses the ability to selectively attend to specific stimuli in an environment, to inhibit involuntary responses and to focus attention for a prolonged period of time (Anderson, 2002). The OFC is responsible for reward and value based action planning (O’Reilly, 2010; Johnstone, Wahlestedt, & Silva, 2013). It is associated with the ability to take the demands of a given task and the goal of the action into account prior to the initiation any motor response (Johnson-Frey, McCarty, & Keen, 2004). The prolonged myelination and increased vulnerability of the PFC to concussive injuries results in increased risk of injury to the dIPFC impairing attention and control, as well as the OFC impairing action planning (Halstead & Walter, 2011; Grubenhoff et al., 2011). Consequently, impairment in EDM functions is commonly associated with paediatric concussions (Levin & Hanten, 2005; Halstead & Walter, 2010).
2.1.2 Methods for diagnosis of concussion effects in children and adolescents

There is currently no method to visualize axonal sheering damage. Therefore, diagnosis relies on self-report of symptoms that often do not correlate specifically with the extent of disruption in brain function (Powell, 2001; Giza & Hovda, 2001; Broglio & Puetz, 2008). The ability to quantify the impairments in functioning of EDM in terms of working memory, attention, processing time, and action planning following a concussion may provide an objective measure for paediatric concussion diagnosis and management. The issue with establishing a method to assess altered EDM following a paediatric concussion is that brain areas associated with EDM are undergoing the prolonged process of myelination and experience age related gains (Casey, Giedd, & Thomas, 2000). For example, action planning improves between three to six years of age (Craje et al., 2010) and there is significant growth in working memory between seven and thirteen years of age (Siegel & Ryan, 1989). Therefore in order to detect altered EDM following a paediatric sport-related concussion, methods for accurately detecting the age related gains in EDM functioning over the prolonged course of myelination need to be established. Then the normal variability in the EDM with age can be established and can be used to determine abnormalities and impairments that result from injury over the continuum of development (Anderson, 2002).

2.2 Current EDM assessment techniques

2.2.1 Adult assessment

In adults, the assessment of EDM has been introduced as part of a formal concussion management program, the ImPACT. The ImPACT is a tool for the assessment of neurocognitive sequelae of concussion and provides objective data to inform clinical decisions associated with concussion management (Schatz et al., 2006). The ImPACT consists of three main parts,
demographic data, neurocognitive tests, and the Post-Concussion Symptom Scale (PCSS). The demographic data supplies relevant sport, medical and concussion history, while the PCSS is a 21-symptom checklist of self-reported symptoms. The neurocognitive and EDM assessments are completed with a series of six neuropsychological tasks which are each designed to target different aspects of EDM, including attention, working memory, processing speed and reaction time. The six tests involve letter, word, or design memory, symbol or colour match, and counting tasks. The results are combined to generate four composite measures of verbal memory, visual memory, visual motor speed, and reaction time. The ImPACT informs diagnosis by utilizing pre-season baseline ImPACT scores as a reference. A lowering in two or more of the composite scores below their 80% confidence interval when retested following a potentially concussive blow in adults indicates the presence of a concussion (Iverson, Lovell, & Collins, 2003). The ImPACT can positively predict the presence of a clinically diagnosed concussion with 90% accuracy (Schatz et al., 2006). However, the ImPACT was designed for adults with the assumption that baseline neurocognitive function does not change over the course of a season. This assumption is not valid for children and adolescents for whom working memory, action planning, and processing time is expected to improve in continuous fashion as a function of brain development and learning (Register-Mihalik et al., 2012; Barlow et al., 2011; Newman et al., 2013; Lichtenstein, Moser, & Schatz, 2014; McCrory et al., 2004). Additionally performance on the ImPACT is dependent on working memory, reading ability and language comprehension (Lichtenstein, Moser, & Schatz, 2014; McCrory et al., 2004) which also have highly variable rates of development in children and adolescents which compounds the issue of using a baseline reference obtained pre-season (de Jong & van der Leij, 2002). It is important to note that when evaluating EDM for the purposes of clinically assessing paediatric concussions, the EDM task must be able to be administered and successfully completed by children and adolescents.
2.2.2 Paediatric assessment

EDM in children and adolescents can be reliably measured with sensorimotor function (Davis, Pitchford, & Limback, 2011; Casey, Giedd, & Thomas, 2000). Certain aspects of motor coordination are associated with specific attributes of EDM (Rigoli et al., 2012; Siegel & Ryan, 1989; Pennequin, Sorel, & Fontaine, 2010; Jenni et al., 2013). One example is a study by Rigoli et al. which used a variety of testing procedures to evaluate whether motor co-ordination was associated with working memory, inhibition and overall cognitive performance in 93 adolescents, 12 to 16 years old. Various components of the Movement Assessment Battery (MABC-2) (Henderson, Sugden, & Barnett, 2007), including total movement assessment, and catching and aiming, could account for significant variance in verbal working memory ($r^2 = 0.122$, $p \leq 0.001$), and visuospatial working memory ($r^2 = 0.048$, $p = 0.0.91$) scores (2012). The literature supports that a motor-performance based approach to EDM assessment following a concussion is possible. Motor co-ordination is established to be associated with components of EDM that are commonly affected by a concussive impact; namely working memory, processing time, and overall performance.

Of the available EDM methodologies in the research, only a few studies demonstrate an association between sensorimotor coordination and cognitive functioning in typically developing children from five to eighteen years of age (Michel, 2012). The majority of studies used participant groups with narrow age ranges and specific age appropriate tasks (Chall, 1979; Rigoli et al., 2012; Siegel & Ryan, 1989; Pennequin, Sorel, & Fontaine, 2010), while the studies that have participant groups with large age ranges typically have issues with saturation and floor and ceiling effects in their task scores (Akshoomoff et al., 2014). One example is the National Institutes of Health (NIH) toolbox cognition battery, which is a computerized approach to testing cognition, sensation, and motor performance. Over 1000 participants aged 3 to 20 years were
assessed using the NIH toolbox; however, the testing protocol had a floor effect, with scores saturating, limiting the utility on children under the age of 7 and a ceiling effects due to saturation of scores on various components of the testing protocol (Akshoomoff et al., 2014). This is problematic for a concussion management tool as it needs to establish an understanding of the changes in EDM with respect to age; testing parameters and participant groups need to include the entire age range over which developmental changes occur (Willoughby, Wirth and Blair, 2012; Rigoli et al., 2012). The Object Hit task implemented on the KINARM may provide a method to objectively measure EDM attributes from childhood to adolescence without floor or ceiling effects (Scott and Dukelow, 2011).

### 2.3 Object Hit task

The Object Hit task, completed in a KINARM exoskeleton robot (KINARM), is a computerized virtual reality (VR) assessment tool (Scott, 1999). VR provides an interface that can control and monitor both the sensory inputs as well as motor outputs of a task (Scott and Dukelow, 2011; Laufer & Weiss, 2011). With VR assessment, the sensory input and task content can be manipulated to assess specific components of sensory-motor function and EDM affected by a concussion (Debert et al., 2012). VR provides a safe and reproducible means for research purposes while also being an engaging experience for participants as it can be fun and challenging video game like experience (Holden, 2005). This is particularly important for pediatric populations, as children are less compliant with standard, repetitive measures that aren’t engaging (Laufer & Weiss, 2001).
2.3.1 Object Hit task procedure

The Object Hit task involves participants using upper limb coordination to move virtual paddles to hit as many as possible of the virtual objects that appear to fall from the top to the bottom of the VR workspace or screen in front of them. The task becomes increasingly more difficult as the rate and speed at which objects fall increase. In order to successfully complete the task the participant must use sensory motor function as well as EDM. The task requires participants to evaluate the incoming sensory information regarding the location of the falling objects, the speed they are falling at, and the location of the paddles on the screen, and to plan and produce motor outputs to optimally hit as many of the moving objects as possible with the paddles.

The Object Hit task provides quantifiable measures of sensory motor function and importantly EDM attributes. The Object Hit task results can be quantified with ten attributes of performance; targets hit, median error, hand selection overlap, hand speed, hand movement area, hand speed bias, hand movement area bias, miss bias, hand transition, and hand bias hits. Five of which were selected to correspond with the developing components of EDM that are commonly affected by a pediatric concussion summarized in Table 1. The five performance attributes not included assess inter-limb differences, and are used when the performance of one limb is impaired (ie. stroke). The five calculated attributes of performance that were assessed include dominant hand movement area, median error, hand selection overlap, mean hand speed and targets hit. The corresponding components of EDM functioning include working memory, processing time, action planning, reaction time, and the integration of all these EDM attributes. Studying the components of EDM individually could allow for the inference of an injury to a specific brain area.
### Table 1: EDM Component Summary

<table>
<thead>
<tr>
<th>EDM Components</th>
<th>Description</th>
<th>Associated Brain Areas</th>
<th>Development</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Working Memory</strong></td>
<td>Temporary storage system that simultaneously processes incoming information while retrieving other information required for the task</td>
<td>PFC, Parietal cortex</td>
<td>Improvement in function occurs linearly from 4 to 15 years of age, hypothesized to occur due to myelination and synaptic pruning processes (^\text{a})</td>
</tr>
<tr>
<td><strong>Action Planning and Inter-limb Coordination</strong></td>
<td>Ability to take into account the demands of the task and the goal of the required action prior to the initiation of said action</td>
<td>OFC, Parietal Cortex</td>
<td>Significant improvements in action planning occur with age and development from 4 to 10 years of age (^\text{b}) Linear improvements in inter-limb coordination are reported between 9 and 24(^{\text{c,d}})</td>
</tr>
<tr>
<td><strong>Processing Time/Reaction Time</strong></td>
<td>The speed and efficiency of the brain in processing incoming information to form and generate an output</td>
<td>PFC, White matter microstructure</td>
<td>Increases in myelination with age improves the speed of information transfer in associated brain areas (^{\text{e,f}})</td>
</tr>
</tbody>
</table>

**Legend:** \(^\text{a}\)Klingberg, Forssberg, & Westerberg, 2002 \(^\text{b}\)Craje et al., 2010 \(^\text{c}\)Luna et al., 2001 \(^\text{d}\)Marion et al., 2003 \(^\text{e}\)Andersen & Cui, 2009 \(^\text{f}\)Lo & Wang, 2006

#### 2.3.2 Working memory and hand movement area

Working memory provides an interface between perception, long term memory and action during a sensory motor task (Baddeley, 2003; Baddeley, 2012). It acts as a temporary information storage system that simultaneously processes incoming information while retrieving other
required information for task completion (Bayliss et al., 2003). Working memory is correlated with activation in the PFC and parietal regions (D’Esposito et al., 1995). In the Object Hit task, working memory is quantified by the hand movement area. The movement area of the hand quantifies the distribution of locations where object hits were made. In order to make a hit the brain must maintain an accurate representation of the VR workspace in its working memory. Limited working memory would result in a constrained area where virtual object hits would be concentrated.

Working memory improves significantly between the ages of 7 and 13 years. Siegel & Ryan (1989) evaluated the performance of seventy four typically developing children 7 to 13 on working memory tasks. They used a sentence-based working memory task where children were presented a sentence with a missing final word. The children supplied the missing word and had to repeat all the missing words in a set of between two to five words. They also used a counting-based working memory task involving counting yellow dots in a field of blue and yellow dots of varying sizes. The children were instructed to count the number of yellow dots in field and then recall the number of dots in all the fields given (Siegel & Ryan, 1989). Significant improvements in working memory were found to be associated with age in children typically developing as well as those with learning disabilities ( F(1, 114) = 27.09,  p ≤ 0.0001) (Siegel & Ryan, 1989). These findings indicate that improvements in the hand movement area occur with age as the areas in the PFC and parietal regions undergo myelination.

2.3.3 Processing time and median error

Information processing or processing time refers to the speed and efficiency of the brain in processing incoming information to form and generate an output (Anderson, 2002). Through
increases in myelination, processing time improves as the connections between regions of the PFC and parietal regions are strengthened (Anderson, 2002; Kail, 1993). Median error or the measure of how far into the task a participant can get before they make 50% of their misses quantifies processing time. Increased median error results indicate that a participant was able to successfully complete the task when it occurred at a faster rate and speed. In order to perform well at the faster pace of the task, participants would have to process the incoming sensory information, plan actions, and produce action outputs at a faster rate. This would require functional and established connections between the EDM network and a shorter processing time.

Processing time was observed to decrease in children and adolescents from 7 to 14 years of age using four different timed tasks requiring visual search, number comparison, distracted choice, and coding tasks (Kail & Park, 1994). Mean response times were used to quantify processing time. Processing time was found to decrease in correlation with age in a study with 216 participants 7 to 14 years of age (R² = -0.77, p ≤ 0.01) (Kail & Park, 1994). These results occur regardless of task (numerical, language or motor based), as the results are associated with the rate of information transfer within the brain rather than task specific skill. These results are in agreement with those of Hale (1990), who found that response time decreased linearly with age in 64 participants 10 to 19 years old (F(3,60) = 40.07). These findings indicate that the median error for the Object Hit task should improve with age, as the rate of information transfer improves.

2.3.4 Action planning and hand selection overlap

Action planning is the ability to take the demands of a given task and the goal of the action into account prior to initiation of motion (Johnson-Frey, McCarty, & Keen, 2004). Action planning is a complex task that requires insight into the features of a desired goal, knowledge of a coherent
method to achieve said actions, and the physical ability to complete the task. Hand selection overlap results on the Object Hit task quantify a participant’s ability to plan their actions. Hand selection overlap captures how successful a participant is at using both hands and how often they overlap their hands in the VR workspace. This provides an indication of action planning as effective use of inter-limb coordination requires pre-processing and consideration of object location, and arm locations relative to the midline.

Craje et al. (2010) evaluated action planning by analyzing end position comfort during simple tasks as adults typically plan actions in advance of their performance and tend to prefer a comfortable end position. Twenty-four typically developing children in their study had significant gains in action planning with age from 3 to 6 years old. Bimanual coordination also improves with age. Marion et al. (2003) assessed bimanual coordination with computerized assessments in 67 normally developing children 6 to 15 years of age. Age was significantly associated with accuracy of performance on the task \( r = -0.46, p < 0.001 \). These results indicate that improvements in action planning and bimanual coordination occur with age, and, as such, that improvements in hand selection overlap should occur with age.

### 2.3.5 EDM and targets hit

Overall performance on the task is quantified by the percentage of targets hit, and it provides an indication of the overall performance of all EDM attributes. Successful overall performance on the task is dependent on the combined functioning of working memory, action planning, and processing time. The participant must be able to use working memory to remember the location of virtual objects and their limbs, efficient information processing, and effective action planning
to hit as many targets as possible. Improvements in all of the attributes of EDM are reported to occur with age, and would predict that percentage of targets hit should increase with age.
Chapter 3

Methods

3.1 Statement of ethics

This study was reviewed for ethical compliance by the Queen’s University Health Sciences and Affiliated Teaching Hospitals Research Ethics Board and granted clearance according to the recommended principles of Canadian ethic guidelines and Queen’s University policies (Appendix A). Signed informed consent was obtained from participants 14 years and older (Appendix B). For participants under the age of 14 years, parental consent and child assent were obtained.

3.2 Recruitment strategy

This study is part of a larger population-based study on the development of upper limb sensorimotor coordination in children and adolescents, five to eighteen years old. In this larger study, two hundred children and adolescents were recruited over a five year period. Participants were screened, using a parent-report health questionnaire (Appendix C), to exclude a history of developmental delay or disability, learning disability, attention deficit hyperactivity disorder, attention deficit disorder, depression or other psychiatric disorder, as well as injury to the head, neck and upper limb, including concussion, and other health condition affecting the structure and function of the upper limb. Handedness was assessed using the Modified Edinburgh Handedness Inventory (Oldfield, 1971).
Of this larger study group, forty-nine families consented to be contacted for repeated assessment at 6-month intervals. The goal of these repeated assessments was to provide longitudinal data on the development of upper limb sensorimotor coordination to supplement our cross-section developmental data. Of these forty-nine families, twenty participants completed three to five repeated assessments over the timeline of this thesis. The data of this subgroup of twenty participants formed the content of the study presented in this thesis. The time points of assessment for these twenty participants are listed in Table 2.

Table 2: Assessment Schedule Summary

<table>
<thead>
<tr>
<th>Participant Code</th>
<th>Age at 1st Assessment (years)</th>
<th>Time from First Assessment (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2nd Assessment</td>
</tr>
<tr>
<td>492</td>
<td>7.18</td>
<td>0.58</td>
</tr>
<tr>
<td>574</td>
<td>7.07</td>
<td>0.07</td>
</tr>
<tr>
<td>600</td>
<td>5.85</td>
<td>1.22</td>
</tr>
<tr>
<td>614</td>
<td>13.37</td>
<td>1.03</td>
</tr>
<tr>
<td>615</td>
<td>9.37</td>
<td>1.03</td>
</tr>
<tr>
<td>620</td>
<td>6.98</td>
<td>0.97</td>
</tr>
<tr>
<td>630</td>
<td>5.71</td>
<td>1.03</td>
</tr>
<tr>
<td>670</td>
<td>12.13</td>
<td>0.86</td>
</tr>
<tr>
<td>731</td>
<td>11.96</td>
<td>0.53</td>
</tr>
<tr>
<td>732</td>
<td>6.93</td>
<td>0.18</td>
</tr>
<tr>
<td>745</td>
<td>7.04</td>
<td>0.78</td>
</tr>
<tr>
<td>775</td>
<td>10.18</td>
<td>0.67</td>
</tr>
<tr>
<td>805</td>
<td>5.10</td>
<td>0.07</td>
</tr>
<tr>
<td>835</td>
<td>5.54</td>
<td>0.52</td>
</tr>
<tr>
<td>836</td>
<td>9.10</td>
<td>0.52</td>
</tr>
<tr>
<td>837</td>
<td>6.57</td>
<td>0.52</td>
</tr>
<tr>
<td>841</td>
<td>7.83</td>
<td>0.02</td>
</tr>
<tr>
<td>842</td>
<td>12.68</td>
<td>0.42</td>
</tr>
<tr>
<td>843</td>
<td>11.58</td>
<td>0.02</td>
</tr>
<tr>
<td>849</td>
<td>14.75</td>
<td>0.04</td>
</tr>
</tbody>
</table>
3.3 VR assessment of selected components of EDM

Working memory, processing time, and action planning were assessed using the *Object Hit* task developed by Tyryshkin et al., (2014). The *Object Hit* task consisted of virtual objects (e.g., red balls with a diameter of 2 cm) which dropped from top-to-bottom of a virtual reality (VR) workspace in the horizontal plane of motion of the upper limbs. Participants used virtual paddles to ‘hit’ as many objects as possible before the objects crossed a virtual barrier at the bottom of the workspace. The task was performed in the absence of direct vision of the upper limbs, such that information on hand motion was based on proprioceptive inputs of the upper limb and visual feedback on the location of the virtual paddles.

The task was performed in the KINARM Exoskeleton robot (Scott, 1999; Figure 1). The KINARM is a bilateral robot which uses exoskeletons attached to mechanical linkages to provide gravitational support to the upper limb in the horizontal plane. Two torque motors, fitted with encoders and a series of torque sensors, apply loads via the mechanical linkage directly to the shoulder and elbow joints, either independently or in combination, and continuously monitor the positions and motions of the shoulder and elbow joints (1 KHz sampling frequency). In the *Object Hit* task, the torque motors were used to provide ‘realistic’ sensory feedback information of contact between the virtual paddle and the object. This force-feedback of contact is combined with visual information of hand and target locations to monitor performance in real life situations. The end-point position and motion of the hands were calculated from the encoded data at the shoulder and elbow and known segmental lengths. A calibration routine was used to adjust the size of the virtual workspace to the length of the upper limbs for each participant. The calibration routine was also used to locate the virtual paddles, which participants used to hit virtual objects in the *Object Hit* task, over the distal point of the index finger.
Figure 1: KINARM Exoskeleton Robot

(A) Overall side view of the exoskeleton robot on the right and the virtual reality display on the left (B) Virtual reality display with bib marked with a blue arrow attached at bottom, the circular opening is placed around the head of the participant to ensure vision of their arms is occluded (C) Exoskeleton robot where participant is seated, the upper arm, forearm and hand troughs for the left arm are marked with red arrows

The path of the virtual objects was constrained to ten vertical bins, which were evenly distributed across the VR workspace. These vertical bins were invisible to participants. For each trial, the virtual objects were released along each of the ten vertical bins, with the order of presentation of the bins randomized across trials. Once an object was released in each of the ten bins, a new trial
was triggered in continuous fashion, such that the task was uninterrupted for the participant. For each assessment, thirty trials were completed, with a total exposure to 300 virtual objects, thirty in each of the ten bins (Figure 2). To be counted as a successful ‘hit’, the participant had to contact the virtual object with the paddle in a direction that pushed the virtual object either out through the top of the VR workspace or its sides.

The difficulty of the task was manipulated by increasing both the number of virtual objects released into the VR workspace and the speed at which the virtual objects drop from the top to the bottom of the VR workspace. The number of virtual objects released into the workspace per second was determined by the following equation (Tyryshkin et al., 2014):

\[
0.5 + 0.025 \times \text{Time (s)}
\]

(1)

Accordingly, at the start of the task, one object fell per second, with the order of presentation across the vertical bins randomized. Forty seconds into the trial, two virtual objects were released into the VR workspace in the given second \((0.5 + 0.025 \times 40\text{s} = 1.5 \text{ objects, rounded to 2})\). In the same way, at 80 seconds, three virtual objects were released into the VR workspace per second. Overall, the rate of release of the virtual objects over the length of the task increased from one object per second to a maximum of ten objects per second.

The maximum speed of motion of virtual objects within the task ranged from 15 cm/s to 50 cm/s. The speed of any one object was randomly selected from 50% to 100% of the time set maximum. The increase in the time set maximum speed of motion of virtual objects was determined by the following equation (Tyryshkin et al., 2014):

\[
15 + 0.3 \times \text{Time (s)}
\]

(2)

As an example, an object falling at the tenth second of the task can have any speed of motion randomly selected between 9 cm/s and 18 cm/s \((15 + 0.3\times10\text{s} = 18 \text{ cm/s})\).
Figure 2: Schematic Representation of Object Hit Task

Red circular objects fall from the top of the virtual reality workspace to the bottom as the participant moves their arms in the horizontal plane in order to hit the objects with their green paddles.

3.4 Experimental procedure

All testing was completed in the Child Assessment Laboratory at Hotel Dieu Hospital. Since all participants had previously completed the Object Hit task within the context of the larger study on the development of upper limb sensorimotor coordination, participants were reminded of the purpose of the study and the requirements of the task. The health information questionnaire was reviewed with parents to ensure absence of any new health conditions. Consent, or assent in combination with parental consent, was obtained as appropriate. The Modified Edinburgh Handedness Inventory was administered at each assessment. Participants’ height (cm) and weight (kg) were measured and recorded.
Participants were positioned in the robot. Participants sat in the modified wheelchair base of the robot, with their upper arms, forearms and hands resting in the exoskeleton supports. The exoskeleton components were attached to hinged mechanical linkages which provided gravitational support to the limb in the horizontal plane. The height of the seat was adjusted so that the arms were in the same horizontal plane as the shoulders. The location of the encoders and torque motors, attached to the mechanical linkages, was aligned to the approximate center of rotation of the shoulders, over the distal portion of the acromion. The length of the mechanical linkages was adjusted to align the rotational axes of these linkages with the approximate joint centers of the shoulder and elbow. With adjustments completed, participants were instructed to move their arms through the full range of motion to ensure a comfortable fit in the robot.

The robot seat was advanced to place the participant within the VR environment of the robot (see Figure 1A). To ensure that participants did not have direct vision of their upper limbs during task performance, an opaque bib was used; the bib is attached to VR display and stretched over the participants’ upper limbs and secured around his/her neck. The calibration routine was performed to adjust the position and size of the VR display to participant-specific dimensions of the upper limbs. The calibration adjusted the position of the virtual paddles over the tip of participants’ index finger for both hands, and placed the center of the VR display approximately at the midpoint of the upper limbs’ workspace, defined by the position of the tip of the index finger at the center of the VR display when the shoulder is in 30° of flexion and the elbow in 90° of flexion. Therefore, the position of the virtual objects used in the task within the active workspace of the upper limbs was standardized across participants and assessment sessions.

The Object Hit task was loaded and participants were provided with opportunity to sufficiently practice the task prior to the assessment, with feedback and instructions provided as needed to
confirm good understanding of the task requirements. Participants completed the full task at each assessment session, with a total of 300 virtual objects presented within an approximately two minute time span; at the sixty second and eighty-five second marks of the task, positive encouragement (e.g., ‘you are doing great’; ‘keep up the good work’; ‘almost done keep going’) was given to participants to maintain motivation to complete the task. After task completion, participants were removed from the robot and provided with refreshments and treats to thank them for their time and contribution to the research.

3.5 Measured attributes

Performance on the Object Hit task was quantified by a set of five attributes which address overall success, bilateral coordination, and spatial organization and is summarized in Table 3 (Tyryshkin et al., 2014). Overall success was quantified by two general measures of performance, the number of targets hit or number of misses, and the median error, defined as the point in the task at which participants fail to ‘hit’ 50% of the virtual objects. Bilateral coordination and spatial organization were quantified by measures of the motion of the upper limbs in the area of the VR workspace; the hand movement area or the area of the workspace ‘visited’ by the hands, the mean hand speed within this area, and the hand selection overlap which reflects the capacity to ‘select’ the most appropriate hand to hit virtual objects within the VR workspace regardless of midline. Each of these five attributes were selected for the longitudinal study to assess a distinctive component of EDM; working memory of object locations, improved processing time, effective action planning, reaction time and the integration of the EDM components.
<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>Measurement Description</th>
<th>Associated EDM Attributes</th>
<th>Hypothesized Relationship</th>
<th>Relationship Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hand Speed</strong> (cm/s)</td>
<td>Average hand speed of the dominant hand as it moves to hit the virtual objects</td>
<td>Reaction Time</td>
<td>↑ Hand Speed</td>
<td>Improvements in reaction time and motor skills will increase the speed at which the hand can move to hit objects</td>
</tr>
<tr>
<td><strong>Hand Movement Area</strong> (cm²)</td>
<td>Total space used by the dominant hand to hit virtual objects within the workspace</td>
<td>Working Memory</td>
<td>↑ Hand Movement Area</td>
<td>Increased ability to remember the location of objects will increase the area of the virtual workspace used to hit objects increasing the movement area</td>
</tr>
<tr>
<td><strong>Hand Selection Overlap</strong> (% of total hits)</td>
<td>Number of hits made by overlapping hands or interchanging the hand used</td>
<td>Action Planning</td>
<td>↑ Hand Selection Overlap</td>
<td>Increased ability to effectively plan and coordinate arms regardless of midline will increase the number of hits made by alternating hands</td>
</tr>
<tr>
<td><strong>Median Error</strong> (% of task)</td>
<td>Point in the task where half of the misses were made</td>
<td>Processing Time Overall Performance</td>
<td>↑ Median Error</td>
<td>Increased ability to process information quickly will increase the ability to perform the task at increases speed as it progresses, increasing the point in the task where half the errors were made</td>
</tr>
<tr>
<td><strong>Target Hits</strong> (% of total hits)</td>
<td>Number of virtual objects successfully hit</td>
<td>Overall Performance, combination of all EDM components</td>
<td>↑ Targets Hit</td>
<td>Improvements in function of all the EDM attributes lead to increased ability to perform the task successfully</td>
</tr>
</tbody>
</table>
3.5.1 Targets hit

The attribute of ‘target hits’ is calculated as the number of virtual objects that were successfully hit over the entire duration of the task and is expressed as a percentage of the total number of virtual objects (i.e., 300). This percentage provides a proxy measure of overall performance success. Theoretically, this percentage can vary from 0% (i.e., no objects are hit) to 100% (i.e., all objects are hit). Research in healthy adults indicates an upper limit of performance at around 94% (Tyryshkin et al., 2014); a limit for children and adolescents has not yet been determined. Targets hit is a measure of the integration of each of the EDM attributes the task requires to work concurrently; working memory of object locations, improved processing time as the speed of the task increases, and effective action planning as the rate of objects falling increases throughout the task.

3.5.2 Median error

Median error quantifies the point over the entire duration of the task where 50% of the failures to hit were made by the participant relative to the total virtual objects that fell. Median error can be expressed as a function of the level of difficulty of the task that a participant was to successfully complete. For example, if a given participant missed 10 virtual objects ending with the 150th virtual object in the first half of the task and 10 virtual objects in the last 150, they would have a median error of 50%, and were equally able to complete the task when it was easy at the beginning and when it was difficult and fast moving at the end of the task. From a neurocognitive perspective, median error can be a proxy measure of processing time, as larger values indicate that a participant was better able to input sensory information, integrate the task goals and learned experiences, and produce an accurate motion to a virtual object as the task became more difficult, with increased rate and speed at which virtual objects fall. High median error scores indicate that
the participant could input sensory information and output planned actions accurately at a faster rate, and could perform accurately with decreased processing time.

### 3.5.3 Mean hand speed

Mean hand speed (cm/s) was quantified by calculating the average speed of the hand over 500 ms epochs over the duration of the task and calculating a grand mean for the entire trial. From a neurocognitive perspective, mean hand speed provides a proxy measure of reaction time, that is the speed at which a participant can localize a target, integrate the sensory visual and limb proprioceptive information to plan the motor response and move his/her hand to hit a virtual object. The dominant hand values for each participant were used in this analysis, as dominant hand reaction times are marginally faster, while both dominant and non-dominant reaction time values correlate equally well with cognition and intelligence tests (Gignac & Vernon, 2004).

### 3.5.4 Hand movement area

The movement area (cm$^2$) measures the area of the VR workspace through which the hand travels during the task. Movement area is calculated as the area of the convex polygon defined by the boundaries of the trajectory of each hand (Figure 3). From a perspective of neurocognitive function, movement area provide a proxy measure of the area of the VR workspace a participant can maintain in his/her working memory. A participant that is better able to retain information regarding the properties of the VR workspace will attempt hits over the entire workspace area and thus, have a greater probability of hitting objects.
3.5.5 Hand selection overlap

Inter-limb coordination and the ability to transfer information between hemispheres were quantified by hand selection overlap. *Hand selection overlap (%)* captures how successful a participant was at using both hands and how often they overlapped their hands. The value is computed by calculating the number of times that two successive objects hit in a given bin use different hands divided by the total number of hits. Hand selection overlap is an indication of action planning, as effective use of inter-limb coordination requires pre-processing and consideration of object location, and arm locations relative to the midline. Hand selection overlap is depicted in Figure 4, where the location, arm used and relative time point of each object hit is displayed.
Figure 4: Depiction of Object Hit Task Results

A depiction of the target hit results of when and where each hit and miss was made throughout the task. The use of the right hand to successfully hit an object is indicated in red, while blue indicates a successful left hand hit and white indicates a miss. Hand selection overlap occurs when there is alternating right and left (red and blue) hit in the same bin.

3.6 Statistical analysis

The distribution of values for calculated scale (target hit, median error, hand selection overlap) and continuous (hand speed, movement area) variables was assessed for normality using the Shapiro-Wilks Test ($P \leq 0.05$). The relationship between change in score for each of the five measured attributes over time was evaluated by linear regression analysis. The assessed components of EDM have a linear trend of development so linear regression models were constructed for each of the calculated attributes. The slope of the linear regression line tested the significance of change as a function of age; the level of significance was adjusted using a Bonferroni Correction for repeated measures so $P \leq 0.01$ was considered significant instead of $P \leq 0.05$. The 95% confidence intervals for the linear regression line were constructed for each linear regression model. Individual trend lines were constructed for each participant’s repeated assessments to allow for the identification of the contribution of the underlying structure of individual trends to the overall measurement of age-related change in
performance. All analyses were performed using the Statistical Package for the Social Sciences (SPSS, IBM Corp., Chicago, IL).
Chapter 4

Results

4.1 Description of the study group

Forty-nine individuals were enrolled in the longitudinal arm of the study, however only twenty participants had completed the task three or more times over the past five years. Fallout was primarily due to an inability to attend at each of the collection time points; however lack of interest, relocation, and increase in age played a role in limiting the data size. Performance on the Object Hit task was assessed at three or more time points over four years for twenty participants, 14 males and 19 right-handed. In total, 76 data points were recorded for our study group, with seven participants having three data points, ten having four data points, and three having five data points (See Table 2). The age distribution of the participants when they were initially recruited was between 5.1 to 14.8 years of age with a mean age of 8.8 years. The data collect provides information on age related changes from the youngest participant at 5.1 years of age at initial recruitment to the eldest participant at 17.8 years of age at latest assessment.

4.2 Assessment of normality

The results for the tests of normality of the distribution for each of the five calculated performance attributes are listed in Table 4. The distribution of targets hit, hand selection overlap and mean hand speed calculated measures were not statistically significantly different from a normal distribution. The median error and hand movement area results distributions were statistically significantly different from normal. It is important to note that the assumption of
normality requirement for simple linear regression analysis can be violated with minimal problems as long as data are not markedly skewed (Seltman, 2014).

**Table 4: Assessment of Normality of Distribution for Calculated Performance Attributes**

<table>
<thead>
<tr>
<th>Calculated Performance Attributes</th>
<th>Shapiro-Wilks Statistic</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Targets Hit</td>
<td>0.975</td>
<td>0.144</td>
</tr>
<tr>
<td>Median Error</td>
<td>0.966</td>
<td>0.040</td>
</tr>
<tr>
<td>Hand Selection Overlap</td>
<td>0.979</td>
<td>0.242</td>
</tr>
<tr>
<td>Mean Hand Speed</td>
<td>0.980</td>
<td>0.290</td>
</tr>
<tr>
<td>Hand Movement Area</td>
<td>0.965</td>
<td>0.034</td>
</tr>
</tbody>
</table>

**Legend:** The Shapiro-Wilks statistic and statistical significance for each of the five *Object Hit* task attributes

### 4.3 Linear regression models of calculated performance attributes

The linear regression models for the three scale variables (targets hit, median error, hand selection overlap) and the two continuous variables (mean hand speed, hand movement area) are shown in Figures 5 and Figure 6, respectively. The fit parameters for each of the five linear regression models are reported in Table 5. The summary of all the performance attributes scores for each participant is reported in Appendix D. The linear trend lines of change in score on the variables of target hit, median error, mean hand speed, and hand movement area over time of the study are shown for each of the twenty individuals in Appendix E (FigureA1 and Figure A2).
Figure 5: Linear Regression Analysis for Targets Hit (Panel A), Median Error (Panel B), and Hand Movement Area (Panel C) versus Age

The solid line represents the regression line, the dotted lines mark the lower and upper boundaries of the 95% confidence intervals, and each participant is represented by a different symbol. (A) Age accounted for 84% of the change in targets hits ($R^2 = 0.838, p < 0.001$) (B) Age accounted for 72% of the change in median error ($R^2 = 0.715, p < 0.001$) (C) Age accounted for 27% of the change in hand movement area ($R^2 = 0.269, p < 0.001$).
Figure 6: Linear Regression Analysis for Mean Hand Speed (Panel A) and Hand Selection Overlap (Panel B) versus Age

Each participant is represented with a different symbol. The solid line represents the regression line, and the dotted lines mark the lower and upper boundaries of the 95% confidence intervals. (A) 7% of the change in mean hand speed was accounted for by age ($R^2 = 0.067$, $p = 0.024$) (B) 8% of the change in hand selection overlap can be accounted for by age ($R^2 = 0.084$, $p = 0.011$).

The measures of overall performance, targets hit and median error, were significantly associated with age ($p < 0.001$). Eighty-four to 72% of the change in the variability in targets hit and median
error score were accounted for by age. Hand movement area, mean hand speed, and hand selection overlap scores were not significantly associated with age. Only 27% of the change in hand movement area was accounted for by age ($R^2 = 0.269, p < 0.001$). Although the results are statistically significant ($p < 0.001$), there is an inadequate proportion of change accounted for by age. The slope of the regression line was not significant for mean hand speed and hand selection overlap, and less than 10% of the change in both of these measures was accounted for by age.

The lack of fit in the mean hand speed and hand movement area results with respect to age is exemplified by the large variability in the individual trend lines (Figure A1 and A2). The individualized trend lines for each of the participants hand selection overlap results are shown in Figure 7. Visually there appears to be a change in the individualized trend lines that occurs around 12 years of age that may have contributed to the poor model fit parameters. The trend lines of individuals, children, younger than 12 years of age are variable and have slopes that range between -3.5 and 11.2, while the trend lines of individuals, adolescents, 12 years of age and older than 12 years of age demonstrated less varied slope values ranging from -0.39 to -1.6. The average change in hand selection overlap for participants under 12 years of age was 0.06, while adolescents 12 years of age and older had an average change in hand selection overlap of -2.9. Statistical analysis found that the two means were not significantly different ($p = 0.08$). Individualized hand selection overlap trend lines had a qualitative change at approximately 12 years of age indicating that the relationship may not be linear; however statistical evaluation of the relationship would require a greater number of participants.
Figure 7: Individual Hand Selection Overlap Trend Lines

The results of each individual participant are marked with a different symbol. The solid lines represent the trend line for each individual’s improvements with age, and the dotted lines mark the lower and upper boundaries of the 95% confidence intervals.

4.4 Summary of results

The regression line parameters, 95% confidence boundaries and the statistical significance for the five Object Hit task attributes are summarized in Table 5. The linear regression model was significant for overall performance on the task in the targets hit and median error calculated attributes, with age accounting for 84% and 72% of the variance in the data respectively. The large amount of variability accounted for by age in these two attributes allows for narrow confidence intervals. Narrow confidence intervals are important for the sensitivity of detecting differences following a concussion, as narrower confidence intervals have smaller minimal detectable difference needed for identification of meaningful change. Alternatively the linear regression model was not significant for hand selection overlap and hand speed objective measures. Respectively only 8% and 7% of the variance in the data was accounted for by age.
Hand movement area measures were found to be significant however the change in movement area that was accounted for by age was low, with an R-squared value of 0.269.

Table 5: Summary of Results

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Slope</th>
<th>Intercept</th>
<th>Slope 95% C.I. Lower Bound</th>
<th>Slope 95% C.I. Upper Bound</th>
<th>Intercept 95% C.I. Lower Bound</th>
<th>Intercept 95% C.I. Upper Bound</th>
<th>R Square</th>
<th>Sig. F Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Targets Hit</td>
<td>4.757</td>
<td>10.622</td>
<td>4.274</td>
<td>5.241</td>
<td>5.547</td>
<td>15.698</td>
<td>0.838</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Median Error</td>
<td>1.880</td>
<td>45.555</td>
<td>1.605</td>
<td>2.155</td>
<td>42.671</td>
<td>48.439</td>
<td>0.715</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Hand Movement Area</td>
<td>49.474</td>
<td>642.184</td>
<td>30.601</td>
<td>68.348</td>
<td>444.169</td>
<td>840.199</td>
<td>0.269</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Dominant Hand Speed</td>
<td>0.473</td>
<td>20.480</td>
<td>0.064</td>
<td>0.881</td>
<td>16.190</td>
<td>24.770</td>
<td>0.067</td>
<td>0.024</td>
</tr>
<tr>
<td>Hand Selection Overlap</td>
<td>-0.416</td>
<td>16.686</td>
<td>-0.733</td>
<td>-0.098</td>
<td>13.354</td>
<td>20.019</td>
<td>0.084</td>
<td>0.011</td>
</tr>
</tbody>
</table>

Legend: Regression line parameters, 95% confidence boundaries and the statistical significance for the five Object Hit task attributes
Chapter 5

Discussion

5.1 Object Hit task attributes results

It was hypothesized that the measured attributes of the Object Hit task would be significantly modified by age. This hypothesis was based on documented evidence of age related changes in components of EDM, namely processing time, working memory, and action planning. Concurrent with the literature and the hypothesis, the attributes that measured overall performance on the task were significantly modified by age: age accounted for 84% of the change in targets hit and 72% of the change in median error. The overall performance on the Object Hit task required participants to engage and utilize gross motor coordination, working memory, action planning and processing time in order to complete the task. In the literature, each of these EDM attributes have been documented to change as a result of increasing age and would together contribute to the Object Hit task’s ability to detect improvements with age from five to eighteen years.

Age, however, was not a significant predictor of the Object Hit task performance on the attributes of hand movement area, hand speed, and hand selection overlap, that are associated with specific EDM components of working memory, reaction/processing time, and action planning, respectively.

Hand movement area calculated measures were hypothesized to detect change in working memory with age. Yet age could only account for 27% of the variability in dominant hand movement area. Marked improvements in working memory were reported in typically developing children between seven to thirteen years of age (Siegel & Ryan, 1989). The unresponsiveness of the Object Hit task to detect these documented changes may result from the differences in the
study methodology, (cross-sectional vs. longitudinal) or the task design (multiple tasks used solely to assess working memory vs. a single task to assess EDM and its components). The study by Siegel & Ryan (1989) was cross sectional and determined working memory differences in children across ages rather than following the same children over time as was done in the current study. The unresponsiveness of the task to detect change with age in the current study may result from unequal inter-individual and intra-individual differences, meaning there may be a greater change in working memory skills with respect to age when measured in different people compared to assessments in the same individual with time. Additionally the current study used the Object Hit task, a single task requiring multiple components of EDM for completion, while Siegel & Ryan (1989) used a variety of specific tasks designed solely for measuring working memory. The Object Hit task while capable of detecting overall performance change from 5 to 18 years of age was not designed to assess working memory solely. In the same way, the Object Hit task was not designed to target processing time or action planning solely. The analysis may have benefited from the addition of an established task to solely assess working memory, action planning and processing time to the methods to allow for more direct comparison.

Additionally, hand movement area and mean hand speed and maybe influenced by multiple factors beyond EDM, including changes in strategies or changes in coordination. Individual strategy differs between people, whether actions are fast or accurate, or the concept of the speed/accuracy trade-off (Woodworth 1899; Forster, Higgins & Bianco, 2003). Game strategy indicates that people may reward accuracy, resulting in slower, more precise movements in the Object Hit task, or speed, causing a participant to move as quickly as possible to get as many as virtual objects as possible, resulting in increased hand speed and increased hand movement area on the task (Forster, Higgins & Bianco, 2003). The Object Hit task results support this hypothesis as mean hand speed and hand movement area were positively associated ($R^2 = 0.42$, $p \leq 0.01$),
shown in Appendix E, Figure A3. As children age they switch between strategies in a proposed overlapping waves model (Shrager & Siegler, 1998). Continual alteration of the strategy selected through development could influence the association found with respect to mean hand speed and hand movement area as children age. This contributing factor may be limited by explicitly instructing the participant which strategy to utilize.

Hand speed and movement area may also be influenced by personal motor coordination and personal experiences. Childhood development of hand eye coordination and reaction time or hand speed can be affected by personal experiences (Fisher et al., 2005; Udermann et al., 2004). Increased time spent doing moderate physical activity is significantly correlated with improved movement skills (Fisher et al., 2005). For example, children enrolled in a specific cup stacking program enhanced their reaction time and hand eye coordination when compared to a control group (Udermann et al., 2004). In this way, the hand speed and hand movement area results could be affected by individuals’ recreational activities and sports. The inherent variability in individual experiences and their ability to see, think, and act could influence their motor skills, including their bimanual coordination results on the measured attributes of the Object Hit task, impacting their association with age (Kanai & Rees, 2011). Although individual differences in coordination are expected and result in a range of typical performance, the addition of a more in-depth questionnaire on physical activity involvement may have helped in the analysis of the contribution of increased motor coordination.

Hand selection overlap was hypothesized to change with age as a result of the development of action planning skills. Although the linear regression model was not significant, there was an interesting qualitative change in the individual trend lines with age. The individual trend lines slopes varied greatly between -3.5 and 11.2 between the ages of approximately five and eleven
years, while after twelve years of age, the spread of the values of the individual trend line slopes decreases (range between -0.39 to -1.6). This change in individual trend lines may be an indication of the myelination of the prefrontal cortex, and specifically of the corpus callosum. The corpus callosum is the major white matter commissure that connects the cerebral hemispheres (Keshavan et al., 2002). It integrates the information in the right and left hemispheres and is an important structure in providing a unified view of the bimanual workspace, which is necessary for overlapping hands in the Object Hit task (Zaidel & Sperry, 1977). The ability of children to transfer sensorimotor information between hemispheres allows them to be better able to coordinate both arms in the entirety of the visual display. The corpus callosum undergoes myelination from early childhood well into young adulthood (Giedd et al., 1999; Keshavan et al., 2002), and has been documented through fMRI studies to have a rapid change in myelination and axonal size after the age of approximately twelve years (Keshavan et al., 2002). The observed change in the slopes of the individual trend lines at approximately twelve years of age in the hand selection overlap results could be associated with the myelination of the corpus callosum during this time period, leading to increased sensory information transfer between hemispheres. Changes in bimanual coordination and the observed hand selection overlap results at 12 years of age may also be affected by the onset of puberty and the rapid development of muscle strength especially in males (Thomas & French, 1985). The onset of puberty and improved muscle strength after 12 years of age may have impacted bimanual coordination, and the ability to overlap hands in the Object Hit task. The complexity of the Object Hit task may limit its sensitivity to assess action planning development before 12 years of age; prior to the onset of puberty and the myelination of the PFC and the corpus callosum. Further analysis into this observed trend should be complete with more data.
5.2 Clinical implications

The Object Hit task could have potential use as a tool to inform on the diagnosis of pediatric concussions. Children who experience a concussive injury have impaired EDM, including impaired processing time, action planning and working memory due to the sheering of the white matter in the PFC and parietal cortex (Giza &Hovda, 2001). Impairment in these attributes of EDM would hinder the ability of the individual to optimally perform the Object Hit task. The inability to maintain a working memory of the VR workspace, increased time required to process the incoming sensory information, and impairments in strategically planning bimanual coordination would decrease an individual’s overall ability to perform the task compared to their typically developing age-matched peer.

The overall measures of performance, specifically targets hit results, could be used as the basis for comparison. Target hit result did not have floor or ceiling effects between five and eighteen years of age. Five year old participants were able to complete the task and register a targets hit score greater than 0% and only by the age of 18 years did the participants achieve scores comparable to adults (94%) (Tyryshkin et al, 2014). Eighty-four percent of the variability in the target hit results was accounted for by age, with narrow 95% confidence intervals. This is important for detecting the presence of a concussion, as narrow confidence intervals would improve sensitivity and decrease the amount of change in target hit performance that would be required to detect a concussion.

Targets hit results on the Object Hit task could be used to detect a reduction in EDM functioning beyond the span of function that can be considered typical through the continuum of development. This would be accomplished through clinical implementation of cut-off points.
marking the typical performance for a child at a given age. A sample calculation of the cut-off points for a typically developing 7.0 year old can be seen below. The equations for the upper and lower boundaries are taken from the equations of the lines of the 95% confidence intervals reported in Table 5.

Lower boundary = 5.547 + (AGE*4.274)

   = 5.547 + (7.0*4.274)
   = 35.4

Upper boundary = 15.698 + (AGE*5.241)

   = 15.698 + (7.0*5.241)
   = 52.4

These values would indicate to a clinician that a typically developing 7.0 year old should have hit between 35.4% and 52.4% of the targets in the Object Hit task. The accuracy of this calculation was checked with the results of an individual participant (745) who completed the task when they were 7.04 years old. They achieved a target hit score of 48.1 percent, which is situated between the upper and lower boundaries. A score lower than 35.4% or lower than the 95% confidence boundary for typically developing children 7.0 years of age could indicate that there is impaired EDM at the time of testing, indicating a possible concussion. It should be noted that with increased participant numbers the confidence boundaries would provide better estimates of typical function.
Chapter 6
Conclusions and Limitations

The results from this study indicate that overall measures of performance on the Object Hit task are responsive to longitudinal age related changes in EDM related to sensory motor control from five to eighteen years of age. The overall performance measures were sensitive and able to identify age related improvements over the entire age range with 84% of the change in targets hit accounted for by age, and 72% of the change in median error accounted for by age. The Object Hit task may provide a useful clinical method for quantifying change in overall EDM following a concussion in childhood and adolescence, but further research is required. Attributes specific to working memory, processing time and action planning, components of EDM, that are susceptible to injury following a concussion were not responsive to age. Change in mean hand speed, hand movement area, and hand selection overlap were not largely accounted for by age. Individualized hand selection overlap trend lines had a qualitative change at approximately 12 years of age indicating that the relationship may not be linear; however statistical evaluation of the relationship would require a greater number of participants and more data points.

One limitation with the current study is the small population size of twenty individuals, with 76 data points. Longitudinal studies require a lot of time and money to be accomplished with a great significant power, as well as a lot of dedication from participants in order to have repeat measures done in a timely fashion. In longitudinal studies there is always a significant drop out rate in participant numbers which has to be accounted for with incredibly large participant groups at the starting point (Rajulton, 2001). Although there are many difficulties with longitudinal studies, there are also significant benefits in their ability to detect development at both group and individual levels (Rajulton, 2001). Longitudinal studies are the foundation for understanding
motor skill development and allow for the inference of developmental changes in the underlying mechanisms (Thelen, 2000).

An additional limitation of the study is that the testing protocol would have also benefited from the completion of established clinical tests of EDM (for example, the counting task for working memory assessment) (Case, Kurland, & Goldberg, 1982), or the ImPACT for direct comparison in addition to the general health questionnaire. This would have allowed for a more direct comparison of the results of the Object Hit task to help to reinforce its predictive abilities of EDM and concussion management.
References


Appendix A

REB Approval

QUEEN'S UNIVERSITY HEALTH SCIENCES AND AFFILIATED TEACHING HOSPITALS
RESEARCH ETHICS BOARD ANNUAL RENEWAL

Queen's University, in accordance with the "Tri-Council Policy Statement 2, 2010" prepared by the Interagency Advisory Panel on Research Ethics for the Canadian Institutes of Health Research, Natural Sciences and Engineering Research Council of Canada and Social Sciences and Humanities Research Council of Canada requires that research projects involving human participants be reviewed annually to determine their acceptability on ethical grounds.

A Research Ethics Board composed of

Dr. A.F. Clark, Emeritus Professor, Department of Biomedical and Molecular Sciences, Queen's University (Chair)
Dr. H. Abdollah, Professor, Department of Medicine, Queen's University
Dr. C. Cline, Assistant Professor, Department of Medicine, Director, Office of Bioethics, Queen's University, Clinical Ethicist, Kingston General Hospital
Dr. R. Briton, Professor, Department of Emergency Medicine, Queen's University
Dr. M. Evans, Community Member
Ms. J. Hodasc, Community Member
Mr. D. McNaughton, Community Member
Ms. P. Newman, Pharmacist, Clinical Care Specialist and Clinical Lead, Quality and Safety, Pharmacy Services, Kingston General Hospital
Mr. S. Rodland, Privacy Officer, ICES-Queen's Health Services Research Facility, Research Associate, Division of Cancer Care and Epidemiology, Queen's Cancer Research Institute
Dr. A. Saeigh, Professor, Department of Psychiatry, Queen's University
Dr. J. Walla, Assistant Professor and Clinical Geneticist, Department of Paediatrics, Queen's University and Kingston General Hospital
Ms. K. Weissbaum, LL.B. and Adjunct Instructor, Department of Family Medicine (Bioethics)

has reviewed the request for renewal of Research Ethics Board approval for the project “Developmental Studies of Multi-Joint Upper Limb Movements” as proposed by Dr. L. Pelland of the School of Rehabilitation Therapy, at Queen's University. The approval is renewed for one year, effective January 06, 2014. If there are any further amendments or changes to the protocol affecting the participants in this study, it is the responsibility of the principal investigator to notify the Research Ethics Board. Any unexpected serious adverse event occurring locally must be reported within 2 working days or earlier if required by the study sponsor. All other adverse events must be reported within 15 days after becoming aware of the information.

Alastair J. Clark

Date: April 15, 2014

Chair, Health Sciences Research Ethics Board

Renewal [ ] Renewal 2 [ ] Extension [x] Code# REH-285-06 Room# file# 6004821
Appendix B

Consent Form

EVALUATION STUDIES OF COGNITIVE AND MOTOR DEFICITS FOLLOWING A SPORT RELATED CONCUSSION

VOLUNTARY CONSENT TO PARTICIPANT
This page is the ethics consent page and there are two copies: one is for you to keep and the second is for the researcher. By signing this consent form, you realize that you do not waive your legal rights nor release the investigator and sponsors from their legal and professional responsibilities.

What does my signature mean?
When you sign below, you are declaring that following:

- I was given a verbal presentation about the above mentioned research study.
- I was given this ethics consent letter of information to read and keep
  - If the participant is a minor, he/she has completed the child assent form for this study.
- I was aware that by participating in this study:
  - I will complete a general health survey questionnaire and that my parent (legal guardian) can help me in completing this form as necessary.
  - I will complete a series of upper limb tasks using the KINARM robot if I meet the assessment criteria.
  - I will complete the ImPACT test battery.
  - I will return once a month to perform the KINARM task and ImPACT for a period of six months.
- I realize that I can withdraw at any time without pressure and if I withdraw from this study there will be no affect on the services that I may receive at Hotel Dieu Hospital, Kingston Concussion Center, or the Child Development Center.
- I know that I can contact any of the people identified in the Ethics Consent Letter if I have questions, concerns, or complaints.
- I realize that my data will be kept confidential to researchers only
- I can ask to get a copy of study results
- I agree to participate in this study

______________________________  _________________________
Signature of Child/Youth Participant  Date

______________________________  _________________________
Signature of Parent/Guardian  Date

______________________________  _________________________
Signature of Researcher  Date
Appendix C

Personal Information Form

Questionnaire

EVALUATION STUDIES OF COGNITIVE AND MOTOR DEFICITS FOLLOWING A
SPORT RELATED CONCUSSION

Participant Information

Please answer all the questions that you can. Feel free to ask for clarification of any items. If you are completing this form on behalf of a participant in the study, please answer the questions with respect to the participant. If for any reason you choose not to answer some of these questions please skip ahead to the next question you are willing to answer.

Thank you very much for helping with our study!

A. GENERAL INFORMATION

Participant's name: __________________________________________

Date of Birth: (Day/Mo/Yr): ________________________________

Sex (M/F): __________

Age: __________

Telephone: ______________________

Parent/Guardian (if participant is a minor): ______________________

Address: ________________________________________________

Email: ________________________________________________
B. EDUCATION HISTORY

Last school grade completed: ______________________

Have you ever been diagnosed with a learning disability? No Yes

If yes: When? ______________________

Type? ______________________

Has your child ever been in a special education program? No Yes

If yes: Number of months/years in the special program: ____________

Are they currently in a special program? No Yes

C. MEDICAL HISTORY

How would you describe your child’s health? (Circle one)

Very Poor Poor Fair Good Very Good

How would you describe your child’s hearing? (Circle one)

Poor Fair Good

Has your child’s vision ever been tested? No Yes

If yes, what were the results? ______________________

Is she/he colour blind? No Yes Don’t Know

How would you describe your child’s speech articulation? (Circle one)

Poor Fair Good

Your child’s co-ordination:

Describe gross motor coordination for lower limbs (running, jumping, etc.)

Poor Fair Good

Describe gross motor coordination for upper limbs (catching, throwing, etc.)

Poor Fair Good

Describe fine motor coordination (writing, buttoning, etc.)

Poor Fair Good
(C. MEDICAL HISTORY continued)

Has your child had any accidents resulting in the following? (Check all those that apply)

- Broken bones
- Eye injury
- Severe lacerations
- Head injury
- Lost teeth
- Stomach pump
- Severe bruises
- Sutures
- Upper limb injury
- Other (specify)   

How many accidents has your child experienced?

- 1
- 2-3
- 4-7
- 8-12
- 12+

Does your child have any problems sleeping?  
No  Yes

Does your child have any chronic health problems (e.g., asthma, arthritis etc...)  
No  Yes

If yes, please specify

Have your child ever had a seizure?  
No  Yes

If yes, has there been a diagnosis of seizure disorder or epilepsy?  
No  Yes

Has your child ever been diagnosed with any of the following? Check those that apply. If yes, indicate when the first diagnosis occurred, and whether criteria for the diagnosis are currently met.

<table>
<thead>
<tr>
<th>Disorder</th>
<th>Age diagnosed</th>
<th>Current? (No/Yes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attention Deficit/Hyperactivity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Disorder (ADHD)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anxiety Disorder</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depression</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oppositional Defiant Disorder</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Autism</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asperger’s Disorder</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Developmental Delay</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cerebral Palsy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neurological Disorder</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other? (specify)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Is your child currently taking any medication?  
No  Yes

If yes: What medication(s)?

Date started:  

62
D. FAMILY HISTORY

Is your child adopted?  
No  
Yes

Who does your child live with? (Please list each family member and his or her age)

<table>
<thead>
<tr>
<th>Relationship to child</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

Please indicate mother’s highest grade completed, or degree: __________________________

Please indicate father’s highest grade completed, or degree: __________________________

Please indicate if there is a family history of any of the following. When yes, place a check next to the item and indicate the relationship of the family member(s) to your child (e.g. uncle on mother’s side). If adopted, only complete for biological family members.

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>Family member (relation to participant)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concussion:</td>
<td></td>
</tr>
<tr>
<td>ADHD or ADD:</td>
<td></td>
</tr>
<tr>
<td>Developmental Delay:</td>
<td></td>
</tr>
<tr>
<td>Learning Disability:</td>
<td></td>
</tr>
<tr>
<td>Anxiety disorder:</td>
<td></td>
</tr>
<tr>
<td>Problems with aggressive, or defiant, behaviour as a child:</td>
<td></td>
</tr>
<tr>
<td>Problems with attention and impulse control as a child:</td>
<td></td>
</tr>
<tr>
<td>Other (specify):</td>
<td></td>
</tr>
</tbody>
</table>
E. CONCUSSION HISTORY

Has your child ever suffered from a concussion?  No  Yes

If yes: How many concussions? ______________________

Regarding your most recent concussion:

What was the date of the injury? ______________________

Did the injury occur during an athletic activity?  No  Yes

If No: How did the injury occur? ______________________

If Yes: During what sport/activity? ______________________

Was it competitive or recreational? ______________________

Describe the incident that lead to a concussion: ______________________

Did you seek medical attention?  No  Yes

If No: Why? ________________________________________

If Yes: Where did you go?

Family Doctor  Emergency Department  Other ______________________

How long after the injury did you seek medical attention (hours/days)? __________

Since the concussion, has the child returned to school?  No  Yes

If yes: When? ______________________

Since the concussion, had the child returned to athletic activities?  No  Yes

If yes: When? ______________________

What activities? ______________________
E. CONCUSSION HISTORY (continued)

If you have suffered from multiple concussions, for every time your child has a concussion, please fill out the date of the injury, the cause/mechanism specifically (car accident, sport, fall), return to play date, and if medical attention was sought (yes, no).

<table>
<thead>
<tr>
<th>Date of Injury</th>
<th>Cause</th>
<th>Date of Return to Play</th>
<th>Received Medical Attention?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Thank you very much for your co-operation and your time!!!
<table>
<thead>
<tr>
<th>Participant Code</th>
<th>Date of Birth</th>
<th>Sex</th>
<th>Handedness Quotient</th>
<th>Test Date</th>
<th>Age at Test (Years)</th>
<th>Target Hits (%)</th>
<th>Median Error (%)</th>
<th>Mean Hand Speed (cm/s)</th>
<th>Movement Area (cm²)</th>
<th>Hand Selection Overlap (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>492</td>
<td>30-Apr-03</td>
<td>F</td>
<td>100</td>
<td>14-Mar-13</td>
<td>9.9</td>
<td>62.7</td>
<td>66.3</td>
<td>37.2</td>
<td>1341.0</td>
<td>11.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>30-Jun-11</td>
<td></td>
<td>8.2</td>
<td>53.7</td>
<td>62.7</td>
<td>29.7</td>
<td>1156.7</td>
<td>11.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>03-Feb-11</td>
<td></td>
<td>7.8</td>
<td>40.0</td>
<td>60.0</td>
<td>24.5</td>
<td>784.5</td>
<td>10.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>08-Jul-10</td>
<td></td>
<td>7.2</td>
<td>45.0</td>
<td>55.7</td>
<td>27.7</td>
<td>729.1</td>
<td>11.1</td>
</tr>
<tr>
<td>574</td>
<td>07-May-03</td>
<td>M</td>
<td>25</td>
<td>06-Nov-13</td>
<td>10.5</td>
<td>63.0</td>
<td>70.0</td>
<td>20.9</td>
<td>924.0</td>
<td>14.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>12-Jun-11</td>
<td></td>
<td>8.1</td>
<td>54.3</td>
<td>63.7</td>
<td>20.7</td>
<td>1062.2</td>
<td>12.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>27-Oct-10</td>
<td></td>
<td>7.5</td>
<td>52.7</td>
<td>61.0</td>
<td>32.3</td>
<td>1223.8</td>
<td>10.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>29-Jun-10</td>
<td></td>
<td>7.1</td>
<td>51.0</td>
<td>62.3</td>
<td>28.6</td>
<td>1104.7</td>
<td>12.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>03-Jun-10</td>
<td></td>
<td>7.1</td>
<td>39.3</td>
<td>56.0</td>
<td>23.0</td>
<td>1052.2</td>
<td>7.6</td>
</tr>
<tr>
<td>600</td>
<td>10-Jun-03</td>
<td>M</td>
<td>38</td>
<td>29-Oct-13</td>
<td>8.4</td>
<td>59.3</td>
<td>63.7</td>
<td>24.3</td>
<td>904.0</td>
<td>9.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>25-Jul-11</td>
<td></td>
<td>8.1</td>
<td>49.0</td>
<td>61.3</td>
<td>34.7</td>
<td>1227.4</td>
<td>20.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>12-Jul-10</td>
<td></td>
<td>7.1</td>
<td>41.3</td>
<td>57.7</td>
<td>24.5</td>
<td>960.7</td>
<td>19.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>05-Jul-10</td>
<td></td>
<td>7.1</td>
<td>39.7</td>
<td>55.3</td>
<td>26.2</td>
<td>1028.4</td>
<td>10.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>17-Apr-09</td>
<td></td>
<td>5.9</td>
<td>31.7</td>
<td>54.0</td>
<td>22.6</td>
<td>1133.0</td>
<td>9.5</td>
</tr>
<tr>
<td>614</td>
<td>12-Jan-96</td>
<td>M</td>
<td>50</td>
<td>12-Nov-13</td>
<td>17.8</td>
<td>89.7</td>
<td>83.7</td>
<td>25.9</td>
<td>1089.0</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>12-Jun-11</td>
<td></td>
<td>15.4</td>
<td>83.3</td>
<td>77.0</td>
<td>28.5</td>
<td>1499.1</td>
<td>8.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>05-Jun-10</td>
<td></td>
<td>14.4</td>
<td>74.3</td>
<td>73.7</td>
<td>22.9</td>
<td>1196.7</td>
<td>12.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>26-May-09</td>
<td></td>
<td>13.4</td>
<td>73.7</td>
<td>71.7</td>
<td>23.2</td>
<td>1116.0</td>
<td>8.1</td>
</tr>
<tr>
<td>615</td>
<td>10-Jan-00</td>
<td>M</td>
<td>83</td>
<td>31-Oct-13</td>
<td>13.8</td>
<td>84.7</td>
<td>73.7</td>
<td>25.7</td>
<td>1198.0</td>
<td>11.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>12-Jun-11</td>
<td></td>
<td>11.4</td>
<td>75.7</td>
<td>71.7</td>
<td>27.5</td>
<td>1445.6</td>
<td>15.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>05-Jun-10</td>
<td></td>
<td>10.4</td>
<td>67.7</td>
<td>68.3</td>
<td>25.0</td>
<td>1406.7</td>
<td>18.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>26-May-09</td>
<td></td>
<td>9.4</td>
<td>63.0</td>
<td>66.0</td>
<td>30.4</td>
<td>1512.0</td>
<td>11.1</td>
</tr>
<tr>
<td>Participant Code</td>
<td>Date of Birth</td>
<td>Sex</td>
<td>Handedness Quotient</td>
<td>Test Date</td>
<td>Age at Test (Years)</td>
<td>Target Hits (%)</td>
<td>Median Error (%)</td>
<td>Mean Hand Speed (cm/s)</td>
<td>Movement Area (cm²)</td>
<td>Hand Selection Overlap (%)</td>
</tr>
<tr>
<td>------------------</td>
<td>--------------</td>
<td>-----</td>
<td>---------------------</td>
<td>-----------</td>
<td>---------------------</td>
<td>-----------------</td>
<td>------------------</td>
<td>----------------------</td>
<td>---------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>620</td>
<td>21-Jun-02</td>
<td>F</td>
<td>83</td>
<td>27-Mar-14</td>
<td>11.8</td>
<td>63.3</td>
<td>64.7</td>
<td>20.7</td>
<td>1021.0</td>
<td>6.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>19-Jun-11</td>
<td>9.0</td>
<td>56.3</td>
<td>60.7</td>
<td>22.2</td>
<td>747.4</td>
<td>14.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>01-Jun-10</td>
<td>7.9</td>
<td>45.7</td>
<td>58.7</td>
<td>15.6</td>
<td>1122.9</td>
<td>10.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>12-Jun-09</td>
<td>7.0</td>
<td>39.7</td>
<td>54.7</td>
<td>17.0</td>
<td>773.0</td>
<td>14.3</td>
</tr>
<tr>
<td>630</td>
<td>15-Oct-03</td>
<td>M</td>
<td>-57</td>
<td>05-Nov-13</td>
<td>10.1</td>
<td>65.0</td>
<td>65.7</td>
<td>24.3</td>
<td>964.0</td>
<td>9.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>13-Jul-10</td>
<td>6.7</td>
<td>46.7</td>
<td>63.3</td>
<td>22.6</td>
<td>936.4</td>
<td>10.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>30-Jun-09</td>
<td>5.7</td>
<td>44.3</td>
<td>57.7</td>
<td>21.5</td>
<td>743.0</td>
<td>4.5</td>
</tr>
<tr>
<td>670</td>
<td>06-Jun-97</td>
<td>M</td>
<td>100</td>
<td>18-Jul-11</td>
<td>14.1</td>
<td>81.7</td>
<td>73.3</td>
<td>35.6</td>
<td>2129.0</td>
<td>13.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>07-Jun-10</td>
<td>13.0</td>
<td>81.0</td>
<td>78.3</td>
<td>30.1</td>
<td>1783.3</td>
<td>11.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>31-May-10</td>
<td>13.0</td>
<td>79.3</td>
<td>74.3</td>
<td>33.5</td>
<td>1591.5</td>
<td>13.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>22-Jul-09</td>
<td>12.1</td>
<td>70.7</td>
<td>66.0</td>
<td>25.7</td>
<td>1471.0</td>
<td>16.5</td>
</tr>
<tr>
<td>731</td>
<td>13-Dec-97</td>
<td>M</td>
<td>83</td>
<td>11-Nov-13</td>
<td>15.9</td>
<td>62.0</td>
<td>62.0</td>
<td>28.5</td>
<td>1360.0</td>
<td>7.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>27-Jun-11</td>
<td>13.5</td>
<td>65.3</td>
<td>62.3</td>
<td>32.2</td>
<td>1334.6</td>
<td>17.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>08-Jun-10</td>
<td>12.5</td>
<td>58.7</td>
<td>65.3</td>
<td>30.1</td>
<td>1528.6</td>
<td>10.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>27-Nov-09</td>
<td>12.0</td>
<td>48.0</td>
<td>54.7</td>
<td>19.7</td>
<td>915.3</td>
<td>10.4</td>
</tr>
<tr>
<td>732</td>
<td>22-Dec-02</td>
<td>M</td>
<td>69</td>
<td>02-Mar-13</td>
<td>10.2</td>
<td>63.0</td>
<td>67.3</td>
<td>24.5</td>
<td>1359.0</td>
<td>13.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>21-Feb-11</td>
<td>8.2</td>
<td>55.3</td>
<td>63.3</td>
<td>21.9</td>
<td>1264.6</td>
<td>23.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>01-Feb-10</td>
<td>7.1</td>
<td>54.0</td>
<td>64.0</td>
<td>23.8</td>
<td>1008.5</td>
<td>22.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>27-Nov-09</td>
<td>6.9</td>
<td>37.7</td>
<td>58.0</td>
<td>15.9</td>
<td>582.3</td>
<td>17.7</td>
</tr>
<tr>
<td>745</td>
<td>03-Jan-03</td>
<td>M</td>
<td>83</td>
<td>08-Nov-10</td>
<td>7.8</td>
<td>49.0</td>
<td>58.0</td>
<td>25.7</td>
<td>1440.7</td>
<td>23.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>30-Oct-10</td>
<td>7.8</td>
<td>54.7</td>
<td>56.0</td>
<td>43.1</td>
<td>1434.6</td>
<td>17.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>19-Jan-10</td>
<td>7.0</td>
<td>48.7</td>
<td>56.7</td>
<td>22.1</td>
<td>923.5</td>
<td>11.6</td>
</tr>
<tr>
<td>Participant Code</td>
<td>Date of Birth</td>
<td>Sex</td>
<td>Handedness Quotient</td>
<td>Test Date</td>
<td>Age at Test (Years)</td>
<td>Target Hits (%)</td>
<td>Median Error (%)</td>
<td>Mean Hand Speed (cm/s)</td>
<td>Movement Area (cm²)</td>
<td>Hand Selection Overlap (%)</td>
</tr>
<tr>
<td>------------------</td>
<td>--------------</td>
<td>-----</td>
<td>---------------------</td>
<td>-----------</td>
<td>---------------------</td>
<td>----------------</td>
<td>----------------</td>
<td>-----------------------</td>
<td>-------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>775</td>
<td>25-Dec-99</td>
<td>M</td>
<td>83</td>
<td>16-Jun-11</td>
<td>11.5</td>
<td>69.3</td>
<td>70.0</td>
<td>35.4</td>
<td>1354.7</td>
<td>8.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>30-Oct-10</td>
<td>10.8</td>
<td>59.7</td>
<td>68.0</td>
<td>23.9</td>
<td>1500.5</td>
<td>12.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>28-Feb-10</td>
<td>10.2</td>
<td>52.3</td>
<td>67.3</td>
<td>36.9</td>
<td>1399.4</td>
<td>12.1</td>
</tr>
<tr>
<td>805</td>
<td>26-Apr-05</td>
<td>F</td>
<td>87</td>
<td>06-Nov-13</td>
<td>8.5</td>
<td>49.3</td>
<td>64.3</td>
<td>24.3</td>
<td>1028.0</td>
<td>8.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>12-Jun-11</td>
<td>6.1</td>
<td>41.3</td>
<td>57.3</td>
<td>33.6</td>
<td>975.9</td>
<td>21.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>11-Feb-11</td>
<td>5.8</td>
<td>37.0</td>
<td>58.3</td>
<td>20.3</td>
<td>628.9</td>
<td>9.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>29-Jun-10</td>
<td>5.2</td>
<td>26.3</td>
<td>55.3</td>
<td>28.6</td>
<td>920.0</td>
<td>19.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>03-Jun-10</td>
<td>5.1</td>
<td>27.7</td>
<td>53.0</td>
<td>17.5</td>
<td>597.4</td>
<td>16.9</td>
</tr>
<tr>
<td>835</td>
<td>01-Jul-05</td>
<td>F</td>
<td>71</td>
<td>12-Apr-14</td>
<td>7.8</td>
<td>37.3</td>
<td>58.0</td>
<td>33.8</td>
<td>1263.0</td>
<td>8.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>23-Jul-11</td>
<td>6.1</td>
<td>33.3</td>
<td>56.7</td>
<td>25.0</td>
<td>701.9</td>
<td>13.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15-Jan-11</td>
<td>5.5</td>
<td>23.0</td>
<td>53.0</td>
<td>17.9</td>
<td>598.3</td>
<td>4.3</td>
</tr>
<tr>
<td>836</td>
<td>10-Dec-01</td>
<td>M</td>
<td>37</td>
<td>12-Apr-14</td>
<td>12.3</td>
<td>68.3</td>
<td>68.0</td>
<td>26.3</td>
<td>1328.0</td>
<td>10.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>23-Jul-11</td>
<td>9.6</td>
<td>56.3</td>
<td>60.7</td>
<td>25.1</td>
<td>1348.1</td>
<td>16.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15-Jan-11</td>
<td>9.1</td>
<td>52.0</td>
<td>63.3</td>
<td>24.5</td>
<td>1468.9</td>
<td>16.7</td>
</tr>
<tr>
<td>837</td>
<td>21-Jun-04</td>
<td>M</td>
<td>41</td>
<td>12-Apr-14</td>
<td>8.8</td>
<td>47.3</td>
<td>60.3</td>
<td>19.8</td>
<td>1030.0</td>
<td>7.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>23-Jul-11</td>
<td>7.1</td>
<td>46.3</td>
<td>64.0</td>
<td>24.2</td>
<td>1176.6</td>
<td>15.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15-Jan-11</td>
<td>6.6</td>
<td>40.3</td>
<td>56.0</td>
<td>20.1</td>
<td>1047.3</td>
<td>14.9</td>
</tr>
<tr>
<td>841</td>
<td>24-Mar-03</td>
<td>F</td>
<td>92</td>
<td>30-Nov-13</td>
<td>10.7</td>
<td>71.3</td>
<td>65.0</td>
<td>20.7</td>
<td>983.0</td>
<td>19.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>25-Jul-11</td>
<td>8.3</td>
<td>50.3</td>
<td>60.0</td>
<td>16.5</td>
<td>921.0</td>
<td>21.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>29-Jan-11</td>
<td>7.9</td>
<td>48.7</td>
<td>59.3</td>
<td>14.2</td>
<td>548.2</td>
<td>6.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>22-Jan-11</td>
<td>7.8</td>
<td>45.7</td>
<td>58.0</td>
<td>13.8</td>
<td>664.5</td>
<td>13.9</td>
</tr>
<tr>
<td>842</td>
<td>20-May-98</td>
<td>M</td>
<td>57</td>
<td>30-Nov-13</td>
<td>15.5</td>
<td>83.0</td>
<td>69.3</td>
<td>28.5</td>
<td>1258.0</td>
<td>8.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>26-Jun-11</td>
<td>13.1</td>
<td>78.0</td>
<td>75.7</td>
<td>25.5</td>
<td>1221.3</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>22-Jan-11</td>
<td>12.7</td>
<td>72.0</td>
<td>68.0</td>
<td>24.9</td>
<td>1397.5</td>
<td>13.0</td>
</tr>
<tr>
<td>Participant Code</td>
<td>Date of Birth</td>
<td>Sex</td>
<td>Handedness Quotient</td>
<td>Test Date</td>
<td>Age at Test (Years)</td>
<td>Target Hits (%)</td>
<td>Median Error (%)</td>
<td>Mean Hand Speed (cm/s)</td>
<td>Movement Area (cm²)</td>
<td>Hand Selection Overlap (%)</td>
</tr>
<tr>
<td>------------------</td>
<td>---------------</td>
<td>-----</td>
<td>---------------------</td>
<td>-----------</td>
<td>---------------------</td>
<td>------------------</td>
<td>-------------------</td>
<td>------------------------</td>
<td>----------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>843</td>
<td>24-Jun-99</td>
<td>F</td>
<td>92</td>
<td>30-Nov-13</td>
<td>14.4</td>
<td>85.0</td>
<td>72.7</td>
<td>26.4</td>
<td>1253.0</td>
<td>11.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>25-Jul-11</td>
<td>12.1</td>
<td>77.7</td>
<td>72.7</td>
<td>28.2</td>
<td>1540.4</td>
<td>19.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>29-Jan-11</td>
<td>11.6</td>
<td>68.3</td>
<td>69.0</td>
<td>21.0</td>
<td>1096.7</td>
<td>13.2</td>
</tr>
<tr>
<td>849</td>
<td>23-Apr-96</td>
<td>M</td>
<td>50</td>
<td>30-Nov-13</td>
<td>17.6</td>
<td>89.3</td>
<td>79.0</td>
<td>29.7</td>
<td>1247.0</td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>26-Jun-11</td>
<td>15.2</td>
<td>86.7</td>
<td>80.7</td>
<td>31.2</td>
<td>1294.5</td>
<td>8.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>05-Feb-11</td>
<td>14.8</td>
<td>85.7</td>
<td>71.3</td>
<td>22.6</td>
<td>877.3</td>
<td>9.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>23-Jan-11</td>
<td>14.8</td>
<td>80.0</td>
<td>69.0</td>
<td>23.0</td>
<td>973.8</td>
<td>7.5</td>
</tr>
</tbody>
</table>
Appendix E
Additional Figures

Figure A1: Individualized Trend Lines for Targets Hit (Panel A) and Hand Movement Area (Panel B)

The results of each individual participant are marked with a different symbol. The solid lines represent the trend line for each individual’s improvements with age, and the dotted lines mark the lower and upper boundaries of the 95% confidence intervals.
Figure A2: Individualized Trend Lines for Median Error (Panel A) and Dominant Hand Speed (Panel B)

The results of each individual participant are marked with a different symbol. The solid lines represent the trend line for each individual’s improvements with age, and the dotted lines mark the lower and upper boundaries of the 95% confidence intervals.
Figure A3: Mean Hand Speed and Hand Movement Area

The mean hand speed and the hand movement area performance was evaluated with linear regression analysis. Each data point represents the performance results of a single completed Object Hit task. The solid line represents the linear regression trend line. 42% of the variability in hand movement area was accounted for by mean hand speed ($p \leq 0.001$)